DESIGN, CONSTRUCTION AND PERFORMANCE TESTING OF A LANDSCAPE IRRIGATION RUNOFF MITIGATION SYSTEM

A Thesis

by

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ABSTRACT

The study of water-saving technology is critically important due to urban population growth, drought, and decreasing potable water supplies in Texas and throughout many parts of the world. Because current water supplies are not expected to meet water demand in the coming decades, this could have serious impacts on families, industrial growth, and economic stability. At the same time, water is wasted every year by inefficient or improper landscape irrigation practices. After thorough research on products available on the market today, it was found that none exist with the function of managing lawn/landscape irrigation based on detection of runoff. Thus, designing a device which could mitigate landscape runoff could potentially 1) offer greater landscape irrigation efficiency and water conservation, 2) improve water quality of streams and lakes, and 3) contribute to efforts aimed at addressing the future water crisis.

This research investigated a Landscape Irrigation Runoff Mitigation System (LIRMS) for minimizing irrigation water losses from residential or commercial landscapes. Four types of irrigation runoff sensors were designed and manufactured. A central control module for receiving signals from sensors and controlling several irrigation valves at the same time was also designed. Afterwards, the prototypes were installed in the field and hardwired with the central control module along with two control plots with no runoff sensors installed. The different prototypes were evaluated based on their performance characteristics including the ability of each to work reliably over an extended period of time and to effectively reduce runoff.

A website was designed so that irrigation data could be accessed online. Also, a wireless communication module and an autonomous energy system were designed and tested to allow the wireless communication between the irrigation runoff sensor and the control unit as well as to reduce energy consumption.

The Landscape Irrigation Runoff Mitigation System (LIRMS) equipped with the cubic float prototype/conductivity prototype showed the highest potential for water conservation, leading to a runoff reduction rate of 40% - 50%. Further studies should focus on advancing the wireless communication module and conducting more tests under different irrigation strategies for refining the system to reduce even greater amounts of runoff.

DEDICATION

To Dr. Jorge L. Alvarado for his inspiration and support

To my parents, for all of their love and support.

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NOMENCLATURE

Variables

C	Specific Heat
R	Irradiance
G	Ground Soil Heat Flux
ρ	Density
e	Pressure
r	Resistance
Q	Runoff Flow Rate
N	Rotational Speed
D	Diameter

Greek symbols

Δ	Rate that Saturation Specific Humidity Changes With Air Temperature Change
γ	Psychrometric Constant

Subscripts

n	Net
a	Air
s	Surface
p	Constant Pressure

Acronyms

LIRMS	Landscape Irrigation Runoff Mitigation System
SS	Suspended Solids
VSS	Volatile Suspended Solids
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
PAH	Polycyclic Aromatic Hydrocarbons
DU	Distribution Uniformity
ET Controller	Evapotranspiration based Controller
SMS	Soil Moisture Sensor
VWC	Volume Water Content
GPM	Gallons per Minute
RPM	Rounds per Minute
ABS	Acrylonitrile Butadiene Styrene
PVC	Polyvinyl Chloride
PS	Polystyrene
PCB	Printed Circuit Board
SD	Secure Digital
EIT	Effective Irrigation Time
WT	Wait Time
TAW	Total Allowable Window
IT	Irrigation Time

WIF	Weekly Irrigation Frequency
SI	Start of the Irrigation
RDT	Runoff Detection Time
RET	Runoff Existing Time

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1. INTRODUCTION+

1.1 Background

Greater stewardship of municipal water supplies has become critical in Texas, given the anticipated population growth between 2010 and 2060, which could be around 82%. This is likely to place strains on current water supplies in the state [2]. According to the Texas 2012 State Water Plan, water demand is expected to outpace water supplies by the year 2060. The amount of the water needed and supplied is depicted in Figure 1.

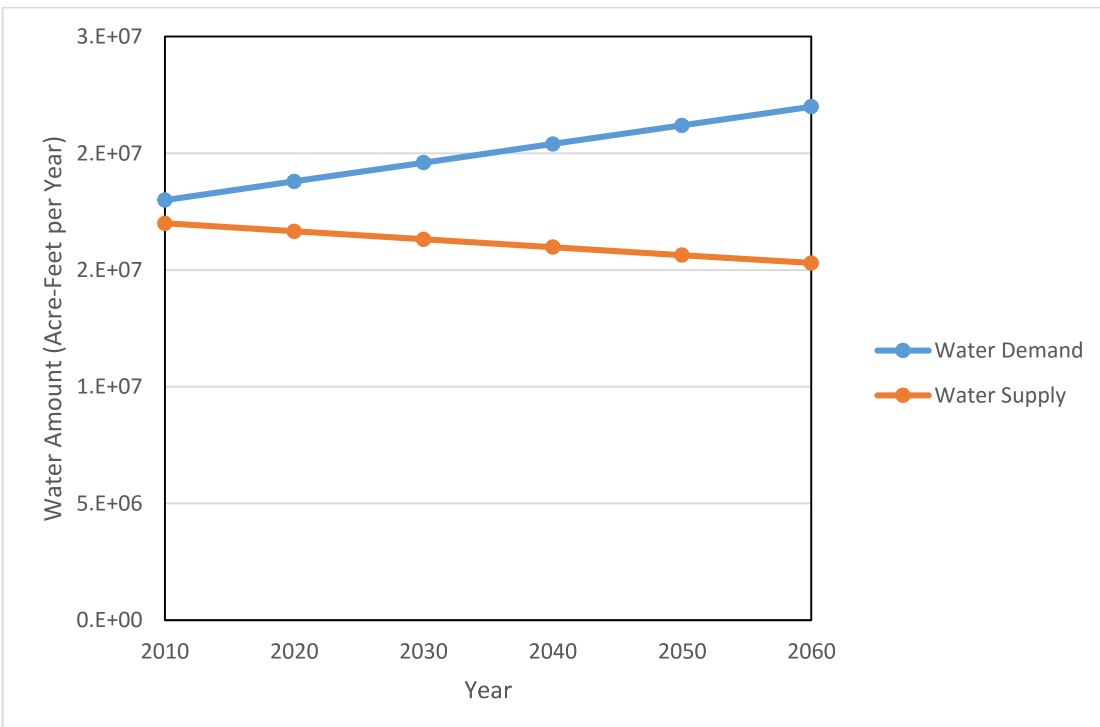

Figure 1. Amount of Water Needed and Supplied (Acre-Feet per Year) (Generated from the Data in Texas 2012 State Water Plan)

A provisional patent for the LIRMS has been filed with the U.S. Patent andTrademark office [1].

Municipal water conservation is a cost-effective means of ensuring water availability for the future. Second only to agricultural uses, urban-municipal uses are the second largest component of water use in Texas, which occupied 27% of water demand in Texas in 2010 [3]. Also, about 30 percent of residential water usage is devoted to outdoors uses, while this number could be as high as 60 percent in Southwest of United States [4]. Many households use much more water than is necessary for irrigating outdoors, which leads to the excess water running into the street, also referred to as 'runoff', shown in Figure 2 [5-6].

Figure 2. Wasted Irrigation Water Running Off a Residential Texas Landscape and into Storm Sewer Drains

Runoff occurs when the irrigation precipitations rate exceeds the infiltration rate of the soil. It could also be affected by the soil and site characteristics such as slope or compacted soil [7]. While this is an obvious waste of water, it also is a concern because of the potential for transport of fertilizers and pesticides into storm sewers and eventually surface waters [8]. With the increasing implementation of municipal water restrictions, irrigation events are often limited to only once a week or less. This has resulted in a tendency of homeowners to irrigate excessively on their given watering day, a problem which can be compounded further by poor soil quality.

According to the results of the research done by Wherley and White at the Texas A&M Urban Landscape Runoff Field Laboratory, runoff amounts of up to 1/3 of the typical amount of water (2 to 3 cm) from irrigation occurred if cycle-soaking was not applied correctly.

Commercial add-on products used to enhance efficiency of irrigation have already appeared in the market. Developed with different working mechanisms, most of these are sold as ‘add-on’ features to existing irrigation controllers to help better manage irrigation efficiently. However, these add-on items are usually expensive, which limits their wide spread use and expansion. Also, some of the add-ons, such as rain sensor, simply stop irrigation when rain is occurring and would not necessarily prevent excess irrigation by user. A sensor which is based on controlling irrigation based on detection of runoff could therefore be a great complement to these add-ons.

1.2 Landscape Irrigation Runoff Mitigation System Design and Strategies

In this study, a landscape irrigation runoff mitigation system (LIRMS) has been designed which its working principle or activation mechanism is based on runoff. The LIMRS contains a central control unit, could detect the existence of runoff in the field and control the valves which provide water to the sprinklers. If runoff is detected by the system, it is able to communicate wirelessly with the central control unit, allowing the irrigation process to stop for a given period of time before restarting to finish the irrigation cycle. Upon resuming irrigation, the system will detect the runoff again and pause if the runoff is detected again. This working/pause schedule will continue until the total expected irrigation time is satisfied. An automated, smart cycle-soaking is achieved by the working mechanism as a result.

The LIMRS is required to be durable, reliable and low-cost. It is designed to be either installed at the construction phase or an add-on item for existing irrigation systems in a household or other areas. Given its advanced working principle, it could complement or take place of some of the existing add-ons, such as rain sensors. It may have to be adapted to different types of soil conditions and provide reliable feedback of runoff during irrigation events.

1.3 Motivation for Current Work

The study of water-saving technology is a critically important issue due to urban population growth, drought, and decreasing potable water supplies in Texas and throughout many parts of the world. Because current water supplies are not expected to meet water demand in the coming decades, this could have serious impacts on families, industrial growth, and economic stability. At the same time, water is wasted every year by inefficient or improper landscape irrigation practices. Thus, designing a device which could mitigate landscape runoff could potentially 1) offer greater landscape irrigation efficiency and water conservation, 2) improve water quality of streams and lakes, and 3) contribute to efforts aimed at addressing the future water crisis.

After a thorough research on similar products available in market today, it was found that no products exist with the function of managing lawn/landscape irrigation based on the detection of runoff. Therefore, the study of designing and characterizing a reliable, durable and low cost landscape irrigation runoff mitigation system was undertaken.

2. LITERATURE REVIEW

This section highlights many of the current issues and problems that have led to the need for development of a landscape irrigation runoff mitigation system (LIRMS). The section has been divided into four parts. The first part focuses on current circumstances and effects of the urban runoff. The second part discusses water conservation status in urban areas. In addition, the third part discusses the concepts and examples of commercial irrigation sensors. The fourth part focuses on current runoff mitigation strategies.

2.1 Current Circumstances and Effects of Urban Runoff

Much research has been done to investigate the effects of urban runoff on the environment. Weibel et al. [9] introduced the study of role of urban land runoff in stream pollution as early as 1962. A residential area with a population of about 240 and a density of 9 persons/acre was chosen in the study. The sample area included family homes, stores, restaurants and other public buildings. It was also partially equipped with grassed or gravel gutters. Weibel et al. [9] showed that storm runoff increased suspended solids (SS) in nearby streams by 140 percent; volatile suspended solids (VSS) by 44 percent; chemical oxygen demand (COD) by 25 percent; biochemical oxygen demand (BOD) by 6 percent; phosphate by 9 percent; and nitrogen by 11 percent. As a result, urban runoff could not be neglected as a factor of pollution.

Gromaire-Mertz et al. [10] conducted research on urban runoff pollution in Paris. Growing population was considered to make urban runoff a major threat to both flow quantity and quality. In their work, a district named "Le Marais" was selected and three major urban runoff types were investigated: runoff from roofs; runoff from streets and runoff from courtyards, public areas and gardens. Their research found that heavy metal concentrations in runoff greatly exceeded level 2 water quality standards in France, especially for the Zn and Pb concentrations, which even exceeded the limits of industrial discharged water. Gromaire-Mertz et al.'s characterization confirmed that urban runoff could directly impact water quality.

A study by Kimbrough et al. [11] investigated pesticide levels in Colorado streams from April 1993 to April 1994. The study compared levels of pesticides in streams within both agricultural and an urban areas of the state. The water samples, which were analyzed for 47 pesticides, showed 30 pesticides were detected in agricultural areas, while 22 pesticides detected in urban areas. The study demonstrated that agricultural and urban areas both contribute to the spread of pesticides in streams. Similar research was conducted by Weston et al. [12]. The research focused on the pyrethroid pesticides carried by the residential runoff to urban streams. From earlier tests of 20 urban streams in California, pyrethroid pesticides were found exceeding toxicity thresholds and it was believed that this situation was not unique to California only. Also, highest concentration of pyrethroid pesticides were found in drain outfalls from earlier work by Weston et al. and thus storm drains have been assumed to be a major source of the pollution in California streams. Later tests showed all samples collected from the streams contained pyrethroid pesticides and could kill H.azteca, leading to a survival rate between 9 and 70%. The research indicated that the storm runoff is the most significant cause of transporting pyrethroid pesticides to local creeks, while summer irrigation runoff could not be neglected as a source of pollution either.

Hoffman et al. [13] proposed that urban runoff could also result in the presence of polycyclic aromatic hydrocarbons (PAHs) in coastal areas. The author collected urban runoff from four storm drains, each linked to a different type of land use; specifically suburban residential, commercial, heavy industrial, and multilane highway. Collected samples were analyzed for PAH, with the amount of PAH created by a storm calculated by multiplying the concentration of PAH by drain flow rate and time interval. Results of the study showed PAH loading factors were similar between suburban residential and commercial locations, with industrial locations also sharing a similar loading potential as highways. The results showed that the urban runoff was responsible for 71% of the total higher molecular weight of PAHs and 36% of the total PAHs that enter the Narragansett Bay.

Finally, nutrient loss caused by the runoff from turfgrass was investigated by Gross et al. [14]. An unfertilized plot was set aside as the control group while granular and liquid forms of fertilizers were applied to the experimental plots. Results showed that runoff from the experimental groups had significantly higher concentrations of total Nitrogen, Percolate NO_3-N and NO_3-N compared with the control group, which proved that runoff from turfgrass flushes or removes nutrients from soil and thus represents a threat to surface water.

2.2 Water Conservation in Urban Areas

With declining water quality and potable water supplies occurring throughout much of the world, water conservation has become highly important within the last few decades and is likely to remain important in the future. Based on the 2012 Texas Water Plan [2], water demand is predicted to increase by 22 percent over the next 50 years. Moreover, ground water supplies are expected to decrease by 30 percent, though the surface waters are expected to increase by 6 percent. As a result, water is likely to be in short supply, making water conservation circumstance high priority throughout the state. Ferguson [15] conducted research focusing on possible solutions to achieving water conservation in urban areas. Based on his findings, it is estimated that between 10 to 50 inches of water is used for managing lawns in the United States annually. Also, lawn irrigation use is greatest in arid western states. While some water conservation techniques have already been adopted in agriculture, these same techniques cannot be easily adapted for use in urban areas due to differences between these two area uses. Three different factors impacting water conservation have been identified by Ferguson: urban landscape design, irrigation hardware, and landscape maintenance. For the urban design, adapted plants should be used that fit the moisture requirements of the geographic location in order to minimize water use. Also, runoff from rainfall and irrigation and recycled waste water should be used for irrigation, if at all possible, yet it still remains a challenge due to limited infrastructure in most communities. From the aspect of irrigation hardware, new products such as efficient drip system and programmable automatic controllers are recommended for improving irrigation efficiency and minimizing wasteful water loss. Landscape maintenance practices were also identified as an approach to improving water conservation. This included, for example, reprogramming irrigation controllers frequently to match the changing water requirements of the plants in different seasons.

Finally, another method of basing irrigation requirements on net evapotranspiration was developed by Allen et al. [16]. Reference evapotranspiration could be calculated by using Equation (1), Penman-Monteith Equation:

$$\lambda \mathrm{ET} = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{1}$$

where R_n is the net irradiance, G is the ground soil heat flux, ρ_a is the dry air density, c_p is the specific heat of air at constant pressure, $(e_s - e_a)$ is the pressure deficit of air, r_a and r_s are the aerodynamic and surface resistances, Δ is the rate that saturation specific humidity changes with air temperature change and γ is the psychrometric constant. Based on Penman-Monteith Equation, Cabrera et al. [3] conducted an evaluation of urban landscape water use in Texas. The authors then introduced several methods which could be applied to conserve water. Using water-saving plants and designing the ecogeographical region intelligently have been recommended as the basic method to conserve water. Also, precision landscape irrigation could be applied to any existing landscapes to improve irrigation efficiency. Moreover, designing irrigation systems specifically to the site, soil and plant type, tuning them after installation and properly utilizing the irrigation sensors could contribute to water conservation. Finally, reduced use of fresh water and greater use of alternative water sources such as recycled wastewater, condensate water, and graywater for irrigation are critical for alleviating demand on potable water supplies.

2.3 Potential and Commercial Products for Irrigation Control

Commercial smart irrigation controllers have already been developed to conserve water and optimize the irrigation process. The most widely recognized smart irrigation controllers are evapotranspiration based controllers, rain sensors and soil moisture sensors.

Based on the working mechanism, rain sensors are divided into water weight, electrical conductivity of water and expansion disks. It has been claimed that substantial savings of water could be expected with rain sensors, though no tests or figures have been listed. Bernard Cardenas-Lailhacar et al. [17] conducted experiments concentrating on the performances and potential water consumption savings of expanding disk rain sensors. Two different types of rain sensors, a mini-click rain sensor and wireless rain-click rain sensor were selected. In the experiments, the mini-click rain sensors were divided into three groups with different thresholds while there was only one group of wireless rain-click rain sensor. During the experimental period, rain occurred on 62% of tested days. As a result, the wireless rain-click rain sensor saved up to 44% water, while the mini-click rain sensor with different thresholds saved between 3% and 30% of water, compared with a system that irrigated regardless of rain.

Another study was conducted by McCready et al. [18] from 2006 to 2007 investigating on the performances and potential for water conservation using existing smart irrigation controllers, including ET controllers, rain sensors and SMS controllers.

In this study, two different types of ET controllers (the Toro Intelli-Sense and the Rain Bird ET Manager) were used as well as two different types of SMS controllers (the Acclima Digital TDT RS500 and the LawnLogic LL1004). The smart controllers were then set to different thresholds for testing purposes. The experiment groups and their descriptions are listed in Table 1.

Table 1. Types of Irrigation Sensor Controllers under Different Irrigation Specifications (Revised and Organized from Table 1 in [18])

<table>
<tr><th>Sensor Type</th><th>Sensor Brand</th><th>Irrigation Frequency (times/week)</th><th>Description</th></tr>
<tr><td rowspan="7">SMS Controller</td><td rowspan="4">Acclima</td><td rowspan="4">2</td><td>Volume Water Content (VWC): 7%</td></tr>
<tr><td>VWC: 10%</td></tr>
<tr><td>VWC: 13%</td></tr>
<tr><td>Individually Controlled</td></tr>
<tr><td rowspan="3">LawnLogic</td><td rowspan="3">2</td><td>Low setting</td></tr>
<tr><td>Medium setting</td></tr>
<tr><td>High setting</td></tr>
<tr><td rowspan="2">ET Controller</td><td>Rain Bird ET Manager</td><td>2</td><td>N/A</td></tr>
<tr><td>Toro Intelli-Sense</td><td>2</td><td>N/A</td></tr>
<tr><td rowspan="7">Rain Sensor</td><td rowspan="7">Rain Sensor</td><td>1</td><td rowspan="3">Threshold: 3 mm rainfall</td></tr>
<tr><td>2</td></tr>
<tr><td>7</td></tr>
<tr><td>1</td><td rowspan="3">Threshold: 6 mm rainfall</td></tr>
<tr><td>2</td></tr>
<tr><td>7</td></tr>
<tr><td>2</td><td>Reduced Irrigation</td></tr>
<tr><td rowspan="2">Control</td><td rowspan="2">N/A</td><td>2</td><td>No sensor</td></tr>
<tr><td>0</td><td>No irrigation</td></tr>
</table>

Results showed that the rain sensor could reduce irrigation water use by 7% - 30%, the SMS sensor could reduce water use by up to 74% and the ET sensor could reduce water use by 25% - 62% relative to the standard scheduled irrigation practice. The investigation proved that irrigation water consumption could be reduced with proper installation and use of the smart irrigation controllers without negative impacts on turfgrass quality.

Although studies by Bernard Cardenas-Lailhacar et al. and McCready et al. proved that both rain sensors, i.e. SMS sensor and ET sensor could contribute to irrigation water conservation, major drawbacks prevent these sensors from further implementation. The rain sensors were characterized by faulty operating conditions [19] due to the presence of debris or disk malfunction. To be more specific, rain sensors can be divided into several different types, with each one having its own advantages and disadvantages [20]. One type of rain sensor uses a bucket to collect rain to determine when irrigation cycles must pause. Its operating principle is based on the weight of collected rain. The major drawback of this type of sensor is its ability to be activated by other objects such as stones or leaves which might fall into the bucket. Electrodes are used in other rain sensors. The sensor needs periodical checks and maintenance, which are both tedious and time-consuming. The last type is the expansion disk. Disk malfunction is not rare in the applications of this type.

The SMS sensor, which is also capable of saving water, also has certain disadvantages that limit its applications. The usefulness of SMS sensor is limited when the landscape has a mixed plants layout with different water needs or root depth [21].

Also, SMS sensor requires precise calibrations and adjustments to adapt it to a specific soil type and its measurement accuracy could be easily affected by salinity, fertilizer content and temperature [22]. Based on the methods to measure soil moisture content, SMS sensor could be divided into four types [23]. The first type uses a tensiometer, a tube with a porous cup as end and vacuum gauge as top, to pull in or eject out water based on the soil moisture content. However, this type has a poor performance in coarse sand and the gauges are easily damaged since it is aboveground. The second type consists of electrical resistance blocks whose resistances could change with different moisture levels. The drawback of this type is the need of a specific meter for measuring the resistance and thus changing the settings. The third type is the neutron probe which uses a radioactive source to measure soil moisture. The fourth type is a di-electric sensor which could measure the di-electric constant of soil (a characteristic that changes with soil moisture level). The common drawback of these two types is the high cost.

ET controllers use various methods to collect data and calculate the amount of water needed [24]. The conventional ET method cannot account for unusual weather conditions and the sensor-based method leads to calculation accuracy problems. The ET method is subject to bias since it relies on weather information obtained through the internet. Lastly, the on-site weather station method can be quite costly.

2.4 Current Runoff Mitigation Strategies

Various studies have been conducted on the strategies for mitigating runoff. Daniel et al. [25] used a green roof to mitigate the storm water runoff in urban areas. During the study, a green roof was fabricated and tested along with a control roof on a same commercial building. The results showed that the green roof could reduce storm runoff by up to 70 percent compared to a conventional roof. Fassman-Beck et al. [26] conducted further research on the effects of different specifications of extensive roofs on runoff mitigation. Four extensive green roofs and three conventional roofs were tested. Based on the study, the green roof could reduce peak flow rate by 62 to 90 percent compared to conventional roofs. Also, the specifications of the roof, namely horizontal flow path length, drainage layer roughness and materials, could both affect the effectiveness of green roofs.

Another study conducted by Fassman et al. [27] investigated on the effectiveness of applying a permeable pavement system over impermeable soils to mitigate urban runoff. For the permeable pavement system, precipitation and runoff flows over the surface and infiltrates into a storage reservoir below the permeable surface. Afterwards, water in the storage reservoir flows back out and through the porous media around the reservoir and infiltrates into the adjacent soil. During the experiments, a 200 m^2 permeable pavement site was constructed and tested with an adjacent conventional asphalt section acting as a control site. The results showed that the permeable pavement system could mitigate the peak flow rate by up to 70 percent. The authors believed that the permeable pavement system should be considered as a low impact runoff control system, which requires correct installation to ensure proper function.

Betty et al. [28] conducted a study concentrating on the effects of parking lot design on reducing runoff as well as pollution loads. Impervious pavements and basins with and without swales were divided into four different groups. Results showed that swales could reduce runoff by 30 percent while the basin could add another 10 percent runoff reduction. Other useful methods have also been researched by other scientists to reduce runoff. However, very few methods which base their controls on the overall volume of runoff (as opposed to flow rates) have been considered and developed.

3. DESIGN AND FABRICATION OF LANDSCAPE IRRIGATION RUNOFF MITIGATION SYSTEM

3.1 Aim and Objective

The objective of the study was to design a Landscape Irrigation Runoff Mitigation System (LIRMS) equipped with a reliable, durable and low-cost irrigation runoff sensor for minimizing irrigation water losses from residential or commercial landscapes.

At the first step, four types of irrigation runoff sensors, based on different working principles, were designed and manufactured. These sensors needed to be able to fit into a section of curb with a size of $6" \times 6"$ or less. Then, a central control unit which is capable of receiving signals from sensors and controlling several irrigation valves at the same time was designed.

The second step consisted of installing all the prototypes in the field and hardwiring them with the central control unit. Two control groups were set and the performances of four different types were compared. The amount of runoff was recorded as the index of performance. The different types were evaluated based on their performance characteristics including the ability of each prototype to work reliably over an extended period of time.

Internet access was added to the system to access the irrigation data online. Wireless communication between the irrigation runoff sensors and the central control unit was established. Quality of the wireless communication and the performances of the new wireless irrigation runoff sensor systems were evaluated.

An autonomous energy system was designed by combining solar panels and rechargeable batteries. The solar panels provided energy for the sensor and for recharging the batteries during daytime so the system could work in the evening. The performance of the autonomous energy system was tested.

3.2 Landscape Irrigation Runoff Mitigation Sensor Prototype Design, Fabrication and Test

In this section the different types of runoff sensor designs including working mechanisms are discussed.

3.2.1 General Working Requirements of the Landscape Irrigation Runoff Mitigation Sensor

The runoff sensor itself is the essential part of the landscape irrigation runoff mitigation sensor system, converting the runoff signal into an electronic signal which can be utilized by a microcontroller to control the irrigation system. To ensure the proper function of the system, the runoff sensor needs to be reliable in all environmental circumstances and strong enough to endure impact or mechanical failure. Also, it needs to be low-cost for mass production purposes. Moreover, an energy-saving version is desired in order to be environmental friendly. Finally, it has to be a unit smaller than 6" $\times$ 6"in order to easily be installed into most residential curbs.

3.2.2 Materials Selection for Fabricating Prototypes

The selected materials to build the prototypes need to be reliable in both hot and cold weather, corrosion-resistant, impact-resistant and should be inexpensive. Different types of materials have been evaluated to construct the prototypes, including acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), polystyrene (PS) stainless steel and aluminum. The comparison of different materials have been listed in Table 2.

Table 2. Comparison of Different Materials for Runoff Prototypes

Material	Advantages	Disadvantages	Comments
ABS	Low-hazard material, impact-resistant, tough, low cost	Narrow thermal tolerance range	Suitable for constructing the prototype due to the great impact-resistant and reliable features as well as the low cost. The temperature range works for the irrigation use (-20 - 80 C).
PVC	High hardness and good mechanical properties, good insulation properties, low cost	Poor heat stability	Suitable for constructing the prototype because it could be easily machined when heated.
PS	Hard, inexpensive	Highly flammable	Not selected due to the flammability. The hot weather and the heat produced by electronic devices increases the risk of fire.
Stainless Steel	Tough and reliable, corrosion-resistant, impact-resistant, high thermal tolerance	Expensive, more tools are needed for machining	Not Selected due to the price and the higher requirements of machining tools.
Aluminu m	Tough and reliable, corrosion-resistant, light in weight, impact-resistant, high thermal tolerance	Expensive aluminum alloys, more tools are needed for machining	Not selected due to the price and the higher requirements of machining tools.

Taking both requirements into consideration, ABS and PVC were chosen to fabricate the prototypes. For the elbow float prototype and the conductivity prototype, a commercial PVC elbow pipe was selected to be the outer case, while a thin PVC sheet is used for the construction of the paddle wheel of the paddle-wheel prototype. Also, ABS was chosen as the material for building the cubic-float and paddle-wheel prototypes.

3.2.3 Original Designs of the Landscape Irrigation Runoff Mitigation System Sensor Prototypes

Several different types of irrigation runoff sensor prototypes have been developed taking the prescribed requirements into consideration. They work on various principles including on-off or continuous operation, which requires a distinct process to convert runoff signals to data that could be used by the electronic system. These designed runoff sensors include an eductor prototype, float sensor prototype, infrared prototype, paddle wheel prototype, tip bucket prototype and conductivity prototype.

3.2.3.1 Conceptualized Eductor Prototype

The eductor prototype utilizes the concept of a water eductor. The structure of the water eductor is shown in Figure 3.

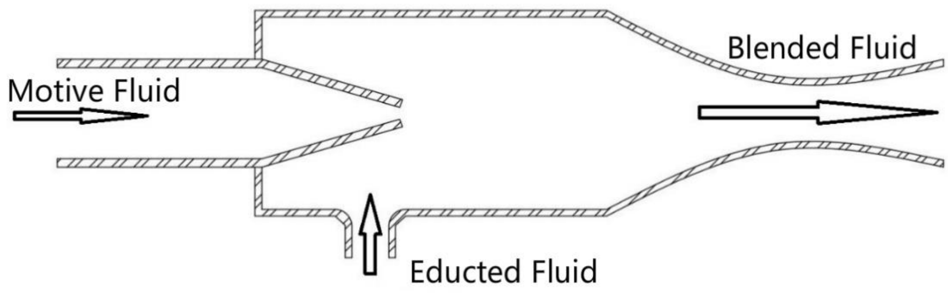

Figure 3. Structure of Water Eductor

As Figure 3 shows, the educted fluid will be extracted when there is motive liquid going through the chamber. The structure of the eductor prototype is shown in Figure 4.

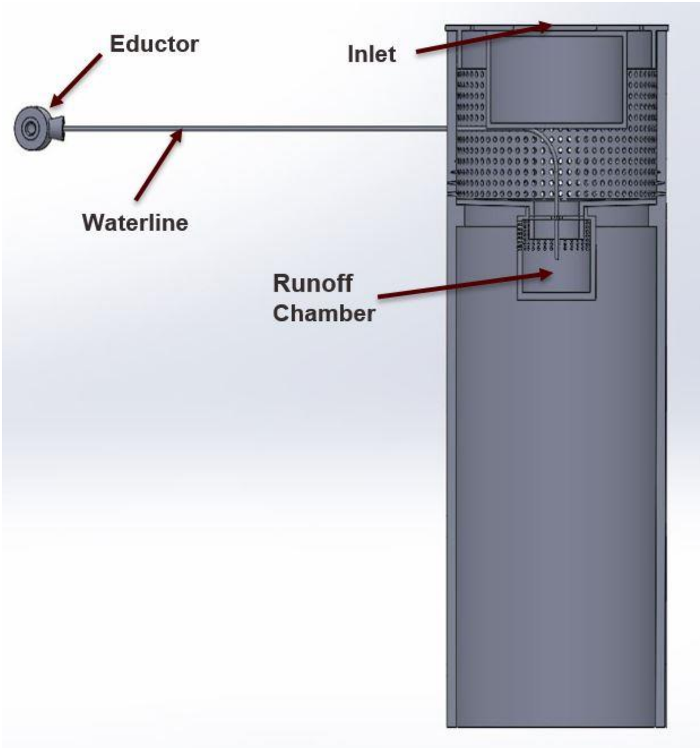

Figure 4. Structure of Eductor Prototype

The runoff will be collected in a chamber and when the water level reaches a certain level, then the eductor should extract the water out of the chamber. As a result, the runoff should be detected by using an instrument downstream from the device.

The eductor prototype is sensitive and reliable since it does not have moving parts. However, a highly efficient filter system is needed since the small diameter of the waterline could make it easy to be clogged. Also, the eductor prototype might be hard to install in the field.

3.2.3.2 Conceptualized Infrared Prototype

The infrared prototype is based on the use of an infrared sensor. The structure of the infrared prototype is shown in Figure 5.

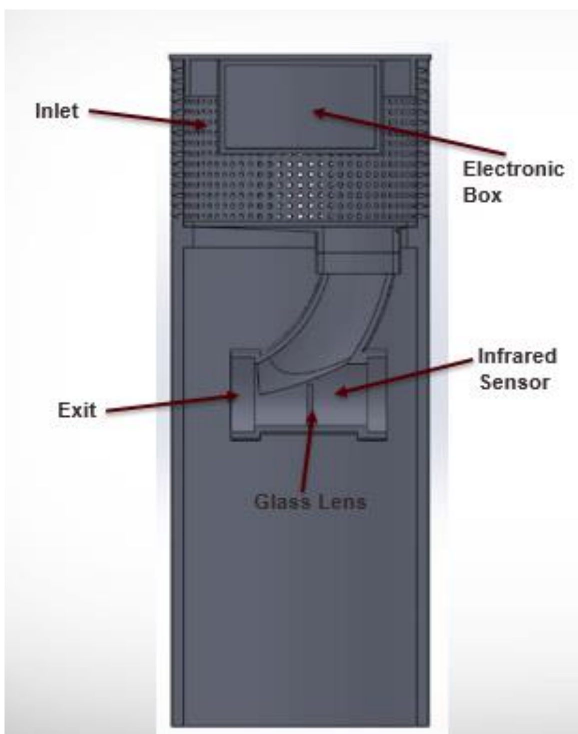

Figure 5. Structure of Infrared Prototype

A glass lens is set at the middle of the bottom cylindrical tube. When runoff enters the prototype and passes over the lens, a reflective angle will be created and should be detected by the infrared sensor. The runoff signal is then sent to the control part to adjust the irrigation progress.

The infrared prototype requires limited maintenance and is very reliable. Also, the drain line is not necessary for the infrared prototype. However, it can be expensive and might require a complex software program.

3.2.3.3 Conceptualized Paddle Wheel Prototype

The paddle wheel prototype detects and measures runoff by using paddle wheel. The angular speed of the paddle wheel should be measured and calibrated to determine the true amount of runoff. A sensor is needed to detect the angular speed and send the signal to the microcontroller. The structure of the paddle wheel prototype is shown in Figure 6.

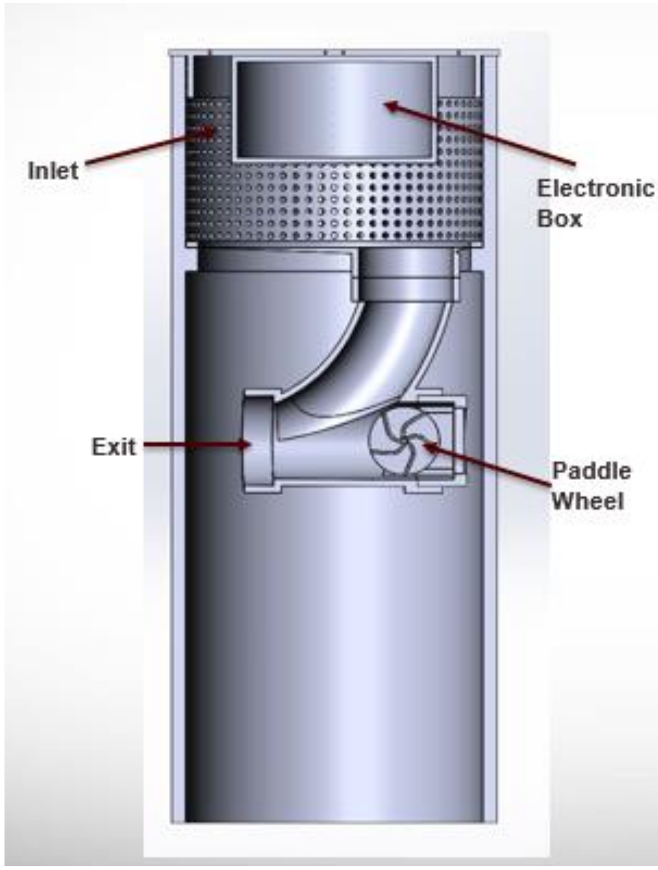

Figure 6. Structure of Paddle Wheel Prototype

When runoff occurs and enters the prototype from the top, it will flow through the prototype and then drive the paddle wheel at the downstream location. The relationship between the amount of runoff that enters the prototype and the rotational speed of the paddle wheel could be measured under lab conditions. As a result, this prototype should measure the amount of runoff that runs through it, which is the biggest advantage of this prototype when compared with other prototypes.

However, the paddle wheel prototype has some disadvantages. The moving parts in this prototype increase the risk of mechanical problems, while debris such as grass and stones could easily restrict the motion of the paddle wheel.

3.2.3.4 Conceptualized Tip Bucket Prototype

The tip bucket prototype utilizes a bucket to collect runoff. The structure of the tip bucket prototype is shown in Figure 7.

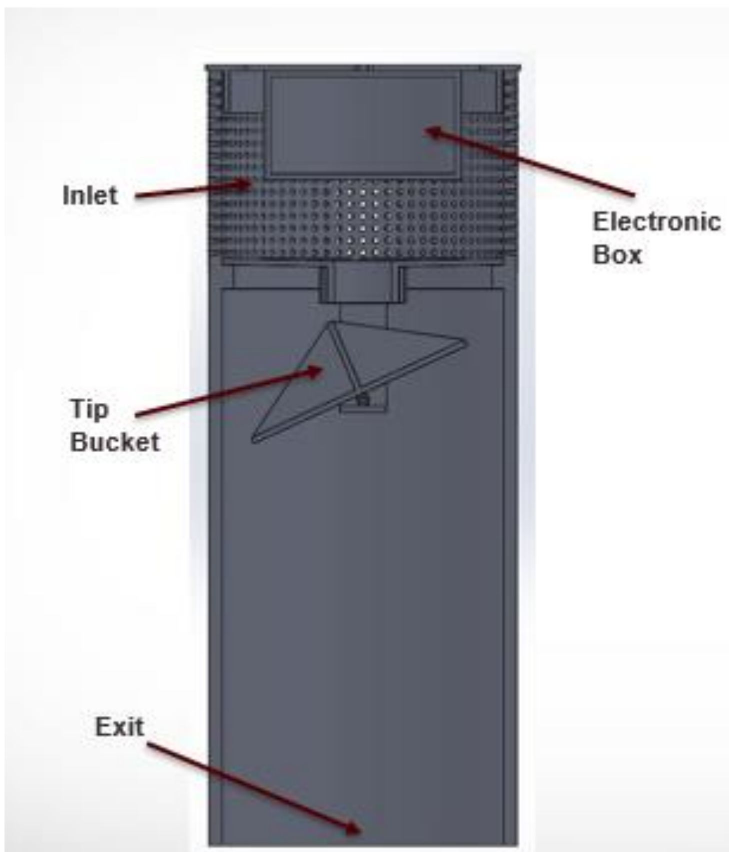

Figure 7. Structure of Tip Bucket Prototype

When runoff occurs, it will enter the prototype and gets collected in the bucket. As soon as the runoff is collected in the bucket, it reaches a certain threshold, then the bucket will tip and the runoff will fall down and leave the prototype. A switch or infrared sensor might be needed to detect the tips of the bucket.

The tip bucket prototype will be able to calculate the runoff flow rate once preliminary experiments have been conducted to investigate the amount of water that could make the bucket tip. Also, this prototype does not need much maintenance. However, debris in the runoff could accumulate in the bucket and restrain the motion or even prevents the buckets from moving altogether, which will significantly affect the performance of the prototype.

3.2.3.5 Conceptualized Float Prototype

The float prototype is equipped with a float sensor to detect the runoff. The structure of the float prototype is shown in Figure 8.

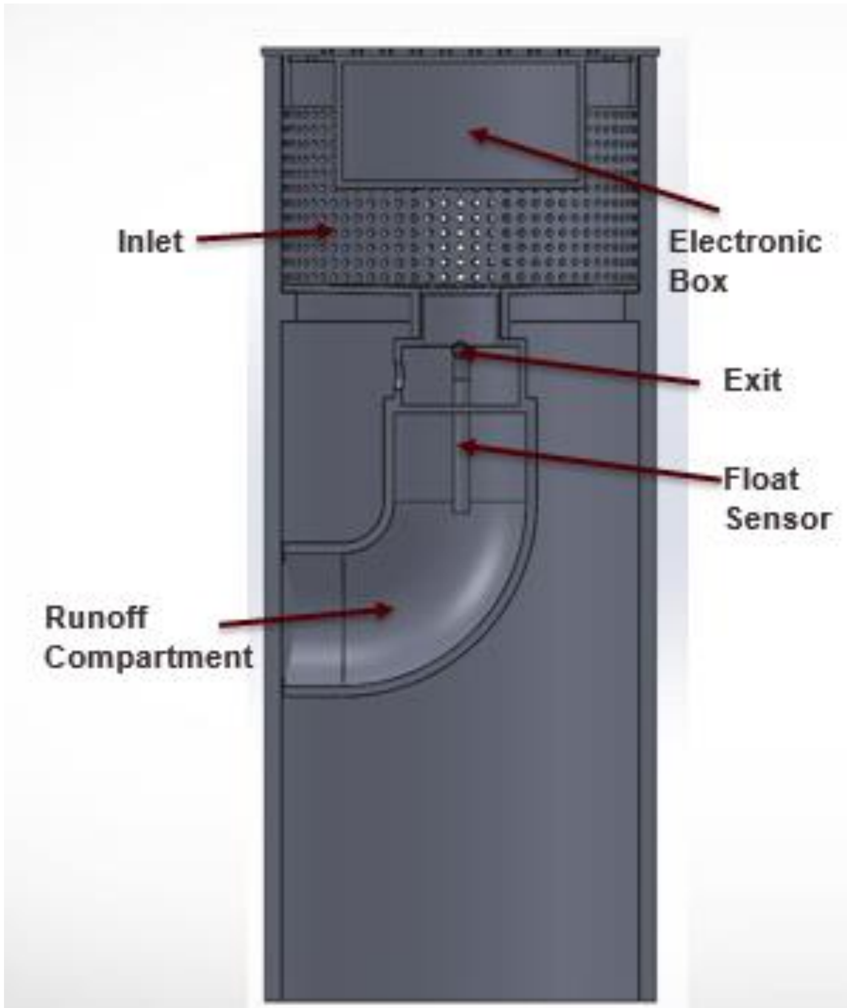

Figure 8. Structure of Float Prototype

Runoff enters the prototype and is accumulated in the runoff compartment. A float sensor is installed at the top of the compartment. When water level in the compartment reaches a set threshold, the float switch will be activated and the runoff signal would be sent to the controller.

The float runoff sensor has very few moving parts and it is very simple and reliable. However, this prototype also requires a very efficient filtering system. Also, it needs to accumulate some runoff before being activated, which could lead to a lagged response.

3.2.3.6 Conceptualized Conductivity Prototype

The conductivity prototype uses two electrodes as an ON/OFF switch to detect runoff. The structure of the conductivity prototype is shown in Figure 9.

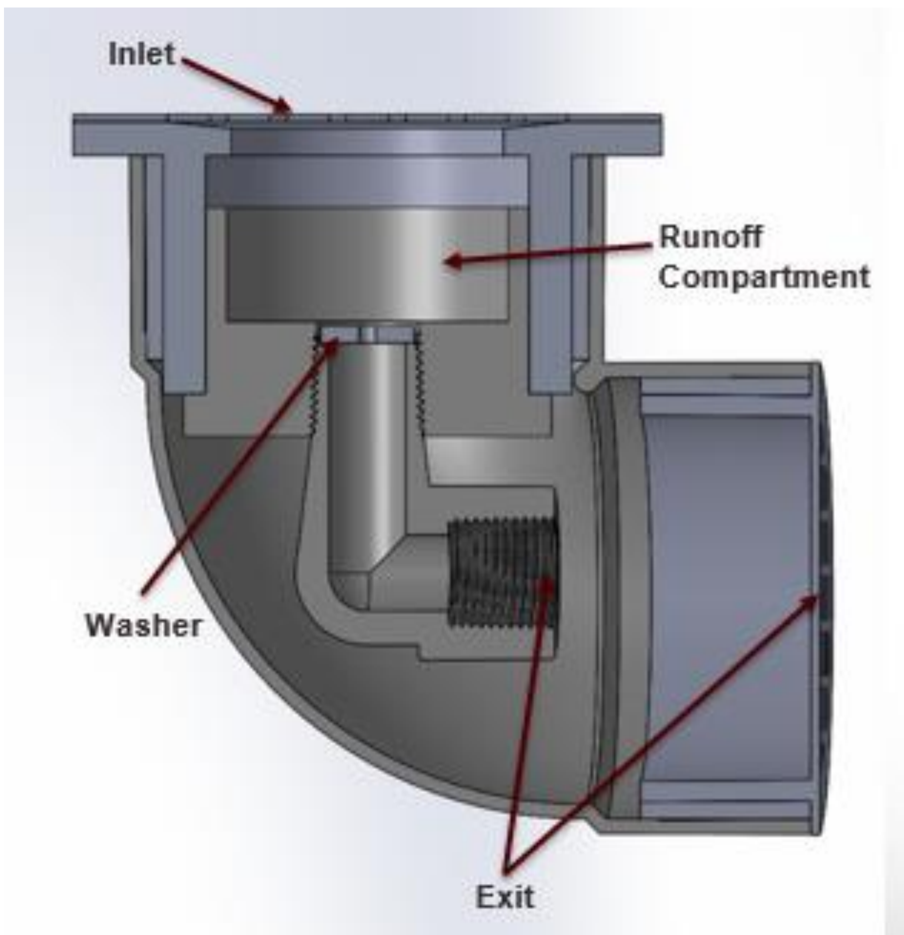

Figure 9. Structure of Conductivity Prototype

Runoff enters the prototype and is accumulated in the runoff compartment. One electrode is installed at the bottom of the compartment while the other one is installed at a set height above the bottom electrode. When water level in the compartment rises and the two electrodes are submerged in the water, water will act as a conductive medium and a small current should run from one electrode to the other. The electrodes should then activate the ON/OFF switch this way.

The conductivity runoff sensor does not have moving parts. It is very easy to make and it is durable. However, this prototype also requires a very efficient filtering system to avoid clogging issues. Also, just like the float prototype, it needs to accumulate some runoff before it can be activated, which could lead to a lagged response. The sensitivity of the device can be adjusted by changing the diameter of the outflow orifice.

3.2.3.7 Design Decision Making Scheme

In order to down select design options, a list of attributes including advantages and disadvantages of each prototype were identified and specified, as shown in Table 3.

Table 3. Design Decisions of Landscape Irrigation Runoff Mitigation Sensor Prototypes

Device Type	Advantages	Disadvantages	Constructed?	Comments
Eductor Prototype	1. Sensitive 2. Reliable 3. No moving parts	1. Need high efficiency filter system to avoid clogging issue 2. Hard to install 3. Need power input	No	Based on the working principle of the eductor prototype, the waterline should have a very small diameter, which could get clogged very easily. Also, it needs an extra power input, which requires more energy. Thus this idea has not been adopted.
Infrared Prototype	1. Do not need drain line 2. Reliable 3. Do not need much maintenance	1. High cost 2. Complex program	No	The high cost and complex program make this prototype not suitable for a low-cost and user-friendly runoff sensor. Thus this idea has not been adopted.
Paddle Wheel Prototype	1. Could measure the amount of runoff that runs through the sensor	1. Has moving parts 2. Clogging issue 3. Debris may affect the motion of the paddle	Yes	Despite the disadvantages mentioned, its greatest feature is its ability to measure runoff on a continuous basis, which is direct and useful for performance evaluation and irrigation control. Thus this prototype has been constructed.

Table 3. Design Decisions of Landscape Irrigation Runoff Mitigation Sensor Prototypes (Continued)

Device Type	Advantages	Disadvantages	Constructed?	Comments
Tip Bucket Prototype	1. Could measure the amount of runoff that runs through the sensor 2. Do not need much maintenance	1. Has moving parts 2. Clogging issue 3. Debris may accumulate in the buckets and affect the motion of it	No	The tip bucket prototype has a very similar working principle and mechanism as the paddle wheel prototype. Since the paddle wheel prototype has been constructed, the tip bucket prototype has not been adopted.
Float Prototype	1. Simple 2. Reliable 3. No moving parts	1. Need high efficiency filter system to avoid clogging issue 2. Lag in response time	Yes	The float prototype is simple and easy to build, plus it is reliable and inexpensive. Though it exhibits a lagging response, it has been constructed and adopted.
Conductivity Prototype	1. Easy to build 2. Heavy-built 3. No moving parts	1. Need high efficiency filter system to avoid clogging issue 2. Lag in response time 3. Rust on electrodes	Yes	The conductivity prototype is reliable and inexpensive. It can endure great impact and could also be constructed quickly. Though it exhibits a lagging response, it has been constructed and adopted.

Based on the advantages/disadvantages listed in the table, the paddle wheel prototype, the float prototype and the conductivity prototype were constructed for further tests.

3.2.4 Fabrication Tools and Procedures

Taking into account the advantages and disadvantages of different prototypes, the float prototype, the paddle wheel prototype and the conductivity prototype were manufactured. ABS and PVC were utilized for the prototypes to fulfill the goals of having a reliable, low-cost and easy to machine device. Various tools and machines were used during the fabrication processes, as shown in Figure 10.

Figure 10. Tools and Machines for Fabricating Runoff Prototypes

The jig and the hot air gun were used for manufacturing the curved sheet of the paddle wheels. PVC sheets were bent easily when heating them with the hot air gun, which allowed for the fabrication of the curved paddle wheel fins.

A band saw was used for cutting large rectangular ABS boards for fabricating the outer shells of the different prototypes, while the laser cutter was used for precise manufacturing of inside components of all the prototypes. Drawings should be specifically designed for the laser cutter with the width of the laser taken into consideration, as shown in Figure 11.

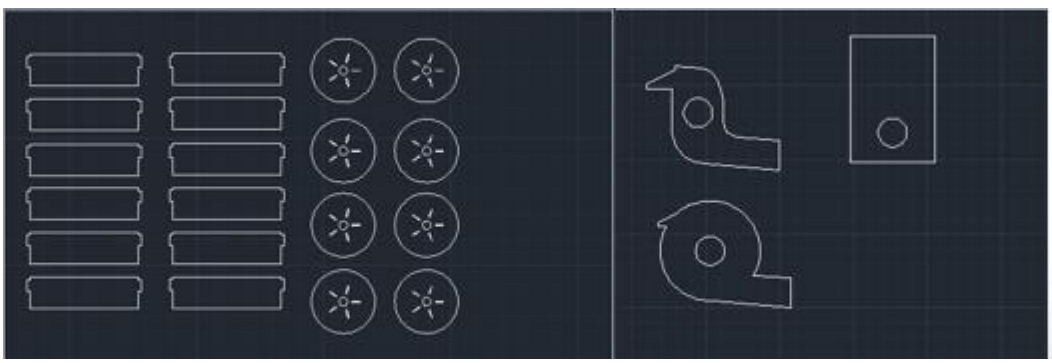

Figure 11. AutoCAD Drawings of the Components of the Paddle Wheel Prototypes for the Laser Cutter

The advantages, disadvantages and applications of different tools and machines were listed in Table 4, as shown below.

Table 4. Comparisons and Applications of Different Tools and Machines

Method	Advantages	Disadvantages	Applications
Jig & Hot Air Gun	Could make fine curved surface	Need expertise Need to make the wood jig first	Fabricate the paddle wheels and curved outer shells of the paddle wheel prototype
Laser Cut	Fast. Precise Could make very complex shape precisely	Need to take shrinking into consideration to make specific mechanical drawings for the machine to use Some materials are not suitable for laser-cutting, especially for those which are vulnerable to heat	Fabricate the outer shells and cut the holes with large diameters on the parts of the cubic float prototype
Band Saw	Fast Easy to use	Not for precise cutting if lacking expertise.	Fabricate the parts of float prototype and conductivity prototype
Drill	N/A	N/A	Drill holes for screws for both prototypes

3.2.5 Final Designs of the Landscape Irrigation Runoff Mitigation Sensor Prototypes

The paddle wheel prototype, the float prototype and the conductivity prototype were manufactured for testing purposes. While the working principles remain the same between the original and final designs of each prototype; however, the inner structures and layouts of the original designs were changed to make the devices easier to fabricate.

3.2.5.1 Final Paddle Wheel Prototype

The original paddle wheel prototype was revised to fit the testing facility. The prototype was redesigned to accommodate the electronic system responsible for relaying information to the main controller. Furthermore, the water receiving end was modified so water did not have to go through the entire system. The mechanical system was separated from the electronic side by using a shaft. The structure of it is shown in Figures 12 and 13.

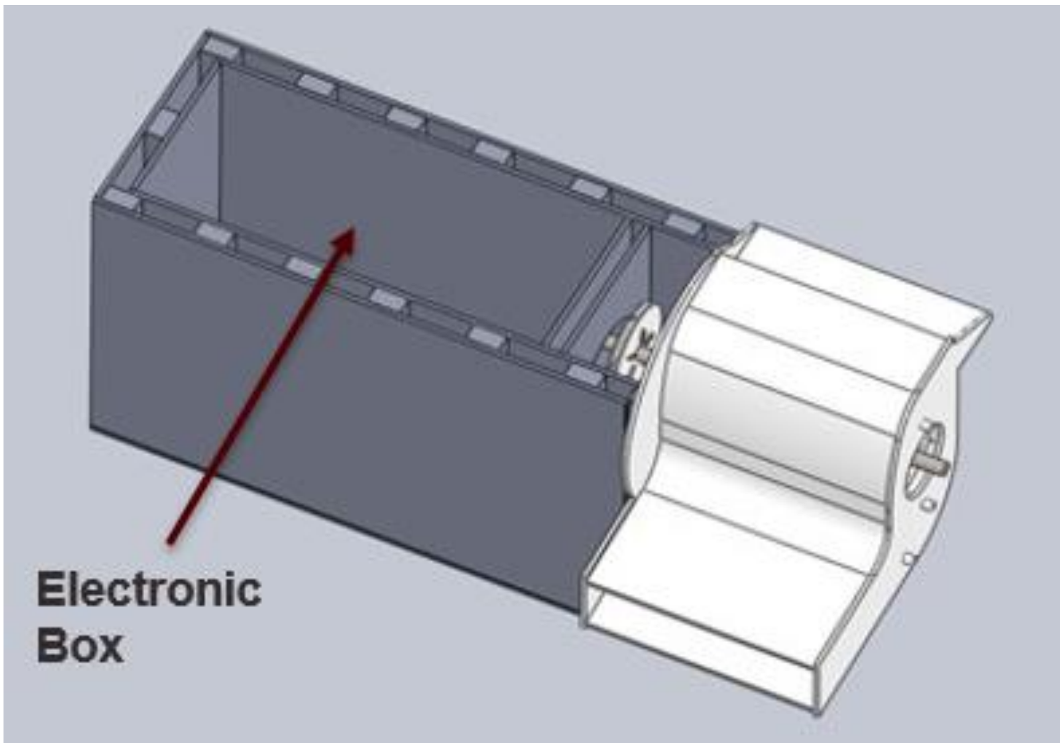

Figure 12. Structure of the Final Paddle Wheel Prototype

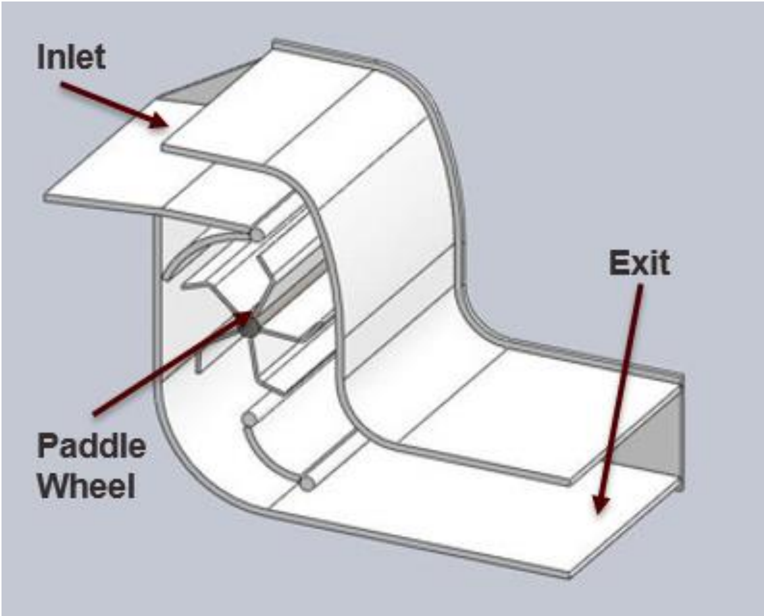

Figure 13. Structure of the Final Paddle Wheel Prototype (cutaway view)

The photo of the fabricated paddle wheel prototype is shown in Figure 14.

Figure 14. Installed Paddle Wheel Prototype

3.2.5.2 Final Cubic Float Prototype

The float prototype was further developed into two different designs: the cubic float prototype and the elbow float prototype. Both designs share the same working principle. The only difference between the two prototypes is the shape.

The cubic float prototype was redesigned to be equipped with an electronic box for the controller. Furthermore, the shape of the float prototype was redesigned to accommodate an inlet conduit for higher efficiency of gathering runoff. The cubic float prototype consists of the inlet conduit, the cubic runoff compartment, the electronic box, the vertical float switch and the exit orifice. The vertical float switch and the cubic float prototype's layout are shown in Figure 15 and 16.

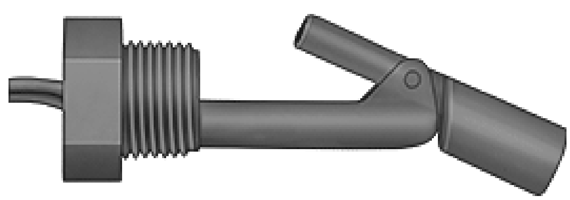

Figure 15. Vertical Float Switch with Two Output Wires

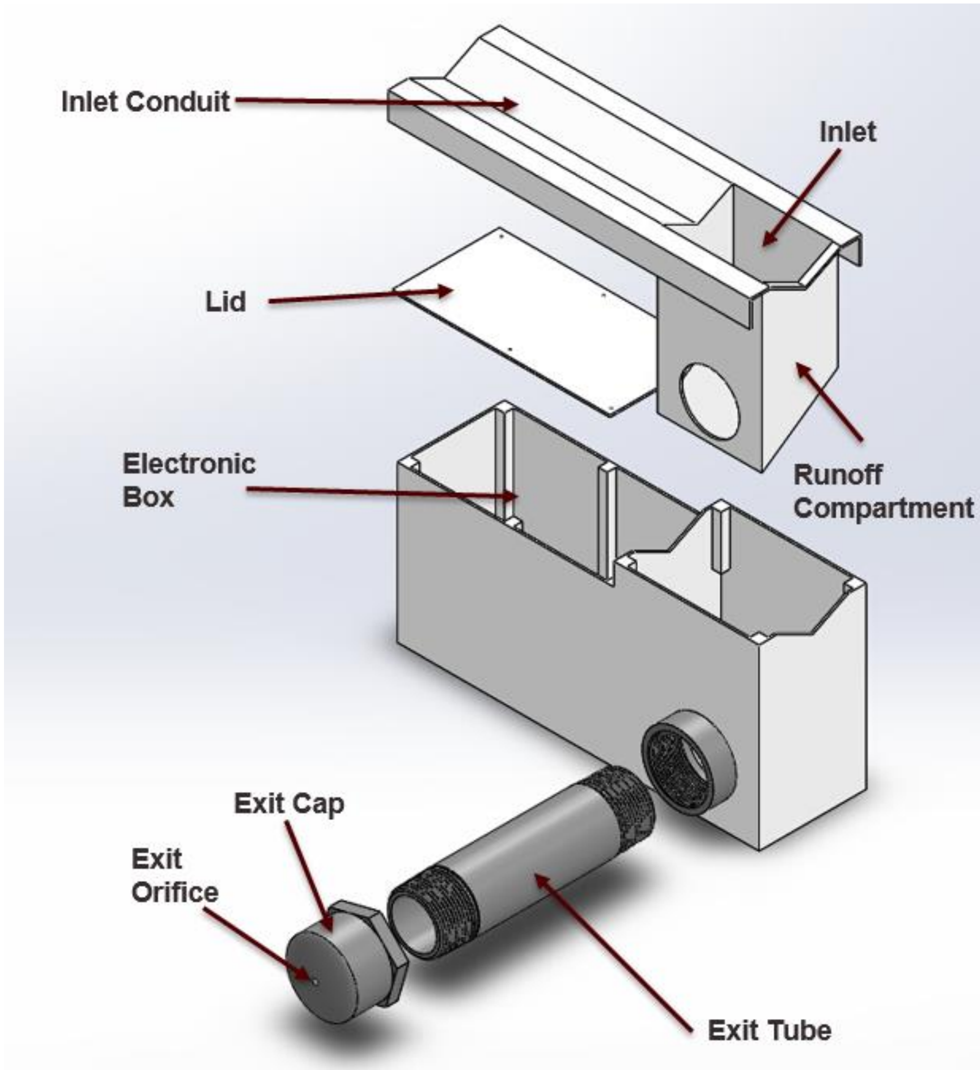

Figure 16. Exploded View of the Cubic Float Prototype

The runoff enters the runoff compartment, where the float switch is installed, through the inlet conduit. When the runoff flow rate exceeds the maximum flow rate that the exit hole allows to escape the runoff compartment, runoff starts to accumulate in the compartment and activates the float switch when fluid reaches a certain water level. The two output wires are extended either directly to the main irrigation controller which controls the valves, or into the electronic box where the wireless communication module is installed.

The photo of the fabricated cubic float prototype is shown in Figure 17.

Figure 17. A Cubic Float Prototype Equipped with an Energy Supply Module

3.2.5.3 Final Elbow Float Prototype

The elbow float prototype was designed by using the same outer shell as the conductivity prototype. The new layout accommodated a vertical float sensor, which led to a more compact and heavy-built prototype comparing to the cubic float one. Its structure is shown in Figure 18.

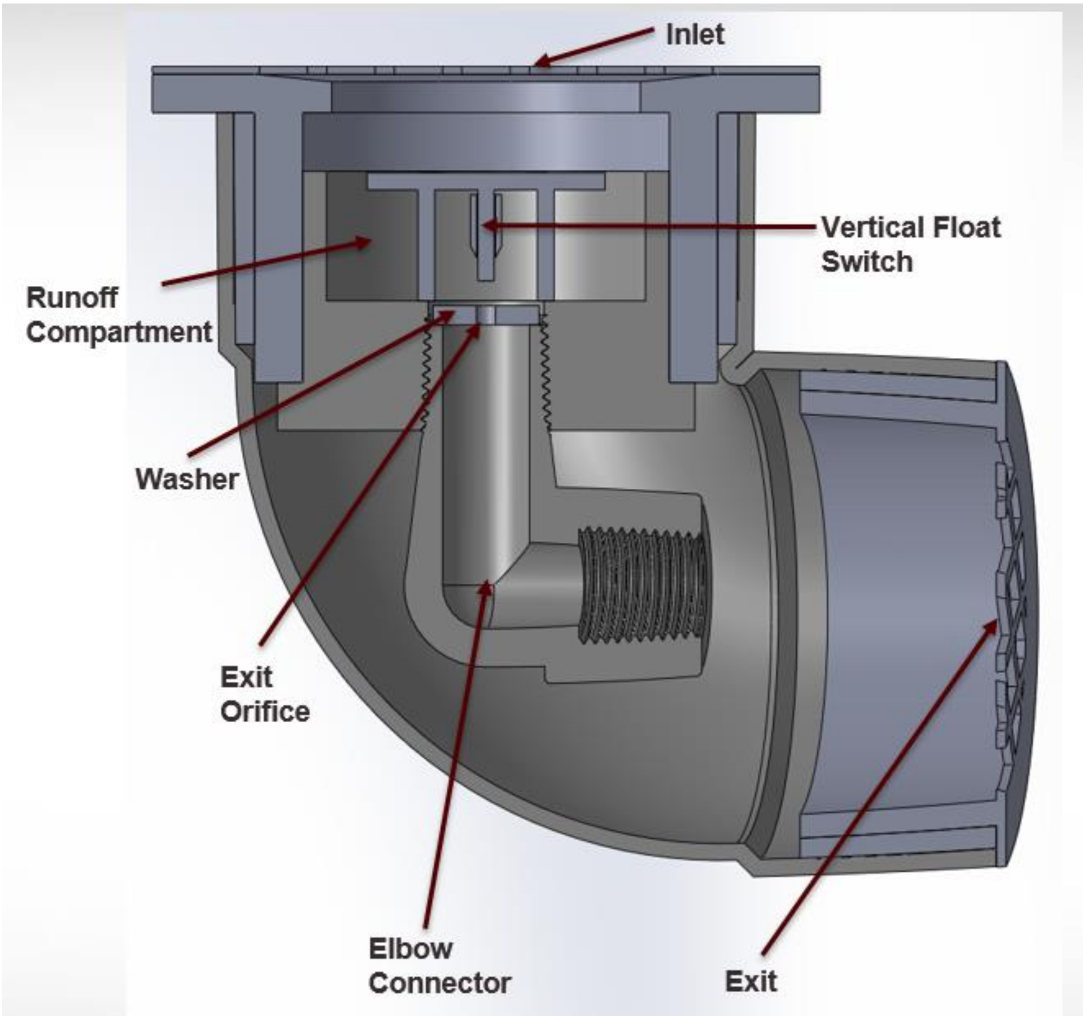

Figure 18. Section View of the Elbow Float Prototype

Its working principle is the same as the one of the cubic float prototype. The vertical type switch is installed in the elbow float prototype. Compared to the cubic one, the elbow float prototype is more heavy-built and compact. The elbow float prototype has a changeable orifice size by using as washer as shown in Figure 18. The photo of the fabricated elbow float prototype is shown in Figure 19.

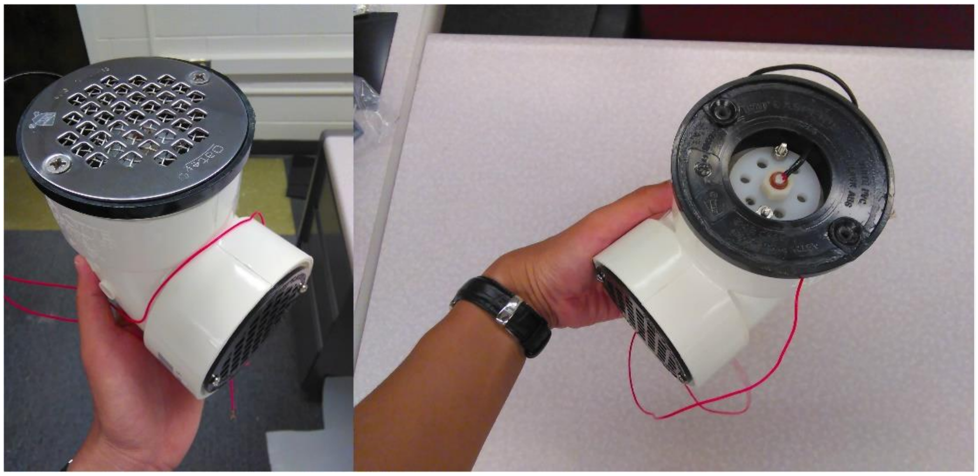

Figure 19. An Assembled Elbow Float Prototype

3.2.5.4 Final Conductivity Prototype

The conductivity prototype remained its original design, which is shown in Figures 20 and 21.

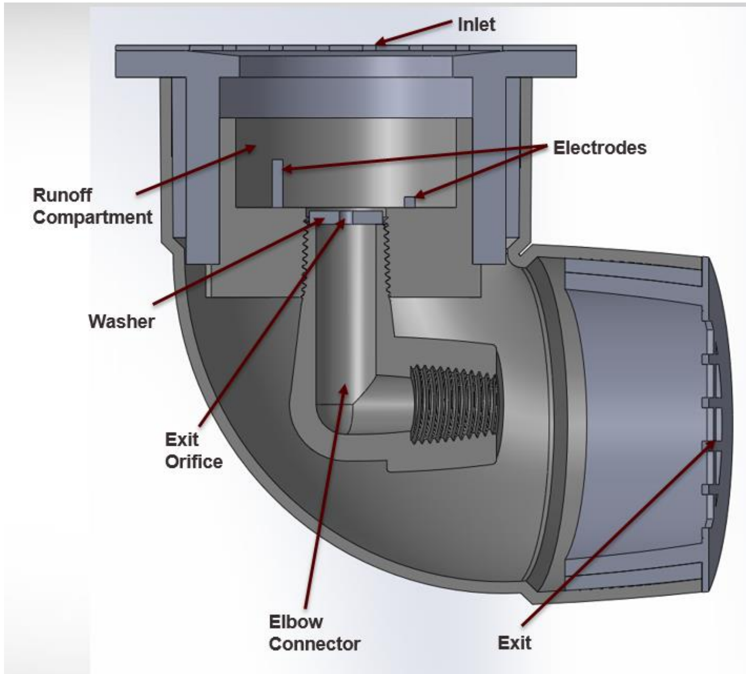

Figure 20. Section View of the Conductivity Prototype

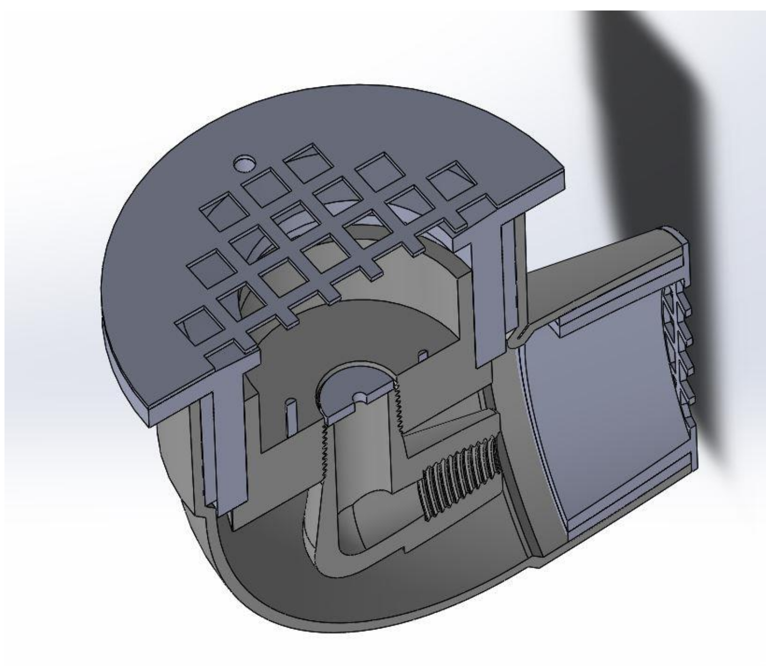

Figure 21. Section View of the Conductivity Prototype (45 Degree Angle)

When runoff occurs, it enters the runoff compartment through the inlet. Runoff starts to accumulate when the flow rate reaches a certain flow rate that exceeds the flow rate through the exit of the runoff compartment. As a result, accumulated runoff acts as the conductive medium between the two electrodes when the electrodes are submerged in water. Similar to the float prototype, each electrode is connected to a wire, and the two output wires are extended either directly to the main irrigation controller which control the valves, or into the electronic box where the wireless communication module is installed. The exit orifice of the conductivity prototype can be changed by changing the size of the washer.

The photo of the fabricated elbow float prototype is shown in Figure 22.

Figure 22. Assembled Conductivity Prototype

3.3 I/O Communication and Control Module Design and Fabrication

In this section the design and development of the I/O communication and control module is discussed.

3.3.1 General Working Requirements of the I/O Communication and Control Module

The I/O communication and control module is the brain of the landscape irrigation runoff mitigation sensor system. It receives the runoff signals from the irrigation runoff sensors and then controls the irrigation process intelligently. The I/O communication and control module needs to fulfill the cycle-soaking process when working together with an irrigation runoff sensor and has to be reliable in all environmental circumstances. Also, an I/O communication and control module needs to control multiple field plots at the same time and should be able to store the irrigation data securely. Finally, a low energy consumption module is desired so it can operate uninterruptedly.

3.3.2 General Working Principle and Mechanism of the I/O Communication and Control Module

The I/O communication and control module has to be able to control the irrigation cycle by setting the system on ON and OFF mode based on the received runoff signals from the irrigation runoff sensors. Its working principle is shown in Figure 23.

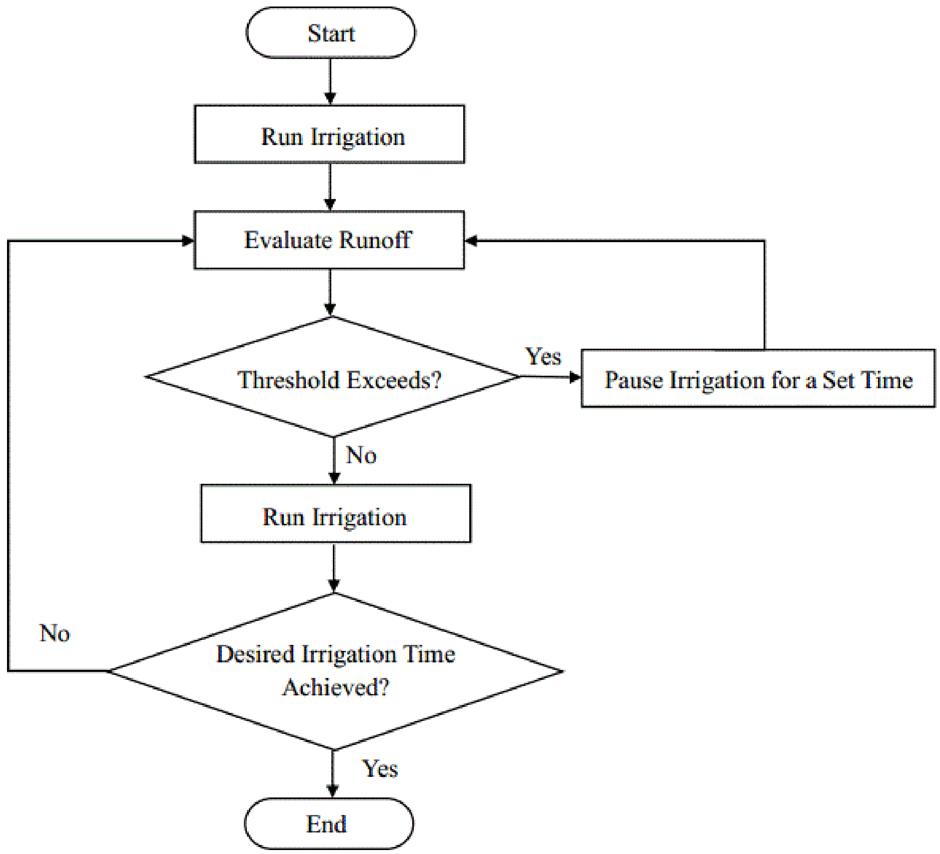

Figure 23. Operating Principle of the I/O Communication and Control Module

An I/O communication and control module is able to control the irrigation for multiple plots at the same time. When the irrigation starts, it will open all the valves so that the sprinklers could spray water to the field. As soon as the irrigation runoff sensors detect runoff and the I/O communication and control module receives the runoff signals, the valves of the plots with runoff detected will be closed and the irrigation will be switched to OFF mode for a set amount of time. After that the I/O communication and control module checks the runoff status, it will keep the valves closed if runoff has been detected again. If no runoff has been detected, the sprinklers will work until the desired irrigation time has been reached for all the plots.

3.3.3 Printed Circuit Board (PCB) Design and Fabrication

Two generations of printed circuit boards (PCB) were designed to be the I/O communication and control module. The first generation had a transmitter board on the irrigation runoff sensor side and a receiver board on the I/O communication and control module side. The second generation had only one board installed on the I/O communication and control module side.

3.3.3.1 Design and Fabrication of the First Generation of the I/O Communication and Control Module with Transmitters and Receivers

The first generation of the I/O communication and control module was equipped with the ATmega328 microcontroller and consisted of one transmitter board and one receiver board. The working principle is shown in Figure 24.

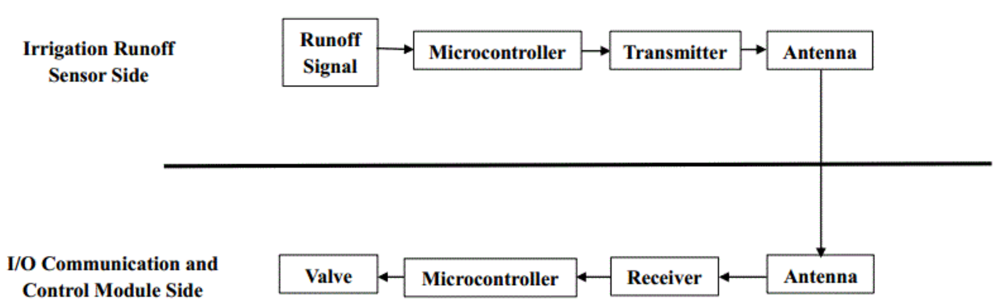

Figure 24. Working Principle of the 1st Generation of I/O Communication and Control Module

The transmitter board (the upper part of Figure 24) is installed on the irrigation runoff sensor side, while the receiver board (the lower part of Figure 24) is on the I/O communication and control side. When runoff has been detected, the microcontroller on the transmitter board receives the runoff signal and then sends that to the transmitter. This signal is amplified by the antenna to ensure signal quality. Then the signal will be captured by the receiver on the receiver board and processed by the microcontroller installed on it. Thus the microcontroller will close the valve for a set time. The structures of the transmitter board and the receiver board are shown in Figure 25 and 26.

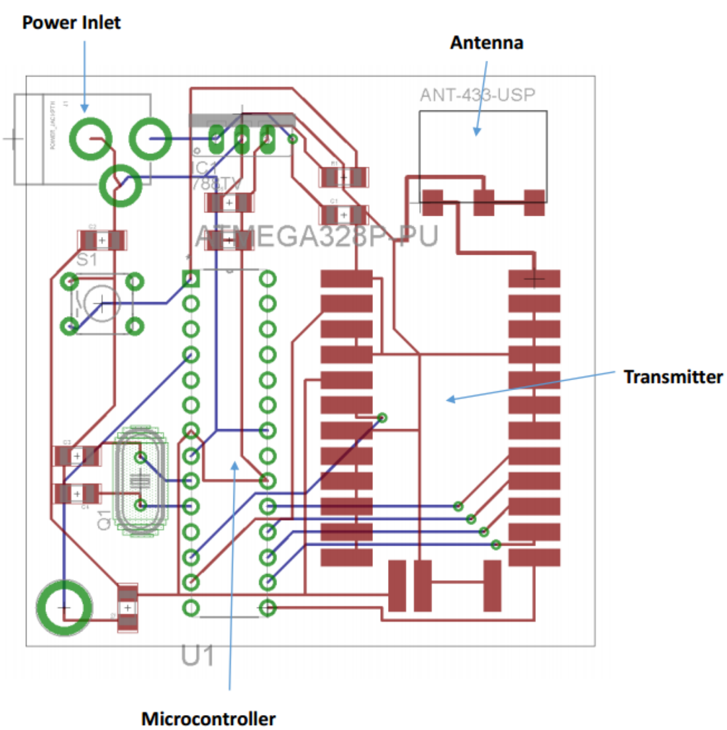

Figure 25. Structure of the Transmitter Board on the Irrigation Runoff Sensor Side

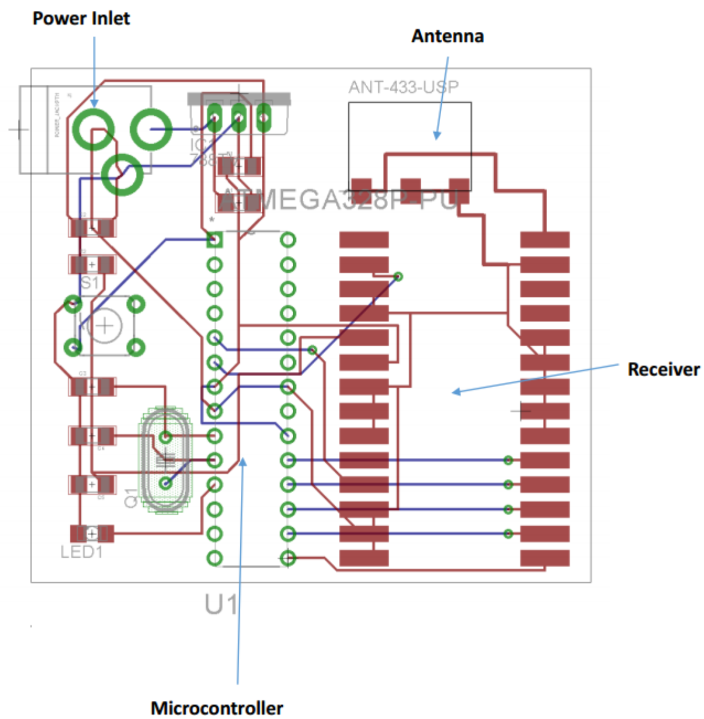

Figure 26. Structure of the Receiver Board on the I/O Communication and Control Module Side

The photos of the transmitter board and the receiver board are shown in Figure 27 and 28.

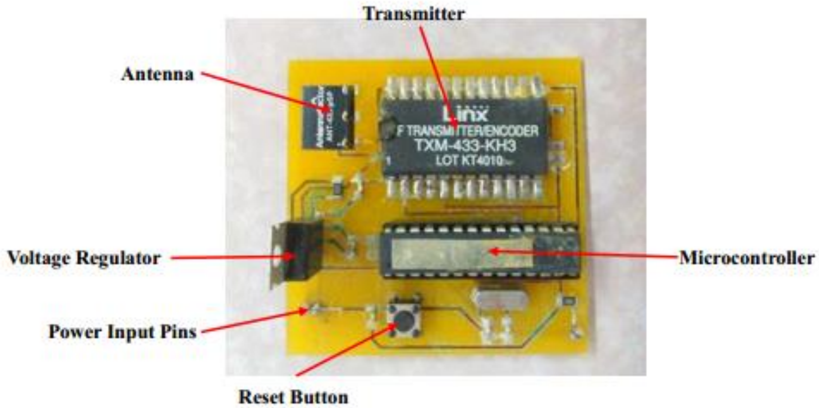

Figure 27. A Fabricated and Assembled Transmitter Board

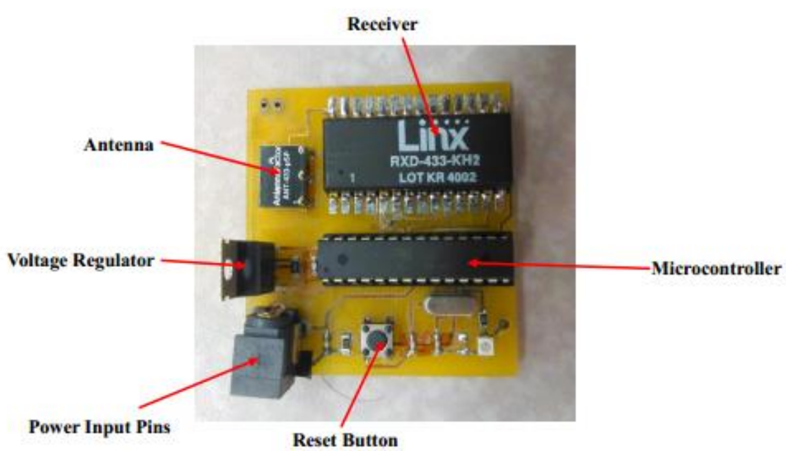

Figure 28. A Fabricated and Assembled Receiver Board

The first generation of the I/O communication and control module is capable of wireless communication between the irrigation runoff sensor and the controller. The prototype boards have achieved the desired functions and are able to establish a stable wireless communication for up to 30 meters during the field tests. However, the quality of the wireless communication could be dramatically affected by a nearby signal tower or other interference. Also, each irrigation runoff sensor must be equipped with a transmitter board and a receiver board, which could result in a high cost.

3.3.3.2 Design and Fabrication of the Second Generation of I/O Communication and Control Module

The second generation of the I/O communication and control module was equipped with the ATmega328P microcontroller and just has one PCB. Its structure is shown in Figure 29.

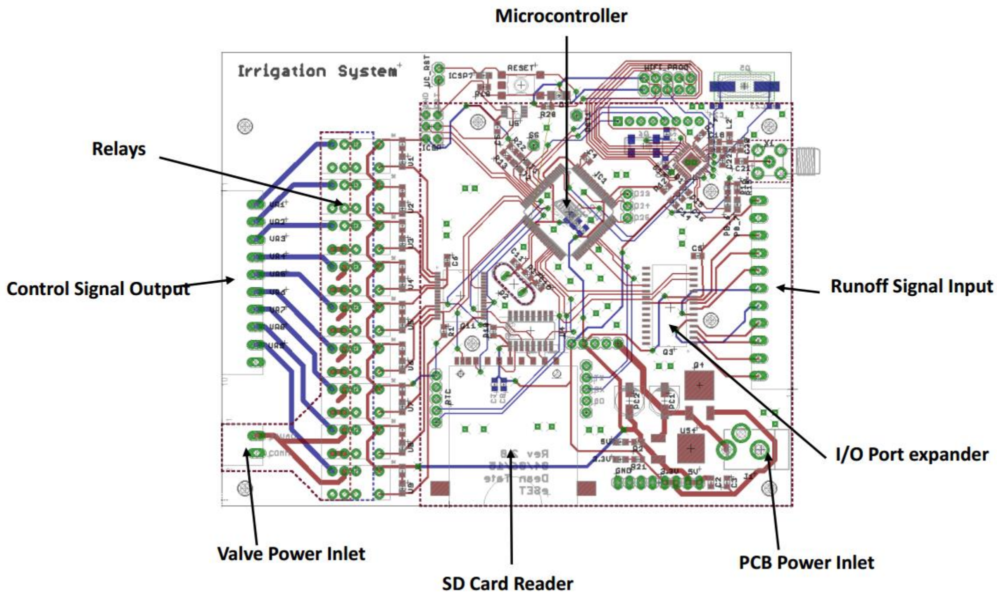

Figure 29. Structure of the Current I/O Communication and Control Module PCB

For this version of the I/O communication and control module, all the irrigation runoff sensors are hardwired to the PCB through the Runoff Signal Input ports as shown in Figure 29. When runoff occurs, the irrigation runoff sensor detects it and sends the signal to the runoff signal input on the PCB. Then the microcontroller on the PCB receives the signal and controls the relay. The relay is located between the power supply and the valve. The microcontroller opens the relay when runoff is detected so that the valve has no power, which turns the irrigation system off. It closes the relay to continue irrigation in the field when no runoff is detected. The irrigation results and data are stored in the secure digital (SD) card. The photo of the PCB is shown in Figure 30.

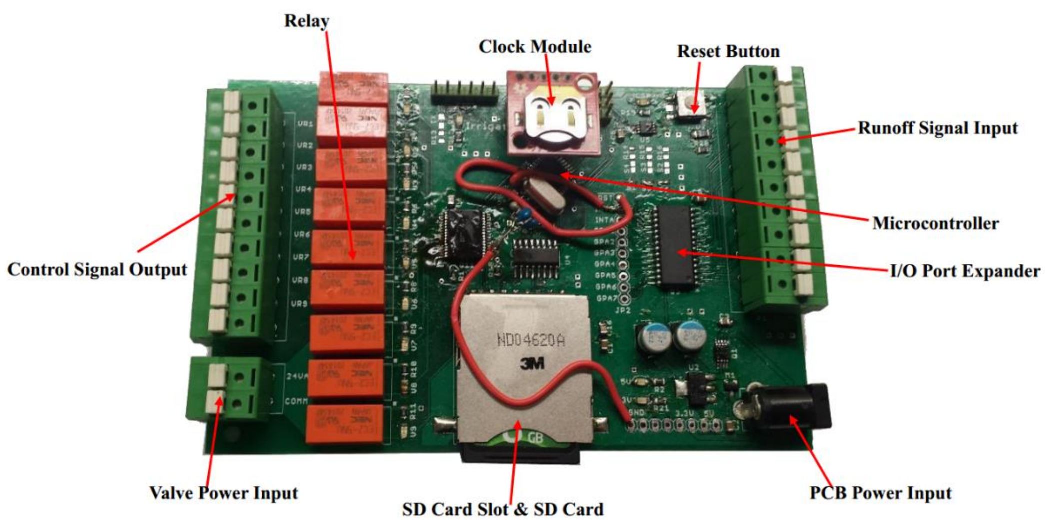

Figure 30. A Fabricated and Assembled I/O Communication and Control Module PCB

The I/O communication and control module provides precise and reliable controls for up to 9 plots during the field tests. It could either work as a stand-alone irrigation controller or as an add-on item to an existing controller, as shown in Figures 31 and 32.

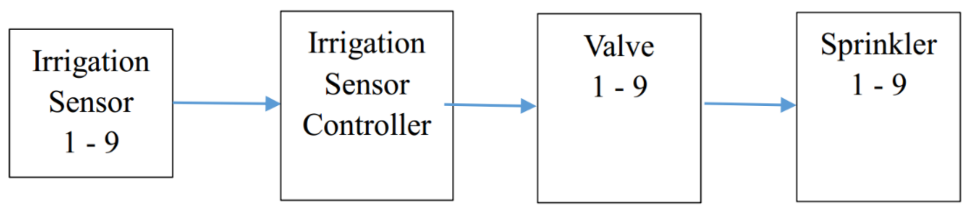

Figure 31. Working Principle of Acting as an Individual Irrigation Controller

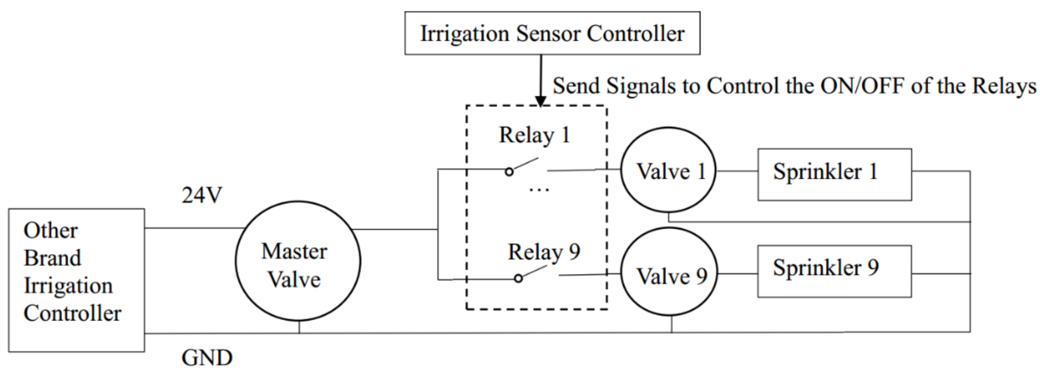

Figure 32. Working Principle of Acting as an Add-On to an Existing Irrigation Controller

When the I/O communication and control module works as an individual irrigation controller, runoff signals are sent to the PCB and the PCB will control the sprinklers by opening and closing the corresponding valves. If the I/O communication and control module works as an add-on item to an existing irrigation controller, the existing irrigation controller of other brand will control the master valve directly to control the water supply to the system. When the master valve is open and the runoff signals are detected, the I/O communication and control module will control the sprinklers by controlling the corresponding relays and valves.

Compared to the first generation, the second generation of the I/O communication and control module is low cost and could hardly be affected by the surroundings or environmental noise. Also, the first generation maintains a constant energy consumption level 24 hours a day for 7 day, which requires more energy in the long run. The second generation I/O system relies on a sleep model, which turn the whole system off when it is not in operation. Therefore, it does not consume energy when it is not in operation (i.e. irrigating). The energy consumption comparison between the two generations based on a one hour weekly irrigation event for a 9-plot field is shown in Table 5. The second generation results in 78.6% saving in energy compared to the first generation.

Table 5. Comparison of Energy Consumptions between the Two Generations of the I/O Communication and Control Module

	Voltage (V)	Current (A)	Power (W)	Number of PCB Needed	Weekly Working Time (h)	Weekly Energy Consumption (Watt-Hour)
1^{st} Generation	5	0.05	0.25	9	168	42
2^{nd} Generation	9	1	9	1	1	9

With all these advantages, the second generation turns out to be the final option for the I/O communication and control module.

3.3.4 Autonomous Power Supply Module Design and Fabrication

The I/O communication and control module is desired to use as little energy possible. An autonomous power supply module consisting of solar panels and rechargeable batteries was designed to provide the I/O communication and control module with needed power. The circuit diagram is shown in Figure 33.

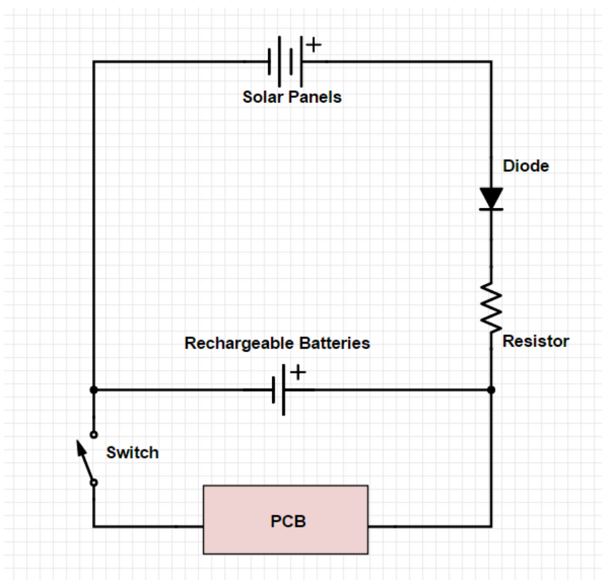

Figure 33. Circuit Diagram of the Autonomous Power Supply Module

During daytime, the solar panels of the autonomous power supply module provides the energy for the PCB which recharges the batteries. During times without sunlight, the rechargeable batteries provide the PCB with the energy. Moreover, the batteries could not charge the solar panels due to the diode. The switch in Figure 33 is used to open and close the autonomous power supply module.

The autonomous power supply module has been tested in the field and functions as desired. The installation is shown in Figure 34.

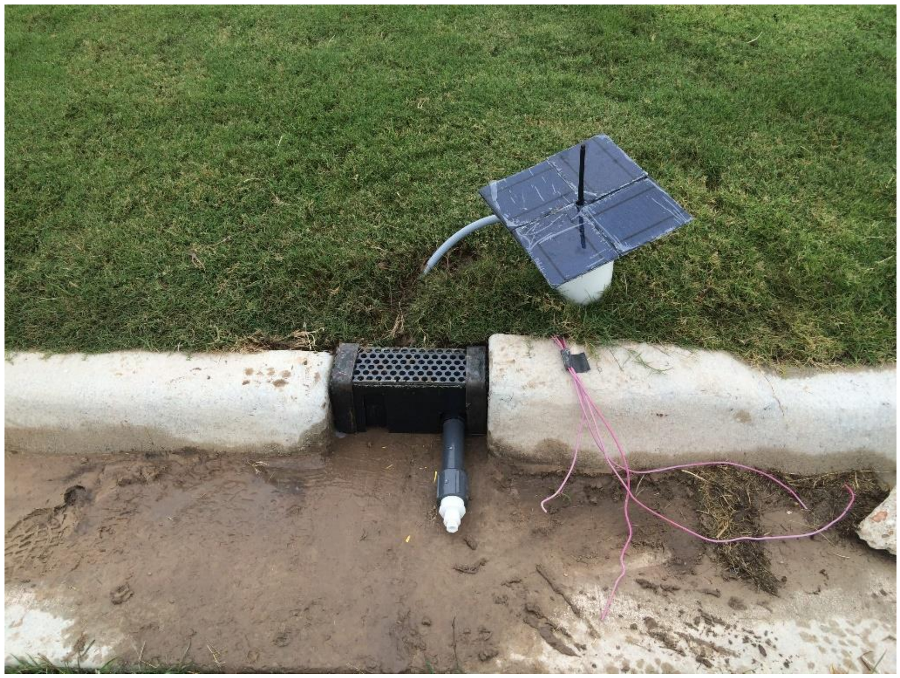

Figure 34. A Cubic Float Prototype with an Autonomous Power Supply Module Installed in the Field

3.3.5 *Irrigation Results Analysis Website Design*

An irrigation results analysis website (http://irrigationrom-kossel.rhcloud.com/) was designed to store the irrigation data in the web server and plot the irrigation result charts, as needed. The irrigation data and results in the SD card could be manually uploaded to the web server, as shown in Figure 35.

Figure 35. Webpage for Manually Uploading the Irrigation Results and Data

The website is also capable of storing results and data in the web server and drawing the irrigation result charts for designated dates automatically, as shown in Figure 36.

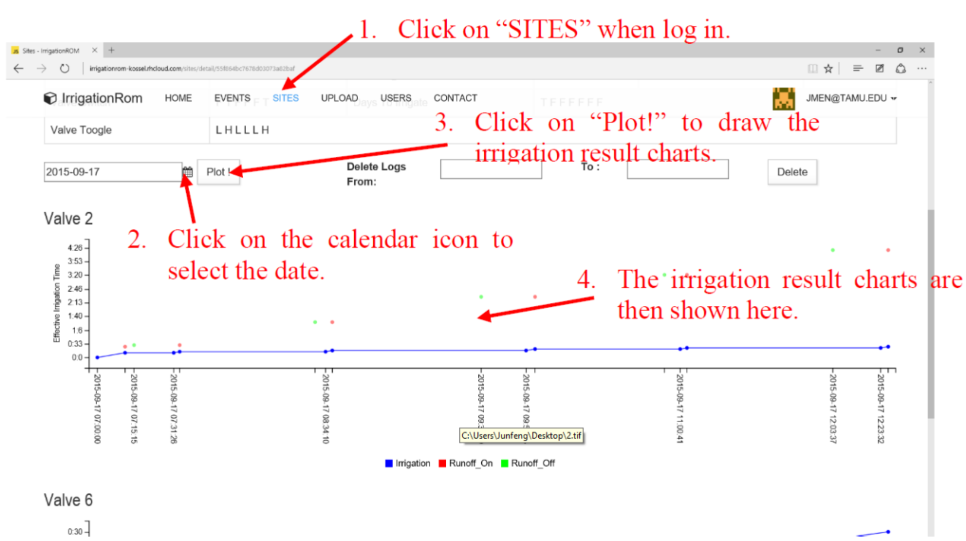

Figure 36. Webpage for Drawing the Irrigation Result Charts of Designated Dates

4. RESULTS AND DISCUSSION

This section includes the tests results of the irrigation runoff prototypes under different situations. The first section deals with the lab testing of different prototypes. The second section focuses on the qualitative field testing of all the prototypes. Finally, the last section discusses the quantitative field testing results of different irrigation runoff sensor prototypes.

4.1 Lab Testing Results of Different Prototypes

Lab tests were conducted to evaluate the effectiveness of the designed and built prototypes. The paddle wheel, cubic float, elbow float and the conductivity prototypes have been tested and validated in the lab as described below.

4.1.1 Lab Testing Results of Paddle Wheel Prototype

During the lab tests, the runoff flow rates and corresponding rotational speeds of the paddle wheel were recorded and a correlation equation between both variables was derived, as shown in Figure 37.

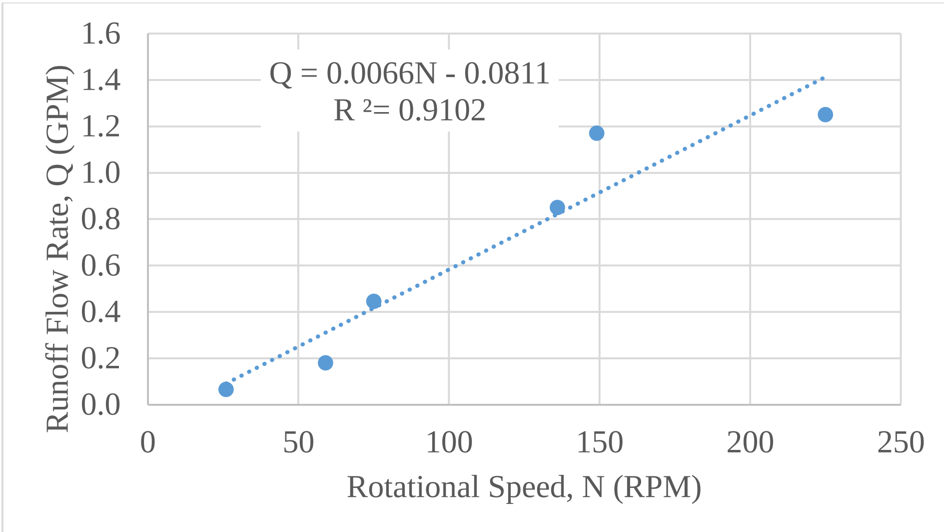

Figure 37. Lab Test Results of Runoff Flow Rate and Rotational Speed of Paddle Wheel Prototype

Based on Figure 37, the relation between the runoff flow rate in gallons per minute Q (GPM) and the rotational speed in rounds per minute N (RPM) is as follows:

$$Q[GPM] = 0.0066 \times N[RPM] - 0.0811 \tag{2}$$

With Eq. (2), the amount of the water that runs through the prototype can be estimated by recording the rotational speed.

4.1.2 Lab Testing Results of Cubic Float Prototype

The cubic float prototype has also been tested in the lab. The exit orifice diameters with the corresponding runoff flow rates have been documented as shown in Table 6.

Table 6. Lab Tests Results of the Cubic Float Prototype

Exit Orifice Diameter (inch)	Runoff Flow Rate (GPM)
0.25	0.296
0.1875	0.156
0.125	0.071
0.0625	0.018

The relationship between the runoff flow rate and exit orifice diameter is shown in Figure 38.

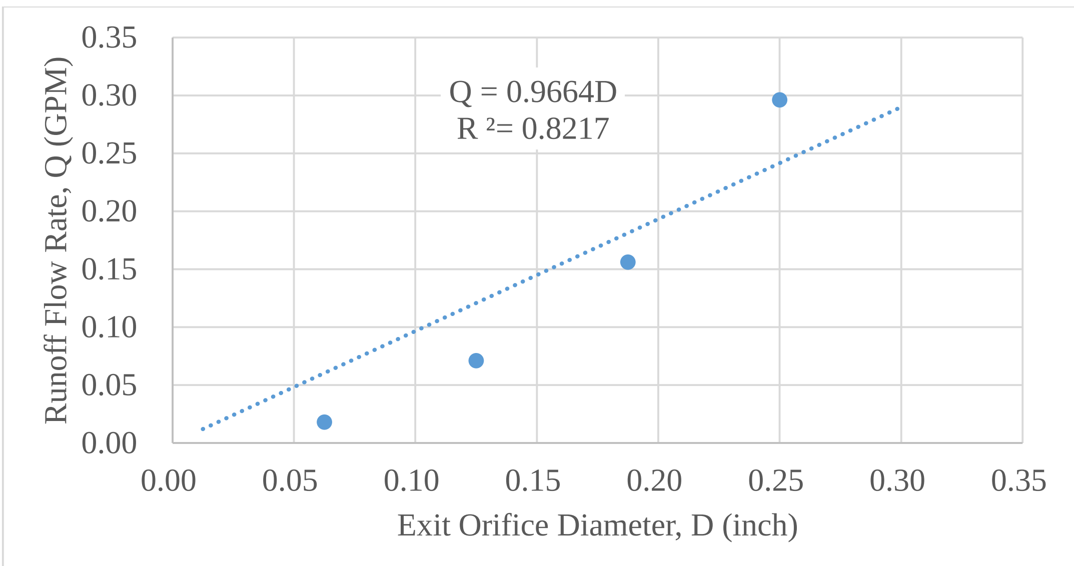

Figure 38. Lab Test Results of Runoff Flow Rates and Exit Orifice Diameters of Cubic Float Prototype

Based on Figure 38, the relation between the runoff flow rates in gallons per minute Q (GPM) and the exit orifice diameters D (inch) is as follows:

$$Q[GPM] = 0.9664 \times D[inch] \quad (3)$$

4.1.3 Lab Testing Results of Elbow Float Prototype

During lab tests, the runoff flow rate which could activate the elbow float switch has been documented as shown in Table 7.

Table 7. Lab Test Results of the Elbow Float Prototype

Exit Orifice Diameter (inch)	Runoff Flow Rate (GPM)
0.5	1.183
0.25	0.598
0.125	0.253

The relationship between the runoff flow rates and exit orifice diameters is shown in Figure 39.

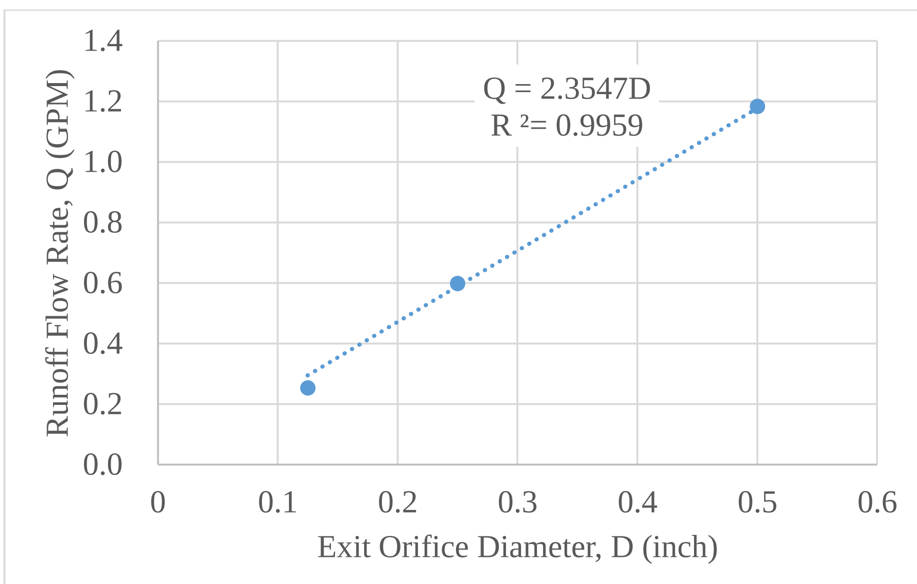

Figure 39. Lab Test Results of Runoff Flow Rates and Exit Orifice Diameters of Elbow Float Prototype

Based on Figure 39, the relation between the runoff flow rates in gallons per minute Q (GPM) and the exit orifice diameters D (inch) is as follows:

$$Q[GPM] = 2.3547 \times D[inch] \tag{4}$$

4.1.4 Lab Testing Results of Conductivity Prototype

During lab tests, the runoff flow rates which could activate the conductivity prototype with different exit orifice diameters have been documented as shown in Table 8.

Table 8. Lab Test Results of the Conductivity Prototype

Exit Orifice Diameter (inch)	Runoff Flow Rate (GPM)
0.125	0.22
0.6875	1.4
0.75	1.61

The relationship between the runoff flow rates and exit orifice diameters is shown in Figure 40.

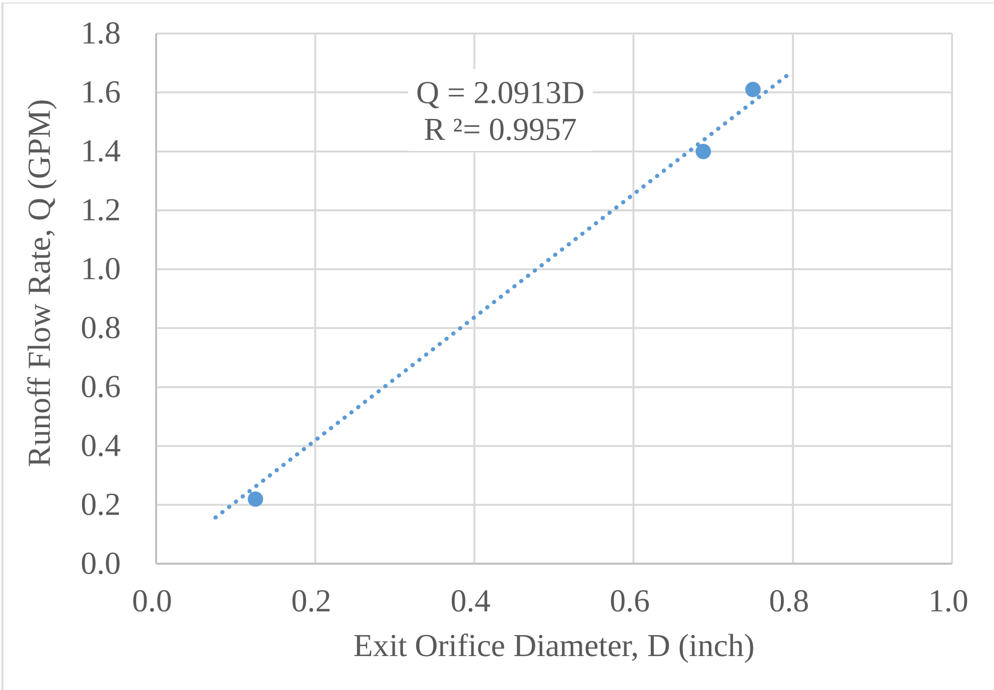

Figure 40. Lab Test Results of Runoff Flow Rates and Exit Orifice Diameters of Conductivity Prototype

Based on Figure 40, the relation between the runoff flow rates in gallons per minute Q (GPM) and the exit orifice diameters D (inch) is as follows:

$$Q[GPM] = 2.0913 \times D[inch] \quad (5)$$

4.1.5 Working Ranges of Different Prototypes

The working ranges of different prototypes has been tested and recorded, as shown in Table 9.

Table 9. Working Ranges of Different Prototypes under Lab Conditions

Prototype	Working Range (GPM)
Paddle Wheel Prototype	0.08 - 1.78
Cubic Float Prototype	0.01 - 0.3
Elbow Float Prototype	0.05 - 1.4
Conductivity Prototype	0.05 - 1.7

As the table shows, the paddle wheel prototype and the conductivity prototype have the greatest range. On the other hand, cubic float prototype has a narrower range of operation, which makes the device more sensitive to runoff. The cubic float prototype, the elbow float prototype and the conductivity prototype can detect small flow rate when a small exit orifice hole is used. However, small orifices are more prone to clogging and may require regular cleaning.

4.2 Qualitative Field Testing Results of Different Prototypes

The qualitative field testing aims at evaluating the functionalities and effectiveness of different sensor prototypes. Several performance related parameters, including effective irrigation time, wait time, start time, total allowable window and the irrigation time were used to control the irrigation process. The effective irrigation time (EIT) is the total amount of the time when the sprinklers are on during an irrigation event. Also, the wait time (WT) is a manually set value of the pause time of the irrigation system when runoff is detected. Meanwhile, the start time is the time of the day when the irrigation is set to begin. The real irrigation time (RIT) is the total time that the whole system is in operation. Lastly, the total allowable window (TAW) acts as top or maximum limit, which should not be exceeded. When RIT is equal or larger than TAW, the whole system will be closed permanently until next irrigation day no matter EIT is reached or not. Figure 41 shows the different time variables for a typical irrigation event.

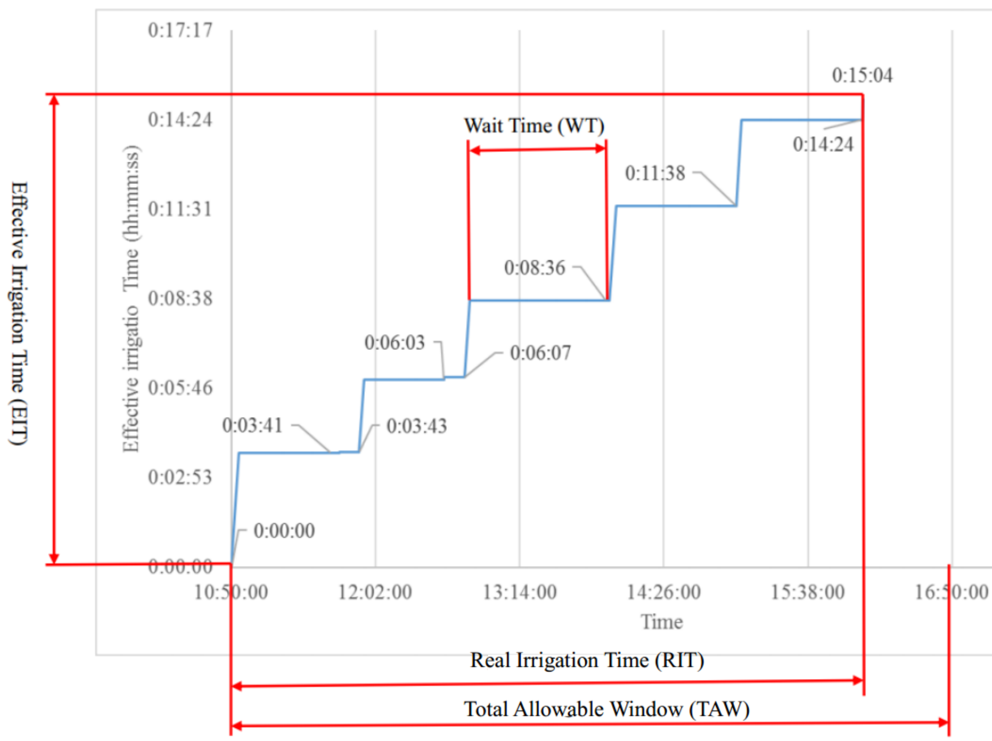

Figure 41. Different Time Variables for a Typical Irrigation Event

4.2.1 Qualitative Field Testing Results for April 8th 2015

A cubic float prototype and a conductivity prototype have been also tested. The irrigation specifications are shown in Table 10.

Table 10. Irrigation Specifications of Test on April 8th 2015

Start Time	7:00 AM
Effective Irrigation Time (EIT)	30 minutes
Wait Time (WT)	20 minutes
# of Tested Plot	5 (Cubic Float Prototype), 6 (Conductivity Prototype)

The results of the irrigation are shown in Figure 42 – 45.

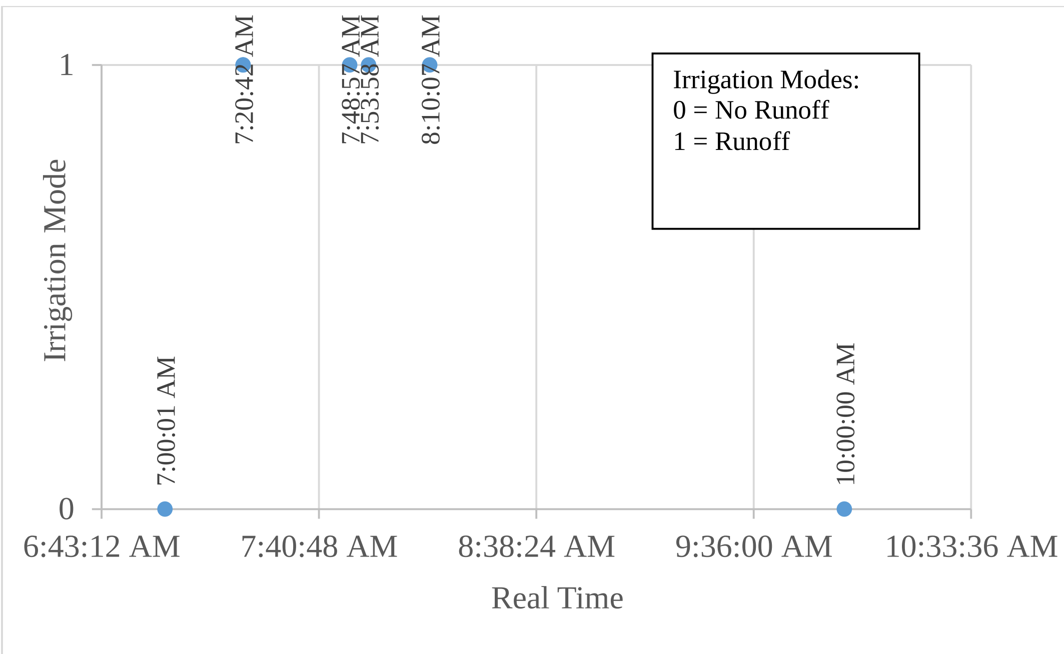

Figure 42. The Runoff Status of Plot 5 (Cubic Float Prototype) on April 8th 2015

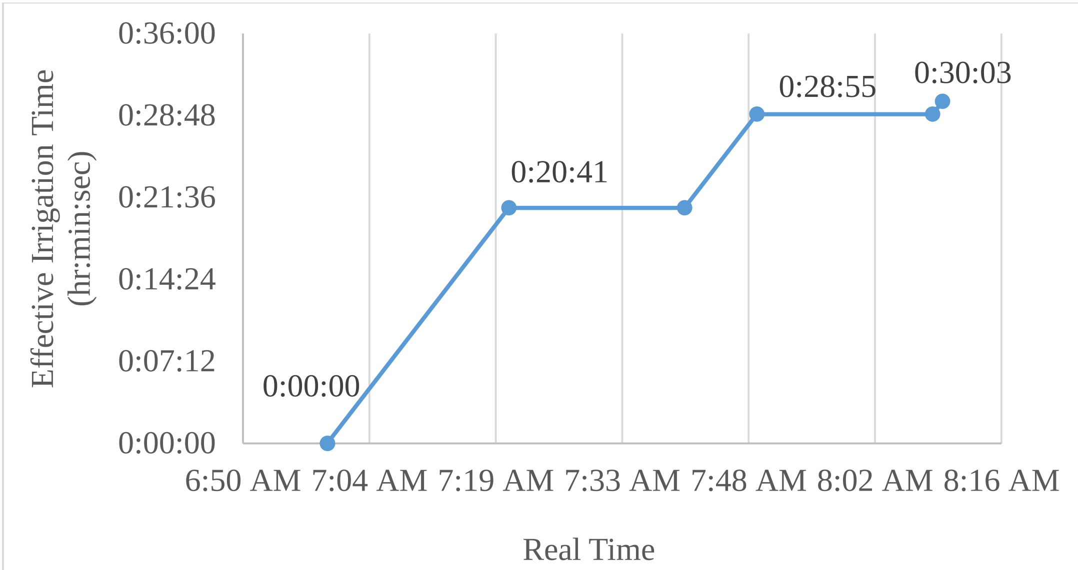

Figure 43. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on April 8th 2015

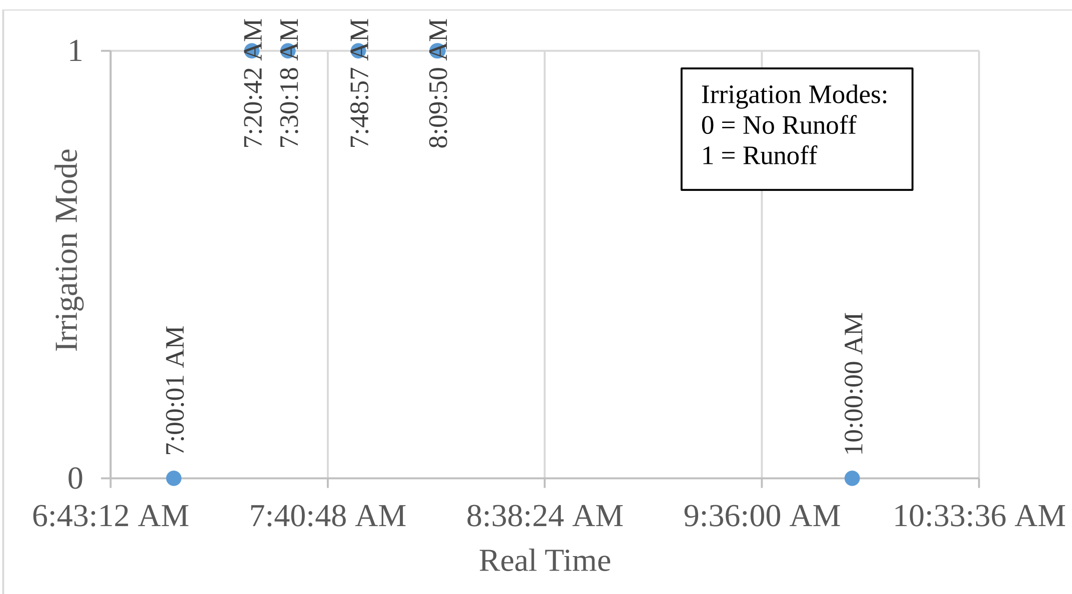

Figure 44. The Runoff Status of Plot 6 (Conductivity Prototype) on April 8th 2015

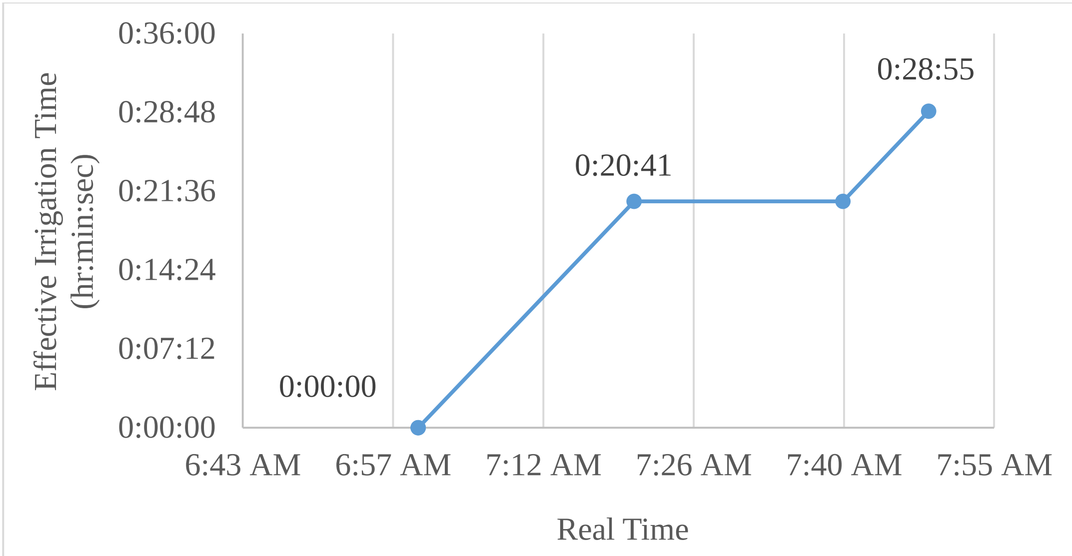

Figure 45. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on April 8th 2015

Based on the irrigation results, both prototypes have shown the capability of detecting runoff and fulfilling the complete cycle-soaking. However, the different EITs of the two devices may be caused by the interference or noises on the PCB, which interrupted the operation of the irrigation system for plot 6. As a result, the ETI of the conductivity prototype was less than expected. Insulating panels have been applied to the PCB to avoid the noise as a hardware method.

4.2.2 Qualitative Field Testing Results for April 15th 2015

Two cubic float prototypes, two conductivity prototypes and two control plots without irrigation runoff sensors have been tested. The irrigation specifications for those tests are shown in Table 11.

Table 11. Irrigation Specifications of Test on April 15th 2015

Start Time	7:30 AM
Effective Irrigation Time (EIT)	30 minutes
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 8 (Control Plot)

The results of the irrigation are shown in Figure 46 - 57.

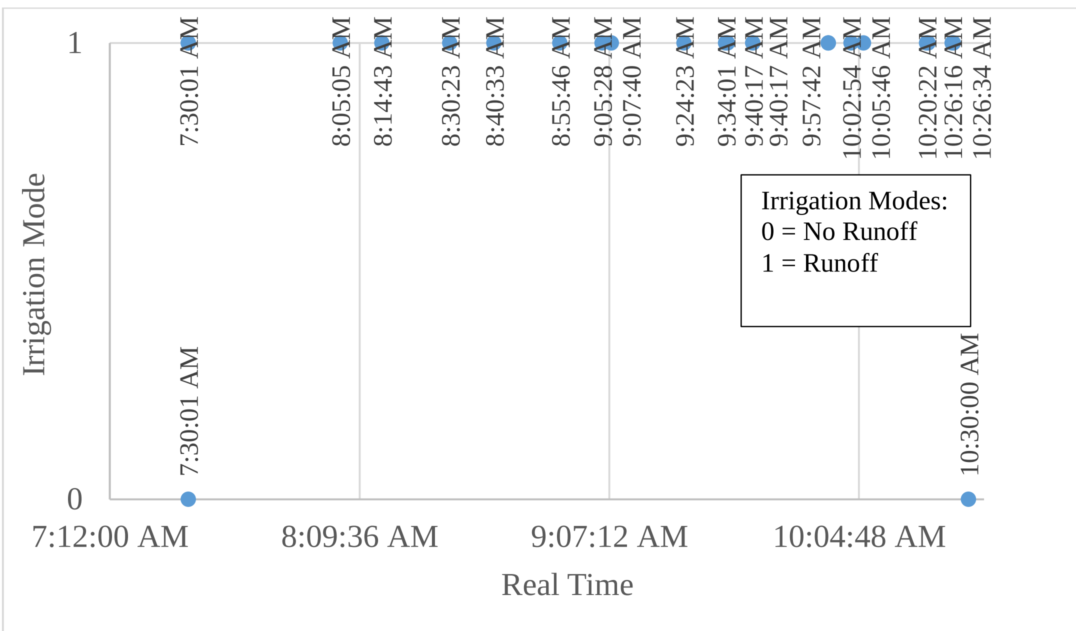

Figure 46. The Runoff Status of Plot 2 (Conductivity Prototype) on April 15th 2015

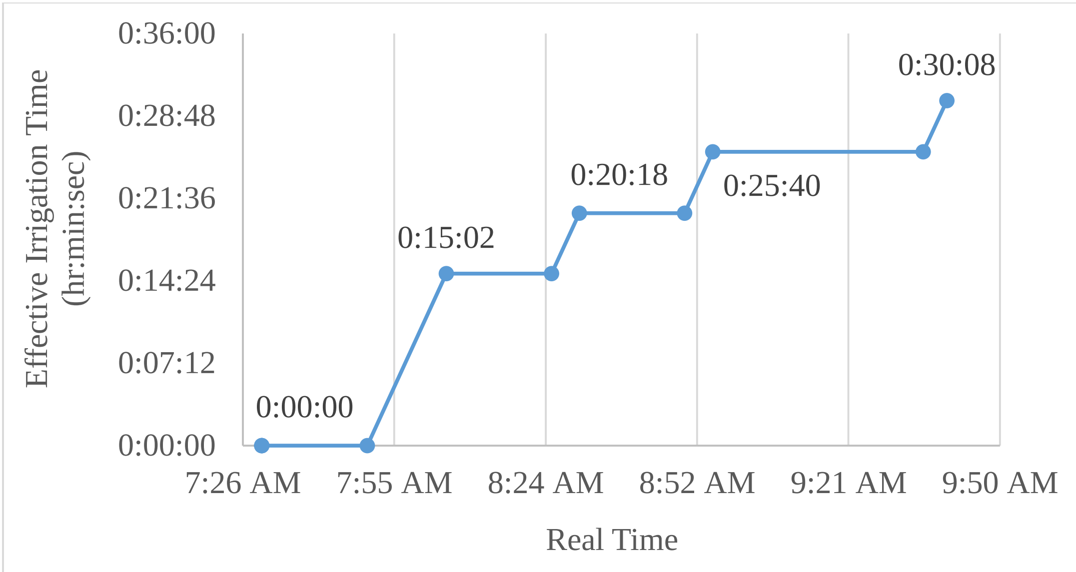

Figure 47. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on April 15th 2015

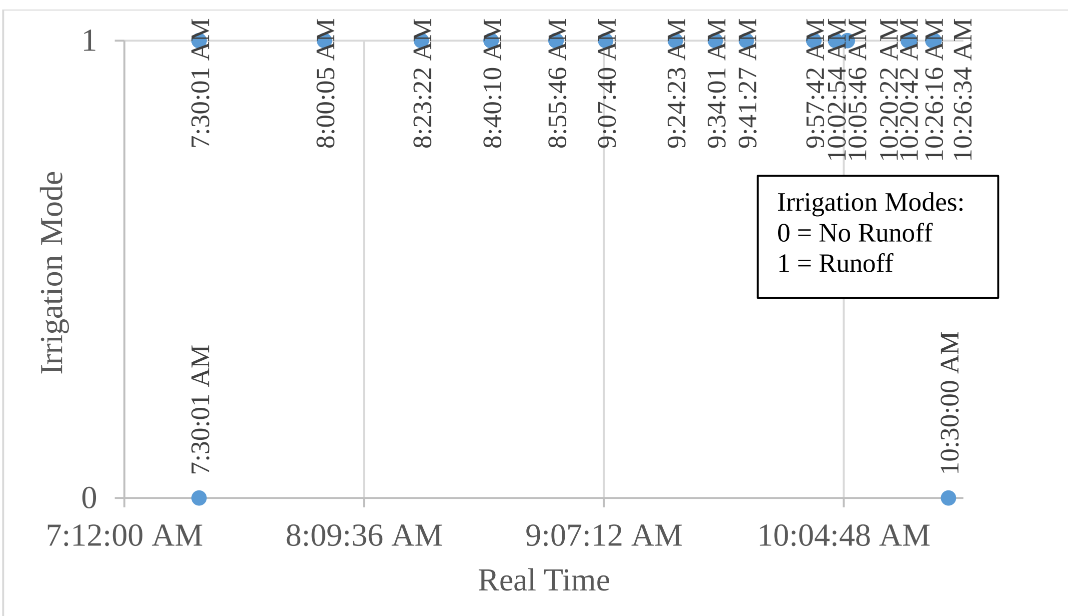

Figure 48. The Runoff Status of Plot 4 (Cubic Float Prototype) on April 15th 2015

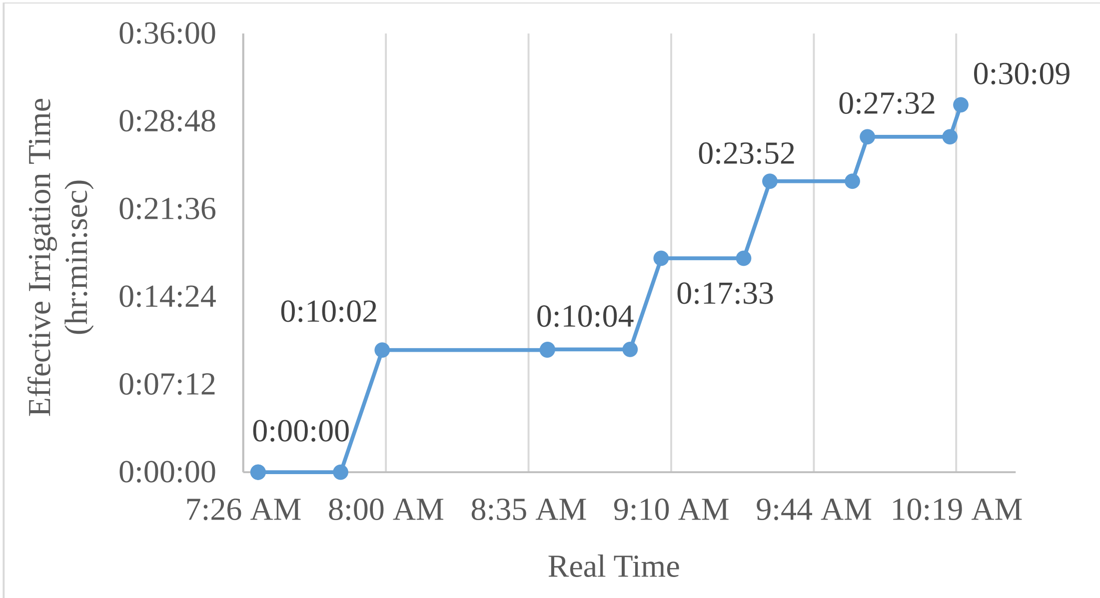

Figure 49. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on April 15th 2015

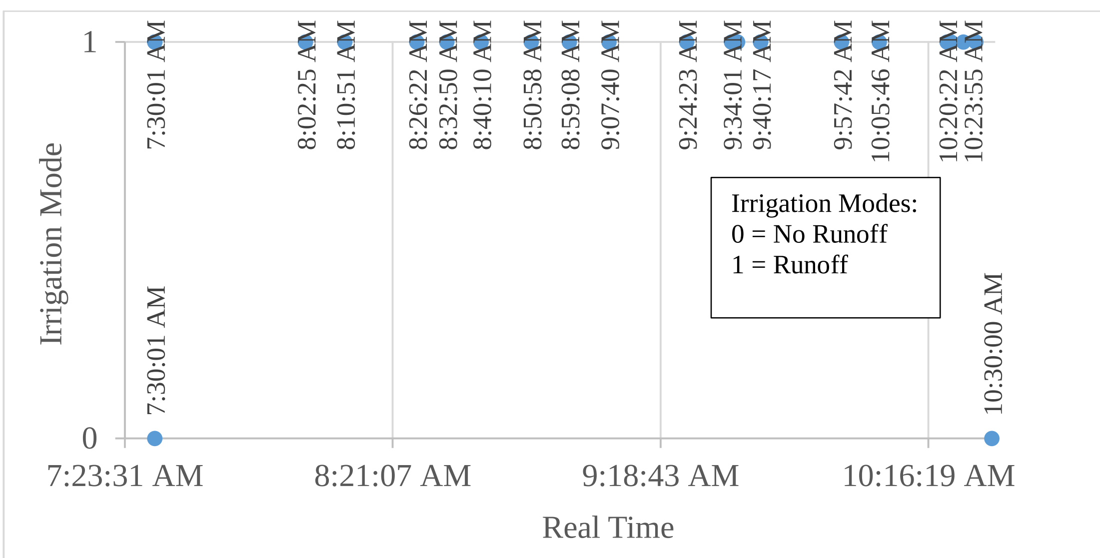

Figure 50. The Runoff Status of Plot 5 (Cubic Float Prototype) on April 15th 2015

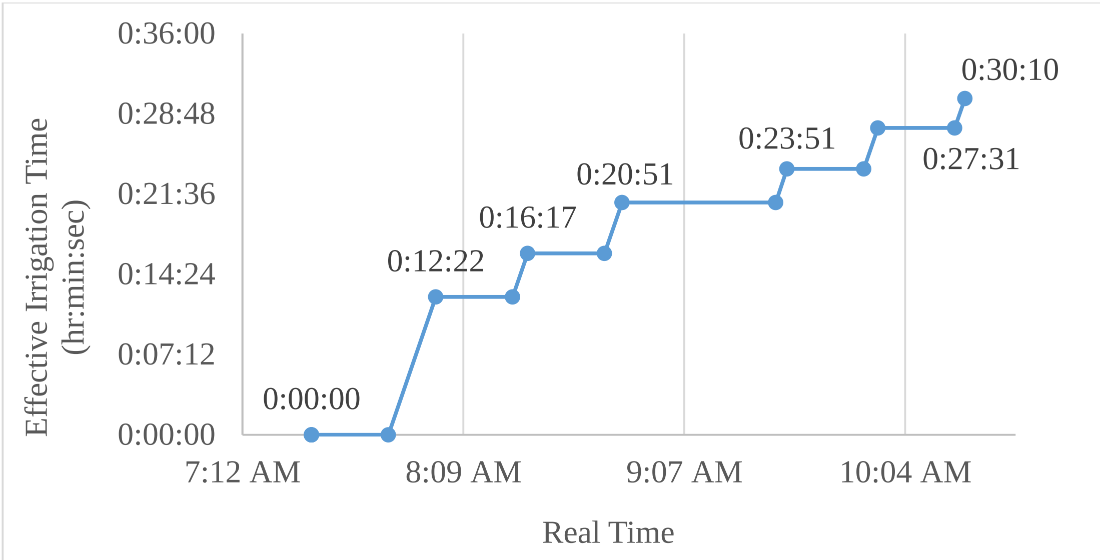

Figure 51. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on April 15th 2015

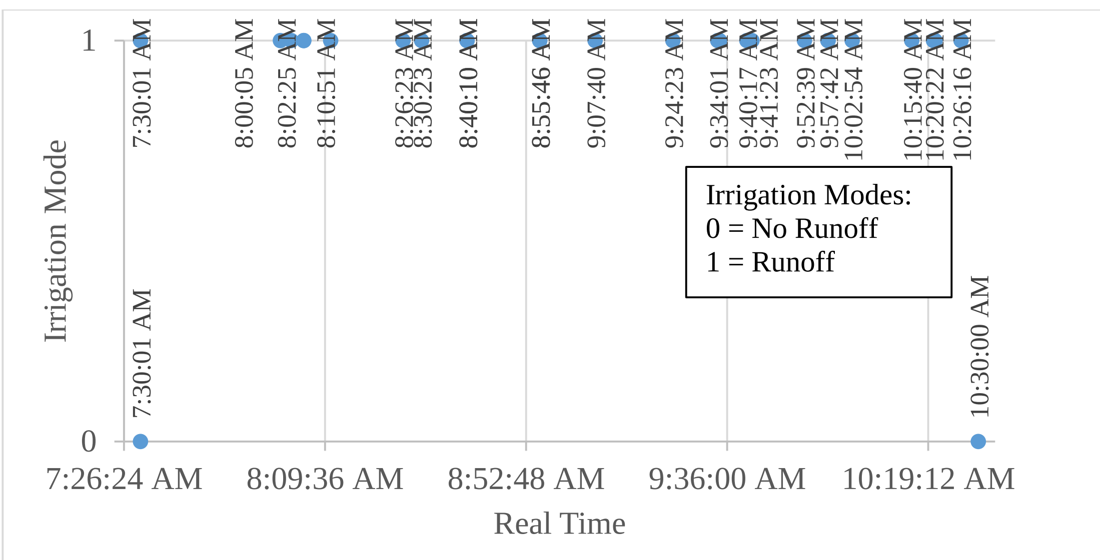

Figure 52. The Runoff Status of Plot 6 (Conductivity Prototype) on April 15th 2015

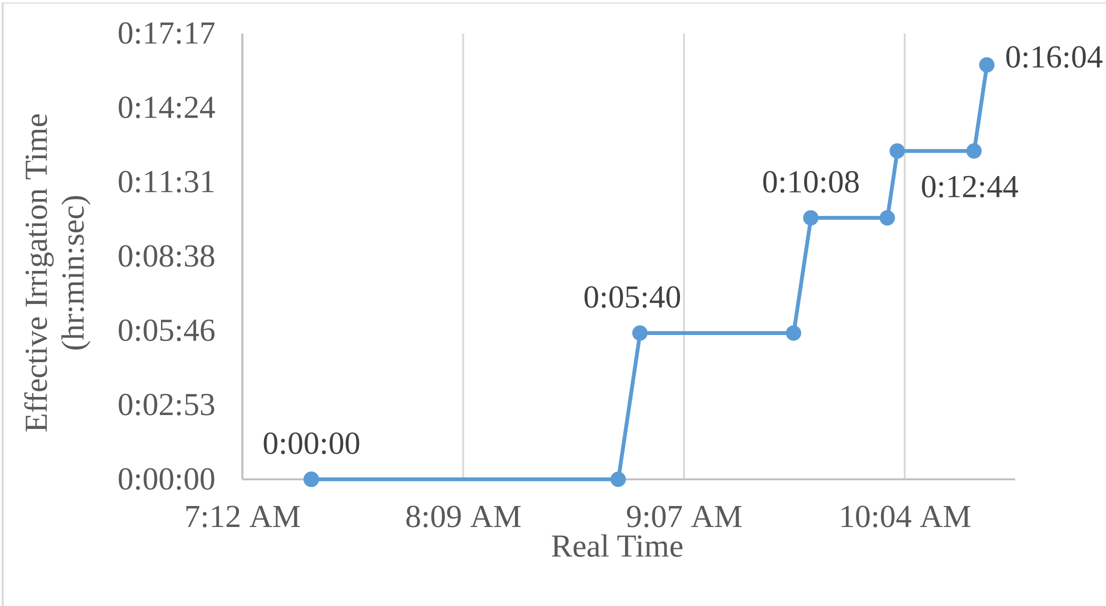

Figure 53. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on April 15th 2015

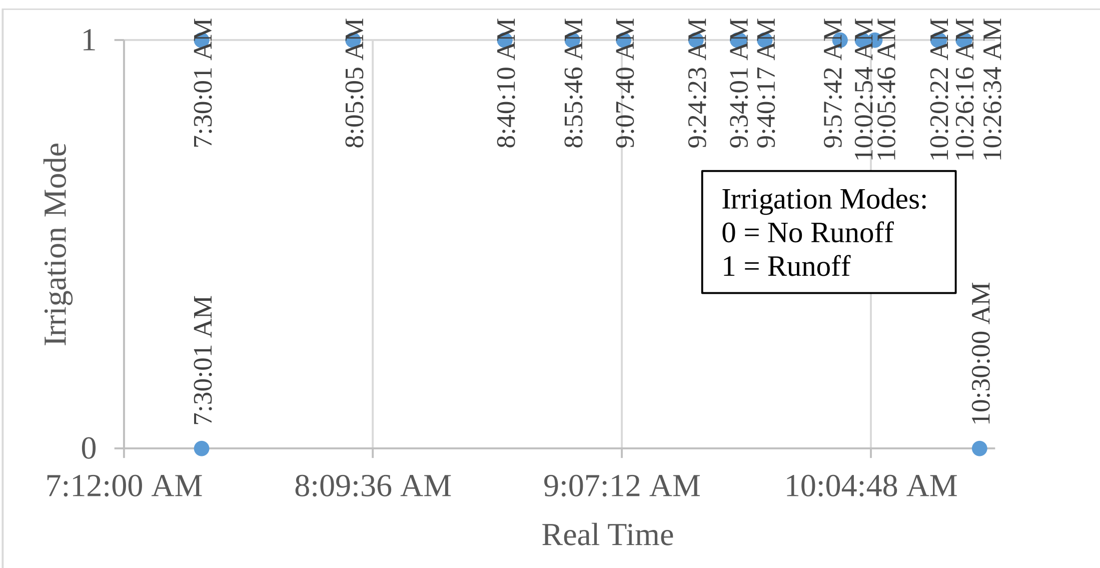

Figure 54. The Runoff Status of Plot 7 (Control) on April 15th 2015

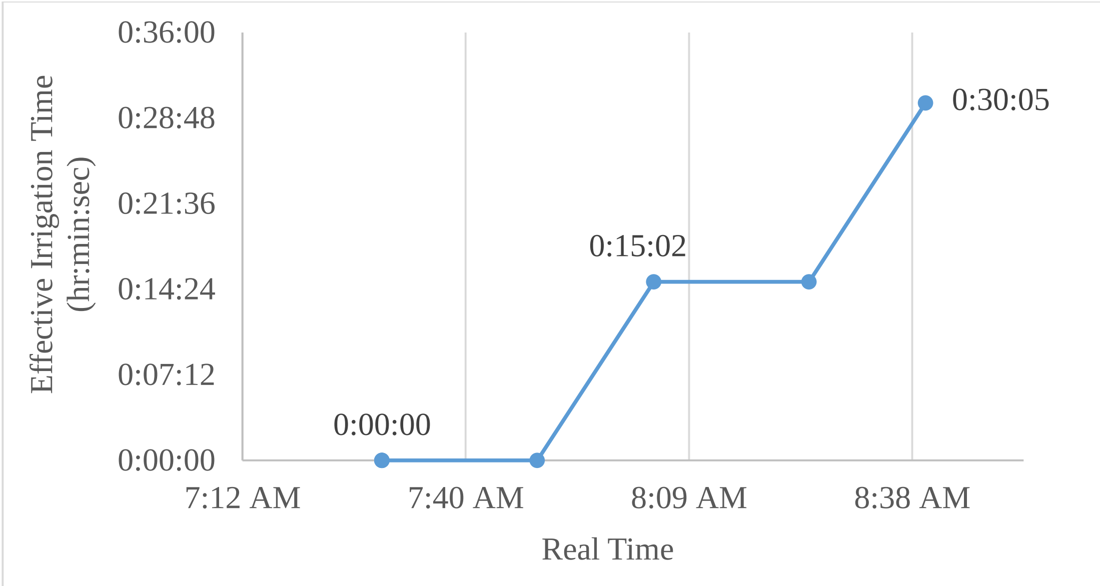

Figure 55. The Effective Irrigation Time of Plot 7 (Control) on April 15th 2015

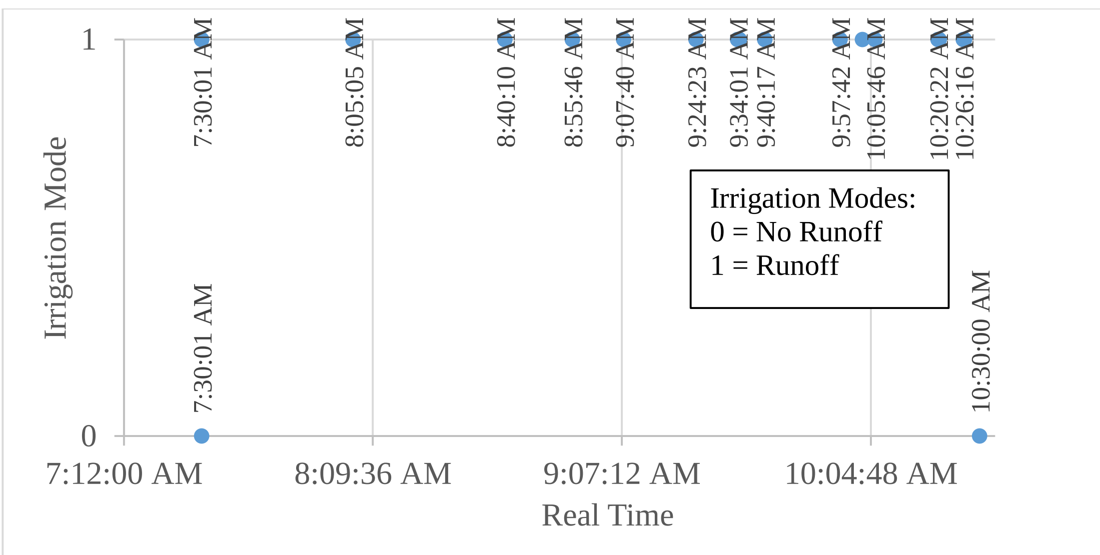

Figure 56. The Runoff Status of Plot 8 (Control) on April 15th 2015

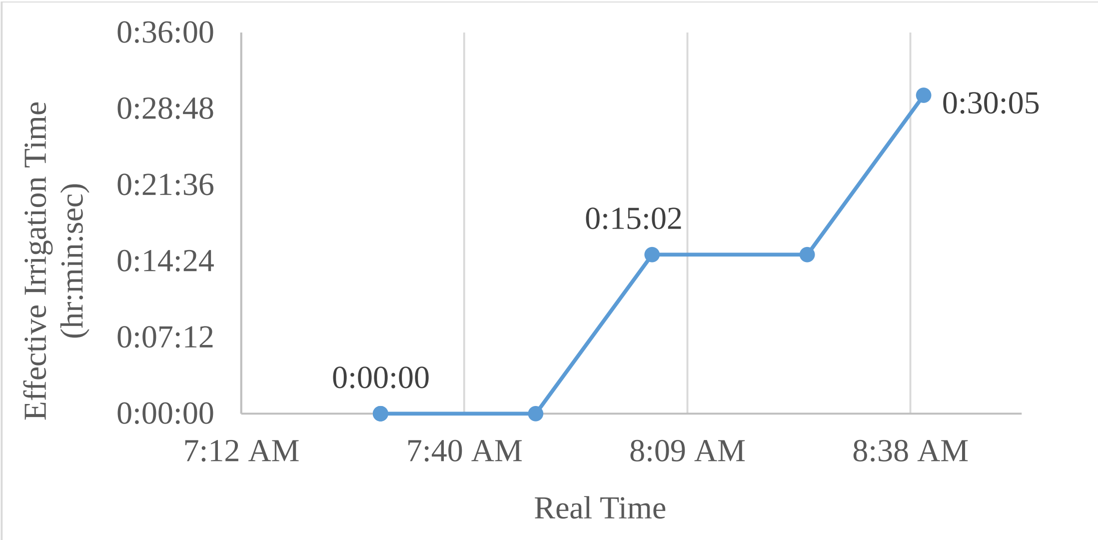

Figure 57. The Effective Irrigation Time of Plot 8 (Control) on April 15th 2015

Based on the irrigation results, the cubic float prototypes and the conductivity prototypes have shown the capability of detecting runoff and fulfilling the complete cycle-soaking. Also, all the prototypes have more accumulated WT than the control plots, allowing more time for water absorption. However, the pause at the beginnings of each irrigation cycle as shown in the figures and during the irrigation of the control plots shows the interruption of irrigation which was triggered by noise and interference as it was the case for the tests conducted on April 8th. The noise-related problem was eliminated by analyzing the runoff signal over a 5 minute period using the data analysis software. The software basically was able to calculate the average value of the runoff signal, and if its value exceeded 4.5 volts, then the runoff was assumed to take place.

4.2.3 Qualitative Field Testing Results for June 16th 2015

Two cubic float prototypes, one conductivity prototype, one paddle wheel prototype and two control plots without irrigation runoff sensors have been tested. The irrigation specifications for the tests are shown in Table 12.

Table 12. Irrigation Specifications of Test on June 16th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 3 (Paddle Wheel Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 7 (Control Plot), 8 (Control Plot)

The results of the irrigation are shown in Figure 58 - 69.

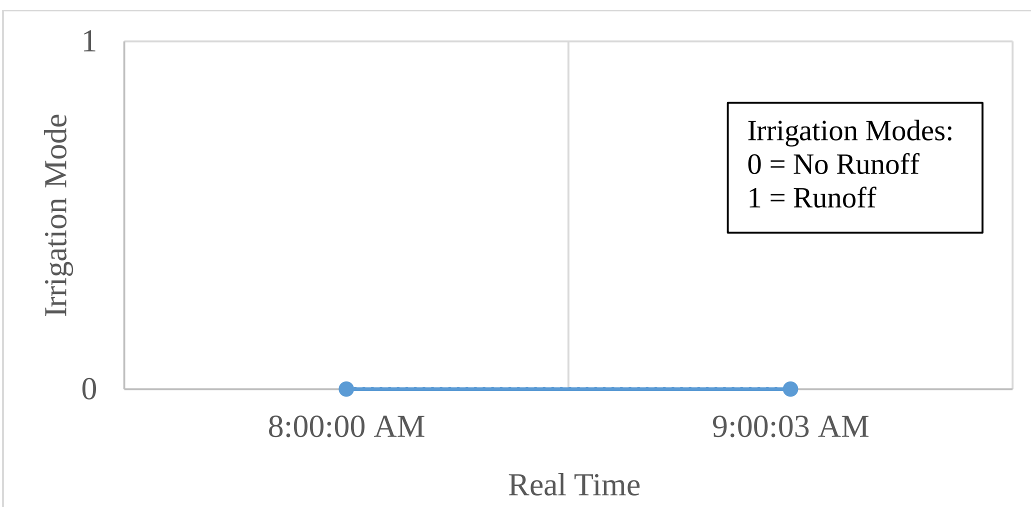

Figure 58. The Runoff Status of Plot 2 (Conductivity Prototype) on June 16th 2015

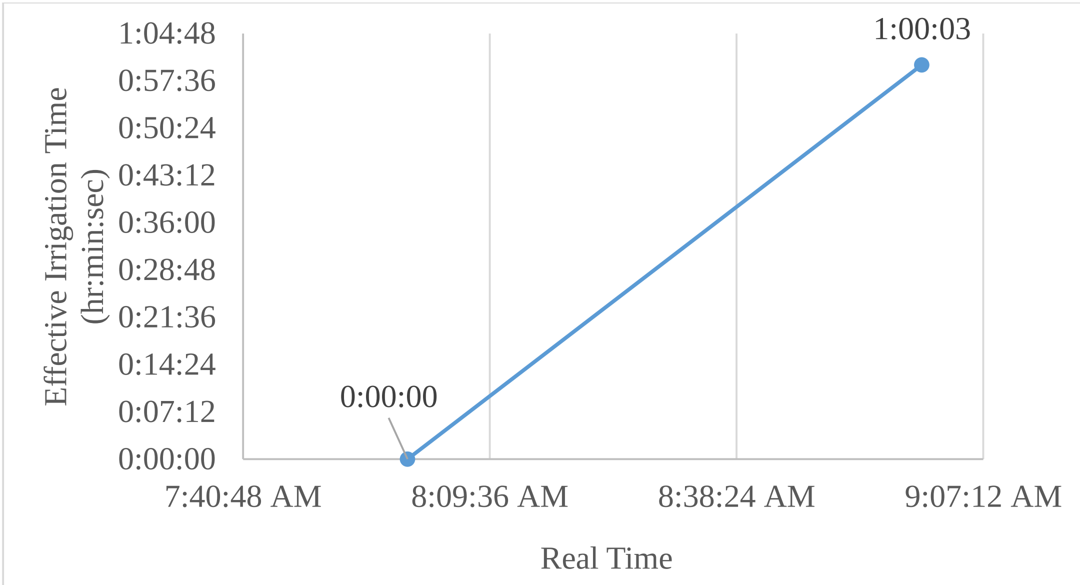

Figure 59. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on June 16th 2015

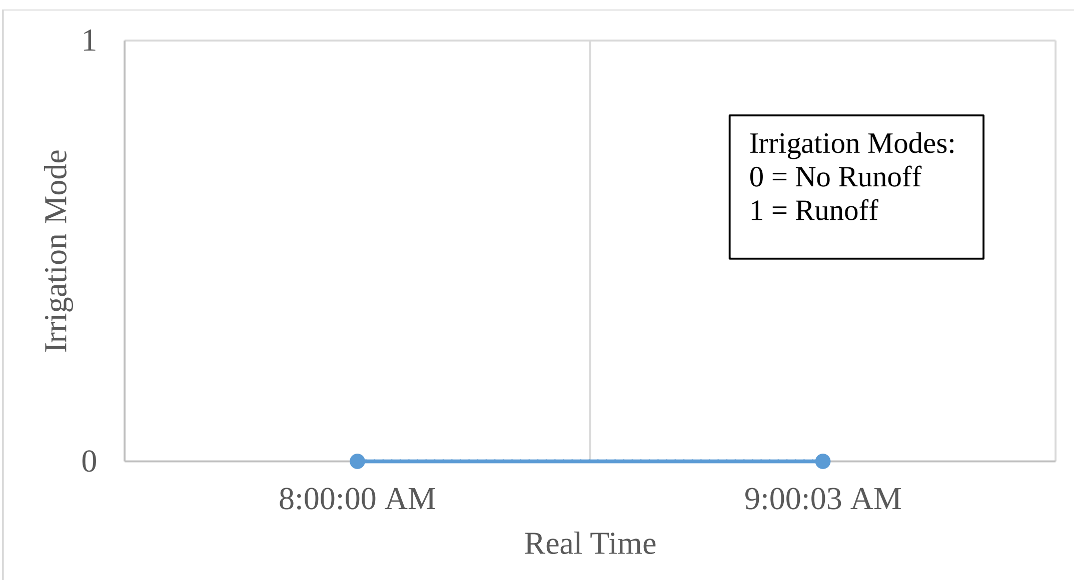

Figure 60. The Runoff Status of Plot 3 (Paddle Wheel Prototype) on June 16th 2015

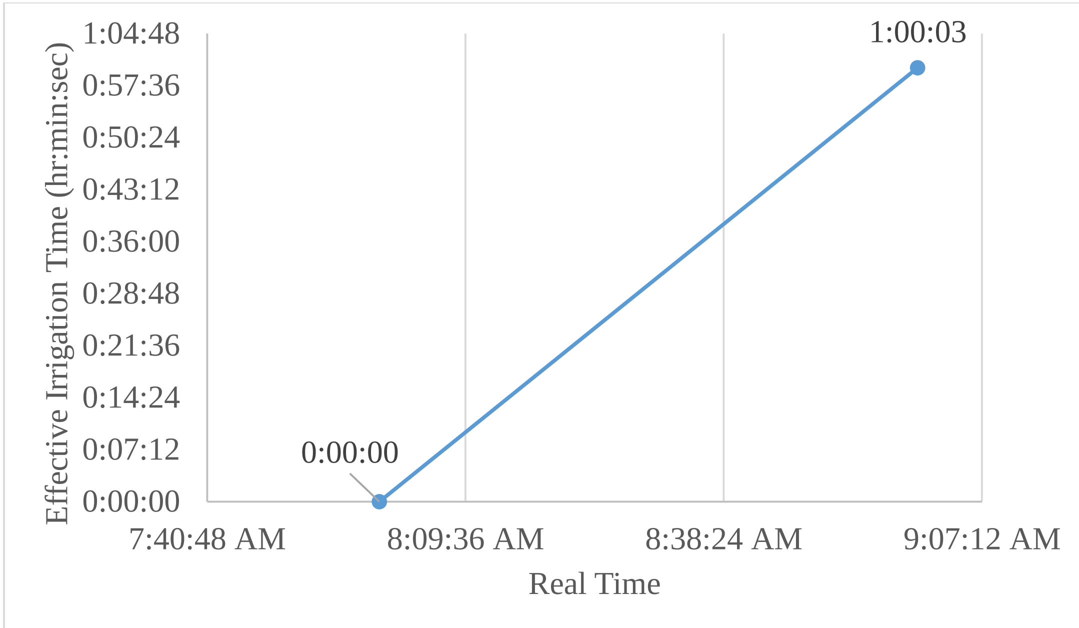

Figure 61. The Effective Irrigation Time of Plot 3 (Paddle Wheel Prototype) on June 16th 2015

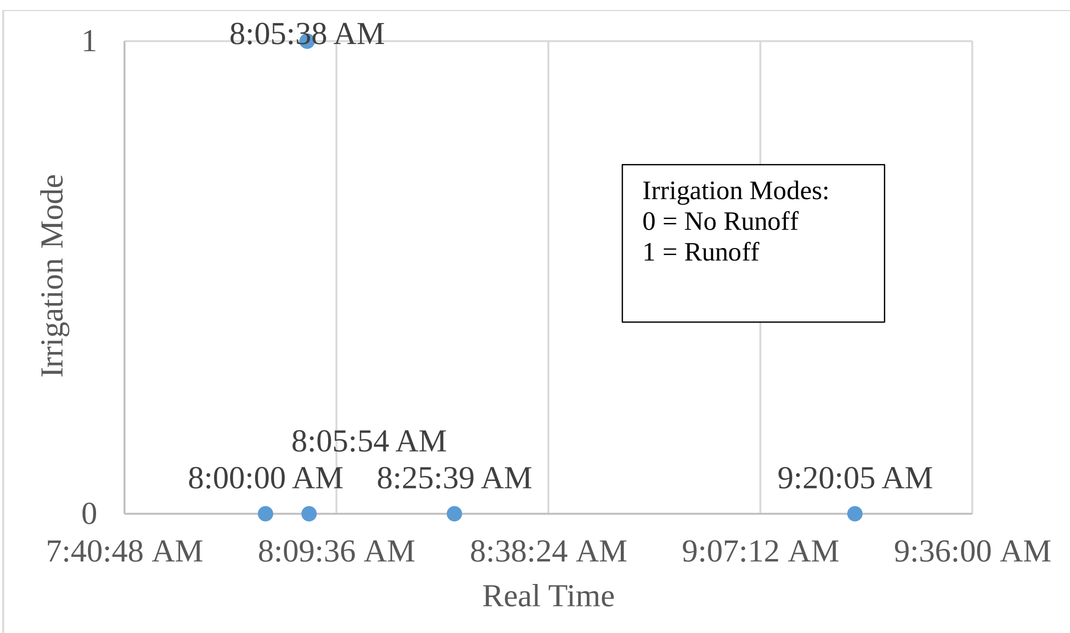

Figure 62. The Runoff Status of Plot 4 (Cubic Float Prototype) on June 16th 2015

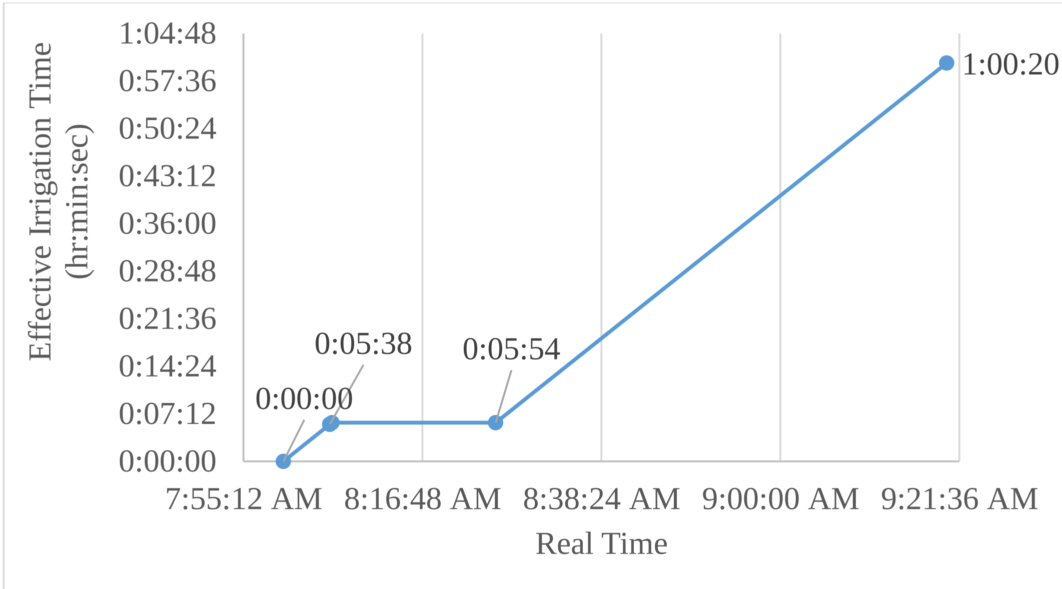

Figure 63. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on June 16th 2015

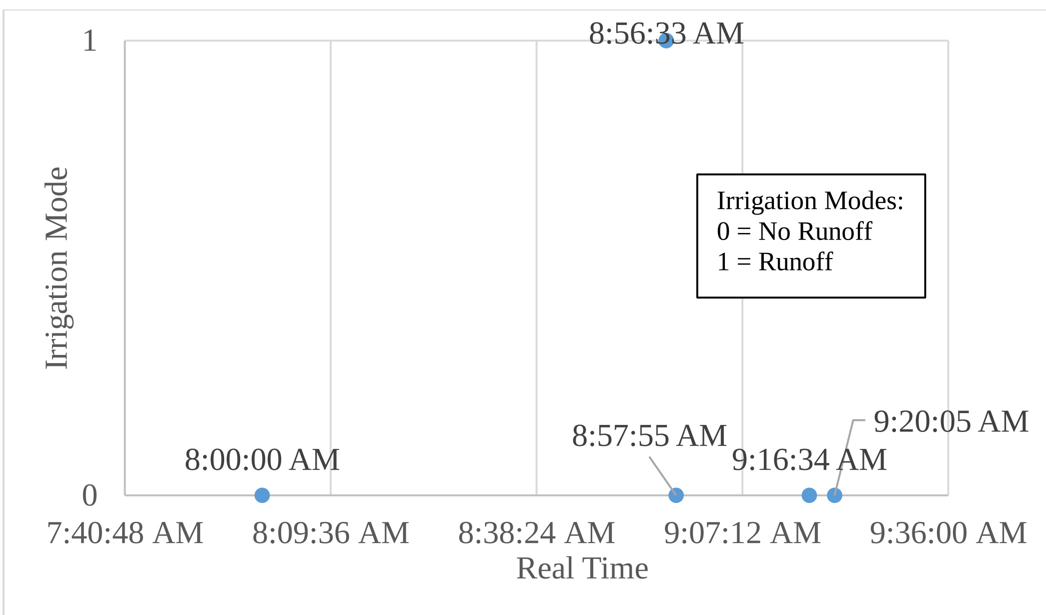

Figure 64. The Runoff Status of Plot 5 (Cubic Float Prototype) on June 16th 2015

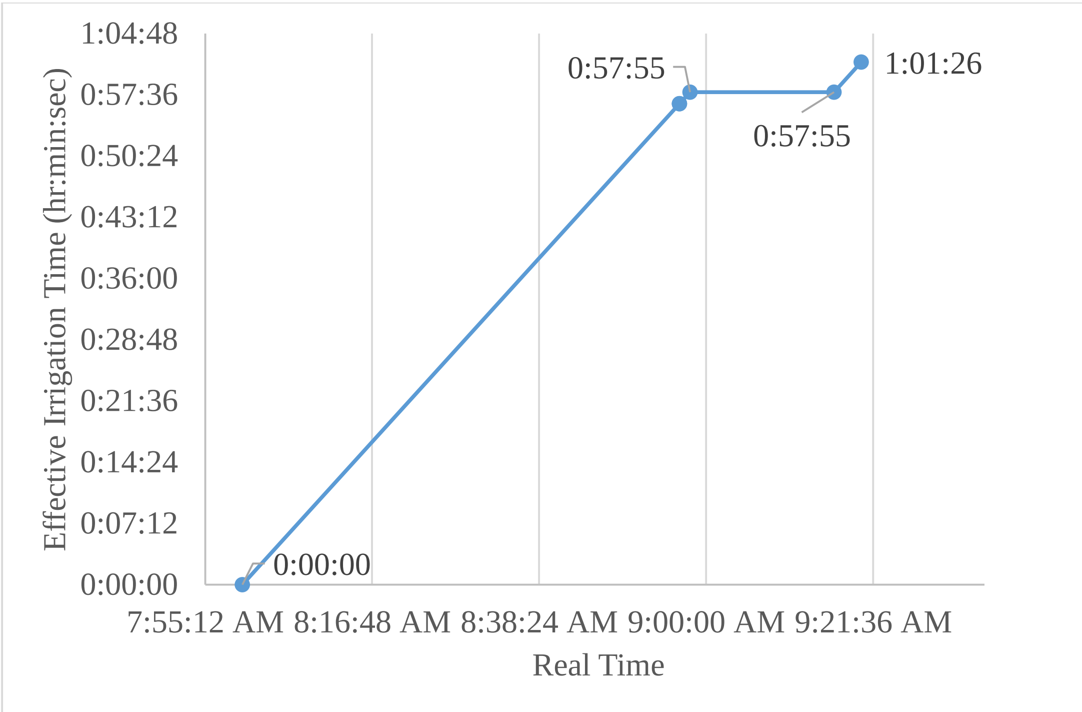

Figure 65. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on June 16th 2015

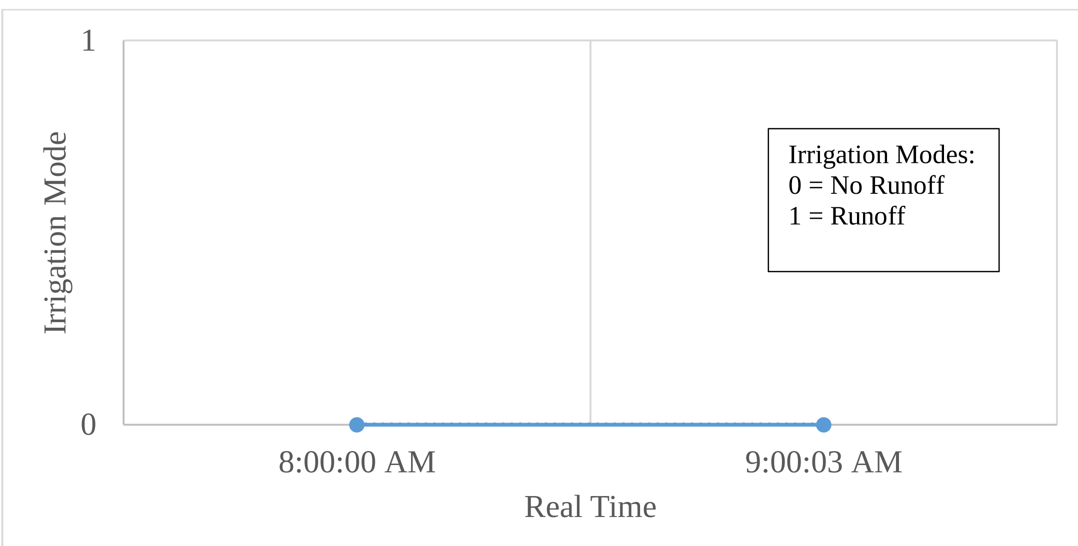

Figure 66. The Runoff Status of Plot 7 (Control) on June 16th 2015

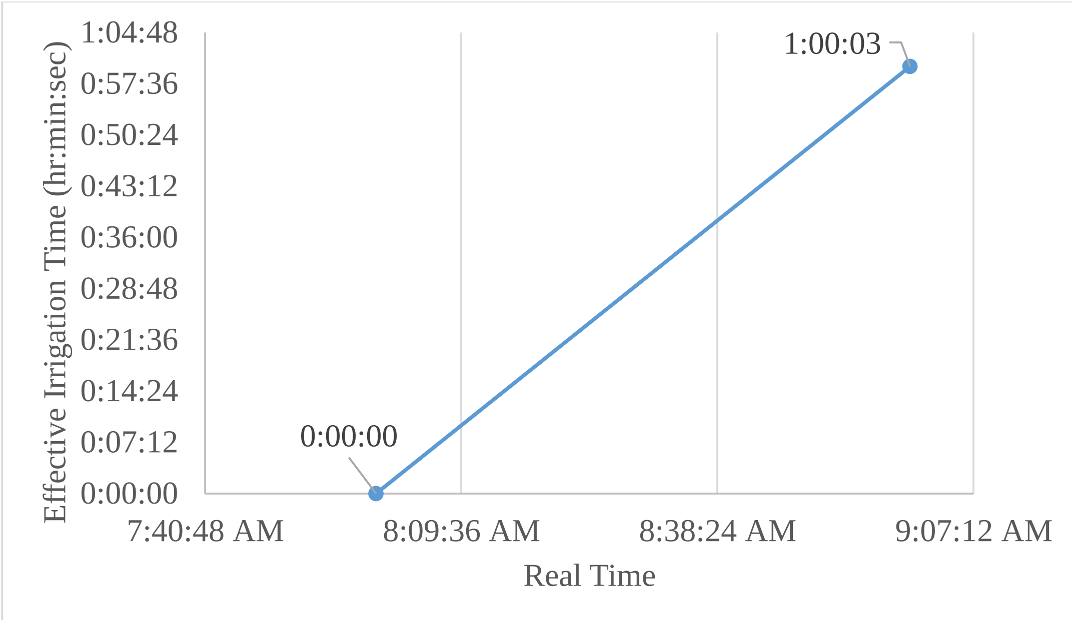

Figure 67. The Effective Irrigation Time of Plot 7 (Control) on June 16th 2015

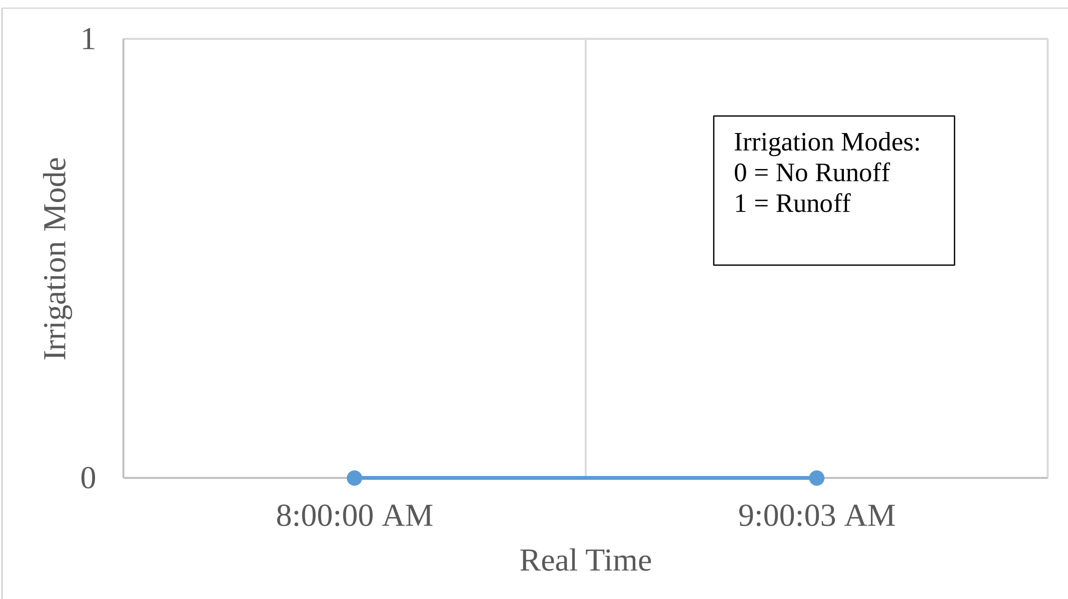

Figure 68. The Runoff Status of Plot 8 (Control) on June 16th 2015

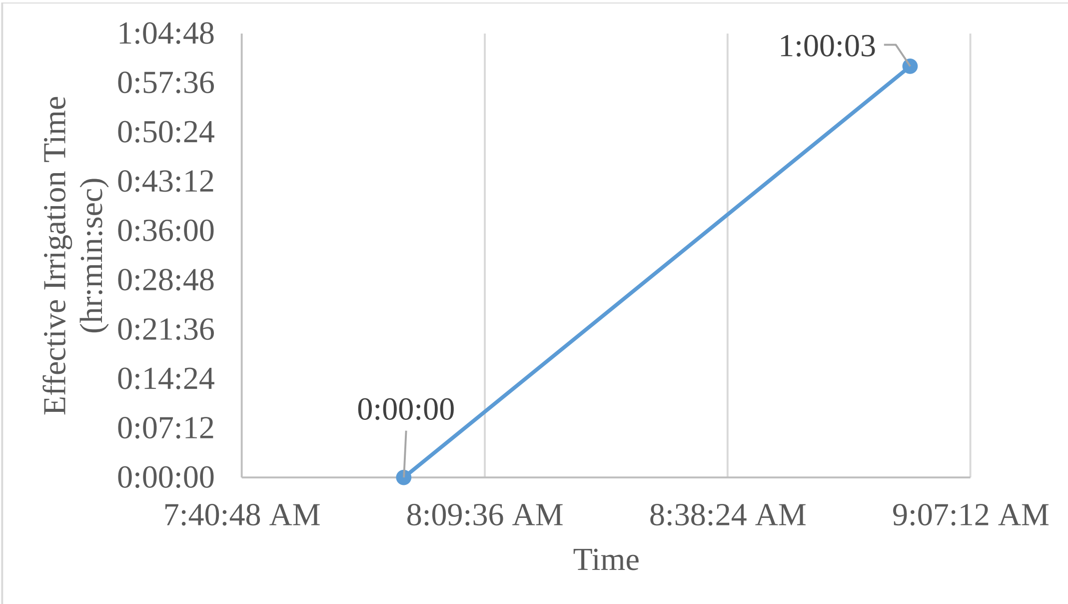

Figure 69. The Effective Irrigation Time of Plot 8 (Control) on June 16th 2015

Only the cubic float prototypes have been activated by the runoff which led to a pause of the irrigation cycle as expected. The paddle wheel prototype and the conductivity prototype have not been activated and thus plots 2, 3 and the two control plots have the same effective irrigation time. The conductivity prototype had clogging issue during the test, while the paddle wheel prototype has been water-damaged. However, no evidence of the noise and interference has been noticed compared to the former two tests. Therefore, the implemented software based criterion for identify noise versus signal is adequate for field implementation.

4.2.4 Qualitative Field Testing Results for June 24th 2015

Two cubic float prototypes, two conductivity prototypes and two control plots without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 13.

Table 13. Irrigation Specifications of Test on June 24th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 8 (Control Plot)

The results of the irrigation are shown in Figure 70 - 81.

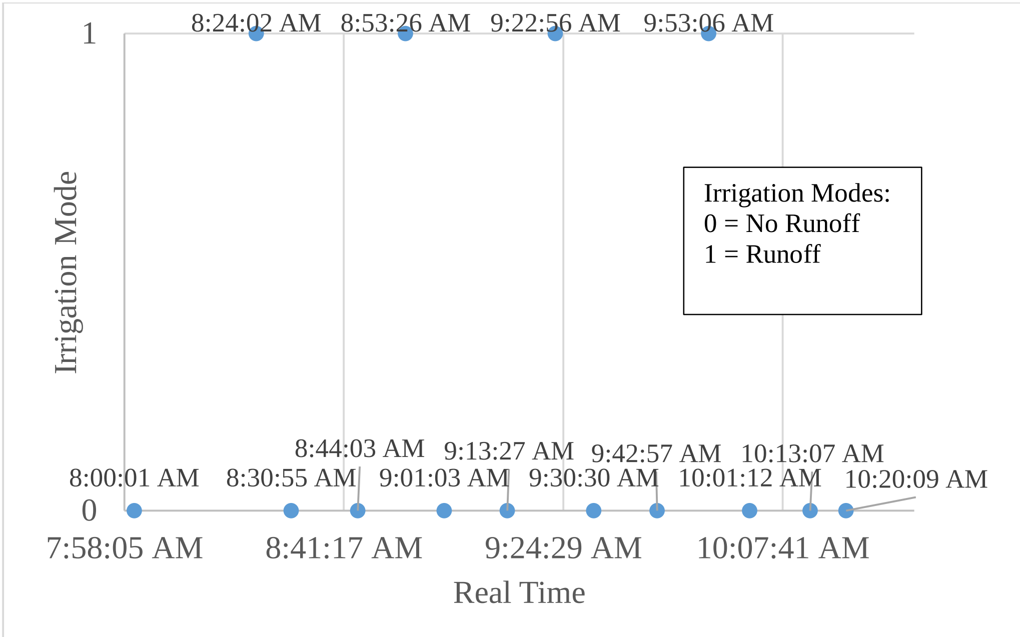

Figure 70. The Runoff Status of Plot 2 (Conductivity Prototype) on June 24th 2015

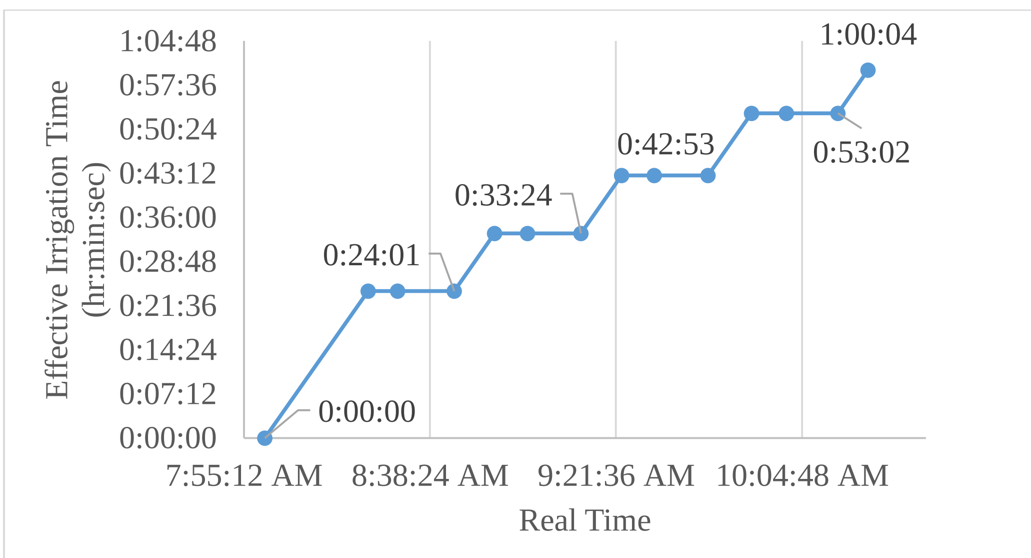

Figure 71. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on June 24th 2015

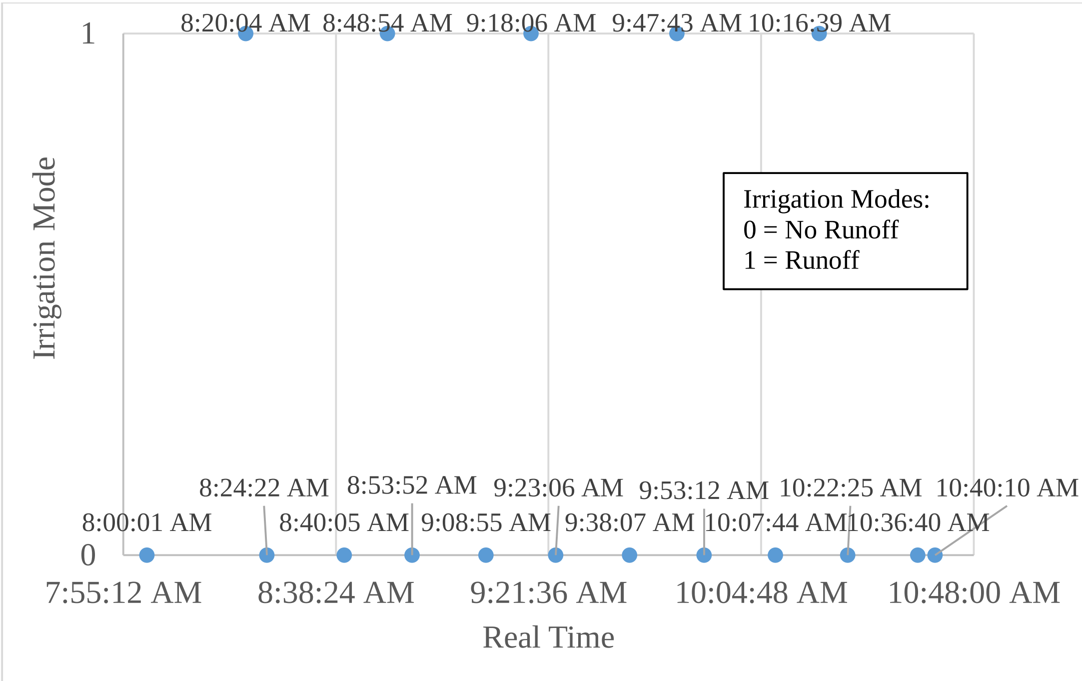

Figure 72. The Runoff Status of Plot 4 (Cubic Float Prototype) on June 24th 2015

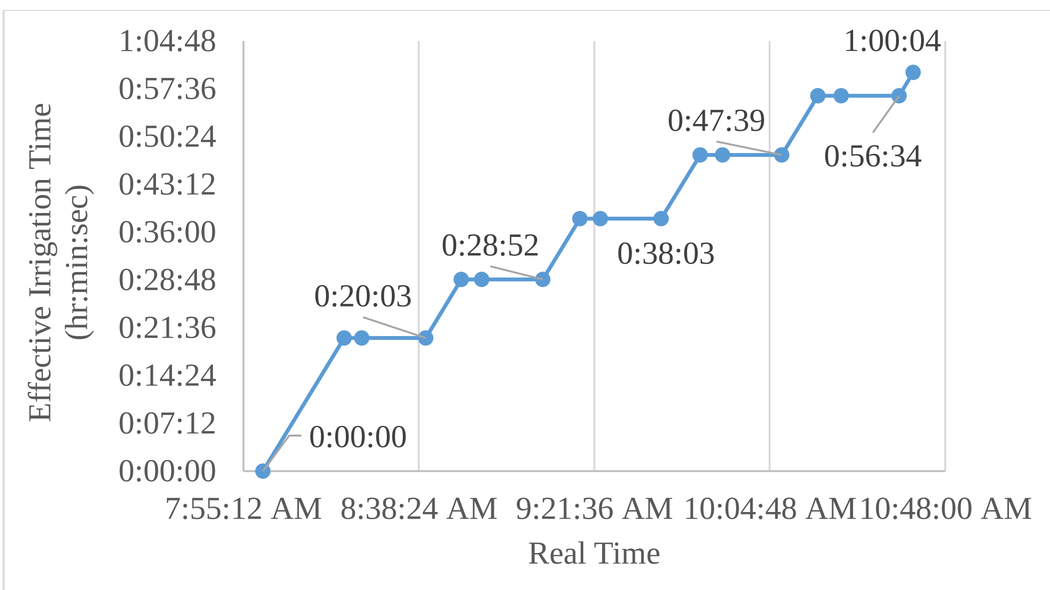

Figure 73. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on June 24th 2015

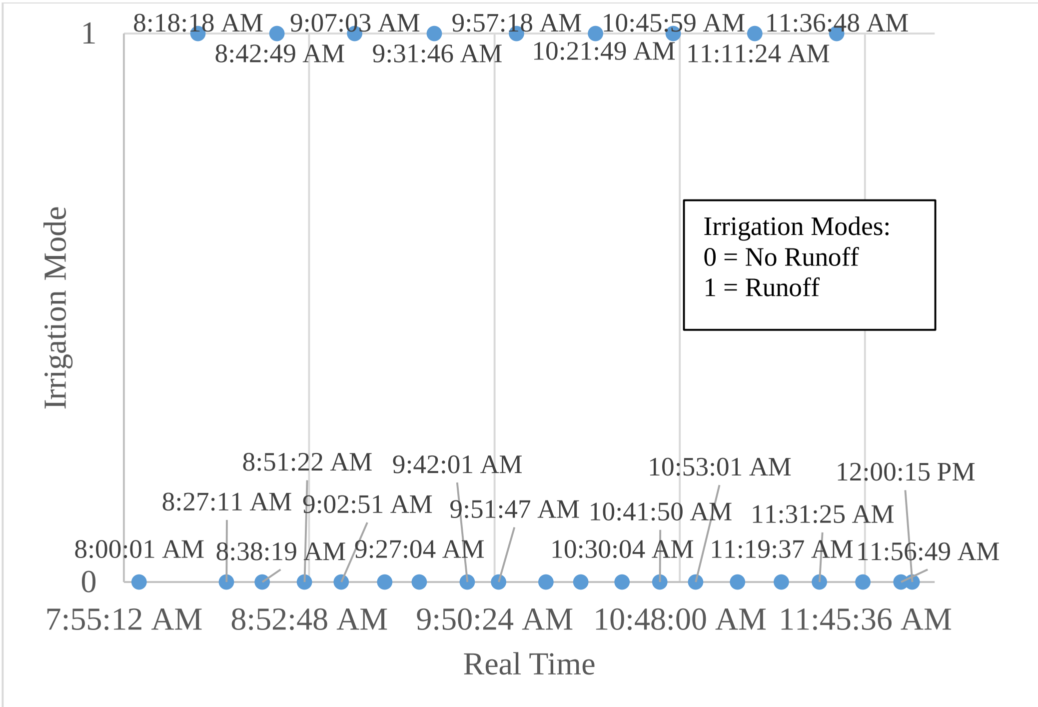

Figure 74. The Runoff Status of Plot 5 (Cubic Float Prototype) on June 24th 2015

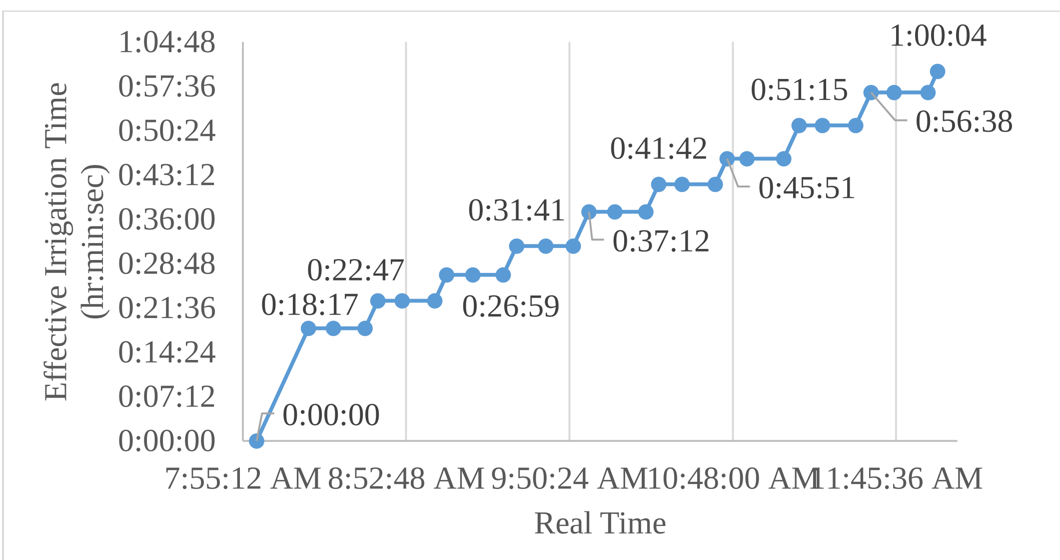

Figure 75. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on June 24th 2015

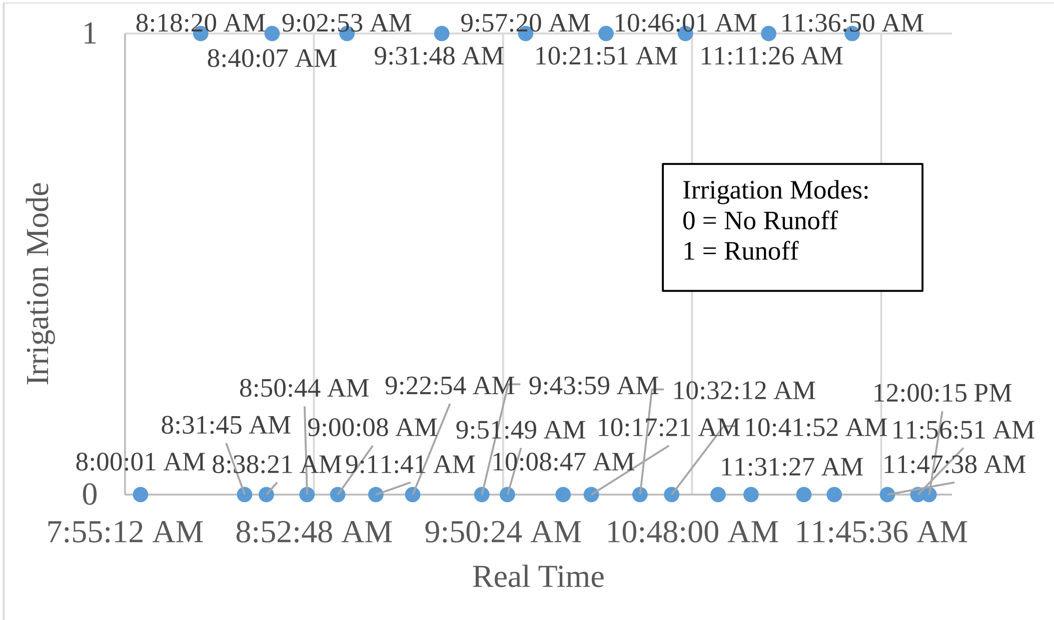

Figure 76. The Runoff Status of Plot 6 (Conductivity Prototype) on June 24th 2015

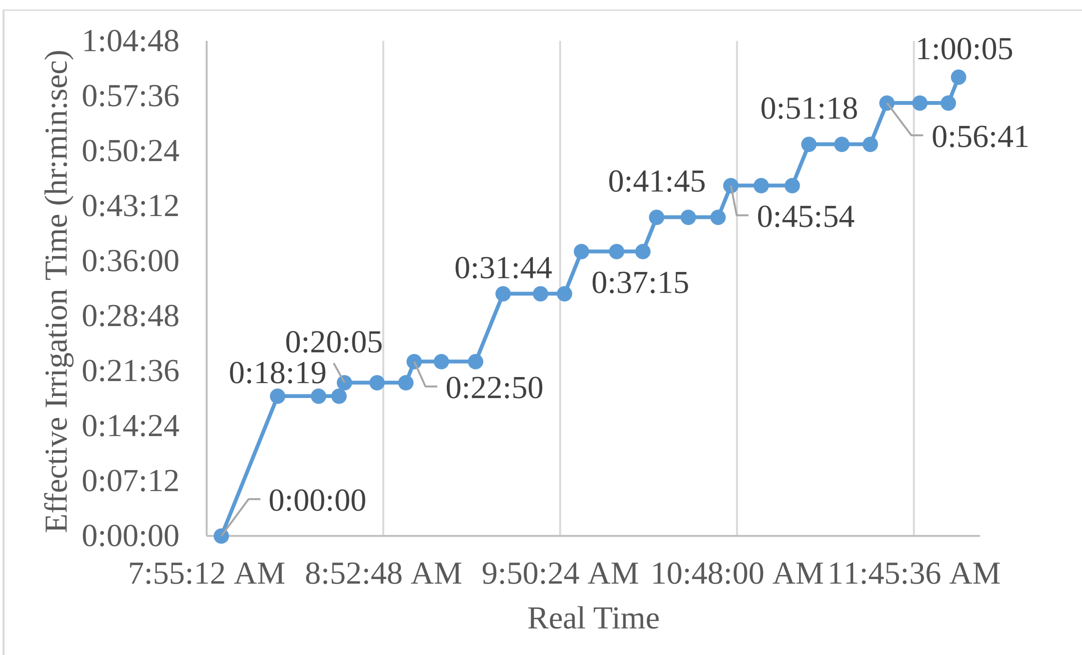

Figure 77. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on June 24th 2015

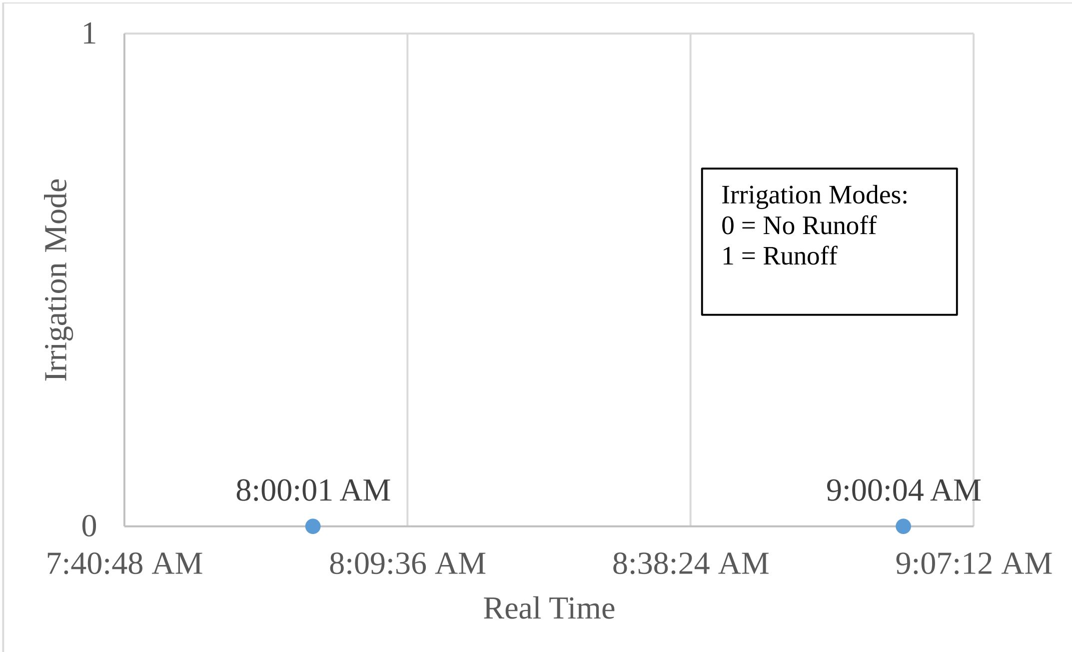

Figure 78. The Runoff Status of Plot 7 (Control) on June 24th 2015

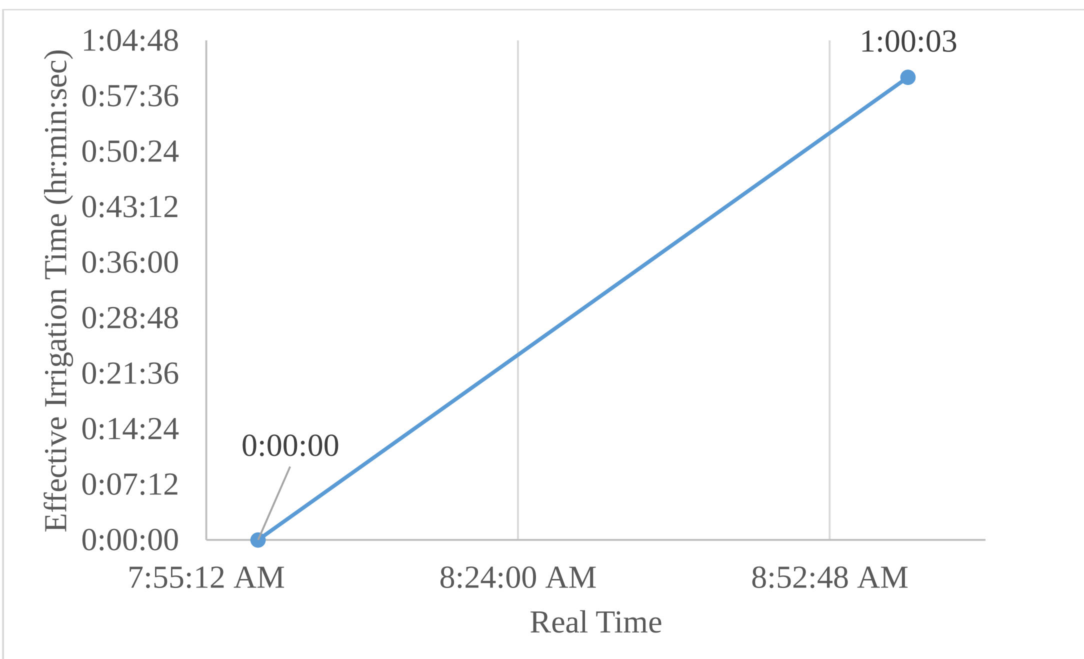

Figure 79. The Effective Irrigation Time of Plot 7 (Control) on June 24th 2015

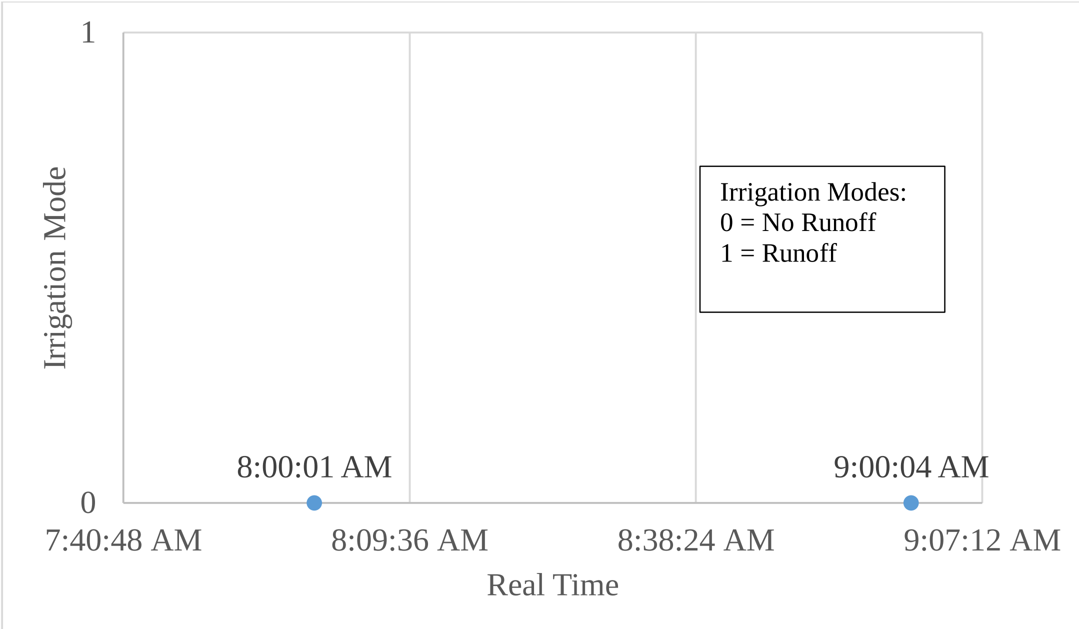

Figure 80. The Runoff Status of Plot 8 (Control) on June 24th 2015

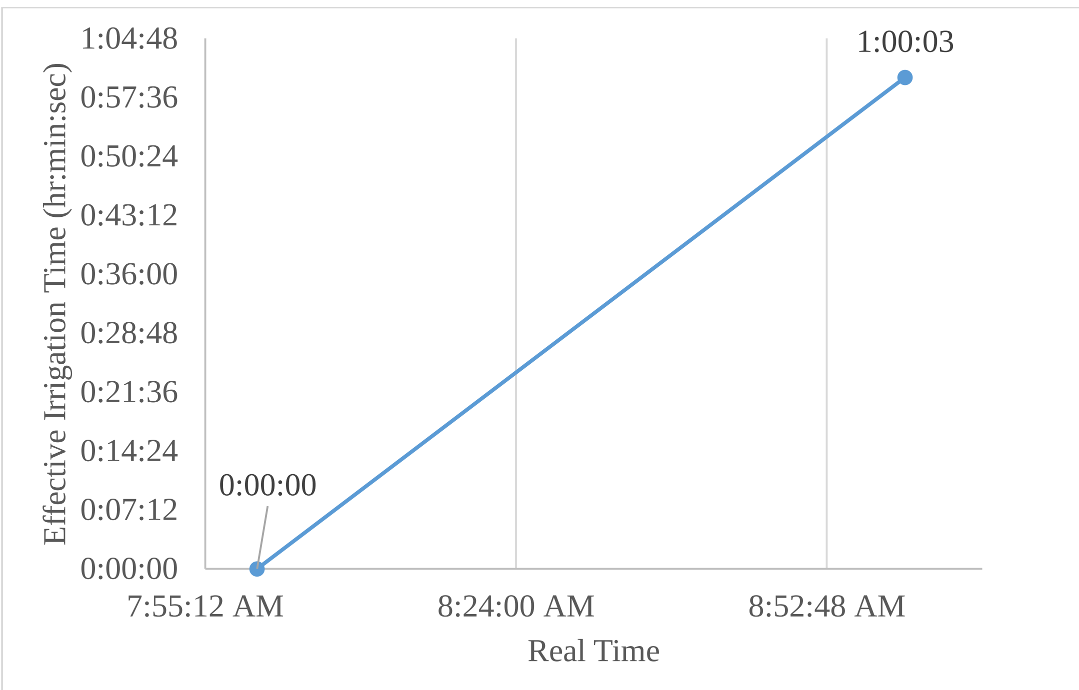

Figure 81. The Effective Irrigation Time of Plot 8 (Control) on June 24th 2015

Both the cubic float prototypes and the conductivity prototypes have shown the capability of detecting runoff and fulfilling the complete cycle-soaking. In the meantime, the cubic float prototypes have exhibited to be more sensitive than the conductivity prototype, allowing more WT during the irrigation cycle.

4.2.5 Qualitative Field Testing Results for June 30th 2015

Two cubic float prototypes, two conductivity prototypes and two control plots without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 14.

Table 14. Irrigation Specifications of Test on June 30th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 8 (Control Plot)

The results of the irrigation are shown in Figure 82 - 93.

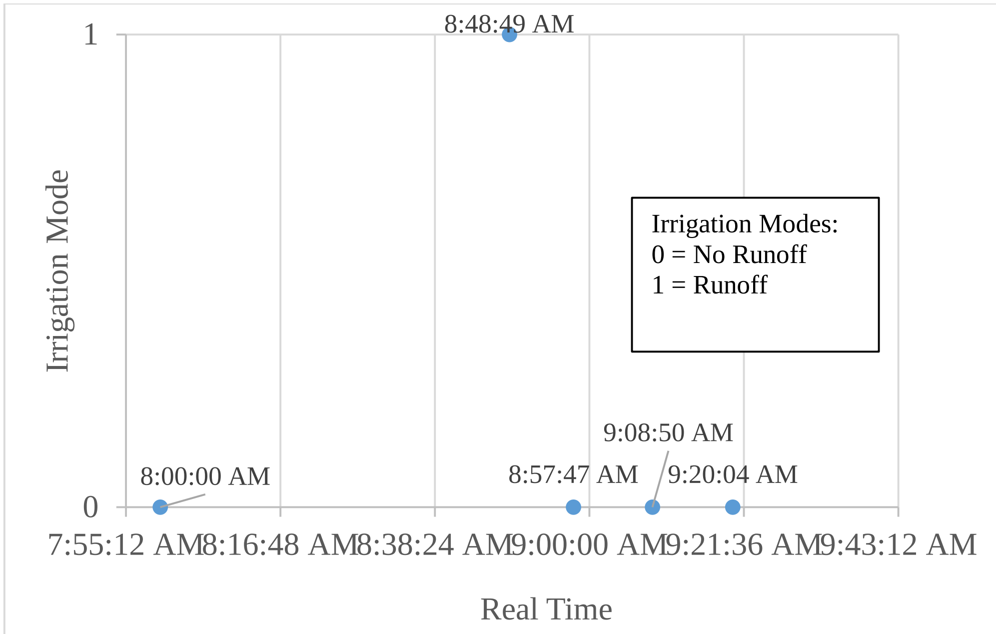

Figure 82. The Runoff Status of Plot 2 (Conductivity Prototype) on June 30th 2015

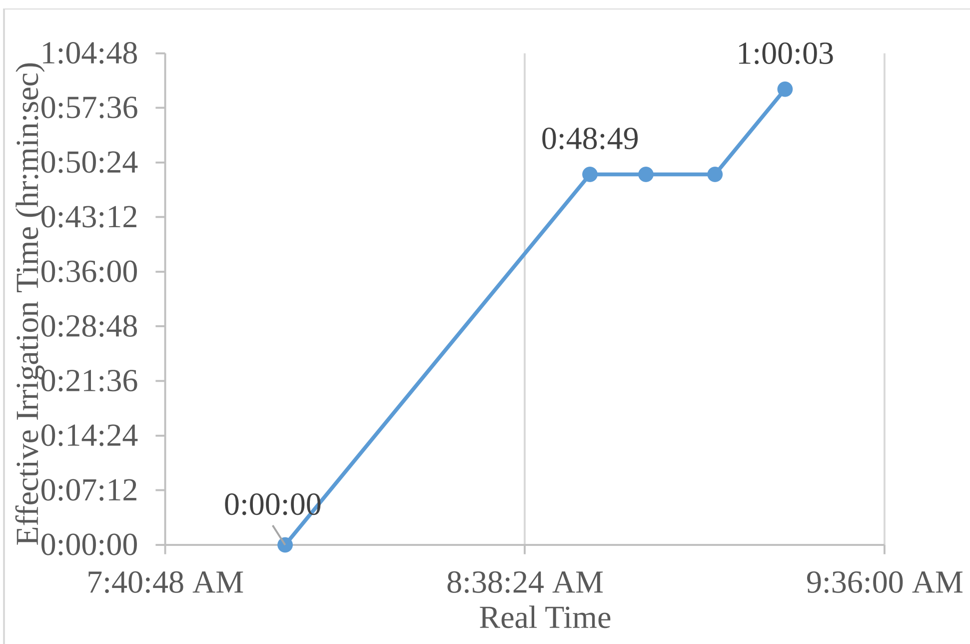

Figure 83. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on June 30th 2015

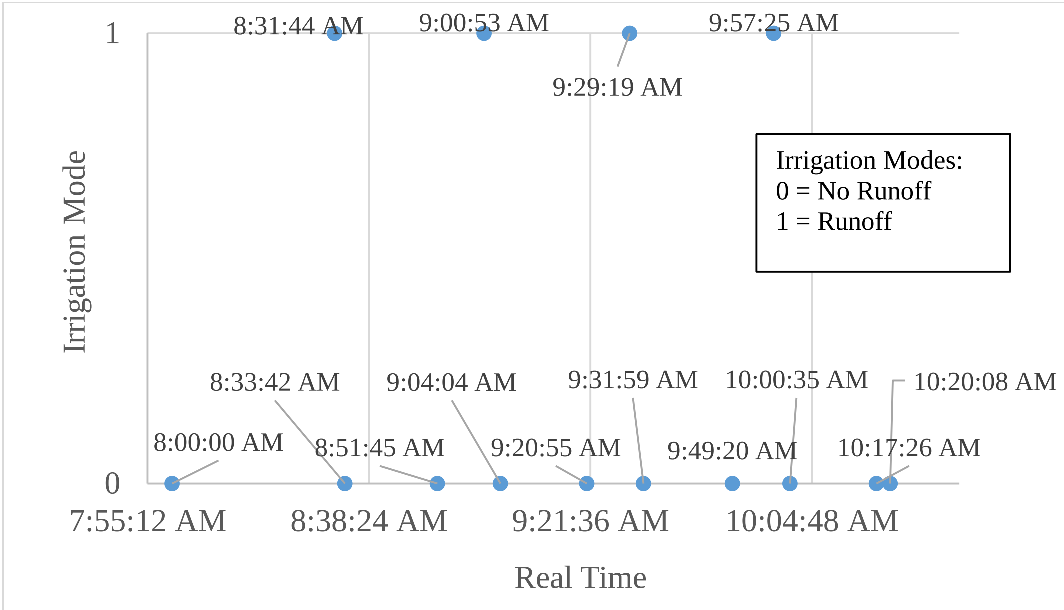

Figure 84. The Runoff Status of Plot 4 (Cubic Float Prototype) on June 30th 2015

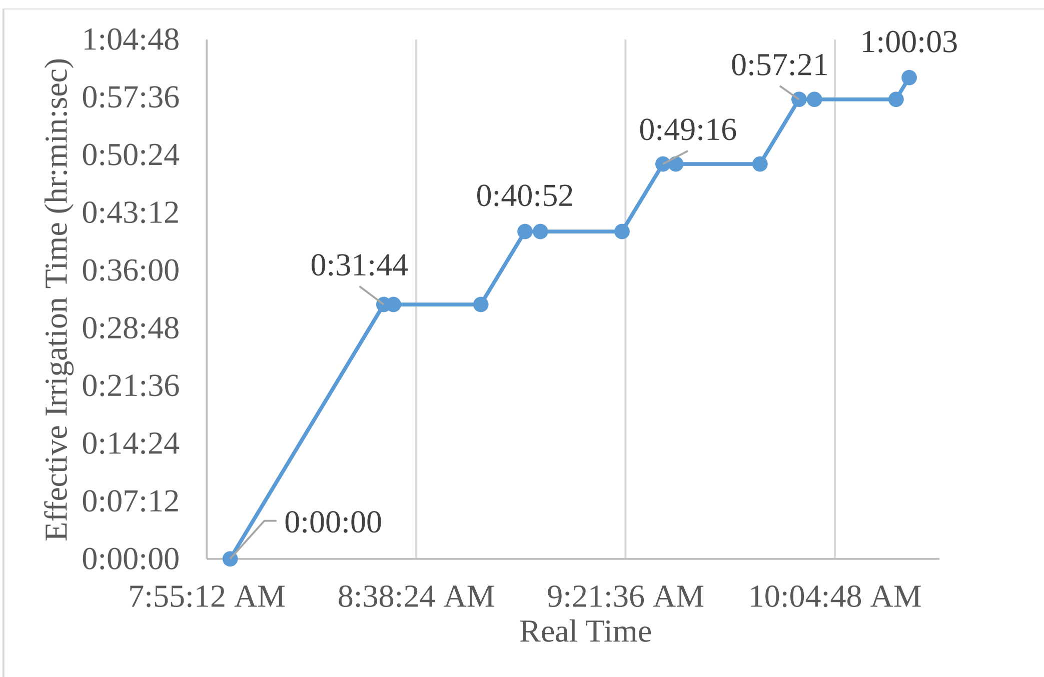

Figure 85. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on June 30th 2015

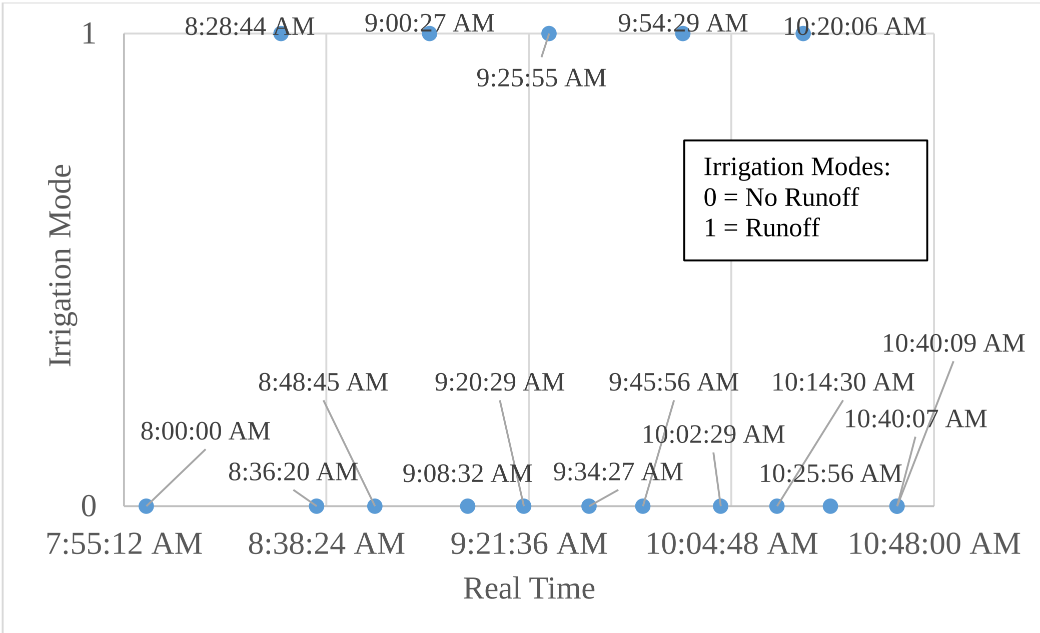

Figure 86. The Runoff Status of Plot 5 (Cubic Float Prototype) on June 30th 2015

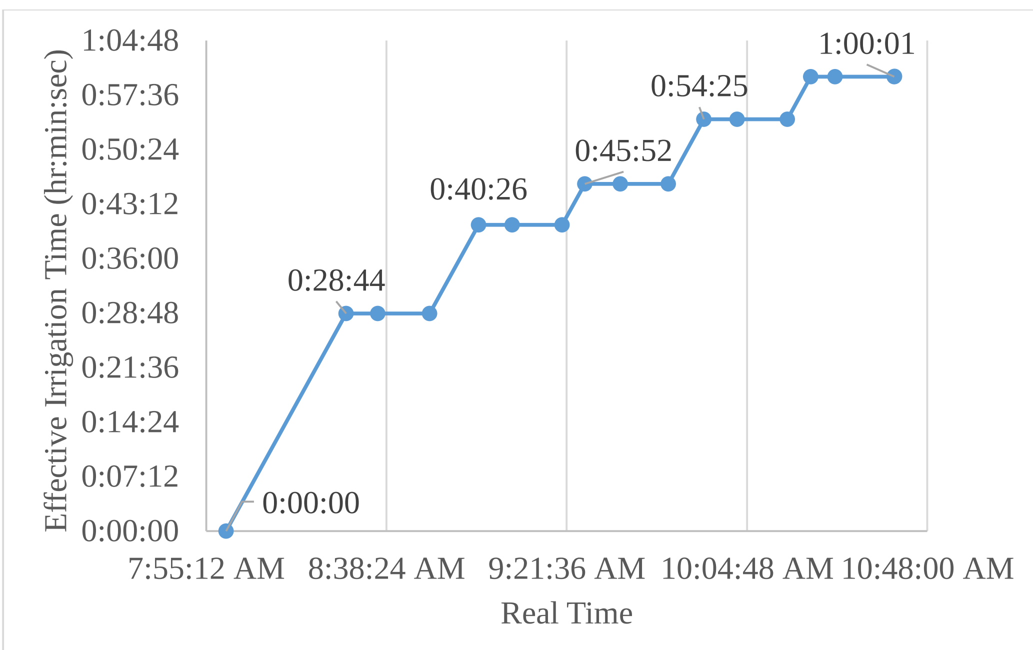

Figure 87. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on June 30th 2015

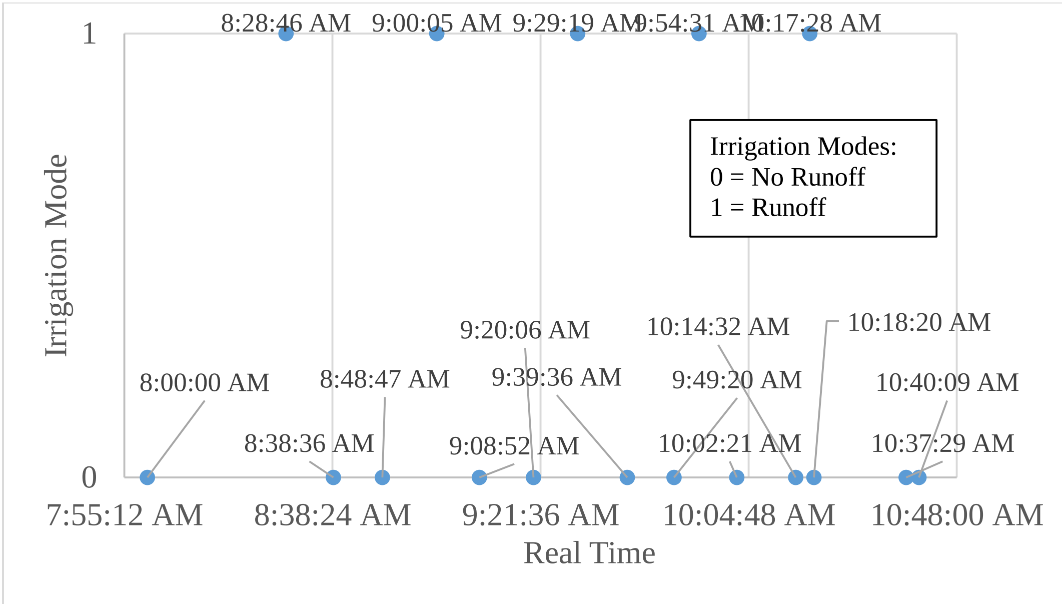

Figure 88. The Runoff Status of Plot 6 (Conductivity Prototype) on June 30th 2015

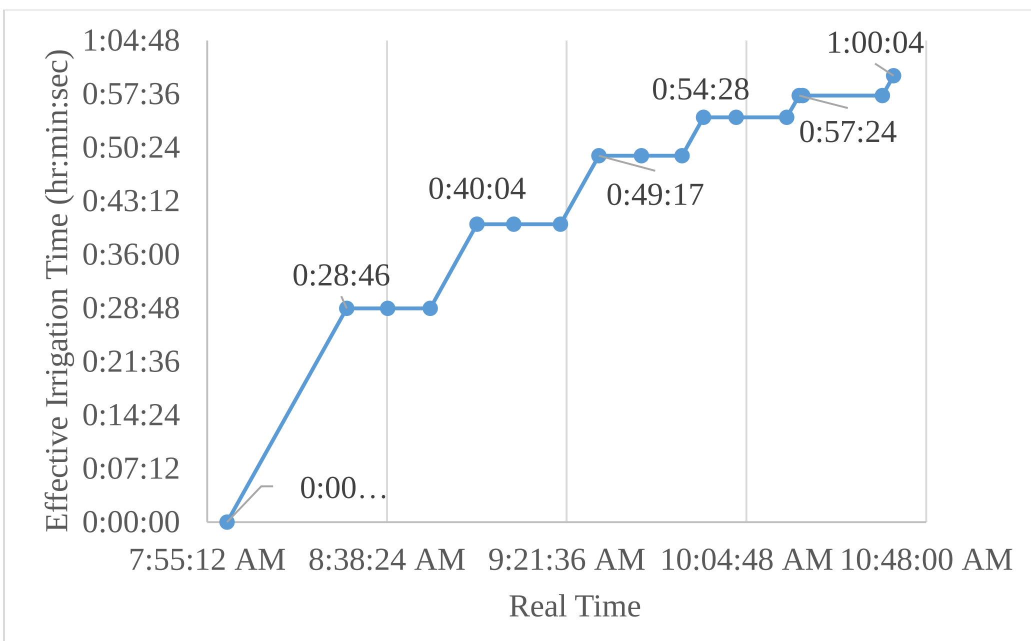

Figure 89. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on June 30th 2015

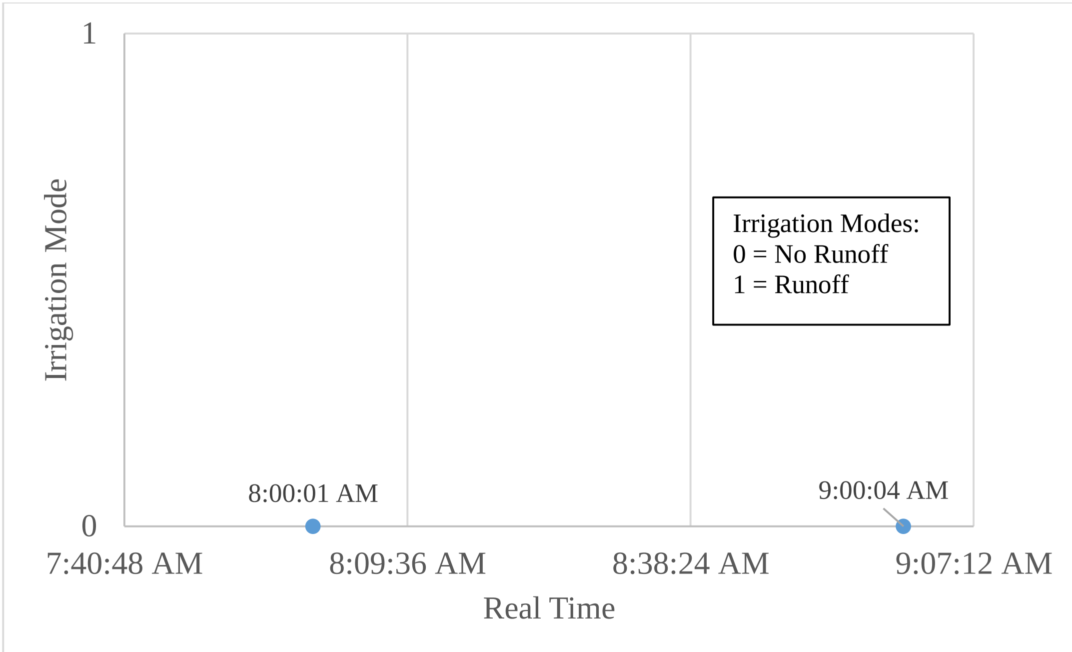

Figure 90. The Runoff Status of Plot 7 (Control) on June 30th 2015

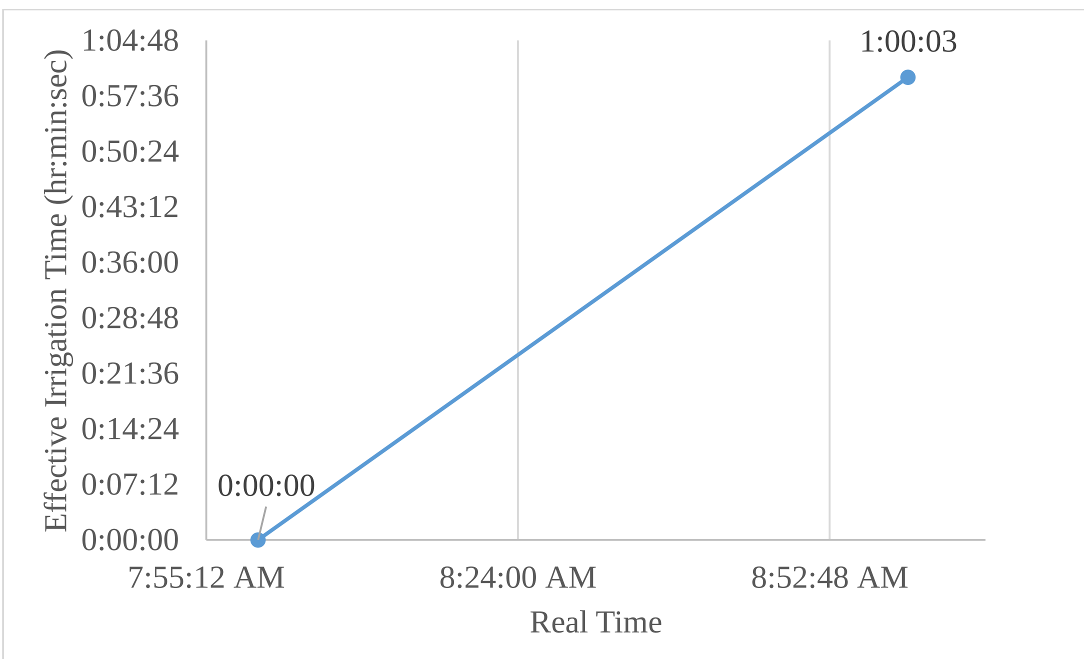

Figure 91. The Effective Irrigation Time of Plot 7 (Control) on June 30th 2015

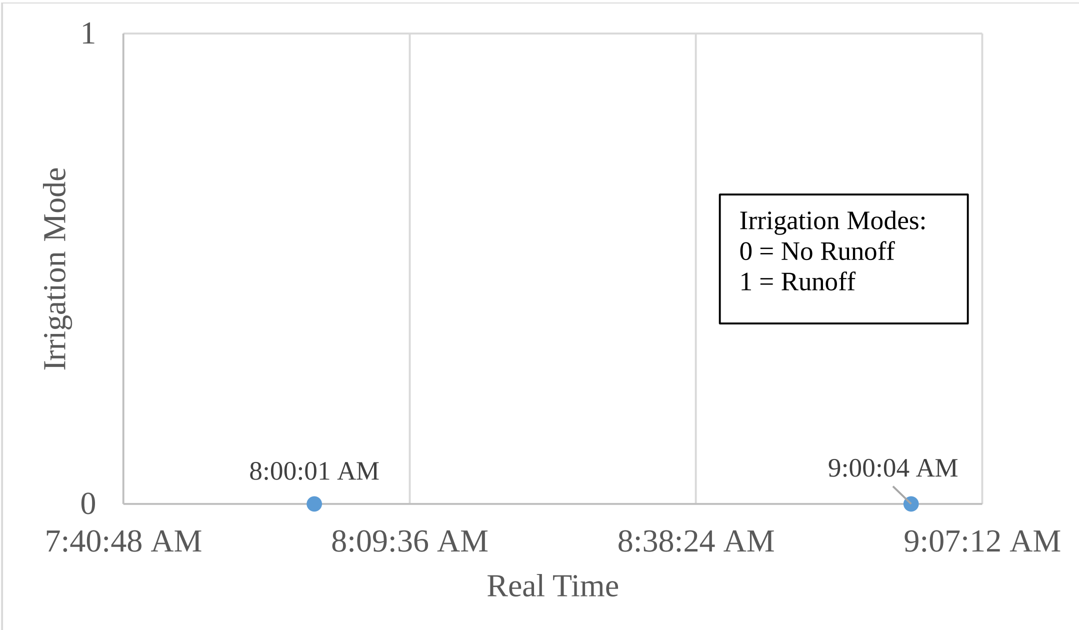

Figure 92. The Runoff Status of Plot 8 (Control) on June 30th 2015

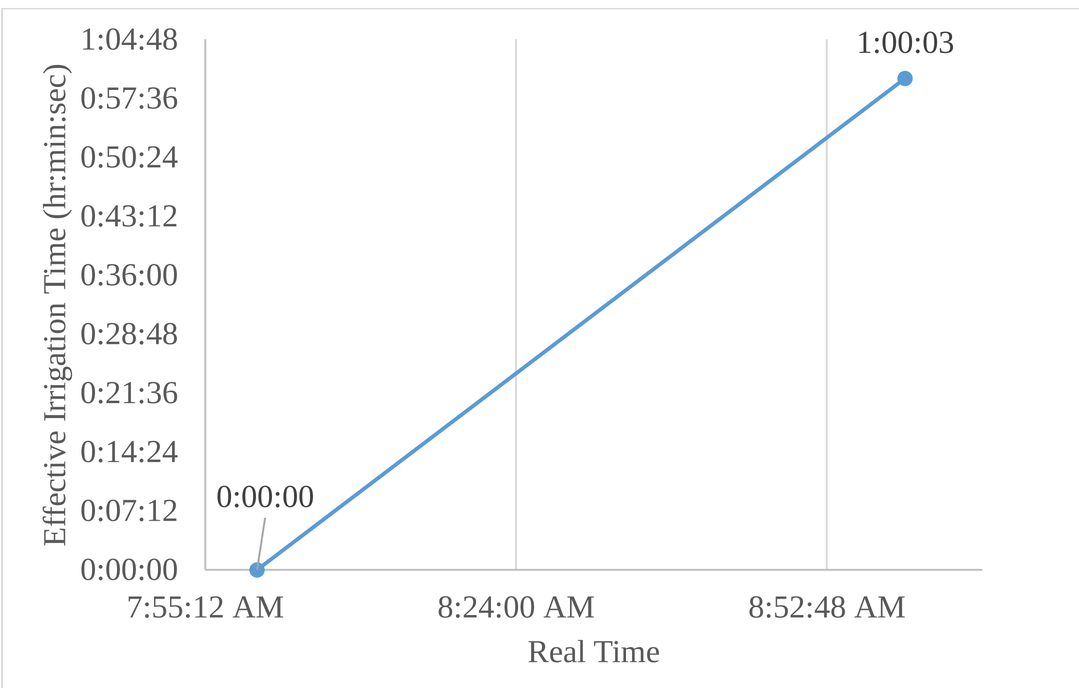

Figure 93. The Effective Irrigation Time of Plot 8 (Control) on June 30th 2015

Based on the testing results, both the cubic float prototypes and the conductivity prototypes have successfully detected runoff and paused the irrigation cycle. Similar to the former tests, the cubic float prototypes have exhibited to be more sensitive than the conductivity prototype, allowing more WT during the irrigation cycle.

4.2.6 Qualitative Field Testing Results for July 11th 2015

Two cubic float prototypes, two conductivity prototypes, one elbow float prototype and one control plot without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 15.

Table 15. Irrigation Specifications of Test on July 11th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 9 (Elbow Float Plot)

The results of the irrigation are shown in Figure 94 - 105.

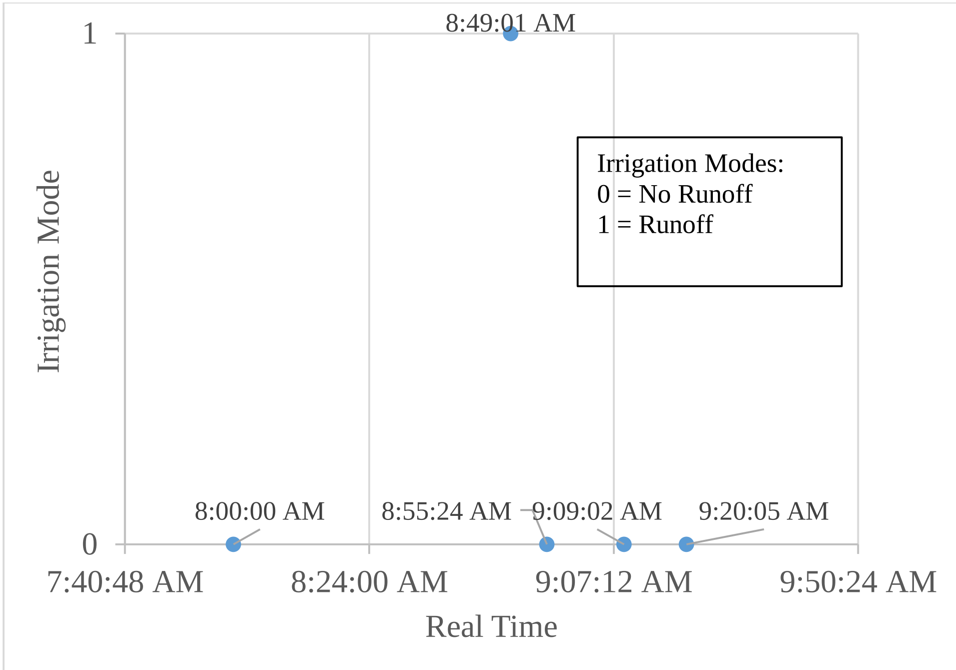

Figure 94. The Runoff Status of Plot 2 (Conductivity Prototype) on July 11th 2015

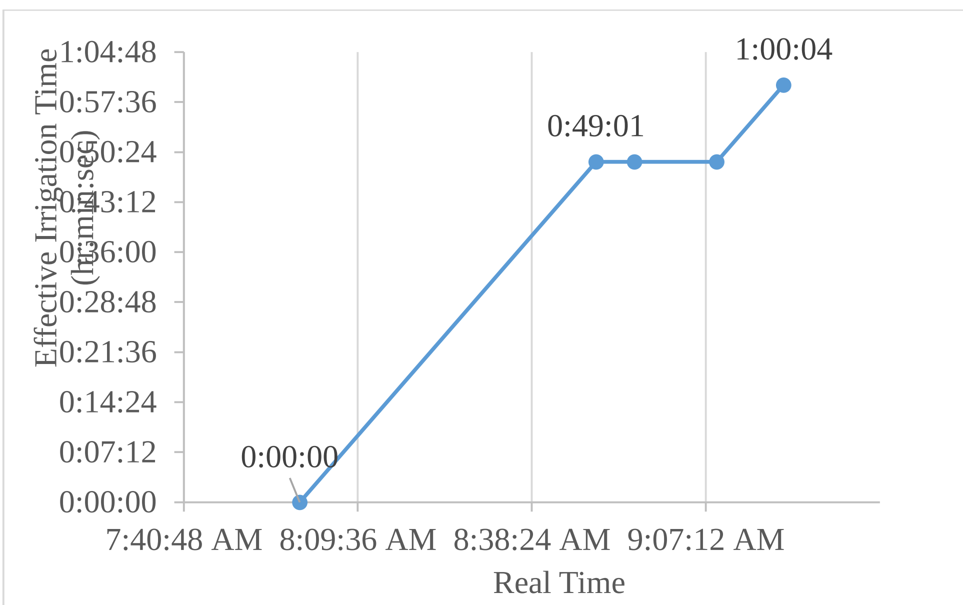

Figure 95. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on July 11th 2015

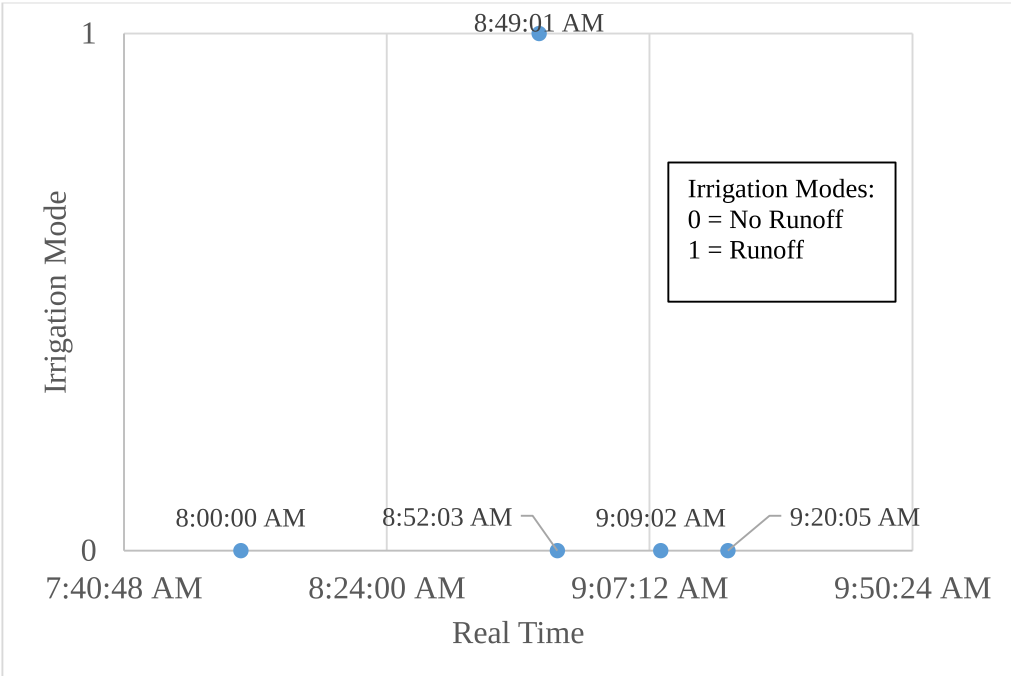

Figure 96. The Runoff Status of Plot 4 (Cubic Float Prototype) on July 11th 2015

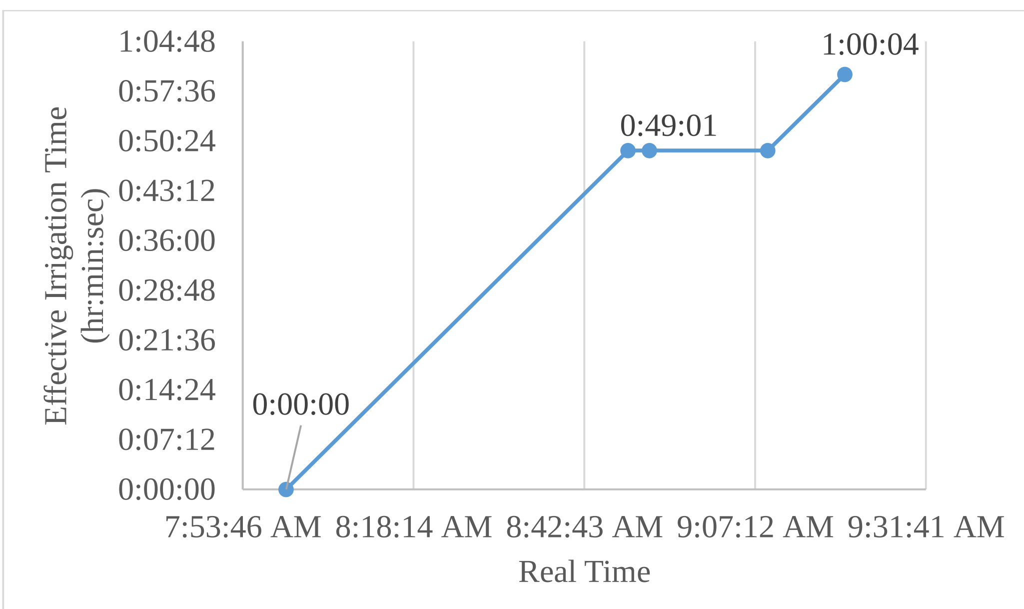

Figure 97. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on July 11th 2015

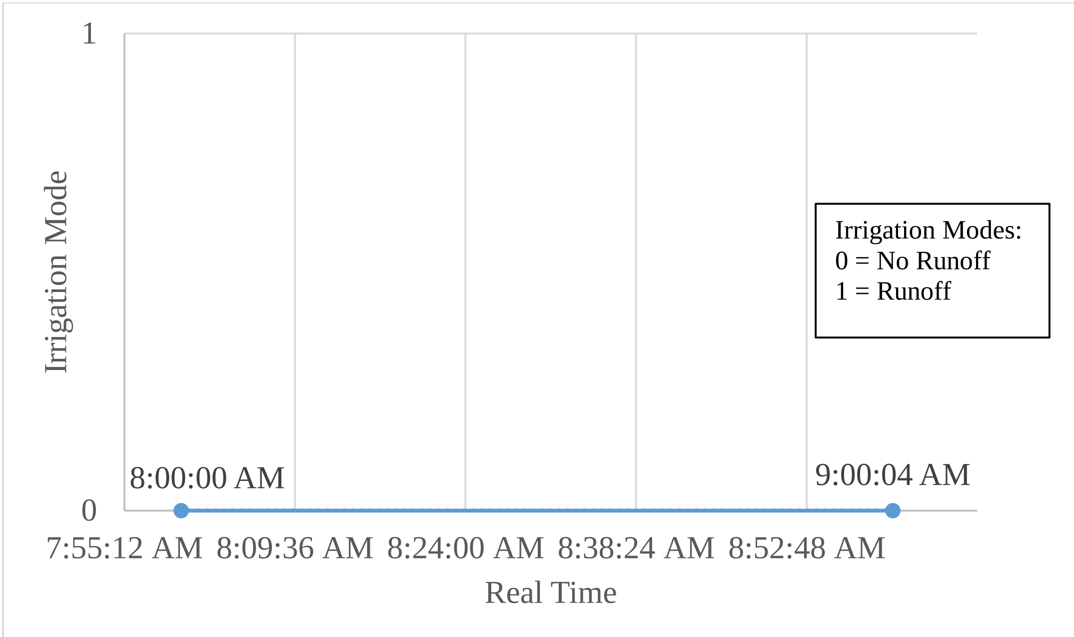

Figure 98. The Runoff Status of Plot 5 (Cubic Float Prototype) on July 11th 2015

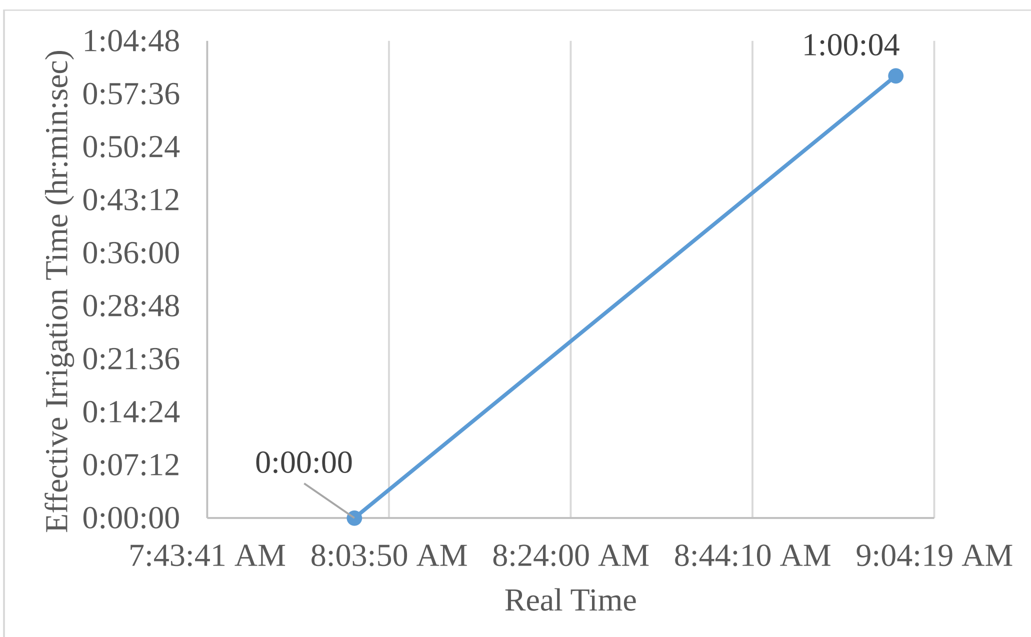

Figure 99. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on July 11th 2015

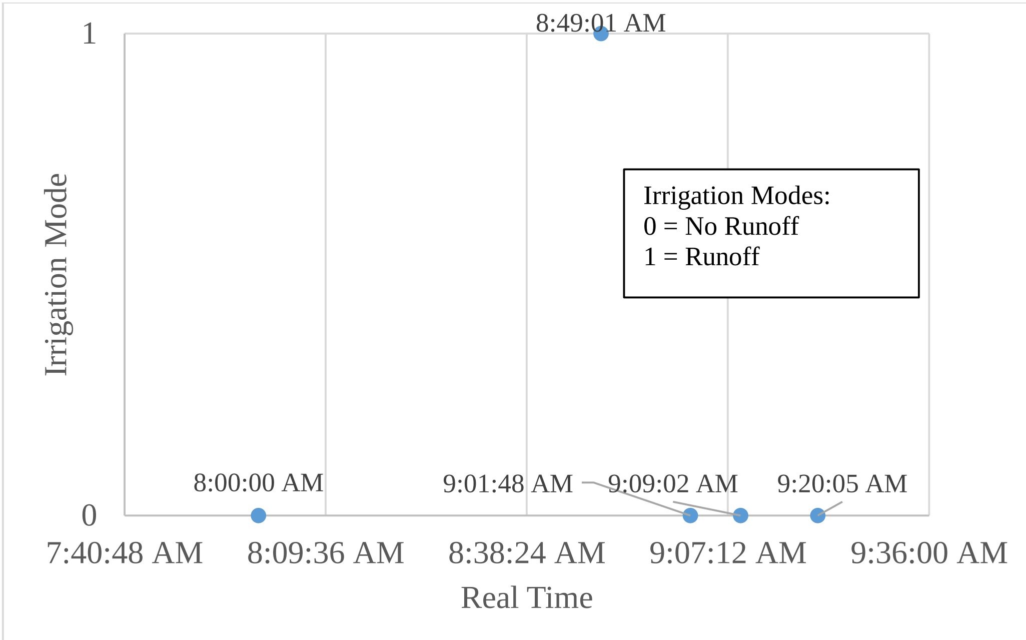

Figure 100. The Runoff Status of Plot 6 (Conductivity Prototype) on July 11th 2015

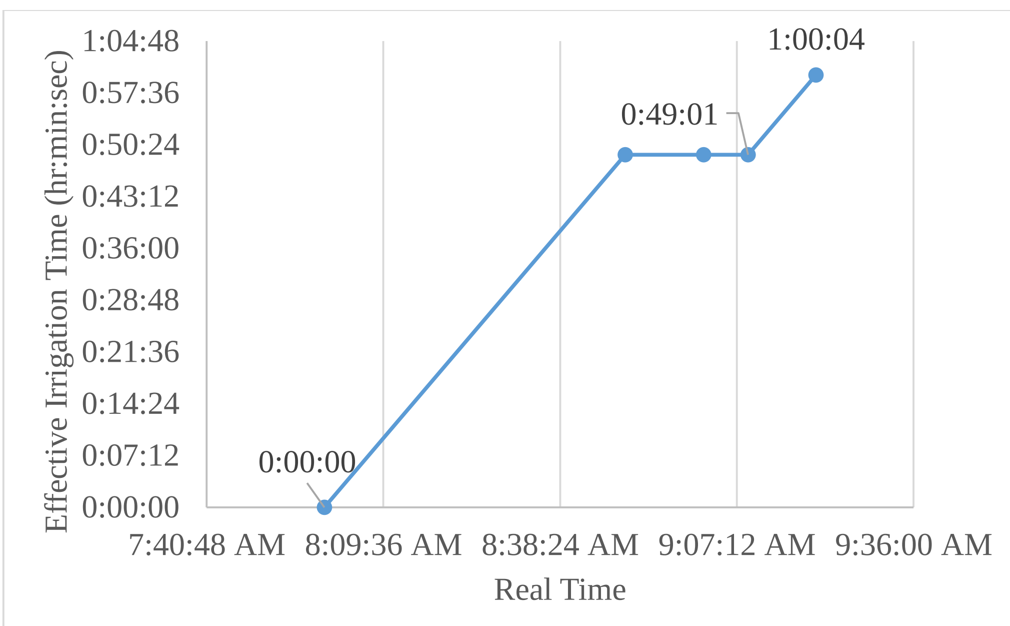

Figure 101. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on July 11th 2015

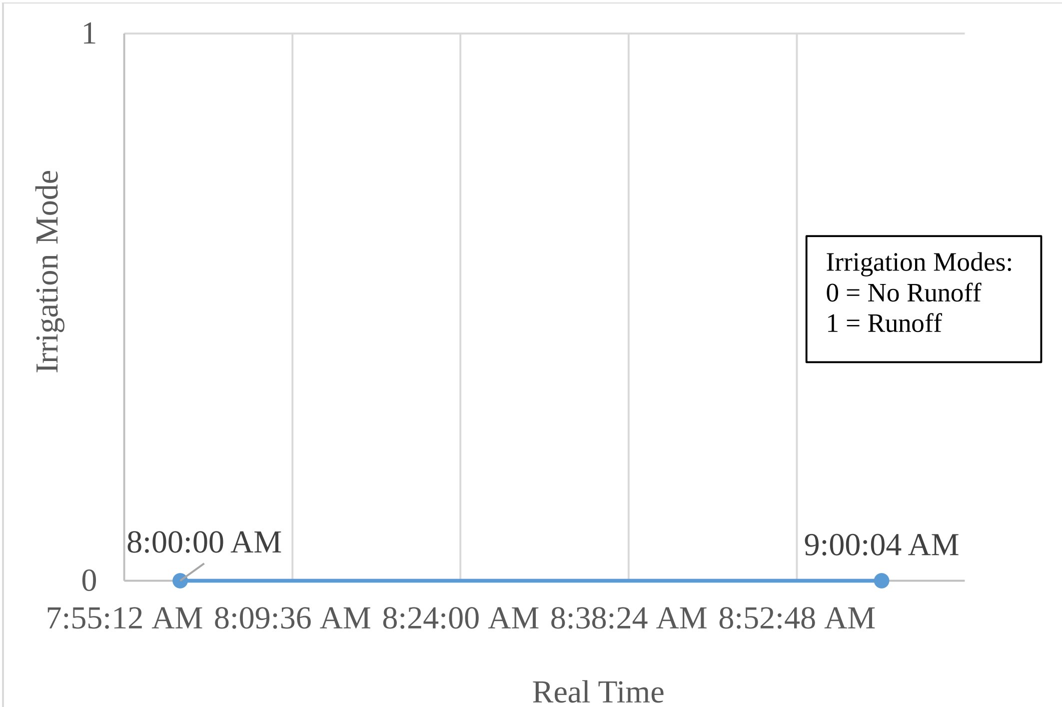

Figure 102. The Runoff Status of Plot 7 (Control) on July 11th 2015

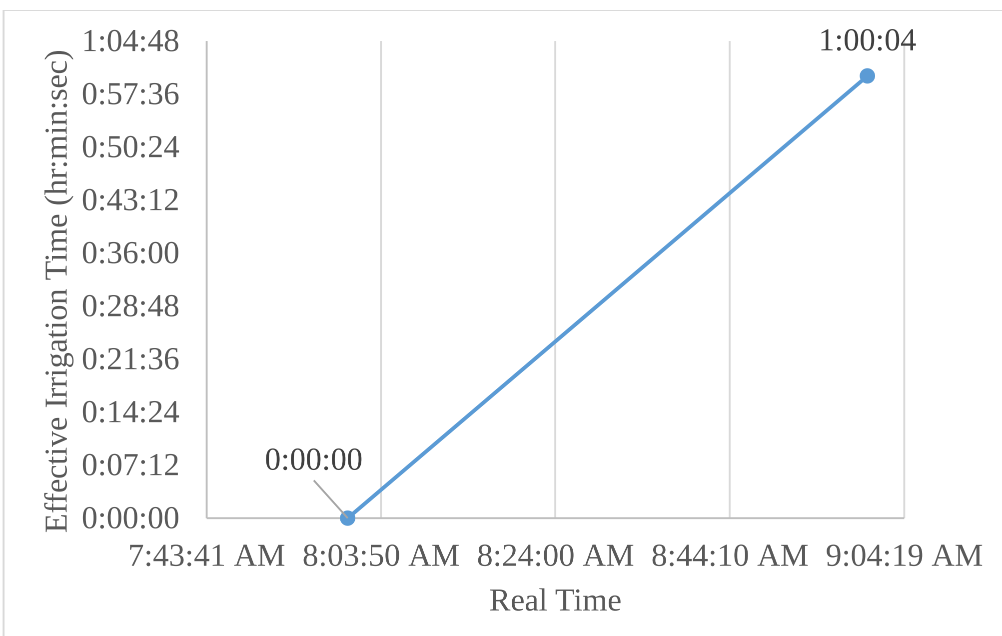

Figure 103. The Effective Irrigation Time of Plot 7 (Control) on July 11th 2015

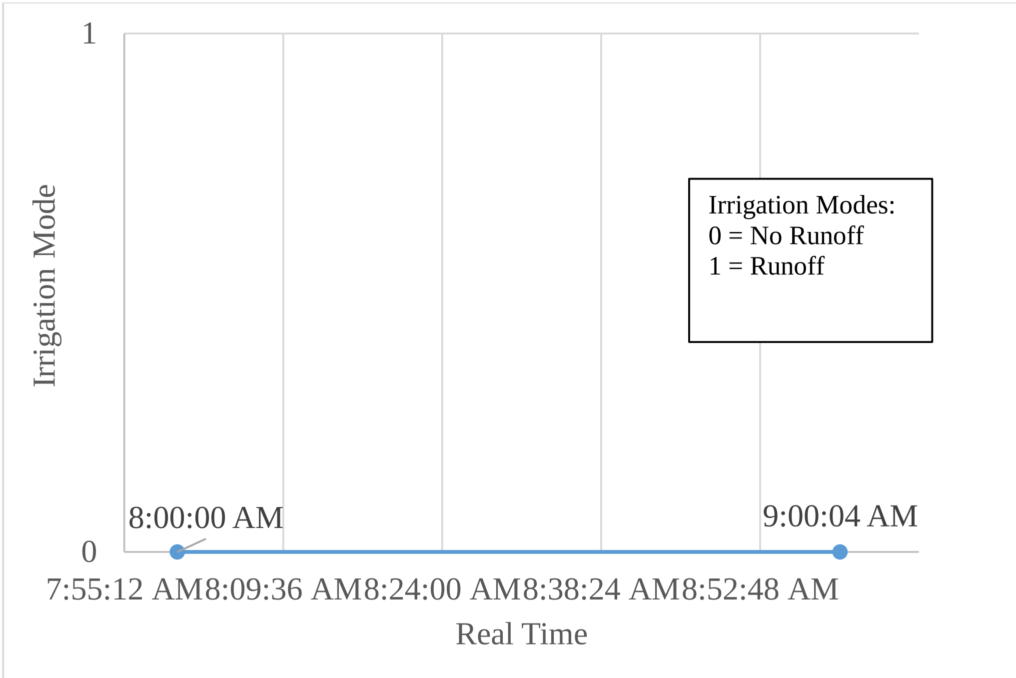

Figure 104. The Runoff Status of Plot 9 (Elbow Float Prototype) on July 11th 2015

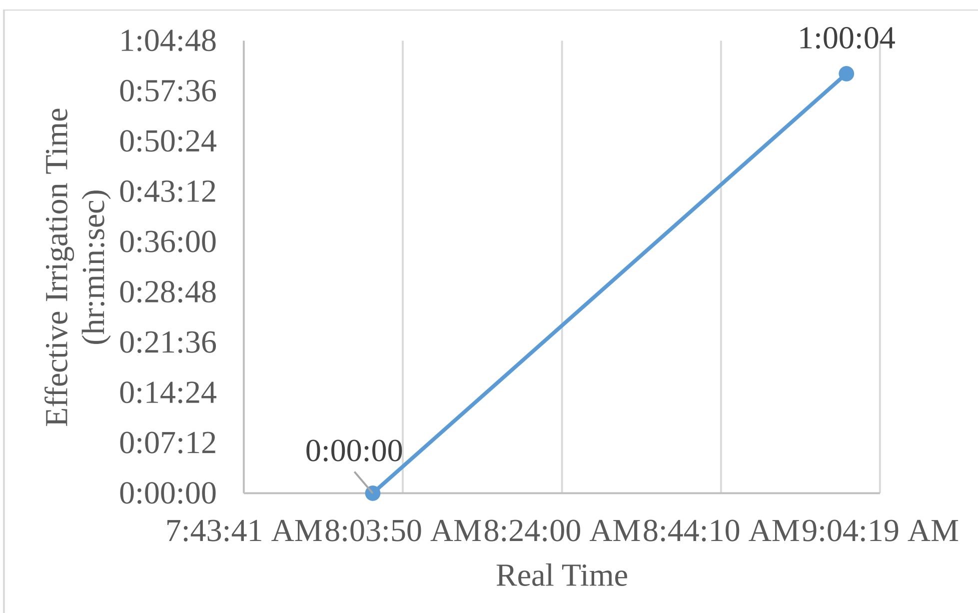

Figure 105. The Effective Irrigation Time of Plot 9 (Elbow Float Prototype) on July 11th 2015

During the tests, only one cubic float prototype and two conductivity prototypes have paused irrigation based on detecting runoff. The other plots started to have runoff after irrigation stopped. The dry and hot weather on that day may be responsible for the results.

4.2.7 Qualitative Field Testing Results for July 14th 2015

Two cubic float prototypes, two conductivity prototypes, one elbow float prototype and one control plot without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 16.

Table 16. Irrigation Specifications of Test on July 14th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1.5 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 9 (Elbow Float Plot)

The results of the irrigation are shown in Figure 106 - 117.

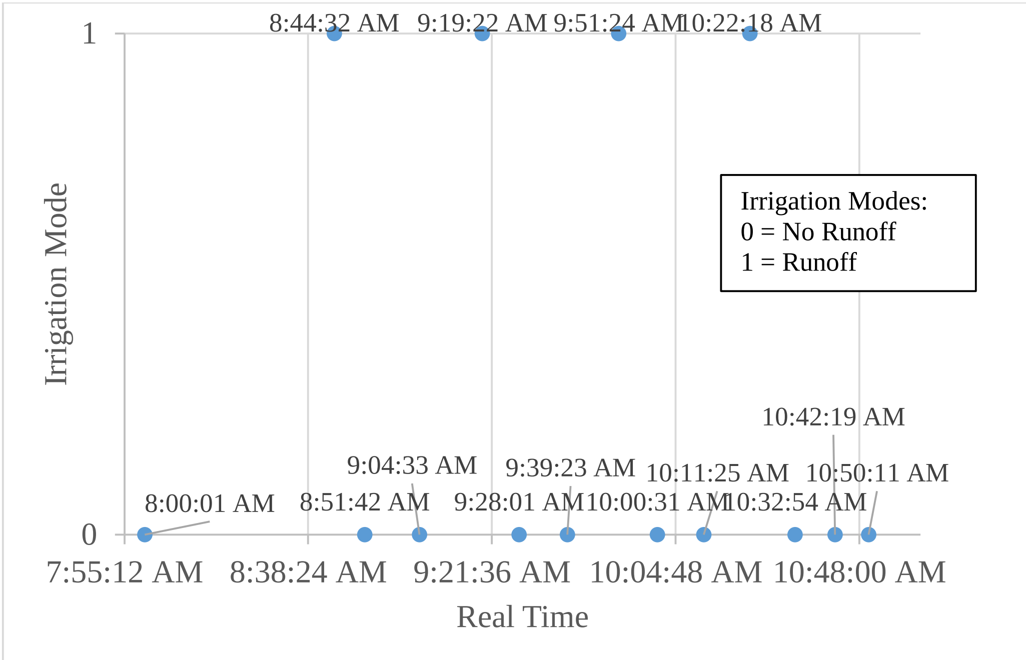

Figure 106. The Runoff Status of Plot 2 (Conductivity Prototype) on July 14th 2015

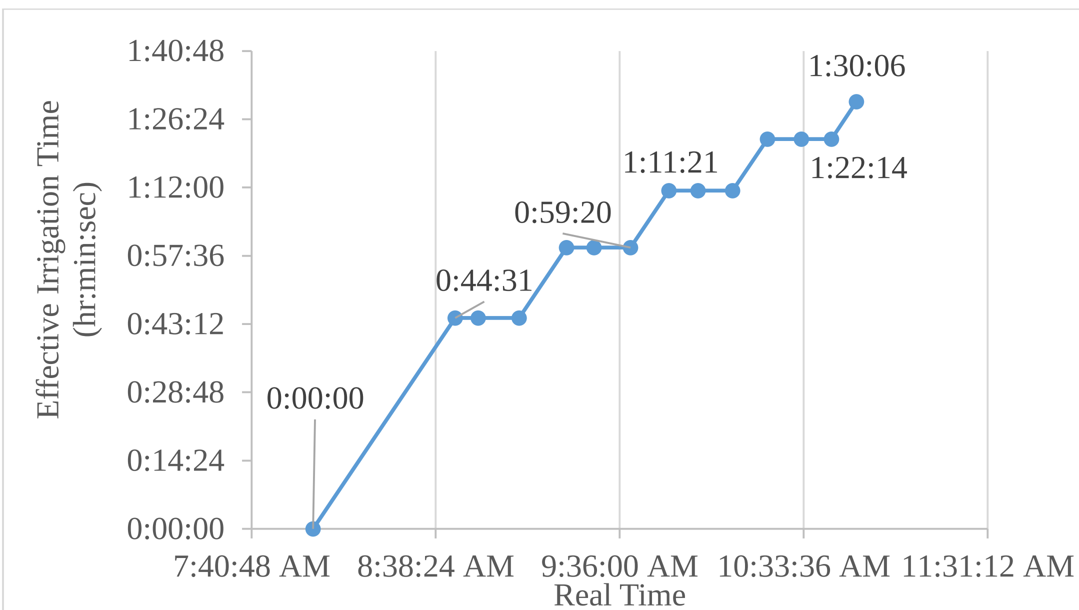

Figure 107. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on July 14th 2015

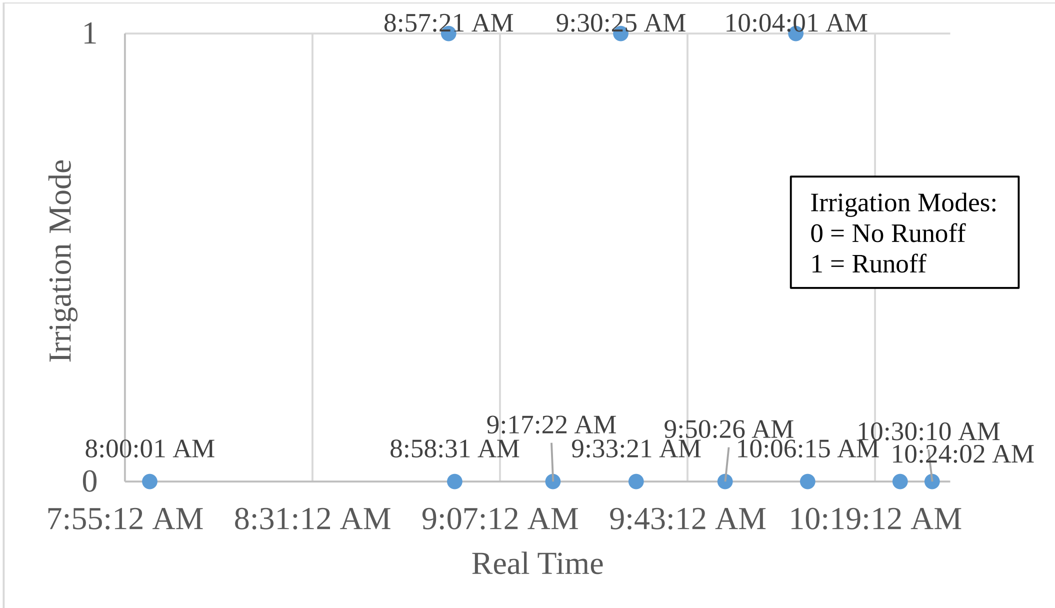

Figure 108. The Runoff Status of Plot 4 (Cubic Float Prototype) on July 14th 2015

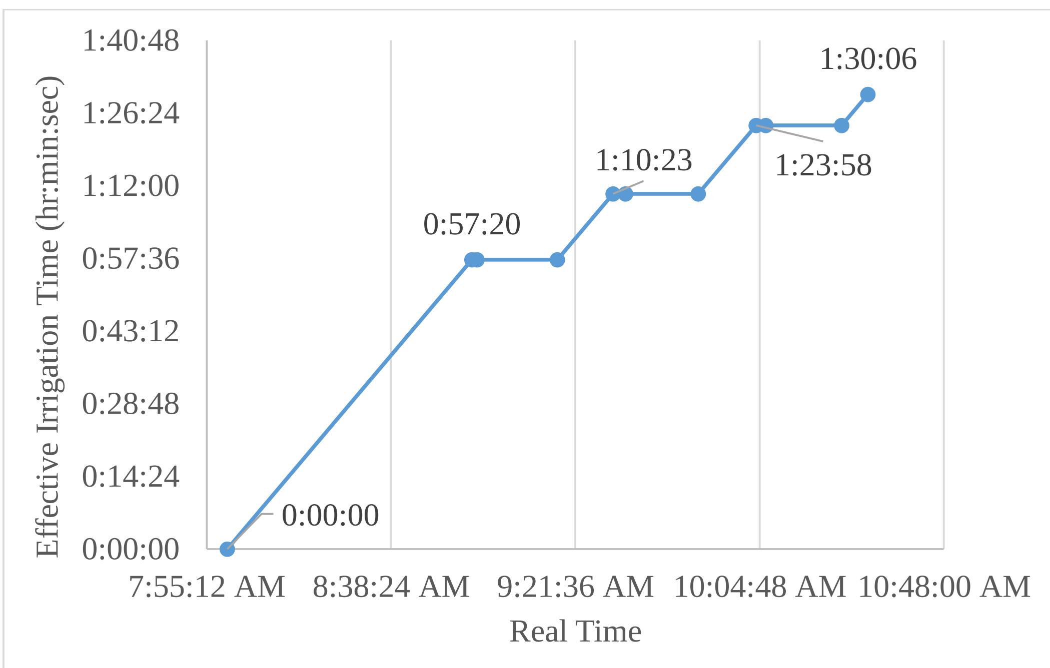

Figure 109. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on July 14th 2015

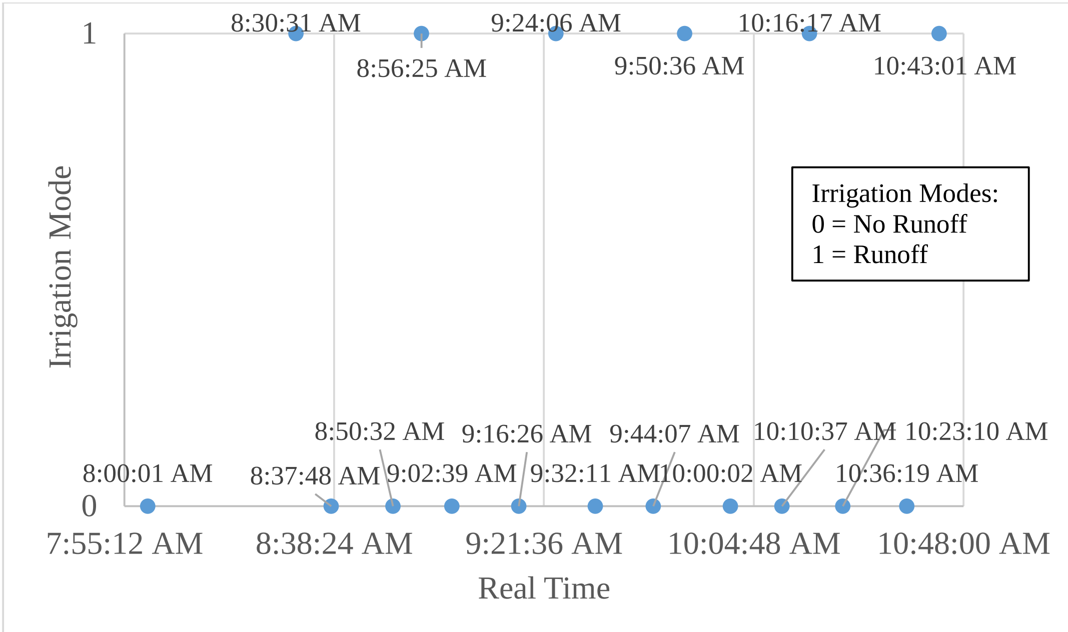

Figure 110. The Runoff Status of Plot 5 (Cubic Float Prototype) on July 14th 2015

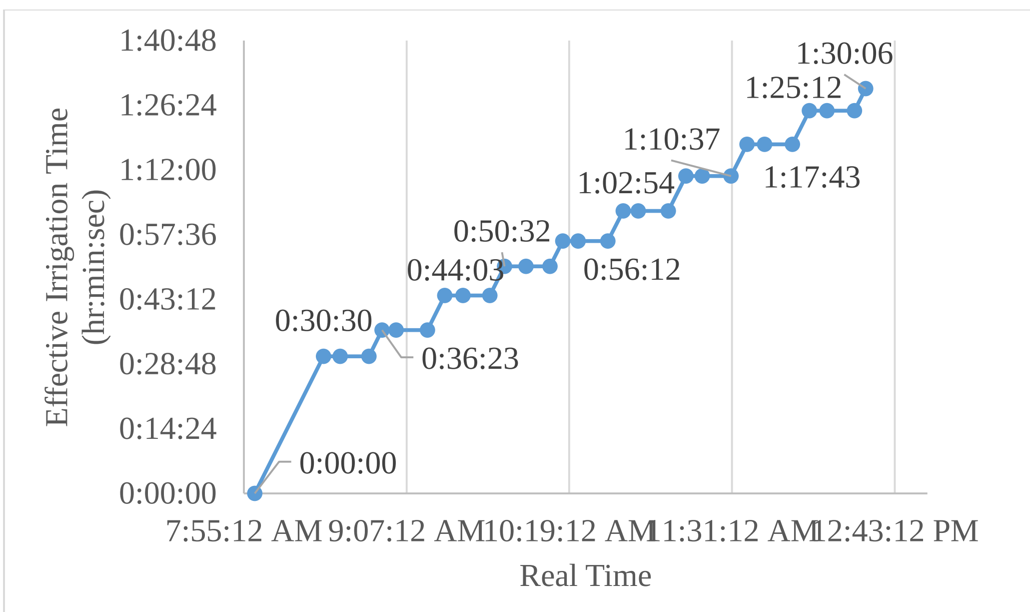

Figure 111. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on July 14th 2015

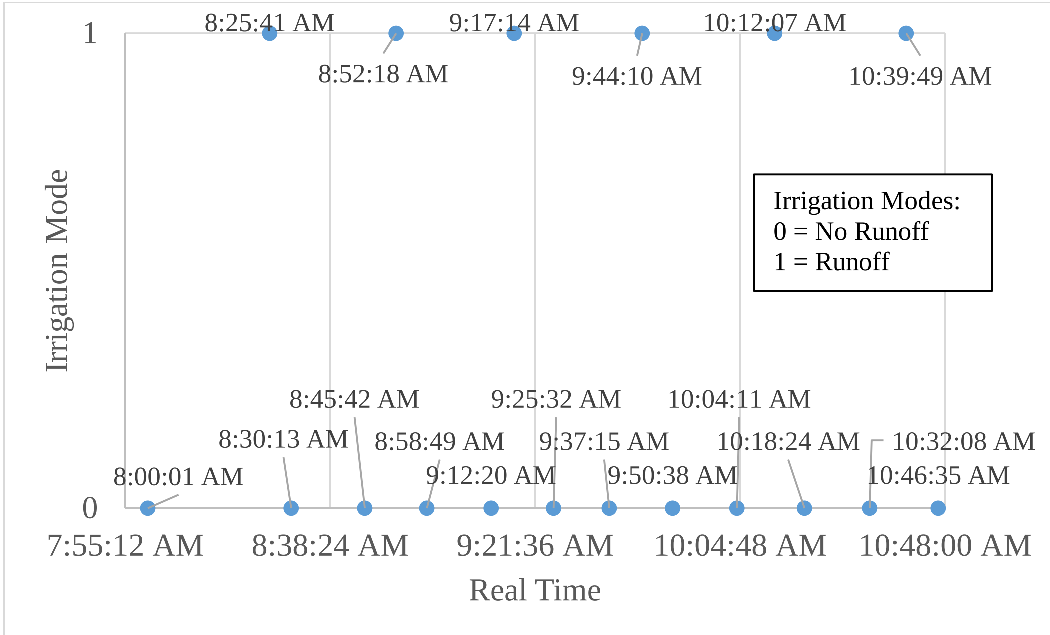

Figure 112. The Runoff Status of Plot 6 (Conductivity Prototype) on July 14th 2015

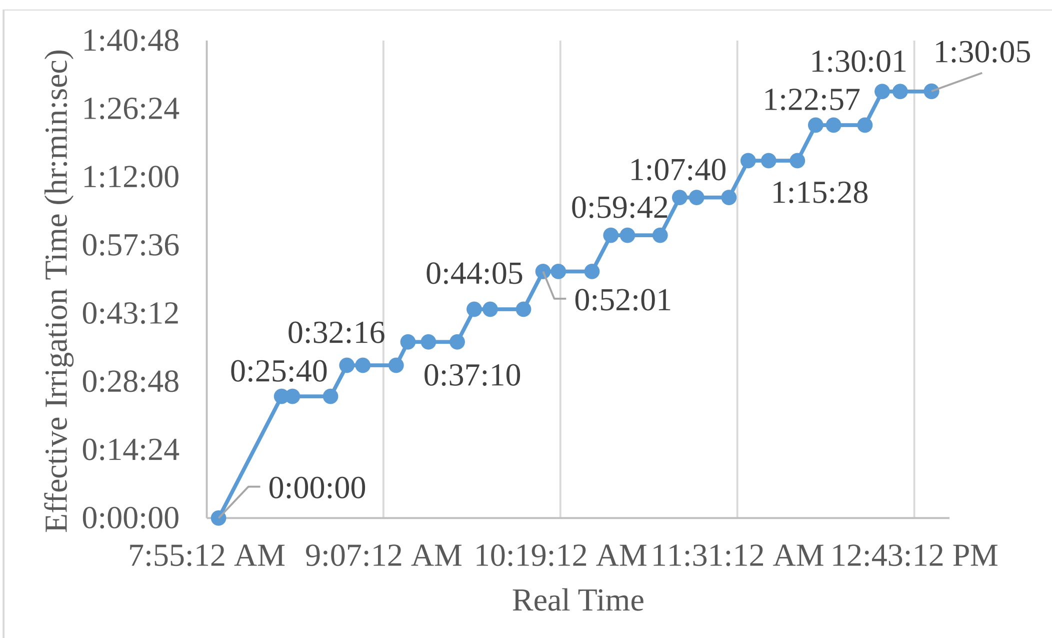

Figure 113. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on July 14th 2015

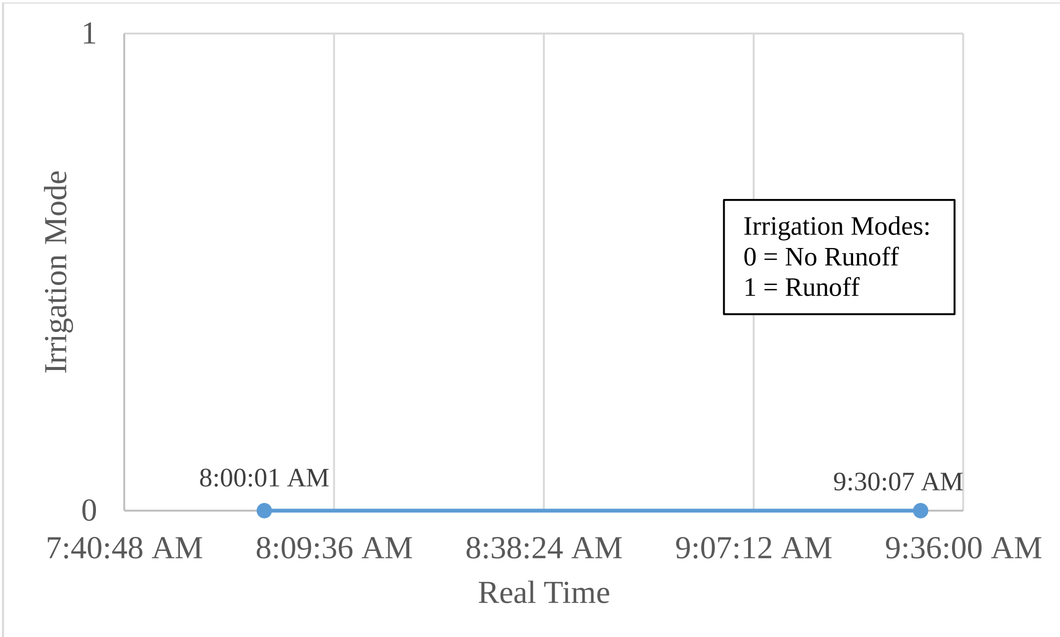

Figure 114. The Runoff Status of Plot 7 (Control) on July 14th 2015

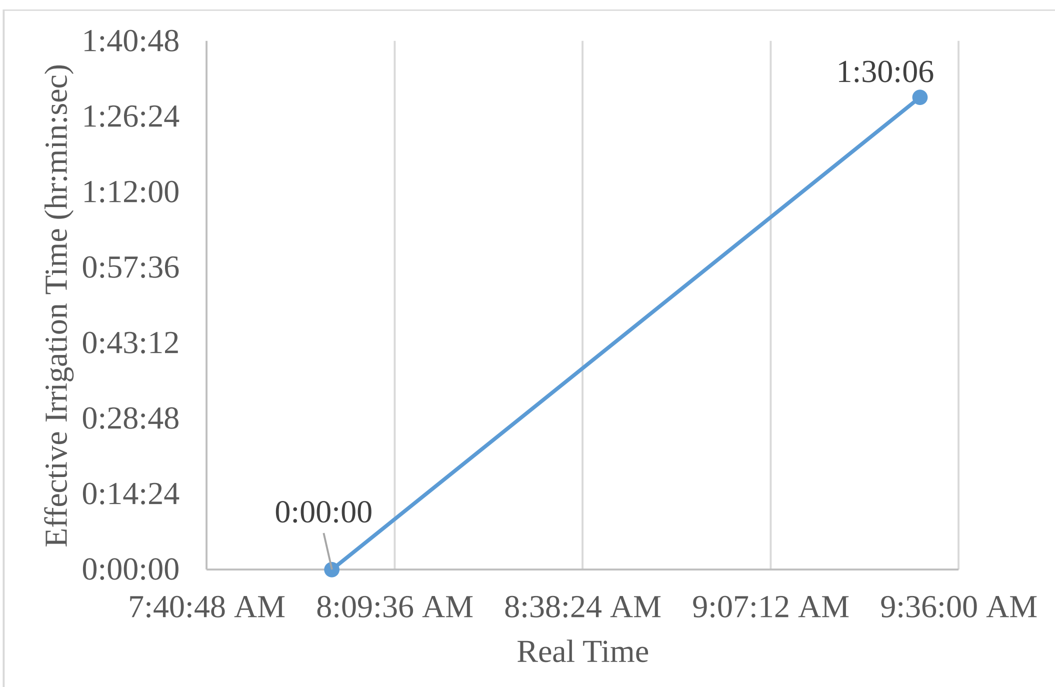

Figure 115. The Effective Irrigation Time of Plot 7 (Control) on July 14th 2015

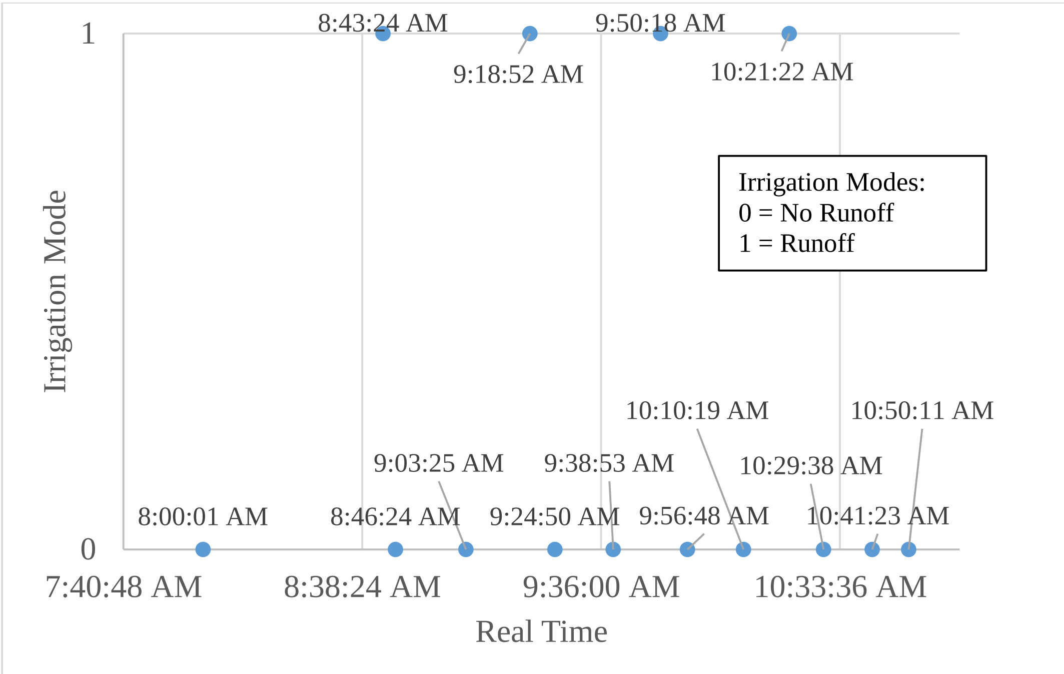

Figure 116. The Runoff Status of Plot 9 (Elbow Float Prototype) on July 14th 2015

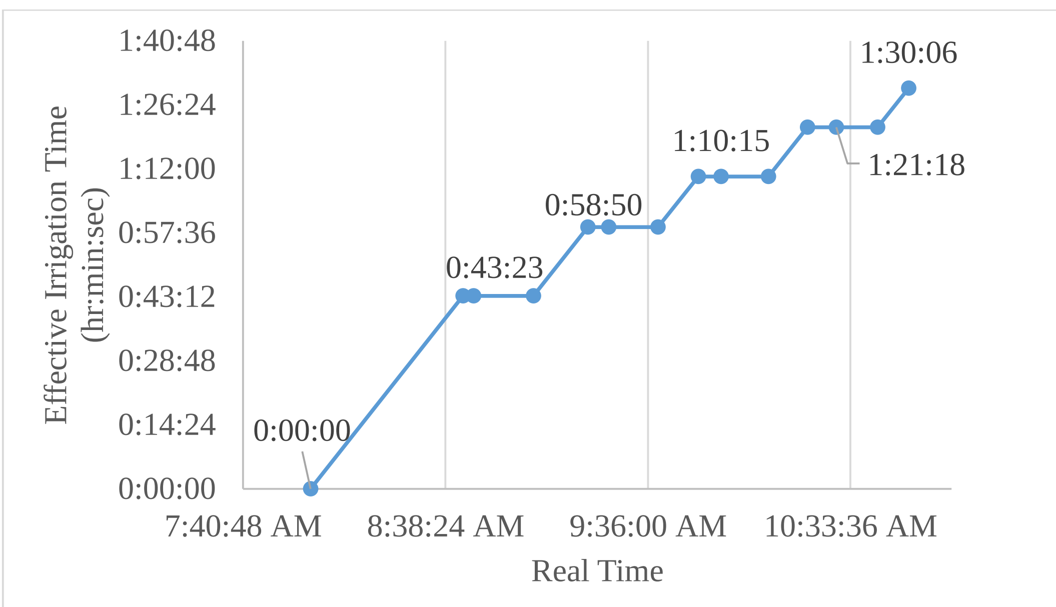

Figure 117. The Effective Irrigation Time of Plot 9 (Elbow Float Prototype) on July 14th 2015

Based on the testing results, both the conductivity prototypes, the cubic float prototypes and the elbow float prototype have detected runoff and paused the irrigation. During these tests, the conductivity prototypes and the cubic float prototypes have shown similar sensitivity to runoff, which is higher than the elbow float prototype.

4.2.8 Qualitative Field Testing Results for July 21st 2015

Two cubic float prototypes, two conductivity prototypes, one elbow float prototype and one control plot without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 17.

Table 17. Irrigation Specifications of Test on July 21st 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1.5 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 9 (Elbow Float Plot)

The results of the irrigation are shown in Figure 118 - 129.

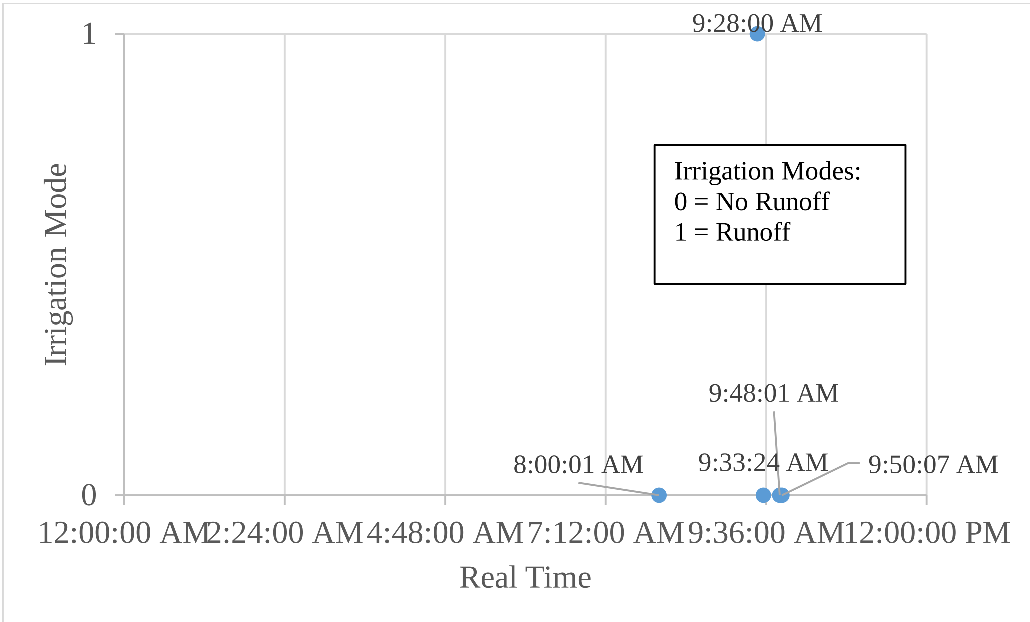

Figure 118. The Runoff Status of Plot 2 (Conductivity Prototype) on July 21st 2015

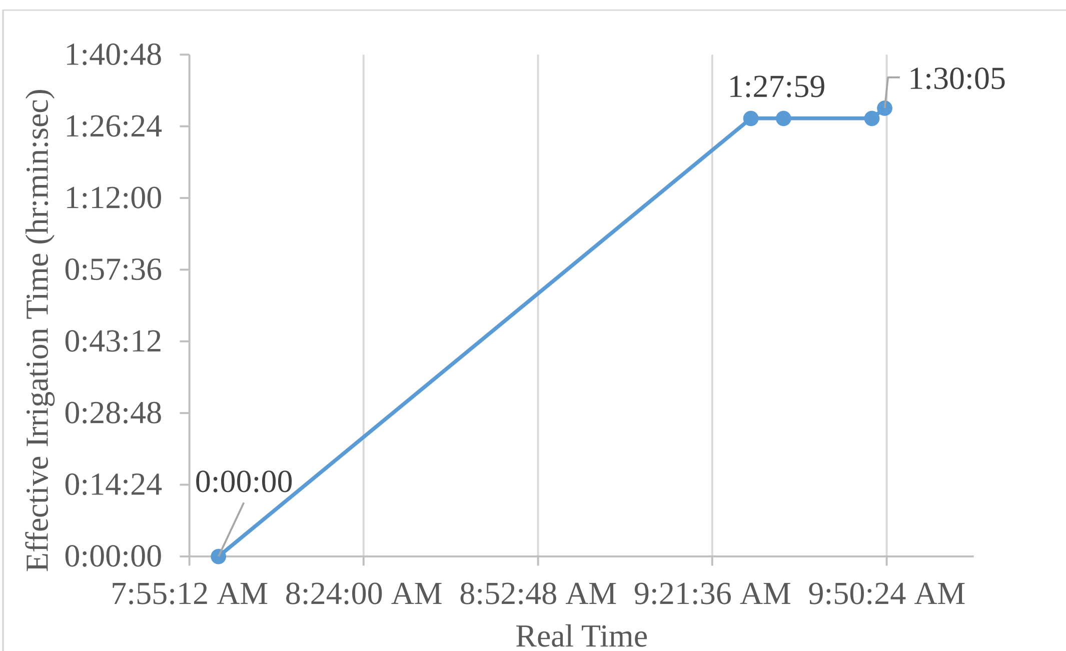

Figure 119. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on July 21st 2015

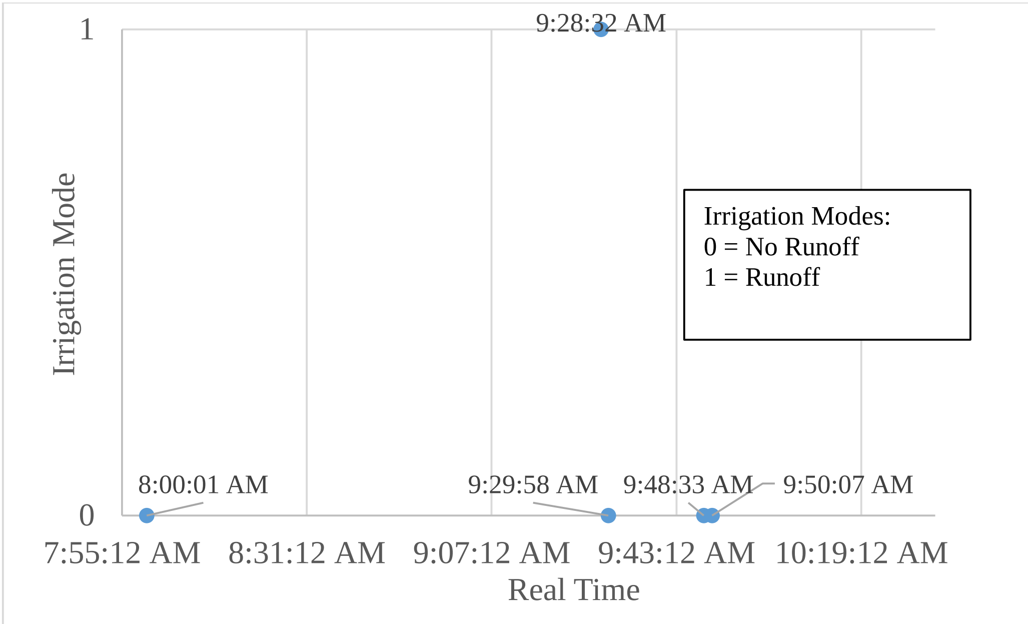

Figure 120. The Runoff Status of Plot 4 (Cubic Float Prototype) on July 21st 2015

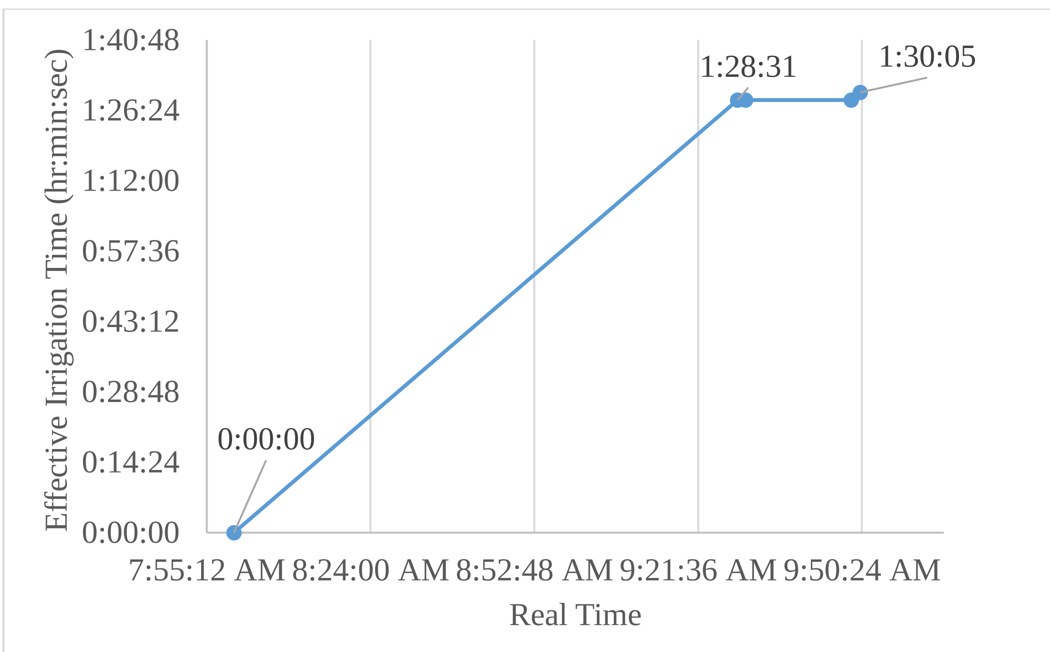

Figure 121. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on July 21st 2015

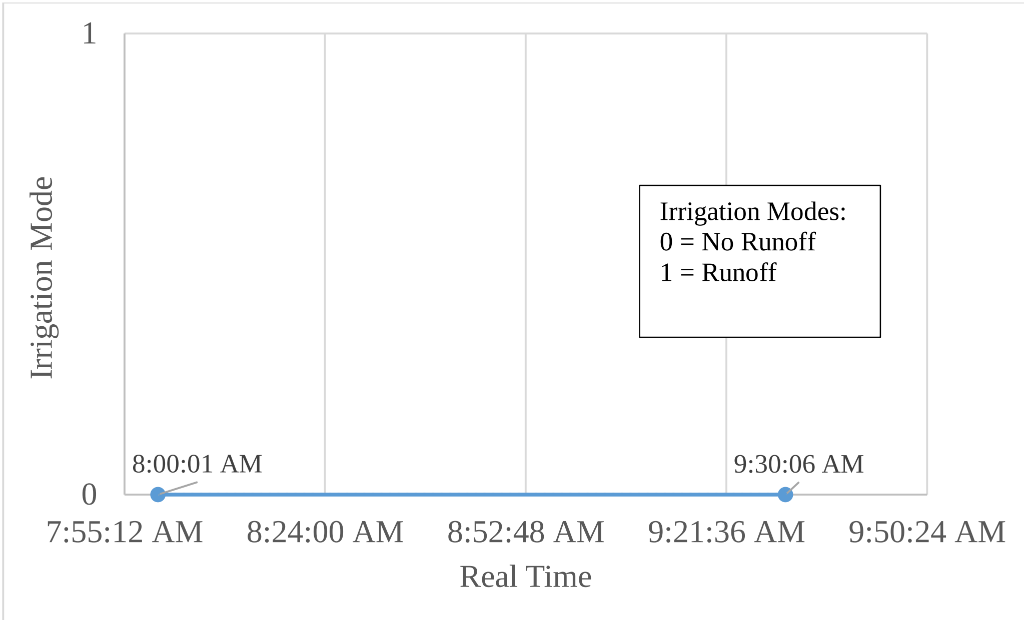

Figure 122. The Runoff Status of Plot 5 (Cubic Float Prototype) on July 21st 2015

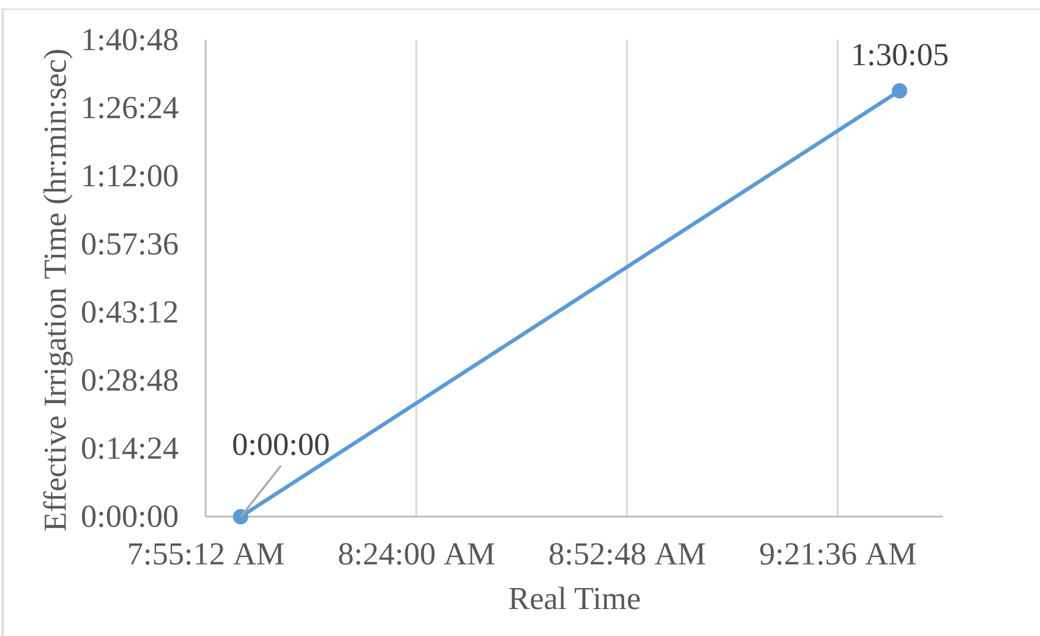

Figure 123. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on July 21st 2015

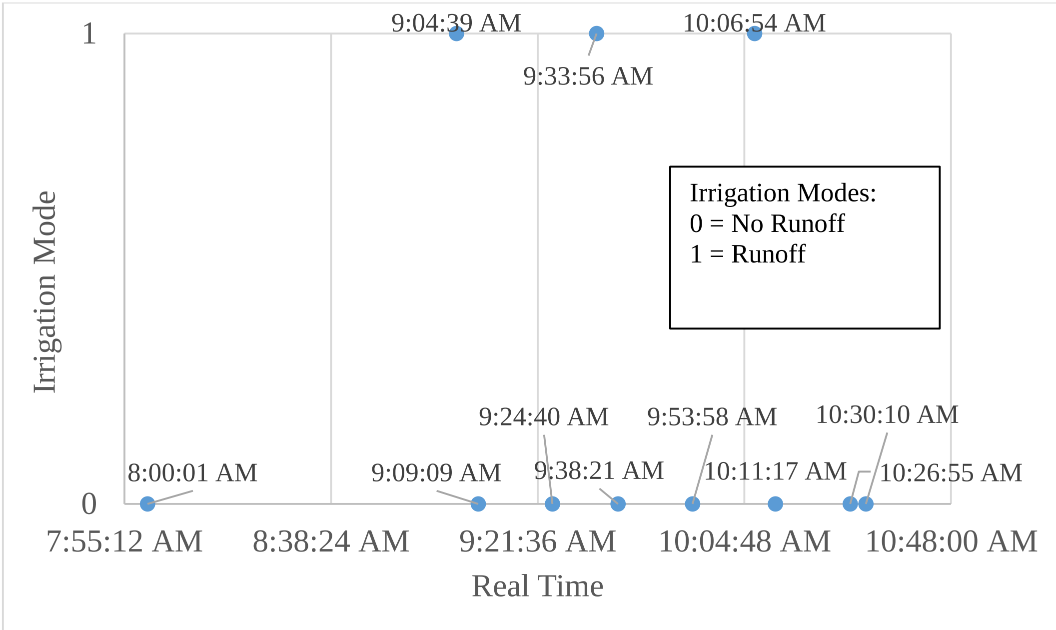

Figure 124. The Runoff Status of Plot 6 (Conductivity Prototype) on July 21st 2015

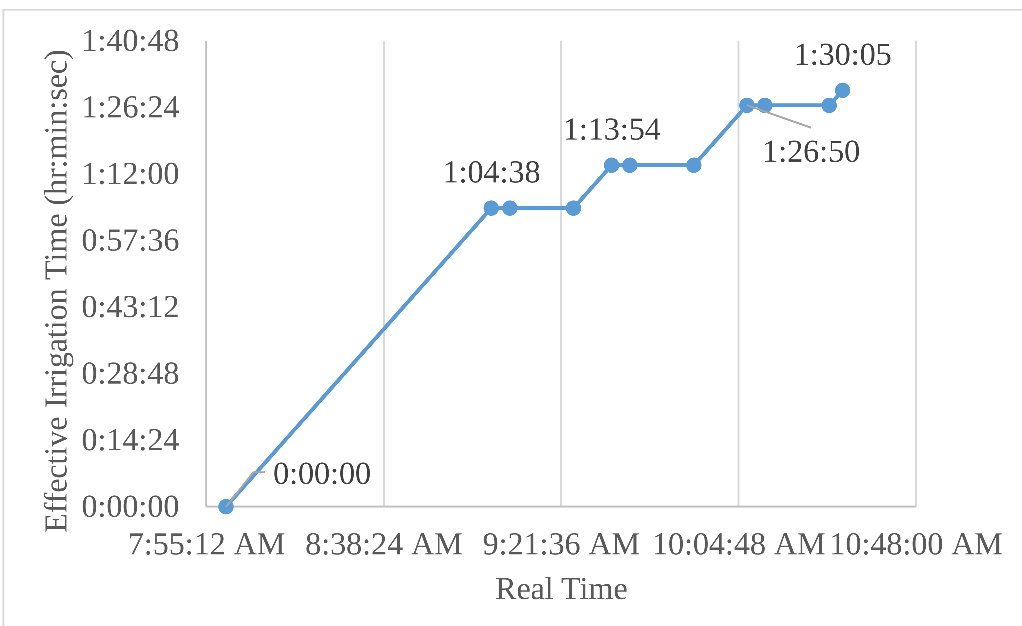

Figure 125. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on July 21st 2015

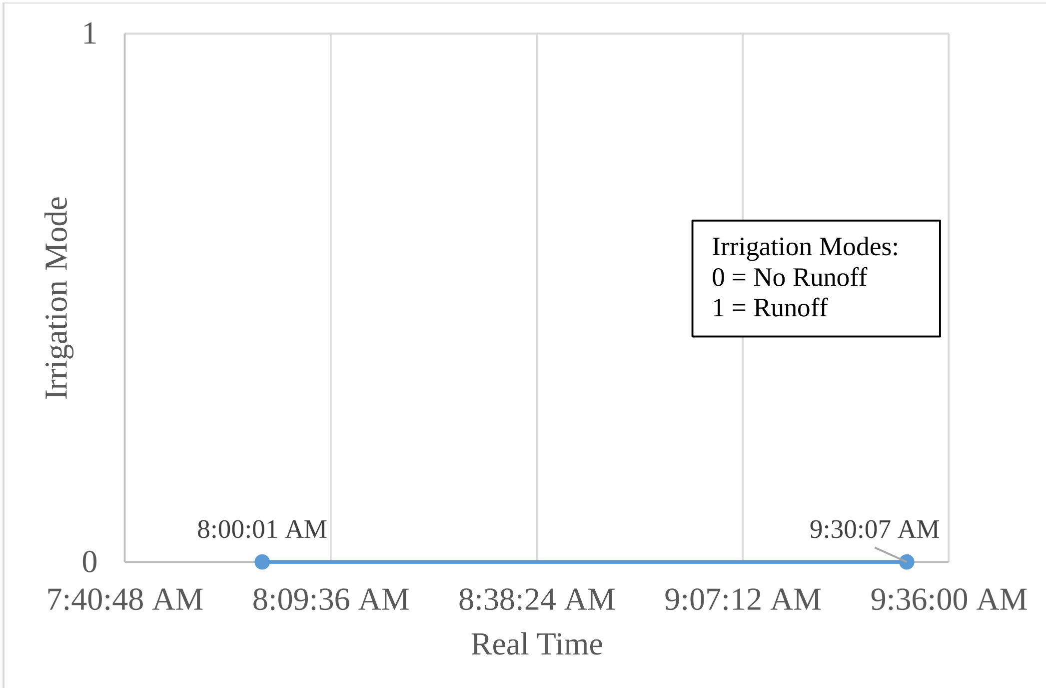

Figure 126. The Runoff Status of Plot 7 (Control) on July 21st 2015

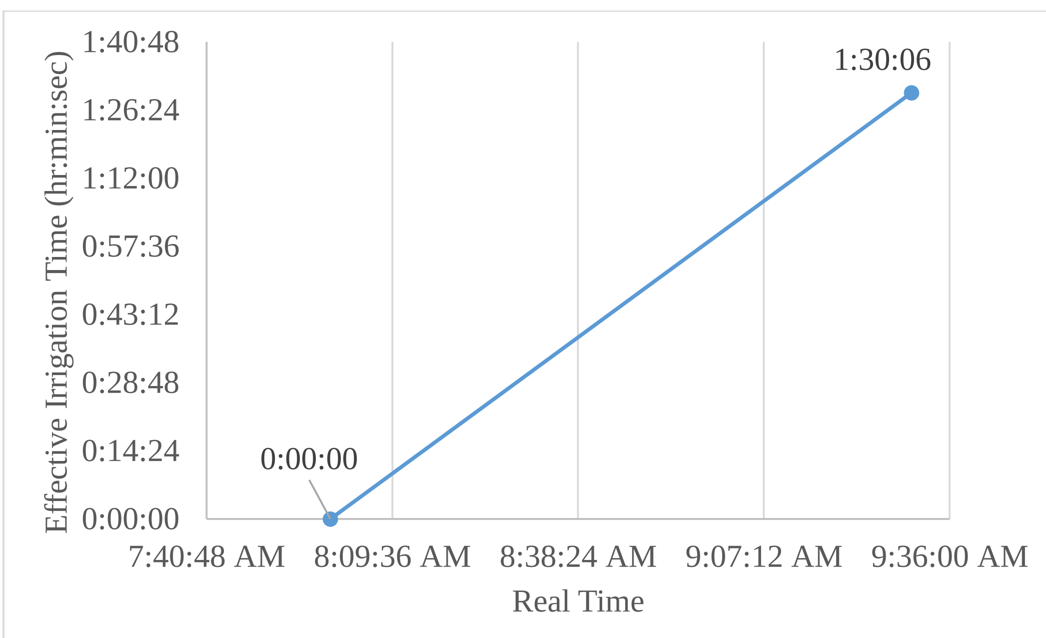

Figure 127. The Effective Irrigation Time of Plot 7 (Control) on July 21st 2015

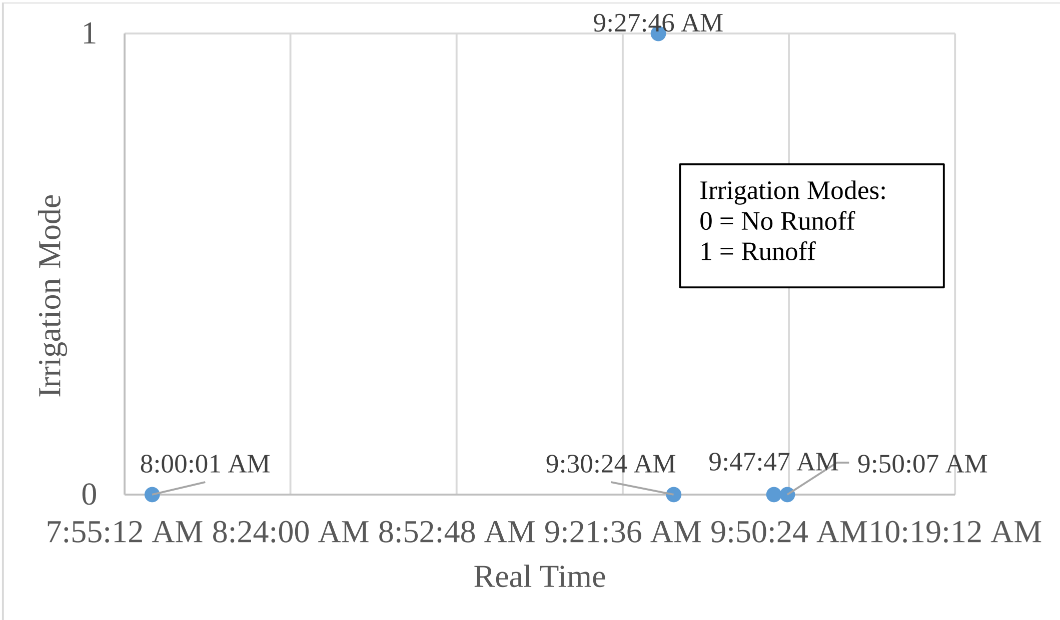

Figure 128. The Runoff Status of Plot 9 (Elbow Float Prototype) on July 21st 2015

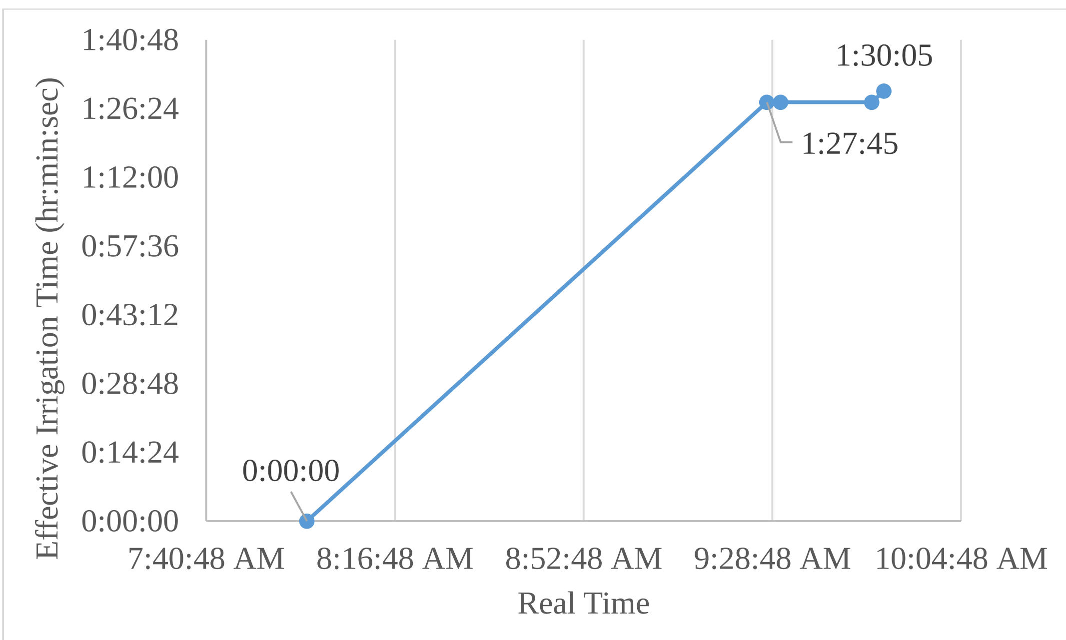

Figure 129. The Effective Irrigation Time of Plot 9 (Elbow Float Prototype) on July 21st 2015

From the testing results, only one cubic float prototype has not been activated by runoff during the test during the 30 minute of irrigation. However, it has detected runoff just after the irrigation stopped. Most irrigation runoff sensor prototypes have detected runoff when approaching the end of the irrigation with plot 4 (cubic float prototype) as an exception, which showed the higher sensitivity of this prototype.

4.2.9 Qualitative Field Testing Results for Aug 4th 2015

Two cubic float prototypes, two conductivity prototypes, one elbow float prototype and one control plot without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 18.

Table 18. Irrigation Specifications of Test on Aug 4th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1.5 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 5 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 9 (Elbow Float Plot)

The results of the irrigation are shown in Figure 130 - 141.

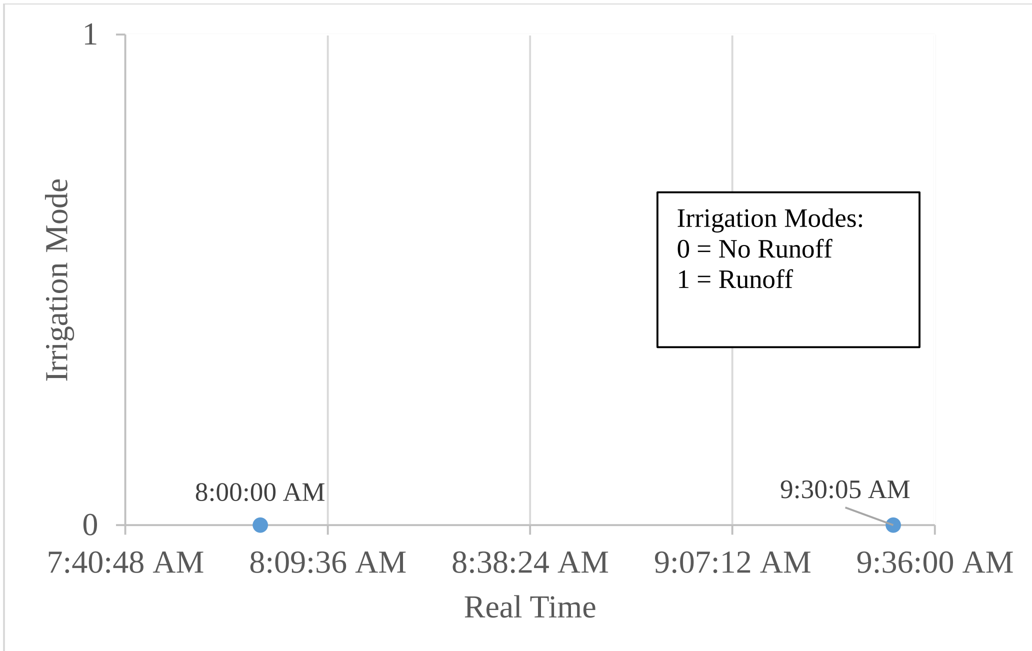

Figure 130. The Runoff Status of Plot 2 (Conductivity Prototype) on Aug 4th 2015

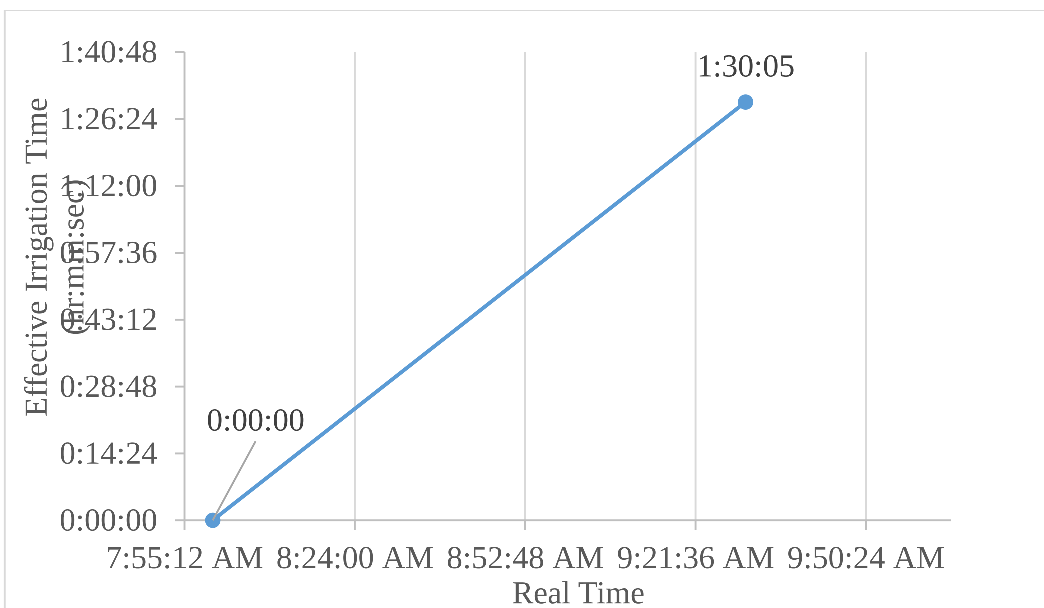

Figure 131. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on Aug 4th 2015

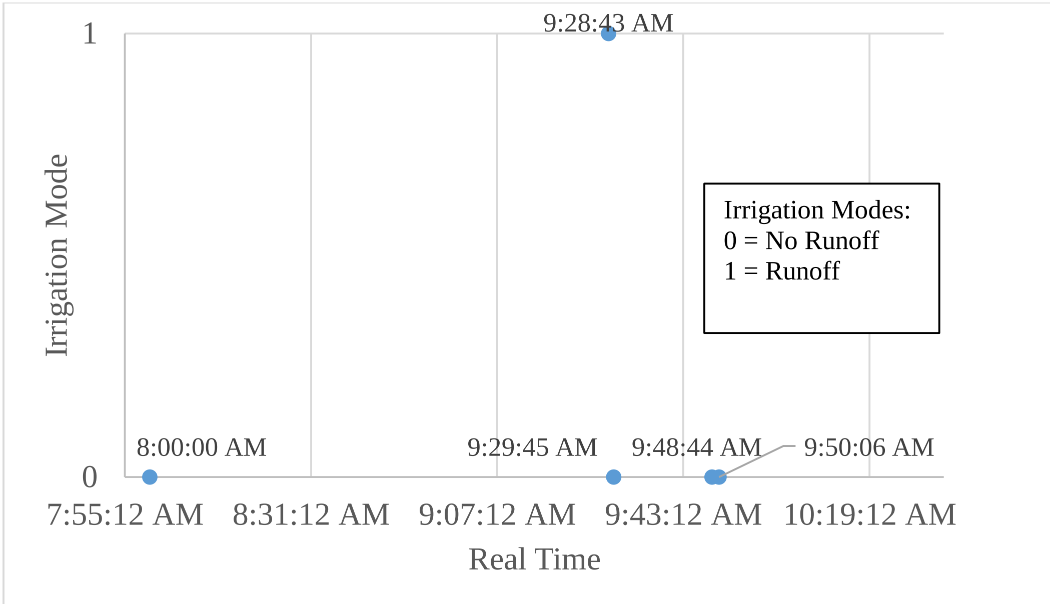

Figure 132. The Runoff Status of Plot 4 (Cubic Float Prototype) on Aug 4th 2015

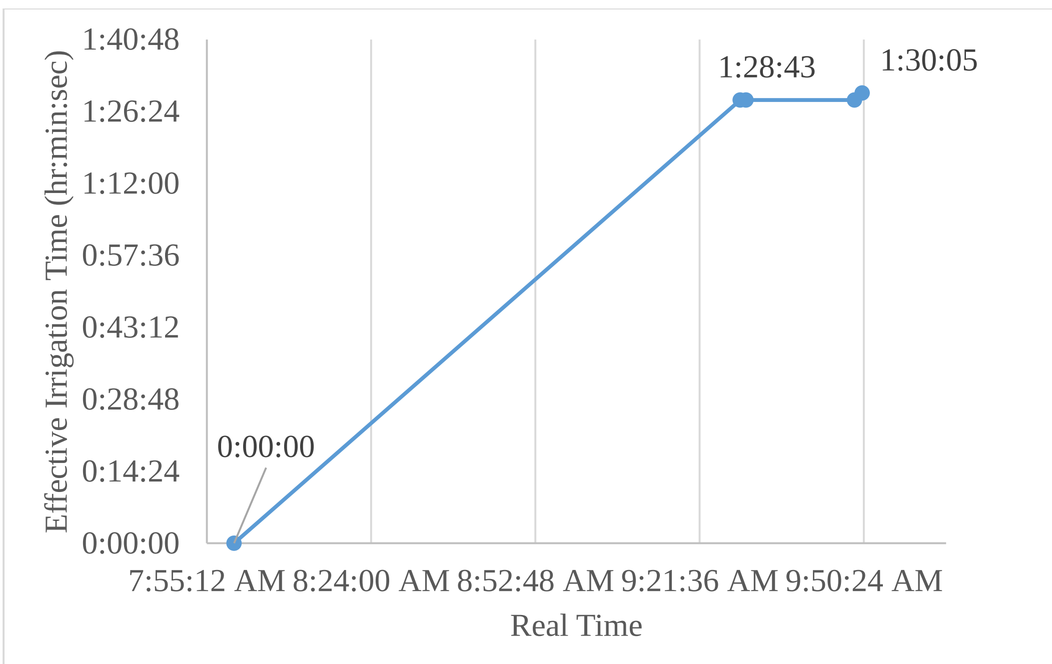

Figure 133. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on Aug 4th 2015

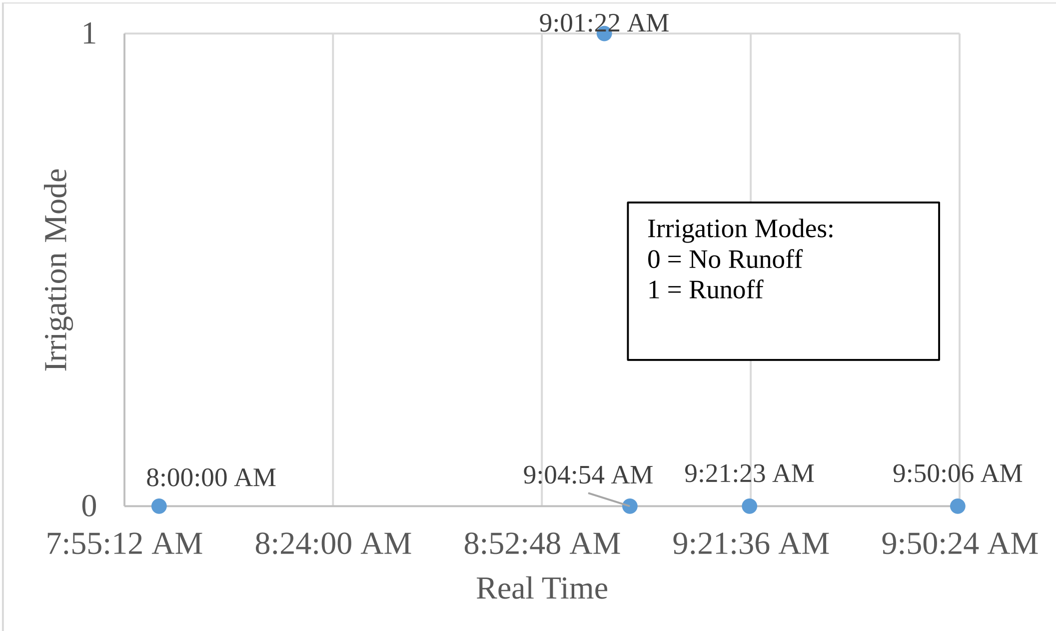

Figure 134. The Runoff Status of Plot 5 (Cubic Float Prototype) on Aug 4th 2015

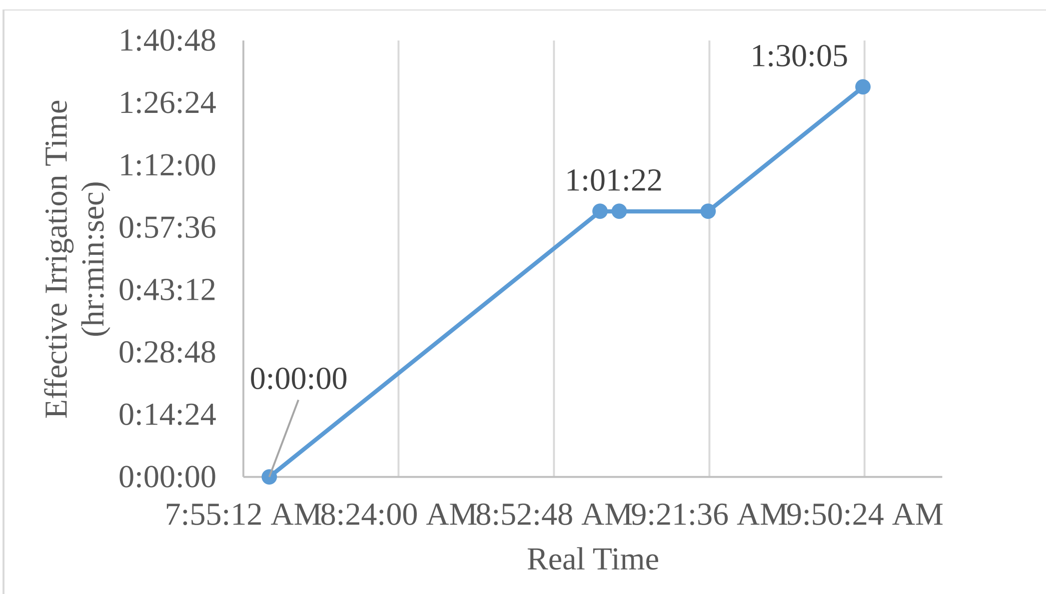

Figure 135. The Effective Irrigation Time of Plot 5 (Cubic Float Prototype) on Aug 4th 2015

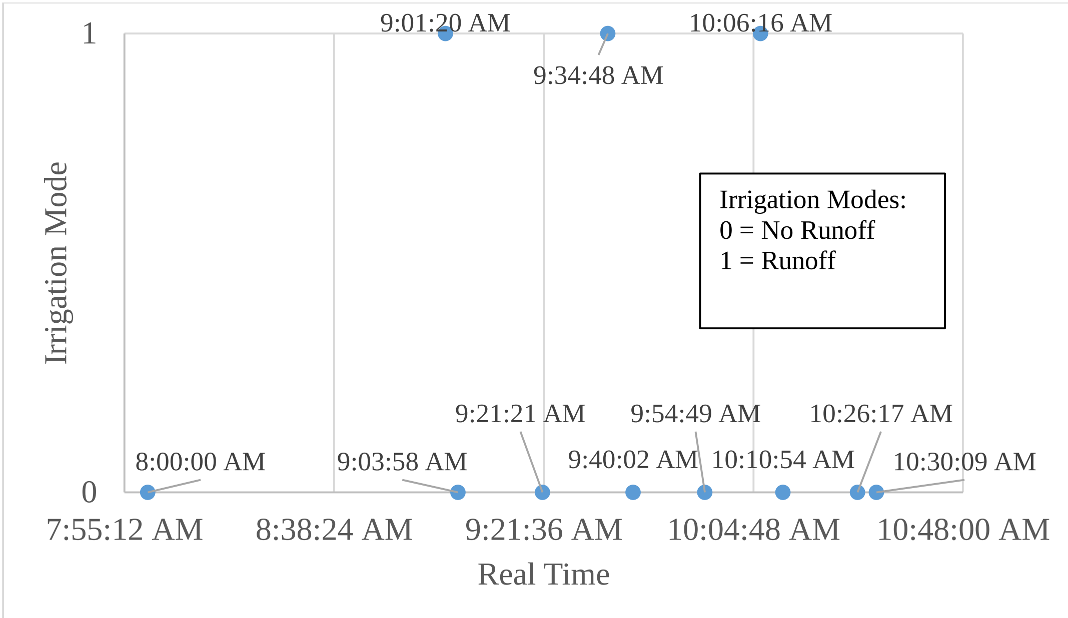

Figure 136. The Runoff Status of Plot 6 (Conductivity Prototype) on Aug 4th 2015

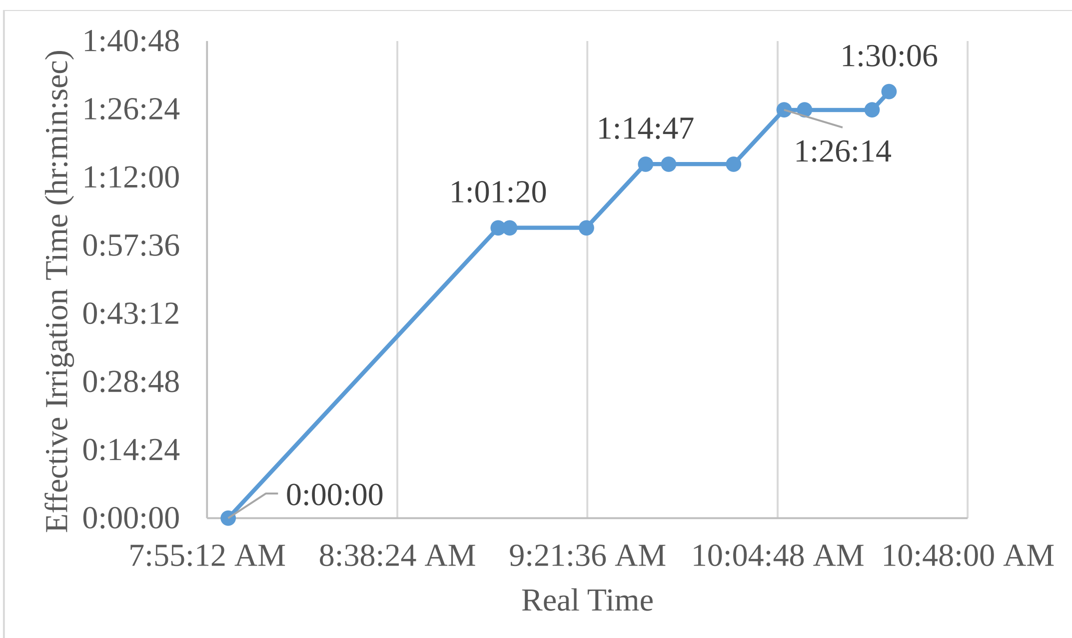

Figure 137. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on Aug 4th 2015

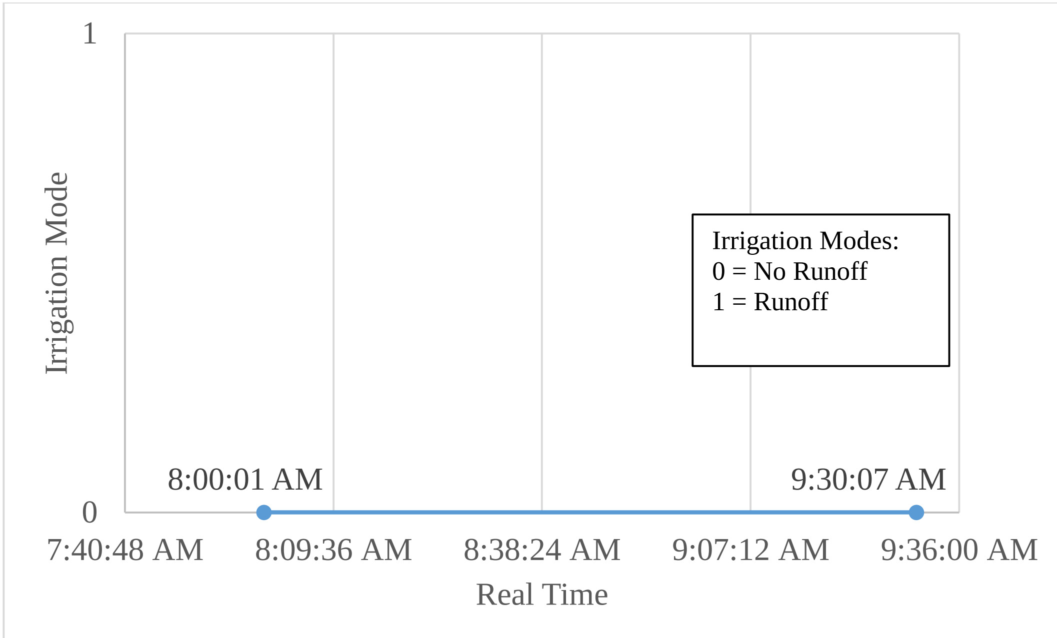

Figure 138. The Runoff Status of Plot 7 (Control) on Aug 4th 2015

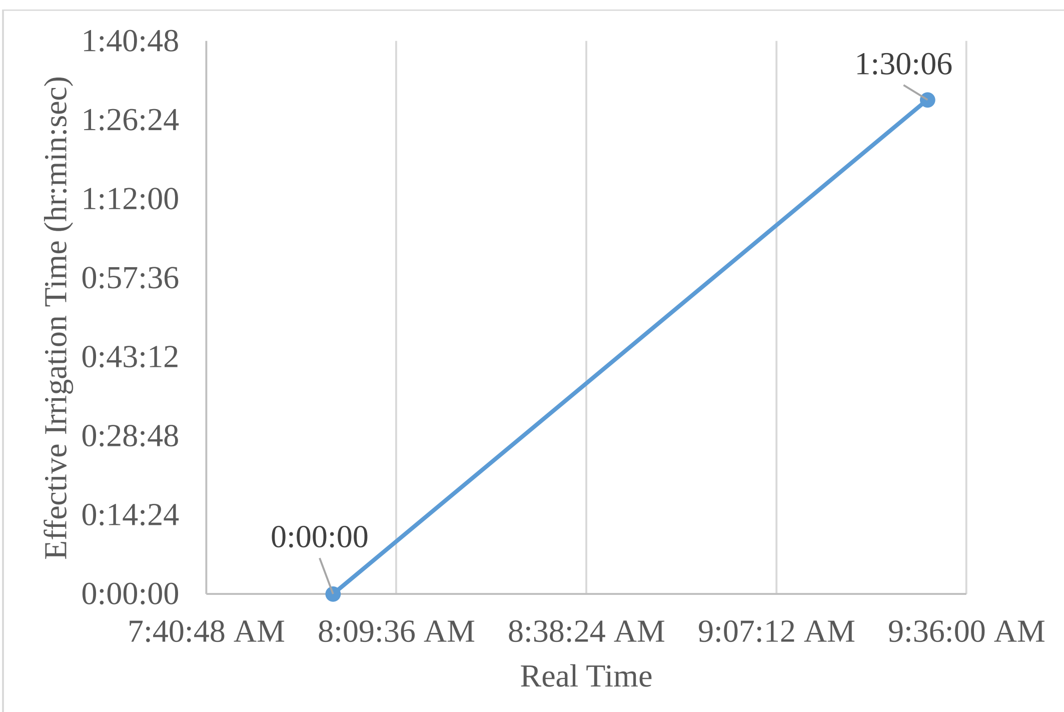

Figure 139. The Effective Irrigation Time of Plot 7 (Control) on Aug 4th 2015

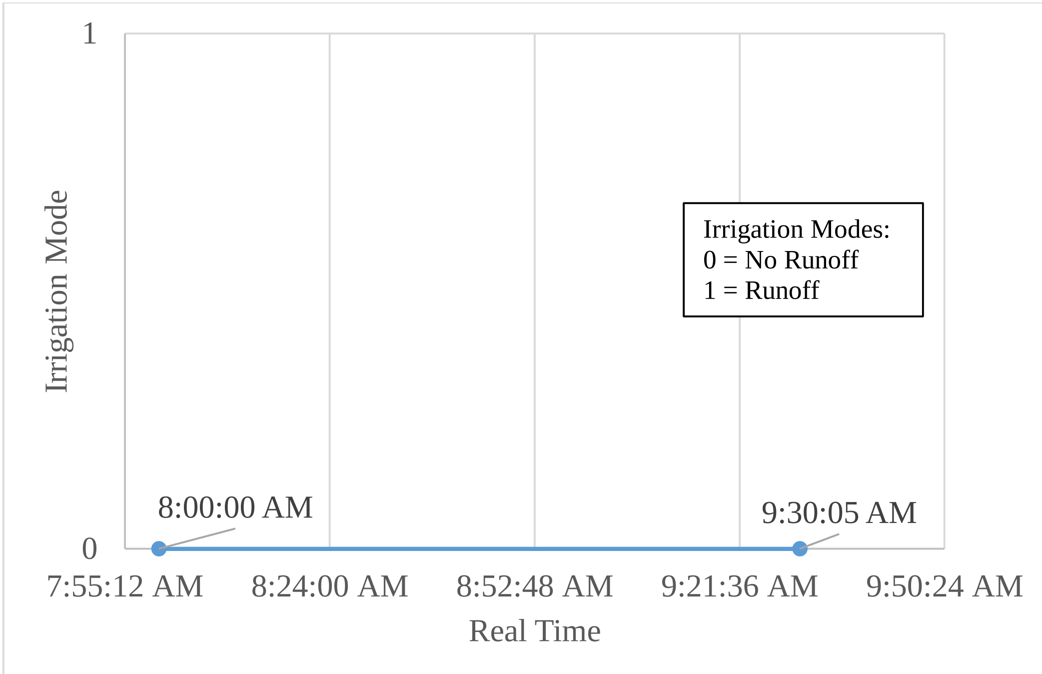

Figure 140. The Runoff Status of Plot 9 (Elbow Float Prototype) on Aug 4th 2015

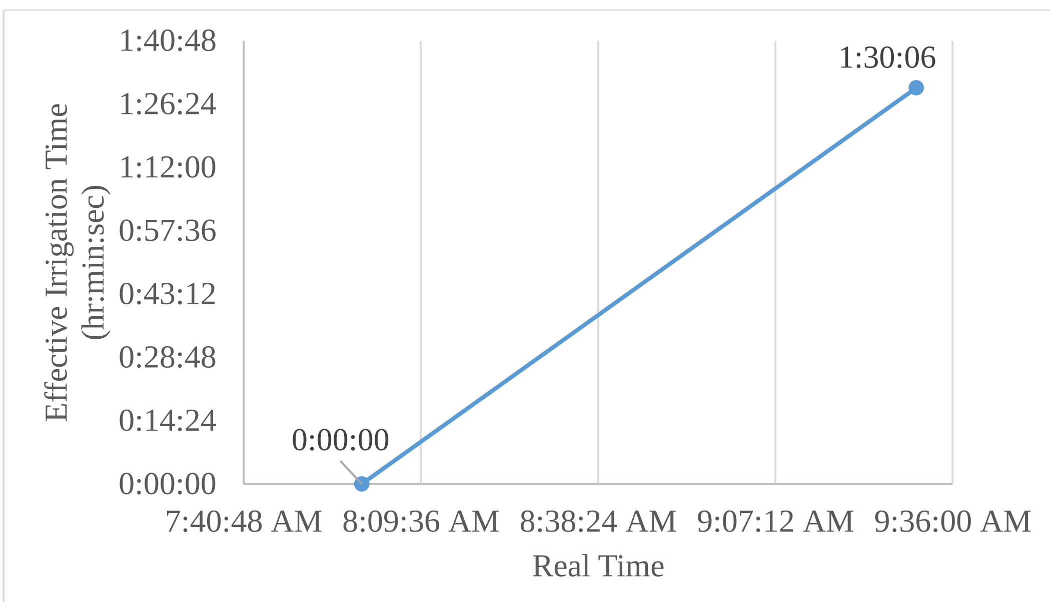

Figure 141. The Effective Irrigation Time of Plot 9 (Elbow Float Prototype) on Aug 4th 2015

Based on the irrigation results, one conductivity prototype and one elbow float prototype have not detected runoff and did not pause the irrigation cycle. The malfunctioning conductivity prototype was found to be clogged by debris while the vertical float sensor in the elbow float prototype has been found broken. The conductivity prototype was fixed once it was cleaned to remove the debris that was clogging it.

4.2.10 Qualitative Field Testing Results for Aug 25th 2015

One cubic float prototypes, two conductivity prototypes and two control plots without irrigation runoff sensors have been tested. The irrigation specifications have been listed, as shown in Table 19.

Table 19. Irrigation Specifications of Test on Aug 25th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	1.5 hour
Wait Time (WT)	20 minutes
# of Tested Plot	2 (Conductivity Prototype), 4 (Cubic Float Prototype), 6 (Conductivity Prototype), 7 (Control Plot), 8 (Control Plot)

The results of the irrigation are shown in Figure 142 - 151.

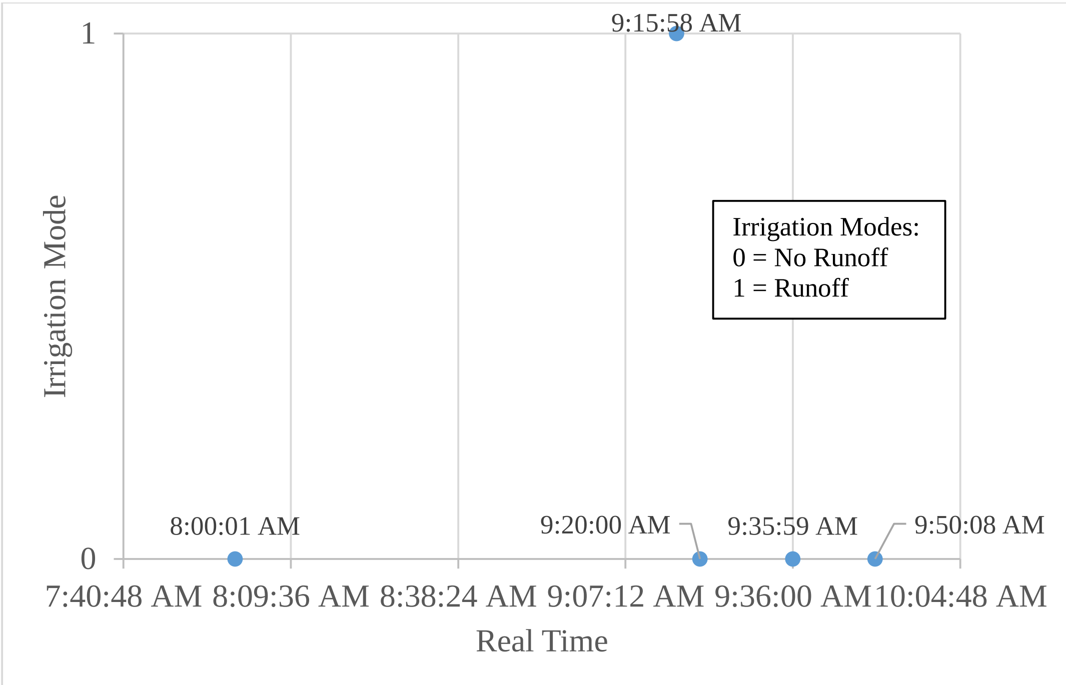

Figure 142. The Runoff Status of Plot 2 (Conductivity Prototype) on Aug 25th 2015

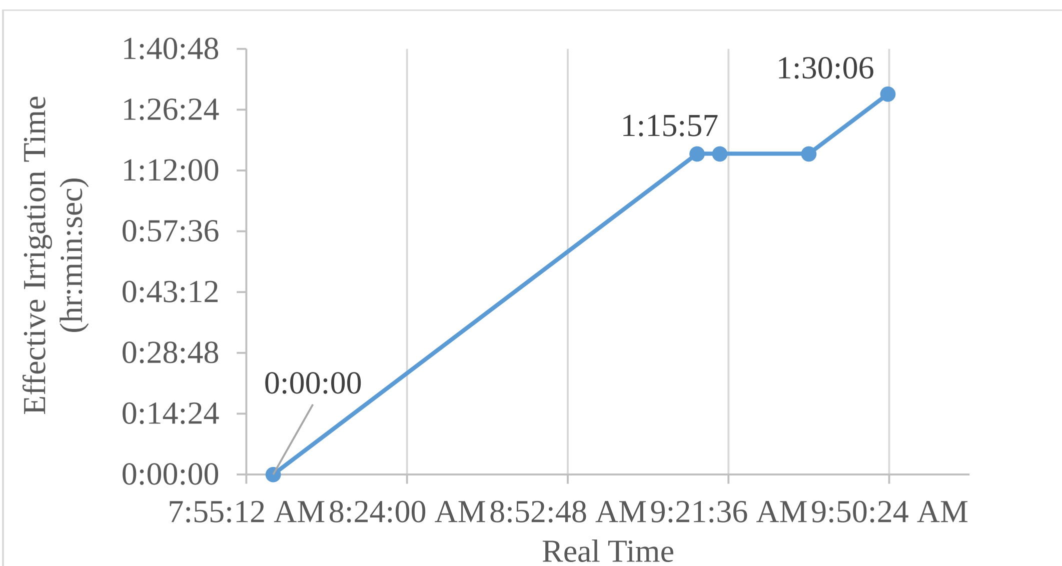

Figure 143. The Effective Irrigation Time of Plot 2 (Conductivity Prototype) on Aug 25th 2015

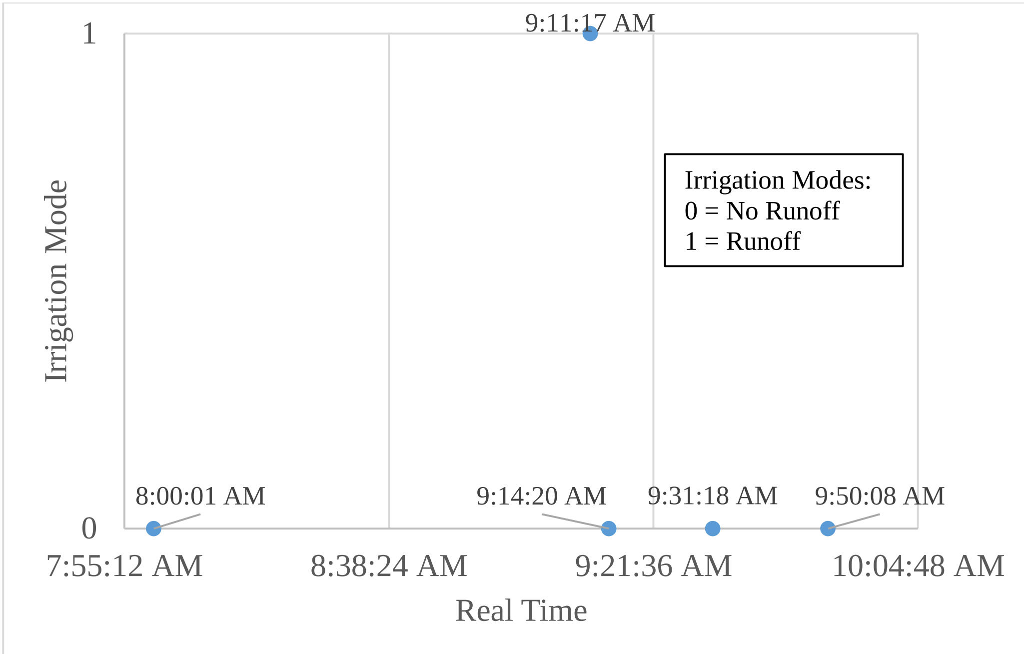

Figure 144. The Runoff Status of Plot 4 (Cubic Float Prototype) on Aug 25th 2015

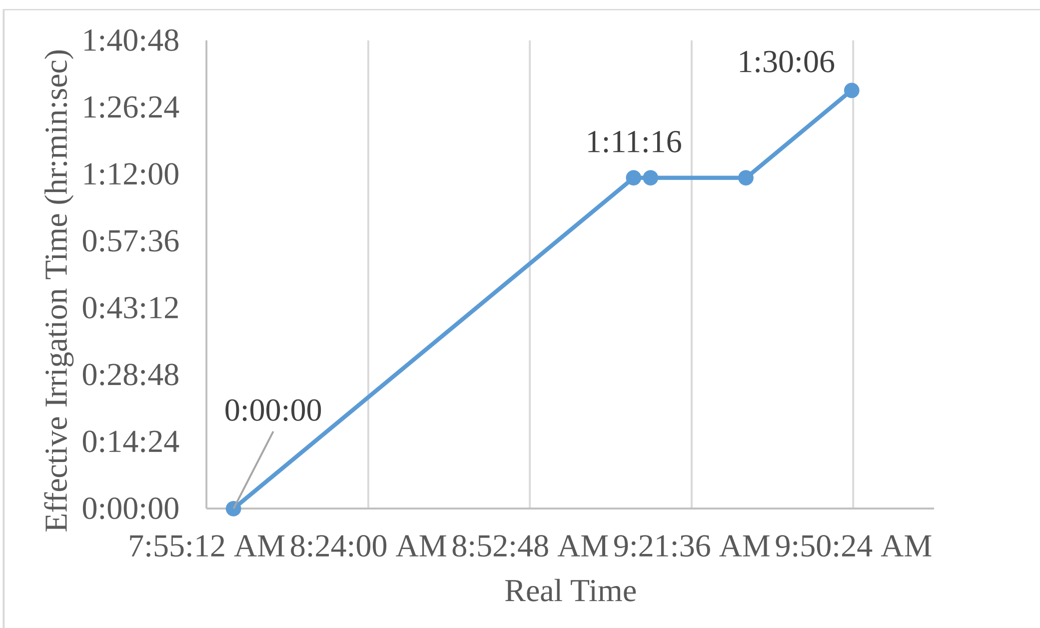

Figure 145. The Effective Irrigation Time of Plot 4 (Cubic Float Prototype) on Aug 25th 2015

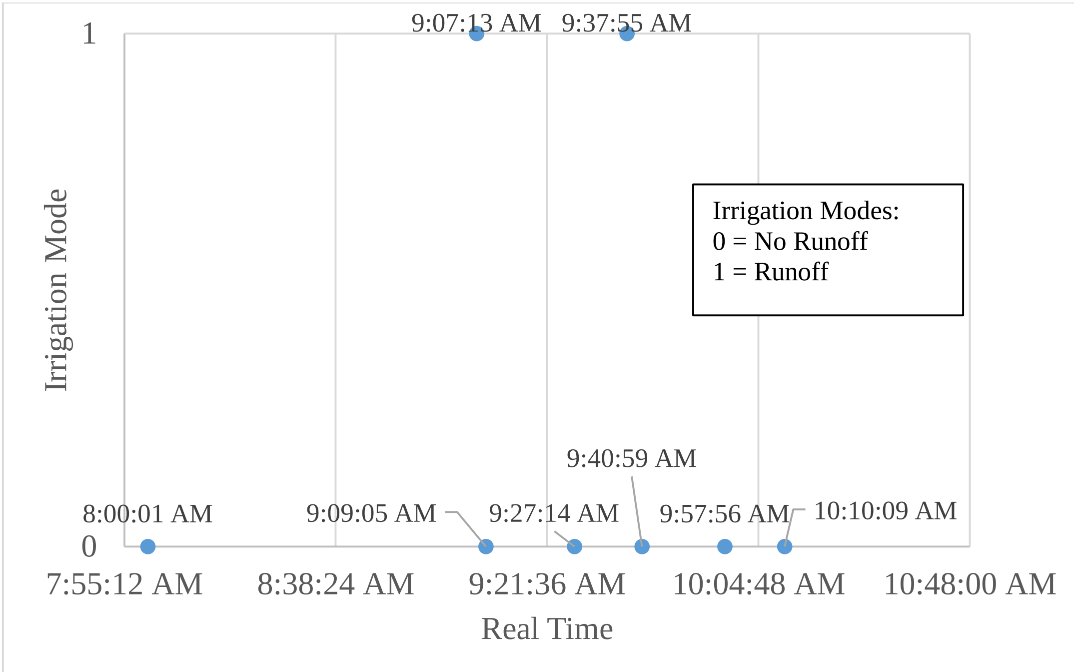

Figure 146. The Runoff Status of Plot 6 (Conductivity Prototype) on Aug 25th 2015

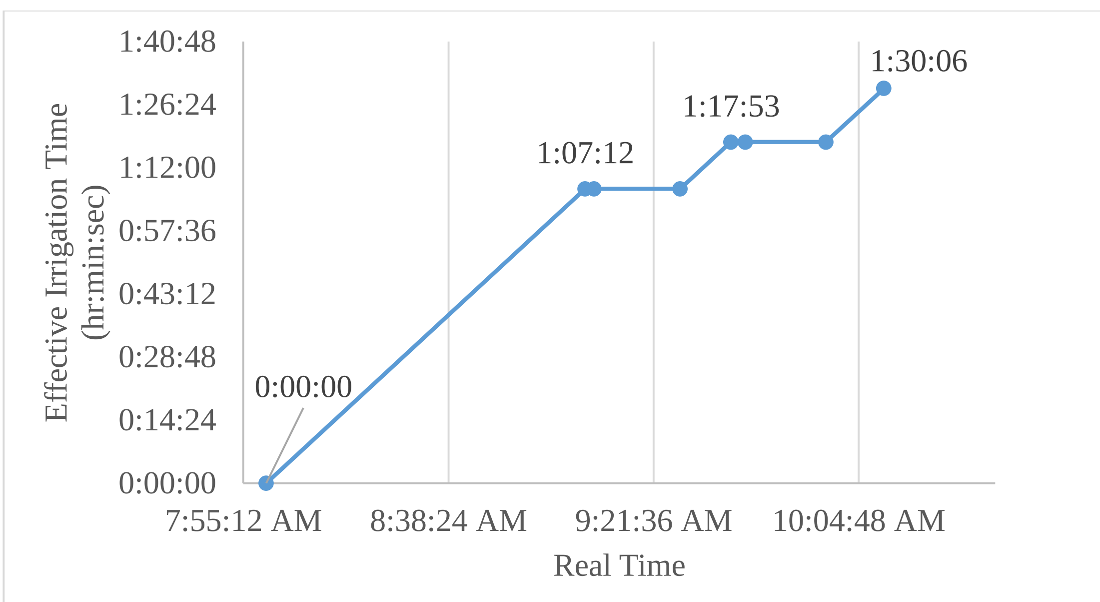

Figure 147. The Effective Irrigation Time of Plot 6 (Conductivity Prototype) on Aug 25th 2015

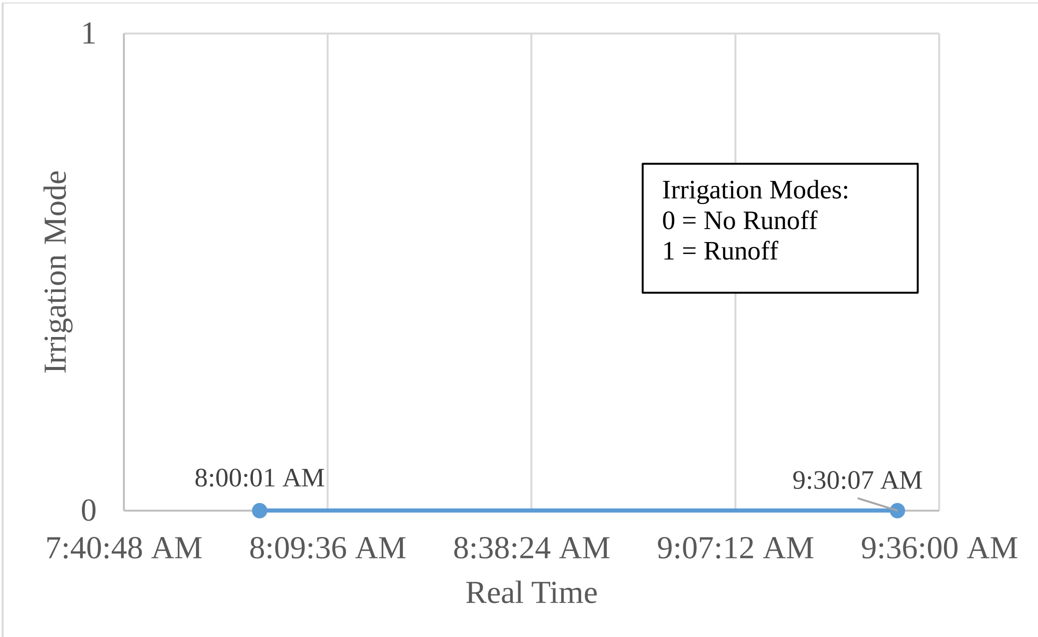

Figure 148. The Runoff Status of Plot 7 (Control) on Aug 25th 2015

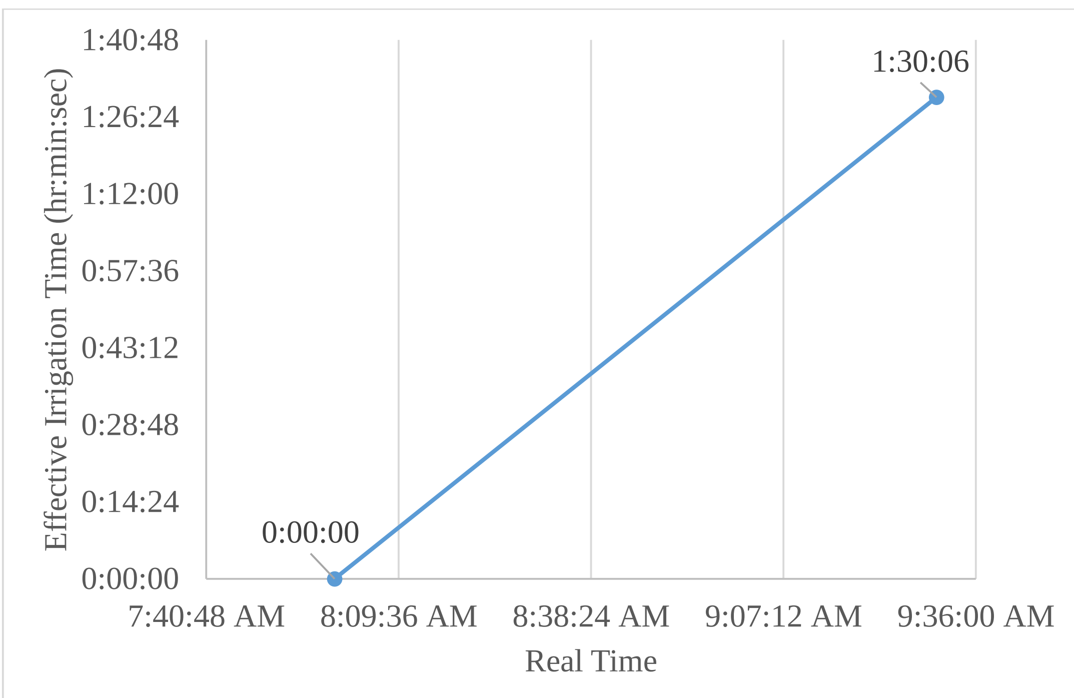

Figure 149. The Effective Irrigation Time of Plot 7 (Control) on Aug 25th 2015

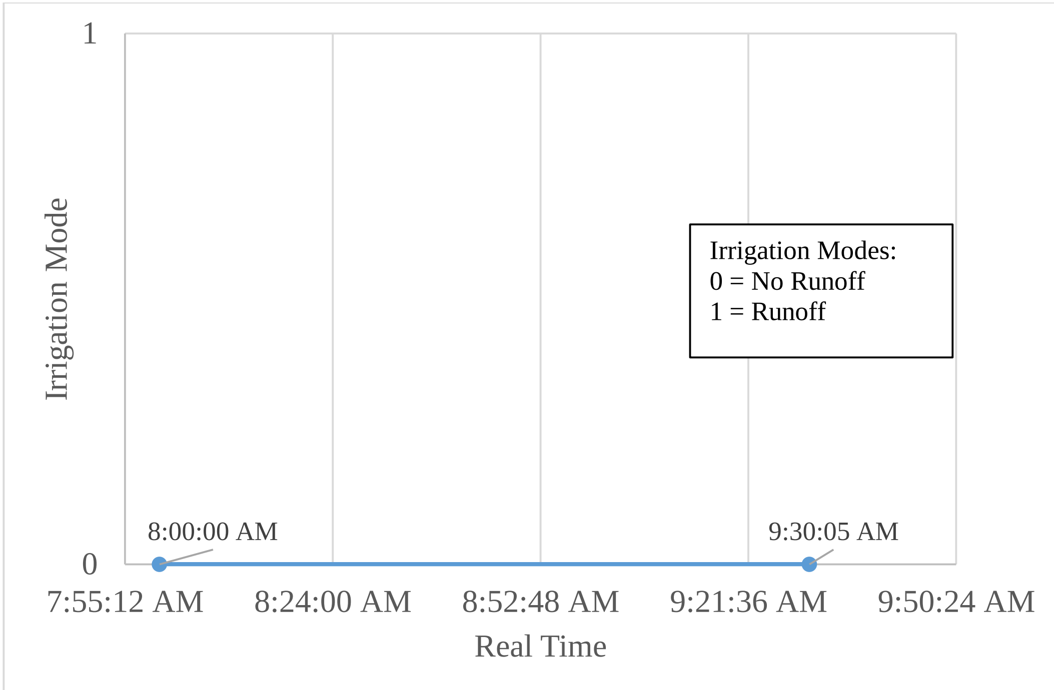

Figure 150. The Runoff Status of Plot 8 (Control Plot) on Aug 25th 2015

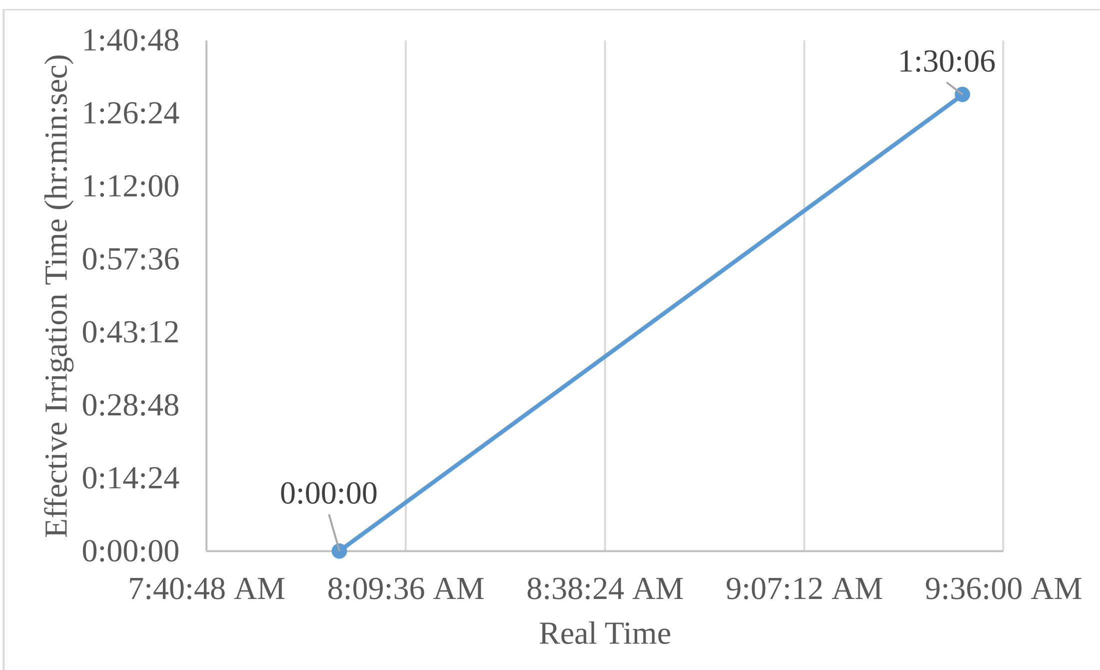

Figure 151. The Effective Irrigation Time of Plot 8 (Control Plot) on Aug 25th 2015

From the irrigation results, both prototypes have successfully detected runoff and paused the irrigation as prescribed.

4.2.11 Qualitative Field Testing Result Analysis

Based on the irrigation results for the ten qualitative field tests shown above, the performance of the different prototypes has been evaluated taking into account functionality and reliability. Table 20 shows relevant data of all the tested prototypes for comparison purposes.

Table 20. Analysis and Comparison of the Performance of the Irrigation Runoff Sensors during Qualitative Field Testing

Prototype	Plot #	Times of Being Tested	Times of Successful Tests	Success Rate (Successful test/Total number of tests)	Longest Working Time without Breaking Down	Comments
Paddle Wheel Prototype	1	N/A	N/A	N/A	N/A	The paddle wheel prototypes have encountered various problems preventing them from working properly. Plot 1 never worked while plot 3 kept having clogging issues and water-damage.
	3	1	0	0	N/A	

Table 20. Analysis and Comparison of the Performance of the Irrigation Runoff Sensors during Qualitative Field Testing (Continued)

Prototype	Plot #	Times of Being Tested	Times of Successful Tests	Success Rate (Successful test/Total number of tests)	Longest Working Time without Breaking Down	Comments
Cubic Float Prototype	4	9	9	100%	15 Weeks	The cubic float prototypes could work for a long time without maintenance. During the 4-month testing period, no problem has been detected.
	5	9	9	100%	16 Weeks	
Elbow Float Prototype	9	4	3	75%	3 Weeks	The elbow float prototype has had a problem of clogging and thus needed a maintenance biweekly. The vertical float sensor finally broke down after 3 weeks.
Conductivity Prototype	2	9	7	77.8%	8 Weeks	The conductivity prototypes have had problems of rusting and clogging, which needed biweekly maintenance. The conductivity prototypes have also shown the capability of working reliably and properly for a long time with appropriate maintenance.
	6	9	9	100%	16 Weeks	

Taken the performance of different prototypes into consideration, the cubic float prototype and the conductivity prototype have been selected for the quantitative field testing phase.

4.3 Quantitative Field Testing Results of the Cubic Float and Conductivity Prototypes

The cubic float prototype and the conductivity prototype have been selected out of the four prototypes for the quantitative field testing based on their performance during the qualitative field testing phase. During quantitative field testing, each plot has been irrigated for 30 minutes including the control plot. The amount of irrigation water and the runoff of water have been calculated by the water meters in the field. Then the amount of runoff of the irrigation sensor plot and the control plot have been compared to show the capability of reducing runoff.

4.3.1 Quantitative Field Testing Results for Sept 17th 2015

A conductivity prototype has been installed in plot 15 while a control plot (plot 18) was used during each test for comparison purposes. The irrigation specifications have been listed, as shown in Table 21.

Table 21. Irrigation Specifications of Test on Sept 17th 2015

Start Time	8:00 AM
Effective Irrigation Time (EIT)	30 minutes
Wait Time (WT)	20 minutes
# of Tested Plot	15 (Conductivity Prototype), 18 (Control)

The results are shown in Figures 152 - 156.

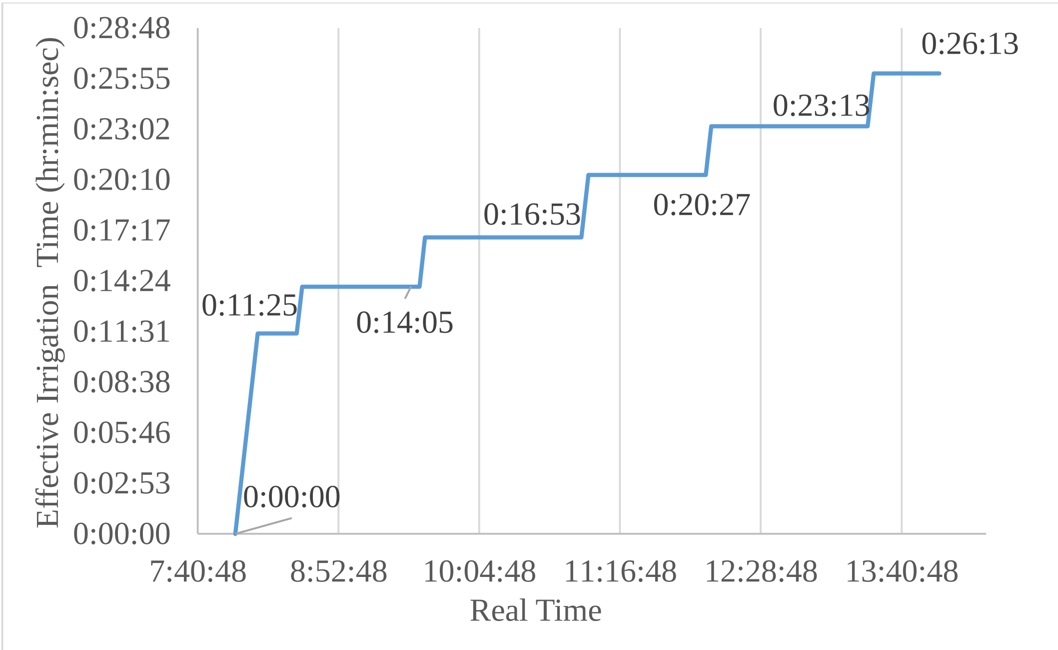

Figure 152. Plot 15 (Conductivity Prototype) Irrigation Results on Sept 17th 2015

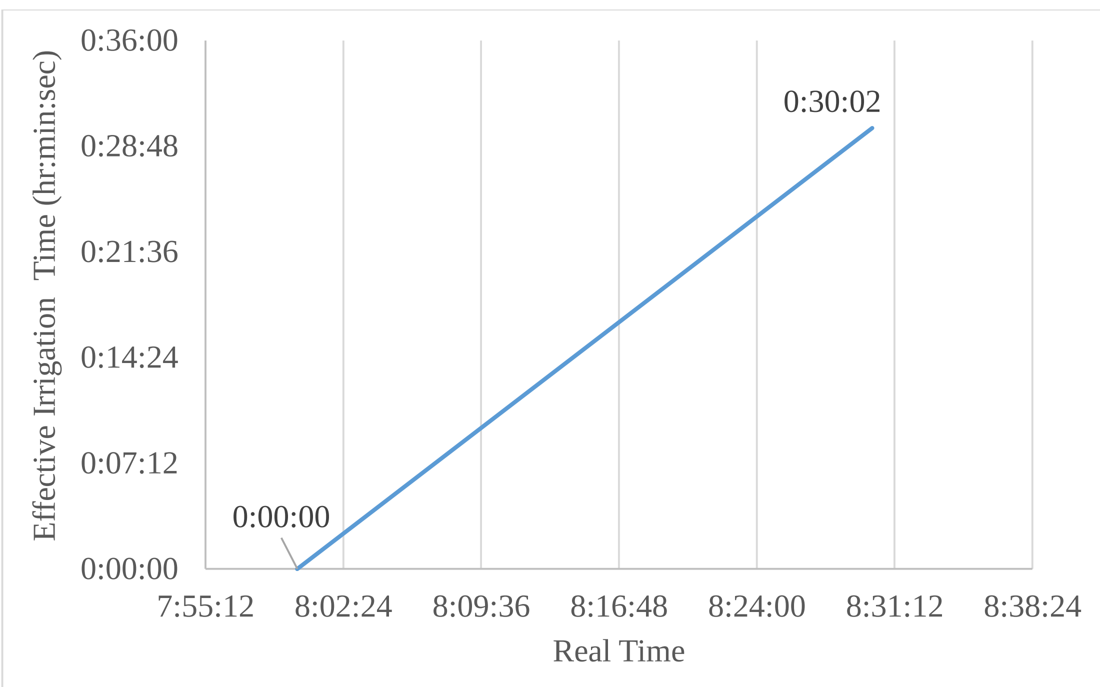

Figure 153. Plot 18 (Control) Irrigation Results on Sept 17th 2015

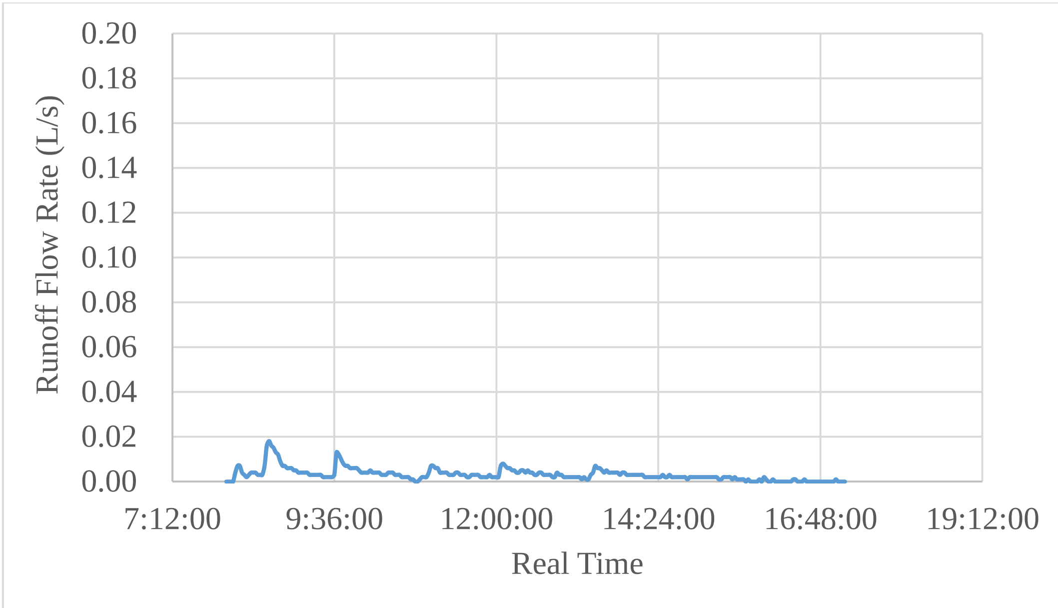

Figure 154. Runoff Flow Rate of Plot 15 (Conductivity Prototype) on Sept 17th 2015

(Scale: 0 to 0.2 L/s)

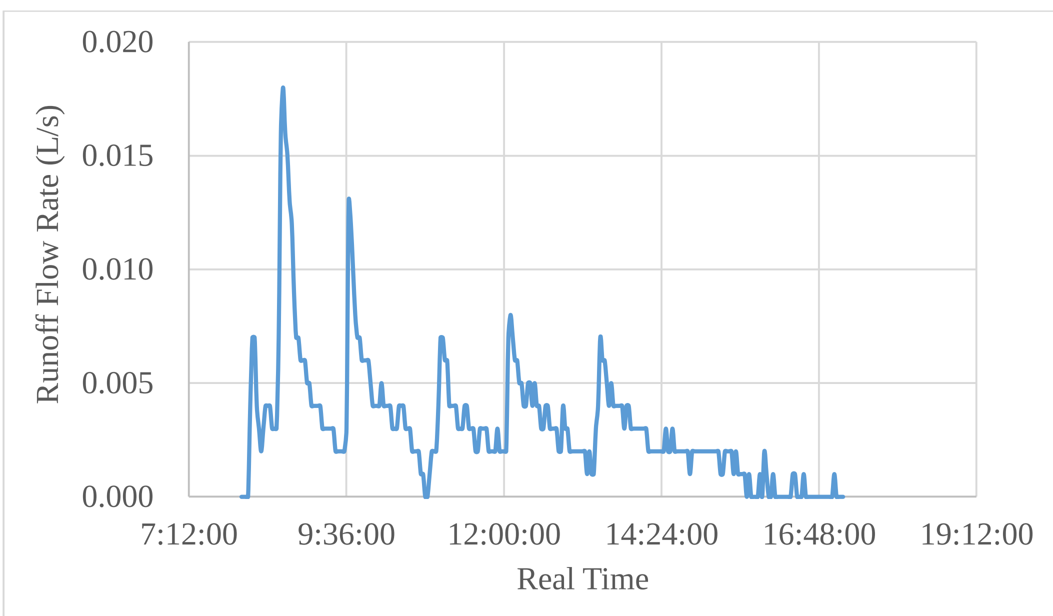

Figure 155. Runoff Flow Rate of Plot 15 (Conductivity Prototype) on Sept 17th 2015

(Scale: 0 to 0.02 L/s)

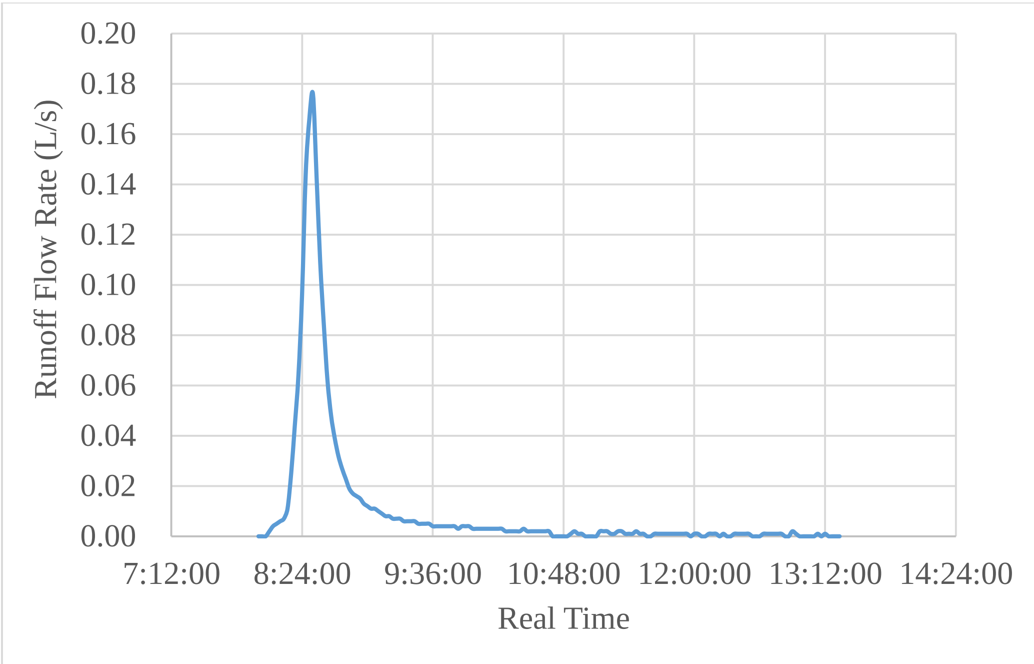

Figure 156. Runoff Flow Rate of Plot 18 (Control) on Sept 17th 2015

(Scale: 0 to 0.2 L/s)

The total amount of the used water, runoff and the water absorbed by the field are listed in Table 22.

Table 22. Water Usage and Runoff Analysis of Irrigation on Sept 17th 2015

	Real Irrigation Time, RIT (hr:min:sec)	Total Amount of Used Water (Gallon)[1]	Runoff (Gallon)	Runoff Rate: (Runoff / Total Use)	Water Absorbed by Soil (Gallon)	Water Absorption Rate: (Water Absorbed / Total Use)	% of Runoff Reduction[2]
Plot 15 (Conductivity Prototype)	5:26:32	217	27.07	12.5%	189.93	87.5%	46.5%
Plot 18 (Control)	0:30:02	229	53.38	23.3%	175.62	76.7%	

Note:

(1) Total amount of water used by Plots 15 and 18 is within 5.2% of each other.

(2) % of Runoff Reduction was calculated as follows:

$$\%\text{ of Runoff Reduction} = \frac{\left(\text{Runoff Rate}_{Control} - \text{Runoff Rate}_{Experimental}\right)}{\text{Runoff Rate}_{Control}} \cdot 100\%$$

Based on the results shown in Figures 152 - 156 and Table 22, the conductivity prototype resulted in a shorter effective irrigation time (EIT) when compared to the control plot because the total allowable window (TAW) was reached before EIT had been reached. The conductivity prototype resulted in a 46.5% reduction in runoff and a higher water absorption rate as shown in Table 22. Moreover, the smaller EIT has shown the capability of the conductivity prototype to prevent over-irrigation by appropriately setting the EIT and TAW. The conductivity prototype has allowed much longer time for the irrigation, which can prevent nutrients and other important lawn components from being flushed by the runoff.

4.3.2 Quantitative Field Testing Results for Sept 19th 2015

A conductivity prototype has been installed in plot 15 while a control plot (plot 18) was used during each test for comparison purposes. The effective irrigation time has been set to 15 minutes for the first test, with a 15-minute test starting one hour after the end of the first test. The irrigation specifications are listed in Table 23.

Table 23. Irrigation Specifications of Test on Sept 19th 2015

Start Time	7:55 AM (1st Test) 10:50 AM (2nd Test)
Effective Irrigation Time (EIT)	15 minutes for each test
Wait Time (WT)	10 minutes
# of Tested Plot	15 (Conductivity Prototype), 18 (Control)

The results for the two 15-minute tests are shown in Figures 157 - 163.

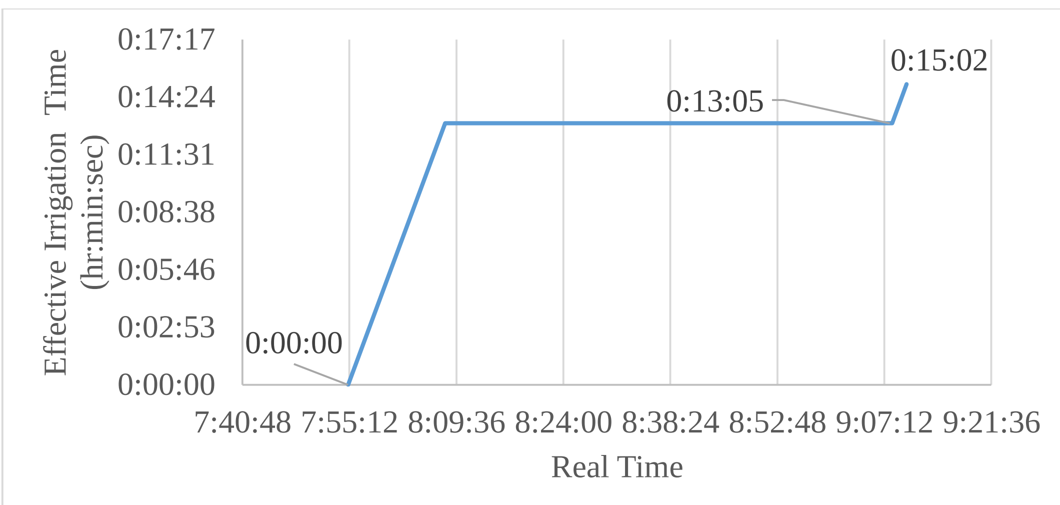

Figure 157. Plot 15 (Conductivity Prototype) Irrigation Results of the First 15-Minute Test on Sept 19th 2015

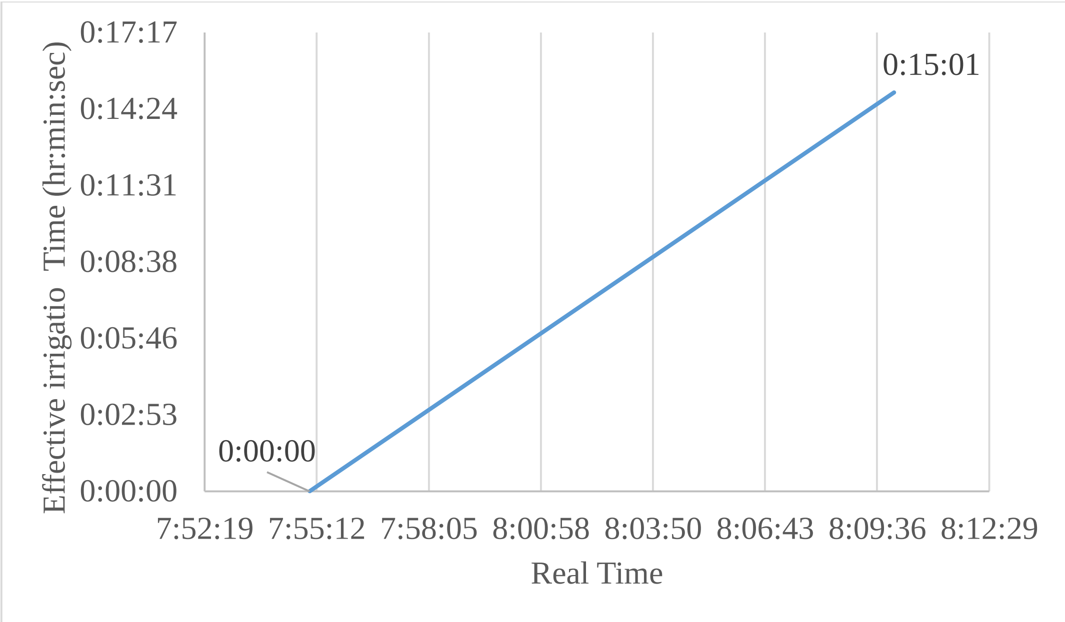

Figure 158. Plot 18 (Control) Irrigation Results of the First 15-Minute Test on Sept 19th 2015

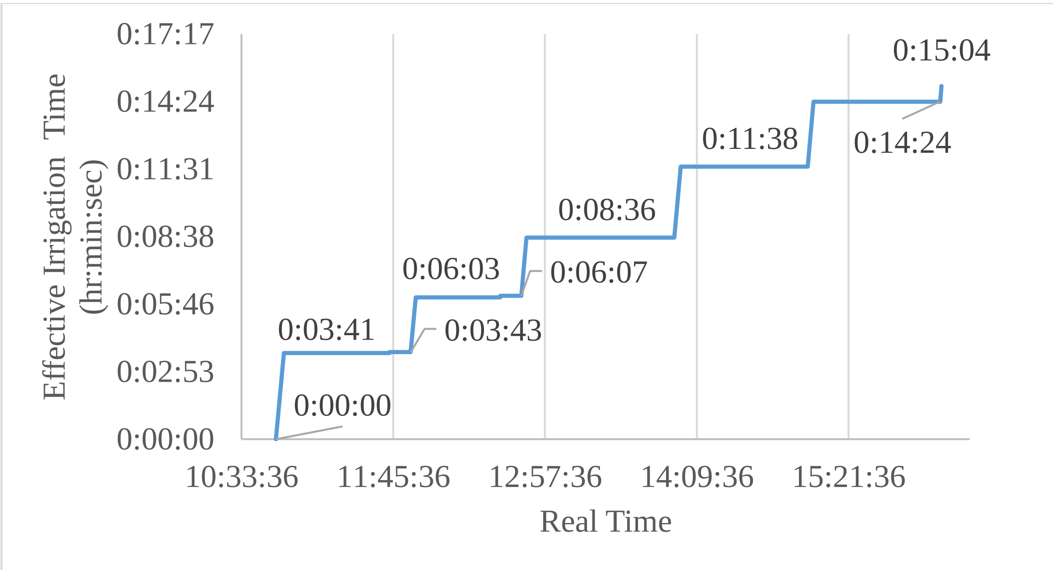

Figure 159. Plot 15 (Conductivity Prototype) Irrigation Results of the Second 15-Minute Test on Sept 19th 2015

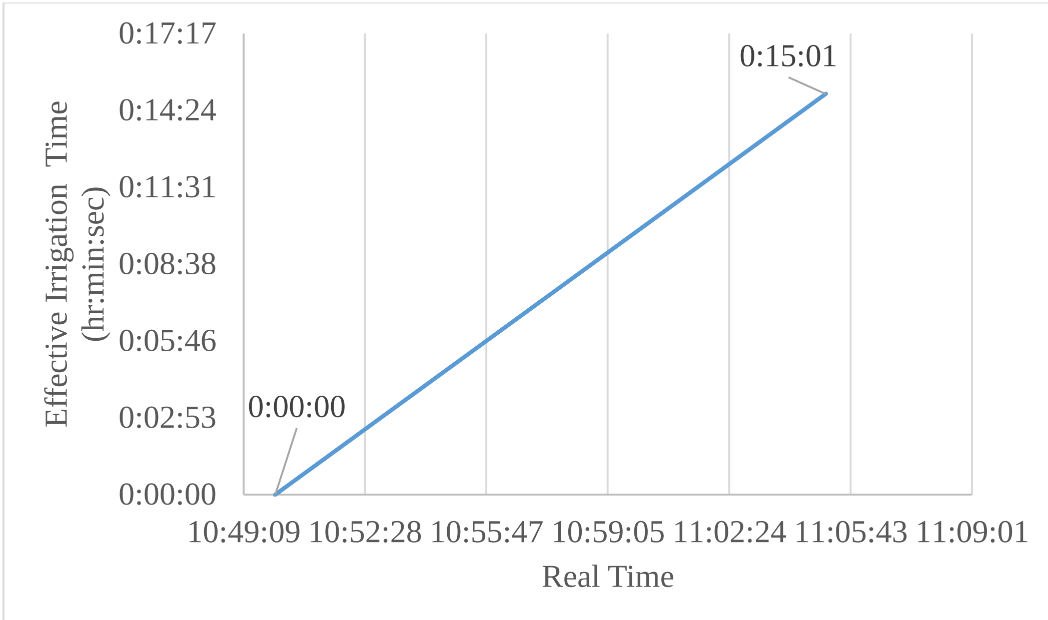

Figure 160. Plot 18 (Control) Irrigation Results of the Second 15-Minute Test on Sept 19th 2015

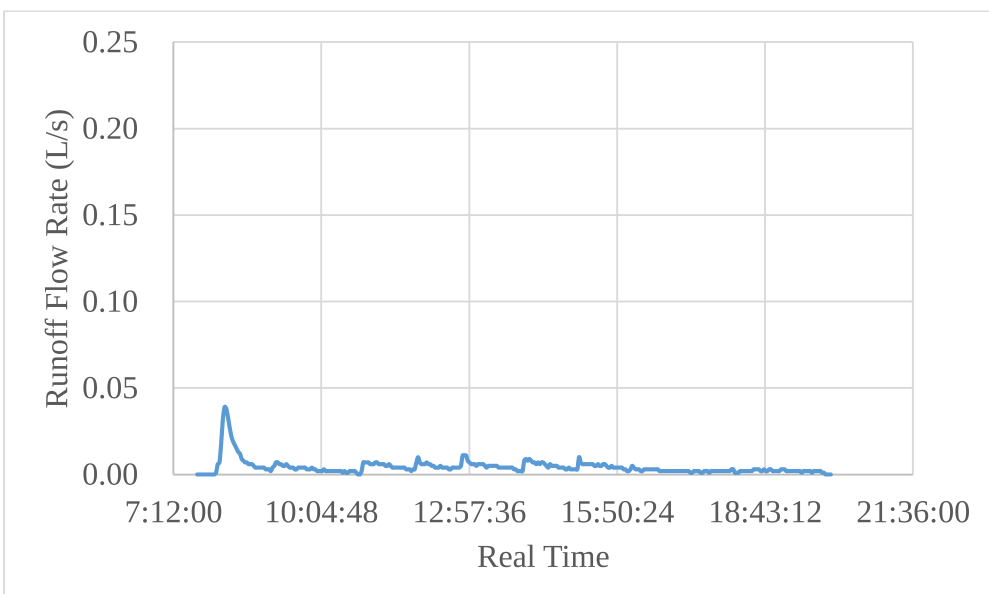

Figure 161. Runoff Flow Rate of Plot 15 (Conductivity Prototype) on Sept 19th 2015

(Scale: 0 to 0.25 L/s)

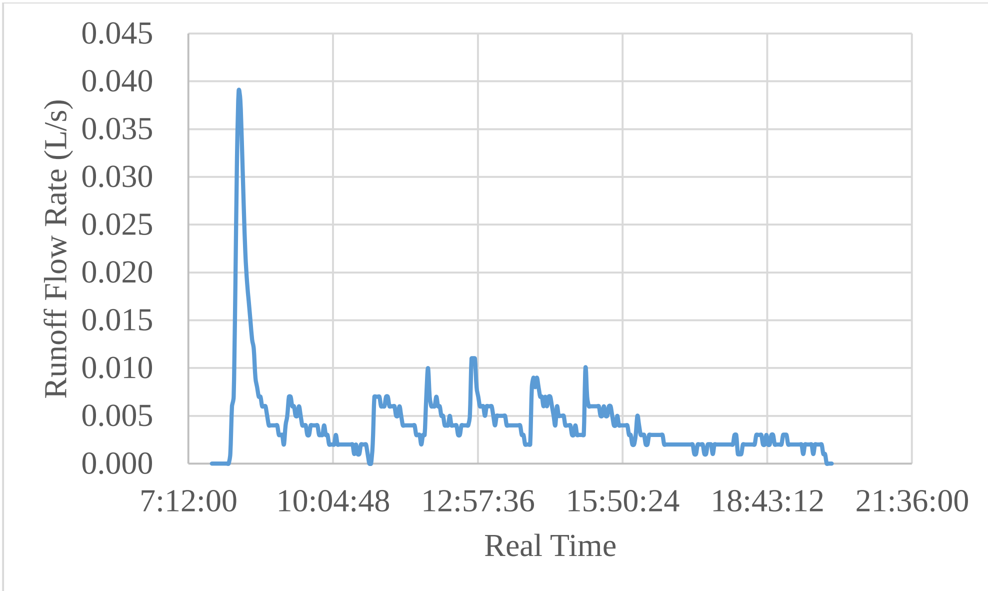

Figure 162. Runoff Flow Rate of Plot 15 (Conductivity Prototype) on Sept 19th 2015

(Scale: 0 to 0.045 L/s)

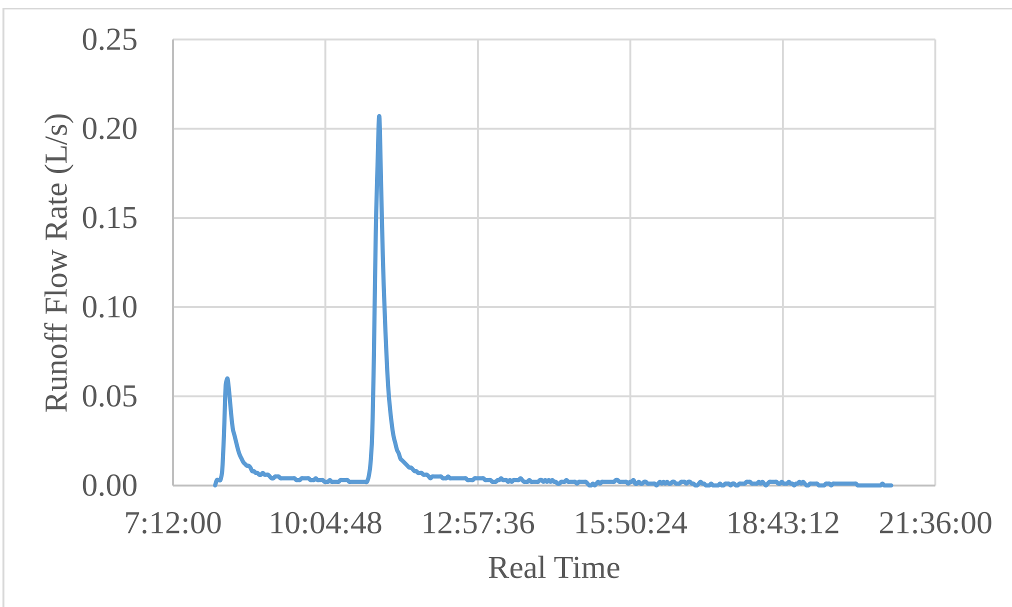

Figure 163. Runoff Flow Rate of Plot 18 (Control) on Sept 19th 2015

(Scale: 0 to 0.25 L/s)

The total amount of the used water, the runoff and the water absorbed by the field for both two tests have been listed. Also, the results of combining the two tests together (Effective irrigation time = 30 minutes) have also been listed, as shown in Table 24.

Table 24. Water Usage and Runoff Analysis of Irrigation on Sept 19th 2015

		Real Irrigation Time, RIT (hr:min:sec)	Total Amount of Used Water (Gallon)	Runoff (Gallon)	Runoff Rate: (Runoff / Total Use)	Water Absorbed by Soil (Gallon)	Water Absorption Rate: (Water Absorbed/Total Use)	% of Runoff Reduction[4]
First Test (EIT: 15 minutes)[1]	Plot 15 (Conductivity Prototype)	1:15:11	120	17.23	14.4%	102.77	85.6%	24.1%
	Plot 18 (Control)	0:15:01	115	21.75	18.9%	93.25	81.1%	
Second Test (EIT: 15 minutes)[2]	Plot 15 (Conductivity Prototype)	5:15:44	122	33	27.1%	89	73.0%	49.1%
	Plot 18 (Control)	0:15:01	116	61.66	53.2%	54.34	46.8%	
Total (EIT: 30 minutes)[3]	Plot 15 (Conductivity Prototype)	6:30:12	242	50.23	20.8%	191.77	79.2%	42.5%
	Plot 18 (Control)	0:30:02	231	83.41	36.1%	147.59	63.9%	

Note:

(1) Total amount of water used by Plots 15 and 18 during the first test is within 4.3% of each other.

(2) Total amount of water used by Plots 15 and 18 during the second test is within 4.9% of each other.

(3) Total amount of water used by Plots 15 and 18 during the two tests is within 4.8% of each other.

(4) % of Runoff Reduction was calculated as follows:

$$\%\text{ of Runoff Reduction} = \frac{\left(\text{Runoff Rate}_{Control} - \text{Runoff Rate}_{Experimental}\right)}{\text{Runoff Rate}_{Control}} \cdot 100\%$$

Based on the results, the conductivity prototype and the control plot have allowed similar effective irrigation time, leading to the similar total amount of water being used by each plot. However, the conductivity prototype has resulted in a 24.1% reduction of runoff in the first 15 minutes test, while the reduction rate grows to 49.1% in the second 15 minutes test. When combing the two tests together, the effective irrigation time is 30 minutes and the runoff reduction rate then is 42.5%. Moreover, the tests have also shown that the conductivity prototype has led to a higher runoff reduction rate during the longer irrigation period which helped keep the soil wetter for a longer period of time.

4.3.3 Quantitative Field Testing Results for Sept 21st 2015

A conductivity prototype has been installed in plot 15 while a control plot (plot 18) was used during each test for comparison purposes. The irrigation specifications have been listed, as shown in Table 25.

Table 25. Irrigation Specifications of Test on Sept 21st 2015

Start Time	7:20 AM
Effective Irrigation Time (EIT)	30 minutes
Wait Time (WT)	10 minutes
# of Tested Plot	15 (Conductivity Prototype), 18 (Control)

The results have been shown in Figures 164 - 168.

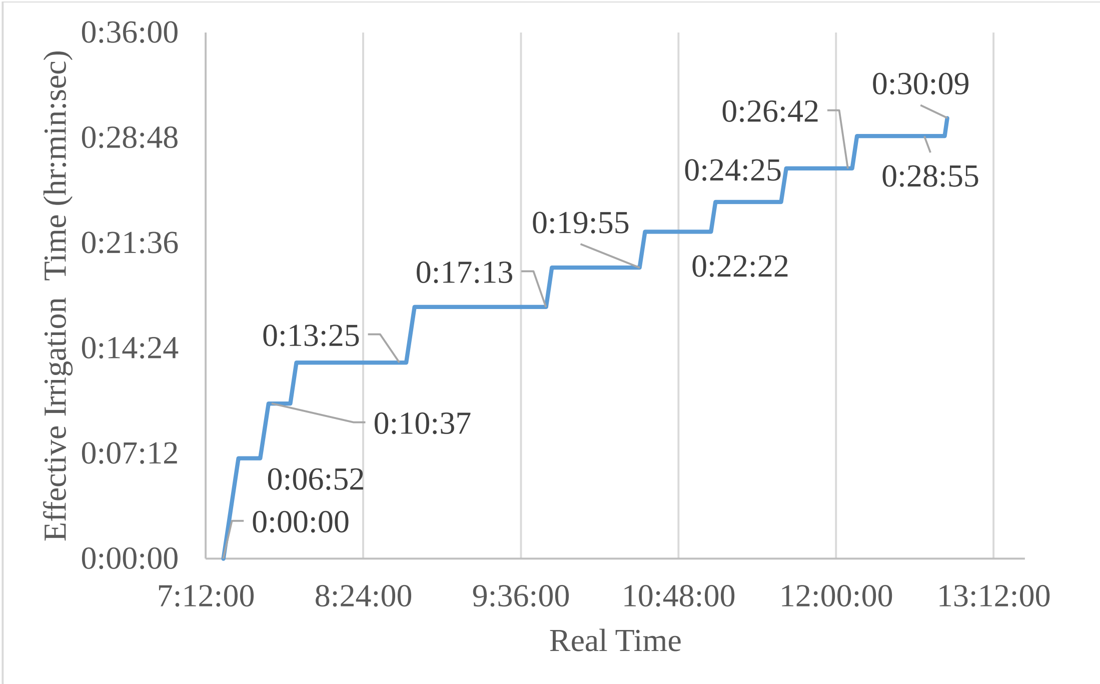

Figure 164. Plot 15 (Conductivity Prototype) Irrigation Results on Sept 21st 2015

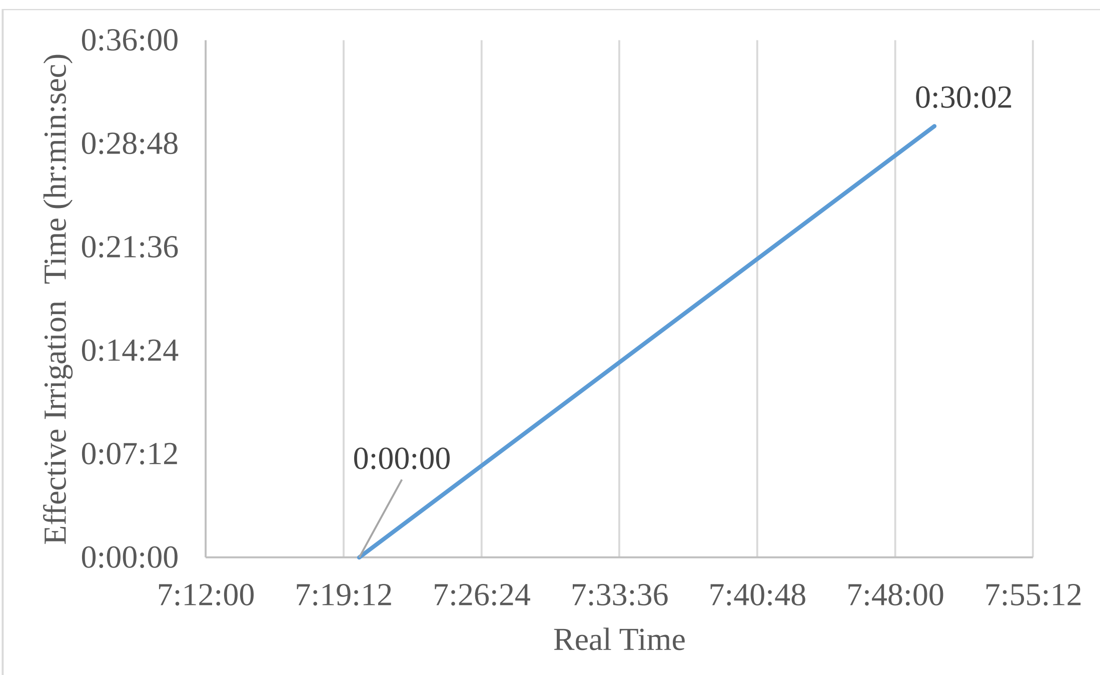

Figure 165. Plot 18 (Control) Irrigation Results on Sept 21st 2015

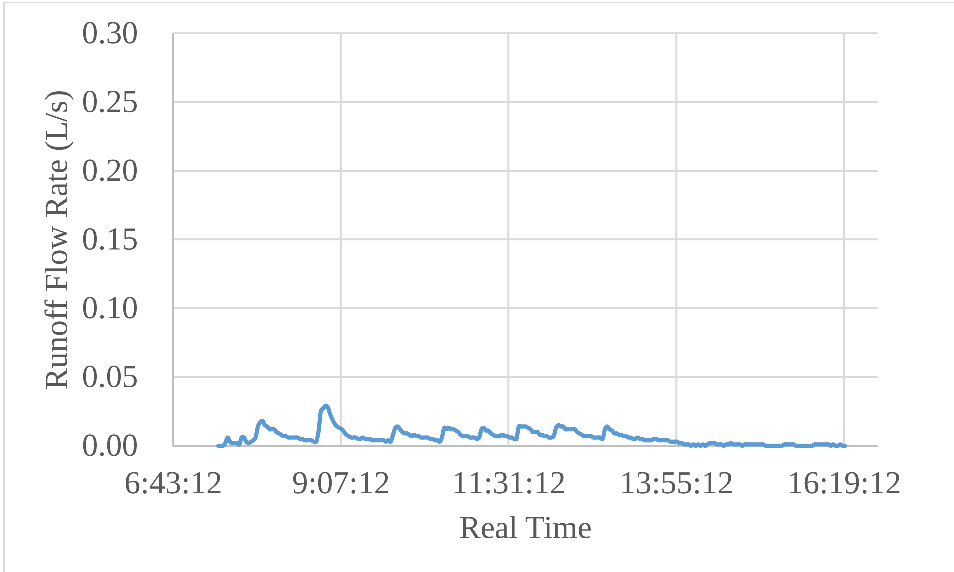

Figure 166. Runoff Flow Rate of Plot 15 (Conductivity Prototype) on Sept 21st 2015

(Scale: 0 to 0.3 L/s)

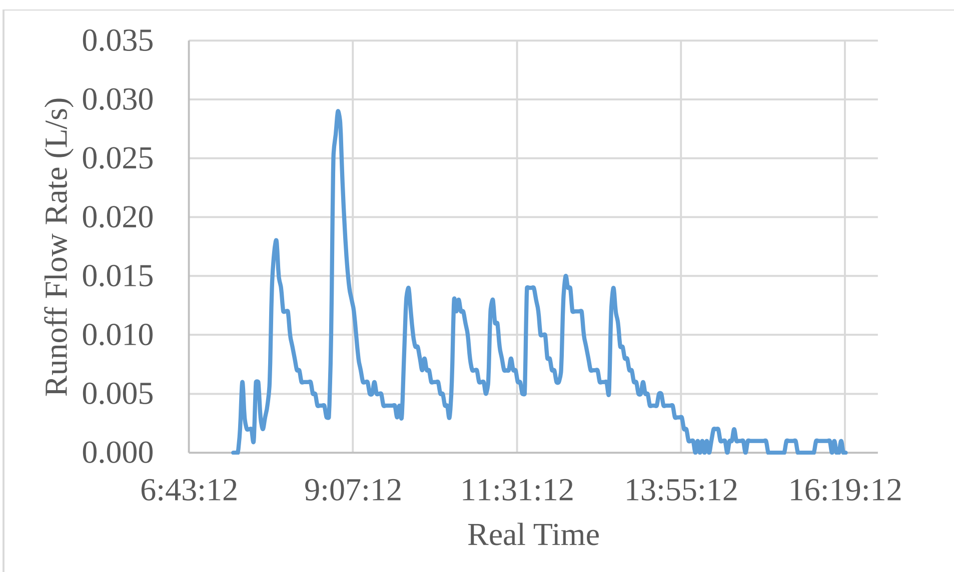

Figure 167. Runoff Flow Rate of Plot 15 (Conductivity Prototype) on Sept 21st 2015

(Scale: 0 to 0.035 L/s)

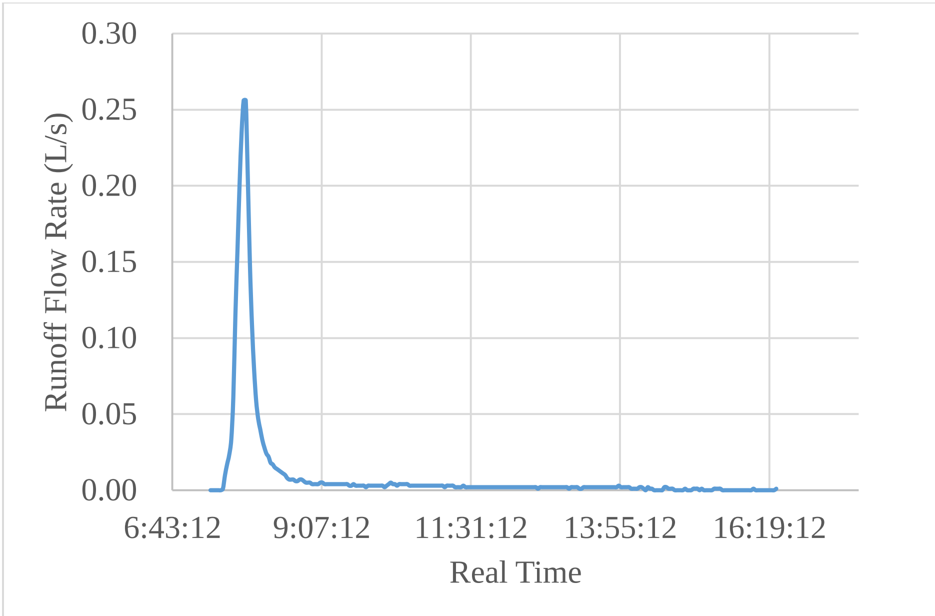

Figure 168. Runoff Flow Rate of Plot 18 (Control) on Sept 21st 2015

(Scale: 0 to 0.3 L/s)

The total amount of the used water, the runoff and the water absorbed by the field have been listed, as shown in Table 26.

Table 26. Water Usage and Runoff Analysis of Irrigation on Sept 21st 2015

	Real Irrigation Time, RIT (hr:min:sec)	Total Amount of Used Water (Gallon)[1]	Runoff (Gallon)	Runoff Rate: (Runoff / Total Use)	Water Absorbed by Soil (Gallon)	Water Absorption Rate: (Water Absorbed/Total Use)	% of Runoff Reduction[2]
Plot 15 (Conductivity Prototype)	5:30:53	237	51.55	21.8%	185.45	78.2%	43.0%
Plot 18 (Control)	0:30:02	231	88.13	38.2%	142.87	61.8%	

Note:

(1) Total amount of water used by Plots 15 and 18 is within 2.6% of each other.

(2) % of Runoff Reduction was calculated as follows:

$$\%\text{ of Runoff Reduction} = \frac{\left(\text{Runoff Rate}_{Control} - \text{Runoff Rate}_{Experimental}\right)}{\text{Runoff Rate}_{Control}} \cdot 100\%$$

From the results, both plots have had a 30 minutes effective irrigation. The conductivity prototype have shown the capability of reducing the runoff by 43.0% and leads to a higher water absorption rate. The conductivity prototype has allowed 5 additional hours longer of irrigation, but in a manner that minimizes runoff, which prevents nutrients from being flushed by the runoff.

4.3.4 Quantitative Field Testing Results for Sept 25th 2015

A cubic float prototype has been installed in plot 15 while a control plot (plot 18) was used during each test for comparison purposes. The irrigation specifications have been listed, as shown in Table 27.

Table 27. Irrigation Specifications of Test on Sept 25th 2015

Start Time	6:00 AM
Effective Irrigation Time (EIT)	30 minutes
Wait Time (WT)	10 minutes
# of Tested Plot	15 (Cubic Float Prototype), 18 (Control)

The results have been shown in Figures 169 - 173.

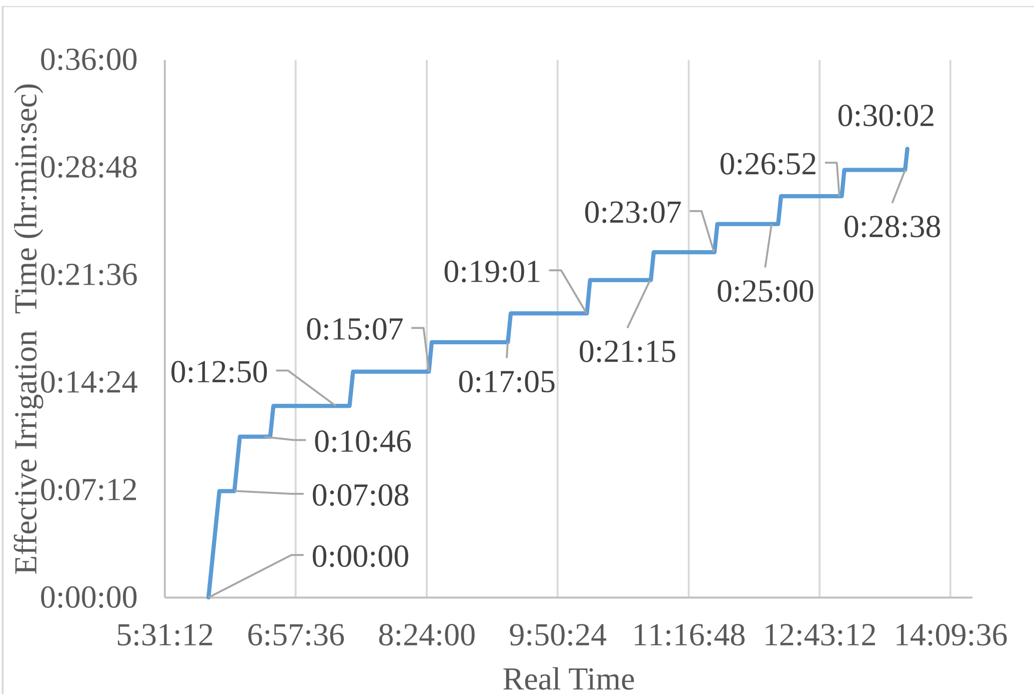

Figure 169. Plot 15 (Cubic Float Prototype) Irrigation Results on Sept 25th 2015

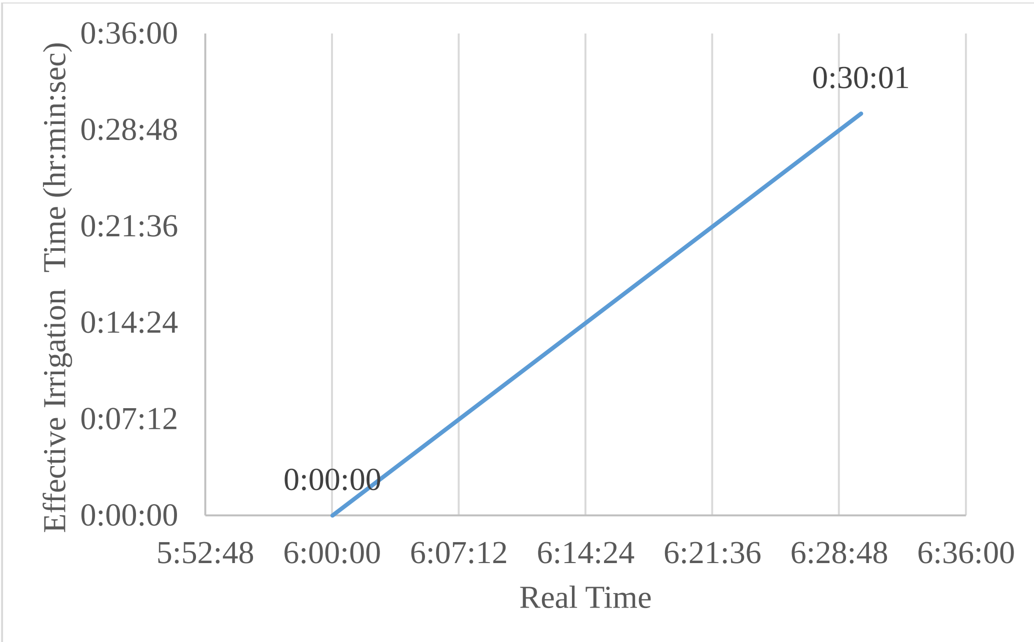

Figure 170. Plot 18 (Control) Irrigation Results on Sept 25th 2015

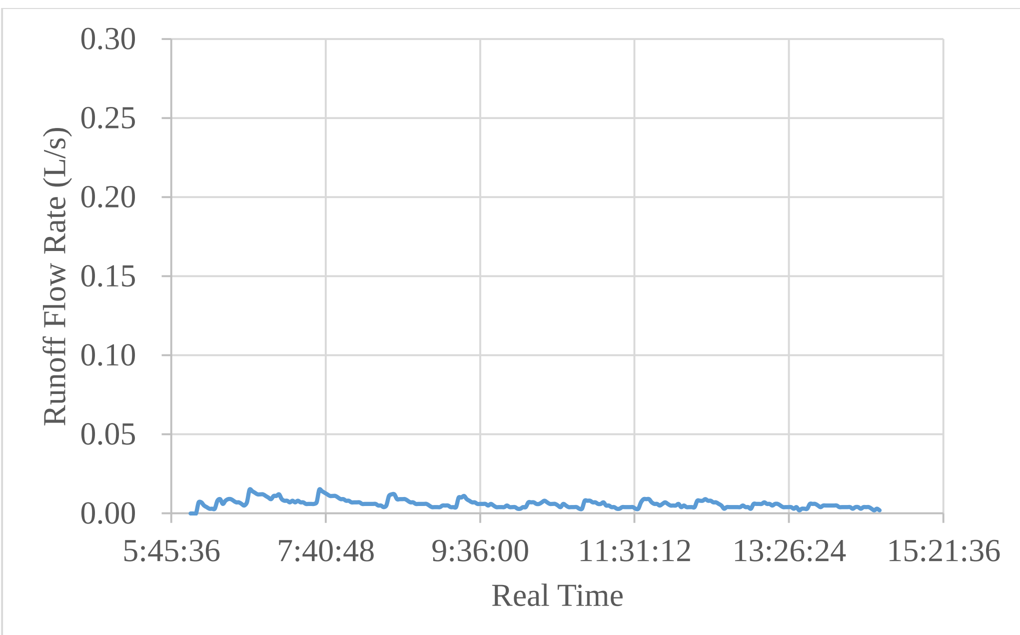

Figure 171. Runoff Flow Rate of Plot 15 (Cubic Float Prototype) on Sept 25th 2015

(Scale: 0 to 0.3 L/s)

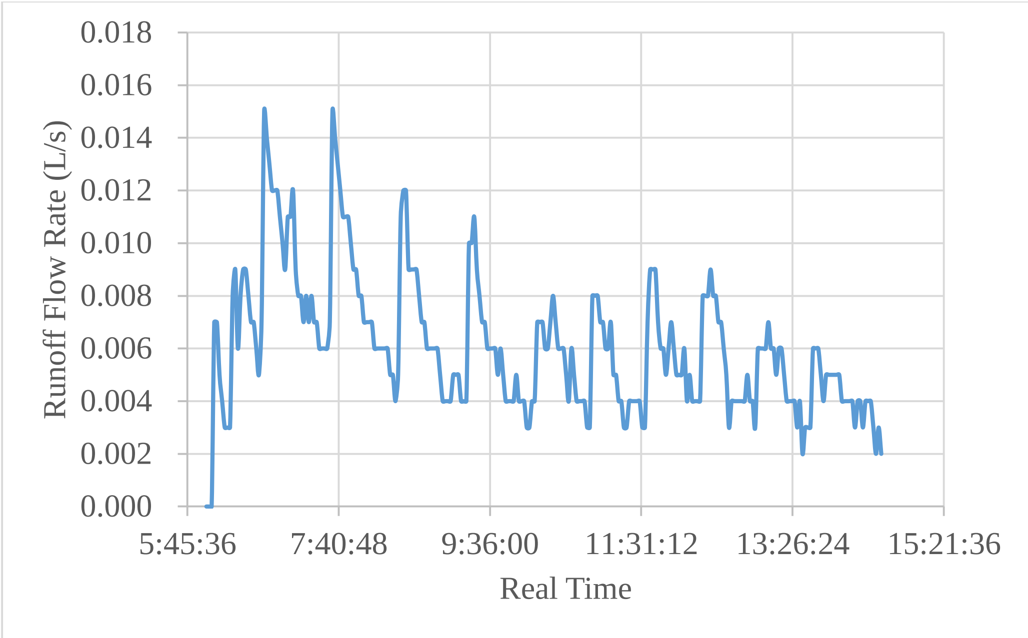

Figure 172. Runoff Flow Rate of Plot 15 (Cubic Float Prototype) on Sept 25th 2015

(Scale: 0 to 0.018 L/s)

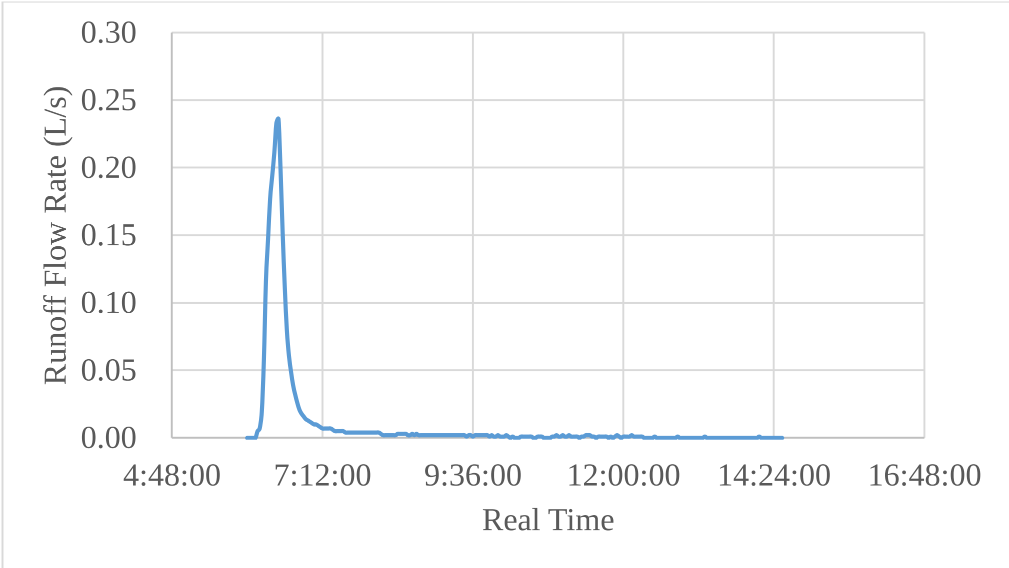

Figure 173. Runoff Flow Rate of Plot 18 (Control) on Sept 25th 2015

(Scale: 0 to 0.3 L/s)

The total amount of the used water, the runoff and the water absorbed by the field have been listed, as shown in Table 28.

Table 28. Water Usage and Runoff Analysis of Irrigation on Sept 25th 2015

	Real Irrigation Time, RIT (hr:min:sec)	Total Amount of Used Water (Gallon)[1]	Runoff (Gallon)	Runoff Rate: (Runoff / Total Use)	Water Absorbed by Soil (Gallon)	Absorption Rate: (Water Absorbed/Total Use)	% of Runoff Reduction[2]
Plot 15 (Cubic Float Prototype)	7:41:02	241	49.8	20.7%	191.2	79.3%	44.3%
Plot 18 (Control)	0:30:01	223	82.77	37.1%	140.23	62.9%	

Note:

(1) Total amount of water used by Plots 15 and 18 is within 8.1% of each other.

(2) % of Runoff Reduction was calculated as follows:

$$\text{\% of Runoff Reduction} = \frac{\left(\text{Runoff Rate}_{Control} - \text{Runoff Rate}_{Experimental}\right)}{\text{Runoff Rate}_{Control}} \cdot 100\%$$

Based on the results, both plots have had a 30 minutes of effective irrigation. The cubic float prototype have shown the capability of reducing the runoff by 44.3%, while more water has been allowed to be absorbed by soil. The float prototype has allowed an even longer time for irrigation, compared to the conductivity one. It has also increased the water absorption rate, which is similar to the conductivity prototype.

In general, both prototypes are capable of reducing runoff while increasing the amount of water being absorbed by the plots. However, the cubic float prototype did not experience clogging or rust problems. Furthermore, the electronic system that supports the irrigation and runoff systems were able to perform flawlessly during all the quantitative tests.

5. CONCLUSION

A Landscape Irrigation Runoff Mitigation System (LIRMS) was designed, built and field-tested for minimizing irrigation water losses from residential or commercial landscapes. Future work should focus on investigating more water conservation strategies.

5.1 Conclusions of the Design, Construction and Performance Testing of the Landscape Irrigation Runoff Mitigation System

A Landscape Irrigation Runoff Mitigation System (LIRMS) was designed, built and field-tested for minimizing irrigation water losses from residential or commercial landscapes. Four types of irrigation runoff sensors, based on different working principles, were designed and manufactured using common materials and components. Then a central control module capable of receiving signals from sensors and controlling several irrigation valves at the same time was designed, built and tested. Afterwards, the prototypes were installed in the field and hardwired with the central control module along with two control plots that had no runoff sensors installed. The different types were evaluated based on their performance characteristics including the ability of each prototype to work reliably over an extended period of time. The conductivity prototype and the cubic float prototype showed to be stable, reliable and functional. These two types of prototypes were then used in the field for the quantitative field testing phase. The amount of runoff of the prototypes were recorded and compared, leading to the final selection of the irrigation runoff sensor prototype. The conductivity prototype resulted in 40% - 50% reduction in runoff and 10% - 30% increase in water absorption by soil based on a 30 minutes effective irrigation. The cubic float prototype showed the ability of reducing runoff by 45% and allowed greater water absorption.

A web-based interface (i.e. server) was designed and programmer so that irrigation data could be accessed online. Also, a wireless communication module and an autonomous energy system were designed and tested to allow wireless communication between the irrigation runoff sensors and the control unit which also allowed for energy savings.

The cubic float prototype was tested and used for a longer irrigation time. The conductivity prototype resulted in a higher runoff reduction rate. The main requirements of the devices were met in term of being inexpensive, reliable and durable during the field-testing phase. The Landscape Irrigation Runoff Mitigation System (LIRMS) equipped with the cubic float prototype/conductivity prototype showed the great capability for water conservation.

5.2 Future Work

Further studies should focus on investigating different irrigation strategies for runoff reduction, grass quality and economic benefits. Equipped with advanced strategies, the current LIMRS system could greatly improve the irrigation results while preserving lawn quality.

5.2.1 Reduction of Effective Irrigation Time

Based on the results of the tests during the quantitative field testing phase, it has been shown that more water has been absorbed by the experimental plot (the plot with the irrigation runoff sensor prototype) than the control plot during the same effective irrigation time (EIT). Thus, the effective irrigation time of the experimental plot could be reduced in order to maintain the same quality of the grass as the control plot by reducing the level of water absorption for the same weekly irrigation frequencies. The suggested tests' specifications and changes have been listed, as shown in Table 29.

Table 29. Changes of Specifications between the Experimental and Control Plots: Reduction of Effective Irrigation Time

	Experimental Group	Control Group
Effective Irrigation Time	EIT < 30 minutes	30 minutes
Weekly Irrigation Frequency (WIF)	1/Week	1/Week
Amount of Water Absorbed	Same	

Further tests should be done to determine the effective irrigation time of the experimental group in order to get the same amount of water absorbed by soil as in the control group.

5.2.2 Reduction of Irrigation Frequency

In order to maintain the same quality of grass of the experimental and the control plots, the weekly irrigation frequency of the experimental plot can be reduced while the effective irrigation time of every irrigation event remains the same. As a result, the experimental plot will have the same amount of water absorption with the control plot, which can further reduce the total amount of water usage and the runoff. The tests' specifications and changes have been listed, as shown in Table 30.

Table 30. Changes of Specifications between the Experimental and Control Plots: Reduction of Irrigation Frequency

	Experimental Group	Control Group
Effective Irrigation Time	30 minutes	30 minutes
Weekly Irrigation Frequency (WIF)	WIF < 1/Week	1/Week
Amount of Water Absorbed	Same	

Further tests should be done to determine the irrigation frequency of the experimental group in order to get the same amount of water absorbed by soil as in the control group.

5.2.3 Self-Adjustable LIRMS for Minimum Runoff

An intelligent controller module with autonomous learning abilities should be considered in the future. The control module should be able to correlate runoff time and total irrigation time so an optimum EIT can be identified by using historical irrigation data. The intelligent controller should adjust the time between the start of the irrigation (SI) and the time of runoff detection referred as the Runoff Detection Time (RDT), so that the time between detection and disappearance of runoff referred as Runoff Existing Time (RET) can be minimized. The real irrigation time represents the time when the irrigation system is in operation. Several case scenarios are shown in Table 31.

Table 31. Case Scenarios of the LIRMS System with Autonomous Learning Ability

	Real Irrigation Time	RDT	RET
1st Trial	30 minutes	30 minutes	4 minutes
2nd Trial	28 minutes	40 minutes	2 minutes
3rd Trial	26 minutes	45 minutes	1 minute

The LIMRS system with a new intelligent control module should be installed in the field. For the first irrigation cycle, the system irrigates the field for 30 minutes and then detects runoff. The runoff is assumed to last 4 minutes. Thus the RDT is 30 minutes while the RET is 4 minutes. During the second irrigation case scenario, the LIRMS system should have taught itself to reduce the irrigation time (i.e. to 28 minutes), so runoff occurs after 40 minutes or more from the start of the irrigation. During the third test, the irrigation time is set to be 26 minutes, runoff is assumed to be detected after 45 minutes from the start of the irrigation while the RET is detected to be 1 minute. Optimally, the LIRMS system should keep adjusting RDT and RET, with the ultimate goal of maximizing RDT while minimizing RET. Further water savings are expected with the procedures of autonomous learning, as outlined above.

REFERENCES

[1] Wherley, B., J. Alvarado, R. White, J. Thomas, J. Men, F. Jaber, C. Reynolds, and R. Wooley. 2015. Method and System for Reduction of Irrigation Runoff. Provisional Patent Application. Attorney Docket No. 13260-P069V1. *Filed July 2015.*

[2] *Water for Texas, 2012*. Austin, Tex.: Texas Water Development Board, 2012. Print.

[3] Cabrera, Raul, Kevin Wagner, and Benjamin Wherley. "An Evaluation of Urban Landscape Water Use in Texas." *Texas Water Journal* 4.2 (2013): 14-27. Print.

[4] "Outdoor Water Use in the United States." *EPA*. Environmental Protection Agency. Web. <http://www.epa.gov/watersense/pubs/outdoor.html>.

[5] Haley, Melissa B., Michael D. Dukes, and Grady L. Miller. "Residential Irrigation Water Use in Central Florida." *Journal of Irrigation and Drainage Engineering J. Irrig. Drain Eng.* 133.5 (2007): 427-34. Print.

[6] Pannkuk, Tim, & Lawrence A. Wolfskill. "Residential outdoor water use in one East Texas community." *Texas Water Journal* [Online], 6.1 (2015): 79-85. Web. 13 July 2015.

[7] Gardner, Ron. "The Problem of Runoff." *Pesticide Environmental Stewardship*. Web. <http://pesticidestewardship.org/water/Pages/Runoff.aspx>.

[8] Weibel, S. R., and Robert J. Anderson. *Urban Land Runoff as a Factor in Stream Pollution*. Cincinnati: U.S. Dept. of Health, Education, and Welfare, Public Health Service, R.A. Taft Sanitary Engineering Center, 1963. Print.

[9] Wherley, Benjamin G., Jacqueline A. Aitkenhead-Peterson, Nina C. Stanley, James C. Thomas, Charles H. Fontanier, Richard H. White, and Phil Dwyer. "Nitrogen Runoff Losses during Warm-Season Turfgrass Sod Establishment." *Journal of Environment Quality* (2015): 1137-147. Print.

[10] Gromairemertz, M., S. Garnaud, A. Gonzalez, and G. Chebbo. "Characterisation of Urban Runoff Pollution in Paris." *Water Science and Technology* 39.2 (1999): 1-8. Print.

[11] Kimbrough, Robert A., and David W. Litke. "Pesticides in Streams Draining Agricultural and Urban Areas in Colorado." *Environmental Science & Technology Environ. Sci. Technol.* 30.3 (1996): 908-16. Print.

[12] Weston, D.p., R.w. Holmes, and M.j. Lydy. "Residential Runoff as a Source of Pyrethroid Pesticides to Urban Creeks." *Environmental Pollution* 157 (2009): 287-94. Print.

[13] Hoffman, Eva J., Gary L. Mills, James S. Latimer, and James G. Quinn. "Urban Runoff as a Source of Polycyclic Aromatic Hydrocarbons to Coastal Waters." *Environmental Science & Technology Environ. Sci. Technol.* 18 (1984): 580-87. Print.

[14] Gross, C.M., J.S. Angle, and M.S. Welterlen. "Nutrient and Sediment Losses from Turfgrass." *Journal of Environmental Quality (USA)* 4 (1990): 663. *AGRIS*. Print.

[15] Ferguson, Bruce K. "Water Conservation Methods in Urban Landscape Irrigation: An Exploratory Overview." *Journal of the American Water Resources Association J Am Water Resources Assoc* 23.1 (1987): 147-52. Print.

[16] Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Rome: Food and Agriculture Organization of the United Nations, 1998. 19-25. Print.

[17] Cardenas-Lailhacar, Bernard, and Michael D. Dukes. "Expanding Disk Rain Sensor Performance and Potential Irrigation Water Savings." *Journal of Irrigation and Drainage Engineering J. Irrig. Drain Eng.* 134.1 (2008): 67-73. Print.

[18] Mccready, M.s., M.d. Dukes, and G.l. Miller. "Water Conservation Potential of Smart Irrigation Controllers on St. Augustinegrass." *Agricultural Water Management* 96 (2009): 1623-632. Print.

[19] NickMillward. "Rain Sensor Problems?" *City Rain*. Web. <http://www.cityraininc.com/rain-sensor-problems/>.

[20] "Rain Sensors on Sprinkler Systems: Save Water and Money." *Exploded Home*. 19 Mar. 2014. Web. <http://www.explodedhome.com/rain-sensors-sprinkler-systems-save-water-money/>.

[21] McGuirk, Steve. "Irrigation Sensors for the Landscape." *Grounds Maintenance*. Web. <http://grounds-mag.com/mag/grounds_maintenance_irrigation_sensors_landscape/>.

[22] *Weather and Soil Moisture Based Landscape Irrigation Scheduling Devices: Technical Review Report*. 5th ed. U.S. Dept. of Interior, Bureau of Reclamation, Lower Colorado Region, Southern California Area Office, 2015. Print.

[23] Wolpert, Jim. "Soil Moisture Sensors." *eXtension*. 22 Feb. 2013. Web. <http://www.extension.org/pages/31515/soil-moisture-sensors#.VeUJ0W5Vi8U>.

[24] "Comparing Smart Irrigation Technologies." *Baseline Systems*. Web. <http://www.baselinesystems.com/mediafiles/pdf/ET_SMS_comparison.pdf>.

[25] Bliss, Daniel J., Ronald D. Neufeld, and Robert J. Ries. "Storm Water Runoff Mitigation Using a Green Roof." *Environmental Engineering Science*: 407-18. Print.

[26] Fassman-Beck, Elizabeth, Emily Voyde, Robyn Simcock, and Yit Sing Hong. "4 Living Roofs in 3 Locations: Does Configuration Affect Runoff Mitigation?" *Journal of Hydrology*: 11-20. Print.

[27] Fassman, Elizabeth A., and Samuel Blackbourn. "Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils." *Journal of Hydrologic Engineering J. Hydrol. Eng.*: 475-85. Print.

[28] Rushton, Betty T. "Low-Impact Parking Lot Design Reduces Runoff and Pollutant Loads." *J. Water Resour. Plann. Manage. Journal of Water Resources Planning and Management*: 172-79. Print.

APPENDIX A

2-D AutoCAD mechanical drawings of the paddle wheel prototype, the cubic float prototype, the elbow float prototype and the conductivity prototype discussed in section 3.2.5 are included as separate files:

PaddleWheel_2D Drawings.DWG

CubicFloat_2D Drawings.DWG

ElbowFloat_2D Drawings.DWG

Conductivity_2D Drawings.DWG

APPENDIX B

Main Program:

```
#include "Arduino.h"
#include "I2C.h"
#include "RTC.h"

#define byte uint8_t
#define DS1307_ADDRESS 0x68

//char mess[128] = {0};

void DateTime::set_time(uint8_t sec, uint8_t minu, uint8_t hr, uint8_t wkday, uint8_t dy, uint8_t mon, uint16_t
yr){
      second = sec;
      minute = minu;
      hour = hr;
      weekday = wkday;
      day = dy;
      month = mon;
      year = yr;
}

uint8_t DateTime::dayofweek(const DateTime& A){
  return A.weekday;
}

byte bcdToDec(byte val)    {
// Convert binary coded decimal to normal decimal numbers
    return ( (val/16*10) + (val%16) );
}


void DateTime::round_time(){
  year = year + (month + (day + (hour + (minute + (second)/60)/60)/24)/30)/12;
  month = (month + (day + (hour + (minute + (second)/60)/60)/24)/30)%12;
  day = (day + (hour + (minute + (second)/60)/60)/24)%30;
  hour = (hour + (minute + (second)/60)/60)%24;
  minute = (minute + (second)/60)%60;
  second = second%60;
}

void DateTime::current_time(){

    I2c.read(0x68, 0x00, 7);

    second = bcdToDec(I2c.receive());
    minute = bcdToDec(I2c.receive());
    hour = bcdToDec(I2c.receive() & 0b111111); //24 hour time
    weekday = bcdToDec(I2c.receive()); //0-6 -> sunday - Saturday
    day = bcdToDec(I2c.receive());
```

```
  month = bcdToDec(I2c.receive());
  year = bcdToDec(I2c.receive());
}

void DateTime::print_time(){
  Serial.print(month);
  Serial.print(F("/"));
  Serial.print(day);
  Serial.print(F("/"));
  Serial.print(year);
  Serial.print(F("   "));
  Serial.print(hour);
  Serial.print(F(":"));
  Serial.print(minute);
  Serial.print(F(":"));
  Serial.print(second);
  Serial.println();
}

void DateTime::logtime(char *time){
  sprintf(time,"%d/%d/%d %d:%d:%d%c",month, day, year, hour, minute, second, '\0');
}

DateTime DateTime::operator+(const DateTime& A){
  /*const int month_days[] = {31,28,31,30,31,30,31,31,30,31,30,31};     //Good till 2016 when next leap year
  DateTime date;
  date.set_time(0,0,0,0,0,0,0);
  date.second = this->second + A.second;
  date.minute = this->minute + A.minute;
  date.hour = this->hour + A.hour;
  date.weekday = this->weekday + A.weekday;
  date.day = this->day + A.day;
  date.month = this->month + A.month;
  date.year = this->year + A.year;
  date.round_time();
  if(date.day >= month_days[date.month])
    date.month+=1;
    date.day/=month_days[date.month];
  return date;*/
  DateTime date;
  date.set_time(0,0,0,0,0,0,0);
  date.second = this->second + A.second;
  date.minute = this->minute + A.minute;
  date.hour = this->hour + A.hour;

  date.round_time();

  return date;
}

DateTime DateTime::operator-(const DateTime& A){
 DateTime right, left;
 right.set_time(0, 0, 0, 0, 0, 0, 0);
 left.set_time(0, 0, 0, 0, 0, 0, 0);
 // this is left, A is right
  right.hour = A.hour;
```

```
    right.minute = A.minute;
    right.second = A.second;
    left.hour = this->hour;
    left.minute = this->minute;
    left.second = this->second;

    if (left.minute < right.minute){
        left.minute+=60;
        --left.hour;
    }
    if(left.second < right.second){
        left.second+=60;
        --left.minute;
    }

    right.hour = left.hour - right.hour;
    right.minute = left.minute - right.minute;
    right.second = left.second - right.second;

    return right;                //Return final DateTime
}


boolean DateTime::operator>=(const DateTime& A){
    // "this" is on the left and "A" on the right

    // No need to irrigate for more than 24 hours
    if (this->hour > A.hour) return 1;
    if (this->hour < A.hour) return 0;
    if (this->minute > A.minute) return 1;
    if (this->minute < A.minute) return 0;
    if (this->second > A.second) return 1;
    return 0;
}
```

SD Card Program:

```
#include <SD.h>
#include "SPI.h"
#include "SDcard.h"

// On the Ethernet Shield, CS is pin 4. Note that even if it's not
// used as the CS pin, the hardware CS pin (10 on most Arduino boards,
// 53 on the Mega) must be left as an output or the SD library
// functions will not work.
const uint8_t SD_CS = 5;
const uint8_t SD_CD = 4;

SDcard::SDcard(){
}

void SDcard::inserted()
{
```

```
   SD_SPI_setup();
   Serial.print(F("Initializing SD card..."));
   // make sure that the default chip select pin is set to
   // output, even if you don't use it:

   // see if the card is present and can be initialized:
   if (!SD.begin(SD_CS)) {
      Serial.println(F("Card failed, or not present"));
      // don't do anything more:
      return;
   }
   Serial.println(F("card initialized."));
}

void SDcard::SD_SPI_setup(){
   SPI.setClockDivider(4);
   SPI.setBitOrder(MSBFIRST);
   SPI.setDataMode(SPI_MODE3);      // Data mode 0, 3 work
}

void SDcard::SD_setup(){
     pinMode(SD_CS, OUTPUT);    // Chip select
     pinMode(SD_CD, INPUT);     // Chip detect
     pinMode(10, OUTPUT);       // Needed for SD library to work correctly
     digitalWrite(SD_CS, HIGH);    // Dectivate SD for setup
     SD_SPI_setup();
}

boolean SDcard::logdata(String dataString, int newline)
{
   SD_SPI_setup();      // Reconfigure SPI settings to be able to read from the card

   // open the file. note that only one file can be open at a time,
   // so you have to close this one before opening another.
   File dataFile = SD.open("datalog.txt", O_CREAT | O_WRITE);    //O_CREAT | O_WRITE

   // if the file is available, write to it:
   if (dataFile) {
      if (newline) dataFile.println(dataString);
      else dataFile.print(dataString);
      dataFile.flush();

      dataFile.close();
      // print to the serial port too:
      return true;    //Data logged without errors
   }
   // if the file isn't open, pop up an error:
   else {
      return false;    // Error with logging data
   }

}


SDcard SDc = SDcard();
```