MODELLING A LOW COST, DATA ACQISITION AND IRRIGATION SEQUENCING SYSTEM FOR A GREENHOUSE ON AN 8 BIT PIC MICROCONTROLLER

A thesis submitted in partial fulfillment of the requirements of the requirements for the award of Degree in Computer Science

Master of Science in computer Science

BY

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Abstract

The debate on climate change is still going on and on, and there is still no convincing evidence that greenhouse gases are the real, real cause of the recent changes in climate patterns. Some records tend to suggest that the climate change that is taking place is a normal cycle. However with the ever increasing world population, we cannot be to sure about the future of food and water.

A variety of Water use efficiency methods have been proposed, but most of them have been found to be very expensive and complicated to use. In future each and every farmer, whether poor or uneducated might wake up in need of such a system, therefore the proposed applications need minimal cost components, less powerful controllers, minimal human-computer interaction.

This thesis presents a strategy to provide a computer-less Irrigation control system, which uses a cheap 8 bit, low processing power, small working memory and small storage capacity PIC Microcontroller which requires minimal human-computer interaction, uses a single sensor and low electrical power.

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Firstly I would like to thank the Lord for everything he has done for me in my life and his unconditional love. All the honour and glory goes to you. Special thanks go to my supervisors Mr Munyaradzi and Mr mashonjowa, who gave me an opportunity to work with them and explore the field of Micro-computing in Agriculture. Thank you for all the encouragement, guidance, help and support. Let me also take this opportunity to express my gratitude to my, twin brother Hilary, my mother, my sisters, and my brothers for their strong encouragement and support.

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l dedicate this research to the brave men and women of the Columbia space shuttle , the last crew of astronauts to perish inside a space shuttle , who perished on the 1st of July 2003 after re-entry into the earthôs atmosphere, 16 minutes before the scheduled landing time. Crew members (All from the NASSA space center in Washington DC and J.F Kennedy space center in Miami)

Mr David M Brown

Mr Rick D Husband (Head space shuttle crew)

Mrs Laurel B Clark

Dr Kalpana Chalwa (Mrs)

Mr Michael P Anderson

Mr Han Ramon

Mr William C McCool

We shall always remember you all for your dedication, for your determination, for your courage and for the knowledge and pride that you brought to our earth. May their souls rest in eternal peace.

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Chapter 1

Background and justification

1.0 Introduction

According to IPCC (2007a:10), It is predicted that future climate changes will include further global warming (i.e., an upward trend in global mean temperature), sea level rise, and a probable increase in the frequency of some extreme weather events. Some areas of the earth will become wetter, while most areas will experience heavy droughts. According to the Intergovernmental Panel on Climate, Africa, where water is already a scarce commodity, will have less and less water with warmer temperatures.

However, according to the capitalist magazine, the Earth's warming since 1850 totals about 0.7 degrees Celsius. Most of this occurred before 1940. The cause was a long, moderate 1,500-year climate cycle first discovered in the Greenland ice cores in 1983. The cycle abruptly raises our temperature 1 to 3 degrees C above the mean for centuries at a time--as it did during the Roman Warming (200 BC to 600 AD) and Medieval Warming (950 to1300 AD).Between warmings, Earth's temperatures shift abruptly lower by 1 to 3 degrees C--as they did during the 550 years of the Little Ice Age, which ended in 1850. The ice cores and seabed fossils show 600 of these 1,500-year cycles, extending back at least 1 million years.

In Al Gore's movie, the ice record from the Antarctic shows temperatures and atmospheric CO_2 levels tracking closely together through the radical ups and downs of four Ice Ages. The movie implies that more CO_2 in the air produces higher temperatures, but recently done, more refined ice studies show that temperatures changed about 800 years *before* the CO_2 levels. More CO_2 did not produce higher temperatures; instead, higher temperatures released more CO_2 from the oceans into the atmosphere. If the climate models' original greenhouse predictions had been valid, the Earth's temperatures would have risen several degrees more by now than they have.

The Earth's net warming since 1940 is a barely noticeable 0.2 degrees C, over 70 years. Moreover, the Earth has experienced no discernible temperature increase since 1998, nearly nine years ago. Remember, too, that the atmosphere is approaching CO2 saturation--after which more CO_2 will have no added climate forcing power.

"There is no convincing scientific evidence that human release of carbon dioxide, methane, or other greenhouse gasses is causing, or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate." That statement comes from a petition signed by more than 19,000 American scientists, available online at a site hosted by the Oregon Institute for Science and Medicine at www.oism.org. However, the absence of evidence is not the evidence of the absence of evidence. No one can be pretty sure what our climate will be like in 25, 50, or 100 years. You could be standing in a future desert or a future ocean. One thing is certain, though, our planet as a whole will be a lot better off if we can stabilize global carbon output.

Irrigation scheduling has conventionally aimed to achieve an optimum water supply for productivity, with soil water content being maintained close to field capacity. The increasing worldwide shortages of water and costs of irrigation are leading to an emphasis on developing methods of irrigation that minimize water use (maximize the water use efficiency).

1.1 Problem statement

Although there exists many methods for data acquisition and irrigation sequencing, each of these methods is very expensive and beyond the reach of many farmers. Most methods require that a farmer must have some of the following:

- a computer
- several sensory devices
- networking devices to transmit signals
- knowledge of his soil properties

- knowledge of plant properties

1.2 Aims and objectives

i) Develop an irrigation sequencing algorithm based on Agro-Meteorological data and equation

ii) Design an algorithm for irrigation sequencing

iii) Design and development of an appropriate automated irrigation control system.

1.3 Expected benefits

i) Increased water use efficiency for low to average income farmers

ii) Reduced user-computer interaction

1.4 Thesis layout

The thesis is organized in the following way:

Chapter 1 (Introduction):

This chapter introduces the research topic and sets the direction in which the thesis will proceed.

Chapter 2 (Literature Review):

A review of all the information that is relevant to the research.

Chapter 3 (Methodology):

In this chapter the proposed solution is presented. It is explained and analysis of Circuits and algorithm is made.

Chapter 4 (Conclusion)

This chapter gives the conclusions drawn from the research and its results as well as recommendations on future work that can be done.

Chapter 2

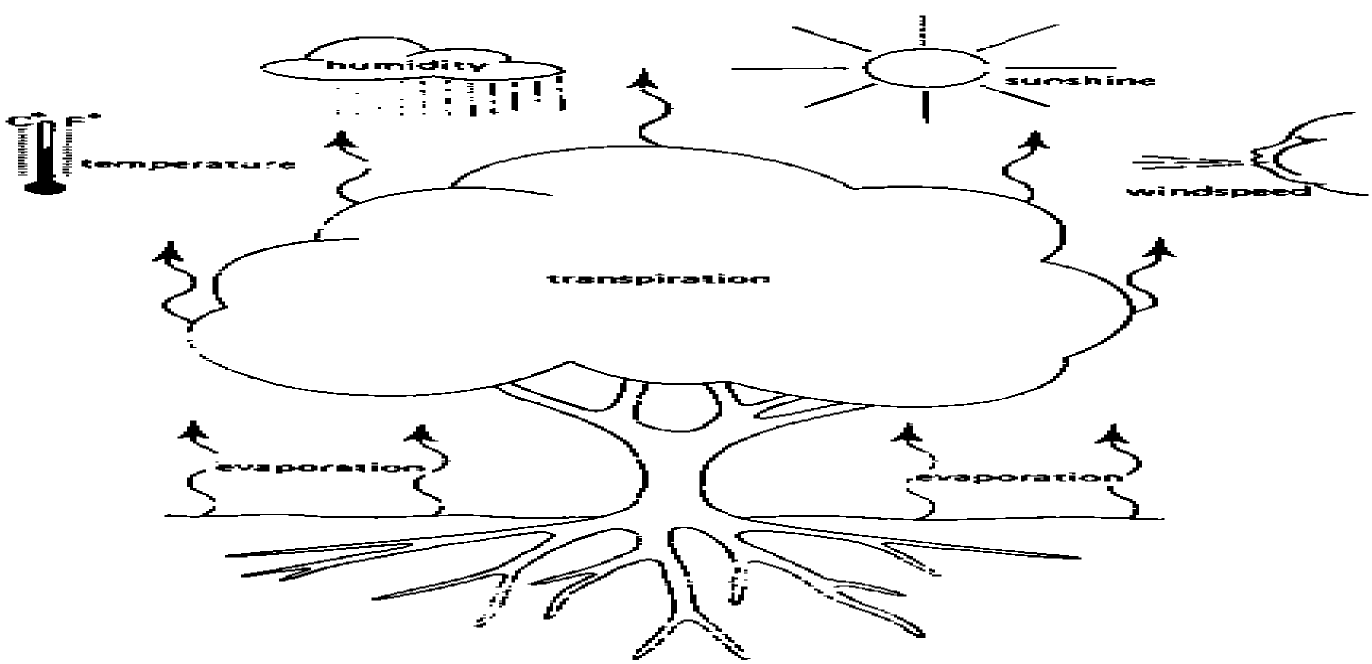
Literature review

2.0 Introduction

The major climatic factors (see Fig. 2.0) which influence the crop water needs are:

- sunshine
- temperature
- humidity
- wind speed

Fig. 2.0 Major climatic factors influencing crop water needs



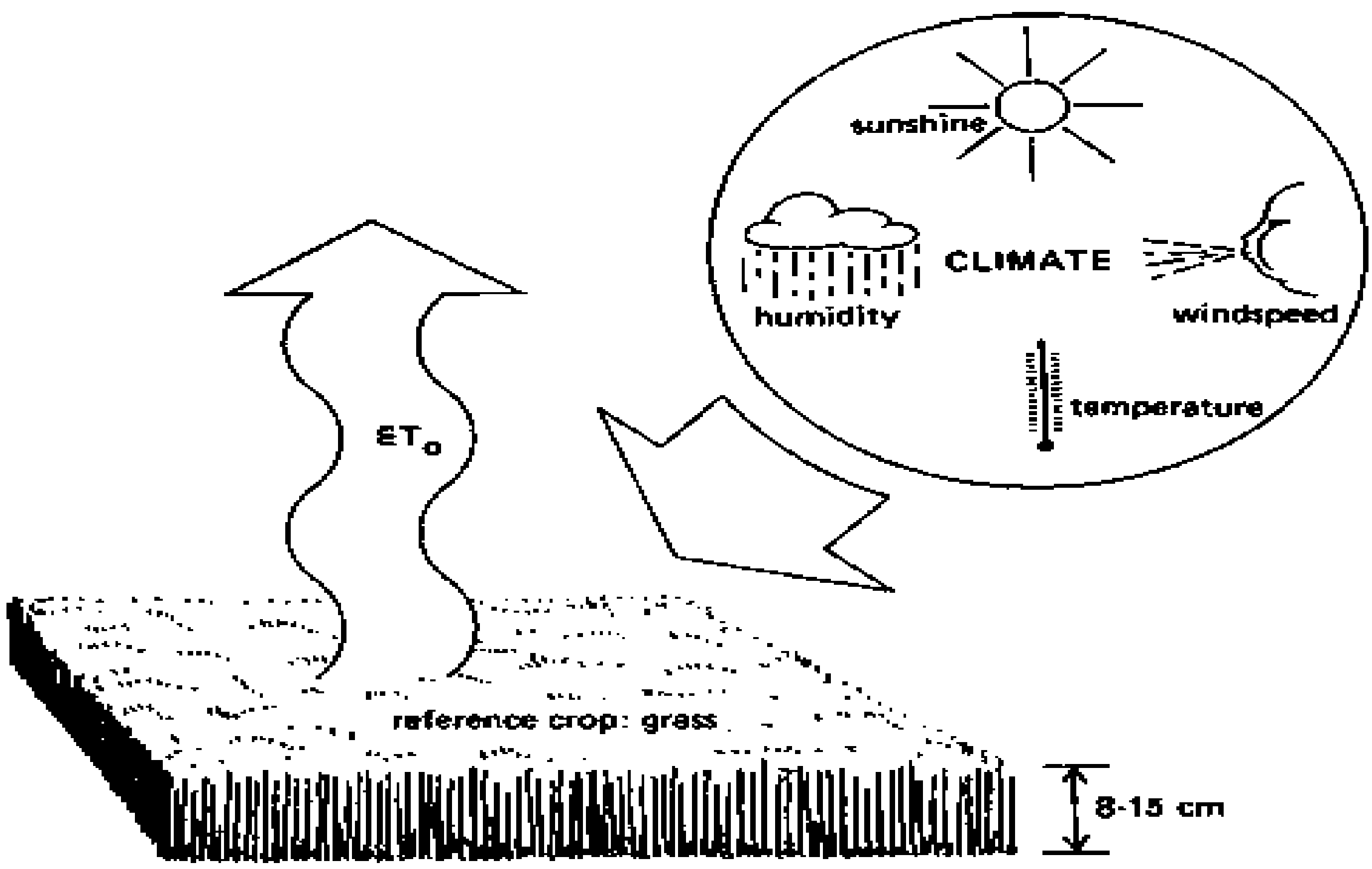
The highest crop water needs are thus found in areas which are hot, dry, windy and sunny. The lowest values are found when it is cool, humid and cloudy with little or no wind.

2.1 Water use and management in agriculture

2.1.1 Evapotranspiration

The influence of the climate on crop water needs is given by the reference crop evapotranspiration (ETo). The ETo is usually expressed in millimetres per unit of time, e.g. mm/day, mm/month, or mm/season. Grass has been taken as the reference crop. ETo is the rate of evapotranspiration from a large area, covered by green grass, 8 to 15 cm tall, which grows actively, completely shades the ground and which is not short of water.

Fig. 2.1 Reference crop evapotranspiration



There are several methods to determine the ETo . They are either:

- ✓ experimental, using an evaporation pan, or
- ✓ theoretical, using measured climatic data, e.g. the Blaney-Criddle method

2.1.2 Crop water requirements

The crop water need (ET crop) is defined as the depth (or amount) of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by the various crops to grow optimally. The crop water need always refers to a crop grown under optimal conditions, i.e. a uniform crop, actively growing, completely shading the ground, free of diseases, and favourable soil conditions (including fertility and water). The crop thus reaches its full production potential under the given environment.

The crop water need mainly depends on:

- ✓ the climate: in a sunny and hot climate crops need more water per day than in a cloudy and cool climate

- ✓ the crop type: crops like maize or sugarcane need more water than crops like millet or sorghum

- ✓ the growth stage of the crop; fully grown crops need more water than crops that have just been planted.

2.2 Irrigation scheduling

The advent of precision irrigation methods such as trickle irrigation has played a major role in reducing the water required in agricultural and horticultural crops, but has highlighted the need for new methods of accurate irrigation scheduling and control.

The choice of irrigation scheduling method depends to a large degree on the objectives of the irrigator and the irrigation system available. The more sophisticated scheduling methods generally require higher-precision application systems; nevertheless even less sophisticated systems such as flood irrigation scheduling can benefit from improvements in irrigation scheduling as outlined here. The pressures to improve irrigation use efficiency and to use irrigation for precise control of vegetative growth both imply a requirement for increased precision in irrigation control, maintaining the soil moisture status within fine bands to achieve specific objectives in crop management. Such objectives can only be met by precision irrigation systems such as trickle irrigation that can apply precise amounts of water at frequent intervals (often several times per day). Effective operation of such systems equally requires a sensing system that determines irrigation need in real time or at least at frequent intervals; this rules out large-scale manual monitoring programmes for such purposes and indicates a need for automated monitoring systems.

2.3 Irrigation scheduling techniques

Irrigation scheduling is conventionally based either on ósoil water measurementö, where the soil moisture status (whether in terms of water content or water potential) is measured directly to determine the need for irrigation, or on ósoil water balance calculationsö, where the soil moisture status is estimated by calculation using a water balance approach in which the change in soil moisture ($\Delta\theta$) over a period is given by the difference between the inputs (irrigation plus precipitation) and the losses (runoff plus drainage plus evapotranspiration).

A potential problem with all soil-water based approaches is that many features of the plant's physiology respond directly to changes in water status in the plant tissues, whether in the roots or in other tissues, rather than to changes in the bulk soil water content (or potential). The actual tissue water potential at any time therefore depends both on the soil moisture status and on the rate of water flow through the plant and the corresponding hydraulic flow resistances between the bulk soil and the appropriate plant tissues. The plant response to a given amount of soil moisture therefore varies as a complex function of evaporative demand. As a result it has been suggested (Jones, 1990*a*) that greater precision in the application of irrigation can potentially be obtained by a third approach, the use of óplant "stress" sensingô. For this approach irrigation scheduling decisions are based on plant responses rather than on direct measurements of soil water status.

Although the water balance approach is not very accurate, it has generally been found to be sufficiently robust under a wide range of conditions. Nevertheless it is subject to the serious problem that errors are cumulative over time. For this reason it is often necessary to recalibrate the calculated water balance at intervals by using actual soil measurements, or sometimes plant response measurements.

2.3.1 Plant-based methods for irrigation control

If soil water-based measures are to be replaced by plant-based measures it is important to consider what measures might be most appropriate for irrigation scheduling purposes. Possible measures include direct measurements of some aspect of plant water status as well as measurements of a number of plant processes that are known to respond sensitively to water deficits. One might expect that a direct measure of plant water status should be the most rigorous and hence the most useful indicator of irrigation requirement, although the question remains as to where in the plant that quantity should be measured. In practice, as has been argued strongly by Jones (1990*b*), most plants exercise some measure of autonomous control over their shoot or leaf water status, tending to minimize changes in shoot water status as the soil dries or as evaporative demand increases (Bates and Hall, 1981; Jones, 1983). In the long term, this control is achieved through changes in leaf area and root extension, and in the shorter term through changes in leaf angle, stomatal conductance, and hydraulic properties of the transport system. In extreme cases, plants with good endogenous control systems maintain a stable leaf water status over a wide range of evaporative demand or soil water supplies; these plants are termed óisohydricô(Stocker, 1956), and include especially plants such as cowpea, maize, and poplar (Bates and Hall, 1981; Tardieu and Simonneau, 1998). This is by contrast with those species such as sunflower or barley which appear to have less effective control of leaf water status and have been termed ánisohydricâ. In practice the distinctions between isohydric and anisohydric behaviour are often not clear-cut; even different cultivars of grapevine have been shown to have contrasting hydraulic behaviours (Schultz, 2003).

The choice of which plant-based measure to use depends on their relative sensitivity to water deficits. The definition of sensitivity, however, is somewhat problematic. The relative sensitivities of different physiological processes were reviewed in some detail by Hsiao (1973), who identified cell growth as being most sensitive to tissue water deficits, closely followed by wall and protein synthesis, all of which could respond to water deficits of less than 0.1 MPa. Hsiao reported that stomatal closure was only rarely affected when tissue water potential fell by 0.2ï 0.5 MPa, with decreases of 1.0 MPa or more being required for stomatal closure in many cases. Although photosynthesis was classified as moderately sensitive by Hsiao, largely as a result of its dependence on stomatal aperture, some component processes such as electron transport are now known to be particularly insensitive (Massacci and Jones, 1990). It is now believed that Hsiao's (1973) classification is somewhat misleading, and underestimates the true sensitivity of the stomata, as it is based on observed responses to *leaf* water potential alone and ignores the internal rootï shoot signalling that is now known to play a major part in controlling stomatal aperture (Davies and Zhang, 1991).

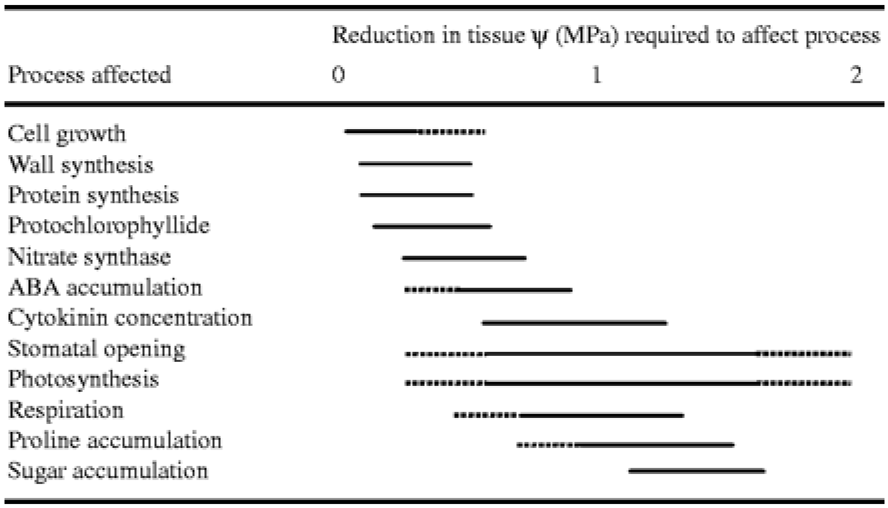


Fig. 2.2 Generalized sensitivities of plant processes to water deficits (modified with permission from Hsiao, 1973).

The error arising from a reliance on leaf water status is readily apparent when one considers that many plants operate when optimally watered with the leaf water potential at around ï 2 MPa, yet the stomata may close as the soil dries by only a few tens of Pa, with little change in leaf water potential (Bates and Hall, 1981). A further consideration is that any attempt to relate stomatal aperture to leaf water potential in a long-term drought experiment can also be misleading, because with slowly developing stress the plant adapts by decreasing leaf area; as a result stomatal conductance and photosynthesis rate per unit leaf area may remain fairly stable as soil dries (Moriana and Fereres, 2002). Nevertheless, over shorter time-scales it still appears that stomata are a particularly sensitive early indicator of water deficits.

In principle, water status is not ideal as a measure of water deficit as it is already subject to some physiological control, and indeed, as has been outlined above, leaf water potential generally shows some homeostasis. Nevertheless, changes in water status somewhere in the plant system are assumed to be a prerequisite for any physiological adaptation or other response. All that a homeostatic system can do is to minimize, not eliminate, the changes in water status; indeed for a feedback system of stomatal control it is not theoretically possible for such a system to stably eliminate changes in shoot water status if that is the variable that actually controls the stomata (Jones, 1990*b*; Franks *et al.*, 1997).

In general, the use of any plant-based or similar indicator for irrigation scheduling requires the definition of reference or threshold values, beyond which irrigation is necessary. Such reference values are commonly determined for plants growing under non-limiting soil water supply (Fereres and Goldhamer, 2003), but obtaining extensive information on the behaviour of these reference values as environmental conditions change is an important stage in the development and validation of such methods. Another general limitation to plant-based methods is that they do not usually give information on óhow muchô irrigation to apply at any time, only whether or not irrigation is needed.

2.3.1.0 Plant water status

Perhaps the first approach to the use of the plant itself as an indicator of irrigation need, and one that is still frequently adopted today was to base irrigation on visible wilting. Unfortunately, by the time wilting is apparent a substantial proportion of potential yield may already have been lost (Slatyer, 1967). More rigorous and more sensitive measures of plant water status are therefore required. Although relative water content (RWC) (Barrs, 1968) is a widely used measure of water status that does not require sophisticated equipment, it is often argued that water potential, especially of the leaves (ψ_{leaf}) is a more rigorous and more generally applicable measure of plant water status (Slatyer, 1967; Jones, 1990*b*). In spite of this, RWC has the advantage that it can be more closely related to cell turgor, which is the process directly driving cell expansion, than it is to the total water potential (Jones, 1990*b*).

The fact that plant water status, and especially leaf water status, is usually controlled to some extent by means of stomatal closure or other regulatory mechanisms, argues against the use of such measures, especially in strongly isohydric species. A further problem with the use of leaf water status as an indicator of irrigation need was pointed out by Jones (1990*b*), who noted that even though there was often homeostasis of leaf water potential between different soil moisture regimes, rapid temporal fluctuations are often observed as a function of environmental conditions (such as passing clouds). This makes the interpretation of leaf water potential as an indicator of irrigation-need doubly unsatisfactory. Nevertheless, in spite of the concerns with the use of leaf water status that have been outlined above, it has been reported that leaf water potential can, when corrected for diurnal and environmental variation, provide a sensitive index for irrigation control (Peretz *et al.*, 1984).

As a partial solution to the variability of leaf water status, various workers have proposed that a more useful and more robust indicator of water status is the xylem water potential or stem water potential (SWP), measured by using a pressure chamber on leaves enclosed in darkened plastic bags for some time before measurement and allowed to equilibrate with the xylem water potential; McCutchan and Shackel, 1992). As a more stable measure of water status, others have even recommended that measurements should be made on pre-equilibrated leaves from root suckers (Jones, 1990*a*; Simonneau and Habib, 1991). These methods are thought to be preferable largely because they approach more closely the soil water status than does the value of leaf water potential, although as a result they therefore miss out on the potential advantages of plant-based methods.

Perhaps an even better estimator of the soil water potential is the predawn leaf water potential (as ψ_{leaf} should largely equilibrate with ψ_{soil} by dawn). Unfortunately this is often found to be rather insensitive to variation in soil moisture content (Garnier and Berger, 1987). Further, this is not very convenient for irrigation scheduling as routine measurements predawn are expensive to obtain, and at best can only be obtained daily. As yet another alternative, Jones (1983) suggested the indirect estimation of an effective soil water potential at the root surface of transpiring plants based on measurements of leaf water potential and stomatal conductance during the day, and argued that this should have significant advantages over predawn measurements. Such an approach has been successfully tested by Lorenzo-Minguez *et al.* (1985).

None of the above plant-based methods are well adapted for automation of irrigation scheduling or control because of the difficulties of measurement of any of the variables discussed. Although it may be possible to use automated stem or leaf psychrometers (Dixon and Tyree, 1984), these instruments are notoriously unreliable. In conclusion, it is apparent from the above discussion that the favoured way to use plant water status is actually as an indicator of soil water status; this negates many of the advantages of selecting a plant-based measure! Indeed soil water potential can be measured directly, thus avoiding the need for any plant-based measurement, although it is worth noting that this does not necessarily give a good measure of the effective water potential at the root surface during active transpiration (Jones, 1983).

Several indirect methods for measuring or monitoring water status have been developed as alternatives to direct measurement. The general behaviour of a number of such methods have been compared by McBurney (1992) and Sellés and Berger (1990). In general, these indirect methods suffer from the same disadvantages as do the direct measurements of leaf water status, but in certain circumstances have been developed into commercial systems. Some of these approaches are reviewed below.

2.3.1.1 Leaf thickness

A number of instruments are available for the routine monitoring of leaf thickness, which is known to decrease as turgidity decreases. Approaches include direct measurement using linear displacement transducers (e.g. LVDTs [Burquez, 1987; Malone, 1993] or capacitance sensors [McBurney, 1992]) or through measurements of leaf ósuperficial densityô using ß-ray attenuation (Jones, 1973). Unfortunately, leaf thickness is frequently even less sensitive to changes in water status than is leaf water content because, especially with younger leaves, a fraction of leaf shrinkage is often in the plane of the leaves rather than in the direction of the sensor (Jones, 1973).

2.3.1.2 Stem and fruit diameter

Stem and fruit diameters fluctuate diurnally in response to changes in water content, and so suffer from many of the same disadvantages as other water status measures. Nevertheless, the diurnal dynamics of changes in diameter, especially of fruits, have been used to derive rather more sensitive indicators of irrigation need, where the magnitude of daily shrinkage has been used to indicate water status, and comparisons of diameters at the same time on succeeding days give a measure of growth rate (Huguet *et al.*, 1992; Li and Huguet, 1990; Jones, 1985). Although changes in growth rate provide a particularly sensitive measure of plant water stress, such daily measurements are not particularly useful for the control of high-frequency irrigation systems. Nevertheless, several workers have achieved promising results for low-frequency irrigation scheduling by the use of maximum daily shrinkage (MDS). For example, Fereres and Goldhamer (2003) showed that MDS was a more promising approach for automated irrigation scheduling than was the use of stem water potential for almond trees, while differences in maximum trunk diameter were also found to be particularly useful in olive (Moriana and Fereres, 2002). The use of such dendrometry or micromorphometric techniques has been developed into a number of successful commercial irrigation scheduling systems (e.g. óPepista 4000ô, Delta International, Montfavet, France); these are usually applied to the study of stem diameter changes. Sellés and Berger (1990) reported that variations in trunk diameter or stem water potential were more sensitive as indicators of irrigation need than was the variation in fruit diameter. This was probably a result of the poor hydraulic connection between fruit tissue and the conducting xylem. There is currently much interest in evaluating such techniques for irrigation scheduling, with a number of relevant papers presented at recent meetings (e.g. the International Society for Horticultural Science 4th International Symposium on Irrigation of Horticultural Crops, 1ï 5 September 2003, Davis, CA, USA [as yet unpublished], and Kang *et al.*, 2003).

2.3.1.3 γ-ray attenuation:

A related approach to the study of changes in stem water content was the use of γ-ray attenuation (Brough *et al.*, 1986). Although this was shown to be very sensitive, safety considerations and cost have largely limited the further application of this approach.

2.3.1.4 Sap flow

The development of reliable heat pulse and energy balance thermal sensors for sap-flow measurement in the stems of plants (Granier, 1987; Cohen *et al.*, 1981; Cermak and Kucera, 1981) has opened up an alternative approach to irrigation scheduling based on measurements of sap-flow rates. Because sap-flow rates are expected to be sensitive to water deficits and especially to stomatal closure, many workers have tested the use of sap-flow measurement for irrigation scheduling and control in a diverse range of crops, including grapevine (Eastham and Gray, 1998; Ginestar *et al.*, 1998*a, b*), fruit and olive trees (Ameglio *et al.*, 1998; Fernandez *et al.*, 2001; Giorio and Giorio, 2003; Remorini and Massai, 2003) and even greenhouse crops (Ehret *et al.*, 2001).

Although the changes in transpiration rate that sap flow indicates are largely determined by changes in stomatal aperture, transpiration is also influenced by other environmental conditions such as humidity. Therefore changes in sap flow can occur without changes in stomatal opening.

Even though rates of sap flow may vary markedly between trees as a result of differences in tree size and exposure, the general patterns of change in response to both environmental conditions and to water status are similar (Eastham and Gray, 1998). Appropriate sap-flow rates to use as ócontrol thresholdsô may be derived by means of regular calibration measurements, especially for larger trees. Alternatively, it is at least feasible in principle to derive an irrigation scheduling algorithm that is based on an analysis of the diurnal patterns of sap flow, with midday reductions being indicative of developing water deficits (though of course diurnal fluctuations in environmental conditions can mimic such changes). Another potential problem with sap flow for precision control is that it tends to lag behind changes in transpiration rate owing to the hydraulic capacitance of the stem and other plant tissues (Wronski *et al.*, 1985).

It follows that, although sap-flow measurement is well adapted for automated recording and hence potentially automated control of irrigation systems, it can be a little difficult to determine the correct control points for any crop.

2.3.1.5 Xylem cavitation

It is generally accepted (Steudle, 2001) that water in the xylem vessels of transpiring plants is under tension; as water deficits increase, this tension is thought to increase to such an extent that the water columns can fracture, or ócavitateõ. Such cavitation events lead to the explosive formation of a bubble, initially containing water vapour. These cavitation events can be detected acoustically in the audio- (Milburn, 1979) or ultrasonic-frequencies (Tyree and Dixon, 1983), and the resulting embolisms may restrict water flow through the stem. Substantial evidence, though largely circumstantial, now indicates that the ultrasonic acoustic emissions (AEs) detected as plants become stressed do indeed indicate cavitation events and that AE rates can be used as an indicator of plant óstressô (Tyree and Sperry, 1989). Nevertheless, there remain many uncertainties as it seems that at least a proportion of the AEs detected as woody tissues dry out may not be related to xylem embolisms. For example, the large numbers observed by Sandford and Grace (1985) as coniferous stems dried out were substantially in excess of the number of conducting tracheids present, thus suggesting a major contribution to observed AEs by the non-conducting fibres (Jones and Peña, 1986). Although the measurement of AEs has proved to be a powerful tool for the study of hydraulic architecture in plants, there has been little progress in adapting this measure as an indicator for irrigation scheduling. Note, however, the recent report by Yang *et al.* (2003), who implemented a control algorithm based on the association of AE rate with transpiration rate for the precision irrigation of tomato. It is likely that the main reasons for the lack of uptake include the fact that the relationship between the number of AEs and water status changes with successive cycles of stress, and the fact that cavitation events are mostly observed during the drying phase, not during rewetting, and so cannot provide an indicator of when irrigation has been sufficient to replenish the soil water supply.

2.3.1.6 Stomatal conductance and thermal sensing

As outlined above, it appears that changes in stomatal conductance are particularly sensitive to developing water deficits in many plants and therefore potentially provide a good indicator of irrigation need in many species. It is in this area that most effort has been concentrated on the development of practical, plant-based irrigation scheduling approaches. Although stomatal conductance can be measured accurately using widely available diffusion porometers, measurements are labour-intensive and unsuitable for automation. The recognition that leaf temperature tends to increase as plants are droughted and stomata close (Raschke, 1960) led to a major effort in the 1970s and 1980s to develop thermal sensing methods, based on the newly developed infrared thermometers, for the detection of **plant** stress (see reviews by Jackson, 1982; Jones and Leinonen, 2003; Jones, 2004).

An early method of accounting for the rapid short-term variation in leaf temperature as radiation and wind speed vary in the field was to refer leaf temperatures to air temperature and to integrate these differences (e.g. the Stress Degree Day measure of Jackson *et al.*, 1977); significant elevation of canopy temperature above air temperature was indicative of stomatal closure and water deficit stress. The method was transformed into a more practical approach following the introduction of the crop water stress index (CWSI) by Idso and colleagues (Idso *et al.*, 1981; Jackson *et al.*, 1981), where *CWSI* was obtained from the canopy temperature (T_{canopy}) according to

$$CWSI = (T_{\mathrm{canopy}} - T_{\mathrm{nws}})/(T_{\mathrm{dry}} - T_{\mathrm{nws}}) \quad (1)$$

where T_{nws} is a so-called non-water-stressed baseline temperature for the crop in question at the same atmospheric vapour pressure deficit, and T_{dry} is an independently derived temperature of a non-transpiring reference crop. In this approach all temperatures are expressed as differences from air temperature so that standard relationships for T_{dry} and T_{nws} can be used. Although this approach was found to be useful in the clear arid climate of Arizona where the method was developed, it has proved to be less useful in more humid or cloudy climates where the signal-to-noise ratio is somewhat smaller (Hipps *et al.*, 1985; Jones, 1999). In spite of its deficiencies, there has been widespread use of infrared thermometry as a tool in irrigation scheduling in many, especially arid, situations (Jackson, 1982; Stockle and Dugas, 1992; Martin *et al.*, 1994), especially with the development of ótrapezoidalô methods involving the combination of temperature data with a visible/near infrared vegetation index (Moran *et al.*, 1994).

In order to improve the precision of the approach in more humid or low-radiation environments, Jones (1999) introduced the approach of using physical dry and wet reference surfaces to replace the notional T_{dry} and T_{nws}. A number of recent papers have shown that this approach can give reliable and sensitive indications of stomatal closure (Diaz-Espejo and Verhoef, 2002; Jones *et al.*, 2002; Leinonen and Jones, 2004) and hence has the potential to be used for irrigation scheduling. The most important recent advances in the application of thermal sensing for plant óstressô detection and irrigation scheduling, however, have been provided by the introduction of thermal imagery (Jones, 1999, 2004; Jones *et al.*, 2002), although their expense has meant that such systems have yet to be widely used.

In addition to the use of the absolute temperature rise as stomata close, it has also been proposed that use may be made of the fact that the variance of leaf temperature increases as stomata close (Fuchs, 1990). Indeed, this may be a more sensitive indicator of stomatal closure than is the temperature rise (Jones, 2004). Again, the introduction of thermal cameras now makes the wider use of such approaches feasible, especially when combined with automated image analysis.

2.3.1.7 Automation of irrigation systems using plant based indicators

The most widespread use of automated irrigation scheduling systems is in the intensive horticultural, and especially the protected cropping, sector. In general, the automated systems in common use are based on simple automated timer operation, or in some cases the signal is provided by soil moisture sensors. For timer-based operation many systems simply aim to provide excess water to runoff at intervals (e.g. flood-beds or capillary matting systems), although some at least attempt to limit water application by only applying enough to replenish evaporative losses (often calculated from measured pan evaporation; Allen *et al.*, 1999). Much greater sophistication is required if an objective is to improve the overall irrigation water use efficiency or to apply an RDI system.

Applications of automated plant-based sensing are largely in the developmental stage, partly because it is usually necessary to supplement the plant-stress sensing by additional information (such as evaporative demand). In principle, with high-frequency on-demand irrigation systems one could envisage a real-time control system where water supply is directly controlled by a feedback controller operated by the stress sensor itself, so that no information on the required irrigation amount is needed. For such an approach care will be necessary to take account of any lags in the plant physiological response used for the control signal.

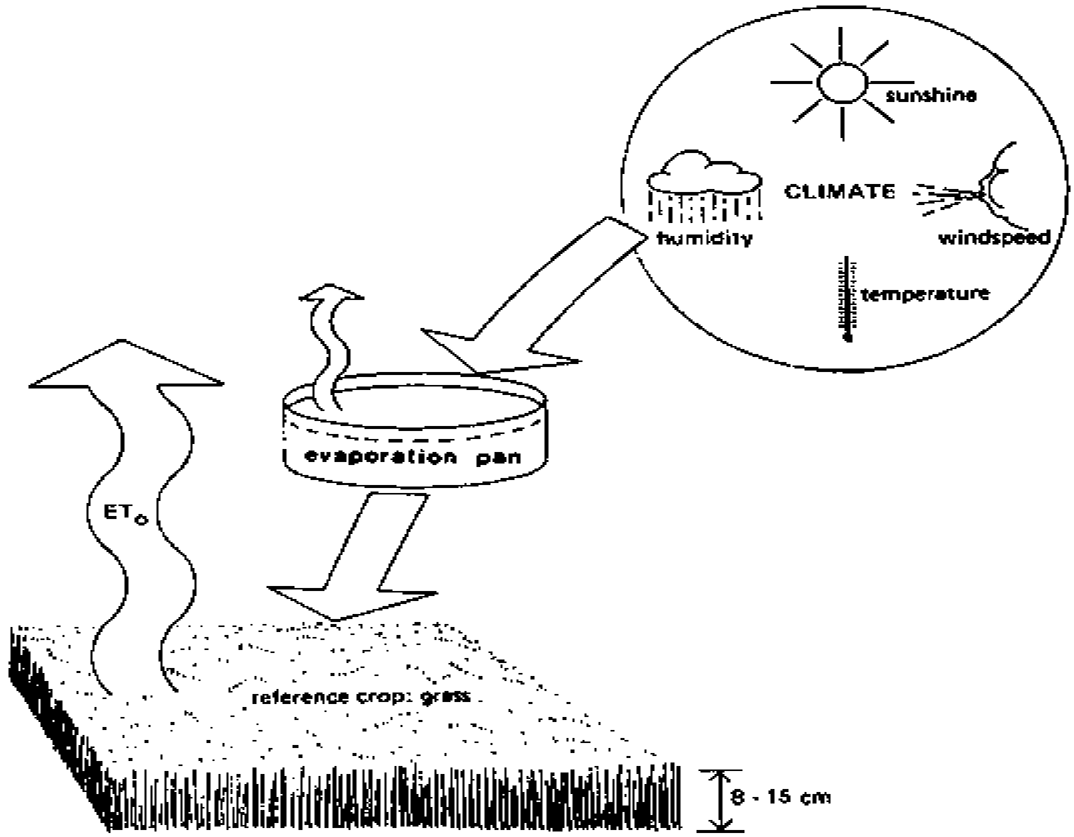
The use of expert systems (Plant *et al.*, 1992), which integrate data from several sources, appears to have great potential for combining inputs from thermal or other crop response sensors and environmental data for a water budget calculation to derive a robust irrigation schedule.

Among the various plant-based sensors that have been incorporated into irrigation control systems are stem diameter gauges (Huguet *et al.*, 1992), sap-flow sensors (Schmidt and Exarchou, 2000) and acoustic emission sensors (Yang *et al.*, 2003), though there has been most interest in the application of thermal sensors. For example, Kacira and colleagues (Kacira and Ling, 2001; Kacira *et al.*, 2002) have developed and tested on a small scale an automated irrigation controller based on thermal sensing of plant stress. Similar approaches have been applied in the field: for example, Evans *et al.* (2001) and Sadler *et al.* (2002) mounted an array of 26 infrared thermometers (IRTs) on a centre pivot irrigation system which they used to monitor irrigation efficiency, but had not developed the system to a stage where it could be used for fully automated control. Colaizzi *et al.* (2003) have tested another system that includes thermal sensing of canopy temperature on a large linear move irrigator (where the irrigator moves across the field). In another approach to the use of canopy temperature that makes use of the ó thermal kinetic windowô, Upchurch *et al.* (1990) and Mahan *et al.* (2000) have developed what they call a óbiologically identified optimal temperature interactive consoleô for the control of trickle and other irrigation systems based on canopy temperature measurements. In this direct control system, irrigation is applied as canopy temperature exceeds a crop-specific optimum. The development of thermal infrared imaging methods of irrigation control will be aided by the recent development of automated image analysis systems for extraction of the temperatures of leaf surfaces from thermal images, including shaded and sunlit leaves, soil, and other surfaces (Leinonen and Jones, 2004).

2.3.3 The Evaporation Pan Method

Evaporation pans provide a measurement of the combined effect of temperature, humidity, windspeed and sunshine on the reference crop evapotranspiration ETo (see Fig. 2.3).

Fig. 2.3 Pan Evaporation method



Many different types of evaporation pans are being used. The best known pans are the Class A evaporation pan (circular pan) (Fig. 2.4a) and the Sunken Colorado pan (square pan) (Fig. 2.4b).

Fig. 2.4a Class A evaporation pan

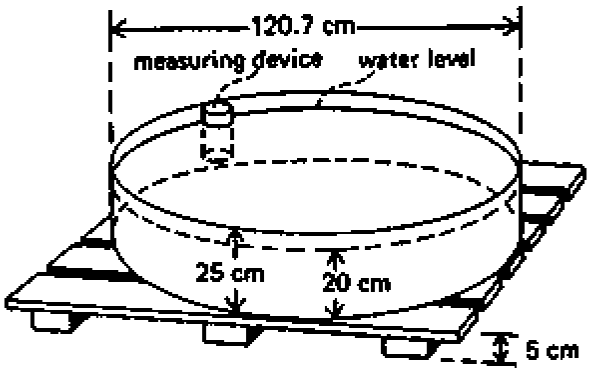
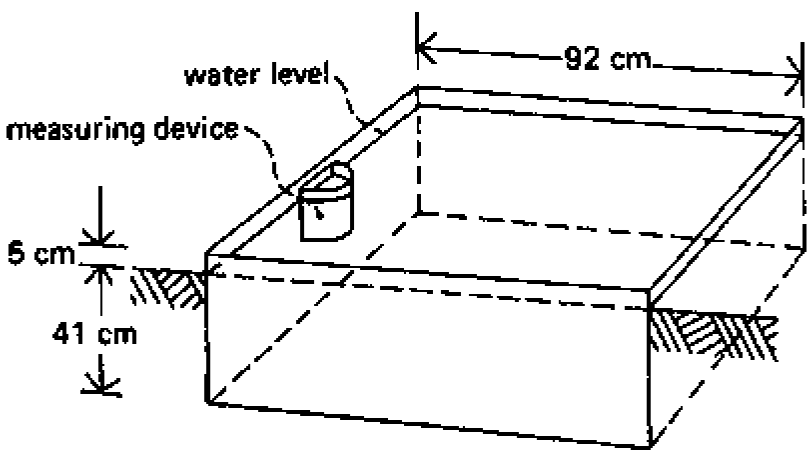


Fig. 2.4b Sunken Colorado pan



The principle of the evaporation pan is the following

i. the pan is installed in the field

ii. the pan is filled with a known quantity of water (the surface area of the pan is known and the water depth is measured)

iii. the water is allowed to evaporate during a certain period of time (usually 24 hours). For example, each morning at 7 o'clock a measurement is taken. The rainfall, if any, is measured simultaneously

iv. after 24 hours, the remaining quantity of water (i.e. water depth) is measured

v. the amount of evaporation per time unit (the difference between the two measured water depths) is calculated; this is the pan evaporation: E pan (in mm/24 hours)

vi. the E pan is multiplied by a pan coefficient, K pan, to obtain the ETo.

If the water depth in the pan drops too much (due to lack of rain), water is added and the water depth is measured before and after the water is added. If the water level rises too much (due to rain) water is taken out of the pan and the water depths before and after are measured.

Determination of K pan

When using the evaporation pan to estimate the ETo, in fact, a comparison is made between the evaporation from the water surface in the pan and the evapotranspiration of the standard grass. Of course the water in the pan and the grass do not react in exactly the same way to the climate. Therefore a special coefficient is used (K pan) to relate one to the other.

The pan coefficient, K pan, depends on:

- ✓ the type of pan used
- ✓ the pan environment: if the pan is placed in fallow or cropped area
- ✓ the climate: the humidity and windspeed

For the Class A evaporation pan, the K pan varies between 0.35 and 0.85. Average K pan = 0.70.

For the Sunken Colorado pan, the K pan varies between 0.45 and 1.10. Average K pan = 0.80.

Details of the pan coefficient are usually provided by the supplier of the pan. If the pan factor is not known the average value could be used.

2.3.4 Weather based approaches

The methods for calculating evapotranspiration from meteorological data require various climatological and physical parameters. Some of the data are measured directly in weather stations. Other parameters are related to commonly measured data and can be derived with the help of a direct or empirical relationship.

2.3.4 .0 Meteorological factors determining ET

i) Solar radiation
ii) Air temperature
iii) Air humidity
iv) Wind speed

The meteorological factors determining evapotranspiration are weather parameters which provide energy for vaporization and remove water vapour from the evaporating surface. The principal weather parameters to consider are presented below.

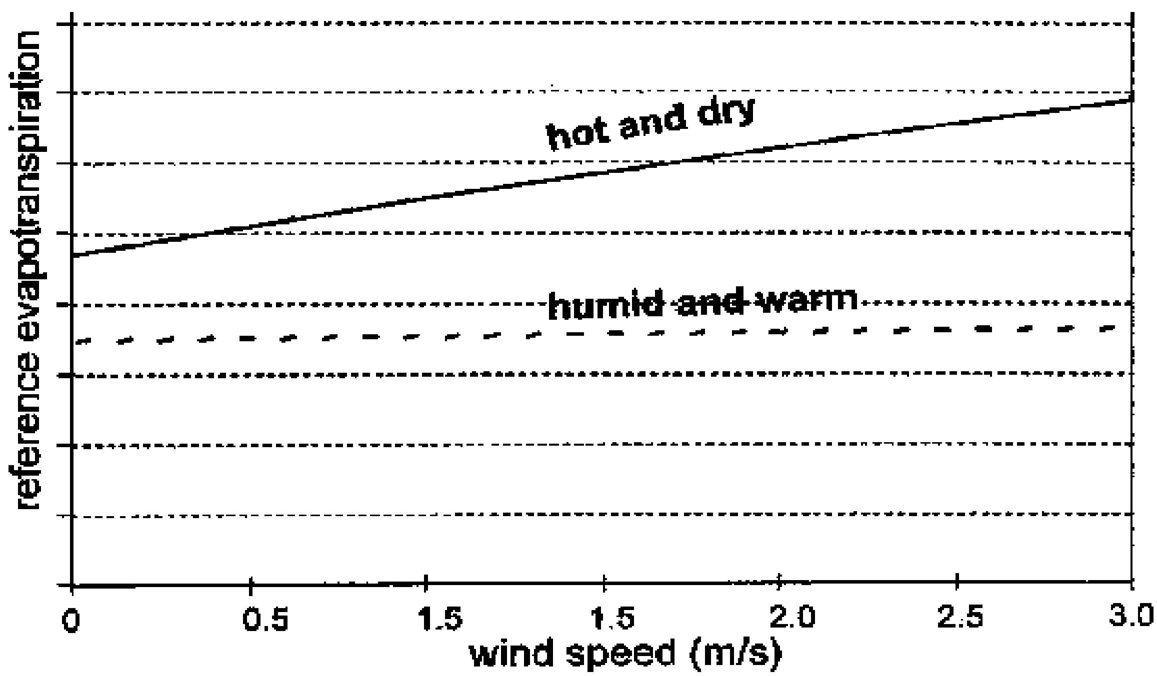
2.3.4 .1 Solar radiation

The evapotranspiration process is determined by the amount of energy available to vaporize water. Solar radiation is the largest energy source and is able to change large quantities of liquid water into water vapour. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons. The actual solar radiation reaching the evaporating surface depends on the turbidity of the atmosphere and the presence of clouds which reflect and absorb major parts of the radiation. When assessing the effect of solar radiation on evapotranspiration, one should also bear in mind that not all available energy is used to vaporize water. Part of the solar energy is used to heat up the atmosphere and the soil profile.

2.3.4 .2 Air temperature

The solar radiation absorbed by the atmosphere and the heat emitted by the earth increase the air temperature. The sensible heat of the surrounding air transfers energy to the crop and exerts as such a controlling influence on the rate of evapotranspiration. In sunny, warm weather the loss of water by evapotranspiration is greater than in cloudy and cool weather.

figure 2.5 Illustration of the effect of wind speed on evapotranspiration in hot-dry and humid-warm weather conditions



2.3.4 .3 Air humidity

While the energy supply from the sun and surrounding air is the main driving force for the vaporization of water, the difference between the water vapour pressure at the evapotranspiring surface and the surrounding air is the determining factor for the vapour removal. Well-watered fields in hot dry arid regions consume large amounts of water due to the abundance of energy and the desiccating power of the atmosphere. In humid tropical regions, notwithstanding the high energy input, the high humidity of the air will reduce the evapotranspiration demand. In such an environment, the air is already close to saturation, so that less additional water can be stored and hence the evapotranspiration rate is lower than in arid regions.

2.3.4 .4 Wind speed

The process of vapour removal depends to a large extent on wind and air turbulence which transfers large quantities of air over the evaporating surface. When vaporizing water, the air above the evaporating surface becomes gradually saturated with water vapour. If this air is not continuously replaced with drier air, the driving force for water vapour removal and the evapotranspiration rate decreases.

The combined effect of climatic factors affecting evapotranspiration is illustrated in Figure 2.5 for two different climatic conditions. The evapotranspiration demand is high in hot dry weather due to the dryness of the air and the amount of energy available as direct solar radiation and latent heat. Under these circumstances, much water vapour can be stored in the air while wind may promote the transport of water allowing more water vapour to be taken up. On the other hand, under humid weather conditions, the high humidity of the air and the presence of clouds cause the evapotranspiration rate to be lower. The effect on evapotranspiration of increasing wind speeds for the two different climatic conditions is illustrated by the slope of the curves in Figure 2.5. The drier the atmosphere, the larger the effect on ET and the greater the slope of the curve. For humid conditions, the wind can only replace saturated air with slightly less saturated air and remove heat energy. Consequently, the wind speed affects the evapotranspiration rate to a far lesser extent than under arid conditions where small variations in wind speed may result in larger variations in the evapotranspiration rate.

2.3.5 Empirical formulae and methods

2.3.5.0 The Penman Equation

In 1948, Howard Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed.

Penman (1948) defined Ea empirically as

$$E_a = W_f \ (e^o - e_a)$$

where Ea is in mm d^{-1}

W_f is called a wind function in mm d-1 kPa-1 [typically expressed as a linear function of wind speed in m s-1 (Uz) at the reference height (z) above the ground]

e^o is the saturated vapor pressure in kPa at mean air temperature, and e^a is mean ambient vapor pressure in kPa at the reference height above ground [ea = RH eo, where RH is mean relative humidity as a fraction; conceptually, ea should equal the saturated vapor pressure at the daily mean dew point temperature].

[e^a = RH e^o, where RH is mean relative humidity as a fraction; conceptually, e^a should equal the saturated vapor pressure at the daily mean dew point temperature]

Penman noted in his 1948 paper one of the experimental problems needing a solution was the reliable estimation of the daily mean dew point temperature. This problem has led to current differences in using Penmanôs equation and has resulted in myriad different versions of a ñmodified Penman equationò with varying wind functions and methods for estimating mean daily vapor pressure deficit (e^o ï e^a) (Jensen et al., 1990).

It is critical to build the Penman-Monteith equation first on an understanding of the Penman equation and its subtleties. Penman (1948) defined E as open water evaporation. He expressed bare-, wet-soil evaporation or grass evaporation, Eo, (we now call this evapotranspiration, especially in the U.S.) as fractions of open water evaporation (Ew)

[i.e., Eo = f Ew, where f is expressed as a fraction].

The ñfò values he measured typically varied from about 0.5-0.6 in winter to near 0.8-1.0 in summer. Grass evaporation ñfò values were slightly larger than ñfô values for bare soil with a water table near the surface (120 to 400 mm beneath the soil surface).

The Penman equation, therefore, only required routine weather observations (although some measurements like wind speed and cloud cover were not available everywhere) from a single level or height above ground. But the theory was rather advanced for its time. Without computers to perform the tedious computations, most engineers continued to rely on simpler evapotranspiration (ET) estimation methods such as the Blaney Criddle , Thornthwaite, or Jensen-Haise (Jensen et al., 1974). One of the earliest uses of the Penman equation in the U.S.

was by Van Bavel (1956) for irrigation scheduling. Another advance to aid the use of the Penman equation was a wider acceptance and familiarity with metric units or the S.I. unit system that greatly streamlined the cumbersome original English units used in 1948.

2.3.5.1 The Penman-Monteith Equation

This so-called combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors. The Penman-Monteith method refers to the use of an equation for computing water evaporation from vegetated surfaces. It was proposed and developed by John Monteith in his seminal paper (Monteith, 1965) in which he illustrated its thermodynamic basis with a psychometric chart (a graph of vapor pressure at various relative saturations versus air temperature at a known air pressure). Monteithôs derivation was built upon that of Howard Penman (Penman, 1948) in the now well-known combination equation (so named based on its ñcombinationò of an energy balance and an aerodynamic formula) given as

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

where R_n is the net radiation,

G is the soil heat flux, (e_s - e_a) represents the vapour pressure deficit of the air,

r $_a$ is the mean air density at constant pressure,

c_p is the specific heat of the air,

D represents the slope of the saturation vapour pressure temperature relationship, g is the psychrometric constant,

and r_s and r_a are the (bulk) surface and aerodynamic resistances

The **Penman-Monteith** equation requires daily mean temperature, wind speed, relative humidity, and solar radiation to predict net evapotranspiration. Other than radiation, these parameter are implicit in the derivation of ȹ, c_p, and $ŭ_q$, if not conductances below.

g_a is Conductivity of air, atmospheric conductance (m s^{-1}) and $g_a = 1/ r_a$

g_s = Conductivity of stoma, surface conductance(m s^{-1}) and $g_s = 1/ r_s$

The Penman-Monteith approach as formulated above includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters are measured or can be readily calculated from weather data. The equation can be utilized for the direct calculation of any crop evapotranspiration as the surface and aerodynamic resistances are crop specific.

2.3.5.1 .0 Solar radiation

The evapotranspiration process is determined by the amount of energy available to vaporize water. Solar radiation is the largest energy source and is able to change large quantities of liquid water into water vapour. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons. The actual solar radiation reaching the evaporating surface depends on the turbidity of the atmosphere and the presence of clouds which reflect and absorb major parts of the radiation. When assessing the effect of solar radiation on evapotranspiration, one should also bear in mind that not all available energy is used to vaporize water. Part of the solar energy is used to heat up the atmosphere and the soil profile

Extraterrestrial radiation (R_a)

The radiation striking a surface perpendicular to the sun's rays at the top of the earth's atmosphere, called the solar constant, is about 0.082 MJ m^{-2} min^{-1}. The local intensity of radiation is, however, determined by the angle between the direction of the sun's rays and the normal to the surface of the atmosphere. This angle will change during the day and will be different at different latitudes and in different seasons. The solar radiation received at the top of the earth's atmosphere on a horizontal surface is called the extraterrestrial (solar) radiation, R_a.

If the sun is directly overhead, the angle of incidence is zero and the extraterrestrial radiation is 0.0820 MJ m^{-2} min^{-1}. As seasons change, the position of the sun, the length of the day and, hence, R_a change as well. Extraterrestrial radiation is thus a function of latitude, date and time of day.

2.3.5.1 .1 Solar or shortwave radiation (R_s)

As the radiation penetrates the atmosphere, some of the radiation is scattered, reflected or absorbed by the atmospheric gases, clouds and dust. The amount of radiation reaching a horizontal plane is known as the solar radiation, R_s. Because the sun emits energy by means of electromagnetic waves characterized by short wavelengths, solar radiation is also referred to as shortwave radiation.

For a cloudless day, R_s is roughly 75% of extraterrestrial radiation. On a cloudy day, the radiation is scattered in the atmosphere, but even with extremely dense cloud cover, about 25% of the extraterrestrial radiation may still reach the earth's surface mainly as diffuse sky radiation. Solar radiation is also known as global radiation, meaning that it is the sum of direct shortwave radiation from the sun and diffuse sky radiation from all upward angles.

2.3.5.1 .2 Relative shortwave radiation (R_s/R_{so})

The relative shortwave radiation is the ratio of the solar radiation (R_s) to the clear-sky solar radiation (R_{so}). R_s is the solar radiation that actually reaches the earth's surface in a given period, while R_{so} is the solar radiation that would reach the same surface during the same period but under cloudless conditions.

The relative shortwave radiation is a way to express the cloudiness of the atmosphere; the cloudier the sky the smaller the ratio. The ratio varies between about 0.33 (dense cloud cover) and 1 (clear sky). In the absence of a direct measurement of R_n, the relative shortwave radiation is used in the computation of the net longwave radiation.

2.3.5.1 .3 Relative sunshine duration (n/N)

The relative sunshine duration is another ratio that expresses the cloudiness of the atmosphere. It is the ratio of the actual duration of sunshine, n, to the maximum possible duration of sunshine or daylight hours N. In the absence of any clouds, the actual duration of sunshine is equal to the daylight hours (n = N) and the ratio is one, while on cloudy days n and consequently the ratio may be zero. In the absence of a direct measurement of R_s, the relative sunshine duration, n/N, is often used to derive solar radiation from extraterrestrial radiation.

As with extraterrestrial radiation, the day length N depends on the position of the sun and is hence a function of latitude and date.

2.3.5.1.4 Albedo (□) and net solar radiation (R_{ns})

A considerable amount of solar radiation reaching the earth's surface is reflected. The fraction, a, of the solar radiation reflected by the surface is known as the albedo. The albedo is highly variable for different surfaces and for the angle of incidence or slope of the ground surface. It may be as large as 0.95 for freshly fallen snow and as small as 0.05 for a wet bare soil. A green vegetation cover has an albedo of about 0.20-0.25. For the green grass reference crop, is assumed to have a value of 0.23.

The net solar radiation, R_{ns}, is the fraction of the solar radiation R_s that is not reflected from the surface. Its value is (1-)R_s.

2.3.5.1.5 Net longwave radiation (R_{nl})

The solar radiation absorbed by the earth is converted to heat energy. By several processes, including emission of radiation, the earth loses this energy. The earth, which is at a much lower temperature than the sun, emits radiative energy with wavelengths longer than those from the sun. Therefore, the terrestrial radiation is referred to as longwave radiation. The emitted longwave radiation ($R_{l, up}$) is absorbed by the atmosphere or is lost into space. The longwave radiation received by the atmosphere ($R_{l, down}$) increases its temperature and, as a consequence, the atmosphere radiates energy of its own. Part of the radiation finds it way back to the earth's surface. Consequently, the earth's surface both emits and receives longwave radiation. The difference between outgoing and incoming longwave radiation is called the net longwave radiation, R_{nl}. As the outgoing longwave radiation is almost always greater than me incoming longwave radiation, R_{nl} represents an energy loss.

2.3.5.1.6 Net radiation (R_n)

The net radiation, R_n, is the difference between incoming and outgoing radiation of both short and long wavelengths. It is the balance between the energy absorbed, reflected and emitted by the earth's surface or the difference between the incoming net shortwave (R_{ns}) and the net outgoing longwave (R_{nl}) radiation. R_n is normally positive during the daytime and negative during the nighttime. The total daily value for R_n is almost always positive over a period of 24 hours, except in extreme conditions at high latitudes.

2.3.5.1.7 Soil heat flux (G)

In making estimates of evapotranspiration, all terms of the energy balance should be considered. The soil heat flux, G, is the energy that is utilized in heating the soil. G is positive when the soil is warming and negative when the soil is cooling. Although the soil heat flux is small compared to R_n and may often be ignored, the amount of energy gained or lost by the soil in this process should theoretically be subtracted or added to R_n when estimating evapotranspiration.

2.3.5.1.8 'bulk' surface resistance (r_s)

The 'bulk' surface resistance describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. Where the vegetation does not completely cover the soil, the resistance factor should indeed include the effects of the evaporation from the soil surface. If the crop is not transpiring at a potential rate, the resistance depends also on the water status of the vegetation

2.3.5.1.9 Air temperature

The solar radiation absorbed by the atmosphere and the heat emitted by the earth increase the air temperature. The sensible heat of the surrounding air transfers energy to the crop and exerts as such a controlling influence on the rate of evapotranspiration. In sunny, warm weather the loss of water by evapotranspiration is greater than in cloudy and cool weather.

2.3.5.2 The FAO Penman-Monteith Equation

By defining the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, the FAO Penman-Monteith method was developed. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide.

From the original Penman-Monteith equation and the equations of the aerodynamic and surface resistance , the FAO Penman-Monteith method to estimate ET_o can be derived.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],

T mean daily air temperature at 2 m height [°C],

u_2 wind speed at 2 m height [m s^{-1}],

e_s saturation vapour pressure [kPa],

e_a actual vapour pressure [kPa],

e_s - e_a saturation vapour pressure deficit [kPa],

slope vapour pressure curve [kPa $°C^{-1}$],

psychrometric constant [kPa $°C^{-1}$].

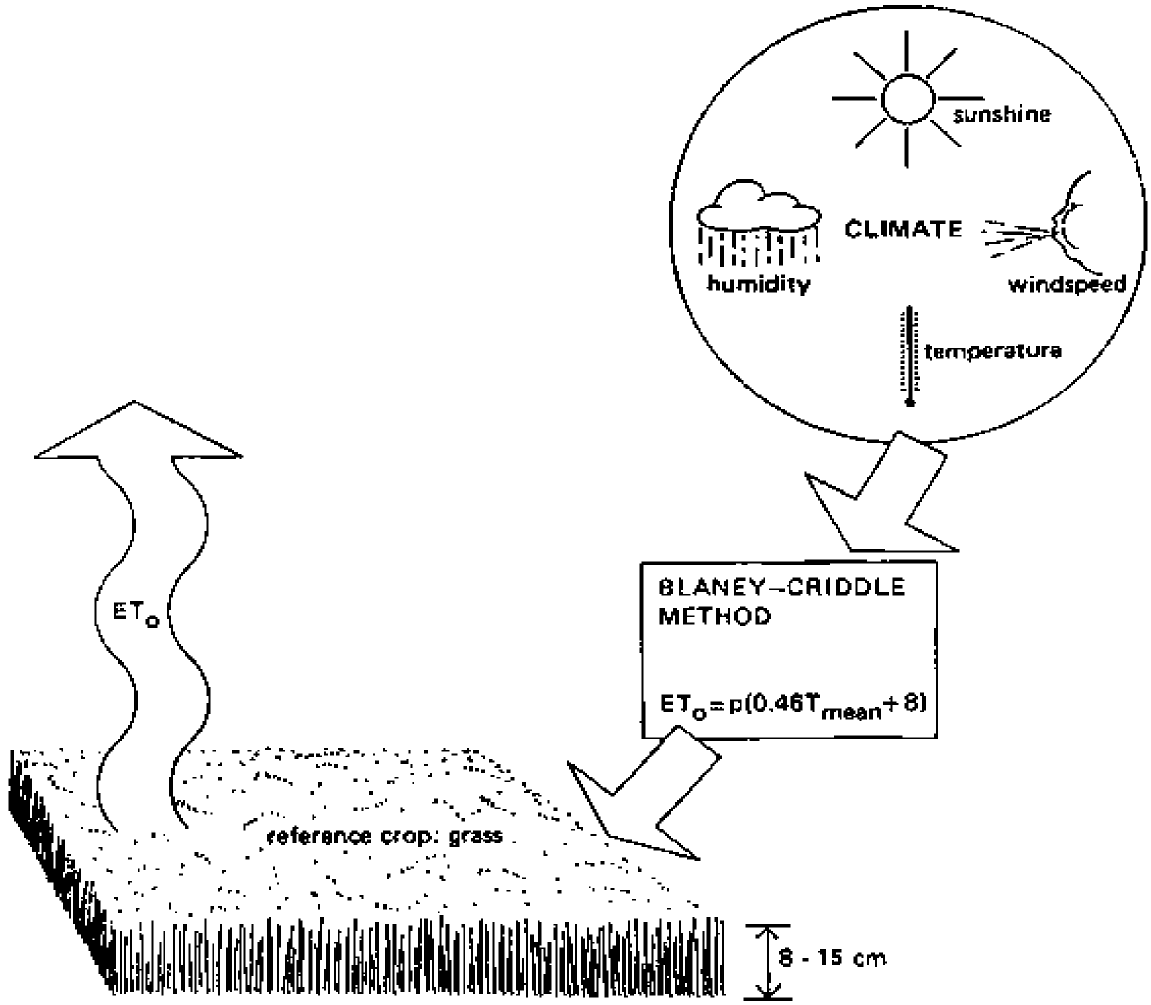
2.3.5.3 Blaney-Criddle Method

If no measured data on pan evaporation are available locally, a theoretical method (e.g. the Blaney-Criddle method) to calculate the reference crop evapotranspiration ETo has to be used. There are a large number of theoretical methods to determine the ETo. Many of them have been determined and tested locally. If such local formulae are available they should be used. If such local formulae are not available one of the general theoretical methods has to be used.

The most commonly used theoretical method is the modified Penman method which is described in detail in FAO Irrigation and Drainage Paper 24. This method, however, is rather complicated and beyond the scope of this manual.

Here only the Blaney-Criddle method is given. The Blaney-Criddle method is simple, using measured data on temperature only. It should be noted, however, that this method is not very accurate; it provides a rough estimate or "order of magnitude" only. Especially under "extreme" climatic conditions the Blaney-Criddle method is inaccurate: in windy, dry, sunny areas, the ETo is underestimated (up to some 60 percent), while in calm, humid, clouded areas, the ETo is overestimated (up to some 40 percent).

Fig. 2.6 The Blaney-Criddle method



The Blaney-Criddle formula: ETo = p (0.46 T mean +8)

ETo = Reference crop evapotranspiration (mm/day) as an average for a period of 1 month
T mean = mean daily temperature (°C)
p = mean daily percentage of annual daytime hours

The use of the Blaney-Criddle formula

Step 1: **Determination of the mean daily temperature: T mean**

The Blaney-Criddle method always refers to mean **monthly** values, both for the temperature and the ETo. If, for example, it is found that T mean in March is 28°C, it means that during the whole month of March the mean daily temperature is 28°C.

If in a local meteorological station the daily minimum and maximum temperatures are measured, the mean daily temperature is calculated as follows:

$$\text{T max} = \frac{\text{sum of all T max values during the month}}{\text{number of days of the month}}$$

$$\text{T min} = \frac{\text{sum of all T min values during the month}}{\text{number of days of the month}}$$

$$\text{T mean} = \frac{\text{T max} + \text{T min}}{2}$$

Step 2: **Determination of the mean daily percentage of annual daytime hours: p**

To determine the value of p. Table 4 is used. To be able to determine the p value it is essential to know the approximate latitude of the area: the number of degrees north or south of the equator Suppose the p value for the month **March** has to be determined for an area with a latitude of 45° South. From Table 4 it can be seen that the p value during March = 0.28.

Step 3: **Calculate ETo,** using the formula: ETo = p (0.46 T mean + 8)

For example, when p = 0.29 and T mean = 21.5°C the ETo is calculated as follows:

ETo = 0.29 (0.46 × 21.5 + 8) = 0.29 (9.89 + 8) = 0.29 × 17.89 = 5.2 mm/day.

2.4 Irrigation Control Systems

A controller is an integral part of an irrigation system. It is an essential tool to apply water in the necessary quantity and at the right time to sustain agricultural production and to achieve high levels of efficiency in water, energy and chemical uses.

Irrigation controllers have been available for many years in the form of mechanical and electromechanical irrigation timers. These devices have evolved into complex computer-based systems that allow accurate control of water, energy and chemicals while responding to environmental changes and development stages of the crop.

2.4.1 Basic Control Strategies

Two general types of controllers are used to control irrigation systems: Open control loop systems, and closed control loop systems. The difference between these is that closed control loops have feedback from sensors, make decisions and apply decisions to the irrigation system. On the other hand, open control loop systems apply a preset action, as is done with irrigation timers.

2.4.1.0 Open Control Loop Systems

When using an open control loop system, a decision is made by the operator or the amount of water and the time at which this water should be applied. The operator then goes on to set an irrigation controller according the desired schedule. These devices require external intervention they are referred to in control terms as open loop systems.

Open loop control systems use irrigation duration or applied volume for control purposes. In this type of controller the basic control parameters are how often and how long irrigation water is to be applied. Open loop controllers are also constructed in such a way that a clock is used to start irrigation and the application of a given volume to stop irrigation. In this type of controller the parameters set by the system operator are how often and the volume of water to be applied.

Open loop control systems have the advantages that they are low cost, readily available, and many variations of the devices are manufactured with different degrees of flexibility related to the number of stations and schedule specification. However, they do not respond automatically to changing conditions in the environment and require frequent resetting to achieve high levels of irrigation efficiency.

2.4.1.1 Closed Control Loop Systems

In a closed control loop the operator sets up a general strategy for control. Once the general strategy is defined, the control system takes over and makes detailed decisions of when to apply water and how much water to apply. This type of system requires that feedback be given back to the controller by one or more sensors. Depending on the feedback of the sensors, the irrigation decisions are made and actions are carried out if necessary. It is important to note that in this type of systems the feedback and control of the system is done continuously. Figure 2.7a shows the elementary components of this type of system.

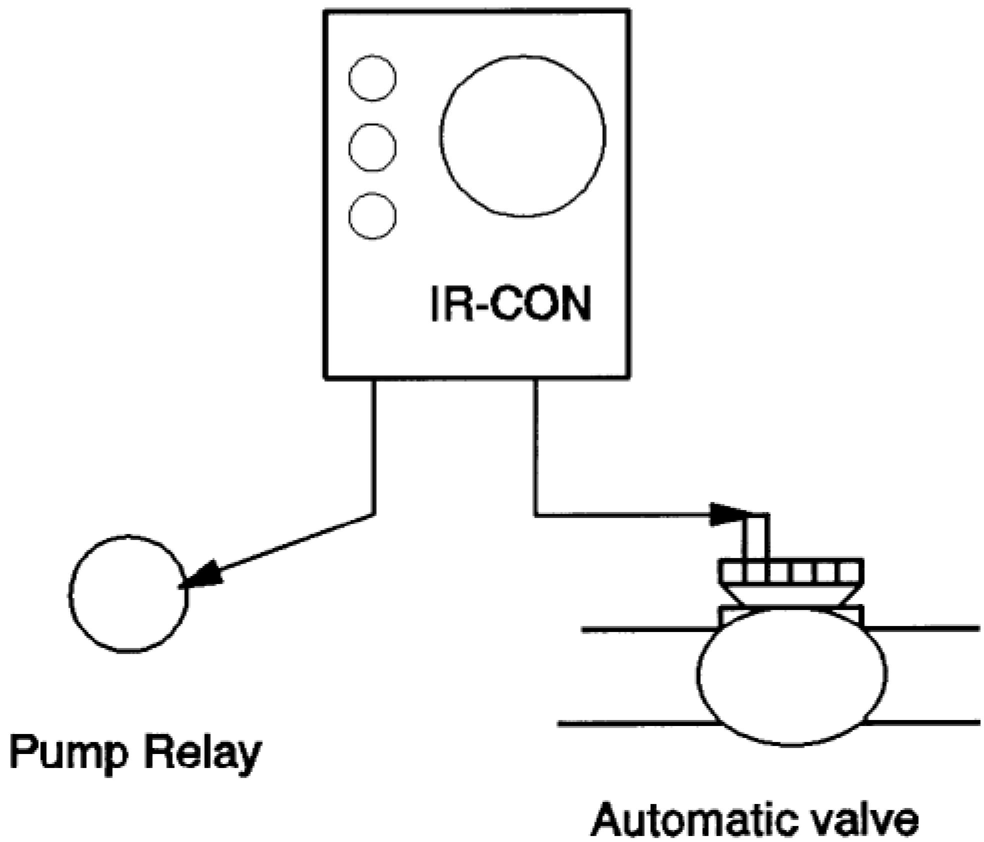


Figure 2.7a Elementary components of a closed loop system

Closed loop controllers require data acquisition of environmental parameters, such as, soil-moisture, temperature, radiation, wind-speed and relative humidity. The state of the system (for example measured soil-moisture using a sensor as illustrated in Figure 2.7a) is compared against a desired state and a decision based on this comparison is made whether irrigation should be applied or not. Closed loop controllers for irrigation systems base their irrigation decisions on:

1) direct measurement of soil-moisture using sensors,

2) calculations of water used by the plants based on climatic parameters, or

3) both soil moisture sensors and climatic parameter measurements.

When using a computer-based controller, a very important component of a closed loop control system is the logic that is used to make decisions about operation of the irrigation system. Some of these systems may be very elaborate and use complicated simulation models that are verified with soil moisture measurements to arrive at an irrigation decision and implement the action at the appropriate time. Systems of this type (with different levels of complexity), are quickly being developed, and some have become commercially available in the past few years.

The simplest form of a closed loop control system is that of a high frequency irrigation controller that is interrupted by a moisture sensor. Figure 2.7b shows this system. The sensor in Figure 3 is wired into the line that supplies power from the controller to the electric solenoid valve. The sensor operates as a switch that responds to soil moisture. When sufficient soil-moisture is available in the soil, the sensor maintains the circuit opens. When soil-moisture drops below a certain threshold, the sensing device closes the circuit, allowing the controller to power the electrical valve.

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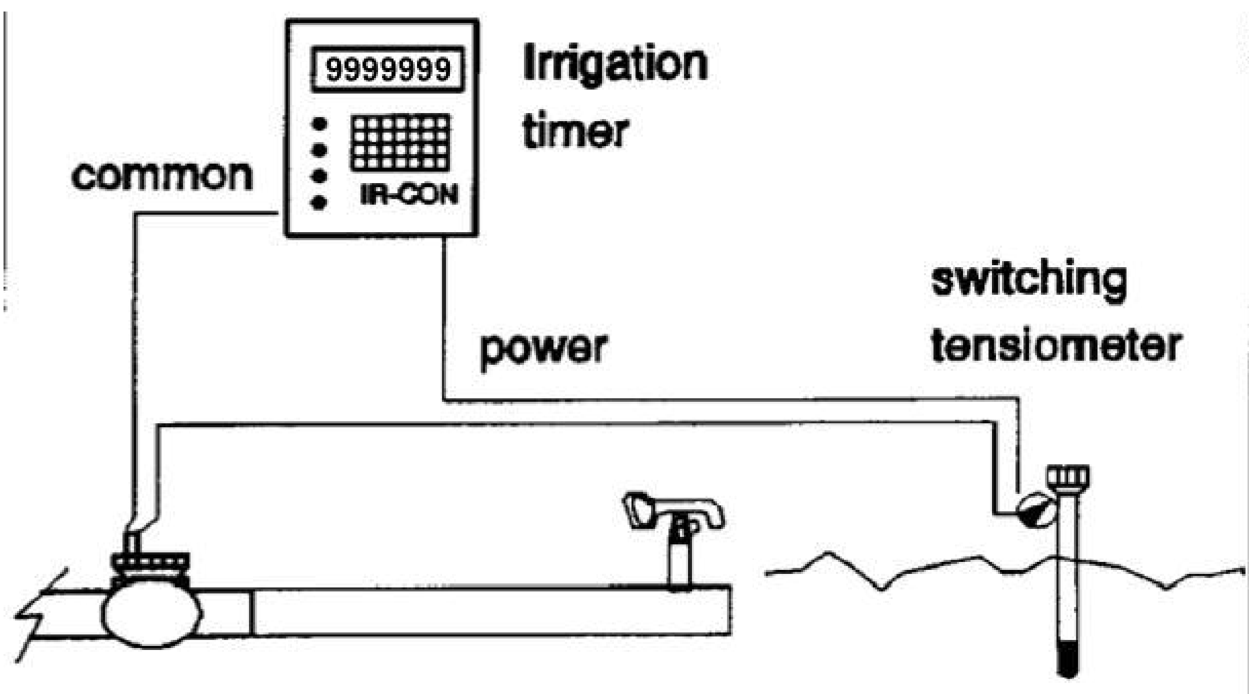


Figure 2.7b shows a closed loop system in its simplest form

Using their arrangement in Figure 2.7b, the controller can be set to irrigate at a very high frequency (4 or 5 times more often than required). When the controller attempts to irrigate, irrigation will occur only if the soil-moisture sensor allows it, which in turn occurs only when soil-moisture has dropped below acceptable levels.

The system has been used successfully in controlling small sprinkler irrigated turf and microirrigated citrus at a research site using switching tensiometers. For turf, the tensiometers were installed at the center of the bottom third of the root system (10 inches deep) and the threshold was set to the point at which water stress symptoms were visible. In citrus a bank of sensors was used under the emitter connected in parallel, in such a way that any of the sensors would allow irrigation to occur.

The feedback system in Figure 3 is very low cost and is easy to install and maintain. However, the system has limitations:

1) Determining the best location of the sensor is not a straight forward task and requires some knowledge of soil-water and root dynamics,

2) spatial variability of soil properties may result in readings that are not representative of the system.

2.5 Computer-Based Irrigation Control Systems

A computer-based control system consists of a combination of hardware and software that acts as a supervisor with the purpose of managing irrigation and other related practices such as fertigation and maintenance. This is done by the use of a closed control loop. A closed control loop consists of:

1) Monitoring the state variables,

2) comparing the state variables with their desired or target state,

3) deciding what actions are necessary to change the state of the system, and

4) carrying out the necessary actions. Performing these functions requires a combination of hardware and software that must be implemented for each specific application.

2.5.0 Hardware Components

Figure 2.8 shows the basic components of a closed loop control system, each of the hardware elements is described below.

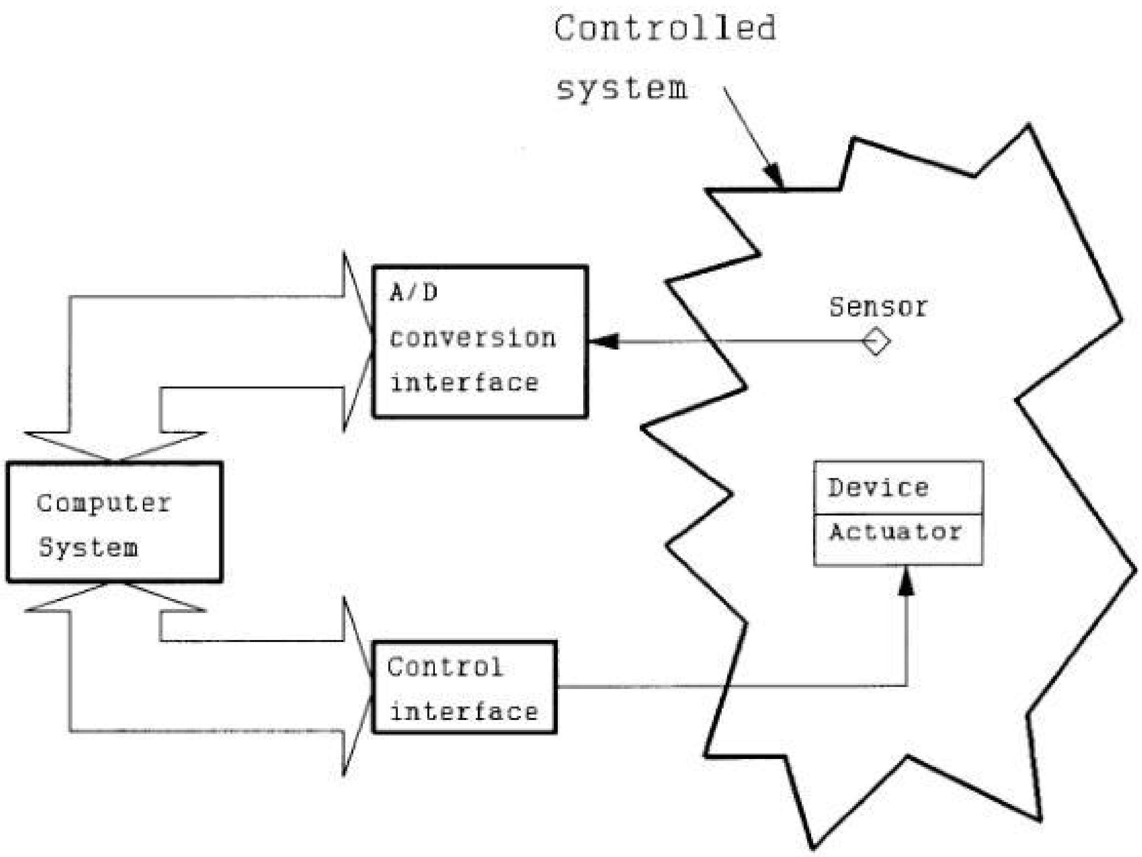
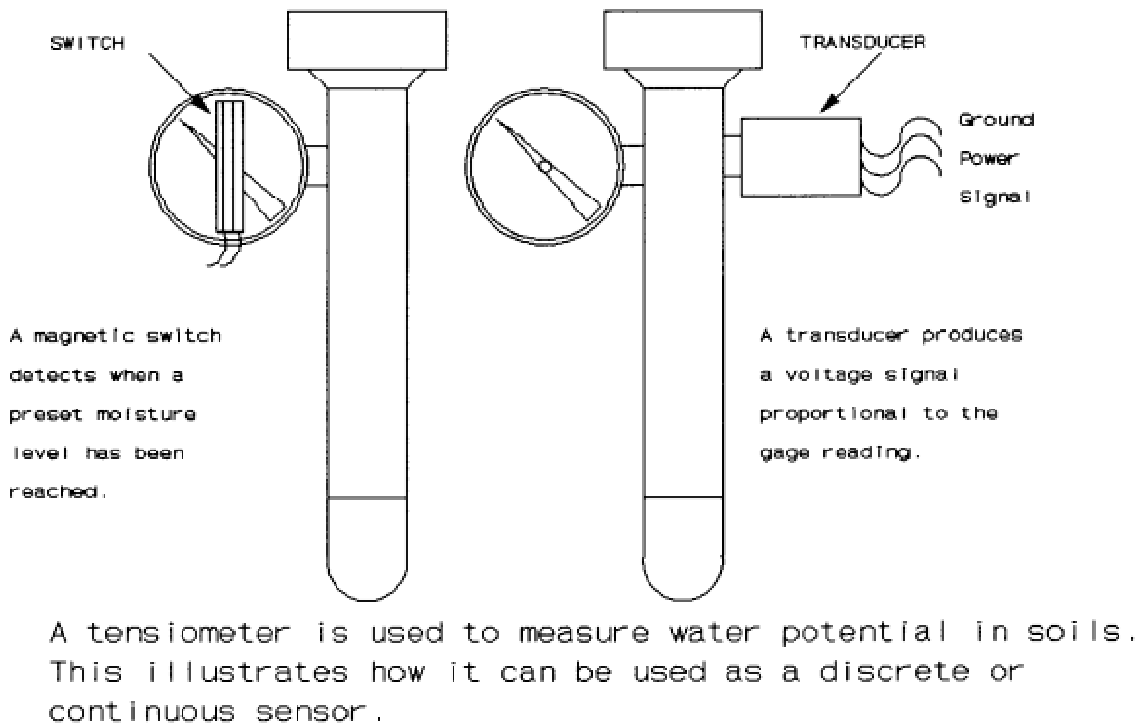


Figure 2.8 basic components of a closed loop control system

2.5.1 Sensors

A sensor is a device placed in the system that produces an electrical signal directly related to the parameter that is to be measured. In general, there are two types of sensors, continuous and discrete:

a) Continuous.



. **Figure 2.9 an example of a continuous sensor**

Continuous sensors produce a continuous electrical signal, such as a voltage, current, conductivity, capacitance, or any other measurable electrical property. For example, sensors of different kinds can be used to measure temperature, such as thermistors and thermocouples. A thermocouple will produce a voltage difference that increases as the temperature increases.

Continuous sensors are used where values taken by a state variable are required and an on/off state is not sufficient, for example, to measure pressure drop across a sand filter.

b) Discrete.

Discrete sensors are basically switches, mechanical or electronic, that indicate whether an on or off condition exists. Discrete sensors are useful for indicating thresholds, such as the opening and closure of devices (vents, doors, alarms, valves, etc.). They can also be used to determine if a threshold of an important state variable has been reached. Some examples of discrete sensors are a float switch to detect if the level in a storage tank is below a minimum desirable level, a switching tensiometer to detect if soil moisture is above a desired threshold, and a thermostat to indicate if a certain temperature has been reached. When combined with time, pulses from switches can be used to measure rates. For example, to the volume of fuel, water or chemical solution passing through a totalizing flow meter with a magnetically activated switch, or the speed of a rotating flywheel.

Sensors are an extremely important component of the control loop because they provide the basic data that drive an automatic control system. Understanding the operating principle of a sensor is very important. Sensors many times do not react directly to the variable being measured. For example, when a mercury thermometer is used to measure temperature, temperature is not being measured, rather, a change in volume due to a change in temperature is measured. Because there is a unique relationship between the volume and the temperature the instrument can be directly calibrated to provide temperature readings. The ideal sensor responds only to the "sensed" variable, without responding to any other change in the environment. It is important to understand that sensors always have a degree of inaccuracy associated with them and they may be affected by other parameters besides the "sensed" variable. The classical example is that of soil moisture measurement using electrical conductivity probes. The electrical signal produced by this sensor is closely related to soil moisture, but is greatly affected by temperature and dissolved salts (fertilizers, etc.) in the soil. Another important factor related to the sensor is its time response. A sensor must deliver a signal that reflects the state of the system within the frame of time required by the application. Using the soil moisture measurement example, the sensor must be able to "keep up" with the changes in soil moisture that are caused by evapotranspiration. Thus, proper selection of the sensors and understanding the principle of operation is critical to the success of a control system. Some of the variables that are often measured in computer based control systems are the following:

1) Flow rate, 2) pressure, 3) soil-moisture, 4) air temperature, 5) wind speed, 6) solar radiation, 7) relative humidity, 8) total salts in irrigation water, and 9) pH of irrigation water.

2.5.2 A/D interface

Since computer systems work internally with numbers (digits), the electrical signals resulting from the sensors must be converted to digital data. This is done through specialized hardware referred to as the Analog-to-Digital (A/D) interface. Discrete signals resulting from switch closures and threshold measurements are converted to 0 and 1. Continuous electrical (analog) signals produced by the sensors signals are converted to a number related to the level of the sensed variable. The accuracy of the conversion is affected by the resolution of the conversion equipment. In general, the higher the resolution the better the accuracy. For, example if a pressure sensor produces a voltage signal ranging from 0 to 5 volts for a range of pressure of 10 atmospheres, an 8 bit resolution A/D board will be able to detect a change in voltage of about 5/255 volts which will results in measurable increments of 10/255 atmospheres. If the resolution of the A/D board was 12 bit, the board would be able to detect a change in voltage of about 5/4095 volts or a measurable increment of 10/4095 atmospheres.

2.5.3 Computer system

The A/D conversion hardware is directly connected to the computer system. Given the current state of technology, the computer system may be a PC (personal computer), a minicomputer, or a specially designed machine that is solely dedicated to the control task. The type of machine depends on the type of application, and is greatly affected by factors such as environment characteristics, complexity of the controlled system, and the speed with which conversions need to take place (controlling a high speed extruder requires much more speed than a golf-course irrigation system). Many agricultural applications can be economically carried out using personal computers (PC), as is evident by the increasing number of system integrators and equipment manufactures that are marketing PC-based control systems. Also, many manufacturers of control equipment have designed and manufactured specialized computer control systems.

2.5.4 Control Interface:

Using control software, decisions may be made to modify the controlled system. The actual changes are achieved by having devices within the system that will affect the controlled variables. These devices are controlled through actuators that respond to signals from the control interface. The devices may be of the nearly continuous or discrete types. For example, the extension of a robot arm of a citrus harvesting robot requires the use of a continuous signal from the computer, while a fan or a valve requires only an on/off (discrete) signal from the computer. In general, any device that can be powered electrically can be computer controlled.

2.6 Computer-based Controller Topologies

2.6.1 Centralized computer

The simplest form in which a computer control system can be arranged is to use a single computer system that included the necessary support hardware and software to support data acquisition and control. The basic system describe in Figure 2.10 is this type of system.

2.6.2 Satellite systems

A centralized computer can be linked to other devices that have specialized purposes. One such type of device can be a datalogging system (a computer in itself) used to collect weather data. Also, in large complex systems, a central computer can be used to download instruction to intelligent controllers.

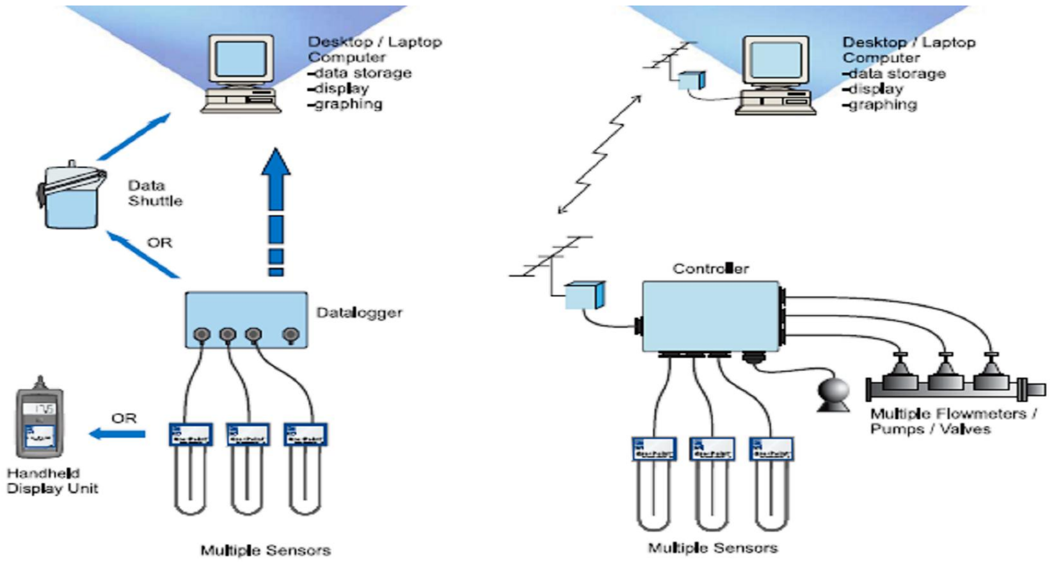


Figure 2.10 Example of computer based topologies

Communications between the central control computer can be implemented in a variety of ways:
a) Serial or parallel communication links.

b) Telephone link using serial communications.

c) Carrier wave using powerline modulation.

d) Communications bus.

Telephone and serial links can be hardwired or wireless. Figure 2.10 shows the components of a typical high-end commercially available computer based control system.

2.7 Controllers

2.7.0 Electromechanical Controllers

Electromechanical controllers use an electrically driven clock and mechanical switching (gear arrays) to activate the irrigation stations. These types of controllers are generally very reliable and not too sensitive to the quality of the power available. They generally are not affected by spikes in the power, and unless surges and brownouts are of such magnitude that they will damage the motor, they will continue to operate. Even if there is a power outage, the programmed schedule will not be lost and is generally delayed only for the duration of the power outage. However, because of the mechanically-based components they are limited in the features they provide. Figure 2.11 shows the components of a commercially available electromechanical controller.

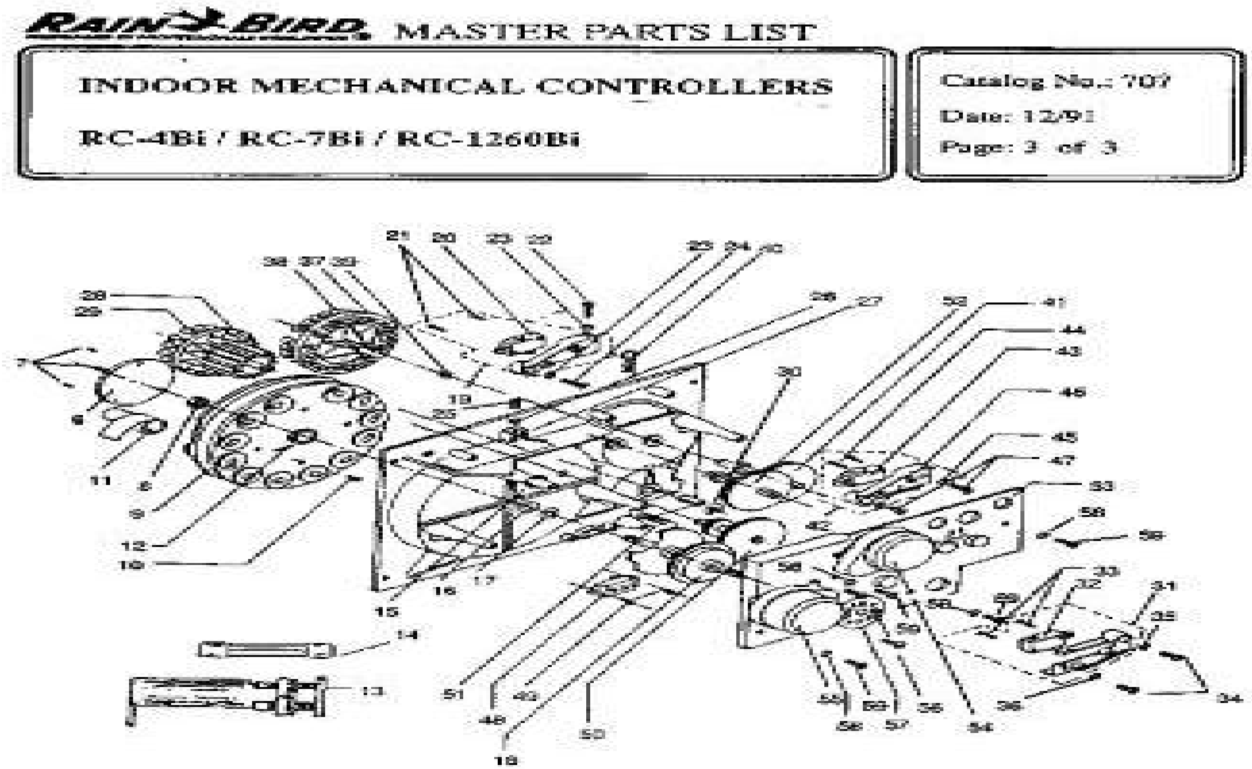


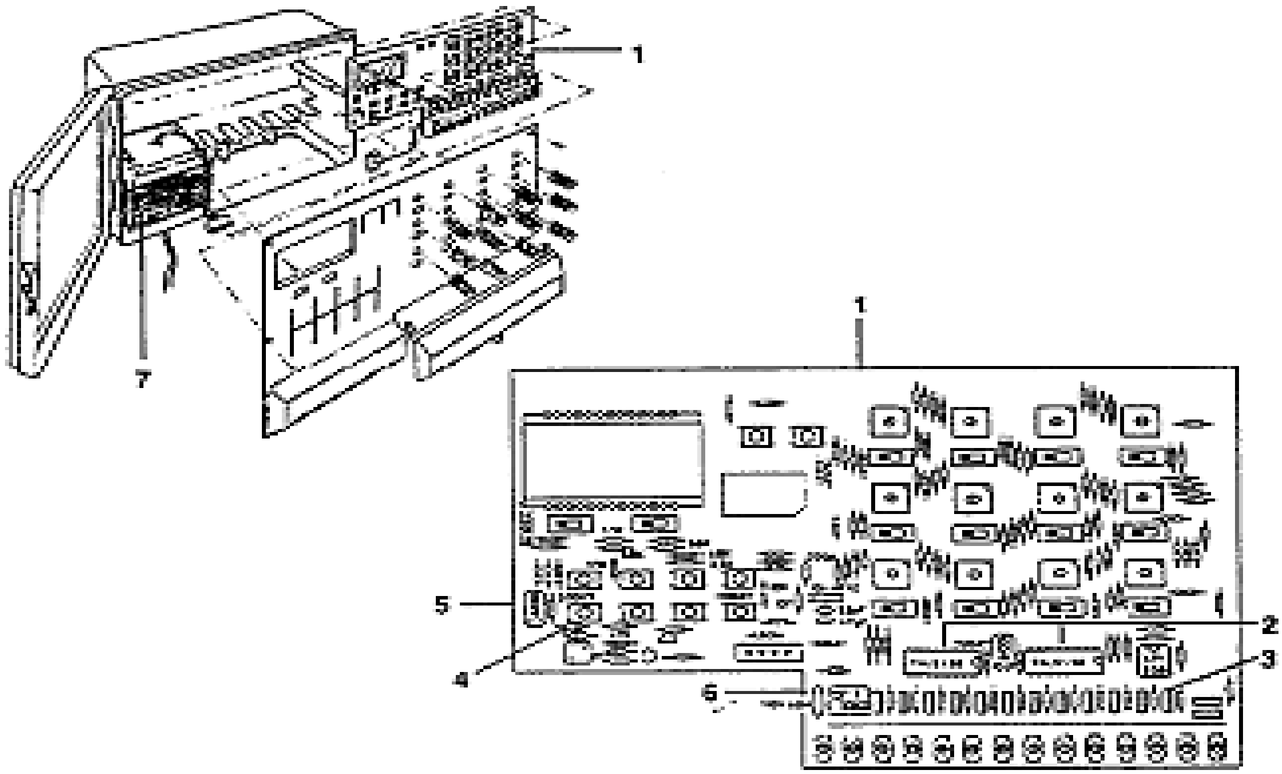
Figure 2.11 a typical commercially available electromechanical controller.

2.7.1 Electronic Controllers

Electronic controllers rely on solid state and Integrated circuits to provide the clock/timer, memory and control functions. These types of systems are more sensitive to powerline quality than electromechanical controllers and may be affected by spikes, surges and brownouts. Particularly spikes and surges are common in rural areas in Florida where lightning tends to be frequent and intense. These types of systems may require electrical suppression devices in order to operate reliably. Because of the inherent flexibility of electronic devices, these controllers tend to be very flexible and provide a large number of features at a relatively low cost. Figure 2.12 shows the components of a commercially available electronic controller (irrigation timer).

RAIN BIRD MASTER PARTS LIST

ELECTRONIC CONTROLLER **HP-6 / HP-8 / HP-12**	Catalog No.: 764 Date: 12/91 Page: 1 of 1



Ref.	Description	HP-6	HP-8	HP-12
1	PWB Assembly 50Hz or 60Hz	402321	402322	402323
2	I.C. 74LS138	650071	650071	650071
3	Triac, Valve Out-put side	628395	628395	628395
4	Diode 1N4002	650077-02	650077-02	650077-02
5	Capacitor, 100MF	650013-45	650013-45	650013-45
6	MOV 68v,500A	650016	650016	650016
7	Transformer 60 Hz	402320	402320	402320
7	Transformer 50 Hz	402400	402430	402430

Note: Part numbers enclosed in brackets ( ) are not available individually, but may be sold in assemblies or kits.

Figure 2.12 shows a typical commercially available electronic controller

2.7.2 Microcontrollers

PIC Microcontroller families

Family PIC12CXXX

PIC12C508: This is a low-cost, 8-pin device with 512 x 12 EPROM program memory and 25 bytes of RAM data memory. The device can operate at up to 4 MHz clock input and there are only 33 single word instructions. The device features a 6-pin I/O port, 8-bit timer, power-on reset, watchdog timer, and internal, 4 MHz RC oscillator capability.

Table 2.1 Some PIC 12CXXX family members

Microcontroller	Program memory	Data Ram	Max speed (MHz)	I/O ports	A/D converter
12C508	512 × 12	25	4	6	–
12C672	2048 × 14	128	10	6	4
12CE518	512 × 12	25	4	6	–
12CE673	1024 × 14	128	10	6	4
12CE674	2048 × 14	128	10	6	4

Family PIC16C5X

PIC16C54: This is one of the earliest PIC microcontrollers. The device is 18-pin with a 512 x 12 EPROM program memory, 25 byte of data RAM, 12 I/O port pins, a timer, and a watchdog timer. The device can operate at up to 20 MHz clock input. Some other members of this family, e.g. PIC16C56 has the same structure but more program memory (1024 x 12). PIC16C58 has more program memory (2048 Å12) and also more data memory (73 bytes of RAM).

Table 2.2 Some PIC16C5X family members

Microcontroller	Program memory	Data RAM	Max speed (MHz)	I/O ports	A/D converter
16C54	512 × 12	25	20	12	-
16C55	512 × 12	24	20	20	-
16C57	2048 × 12	72	20	20	-
16C58A	2048 × 12	73	20	12	-
16C505	1024 × 12	41	4	12	-

Family PIC16CXXX

PIC16C554: This microcontroller has similar architecture to the PIC16C54 but the instructions are 14-bits wide. The program memory is EPROM with 512 x 14 and the data memory is 80 bytes of RAM. There are 13 I/O port pins, a timer, and a watchdog timer.

Some other members of this family, e.g. PIC16C71 incorporates four channels of A/D converter, 1024 x 14 EPROM program memory, 36 bytes of data RAM, timer, and watchdog timer. PIC16F877 is a sophisticated microcontroller which offers eight channels of A/D converters, 8192 x 14 program memory, 368 bytes of data memory, 33 I/O port pins, USART, I2C bus interface, SPI bus interface, 3 timers, and a watchdog timer. PIC16F84 is a very popular microcontroller, offering 1024 x 14 flash EEPROM program memory, 68 bytes of data RAM, 64 bytes of EEPROM data memory, 13 I/O port pins, timer, and a watchdog timer.

Table 2.3 Some PIC16CXXX and PIC16FXXX family members

Microcontroller	Program memory	Data RAM	Max speed (MHz)	I/O ports	A/D converter
PIC17C42	2048 × 16	232	33	33	–
16C554	512 × 14	80	20	13	–
16C64	2048 × 14	128	20	33	–
16C71	1024 × 14	68	20	13	4
16F877	8192 × 14	368	20	33	8
16F84	1024 × 14	68	10	13	–

Family PIC17CXXX and PIC18CXXX

PIC17C42: This microcontroller has a 2048 x 16 program memory. The data memory is 232 bytes. In addition, there are 33 I/O port pins, USART, 4 timers, a watchdog timer, 2 data capture registers, and PWM outputs. PIC 17C44 is similar but offers more program memory.

PIC18CXXX members of this family include PIC18C242 type microcontroller with 8192 x 16 program memory, 512 bytes of data memory, 23 I/O port pins, 5 A/D channels (10-bits wide), USART, I2C, and SPI bus interfaces, PWM outputs, 4 timers, watchdog timer, compare and capture registers, and multiply instructions.

All memory of the PIC microcontroller family is internal and it is usually not very easy to expand the memory externally. No special hardware or software features are provided for expanding either the program memory or the data memory. The program memory is usually sufficient for small dedicated projects. However the data memory is generally small and may not be enough for medium to large projects unless a bigger and more expensive member of the family is chosen. For some large projects even this may not be enough and the designer may have to choose a microcontroller from a different manufacturer with a larger data memory, or a microcontroller where the data memory can easily be expanded (e.g. the Intel 8051 series).

Table 2.4 Some PIC17CXXX and PIC18CXXX family members

Microcontroller	Program memory	Data RAM	Max speed (MHz)	I/O ports	A/D converter
17C43	4096×16	454	33	33	-
17C752	8192×16	678	33	50	12
18C242	8192×16	512	40	23	5
18C252	16384×16	1536	40	23	5
18C452	16384×16	1536	40	34	8

Chapter 3

Materials and Methodology

3.0 Introduction

The following materials were used in this project:

3.1 The PIC 16F872 Microcontroller

Pin Layout

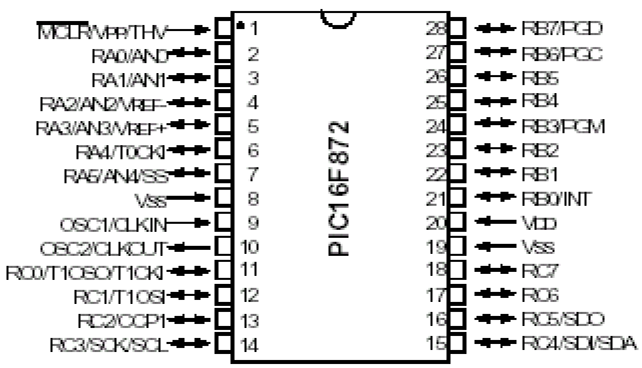


Fig 3.0 PIC16F872 Microcontroller

High-Performance RISC CPU

- Only 35 single word instructions to learn
- All instructions are single cycle (1µs) except for program branches
- Operating speed: DC - 20MHz clock input
- 2 k Bytes Flash Program Memory
- 128 Byte RAM Data Memory

- 64 Byte EEPROM Data Memory
- In-circuit serial programming
- Interrupt Capability (up to 10 sources)

Peripheral Features

- High current sink/source: 25mA
- Two 8-bit timer/counter(TMR0,TMR2) with 8-bit programmable prescalar
- One 16 bit timer/counter(TMR1)
- One Capture, Compare, PWM module
- 10-bit, 5-channel Analog-to-Digital converter
- Synchronous Serial Port (SSP) with SPI (Master mode) and I2C (Master/Slave)
- Watchdog Timer (WDT) with separate RC oscillator

Special Microcontroller Features

- Power-On Reset
- Power-up Timer (PWRT) and Oscillator Start-Up Timer (OST)
- Power saving SLEEP mode
- Programmable code protection
- Selectable Oscillator Options

CMOS Technology

- Low power, high speed CMOS FLASH technology
- Fully Static Design
- Low Power Consumption
- < 2mA @ 5V, 4MHz

- 20µA typical @ 3V, 32kHz
- < 1µA typical standby current

I/O and Packages

- 22 I/O pins with individual direction control
- 28-pin DIP

3.2 CM 3 Pyranometer,

The CM3 pyranometer(Kipp and Zonen, Delft Holland) is an instrument for measuring the solar irradiance. The sensor construction is such that it measures the solar energy that is received from the whole hemisphere (180^o field of view). The output is expressed in Watts per mitre square.

List of specifications

- Response time 95% 18s
- Zero offsets 1 and 2
- 1: 200 W/m2 thermal radiation < 15W/m^2
- 2:5 K/h change in ambient
- Temperature <4W/m^2
- Non-stability <1% change per year
- Non-linearity ±2.5% (D1000W/m^2)
- Directional error for beam radiation < ±25W/m^2 at 1000 W/m^2
- Spectral selectivity ±5% (350-1500nm)
- Temperature dependence of sensitivity 6% (-10 to +40^oC)

3.3 System physical design

Context Diagram

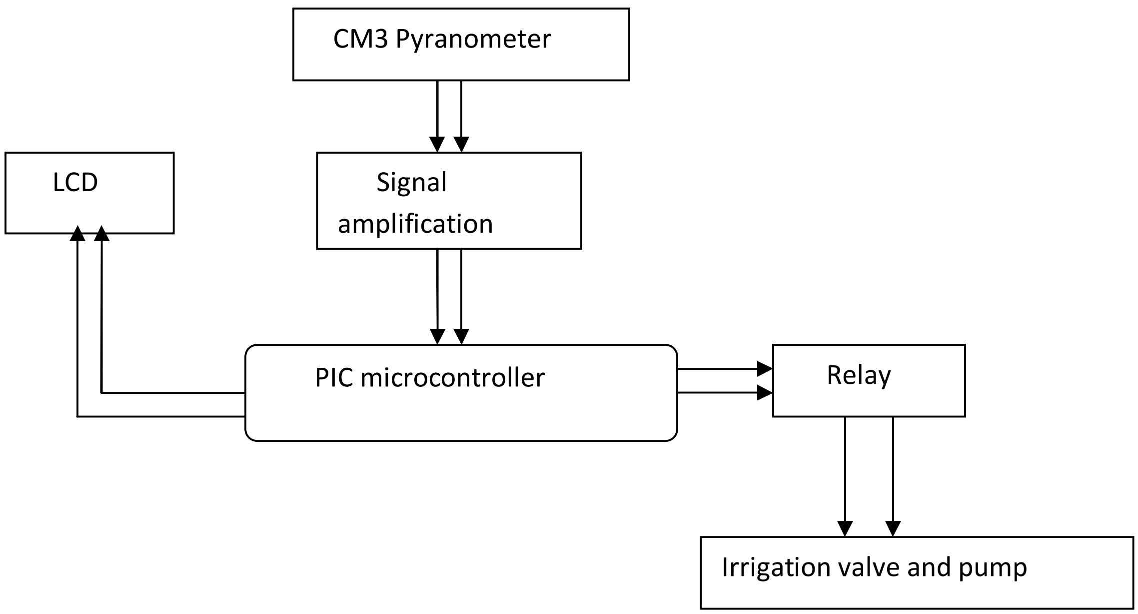


Fig 3.1 Irrigation System's physical design

The system consists of a radiation sensor called the CM3 Pyranometer, which coverts radiation into a voltage and a signal amplification circuit. The analogue voltage signal is then fed into the Analogue to Digital Converter in the PIC Microcontroller. The PIC microcontroller is the one that controls the relay, depending on the inputs from the CM3 Pyranometer. All the data displays are made on the LCD display.

3.4 Data acquisition

The data acquisition process consists of getting radiation readings from the CM3 Pyranometer into then PIC Microcontoller. An electronic circuit is required for signal amplification or signal de-amplification, depending on the nature of the voltage produced by the input device. It is also required for powering the devices, for display purposes and control purposes. Below are the parts of the electronic circuit designed for the irrigation control:

3.4.0 Electronic Circuit diagram design

Components of the Electronic Circuit

1) **Power supply unit**

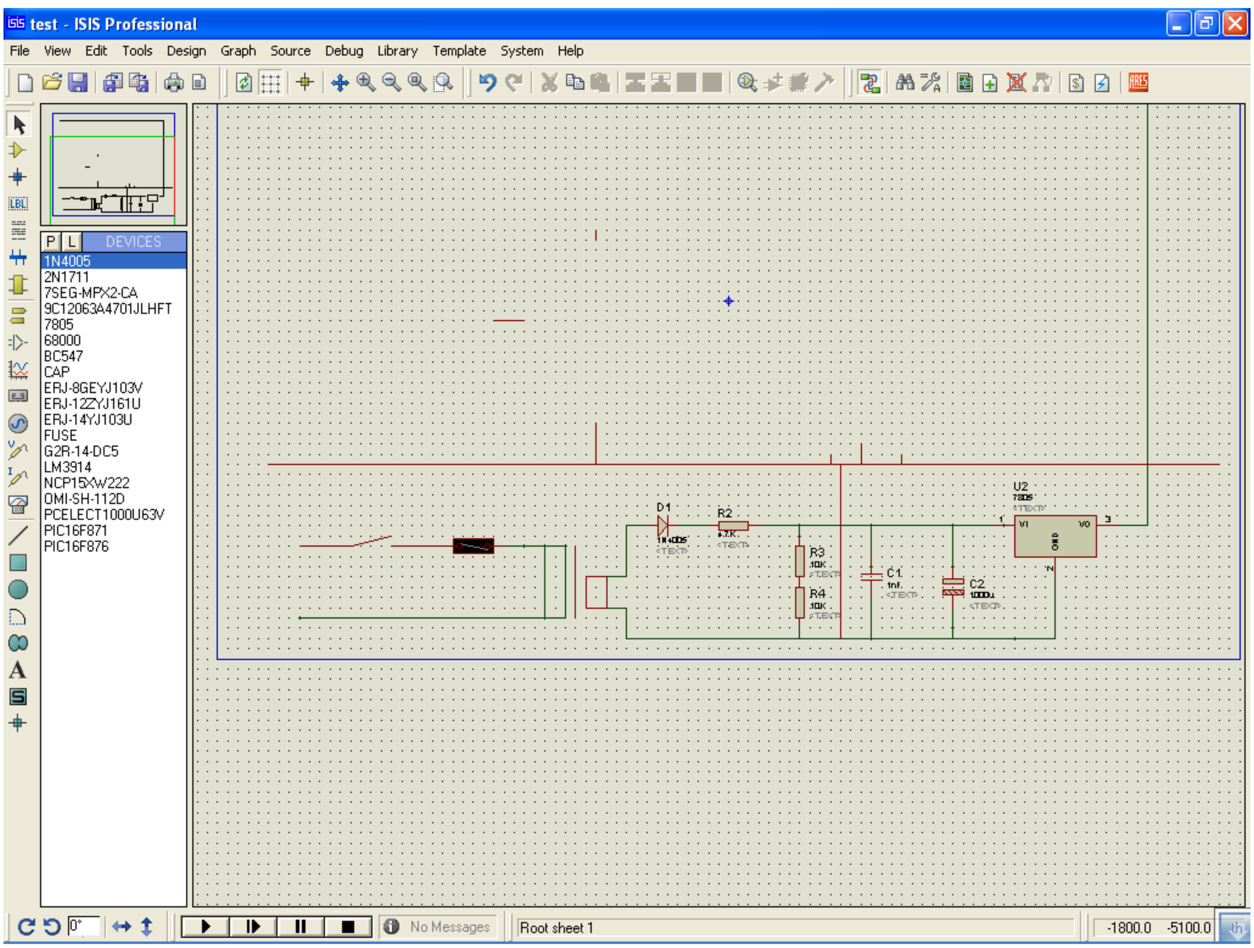


Fig 3.2 Irrigation systems power supply unit

The power supply consists of a transformer to step down the voltage from the mains to 5 volts. It also consists of a regulator which makes sure that the voltage supply remains constant at 5 volts regardless of the load present. The diode is there to make sure that the current flows in one direction, this result in current flowing in pulses, therefore the capacitors are there for smoothing the current.

2) 2-digit Seven segment display

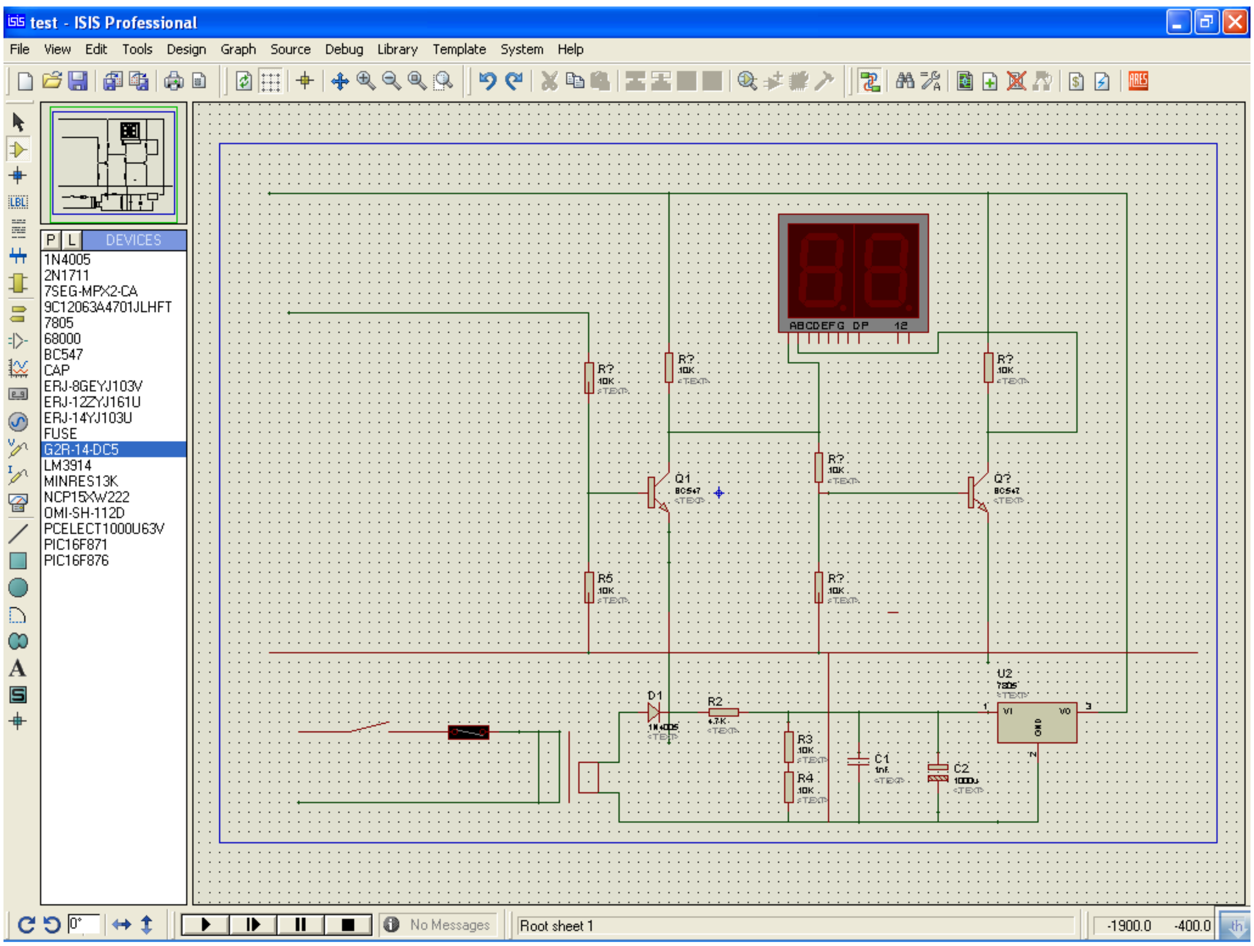


Fig 3.3 Irrigation system's display unit

The 2 digit display consists of the 2 digit LCDs with a capacity of displaying 1 digit at a time. In order to display two digits, we have to multiplex. The multiplexing involves the use of transistors which are controlled by sending either bit 1 or 0 to the pin 0 of Port C. If we send a 1, the current goes up through the transistor and the digit is displayed on the Left of the display. If we send a 0, then the current goes down and the digit is displayed on the right of display. We also need to introduce a small delay (approximately 5 milliseconds) between each digitôs displays, so that the same digit is not displayed at the same time on both sides.

3) Relay

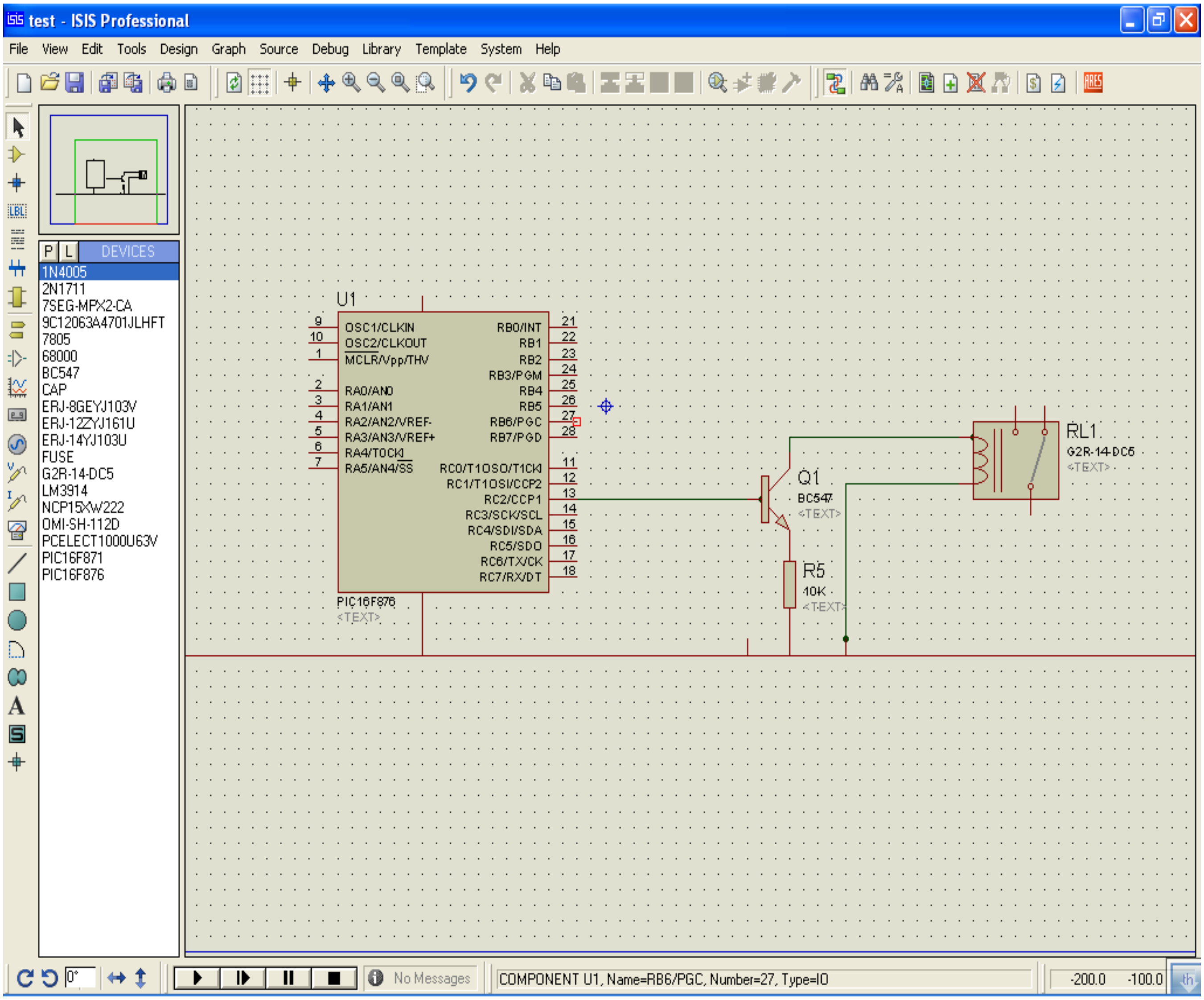


Fig 3.4 Irrigation system's relay unit

The relay consists of a transistor and an adapter connected to the mains. To turn on the relay, we need to send bit 1 though pin 5 of Port C, and to turn off we need to clear the bit.

Physical circuit design

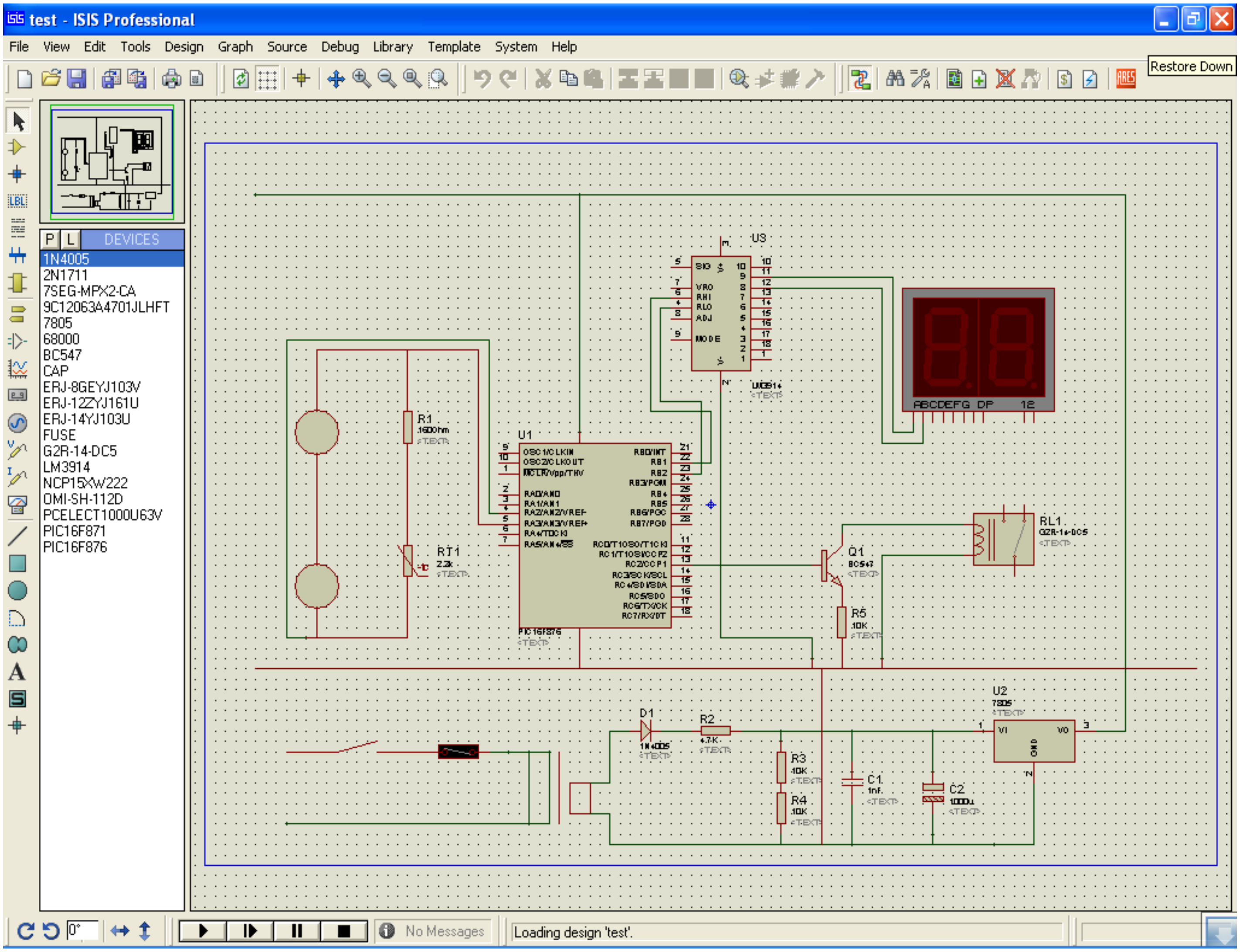


Fig 3.3 Irrigation system's electronic circuit

Every component of the circuit is connected to the PIC Microcontroller. The ports have to be configured as input or output ports in the TRIS registers. The input devices are connected to port A, the display is connected on Port B, and the relay is connected on Port C. The power supply powers the devices on the circuit including the microcontroller. The inputs are generated by varying the readings on the CM3 Pyranometer. The reading is proportional to the voltage that is produced by the CM3 Pyranometer. Inside the PIC Microcontoller thereôs an Analogue to digital converter that converts analogue readings to digital values. After the completion of the Analogue to digital conversion, the digital value will be stored in the lower part of the ADRES register, which is called the ADRESL.

3.5 Data Processing and Irrigation sequencing

Algorithm Design

While (sub-season a)

start :

read radiation every 15 minutes

Rs = Current reading

Rs_{-1} = Previous reading

integrate between aRs and aRs_{-1} over 15 minutes or

alternatively find area under the graph, assuming a smooth increase

Total water lost = × water lost in all 15 min intervals

determine(water to be applied or replaced today)

determine(time to irrigate)

start irrigation()

induce an independent delay(time to irrigate)

End irigation()

End

```
While  (sub-season b)

    start :

        read  radiation every 15 minutes

            Rs   = Current reading

            Rs-1 =  Previous reading

    integrate between aRs  and  aRs-1  over 15  minutes or

     alternatively find area under the graph, assuming a smooth increase

  Total water lost = × water lost in all 15 min intervals

            determine(water to be applied or replaced today)

         determine(time to irrigate)

         start  irrigation()

        induce an independent delay(time to irrigate)

      End irigation()

    End


While (sub-season c,d,e,é  é  é  é  é  é  )

    start :

        read radiation every 15 minutes

            Rs   = Current reading

            Rs-1 = Previous reading
```

integrate between aRs and aRs_{-1} over 15 minutes or

alternatively find area under the graph, assuming a smooth increase

Total water lost = × water lost in all 15 min intervals

determine(water to be applied or replaced today)

determine(time to irrigate)

start irrigation()

induce an independent delay(time to irrigate)

End irigation()

End

The Data processing consists of getting the digital value from the ADRESL register every 15 minutes. Then we have to integrate between the previous readings over the entire 15 minute interval. The totals over each interval are stored in the general purpose registers. Then we have to calculate the total over the entire day. The totals for the entire day and the entire day are stored over multiple registers. We then have to divide the totals by the irrigation application rate to find the time that we need to irrigate.

Chapter 4

Conclusions, recommendations and future work

4.0 Conclusions

In this thesis, we have evaluated the acquisition and processing of data using an 8-bit register. Our results show that using an 8 bit of the acquisition of data whose magnitude can range from 0-1400 watts/m^2 introduces a great deal of inaccuracy in terms of data processing because for the data to be fed into the PIC Microcontroller a transformation(a divide by 10 transformation) has to be performed on the data. Further, during division, we had problems in storing fractions, and therefore another transformation (a multiply by 20 transformation) had to be performed also. So during the whole process several transformations had to be performed on the data so that the data remains in a usable state. The storage of values was also a problem since in some instances a single value had to be stored over multiply register and making arithmetic operations using such values become tedious and therefore confusing for the programmer.

Further the instruction set was too small so much that most of the basic functions which are readily available in most instruction sets, like division, multiplication, square root, etcetera had to be reconstructed from first principles, whilst other complex functions like integration proved to be extremely difficult to construct. However we managed to find close substitutes to these functions, but it also introduced a great deal of inaccuracy.

The PIC Microcontroller 16F872 is not time conscious like the computer and other more advanced controllers, so several independent delays had to be introduced especially for day keeping and during irrigation. The introduction of long independent delays using 8 bit time was very difficult, considering the total available storage space that was available. Hence this resulted in independent delays having some a great deal of dependence, especially in very long independent delays.

4.1 Recommendations

In situations where accuracy in terms of data processing is a priority we will need to introduce a slightly more powerful processor in terms of working memory, storage memory, and also with a slightly bigger instructions with well constructed basic functions e.g 16 bit processor. We will also need to embed some more flexible language like C or C++ within the assembly language code so as to make it easier to construct complex functions.

4.2 Future work

This research did not look at how to deal with power cuts, although it is easy to back-up the power for the electronic circuit, the irrigation pump and equipment requires a lot of electricity. We will need to incorporate into the electronic circuit a sub-circuit which can detect the presence of electricity from the main after a shut down. The signal can then be used to resume or start irrigation after the shutdown. Artificial intelligence would also be required for this kind of work.

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Annexes

Annex A

Initializing the PIC16F870

```
LIST    p=16F870
        #include "P16F870.INC"

; Macro to generate a MOVLW instruction that also causes a model break:
break      MACRO arg
        DW    0x3100 | (arg & H'FF')
        ENDM

        cblock 0x20
          count,                                                         lc1,lc2,lc3,k,
day,temp,DIVIDENT,DIVISOR,DIVRES,TEMPY8,TEMPX8,IDX16,RESULT8,TEMPX,
TEMPY, RESULT, MULY , MULP, MULRES,REM,REMS,RESULTS,WLE,IAPR
 ;
        endc

        ; Vector for normal start up.
        org     0
        goto    start

        org     4
        goto    inthlr
```

Annex B

Look-up table for the analogue to digital conversion

```
; Analogue voltage to  hexadecimal conversion Look up table

HEXTABLE      ;clrf    PCLATH          ; Clear PCLATH for zero page
            addwf PCL,F

          retlw 0x00; 0
```

```
retlw 0x00
retlw 0x01
retlw 0x00
retlw 0x02
retlw 0x00
retlw 0x03
retlw 0x00
retlw 0x04
retlw 0x00
retlw 0x05
retlw 0x00
retlw 0x06
retlw 0x06
retlw 0x07
retlw 0x07
retlw 0x08
retlw 0x08
retlw 0x09
retlw 0x09
retlw 0x00
retlw 0x0A           ;10
retlw 0x00
retlw 0x0B
retlw 0x00
retlw 0x0C
retlw 0x00
retlw 0x0D
retlw 0x00
retlw 0x0E
retlw 0x00
retlw 0x0F
retlw 0x00
retlw 0x10
retlw 0x00
retlw 0x11
retlw 0x00
retlw 0x12
retlw 0x00
retlw 0x13
retlw 0x00
retlw 0x14;20
…………………………………….
……………………………………..
………………………………..
retlw 0x64 ;100
```

```
retlw 0x00
retlw 0x65
retlw 0x66
retlw 0x67
retlw 0x00
retlw 0x68
retlw 0x00
retlw 0x69
retlw 0x00
retlw 0x6A
retlw 0x00
retlw 0x6B
retlw 0x00
```

Annex C

PIC Microcontroller Sub-routines

```
        ;division_function

devide    MOVF   DIVIDENT,W
        MOVWF  TEMPX8
        MOVF   DIVISOR,W
        MOVWF  TEMPY8
        CALL   DIVV8
        MOVF   RESULT8,W
        MOVWF  DIVRES

        MOVF   DIVISOR,W
        MOVWF  MULY

        MOVF   DIVRES,W
        MOVWF  MULP

        CALL   MULTIPLY

        SUBWF  DIVIDENT,W

        MOVWF  REM

        return

DIVV8
```

```
        MOVF   TEMPY8,F
        BTFSC  STATUS,Z ;SKIP IF NON-ZERO
        RETURN
        CLRF   RESULT8
        MOVLW  1
        MOVWF  IDX16

SHIFT_IT8
        BTFSC  TEMPY8,7
        GOTO   DIVU8LOOP
        BCF    STATUS,C
        RLF    IDX16,F
        BCF    STATUS,C
        RLF    TEMPY8,F
        GOTO   SHIFT_IT8



DIVU8LOOP
          MOVF   TEMPY8,W
          SUBWF  TEMPX8
          BTFSC  STATUS,C
          GOTO   COUNT8
          ADDWF  TEMPX8
          GOTO   FINAL8

COUNT8
          MOVF   IDX16,W
          ADDWF  RESULT8

FINAL8
          BCF    STATUS,C
          RRF    TEMPY8,F
          BCF    STATUS,C
          RRF    IDX16,F
          BTFSS  STATUS,C
          GOTO   DIVU8LOOP

          RETURN

;multiplication_function

MULTIPLY   MOVF   MULY,W
          MOVWF  TEMPX
          MOVF   MULP,W
```

```
        MOVWF   TEMPY
        CALL    MULV8
        MOVF    RESULT,W
        MOVWF   MULRES

        RETURN

MULV8
        CLRF RESULT
MULU8LOOP
        MOVF TEMPX,W
        BTFSC TEMPY,0
        ADDWF RESULT
        BCF STATUS,C
        RRF TEMPY,F
        BCF STATUS,C
        RLF TEMPX,F
        MOVF TEMPY,F
        BTFSS STATUS,Z

        GOTO MULU8LOOP

        RETURN

; Display function for Analogue to Digital conversion values


disp_adc    bsf      STATUS,RP0       ; Bank 1.




          movf     ADRESL,W          ; Get ADRES into W.
         CALL     HEXTABLE

         return


disp_adc2   bsf      STATUS,RP0       ; Bank 1.


        bcf      STATUS,RP0       ; Bank 0.
        movwf    PORTB            ; Write it to port
        bsf      PORTC,6          ; Toggle latch enable
        nop                       ; Wait
```

```
 nop                    ; Wait
 bcf     PORTC,6         ; Toggle latch enable
 movf    ADRESL,W        ; Get ADRES into W.
movwf   PORTB           ; Write it to port
 bsf     PORTC,7         ; Toggle latch enable
 nop                    ; Wait
 nop                    ; Wait
 bcf     PORTC,7         ; Toggle latch enable

 return
```

Annex D

PIC configurations and control program for the automated irrigation system

```
; Main program starts here:
start

clrf    0x73
 clrf    0x74
 clrf    0x75
 clrf    0x76
 clrf    0x77
 clrf    0x78
 clrf    PORTC

 movwf   PORTB           ; Ensure PORTB is zero before we enable it.
 movwf   PORTC           ; Ensure PORTC is zero before we enable it.

 movwf   count          ; reset count value.
 movwf   CCPR1H          ; Clear.
 movwf   CCPR1L          ; Clear.

 ; Set up ports:
 bsf     STATUS,RP0      ; Select Bank 1

 movlw   0x01
 movwf   TMR0
 movlw   0xFF                    ; Set W to mask for all inputs.
 movwf   TRISA          ; set TRISA register as inputs.
 movlw   0x00                    ; Set W to mask for all inputs.
 movwf   TRISA          ; set TRISA register as inputs.
```

```
        bcf     STATUS,RP0      ; Select Bank 1
        bsf     PORTA,0
        bcf     PORTA,0
        bsf     PORTA,0
        bcf     PORTA,0
        bsf     STATUS,RP0      ; Select Bank 0

        movlw   0xFF                    ; Set W to mask for all inputs.
        movwf   TRISA           ; set TRISA register as inputs.
        clrf    TRISB           ; Set TRISB register as outputs.
        clrf    TRISC           ; Set TRISC register as outputs.

        movlw   0x81            ; ADFM=1, all inputs analogue, +VREF enabled.
        movwf   ADCON1          ; Save it.
        bcf     STATUS,RP0      ; Select Bank 0.
        movlw   0xC1                    ; Clock/Channel select and enable.
        movwf   ADCON0          ; Save it.
        movlw   0x01                    ; Number of loops of 255 clocks.
        call    swait2          ; Wait for acquire time.


start_new_day     movlw    0x60
                  movwf    day


;Analogue to digital conversion module



do_conv    bsf     ADCON0,GO
wait_eoc   btfsc   ADCON0,GO        ; Is bit still set?
        goto    wait_eoc        ; loop and wait for end of conversion.

        bcf     STATUS,RP0      ; Ensure we have bank 0.
        bsf     PORTC,0         ; Show ISR in progress results.
        incf    count,F         ; Increment count.
        call    disp_adc        ; read captured value.

        movwf   0x25
        bcf     STATUS,C

        addwf   0x26,W          ; Adding current and previous value
```

```
        movwf   DIVIDENT        ; devision to get resultant
        movlw   0x02
        movwf   DIVISOR
        CALL    devide

        movf    DIVRES,W
        movwf   0x72          ; store result in 0x72
        movwf   MULY           ; multiplication by a constant 3
        movlw   0x03
       movwf   MULP

        CALL    MULTIPLY

        movf    MULRES,W
        movwf   0x72          ; store result in 0x72


        movwf   DIVIDENT        ; division by a constant 20
        movlw   0x14
        movwf   DIVISOR
        CALL    devide


        movf    DIVRES,W
        movwf   0x72

        movf    REM,W
        movwf   0x73
        movlw   0x04
        subwf   0x73,1

        btfsc   STATUS,C       ;test for register overfolow
        goto    here4         ; if clear, got label here3


        btfss   STATUS,C        ; if not clear goto label here2
        goto    here5

here4  movlw   0x05           ; if remainder is 5 or more
        addwf   0x72,1         ; then add a constant 5 to the result

        goto   here6


here5  movlw   0x04           ; if remainder is less than 5
```

```
        addwf   0x72,1          ; then add a constant 4 to the result

        goto   here6


here6  bcf    STATUS,C
        movf   0x72,1
        movf   0x72,W



;mul900    ; movlw   0x1E          ;multiply by 900s = 15 minutes
        ; movwf   lc2
;sw2       ; movlw   0x1E
        ;movwf   lc1

        ;movf    0x72,W
;sw3       ;addwf   0x74,1


       ; btfsc  STATUS,C        ;if not clear goto label , save register
        ;call   save_reg

       ; movf    0x74

        ;decfsz  lc1,f
        ;goto    sw3
        ;decfsz  lc2,f
        ;goto    sw2

mul15      movlw   0x0F
        movwf   lc1

        movf    0x72,W
sw3        addwf   0x74,1

        btfsc  STATUS,C        ;if not clear goto label , save register
        call   save_reg

        movf    0x74
        decfsz  lc1,f
        goto    sw3


        movf    0x74,W
```

```
        addwf  0x75,1
        movf   0x75,1

        btfsc  STATUS,C         ;if not clear goto label , save register
        call   save_reg

        movf    0x27,W

        call   disp_adc2

        movf   0x25 ,W
        movwf  0x26


;Routine to LIGHT LCD to show that the system is reading a value

LightLCD1  movlw   0x13
          movwf   PORTC

        CALL swait
        ;CALL swait
        ;CALL swait
        ;CALL swait

        ;CALL swait
        ;CALL swait
        ;CALL swait
        ;CALL swait



         CLRF       PORTC

          bcf     PORTC,0          ; Remove progprogress results bit.

         movlw   0x40             ; Count
           movwf   count            ; Save it.
loop1      nop                    ; Dilly...
          nop                     ; Dally...
          nop                     ; Dilly...
          decfsz count             ; Decrement loop counter
          goto loop1               ; Loop if no zero.

         decfsz day
```

```
goto    do_conv         ; Do another conversion.
```