PART ONE

BACKGROUND AND SCOPE OF THE RESEARCH

CHAPTER 1

INTRODUCTION AND BACKGROUND TO THE STUDY

1.1 ROLE OF IRRIGATION IN SEMI-ARID SOUTHERN AFRICA

Irrigation is essential for food production to overcome deficiencies in rainfall and to stabilize agricultural production especially in the semi-arid and arid areas. Worldwide irrigation is practised on about 263 million ha (1996) with about 49% of the world's irrigation in China, India and the United States. In 2000, the total water requirements of South Africa were 13280 million m^3 per annum, with irrigation and urban usage accounting for 54% and 25% respectively (Shand & Basson, 2003). Rainwater runoff and deep percolation become available as surface – and groundwater of which approximately 62% is used for irrigation (DWAF, 2004), which is equivalent of 2.5% of the rainfall.

Agriculture in southern Africa with its semi-arid climate is a very important activity in terms of economic development and a key to poverty reduction in rural areas, but is also identified as one of the major water users in the region. In South Africa at least 35% of the economically active population of approximately 14 million people is directly or indirectly dependent on agriculture (Dept. Agric, 2001). The total area in South Africa under irrigation for commercial and smallholder agriculture is 1290 132 ha with a potential expansion of 283 350ha, given the available water resources. Irrigated agriculture in southern Africa plays a disproportionately important role because it is generally two or three times more productive than rain-fed agriculture, and because irrigation also uses roughly 70% of the region's water demand as indicated in Table 1.1.

Table 1. 1: Irrigated land and water demand for SADC countries (2004)

Country	[2]Size of country (km^2)	[2]Area arable land (km^2)	[2]Area irrigated land as % of arable land	[1]Water use (million m^3/annum) (1995)	[3] % of total water demand
Angola	*1 246 700*	*24 934*	*3*	*750*	*27*
Botswana	*585 370*	*5 853*	*0.3*	*47*	*31*
Lesotho	*30 355*	*3 339*	*0.9*	*160*	*59*
Malawi	*94 080*	*31 987*	*0.9*	*1 820*	*70*
Mauritius	*1 850*	*906*	*18*	*460*	*Not available*
Mozambique	*784 090*	*31 363*	*3.8*	*3 000*	*93*
Namibia	*825 418*	*8 254*	*0.7*	*248*	*66*
South Africa	*1 219 912*	*121 991*	*10.4*	*12 764*	*54*
Swaziland	*17 203*	*1 892*	*35.4*	*331*	*65*
Tanzania	*886 037*	*26 581*	*5.6*	*10 450*	*85*
Zambia	*740 724*	*51 850*	*0.9*	*1 580*	*72*
Zimbabwe	*386 670*	*32 480*	*3.6*	*4 980*	*80*
Average		*28 452*	*7.0*	*3 049*	*70*

[1] *Heyns, 1995. DWAF, Namibia.*
[2] www.worldatlas.com, 2002
[3] *Rothert, 2000*

1.1.1 Water use efficiency and the implementation of irrigation scheduling

This section aims to put the reason for improving water use efficiency through irrigation scheduling into perspective from the different stakeholders' perspective. The stakeholders include the community as a whole (represented by government), the irrigation farmers, the water management institutions (represented by CMAs and WUA) and the environment.

The efficiency of water use in agriculture is subject to a number of negative perceptions held by stakeholders from other water sectors in terms of water use efficiency. Therefore, the requirement is that water resources must be utilized productively and greater efforts must be made to increase productivity growth and thereby the competitiveness of agriculture (Backeberg, 1996). Frühling (1996) indicated that only 45% of water abstracted from surface and groundwater sources is believed to reach the crop root zone. Approximately 35% of irrigation system losses return to the river systems by overland flow and seepage but this return water is normally nutrient enriched and polluted with herbicides, pesticides and other pollutants that affect water quality of rivers and streams. Irrigation methods, irrigation scheduling, soil preparation, crop selection and evaporation all have a significant impact on the efficient usage of irrigation water (ARC, 1999). As the largest water user, irrigated agriculture will need to ensure that the greatest benefit is being obtained from the use of water resources, while ensuring efficiency and sustainability.

The requirement of proving beneficial use has led many countries to implement benchmarking exercises (Molden *et al.*, 1998; Malano, 2000; Malano & Burton, 2001, Fairweather, Austin & Hope, 2003) like the use of irrigation performance measures and indicators. Benchmarking is the process of identifying and implementing organization-specific practices with the goal of improving competitiveness, performance and efficiency (Malano & Burton, 2001). Thus, benchmarking requires the determination of current levels of performance and the identification of practices that can be implemented to improve the current situation.

The definition of water use efficiency was found to cover a vast range of terms and often led to some confusion. Water Use Efficiency (WUE) is a generic label to describe a “toolbox” of performance indices that can be used to evaluate water use in irrigation. In general, the term index was used to represent a relationship between water (input) and agricultural product (output) and efficiency to relate an output (e.g. water arriving at destination) to an input (e.g. water diverted from the source). In this way, Fairweather *et al.* (2003) and Purcell & Currey (2003) make a distinction between the agronomic performance of the crop and the engineering aspects of the design and management of the system. For example, farm Water Use Index (WUI, kg/ML) is defined as the crop production (kg or trays of fruit or quality of fruit) divided by water delivered to the farm gate (ML) and Farm Efficiency (%) is defined as the water retained in the soil (directly available to the crop) (ML) divided by the water delivered to the farm gate (ML). It is clear from the above-mentioned examples that temporal and spatial boundaries need to be defined with performance term used (Purcell & Currey, 2003). Water use indices are usually calculated over a season, whereas some efficiency terms can be calculated over an event, season or year.

The main pathways for enhancing WUE in irrigated agriculture is to increase the output per unit water, reduce losses of water to unusable sinks and reduce water degradation (environmental aspects). Possible ways of more efficient use of available water supply for irrigation include a coordinated approach at different levels of the water system or irrigation management sub-systems as indicated in Figure1.1. This is the scheme level sub-component, which includes the segment from the water source to the farm boundary, the farm and field sub-systems, which extends from the farm edge to the bottom of the root zone. At the scheme level sub-system, conveyance efficiency is the responsibility of the Catchment Management Associations (CMAs), Water User Associations (WUAs) and Department of Water Affairs (DWAF). Farm efficiency (or the volume of water delivered to the field edge divided by the volume delivered to the farm) and field efficiency (defined as the volume of irrigation water that replenishes the rooting zone as a function of the water supplied to the field) are the responsibility of the farmer.

From the different sub-systems shown in Figure 1.1, six efficiency terms can be defined: conveyance effiency, on-farm distribution efficiency, in-field system effiency, soil storage efficiency, irrigation efficiency and application efficiency. Any definition of water use efficiency on the farm will depend to a large degree on the perception of the person (the social, economic, political and strategic considerations taken into account producing the definition) and will be defined for each of these sub-systems identified. Those managing the

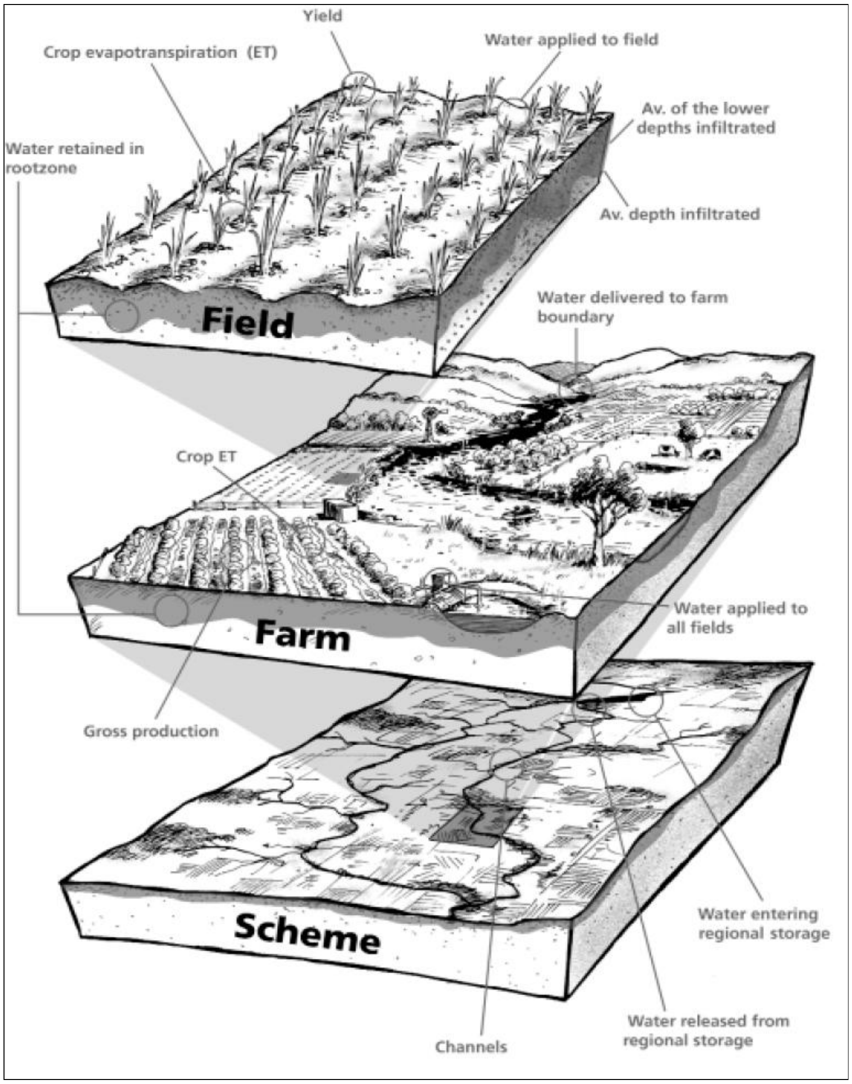

Figure 1. 1: Water use efficiency parameters applicable for the different sub- systems of water management

supply of bulk water tend to see efficiency simply in terms of losses in the delivery system, or the gross amount of water consumed by each of the customers as compared to some average or ideal figure. Irrigation farmers are more interested in how much product or quality of product, or perhaps how much profit, they can produce with a given amount of water. For this reason, the water use efficiency terms for each of these sub-components of the system as indicated in Table 1.2 will have to be used in conjunction with other sources of information when assessing the use of irrigation water.

Table 1.2: Potential water saving options to improve water use efficiencies (CSIRO, 2005)

Efficiency ratio	Water saving options
Irrigation efficiency: Conveyance efficiency	Identify and remediate seepage losses in supply channels
Irrigation efficiency: Farm efficiency	Identify and remediate on-farm seepage losses On-farm storage and recycling of drainage water Covering storage dams
Irrigation efficiency: Field efficiency	Laser leveling Flow monitoring Matching crop and groundwater depth Conversion to pressurized irrigation systems
Irrigation efficiency: Water use efficiency	Irrigation scheduling and soil water monitoring
Irrigation efficiency: Water productivity	Optimizing crop water requirements

Water management on a farm, of which irrigation scheduling is one aspect, expects the farmer to understand the total system that he is involved in. Making improvements to one part of the system or water management sub-component will have implications for the other (e.g. demand base irrigation scheduling requires flexible delivery of water or on-farm water storage facility). Therefore, increases in water use efficiency at the field level will require simultaneous improvements in each of the different sub-components.

Howell (2001) presents four options for the improvement of irrigation efficiency at a field level based on the findings of Walace and Batchelor (1997):

- *Agronomic:* The application of crop management to enhance the capturing of rainfall and reduce water evaporation (e.g. conservation tillage, improved varieties, or advanced cropping strategies to maximize cropped area during period of lower water demands or periods when rainfall may have a greater possibility of occurrence.

- *Engineering:* The selection and use of irrigation systems that reduce application losses improve distribution uniformity; apply cropping systems that enhance rainfall capture.

- *Institutional:* Collaborate and participate in an irrigation district or scheme with regard to water use, water pricing and water conservation.

- *Management*: The application of demand–based irrigation scheduling techniques; deficit irrigation to promote deeper soil water extraction, avoiding over irrigation. Management is an important aspect and as well as being listed explicitly, it is also inherent to the other three options.

There is an increasing interest shown in improving the water use efficiency in South Africa, mainly due to phasing out of subsidies on agricultural inputs, changing policies on the ownership of land and water resources as well as increased public awareness of soil and water ecological issues. Implementation of irrigation scheduling technologies could play an important role in improving water use efficiency on a farm level and reducing the production cost (Annandale *et al.*, 2002).

As this thesis has at its core the objective to determine and analyse the human factors that influence adoption of irrigation scheduling methods by irrigation farmers in an effort to improve the on-farm water use efficiency, the rest of the discussion will primarily focus on the use and implementation of irrigation scheduling methods as possible water saving options. It is however necessary to provide a brief overview of the various definitions, purposes and descriptions of irrigation scheduling contained in the literature.

Irrigation scheduling has been defined as a planning and decision making activity that the farm manager or operator of an irrigated farm is involved in before and during most of the growing season for each crop that is grown (Jensen, 1981). The conceptual framework underpinning the filling and emptying of the root zone is well accepted. The soil has a full point determined by the upper drain limit (UDL), which describes the maximum amount of water, the soil can hold. The UDL has a conventional definition namely, the water content after 48 hours free drainage from covered soil after saturation, which is not only an intrinsic soil property but in reality depends on the complex interplay between the antecedent water content, evapotranspiration rate and soil variability (Stirzaker, 2005). The lower limit (LL) of water storage is defined as the soil water content at which the plant wilts even when the transpiration rate is negligible. The refill point occurs somewhere between the UDL and LL and is often considered the half waypoint or 50% depletion. Total available water and readily available water to plants are calculated by multiplying (UDL-LL) and (UDL-RF) with the rooting depth for each growing stage of a crop (Stirzaker, 2005).

With this conceptual framework in mind, the general aim of irrigation scheduling is to apply water before the crop experiences an unacceptable stress and to replenish, but not overflow the root zone (Hill, 1991). The method used can be based on soil, plant and atmospheric measurements and is commonly known as scientific irrigation scheduling (SIS) (Lieb *et al.*, 2002). Although the acceptance of SIS has grown world wide (Fereres, 1996), the main aim of SIS was found to be solving of specific problems, while the successful dissemination and adoption of irrigation scheduling depends on producers' needs and perceptions on the farm (Howell, 1996).

Irrigation scheduling requires a good workable knowledge of the crop's water requirements and of the different soils' water holding characteristics that determine when to irrigate, while the adequacy of the irrigation system determines the accuracy of how much water to apply. The skill and experience of the farmer will determine the effectiveness of the application of the irrigation scheduling at field level.

1.2 PROBLEM BACKGROUND AND STATEMENT

Water scarcity has become an increasing social and economic concern for policy makers and competitive water users in South Africa and around the world. On a regional level the Comprehensive Africa Agriculture Development Programme of New Partnership for Africa's Development (NEPAD, 2003) identified land and water management as one of the three pillars for priority investment in raising the productivity of agriculture to ensure predictable outputs. In recent years there has been a major shove for the use of modern irrigation technologies to improve on-farm efficiency of water to address the problem of water scarcity and environmental degradation in South Africa (de Lange & Maritz, 1998; Versfeld, 2000; Badenhorst, de Lange, Mokwena & Rutherford, 2002; Seetal, 2002; Karar, 2003).

At the end of 2001, the National Department of Agriculture, Agri SA and National African Farmers Union (NAFU) released the Strategic Plan for South African Agriculture (Department of Agriculture, 2001). One of the core strategies in the sector plan for agriculture is sustainable resource management, which also impacts on efficient water use. With this in mind, the Water Research Commission (WRC) of South Africa has since 2002/2003 embarked on Key Strategic Areas (KSA) of Water Utilization in Agriculture identified for research with the overall objective to utilize scarce water resources efficiently, beneficially and sustainably to increase household food security and farming profitability (Backeberg & Sanewe, 2005).

Embedded in this overall objective of the WRC as identified for this Key Strategic Areas this study was planned and designed to investigate the factors that influence the adoption of irrigation scheduling methods and models amongst irrigation farmers. The science of irrigation scheduling has a long, illustrious pedigree and a large number of soil-atmosphere-plant irrigation scheduling methods and models (Chapter Two) have been developed to determine when crops require water, and how much irrigation needs to be applied. Irrigation scheduling was introduced to farmers thirty years ago (Shearer & Vomocil, 1981; Fereres, 1996). Despite the apparent importance of irrigation scheduling and the large amount of research resources devoted to it, the worldwide adoption of objective irrigation scheduling methods by irrigation farmers has been well below expectations (Cox, 1996; Lynch, Gregor & Midmore, 2000; Leib *et al.,* 2001). A national census in Australia during 1999 revealed that less than 15% of the farmers used scientific–based tools, whereas over 90% relied heavily on local knowledge (Stirzaker, 2003).

Three different approaches of system thinking were found in the literature to address the potential adoption of irrigation scheduling methods. The interplay between these different systems approaches are not only important as a background for the literature, it also provides the framework for the developing and answering of the research questions for the thesis.

First, a hard system approach from the natural science (ecology and physiology) is followed to understand and describe the impact of irrigation scheduling on crop production and the natural resource base. The use of system thinking in this tradition is first to ask, "Why is it so?" Major tools for managing climate variability, are the use of simulation modelling and sophisticated measuring devices and techniques which are grounded in the daily impact of climate on crop and soil processes. With these efforts scientists tried to conserve water/energy (Shearer *et al.,* 1981; Dockter, 1996; Alam, Duke & Orendoff, 1996), improve crop yield and quality (Silva & Marouielli, 1996; Tacker *et al.,* 1996), and reduce non-point pollution (Boesch, Humphrey & Young, 1981; Klock, Schneedloth & Watts, 1996 and Nguyen, Nieber & Misra, 1996).

Secondly, a hard system approach that comes from the applied science of engineering and management science is used. As applied science, the first question is not why it is so - but rather what can we do about it? The engineering and management science treatment of systems has become the dominant approach in applied agricultural science. Therefore, various studies in the literature were found to analyse on-farm adoption of irrigation technologies using the engineering notion of irrigation water efficiency as defined by Whinlesey, McNeal & Obersinner (1986); Barret, Purcell & Associates (1999) (i.e. ratio of water stored in the crop root zone to the total water diverted for irrigation). Other studies evaluate the economic and technical attributes of irrigation technologies, and found that some combination of water saving and yield increase was necessary in order for farmers to induce the adoption of water conserving technologies (e.g. Coupal & Wilson, 1990; Santos, 1996; Droogers, Kite & Murray-Rust, 2000, Arabiyat, Segarra & Johnson, 2001) and that risk has been considered as a major factor reducing the rate of adoption (Jensen, 1982). Squires (1991) argued for the need to classify farming systems so that they could be compared, analysed and evaluated. This approach is using the engineering analogy, while agricultural and management sciences are essentially the exercising of natural science within a social environment.

The pioneering work of Griliches (1957) on the adoption of hybrid corn in the USA, and the analysis of farmer decisions to adopt technology innovation (Linder, 1987; Fischelson & Rymon, 1989; Dinar & Zilberman, 1991; Dinar, Campbell & Zilberman, 1992; Dinar & Yaron, 1992, Federer & Umali, 1993; Ruttan, 1996; Vanclay, 1997, Barr & Cary, 2000; Cary, & Webb, 2001, Cary *et al.,* 2002; Vanclay, 2003), followed a different approach. They have made use of a soft systems approach, in their attempt to explore the influence of socio-economic, demographic and structural factors on adoption behaviour. Ison (1991) maintains that the hard system tradition focuses on how to solve the problem, whereas the soft system approach opens up questions of what is the problem, why does it exist and for whom does the problem exist?

Shearer and Vomocil (1981) indicated that behavioural patterns and attitudes of farmers, as well as the need for continuous technical support of the farmers are some of the major constraints that prevent farmers from implementing irrigation scheduling. Several authors have empirically investigated technology adoption and diffusion taking into account farmers' perception about the degree of risk concerning future yield (Federer & Umali, 1993; Saha, Love & Schwart, 1994, Pannel, 1999; Batz, Peters & Jansen, 1999).

According to Howell (1996) there has been little change in the theory and methodology of irrigation over the last 25 years, however the changes in information technology need to update irrigation scheduling methods, which changed drastically over the last few years. Jensen (1981) indicated that the challenges are to develop complete and reliable irrigation technologies to be adapted to farmers' requirements as well as training of extension personnel. Shearer *et al.* (1981) reported that most of the successful scientific irrigation scheduling programs in Oregon are disbanded once programs are no longer offered free of charge, while Itier, Maraux, Ruelle & Deumier (1996) contend that scheduling methods and techniques must be simplified to match time constraints, training level, and income potential of producers.

Non-adoption of farming practices developed from research findings by individuals occurs for many reasons, but it is typically the result of a logical thought process rather than an uninformed or unruly attitude (Vanclay & Lawrence, 2001, Linehan & Johnson, 2002). Shannon *et al.,* (1996) carried out a participatory learning program amongst cane growers in the Burdekin (Australia). In this study growers were encouraged to collect crop growth and water use data, which helped them in the understanding of the processes and problems and improved the credibility of the result.

In South Africa a limited number of studies (Annandale, vd Westhuizen & Olivier, 1996; Botha, Steyn & Stevens, 2000) referred to possible reasons for the low adoption of irrigation scheduling practices by farmers. Very often, the complexity of computerized systems is an obstacle to the implementation of irrigation scheduling. De Jager & Kennedy (1996) indicated that three levels of technology (high, intermediate and minimum) could be adopted for dissemination of irrigation scheduling advice. Koegelenberg & Lategan (1996) recommended the support of professional trained irrigation advisors in monitoring the soil water balance in the field. While these studies address some of the reasons for the slow adoption of irrigation scheduling, they however did not address the critical behavioural determinants, which according to Tolman (1967) and Düvel (1991) are immediate precursors of behaviour. This study endeavours to analyse and identify the possible socio-economic and human factors that influence the adoption of on-farm irrigation scheduling which will help us to identify what type of irrigation management information and technology in what format should be offered for optimum use by irrigation farmers.

1.3 THEORETICAL OVERVIEW

This literature overview provides a short discussion of the concepts innovation and an overview of the most important models of behaviour change.

1.3.1 Technical and social dimensions of innovations

In order to understand the innovation process, it is important that the reader has clarity of what exactly constitutes an "innovation" and what kind of process is needed to arrive at it. The traditional view of an innovation regards it as an idea, practice or technical product perceived as new by an individual and that is created in a research facility (Rogers, 1983). However, it is well known that many new ideas, products and processes developed within the research facility never reach the stage of being applied in everyday life (Little *et al.*, 2002).

Leeuwis (2004) proposes a more pragmatic conception of an innovation. According to him, an innovation is not only composed of novel technology or procedures, but also of new adapted human practices, including the conditions for such practices to happen. In other words, it may be "a new way of doing things" or even "doing new things", but it can only be considered as an innovation if it actually works in everyday life. Given that innovations consists of a package of social and technical arrangements, the design requires a multi-faceted process taking place at different point in time and space, and involvement of different set of actors (Leeuwis, 2004).

1.3.2 Models of behavioural change

According to Tolman (1967), human behaviour is intentional and governed by experience about the environment. In its simplest form it can be conceived as a type of movement brought about by forces from a system in disequilibrium (Düvel, 1990). This intentional nature makes human behaviour situation specific but also complex, which is inevitable as the same person at different situations make different decisions (Düvel, 1987).

Despite the dynamic nature of human behaviour, social scientists have managed to formulate conceptual constructs of behaviour change models, where important behaviour determinants have been identified that impact on effecting and maintaining behaviour change. Some describe it as various steps in learning while others simply describe it as stages in the problem-solving process. The following is an overview of different models and approaches for the purpose of assessing them with regard to their usefulness as models of behaviour analysis and intervention.

a) Traditional approaches

Albrecht (1964) quoted by (Düvel, 1991) recognized five distinguishable approaches namely, the teaching, socio-cultural, atomistic communication, socio-structural communication and the situation-functional in a critical analysis of adoption research development. Düvel (1991) emphasised the contribution of the situational-functional approach, which in contrast to the other approaches, regards behaviour change not as the cause of a single factor but rather as interplay of a number of dynamic inter-dependent factors.

b) Classical 5-stage adoption process (NSRC, 1955)

Adoption studies indicated that adoption of innovations is not something that happens overnight, but rather it is a final step in a sequence of stages. However the most widely used characterisation of stages in connection with the adoption of innovations derives from the North Central Rural Sociology Committee (1955). This model built heavily on the normative theories about rational decision-making and consisted of the following stages:

1. Awareness: where the individual become aware of an innovation or the problematic situation, and adequate information is required.

2. Interest: the individual becomes more interested in the new idea and seeks additional information.

3. Evaluation: the individual reflects on its advantages/disadvantages and mentally applies innovation to his present and anticipated future situation.
4. Trialling: where the individual test the innovation within his or her current situation.
5. Adoption or Rejection: individual seeks for reinforcement for the decisions made – apply innovation or behaviour changes.

This model assumes that the process starts with awareness of an innovation where people require and search for different kinds of information during each stage. The information requirements evolved from:

- Information clarifying the existence of tensions and problems addressed by the innovation;
- Information about availability of promising solutions;
- Information about relative advantages and disadvantages of alternative solutions;
- Feedback information from one's own or other peoples' practical experiences;
- Information reinforcing the adoption made.

This model illustrated several shortcomings with regard to the adoption process:

- Awareness of an innovation could either be problem-oriented or innovation oriented.
- As been mentioned, the normative models about rational decision-making, heavily influenced the original conception of the adoption process and its stages.

c) Campbell model (1966)

Campbell (1966) argues that many adoption stages are problem-oriented, whereby the individual becomes aware of a problem, then seeks solutions and consequently becoming aware. The decision to adopt or reject can be the result of either rational or non-rational decision-making process. According to Campbell (1966) the decision-maker may take up any of the four proposed paths for adoption (Figure 1.2)

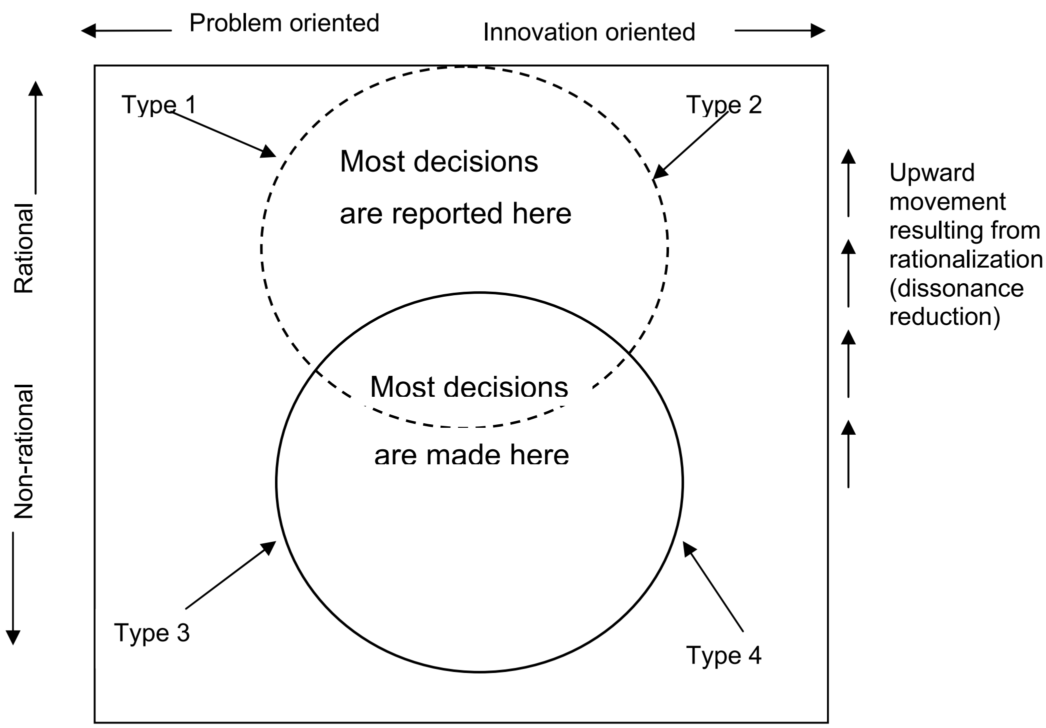

Figure 1. 2: A paradigm of individual decision-making and adoption (Campbell, 1966)

- *Rational-Problem Oriented*: Following stages:-problem ► awareness ►-evaluation ► rejection or trial ►adoption or rejection.

- *Rational–innovation Oriented:* Following stages:-awareness ►interest► evaluation ► rejection or trial ►adoption or rejection.

- *Non-Rational-Problem Oriented*: Following stages:- problem ►awareness► adoption or rejection ►resolution (including information seeking).

- *Non-Rational–innovation Oriented:* Following stages: -awareness►-adoption or rejection ►resolution (including information seeking).

Campbell (1966) is of the opinion that the majority of decisions fall between two extremes namely, "rational" and "non-rational" decision-making, since they have elements of both of them. "Rational" is defined as a process in which the possible alternatives and consequences of the decision are considered before any action is taken, whereas "non-rational" is any process that occurs without consideration of possible alternatives or consequences including impulsive decisions (Campbell, 1966). This model assumes that decision-making starts with a problem or a need, and the relative more rational offering of decision–making, also links to the cognitive dissonance theory of Festinger (1957).

d) Innovation Decision-Making Process (Rogers & Shoemaker, 1971; Rogers, 1995)

Rogers & Shoemaker (1971) and Rogers (1995) describe the innovation-decision process as a process through which an individual passes from first knowledge of innovation, to forming an attitude towards the innovation, to decision to adopt or reject, to implementation of the new idea, and to confirmation of this decision. This model was developed taking into consideration principles of learning, theories of attitude change and decision-making and consist of the following stages:

- Knowledge: about the existence of a new innovation;
- Persuasion: shaping attitudes under the influence of others;
- Decision: adoption or rejection of the innovation;
- Implementation: adapting the innovation and putting it into use;

- Confirmation: seeking reinforcement from others for decisions made, leading to continuation or discontinuation.

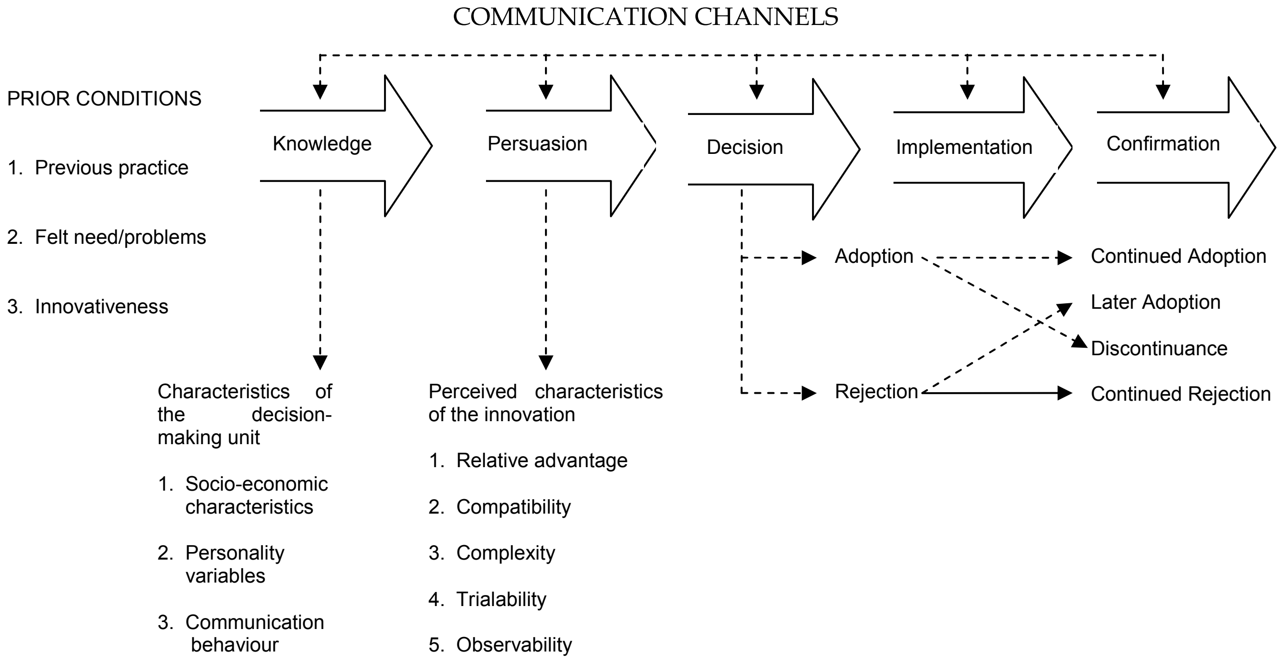

Figure 1. 3: The innovation-decision process (Rogers, 1983)

Düvel (1991) asserts that this model has successfully overcome the weakness of previous models except its shortcoming to offer guidelines in terms of how change can be directed or implemented. Since rational decision-making is often a practical impossibility, this model includes stages, which are less inspired by normative decision-making theory. De Klerk (1979) and Botha (1985) noted that although this model does not accommodate the decisive role of needs or problems in behaviour analysis, it is more flexible than the Classical 5 stage adoption model and therefore useful for behaviour analysis.

Rational decision-making still figures as an important step in the separation between the different stages of adoption in this model. Leeuwis (2004) is of the opinion that this approach of decision-making as described by Rogers (1983) is logically connected with the idea that adoption of innovations is largely an individual affair. Leeuwis (2004) is of opinion to rather start with the assumption that an innovation is a collective process, where other key processes like social learning become important when thinking about adoption.

e) The Psychological Field Theory of Lewin (1951)

According to Düvel (1974), de Klerk (1979) and du Plooy (1980) the model of Lewin (1951) is a most appropriate model and conceptual framework for the behaviour analysis especially from an extension point of view.

The central element of this model is a life space or psychological field in which a person exists. One of the basic principles of the psychological field theory is the principle of contemporary, which states that any behaviour or any change in the psychological field depends on the forces that operate in the psychological field at that time (Lewin, 1951). Anything in a situation that is perceived by the person as a goal, or as a path or barrier to a goal, is understood as a force operating on the person's behaviour. Behaviour (B) is a function of the person (P) in the perceived environment (E).

$$\mathbf{B=f\ (P,\ E)}$$

The factors of both the environment (E) and the personality (P) can become behavioural determinants, which are interdependent according to Lewin (1951). Thus the same facts and objects of the environment or personality may cause different actions.

This model assumes that the basic motivation for every organism is to maintain equilibrium. A disturbed equilibrium is experienced as need tension, i.e. felt need to reduce the tension. In this state the person tends to mobilize forces or energy to reduce the tension and re-establish equilibrium under the given conditions. The effects of the felt tension on perception, cognition and action are therefore such as to change the field in order to restore the tension-reduced situation.

Behaviour change or the lack thereof is in principle explainable by the "force field' that causes action. Change can be brought about and directed by changing the force field i.e. by adding or strengthening "driving forces" (positive forces) and by weakening or eliminating "restraining forces" (negative forces). According to this field theory, a person who finds himself in a relatively stable situation may assume a new behaviour if and only if this seemingly stable situation (equilibrium) is disturbed and need tension (dissonance situation) is created. In an attempt to eliminate or reduce need tension and re-establish a new equilibrium, the person starts from phase 1 where the pressure of positive forces (driving forces) outweigh the opposite pressure from restraining forces (barriers or negative forces). The movement continues to a level or until a new equilibrium is reached (Figure 1.4).

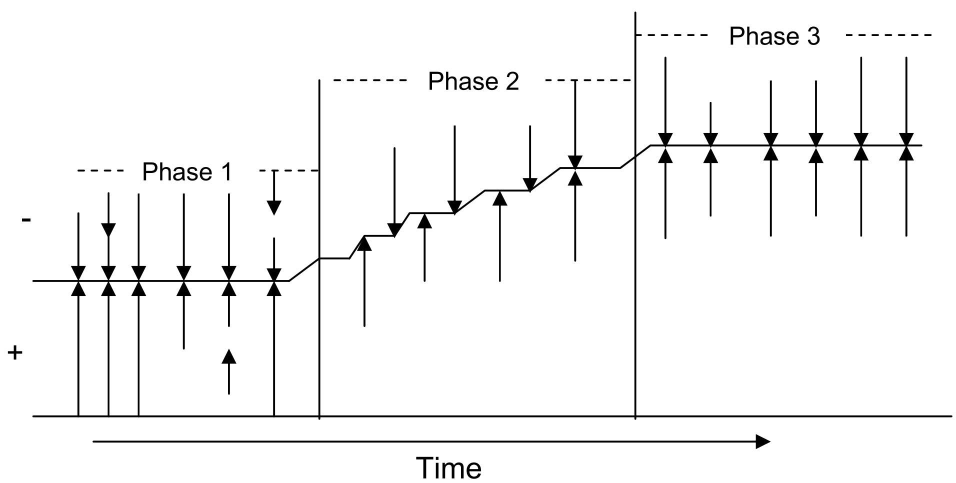

Figure 1. 4: Behaviour change model of Lewin (1951) (Düvel (1974)

According to Düvel (1991) the practical advantages of the model are as follow:

i. It provides a conceptual framework in terms of which the complexity of any real life situation, in respect of behavioural relevant factors, can be analysed.

ii. The theory is not limited to change but also explains non-change. It provides guidelines for situation analysis as well as for the planning of change and for evaluation.

iii. It can also be used for the analysis of greater social units like groups of clients and organisations.

iv. The model is relatively easy and simple to understand with the exception of the mathematical descriptions and quantifications because of familiar concepts and principles used in the model.

This field theory of Lewin (1951) makes provision as to how behaviour change can be brought about, by restricting the causes of behaviour to the psychological field. This model sufficiently overcomes the weakness of the process-centred behaviour models, and was used by Düvel (1974) to analyse behaviour change. He reached the conclusion that perception is an immediate precursor of behaviour change.

f) Tolman model (1967)

The theory of Tolman (1967) is a mixture of behaviourism and combination of aspects of cognition and intension. According to Düvel (1991) this theory makes a valuable contribution to behaviour analysis, since Tolman (1967) is the person who introduced the concept of intervening variables.

The immediate precursor to action is the "behaviour space" which Tolman (1967) defines as "a particularised complex of perceptions as to objects and relations and the behaving self", evoked by the given environmental stimulus situation and by a controlling and activated belief–value matrix which implies a mental trial-and error behaviour. Tolman (1967) differentiates according to his model, three sets of variables, namely independent, dependent and intervening variables (Figure 1.5)

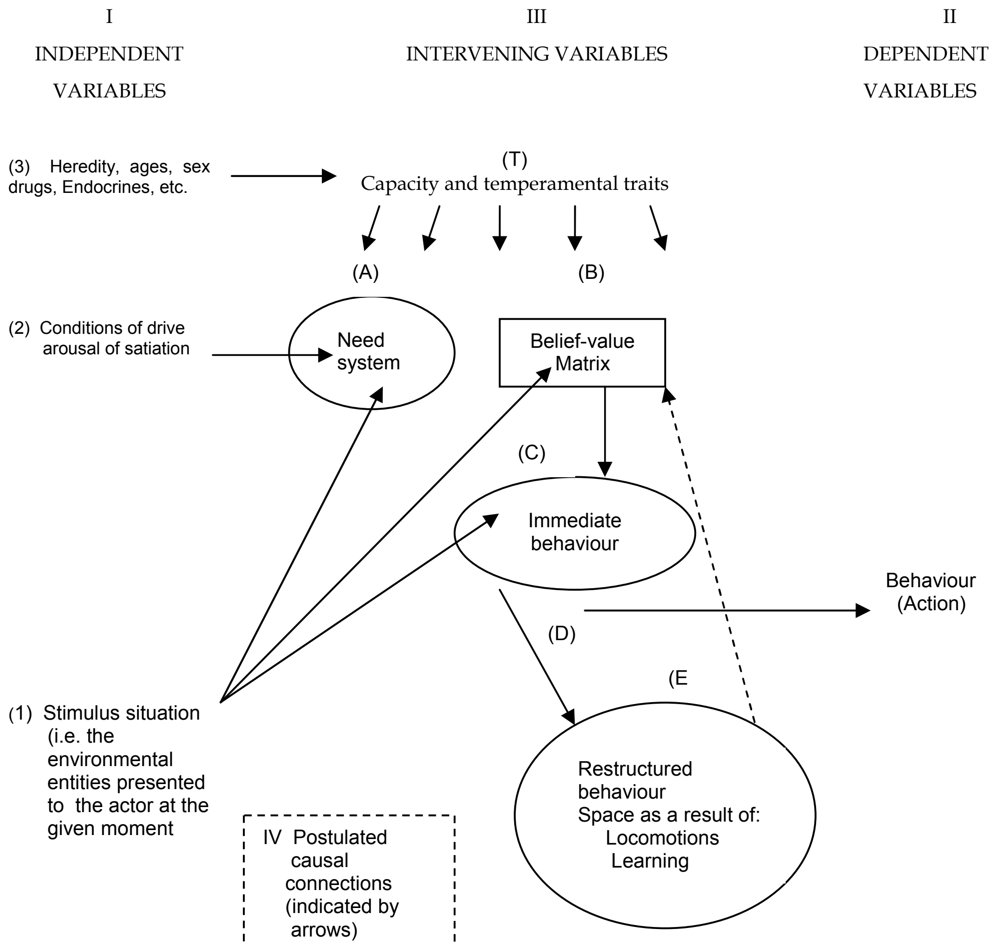

Figure 1. 5: The Tolman model (1967)

Tolman (1967) regarded both independent and dependent variables as observable, as opposed to intervening variables, which he identified as the motives of behaviour and which are not observable. The intervening variables are postulated explanatory entities conceived to be connected by one set of causal functions to independent variables, on the one side, and by another set of functions to the dependent variable of behaviour, on the other side, as illustrated in Figure 1.5.

According to Düvel (1991), Tolman's theory seems a successful combination of the majority of modern theories. Amongst others, it accommodates Lewin's field theory (1951), as well as the similarities between Tolman's "behaviour space" and Lewin's "psychological space". Düvel (1991) indicated that the intervening variables as part of the behaviour space as defined by Tolman (1967), provide the potential to distinguish between direct and indirect causes of behaviour.

g) Fishbein and Ajzen's attitudinal determinants of behaviour

The model that Fishbein and Ajzen (1975) use to describe the determinants of behaviour is called Theory of Reasoned Action (TRA). This model has been developed to determine how attitudes and beliefs are related to individual intention to change their behaviour. According to TRA, as presented in Figure 1.6, attitude towards behaviour is determined by behavioural beliefs about the consequences of behaviour (based on the information available or presented to the individual) and the affective evaluation of those consequences on the part of the individual. Most people hold both positive and negative beliefs about an object, and attitude is viewed as corresponding to the total affect associated with their beliefs. Beliefs are defined as the individuals estimated probability that performing a given behaviour will result in a given consequence. The totality of a person's beliefs serves as the informational base that ultimately determines his attitudes, intentions and behaviours. They elaborated that the performance or non-performance of a specific behaviour with respect to some object usually cannot be predicted from the knowledge of the person's attitude toward the object. Instead, a specific behaviour is viewed as determined by the person's intention to perform that behaviour.

According to Fishbein & Ajzen (1975), a person's intention is the function of beliefs concerned with the behaviour and not about the object. Some of these beliefs may influence a person's attitude toward his behaviour. Affective evaluation is an "implicit evaluation response" to the consequence (Fishbein & Ajzen, 1975). This represents an information processing view of attitude formation and change which states that external stimuli influence attitudes only through changes in the person's belief structure (Ajzen & Fishbein, 1980)

Thus, the Theory of Reasoned Action provides a rationale for the flow of causality from the external stimuli (such as the design of an irrigation scheduling device or practice) through user perception to attitudes about the technology, and finally the actual behaviour (Fihbein & Ajzen, 1975). This theory is based on the assumption that human beings are usually quite rational (reasoned action) and they consider the implication of their action before deciding to engage or not to engage in a given behaviour (Ajzen& Fishbein, 1980). A person's intention is assumed to capture the motivational factors that have an impact on behaviour. According to the TRA, a person's intention is a function of two basic determinants, the one personal in nature (the individual's positive or negative evaluation of performing the behaviour), which is referred to as "attitude towards behaviour" and the other reflecting the social influence, called subjective norms.

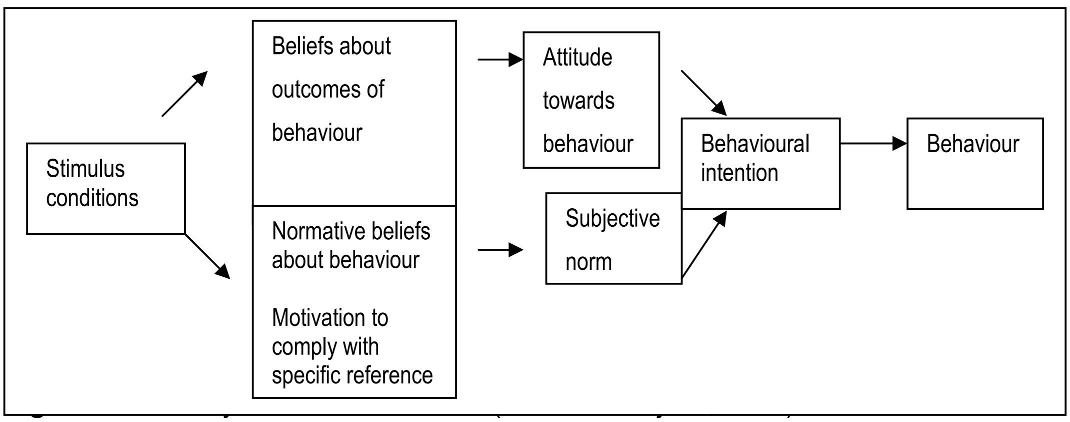

Figure 1. 6: Theory of Reasoned Action (Fishbein & Ajzen, 1975)

The analysis of behaviour by Fishbein & Ajzen (1975) however does not make reference to the role of intervening and independent variables suggested explaining behaviour as was done by other behaviour analysts. They however recognise that factors like personality characteristics and personal variables belong to the "external variables" whose influence is indirect (Ajzen & Fishbein, 1980). They are of the opinion that these variables have an effect on behaviour only to the extent that it influences the determinants of that behaviour and not directly the behaviour itself. This association of independent variables to an only indirect influence on behaviour is very similar to the view of Tolman (1967).

h) The Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM) as described by Davis (1989) is derived from the TRA model and predicts user acceptance based on the influence of two factors: perceived usefulness and perceived ease of use of technology. TAM hypothesizes that user perceptions of the usefulness and ease of use determine attitude towards the use of an innovation or technology. Consistent with TRA, behavioural intentions to use an innovation is determined by the attitudes towards the specific innovation. According to the model, the behavioural intentions to use in turn determine actual use of the innovation. This model proposed that a direct relationship between perceived usefulness and behavioural intentions to use technology exists (Figure 1.7).

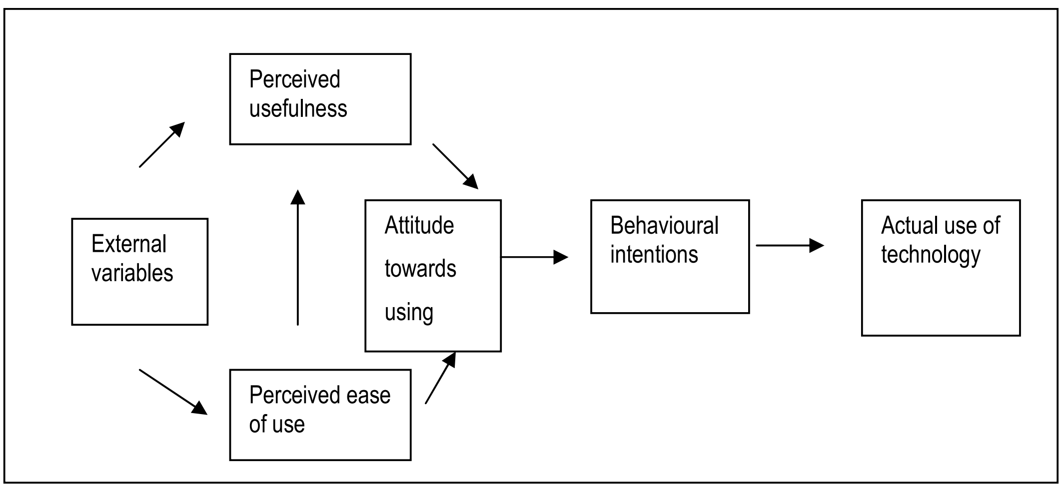

Figure 1. 7: Technology acceptance Model (Davis *et al.,* 1989)

Within TAM, perceived usefulness is defined as the degree to which a user believes that using the technology or innovation will enhance his performance. Perceived ease of use is defined as the degree to which the user believes that using the system will be free from effort. Both perceived usefulness and perceived ease of use are modelled as having a significant impact on the user's attitude towards the innovation. Behavioural intentions to use are modelled as a function of perceived usefulness and perceived ease of use, and therefore determine the actual use of the innovation. Research by Davis *et al.,* 1989; Taylor & Todd, 1995) has consistently shown that behaviour intention is the strongest predictor of the adoption of an innovation.

According to Davis (1989), there exists a direct effect of perceived ease of use on perceived usefulness. In other words, between two technologies that are offering identically functionality, a user should find the one that is easier to implement more useful. Davis (1993), with reference to the use of computer systems states “making a system easier to use, all else held constant, should make the system more useful. The converse does not hold, however”.

As this model is based on the principles of TRA, the shortcomings of this model with reference to the role of intervening variables in behaviour analysis are also applicable. These authors like Fishbein & Ajzen (1975) classified the personal variables as external variables in their model. The goal of the development of TAM is to predict information system acceptance and diagnose design problems before users have any significant experience with a computer system (Davis, 1989). TAM has been found to be extremely robust and has been replicated using different tasks and tools (Adams. *et al.,* 1991). In comparison with other models, Mathieson (1991) found that TAM predicted intention to use for instance a spreadsheet package, better than alternative models. The value of TAM lies in its parsimony - the model is strongly grounded in existing psychological theories, yet it is relative easy to apply (Mathieson, 1991)

i) Düvel’s Behaviour Analysis Model

Based on the findings of Tolman (1967) and Lewin (1951), the concepts of intervening variables as part of the behaviour space and the role of field psychological forces helped Düvel (1975) to establish a conceptual framework for identifying the most significant causal factors that determine human behaviour. The aim with this model is to provide a checklist that is surveyable and still sufficiently comprehensive to make provision (directly or indirectly) for all causes of behaviour. He states that “although the classification of behaviour determinants on the basis of potentially direct and indirect influence on behaviour is reasonably clear, there is no clear cut boundary".

Louw & Düvel (1993) indicated that the model (Figure 1.8) drastically reduced the field forces in accordance with Tolman's view (1967) of the concept of intervening variables, to certain behaviour determinants that are more intervening and mediating in nature and thus represent the more direct precursors or causes of adoption behaviour, while the influence of independent variables are manifested through these intervening variables. The intervening variables perception, needs and knowledge have been identified to be immediate and direct precursors of human behaviour or decision-making. Perception and needs are identified to be more immediate determinants of behaviour. The use of intervening variables as predictor of human behaviour has been tested extensively (Düvel, 1975; Louw & Düvel, 1978; de Klerk & Düvel, 1982; Düvel & Scholtz, 1986; Botha, 1985; Düvel & Botha, 1990).

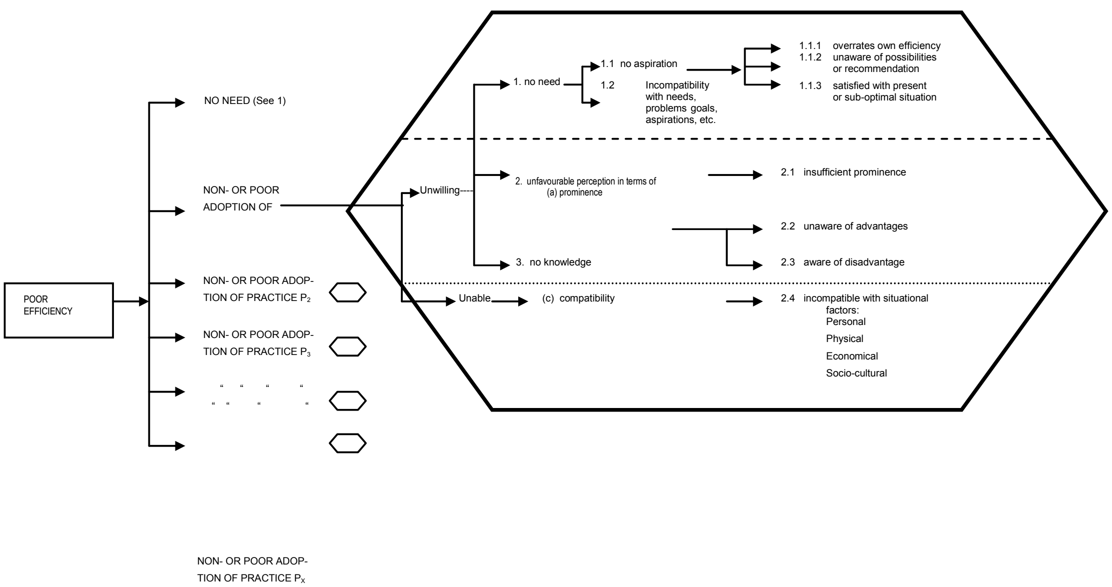

Figure 1. 8: Düvel's behavioural analysis model (1975)

According to Düvel (1989) the major advantages of using intervening variables for behaviour analysis and intervention are the following:

- They are direct determinants of behaviour, the logical focus of intervention, and consequently also the logical criteria of evaluation.

- These determinants will, if properly monitored, reveal why or why not change has occurred. Also progress with regard to the adoption of proposed practices could be monitored, and adaptations could be made where needed.

The literature review showed that researchers have used both hard and soft system approaches in an attempt to explore the influence of engineering, technical, socio-economic and demographic factors as important for behaviour changes. Although these approaches partially addressed reasons for the adoption or rejection of irrigation scheduling methods, it did not address the role of critical decisive intervening factors like needs, knowledge and perception in behaviour determination. The main objectives of this study are to determine the implementation status of on-farm irrigation scheduling and possible reasons responsible for implementation or discontinuing of irrigation scheduling by irrigation farmers. Düvel's behavioural analysis model (1975) and the Technology Acceptance Model (TAM) as described by Davis (1989) were selected to meet these objectives of this study i.e. it provides a frame of reference and directives for the collection and analysis of data to answer the research questions raised in this study.

1.4 TOWARDS THE FORMULATION OF HYPOTHESES

Against the conceptual framework of this study as discussed in this chapter, the following research hypotheses emerge:

Hypothesis 1:

The implementation of on-farm irrigation scheduling practices is determined by independent and intervening variables.

Hypothesis 1.1:

There is a significant relationship between independent personal and environmental factors and the implementation of irrigation scheduling.

Hypothesis 1.2:

There is a significant relationship between intervening variables (perception, knowledge and needs) and the implementation of irrigation scheduling.

Hypothesis 2:

More precise irrigation scheduling offered by scientists is perceived to improve production efficiency.

Hypothesis 3:

The technology level of farmers and the specific farm business characteristics determine irrigation farmers' approach to problem solving and learning.

Hypothesis 4:

Competent ground level support by research and extension professionals is conducive for the implementation of irrigation scheduling.

Hypothesis 5:

Effective research-extension-farmer dialogue is necessary for the improvement of implementation status of irrigation scheduling practices on-farm.

1.5 OBJECTIVES

The research questions that steered this study consist first of all of the identification and classification of the spectrum of soil-atmosphere-plant irrigation scheduling methods and techniques that are available for the use by irrigators, researchers and extensionists in irrigation management in South Africa.

The second research question to be answered was to determine the current adoption or implementation of irrigation scheduling methods and techniques by both small-scale and commercial irrigation farmers on the various irrigation schemes and to determine the human and socio-economic factors that influence the implementation of irrigation scheduling methods and techniques. Part of the second research question was to identify whether the information offered through the implementation of objective scheduling methods was perceived by the farmer to add value to the management decisions made by irrigation farmers.

The identification of networking and information sources that irrigation farmer’s use in their effort to learn more about irrigation management formed the third research question. The study is not aiming at questioning the validity of science, but rather the usefulness that science has for practical irrigation management of irrigation farms. Important questions at this level are appropriate levels of precision in technology and management, and the value of more accurate soil water status information for irrigation management purposes.

The specific objectives of the research aimed at answering the above research questions are therefore as follows:

1. To review concepts of behaviour change and models with a view to assess their potential use as conceptual models appropriate for behaviour analysis and intervention.

2. Identify and quantitavilely describe and classify the spectrum of soil-atmosphere-plant irrigation scheduling methods and techniques used in South Africa.

3. Investigate, analyse and describe the levels of implementation of irrigation scheduling models and methods by a cross section of smallholder and commercial farmers.

4. Investigate, analyse and describe the possible reasons from a cross section of smallholder and commercial farmers for using the different irrigation scheduling methods and models.

5. Investigate, analyse and describe why irrigators discontinue with the implementation of irrigation scheduling.

1.6 AN OVERVIEW OF THE THESIS STRUCTURE

The thesis has been structured in such a way as to ensure adherence to the fact that the concepts presented within the document must flow logically from one part to the next in order to maximise reader comprehension of the various topics presented. In order to ensure that, the individual chapters of this thesis have been grouped together in seven separate parts namely:

- Part 1: Consist of the scope of the research and an overview of the role of irrigation scheduling in the general improvement of on-farm irrigation management and specifically for increasing water use efficiency. It provides a quantitative description and classification of the atmosphere-plant spectrum of soil-irrigation methods and techniques used by irrigation farmers, researchers and extensionists in South Africa.

- Part 2: A quantitative assessment on a national basis among irrigation schemes (macro level) which provides an overview of the current state of irrigation scheduling and factors that influence the implementation of irrigation scheduling methods and models among commercial and small-scale farmers.

- Part 3: Identification and analysis of the possible human and socio-economic factors amongst commercial farmers that influence the adoption of irrigation scheduling practices on the farm (micro) level.

- Part 4: Identification of possible human and socio-economic factors that influence the implementation of irrigation scheduling practices by small-scale irrigation farming through semi-structured interviews with irrigation professionals and case studies of small-scale irrigation farming.

- Part 5: Consists of a detailed analysis of knowledge information systems used by commercial and small-scale irrigation farmers to learn about irrigation scheduling and investigate the supportive role that irrigation consultants and advisors play in the implementation of irrigation scheduling.

- Part 6: Recommendations are provided for the propagation and institutionalising of irrigation scheduling methods and areas for further research are identified.

CHAPTER 2

DESCRIPTION AND CLASSIFICATION OF IRRIGATION SCHEDULING METHODS AND TECHNIQUES

2.1 INTRODUCTION

Every irrigator practises some form of irrigation scheduling. The basis for irrigation scheduling and the level of sophistication vary enormously. It ranges from irrigation based on the experience of the farmers (intuition) and application of simple rules, to the practice of techniques based on computer models and sophisticated instruments that can assess soil, water and atmospheric parameters.

Various strategies for scheduling may be adopted depending on the crop response to water stress, the water holding properties of the soil, the availability of irrigation water, and the limitations of the irrigation application system. Basic scheduling methods normally involve either soil-water budgeting or the monitoring of a single component of the soil-plant-atmosphere continuum. Most irrigation scheduling methods imply that the soil water balance needs to be quantified. To be able to do that, the soil-plant-atmosphere continuum needs to be taken into account as quantitatively as possible. The following section alludes to various irrigation scheduling approaches that attempt to integrate a quantitative description and the classification of the spectrum of soil-atmosphere-plant irrigation scheduling methods and techniques most commonly used by irrigators, researchers and extensionists in South Africa.

2.2 RESEARCH METHODOLOGY

This chapter outlines the methodology adopted to identify and classify the various irrigation scheduling approaches from which irrigation farmers, researchers and extensionists in South Africa can select to assist them with more informed irrigation scheduling decisions. Orientation and planning of this part of the study commenced in 2000 and the purpose for this part of the study was to obtain a clear picture of the technology level available, time required for the collection and interpretation of irrigation data, approximate cost of the irrigation scheduling equipment and potential users of the various methods and computer scheduling models and programs available. This information was not only imperative for the research team to be able to describe, contextualise and understand the choices available for the different managerial needs of irrigation farmers, but was also used for the categorising of the irrigation scheduling aids in an attempt to help farmers, extensionists and researchers in their selection and decision making in this regard. Since the development of a category of irrigation scheduling approaches had not been done for South Africa, various opinion leaders in irrigation management were consulted before this part of the study was started.

A comprehensive literature review was done to identify basic scheduling methods normally involved with either soil-water budgeting or the monitoring of a single component of the soil-plant-atmosphere continuum. This literature review made use of various information sources namely books, conference proceedings, journal articles, newspaper and magazine reports, industry information brochures and internet resources to mention a few. The literature review was much more than the collection of texts, but involved a review of the existing "scholarship or available knowledge" (Mouton, 2001) on the various scheduling approaches. Data on some of the older and more subjective irrigation scheduling methods like Scheeperspan, use of intuition, observation of plant stress, pegboard method, etc was not readily available in the literature and could only be retrieved with the help of key informants through face-to-face interviewing. The classification and qualitative description of irrigation scheduling methods helped the research team to be well informed about the range of research products that are available for potential users in South Africa.

This was followed by wide consultation of key informants in South Africa and abroad (i.e. Australia). The first step was to identify key informants from the irrigation industry (which included retailers and experts from the irrigation industry, irrigation engineers, irrigation scientists from universities and technicons in South Africa involved with irrigation scheduling, researchers from the ARC, developers and designers of irrigation scheduling models, equipment like weather stations and soil water content monitoring devices. A qualitative approach was followed where key informants were interviewed using the face-to-face research method. Data was collected through semi-structured conversations held with them on the specific methods or models in use or which they are familiar with, in an effort to collect as much information and insights possible. The information collected through the literature review served as a discussion document during these interviews together with relevant open-ended questions. Several of the irrigation consultants, extensionists and designers that were selected for the semi-structured interviews as referred to in Part Five (Chapter 19), also participated in this part of this study.

The face-to-face interviews with various key informants was followed by focus group discussions as part of the meeting arranged for steering committee members during annual progress report meetings conducted by the WRC. Since this study was funded by the WRC, regular annual meetings of the steering committee in Pretoria at the WRC headquarters and telephone and Internet (e-mail) discussions took place. The members who were strategically selected to represent different interests of the industry and served on the steering committee of the WRC for this project from 2000 till 2005 appear in Table 2.1.

This focus group helped to steer the research and categorising of scheduling approaches through their critical evaluation and discussions. In addition to the members listed in Table 2.1, Prof. Richard Stirzaker (CSIRO, Australia) was visited and contacted on a regular basis. Their valuable and appreciated vision and insight helped tremendously in the final categorising of the approaches. The main advantage of the focus groups was the opportunity to observe a large amount of interaction on irrigation scheduling approaches over a wide spectrum of users in a limited period of time.

Table 2. 1: List of persons serving on the steering committee as selected by the WRC (2000-2005)

Name of steering committee members	Institution
Dr G Backeberg	Water Research Commission, South Africa
Prof GH Düvel	University of Pretoria
Prof GJ Steyn	University of Pretoria
Prof JG Annandale	University of Pretoria
Prof GCG Fraser	University of Fort Hare
Mr JLH Williams	University of Fort Hare
Prof ATP Bennie	University of Free State
Mr FPJ van der Merwe	Department of Water Affairs and Forestry
Dr NZ Jovanovic	University of the Western Cape
Mr FJ du Plessis	Murray, Biesenbach & Badenhorts Consulting Engineers
Mr NMP Opperman	Agri South Africa
Dr SS Mkhize	Water Research Commission, South Africa
Mr AT van Coller	National Department of Agriculture

The final draft of the categorisation of irrigation scheduling approaches was distributed amongst steering committee members, some of the more progressive irrigation farmers, irrigation extensionists and consultants before finally adopted as a possible classification of irrigation scheduling methods and models available for use by South African irrigation farmers.

2.3 CLASSIFICATION OF IRRIGATION SCHEDULING MODELS AND METHODS

The following chapter refers to the classification of the various irrigation scheduling methods and tools that are commonly used and quantitatively described in Section 2.4. There is a spectrum of soil-atmosphere-plant irrigation scheduling methods and techniques available that users can select from to help them to assist with the decisions to be taken to ensure that peak crop growing conditions prevail by holding soil water content at the optimum level. To assist making a decision on choosing the correct method, the potential users should ask the following questions?

- How much time can I spend on using the specific method or device and what time is needed for interpretation?

- What level of technology am I comfortable with?

- How much money am I willing to spend?

- What level of technical and maintenance support is available?

- The soil variation on the property will also influence the number of units required if soil water content is to be measured?

Taking into account the above-mentioned questions generally asked by potential users, the following principles were used for the classification of the various irrigation scheduling methods as indicated in Figure 2.1:

- First principle was to identify and distinguish between the various soil, plant and atmospheric based irrigation scheduling methods available to try and quantify the soil-plant-atmosphere environment. The spectrum of potential soil-plant-atmosphere scheduling methods and devices identified vary from very simple methods up to scheduling methods where a computer is needed to analyse and view data.

- The second principle was to identify and distinguish between the various integrated soil-water balance methods available for users. These methods available included both pre-programmed irrigation scheduling methods as well as real time irrigation scheduling methods, where daily accounting of the soil water balance is done with the use of sophisticated measuring equipment and the use of computer programs and /or in combination with the use of scheduling simulation models.

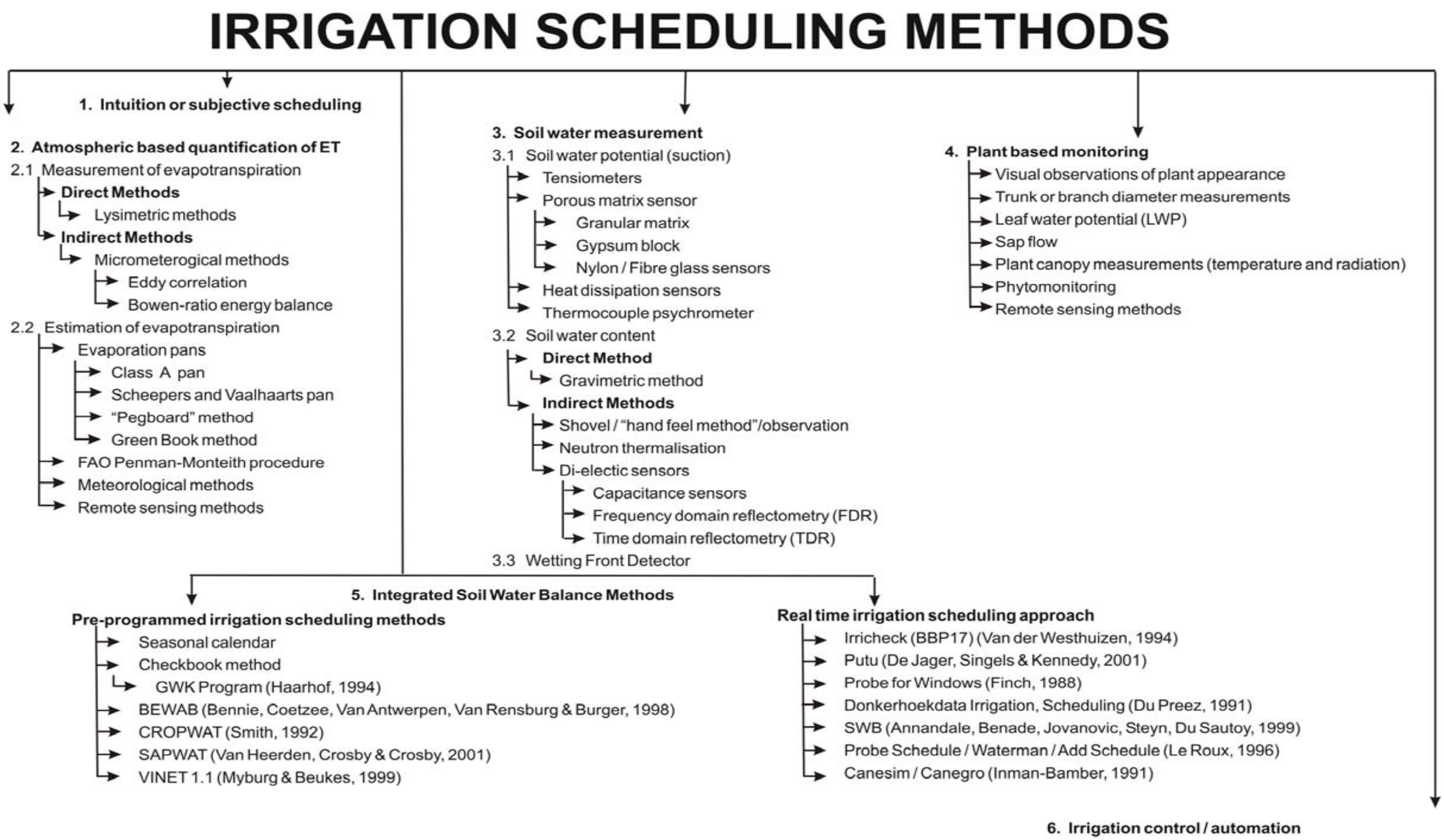

Figure 2. 1: Classification of irrigation scheduling models and methods used in South Africa

It is realised that any attempt to classify the spectrum of soil-plant-atmosphere irrigation scheduling methods and approaches will to a certain degree display the sentiments and objectives that are important to the designer of such a classification, and therefore also this attempt is realised to reflect just that.

2.4 DESCRIPTION OF IRRIGATION SCHEDULING METHODS AND MODELS USED BY IRRIGATORS

The following irrigation scheduling approaches (Figure 2.1) are often used by irrigators of, which some will be transferable to farmers while others will be considered as research tools.

2.4.1 Intuition or subjective scheduling methods
2.4.2 Atmospheric based quantification of evapotranspiration (ET)
2.4.2.1 Measurement of ET
2.4.2.2 Estimation of ET
2.4.3 Soil water measurement:
2.4.3.1 Soil water potential
2.4.3.2 Soil water content
2.4.3.3 Wetting Front Detector
2.4.4 Plant based monitoring
2.4.4.1 Visual observation of plant appearance
2.4.4.2 Trunk and branch diameter measurement
2.4.4.3 Leaf water potential (LWP)
2.4.4.4 Sap flow
2.4.4.5 Canopy measurements (temperature and radiation)
2.4.4.6 Phytomonitoring
2.4.4.7 Remote sensing methods
2.4.5 Integrated soil water balance methods:
2.4.5.1 Pre programmed irrigation scheduling methods
2.4.5.2 Real-time irrigation scheduling methods
2.4.6 Irrigation control or automation

2.4.1 Intuition or subjective irrigation scheduling

Description It varies from where a crop is watered whenever the farmer or his “irrigation manager” fancies it, to irrigation scheduling managed by “the seat of the pants”. Intuition is developed over years of experience plus a basic knowledge level and regular close observation of plant, soil and climate characteristics. The producer has enough experience with a specific crop to determine what the irrigation need is, how much and when to irrigate. There are two types of intuition that farmers apply: the one decision-making criteria is developed by irrigation farmers as a result of years of past experience and intimate contact with the crop, soil, and climate and is mostly applicable to one set of farming circumstances (therefore based on knowledge gained through experience) while the other type of intuition is based on traditional practices used by their father or other role players on the farm (more of a recipe).	
Mode of operation	Intuitive
Advantages: This type of irrigation scheduling management is thought to be remarkably accurate, but no evidence was found or documented about testing for accuracy.	
Shortcomings: Inexperienced farmers lack the necessary skills and knowledge to observe and interpret findings into a “workable” recipe for a specific farm.	
Users: Farmers (small-scale and commercial).	

2.4.2 Atmospheric based quantification of evapotranspiration (ET)

Irrigation scheduling based on estimating evapotranspiration is used worldwide and microcomputer capability has vastly improved this technology. This approach follows a meteorologically imposed evapotranspirational demand as it varies over time, and the irrigation requirements are determined accordingly. This technique requires the use of both an empirical or physically based relationship between ET and any number of meteorological variables.
Irrigation scheduling using these techniques requires both the estimation of the evapotranspiration and the incorporation of this information in some form

of soil-water balance model to predict the interval of watering (Burman *et al.*, 1983). When running a water balance, one obtains ET either through measurements or from estimates. The ability to quantify evaporation from the bare soil and to partition evapotranspiration from soil covered with vegetation into its two components – evaporation (from soil) and transpiration (from plants), is critical to irrigation scheduling.

The drawbacks of this scheduling technique include the development of appropriate crop coefficients suited for different areas and crop types, and the unavailability of computing facilities to small-scale farmers.

2.4.2.1 Measurements of evapotranspiration

A. Direct method

2.4.2.1.1 Lysimetric methods

B. Indirect methods

2.4.2.1.2 Micrometeorological methods:

- Eddy correlation
- Bowen-ratio

A. Direct method

2.4.2.1.1 Lysimetric methods

Description

Direct measurement of ET for time periods when no rain or irrigation occurs is only possible with a weighing lysimeter. A weighing lysimeter measures the mass of the soil water (along with the soil and plant mass), hence any temporal changes in mass are attributed to water uptake and transpiration by plants or evaporation from the soil (or plant) surface. Most weighing lysimeters range from 0.5 to 2.0 m deep and the surface area they cover is in the order of 0.1 to 10 m^2. Because of their large mass they are generally weighed *in situ*. Two methods for measuring evaporation of water from small bare areas of soil are: the evaporimeter tray and the microlysimeter.

Validity of any lysimetric method of determining evaporation hinges on whether the evaporation from the isolated body of soil is essentially the same as from a comparable non-isolated body. A number of factors can cause conditions in a lysimeter to deviate from reality: ❑ Imposition of a water table at the bottom of the lysimeter ❑ Cuttings of roots by the lysimeter walls ❑ Disturbance of the soil inside the lysimeter during construction, and conduction of heat by the lateral walls.	
Mode of operation	Weighing lysimetric method
Advantages: ❑ The microlysimeters are very accurate to within 0.5 mm cumulative evaporation for at least one to two days, depending on the initial soil wetness. Microlysimeters can be used at a large number of locations where the cost of the larger lysimeter is sometimes prohibitive. ❑ The two methods mentioned, namely the evaporimeter tray or atmometer tray and the microlysimeter have the advantage that they could be used for measurement in situations for which the spatial resolution of traditional lysimeters is too large.	
Shortcomings: ❑ It is an expensive method. ❑ Time consuming.	
Users: Mainly used by researchers to determine real time ET, and for irrigation scheduling purposes.	

B. Indirect methods

2.4.2.1.2 Micrometeorological methods:

- **Eddy correlation**

<table>
<tr><td colspan="2">Description
❑ The Eddy correlation and the Bowen-ratio are some of the micrometeorological measurements used for ET measurements near the land surface (i.e. a few meters above the plant canopy) to determine the fluxes of energy, momentum or trace gases. The techniques allow total evaporation to be measured by placing most of the sensors in the atmosphere and are more “portable” than buried sensors (viz. lysimeters).
❑ The Eddy correlation method has gained predominance among micrometeorological methods recently because of its minimal theoretical assumptions and improved instrumentation (Shuttleworth, 1993).
❑ Eddy correlation measurements are based on the correlation between turbulent motions of the air, and the abundance of constituents being transported by turbulent motions (e.g. heat or water vapour) (Campbell & Norman, 1998). The average vertical wind speed above a flat land surface is considered to be zero, because the ground surface is neither a source nor sink for air; therefore, for heat to move from the surface into the atmosphere, the upward motions of turbulence must be warmer than the downward motions. Similarly, for water vapour to undergo turbulent transport from the land surface up into the atmosphere, upward air motions must be more humid than the downward motions.
❑ The correlation between fluctuations in vertical wind speed and humidity is positive during evaporation, and during frost or dew the correlation is negative. The Eddy correlation method uses high frequency (~ 10 Hz) measurements of vertical wind speed, temperature, and humidity to compute the correlation between vertical air motions and the constituent of interest. The flux is then computed directly from this correlation (Shuttleworth, 1993).</td></tr>
<tr><td>Mode of operation</td><td>Measurement of eddies</td></tr>
<tr><td colspan="2">Advantages:
❑ The most direct measurement of sensible and latent heat fluxes is possible with micrometeorological methods (Shuttleworth, 1993).</td></tr>
</table>

- The Eddy correlation methods agreed better with lysimeter measurements than Bowen ratio measurements do, since the low evaporation rates from the play surface result in such low humidity gradients, that the Bowen-ratio was found to be unreliable (Tyler *et al.,* 1997)
- No assumptions are required about the land surface properties such as aerodynamic roughness or zero-plane displacement, and no corrections for atmospheric stability are necessary. This is especially advantageous in sparse heterogeneous vegetation canopies and the widely varying stability conditions that exist in semi-arid environments.
- Off-shelf Eddy correlation systems are freely available (Campbell Scientific, Optical Scientific, Hukseflux Thermal sensors, Ekopower)

Shortcomings:

- Instrumentation is relatively expensive and fragile.

Users:

Mainly used by researchers to determine real time ET, and for calculations of a water budget.

b) Bowen-ratio energy-balance

Description

The heat load on a leaf exposed to full sunlight is very high. This enormous heat load dissolute by the emission of long wave radiation, sensible (or perceptible) heat loss and by evaporative (or latent) heat loss. Evaporative heat loss occurs because the evaporation of water requires energy. Thus, as water evaporates from a leaf, it also withdraws heat from the leaf and cools it. Sensible heat loss and evaporative heat loss are the most important processes in the regulation of leaf temperature, and the ratio of the two is called Bowen-ratio (Campbell & Norman, 1998).

Bowen ratio = sensible heat loss/evaporative heat loss

When the evaporation rate is low, because water supply is limited, the Bowen-ratio tends to be high. The Bowen-ratio is about 10 for deserts, 2-6 for semi-arid regions, 0,4-0.8 for temperate grasslands and forests, 0.2 for tropical forests and 0.1 for tropical oceans (Gay, 1992).

Plants with very high Bowen-ratios conserve water but have to endure very high leaf temperatures in order to maintain a sufficient temperature gradient between the leaf and the air. Slow growth is usually correlated with these adaptations. One can calculate the evapotranspiration rate for an entire canopy using measurements of Bowen-ratio, net incident radiation, the heat loss from the soil, and gradients in temperature and water vapour concentration above the canopy. The Bowen-ratio technique requires measurements of air temperature and water vapour pressure at two vertical points (separated by a distance of about 1 m) above the canopy (typically at 0.5 and 1.5 m above canopy) as well as net irradiance and soil heat flux density measurements. More recently, Campbell scientific has been marketing a Bowen-ratio-CO_2 system for total evaporation, sensible heat and carbon dioxide measurement.	
Mode of operation	Measurement of fluxes
Advantages: ❑ The Bowen-ratio can run unattended for a week or more whereas the Eddy correlation requires almost daily attention (Savage *et al.*, 1996)	
Shortcomings: ❑ Instrumentation is relatively expensive and fragile. ❑ Instrumentation needs to be extremely accurate and well maintained in order to accurately estimate fluxes.	
Users: Researchers to determine real time ET mainly use this method.	

2.4.2.2 Estimation of evapotranspiration

2.4.2.2.1 Meteorogical methods

2.4.2.2.2 Evaporation pans

a) Class A pan

b) Scheepers and Vaalharts pan

2.4.2.2.2.1 Pegboard method

2.4.2.2.2.2 Green Book method

2.4.2.2.3 FAO Penman-Monteith procedure

2.4.2.2.4 Remote sensing methods

2.4.2.2.1 Meteorological methods (Adcon, MCS, Campbell Scientific and Davis automatic weather stations)

<table>
<tr><td colspan="2">Description
The use of meteorological data for irrigation management purposes implies that climate variables like incoming or net radiation, air temperature, relative humidity and wind speed are taken above a bare soil surface or above or within a crop and are interpreted to give estimates of evaporation. The concept of atmospheric evaporation could be used as indirect indicator of when and how much to irrigate. Meteorological data are commonly used in soil water balance computer programs and models like SWB, PRWIN, Irricheck, Donkerhoekdata, Canesim, etc.</td></tr>
<tr><td>Mode of operation</td><td>Meteorological measurements</td></tr>
<tr><td colspan="2">Advantages:
❑ Automated weather stations could be installed on the farm, and data collected and ET calculated for a specific site in a relatively short time.
❑ Weather station networks provide weather statistics that can be used by media outlets like the radio, cell phone Short Message Service (SMS), and fax format (visually), which can reach a broad network of users of weather data for irrigation scheduling. Information from the automatic weather station is processed into a user-friendly format that is useable by irrigators. Previous week's weather data and disease indexes could be retrieved through the use of the phone or a fax by providing the digital code of the nearest automatic weather station. These data are then used to calculate the gross irrigation demand for a specific crop.</td></tr>
<tr><td colspan="2">Shortcomings:
❑ Weather data are normally obtained from a weather station situated far from the specific site, and topography is an important factor that determines the applicability of information. Representative meteorological stations are needed and are critical for high quality information.
❑ Weather instruments need to be maintained properly because erroneous data are difficult to detect, even with good data screening.
❑ Crop factors are often gained from crops planted in other areas and from other varieties.</td></tr>
<tr><td colspan="2">Users:
❑ Researchers, extensionists, consultants and farmers.
❑ The service is available to crop producers in the Free State, Northern Cape and</td></tr>
</table>

Western Cape (Paarl, Worcester, and Robertson). Institutions like the University of the Free State, Agricultural Cooperatives, Department of Agriculture of the Free State and the SA Sugar research Institute are rendering these services to commercial farmers in their respective areas.

2.4.2.2.2 Evaporation pans

Crop ET is estimated using evaporation pans and crop coefficients, which relate crop ET to the evaporation measured in the pan (Doorenbos & Pruitt, 1977). While the standard Class A-evaporation pan is most widely used in South Africa, other pan configurations like the Scheepers and Vaalharts pan, have been successfully used for irrigation management in the past (Myburgh, 2002). Only a few farmers in the Northern Cape still use the Vaalharts pan for the measurement of evaporation.

Evaporation pans are commonly constructed of galvanised steel, but there are also stainless steel and monel (plated steel) models available, but these materials are more expensive.

a) Class A pan
Description This is one of the most widely tried and tested empirical methods used for the last 60-70 years in South Africa. This method assumes that over a given period, evapotranspiration (ET) is directly proportional to pan evaporation (Eo). The following formula is used to determine the daily water depletion of the crop: **ET= Eo x f** ET = daily water depletion in mm of evapotranspiration of the crop Eo = daily A pan evaporation f = constant of proportionality known as the crop factor A cumulative record is kept of the daily water consumption and when the estimated water depletion equals the readily available water (RAW) in the root zone of the crop, the water depleted since the last irrigation must be replaced. A range of environmental factors like wind, soil heat flux, vegetative cover around the pan,

painting and maintenance conditions and use of screens influence the daily evaporation of water from the pan. Therefore, proper exposure and calibration are needed in these respects. The importance of exposure has been shown by Pruitt and Angus (1961) who found that readings from two evaporation pans, one sited in a large grass field and the other in an ungrassed area, differed by 30% (Doorenbos & Pruitt, 1977).	
Mode of operation	Pan evaporation measurement
Advantages: ❑ Best method for people that don't irrigate frequently- in other words they will irrigate once a week/every ten days (low frequency) and then calculate how much they need. ❑ Simple method, however, the pan is not the same as the plant- so there will always be an error within certain bounds. Hence, pan coefficients are better suited to longer periods.	
Shortcomings: ❑ The relevant crop factor for a specific crop is also determined by spacing, age, irrigation frequency and method, and other factors. The RAW (Readily Available Water) in the root zone of the specific crop can therefore differ considerably depending on external factors. ❑ This measure relates to a specific microclimatic condition and may differ considerably for other locations. One should be careful when extrapolating data, for instance to terrain forms or microclimates that might differ substantially from the site of the evaporation pan. ❑ The crop factor may not be sufficiently accurate for critical crop stages (e.g. flowering). ❑ Requires daily attention by the user and some maintenance. ❑ Requires calibration according to local conditions and is excessively sensitive to very high values of evaporative demand.	
Users: Farmers, researchers, extensionists, irrigation consultants. Very popular amongst commercial farmers and consultants in the Breede River water management area.	

<table>
<tr><td colspan="2">b) Scheepers and Vaalharts pan</td></tr>
<tr><td colspan="2">Description
Traditionally been used as on-farm evaporation pan for the measuring of evaporation. This evaporation pan is manufactured by farmers themselves using a standard 200 l oil barrel, and is not made from stainless steel or special low carbon steel as in the case of the commercially available evaporation pans. The pan is usually 250 mm deep and 570 mm in diameter with the measuring scale prepared from Perspex.</td></tr>
<tr><td>Mode of operation</td><td>Pan evaporation measurement</td></tr>
<tr><td colspan="2">Advantages:
❑ The measuring rule could be adapted for different crop factors, thus excluding the calculations needed when using the Class A pan.
❑ Less expensive than the commercial evaporation pans (Class A pan).</td></tr>
<tr><td colspan="2">Shortcomings:
❑ The lowest crop factor that could be taken into account is 0.5, as the pan is too shallow to accommodate lower crop factors.</td></tr>
<tr><td colspan="2">Users:
Commercial farmers and advisors.</td></tr>
</table>

2.4.2.2.2.1 Pegboard method

<table>
<tr><td>Description
This type of scheduling monitors the accumulation of evaporation until predetermined levels are reached, which indicates the need for irrigation application. The operation of the pegboard entails using coloured pegs.
The information on the pegboard relates to:
❑ Canopy: the degree of canopy ground cover during the interval in between irrigations (0-full).
❑ Days: calendar date. At month end calendar peg returns to the beginning of the month.
❑ TAM: Total available water (mm).
❑ FAM: Freely available water (no yield reduction due to water stress) where the soil water is equal to TAM x 60%.
❑ Standing time of sprinkler.
❑ Net mm per standing time.</td></tr>
</table>

- Total accumulated irrigation per crop (George, 1988). The amount of freely available soil water expressed in terms of evapotranspiration, is known as *the evaporation deficit* as represented by the peg in the column of holes under each field. A second peg represents the accumulating daily evaporation amount. This peg will reach the deficit or indicator peg in the number of days it will take to deplete the available moisture and gives a clear indication of when to irrigate. As this method use evapotranspiration, the amount of irrigation and rainfall will have to be divided by the relevant crop factor and the resultant figure will dictate the downward movement of the peg.	
Mode of operation	Accumulation of evaporation
Advantages: - Ease of operation and obvious clarity. - Minimum record to be kept on paper or with any other aid (computer). - This method of scheduling suits any irrigation system. - Can easily be reflected on a spreadsheet.	
Shortcomings: - No permanent record is kept.	
Users: Sugarcane farmers (small-scale and commercial farmers) in KwaZulu Natal and Mpumalanga.	

2.4.2.2.2.2 Green Book method

Description
For many years the Green Book (Green, 1985 a&b) was accepted as the South African standard for the estimation of irrigation requirements of crops for planning and design purposes. The pan evaporation method is used in this method of estimating crop water requirements. The method comprises of the following stages: - An optimum value must be decided upon for the maximum amount of water loss (depletion), which may be permitted from a root zone before irrigation becomes necessary. This establishes how much to irrigate on a particular soil with a particular irrigation system. - The daily rate of water loss (evapotranspiration) is calculated from actual weather records, taking into account the crop type and stage of development. - Starting from field capacity, the daily level of soil water depletion is calculated

by accumulating daily evapotranspiration losses. Recorded daily rainfall is used throughout to adjust the soil water depletion level. When this depletion reaches the permissible maximum value, application of appropriate irrigation amount becomes necessary. ❑ Calculations are carried out continuously through the entire growing season of a crop and repeated for a couple of years. This statistical summary of the irrigation history of the crop is then used as basis for estimation of future irrigation requirements. This method implies that, over a given period, evapotranspiration (ET) is in direct relation with pan evaporation (Eo). **ET = kc x Eo** *Where kc = crop factor. Reviewed kc values empirically related to pan evaporation and growth periods for crops grown in South Africa were developed.*	
Mode of operation	Evaporation and crop factors
Advantages: ❑ Relatively easy to use and low cost. ❑ The evaporation data was obtained from three different sources namely: the Weather Bureau, Department of Water Affairs and Forestry and the National Department of Agriculture. The exposure of pans was therefore mostly in accordance with standards laid down for weather station networks and therefore fairly free of effects of local obstructions.	
Shortcomings: ❑ The lack of knowledge during the stage of development of these manuals did not permit crop factors used in the manuals to be adjusted for the different climatic zones and growing seasons. Once decided upon, the crop factors were used unchanged in all production areas over all the growing seasons.	
Users: Used by some farmers involved in pasture production and advisors in the field.	

2.4.2.2.3 FAO Penman-Monteith procedure

Description
A large number of more or less empirical methods have been developed over the last 50 years worldwide to estimate evapotranspiration from different climatic variables. Relationships were often subject to rigorous local calibrations and proved not to be globally valid. Testing the accuracy of methods under each new set of conditions is

laborious, time-consuming and costly, and yet evapotranspiration data is frequently needed at a short notice for irrigation scheduling. To meet this need, guidelines for predicting crop water requirements were published in the FAO Irrigation and Drainage Paper No 56 (Doorenbos & Pruitt, 1977). Since the 1980's, the preferred terminology used is reference ET, rather than potential ET (Burman *et al.* 1983). This standard ETo method eliminates some of the shortcomings identified with the other methods like the Green Book and the Class A pan. It is recommended the use of hypothetical short grass reference evaporation in association with the four-stage approach for the development of crop factors (viz. initial stage, crop development stage, mid season stage and late season stage). The FAO method of reference evapotranspiration (ETref) is linked to any given crop by way of a standard crop factor (kc) for any given period during the growing season as described by Harrington & Heerman (1981). **ET = kc x ETref** *ET = daily water depletion in mm of evapotranspiration of the crop* *ETref = reference evapotranspiration (mm)* *kc = crop factor* *kc =(kcb x ks) + ke* *kcb = the basal crop coefficient, i.e. corresponding to a crop grown under no water shortage* *ks = a soil water availability factor (0-1, also called stress coefficient)* *ke = the soil water evaporation coefficient.* The modified Penman-Monteith method is considered to offer satisfactory results with the minimum error in relation to the living grass reference crop. The relatively accurate and consistent performance of the Penman-Monteith approach in both arid and humid climate conditions confirmed the recommendation by the FAO for the acceptance of this method as the sole standard method. It is a method with a strong likelihood of correctly predicting ETo in a wide range of locations and climates, and has made provision for application in limited data situations (Doorenbos & Pruit, 1977).	
Mode of operation	Estimation of evapotranspiration
Advantages: ❑ The crop factors cater for regional variations and varieties, management practices and irrigation methods. In contrast to the crop factors used with the	

A pan, reference evapotranspiration and kc can be adjusted consistently and with confidence to accommodate differences in climate zone and farming practice

- It is a method with strong likelihood of correctly predicting ETo in a wide range of locations and climates and has provision for application in limited data situations. The reference (ETref) figures used changed from the A pan crop factors to a modified range based on the universally accepted FAO procedure. For real time irrigation scheduling systems, ETref for the forthcoming days can be directly estimated from meteorological service forecasts.

Shortcomings:

- In situations where large saturation deficits and high temperatures exist, this method did not work satisfactorily and should be used together with field observations.
- ET models are typically one-dimensional and do not take the two-dimensional nature of irrigation and rainfall spatial variability into account.

Users:

Researchers, extensionists, consultants and farmers with the support of professionals.

2.4.2.2.4 Remote sensing methods

Description

In remote sensing methods, evaporation is evaluated (usually in conjunction with meteorological methods) by determining certain radiative properties of the soil and crop as viewed from a great distance. This is a relatively new tool for irrigation scheduling, but unfortunately this tool is not well known to water resource managers and irrigation engineers (Bastiaansen & Bos, 1999). Two aspects could be covered with this method:

- Description of irrigation performance at a multitude of scales
- Estimation of the parameters of the soil-vegetation-atmosphere continuum, such as soil water, crop evapotranspiration and crop biomass production (D'Urso & Menlenti, 1995).

This method provides an opportunity to study the crop growing at scales ranging from individual fields to scheme level. The multi-spectral satellite images can be used for the appraisal of irrigation management information. Information such as land use

surface patterns, crop mapping, identification of irrigated areas and other crop related parameters might be surveyed and monitored extensively in space and time by means of satellite image. This evades the need to use standardised *kc* values such as provided by Doorenbos & Pruitt (1977).	
Mode of operation	Processing of remote imagery
Advantages: ❑ Remote sensing provides opportunities to retrieve new performance indicators such as: depleted fraction of soil water, crop water deficit, relative evapotranspiration, relative soil wetness and biomass yield on a scheme level. ❑ This is a major benefit for large irrigation schemes and river basins in circumstances where the hydro-informatics infrastructure and database management is absent. ❑ This method provides a combination of indicators that enhances the diagnostic opportunities, especially when the entire flow path from the reservoir up to the root zone can be quantified. It provides a more comprehensive description of the total system as compared to classical indicators describing water delivery and service levels (Malano & van Hofwegen, 1999). ❑ It is mainly used to support decision-making in irrigation water management of large districts. This information, together with historical data, constitute the input set for the simulation of soil water flow, from which the actual crop water requirements can be determined.	
Shortcomings: ❑ Remotely sensed information does not explain the causes, it only measures net effects of land surface processes. ❑ High-resolution images are delivered more than a month after acquisition and at a relatively high cost per scene. Low-resolution images can be obtained daily, but the resolution is 1.1 km^2. This is however too coarse for direct interpretations at plot scale for a single crop. Conversion equations are needed to overcome this problem, but it comes at the cost of accuracy (Bastiaansen *et al.*, 1998). ❑ The practical implementation requires a large effort and the whole procedure is heavily reliant on computer skills. The acquisition of a large volume of data input is rather complex and requires the support of professionals.	
Users: Irrigation engineers, scheme managers (e.g. WUA Oranje Riet) and irrigation consultants.	

2.4.3 Soil water measurement

Soil water measurements provide an indication of water extraction and availability within the crop root zone and can be used to directly schedule irrigation events. This is also an accurate way of obtaining information on both how much irrigation water to apply and when to apply it.

Soil water status can be measured directly or estimated indirectly using various parameters. There are three ways of measuring availability of soil water for plant growth:

- Measuring how strong the water is retained through measurement of soil water potential.
- Measuring the soil water content.
- Measuring the depth of the wetting front after irrigation.

Soil water potential, in simple words, is the energy required to remove a finite increment of water from the soil. Soil water content does not tell one how ‘happy’ the plant is, but suction (soil water potential) indicates the water availability to the plant. Some devices are set into the soil permanently while others are portable and could be moved around from point to point to take readings of soil water potential.

Soil water availability is usually expressed as a fraction of available water. This fraction is given by the ratio of available water content over available water capacity, which is defined as the difference between field capacity and wilting point. The available water to the plant is a fraction of the soil water content. Whatever the method used to determine this measurement, one has always to deal with the problem of spatial variability. Generally speaking the more accurate devices are also more expensive and usually portable. Accuracy of measurement of soil water content can be expressed in absolute and relative terms.

- Absolute accuracy refers to the ability of the device to produce readings of the actual moisture content of the soil.

- Relative accuracy is the ability to reflect changes in soil water content accurately.

Wetting front detection: As infiltration from irrigation and rainfall occurs, a wetting front develops. This wetting front is the transition zone between the dry and wet soil. The wetting front detector (Full Stop) is a device that indicates the advance of the wetting front.

The four main methods of soil water measurement which currently dominate irrigation management are:

- Measurement of soil water potential (with tensiometers)
- Electrical resistance/capacitance
- Gravimetric sampling
- Neutron scattering (Hardie, 1985).

2.4.3.1 Soil water potential (suction)

Soil water potential is measured through the use of:

- Tensiometers
- Porous matrix sensors
- Heat dissipation sensors
- Thermocouple psychrometry

2.4.3.1.1 Tensiometers (Irrometer/Jetfill/ Adcon's electro-tensiometer / Delta T)

Description
Tensiometers operate by allowing the soil solution to come into equilibrium with a reference pressure indicator through a permeable ceramic cup placed in contact with the soil. Retention of water by soil and its relationship to the soil water free energy level has become know as "the potential concept of soil-water."

<table>
<tr><td colspan="2">The standard tensiometer is used to measure real time soil matric potential down to –80 kPa. Standard tensiometers are available in standard lengths of 15cm, 30 cm, 45 cm, 60 cm and 90 cm. The new model “LT” irrometer introduced in 1995 is ultimate in sensitivity at the very wet end of the soil water range (below 20 kPa). It was designed to operate in very low water holding capacity soils like coarse sand and planting mixtures used in the container nursery industry, where soil water needs to be maintained in the 5-15 kPa range (Hillel, 1982).

Jetfill tensiometer has basically the same components as a standard tensiometer, but is equipped with a reservoir and a refill mechanism. At a push of the button the Jetfill mechanism instantly injects water from the reservoir into the body of the tensiometer and removes accumulated air.

Electronic tensiometers are portable pressure sensors for measurement of the soil water tension, measured through a tensiometer tube placed in the soil. The measuring device can be moved from tensiometer tube to tensiometer tube allowing an unlimited number of measurements over a short period of time. The measuring range is from 0-1000hPa with a very high accuracy. This device is becoming popular amongst irrigators because they are relatively cheap and data can be logged. However, they need correction for temperature and exhibit some problems under water logging conditions (Lorentz, 2003).</td></tr>
<tr><td>Mode of operation</td><td>Tension measurement</td></tr>
<tr><td colspan="2">Advantages:
❑ The same site is used all season and readings can be compared.
❑ Not affected by osmotic potential of soil solution (the amount of salts dissolved in the soil water), as salts can move into and out of the ceramic cup unhindered.
❑ Very simple instrument to use but attention should be paid to proper preparation before installation, proper installation, proper servicing of tensiometers and storage if removed from the soil after use.
❑ Relatively affordable and easily obtainable.</td></tr>
<tr><td colspan="2">Shortcomings:
❑ It provides point measurements and therefore representative sites or stations are prerequisites before installation in the field. Since the information is localised and site specific, many observations are needed for accurate characterisation of a field.
❑ High labour requirement if it is not automatically logged.</td></tr>
</table>

- High degree of maintenance and management required. Regular service needed after installation – each tensiometer should be inspected for air accumulation often. - Range of operation: between saturation and approximately –70kPa. Therefore not regularly used for measurements at the dry end of the spectrum. - To prevent regular refill of tensiometers that have sucked air, most farmers are tempted to keep tensiometer readings at low suctions (below 50 kPa), often resulting in over irrigation. - The relatively long response time (particularly at suctions above 30kPa) makes tensiometers less suitable as a portable measurement device. - Temperature-sensitive. - Needs a retention curve to convert measured data into volumetric water content.
Users: Farmers, consultants, researchers and extensionists.

2.4.3.1.2 Porous matrix sensors

The principle of operation is that electrical resistance (electrodes embedded in porous matrix) is proportional to its water content. For each type of soil there is a relationship between suction and the soil water content. Electric resistance of a soil volume depends not only upon its water content, but also upon its composition, texture and soluble-salt concentration. Electrical resistance sensors do not directly measure soil matric potential, and therefore empirical calibration is required (Shock *et al.*, 1996).

A variety of porous materials have been used to construct electrical resistance sensors: gypsum (1958), fibreglass (1949), nylon (1949) and granular matrix.

(a) Gypsum block
Description Gypsum blocks slowly dissolve providing a saturated solution of Ca and SO_4 ions in the porous matrix. They are less sensitive to salts than nylon and fibreglass as the saturated solution buffers the effect of changes in the soil salinity on measured electrical resistance. This type of sensor is suited to various irrigation applications where only “full” and “refill” points are required.

For more exact work, gypsum blocks tend not to have the range, sensitivity or reaction time required. Upon drying, tight contact between the block and surrounding soil may be lost.	
Mode of operation	Electrical resistance measurement
Advantages: ❑ They are easier to implement than standard tensiometers and very convenient to use. ❑ Inexpensive, which allows many replicates in the field. ❑ Relatively accurate and can be left in the field for automatically monitor continuously. ❑ Multiple depths are possible with many sensors.	
Shortcomings: ❑ High labour if not logged. The sensors need to be read quite often to get good data. ❑ Disintegration appears over time due to the dissolution of gypsum blocks, changing the pore geometry and altering the calibration. This makes the measurement of matric potential unreliable. Disintegration depends on the pH of the soil water, and gypsum blocks need replacement after 2-3 seasons. ❑ It needs correction in relation to soil temperature as temperature affects the electrical resistance reading. ❑ Soil profile is disturbed during installation. ❑ Because of the pore size of the material used in most electrical resistance blocks, particularly those made of gypsum, the water content and thus electrical resistance of the blocks does not change dramatically at suctions less than 50 kPa. Resistance blocks are therefore not reliable for use in sandy soils. ❑ All such types of blocks are subjected to hysteresis (less resistance in wetting up than drying out at set water tension). The range is usually only up as far as 100 kPa tension. The sensitivity in the dry range is usually very flat (a large change in dryness reflects small changes in measured resistance).	
Users: Farmers, researchers, extensionists	

(b) Nylon and fibre glass sensors
Description The *fibreglass and nylon sensors* are longer lasting, but the electrical resistance output includes both matric and osmotic effects.

Mode of operation	Electrical resistance measurement
Advantages: ❑ Longer lasting than gypsum blocks.	
Shortcomings: ❑ Individual osmotic effects and field calibration of fibreglass units are recommended due to the high variability in calibration of individual sensors.	
Users: Farmers, researchers and extensionists.	

(c) Granular matrix sensors (Watermark / Aquaprobe)	
Description This sensor is made of fine sand material held in place by a synthetic porous membrane. The membrane prevents penetration of fine soil material, which could change the physical properties of the block. The sensor provides a desorption estimate of soil water potential in the range between 0 and 200 kPa (Jovanovic & Annandale, 1997) This is an electrical resistance - type sensor: It is read by a hand–held meter, which converts the electric resistance reading to a calibrated reading of kPa of soil water suction. It operates under the same electrical resistance principle as gypsum blocks and contains a wafer of gypsum imbedded in the granular matrix. The gypsum wafer slowly dissolves, to buffer the effect of salinity of the soil solution on electrical resistance between electrodes. The particle size of the granular filling material and its density determine the pore size distribution in granular matrix sensors and their response characteristics.	
Mode of operation	Electrical resistance measurement
Advantages: ❑ It is very similar to gypsum blocks, cheap and it can monitor multiple depths. ❑ Little maintenance is required. ❑ It is very popular due to the simplicity of management-simple to use and suitable for logging. ❑ It is relatively cheap compared to other soil water sensors. ❑ Problems inherent to gypsum blocks are overcome because most of the granular matrix sensors are supported in a metal or plastic screen. ❑ Manual measurement of matric potential with a hand held meter would certainly be a cheaper option than the installation of a data logging system (Thomson & Armstrong, 1987).	

Shortcomings:
❑ It is hard to establish water use patterns unless daily readings are taken. ❑ It is temperature sensitive: block temperature should be measured in order to compensate for the effect that the soil temperature has on the electrical resistance reading to obtain a reliable estimate of soil water potential. Differences in temperature cause large variations in the soil matric potential values. ❑ It provides point measurements at specific sites – therefore many representative observations are needed to properly characterize a field. ❑ It is susceptible to inaccuracies caused by soil disturbance during installation. ❑ It needs individual calibration (calibration dependent), which is time consuming. Regular calibration and manual reading are often required, although readings could also be logged with a computer. ❑ Retrieval of these instruments is difficult in clay soils.
Users: Farmers, researchers, and extensionists.

2.4.3.1.3 Heat dissipation sensors (Campbell Scientific 229 & BCP Electronics)

Description	
The temperature in a porous block is measured before and after a small heat pulse is applied to it. The amount of heat flow from the pulse-heated point is mostly proportional to the amount of water contained within a porous material. This means a wet material will heat up slower than a dry one. The rise in temperature is measured with an accurate thermocouple in the sensor tip and calibrated against the soil water potential.	
Mode of operation	Thermal conductivity
Advantages: ❑ Accurate and continuous monitoring of both soil water and temperature of the probe site. ❑ With heat dissipation sensors, thermal conductivity is measured rather than electrical conductivity as with gypsum blocks, and hence the salinity of the water has no major effect. ❑ It estimates matric potential over a wide soil water range. The optimal range of measurement is from 0 to 100 kPa.	

Shortcomings:
❑ Fairly extensive power requirements if measurements are required frequently. Computer logger and extensive cabling is required. ❑ The sensitivity of the heat pulse sensor in sandy and sandy loam soils are considered to be fairly good, while sensitivity problems are experienced in heavier clay soils. ❑ Tedious calibration is needed to ensure accuracy.
Users: Researchers.

2.4.3.1.4 Thermocouple psychrometer

Description	
It infers the water potential of the liquid phase of a soil sample from measurements within the vapour phase in equilibrium with it. The major difficulty with measuring stems from the fact that the relative humidity in the soil gas phase changes only slightly. Practically all measurements lie in the narrow relative humidity range between 0.99 –1.0. The first development of an instrument to measure relative humidity in equilibrium with a plant or soil sample was that of Spanner (1951) and since then major developments took place concerning improvement of accuracy and reliability of measurement. Modern psychrometers consist of a miniature thermocouple junction, placed within a sample chamber that can be cooled to condense water on it (Peltier effect). The junction is connected to a voltmeter to estimate its temperature depression as the water evaporates. Neuman & Thurtell (1972) introduced an improved technique that measures the dew point rather than the wet–bulb temperature depression to estimate relative humidity, which has certain advantages.	
Mode of operation	Measurements of humidity
Advantages: ❑ It measures the total water potential rather than water content. ❑ Calibration of sensors and sensor readings are independent of soil type and soil particle size. It is calibrated empirically, with solutions of known water potential connected to the psychrometer chamber.	

Shortcomings:
❑ It is temperature sensitive because it measures relative humidity of the air in equilibrium with the sample. Any difference in temperature between the sample and the chamber air will introduce a systematic error, unless the difference is measured and corrected. ❑ It does not provide good differentiation at the wet end of the soil water potential scale, where critical irrigation decisions must be made for many crops and it is not as easy to log remotely. ❑ Relative expensive equipment needed.
Users: Mainly researchers.

2.4.3.2 Soil water content

Accurate assessment of soil water deficits and irrigation efficiencies are possible using volumetric soil water measurements. Soil water measurements are useful for verifying ET models and for the starting or stopping of irrigation, but are not very useful in forecasting the need of irrigation. Soil water measurements are necessary for feedback information on the irrigation scheduling practice based on ET.

There are direct and indirect methods to measure soil water content, as yet no universally recognised standard method of measurement exist.

- Direct method: water is removed from a sample by evaporation. This includes gravimetry with oven drying.
- Indirect methods: certain physical properties of the soil vary with water content and indirect methods are those that measure the property of the soil that is affected by soil water content. These methods include hand feel method by the use of soil auger and spade, nuclear techniques (the use of the neutron probe) and di-electric conductivity measurement (capacitance sensors, frequency domain reflectometry and time domain reflectometry techniques).

A. Direct methods of soil water measurement

2.4.3.2.1 Gravimetric method

<table>
<tr><td colspan="2">Description
Soil samples are collected at different depths within the root zone with a soil auger and volumetric soil water content (dry and wet mass) is calculated in the laboratory:
$$W = \frac{\text{Wet mass} - \text{Dry mass}}{\text{Dry mass}}$$
(W= gravimetric wetness)
Through this formula the ratio of the mass of water to the mass of the dry soil is obtained.</td></tr>
<tr><td>Mode of operation</td><td>Measurement of mass</td></tr>
<tr><td colspan="2">Advantages:
❑ One of the most accurate methods to determine soil water because it is the only direct method of measuring soil water content. It serves to calibrate other soil water measurement techniques.</td></tr>
<tr><td colspan="2">Shortcomings:
❑ More than one sample (replication) is needed for accuracy.
❑ The sampling method is destructive.
❑ It is laborious and time consuming, since a period of 24 hours is usually considered necessary for complete oven drying at 105°C.
❑ Water content values for stony and gravely soils, both on a mass and volume basis, can be grossly misleading because of the coarse fraction.</td></tr>
<tr><td colspan="2">Users:
Researchers, mostly to calibrate equipment used for indirect measurements.</td></tr>
</table>

B. Indirect methods of soil water measurement

2.4.3.2.2 Measurement of soil water through observation and "feel method" by use of soil auger / shovel or spade

Description As the name implies, the "hand-feel method" involves estimating soil water by feeling the soil. Soil samples are collected at different depths with the help of a soil auger or spade and then the water content is estimated by observation and hand-feel. Soil is squeezed between the thumb and index finger and the operators' experience will indicate the relative amount of water in the soil. To help inexperienced irrigators in this regard, guidelines for determining soil water by feel are available.	
Mode of operation	Feeling soil wetness
Advantages: ❑ Inexpensive. ❑ An easy and simple method but experience is needed for accuracy. ❑ Soil classes are identified through observation, and the soil water content is determined with the help of standard tables.	
Shortcomings: ❑ The major drawback with this method is that estimation of soil water content is subjective and is not the exact amount of soil water. ❑ Cannot compare sites to previous results or other sites. ❑ The reliability of this method depends on the experience of the operator. With repetition and experience it is possible to be accurate within 10-15% ❑ It does not give any lead-time for irrigation. ❑ Not able to supply continuous results. It is hard to establish water use patterns unless daily samples are taken.	
Users: It is the most widely adopted technique by commercial and small-scale irrigators, researchers and extensionists.	

2.4.3.2.3 Neutron thermalisation

(Neutron probe (CPN 503, Waterman, Troxler))

Description	
The neutron probe was first developed in the 1950's and is still regarded as the most accurate instrument for measuring soil water. The volumetric water content is determined through the use of scattering and slowing down of neutrons by the hydrogen nuclei of water molecules. The detector counts the number of slow neutrons. A calibration curve is needed to establish the relationship between the volumetric water content and the counts of slow neutrons. Data is collected at regular intervals and downloaded into specialist software that enables both graphical and tabular analysis.	
Mode of operation	Neutron scattering and measurement of slow neutrons
Advantages: ❑ It is relatively easy to use, reliable and accurate. Soil water measurements can be made at different depths in the soil profile. ❑ It is non-destructive and measurements can be performed with minimum disturbance of the soil. ❑ This allows one to follow the water content changes with time through taking measurements at the same locations and depths. ❑ Unlike the capacitance and TDR probes, the neutron probe has a larger and therefore more representative sphere of measurement. ❑ It is practically independent of temperature and pressure. ❑ It is portable and it is used to measure soil water at many sites.	
Shortcomings: ❑ Initial costs are relatively high, although it can be used at several locations in one field and for several fields. ❑ The main limitations relate to safety rules, which have to be followed for safe operation, transport and storage of the radioactive probe. It requires an operating licence because it contains radioactive material (Stone & Nofziger, 1988). ❑ Calibration is delicate, time and labour consuming. Using the neutron probe with a single calibration equation for all soils provides only limited accuracy (Kennedy *et al.*, 2000). ❑ Background hydrogen molecules, bulk density, and other chemical components may influence the measuring results. ❑ A low degree of spatial resolution is found. Information is localised and site	

specific. It needs many observations for accurate characterisation of a field.
Users: More suited for use by a group of farmers because of the cost of the instrument, estates, irrigation consultants, researchers and extensionists.

2.4.3.2.4 Di-electric sensors:

- Capacitance sensors *(Enviroscan, Diviner 2000, C-probe, Silora, Troxler Sentry, Gopher, Aquaterr)*
- FDR (Frequency Domain Reflectometry)
- TDR (Time Domain Reflectometry) *(Spectrum's TDR 300, Aquaflex)*

Di-electric sensors (Capacitance, FDR and TDR sensors)
Description All of the sensors within this group use an oscillator to generate an AC (alternating current) field, which is applied to the soil in order to detect changes in soil dielectric properties linked to variations in soil water content. The characteristics of this propagation depend on the soil water content through the dielectric properties of the soil. **Capacitance sensors** consist essentially of a pair of electrodes (either an array of parallel spikes or circular metal rings), which form a capacitor with the soil acting as the dielectric medium. The capacitor works with the oscillator to form a tuned circuit, and changes in soil water content are detected by changes in the operating frequency. The capacitance technique determines the dielectric permittivity of a medium by measuring the charge time of a capacitor, which uses this medium as a dielectric medium. These sensors (for example the Sentek) operate from within access tubes and are not in contact with the soil. This allows multiple sensors to be lowered into an access tube and take measurements at all depths. **Frequency Domain** sensors use a swept frequency. The resonant frequency (at which the amplitude is greatest) is a measurement of the soil water content, and the amplitude is a measure of soil electrical conductivity. Like capacitance sensors, their measurement is a single frequency, but the exact frequency depends on the soil water content.

TDR probes also use an oscillator to generate an AC signal but the soil water content is measured from the amplitude of the standing wave, which is formed when the reflected AC signal interacts with the generated AC signal. They operate at a single fixed frequency. TDR depends on discontinuities in the medium of transmission. Combined with knowledge of the propagation velocities of waves in the medium being use, these discontinuities can be located by observing the change in energy levels at fixed points in the medium. Energy that does not become dissipated returns to its source. The probe tips of a TDR appliance present a discontinuity in the wave propagation path of the energy initiated at the signal source.	
Mode of operation	Di-electric measurement
Advantages: ❑ The ability to capture real time variation in soil dynamics and most sensors can be connected to conventional data loggers. Continuous monitoring and automation of irrigation systems are possible when installed semi-permanently. ❑ Non-radioactive. ❑ No specific knowledge of analysing waveforms is required. Most of these sensors operate at lower frequencies (100 MHz or less) and can therefore detect “bound” water in fine particle soil.	
Shortcomings: ❑ Only applicable to the site being measured with heterogeneous soil it becomes very difficult to extrapolate from one site to sites not measured. Regular calibration is needed. ❑ Expensive equipment is required and complex electronics, which is most of the time beyond the range of equipment affordable by farmers. ❑ Adequate software is included, but skilled operator in set-up and interpretation is needed. ❑ Readings are heavily influenced by soil water content and air gaps in the soil volume nearest the electrodes. With the access tube models, it is extremely critical to have good sensor tube-soil contact for reliable estimation of soil water content. It is difficult to use in cracking clay soils.	
Users: ❑ More suited for use by a group of farmers because of the cost of the instrument, researchers, extensionists and consultants.	

2.4.3.3 Wetting Front Detector (WFD)

<table>
<tr><td colspan="2">Description
The detector works on the principle of flow line convergence. Irrigation or rainwater moving downwards through the soil is concentrated when the water molecules enter the wide end of the funnel. The soil in the funnel becomes wetter as the funnel narrows and the funnel shape has been designed so that the soil at its base reaches saturation when the wetting front outside is at a similar depth. Once saturation has occurred, free water flows through a filter into a small reservoir and activates a float (Stirzaker et al. 2000, Stirzaker 2003). The wetting front detector was developed and patented by CSIRO Land and Water, Australia, in 1997.

The wetting front detector can be used to schedule irrigation, because the time it takes for water to reach a certain depth depends on the initial water content of the particular soil (Philip, 1969). If the soil is dry before irrigation, the wetting front moves slowly because the water must fill the soil pores on its way down. Therefore, a lot of water is needed before the detector will respond. If the soil is quite wet before irrigation, then the wetting front will move quickly through the soil. This is because the soil pores are already mostly filled with water so there is little space for additional water to be stored. Thus a short irrigation will cause the detector to respond. The float in the detector is activated when free water is produced at the base of the funnel. Water is withdrawn from the funnel by capillary action after the wetting front dissipates. Depending on the version used, capillary action can be used to “reset” the detector automatically, or water can be removed via a syringe. The water sample can be used for routine salt and fertilizer monitoring.</td></tr>
<tr><td>Mode of operation</td><td>Measurement of wetting front</td></tr>
<tr><td colspan="2">Advantages:
❑ It is robust, accurate and visible even when the farmer is absent and the information is stored until the farmer chooses to reset the device.
❑ A small sample of soil water can be retained for nutrient monitoring.
❑ It is simple, easy to understand and to apply by the farmer. The information that farmers get from the detectors is easy to understand - either the wetting front has or has not reached the desired depth.
❑ The WFD concept acknowledges the existing knowledge of irrigators and each irrigation becomes an experiment from which the farmer can learn. The mechanical version is adapted for the circumstances and needs of the small-</td></tr>
</table>

scale farmer. ❑ Excellent learning tool for farmers and users to become acquainted with irrigation scheduling principles. ❑ WFD can also be used to evaluate the immediate past irrigation events. ❑ This device offers a robust method to combine the WFD with estimates of transpiration from reference crop evaporation and crop factors.
Shortcomings: ❑ It is labour intensive to install. ❑ Sensitivity problems occur with irrigation systems like centre pivot and furrow irrigation. ❑ Installation depth is crucial.
Users: Farmers (commercial and small-scale), researchers, extensionists and consultants.

2.4.4 Plant based monitoring

Instead of measuring the soil water content, a number of plant indicators can be used to determine whether irrigation is needed. These indices include the observation of the general plant appearance, changes in diameter or trunks or branches, leaf water potential, sap flow, canopy temperature and radiation.

Plant water status has remained one of the most difficult parameters to measure (Howell, 1996). Direct measures of plant water status are useful as a measure of plant water stress and can be used to schedule irrigation events. However, the use of this scheduling method is more appropriate for researchers and environmental physiologists rather than for the practical application of irrigation scheduling by farmers, although a few high valued fruit growers in the Western and south-western Cape are using these methods with the necessary support.

While a range of techniques has been used in research applications, plant stress sensors are not widely adopted by commercial farmers in South Africa. One reason may be that measurements of plant water status often do not provide sufficient lead time to schedule irrigation while avoiding crop water deficits affecting yield and often they don't respond fast enough to provide adequate information on when to terminate irrigation applications. The other possible reason is that the available methods of plant monitoring require sophisticated devices and the support of professional people and therefore their practical application for irrigation scheduling has been limited.

The following plant monitoring methods will be discussed:

2.4.4.1 Visual observation of plant appearance
2.4.4.2 Trunk or branch diameter measurements
2.4.4.3 Leaf water potential (LWP)
2.4.4.4 Sap flow
2.4.4.5 Canopy measurements
2.4.4.6 Phytomonitoring
2.4.4.7 Remote sensing methods

2.4.4.1 Visual observation of plant appearance

Description The visual observation of general plant appearance includes observation of possible retardation in foliar growth or fruit development that usually depends on a visual expression of soil water stress. It is likely that, when external symptoms of soil water stress are evident, the crop may already be permanently set back. Knowing what plants look like at the initial stages of soil water stress can be used to indicate irrigation need.	
Mode of operation	Visual observation
Advantages: ❑ Regular monitoring and visual observation, together with weather information and understanding of soil water holding capacity, can make irrigation scheduling successful.	
Shortcomings: ❑ If experience is lacking, the symptoms of plants under stress will be discovered too late and possible economic losses will occur. ❑ Irrigation scheduling by plant stress observation can result in less water application than required. ❑ Farmers with a large area of multiple irrigation systems find simple visual observations of plant symptoms insufficient and time consuming, and must	

usually rely on more complex and sophisticated methods.
Users: The visual observation of plant stress symptoms and leaf extension (*viz.* sugarcane) is a common technique used by experienced farmers, extensionists and researchers.

2.4.4.2 Trunk or branch diameter measurements

Description	
The dendrometer is a sensitive dial gauge attached to the trunk or branch of a tree for measuring small changes in diameter as water status of the plant changes during the day. This sensor helps to determine the need for and the amount of irrigation from the change in diameter, which occurs over a certain time period. Pre dawn and midday leaf water potential have been the most popular plant water status parameters proposed for irrigation scheduling of orchards. Research has indicated that midday stem water potential is a significant reliable plant water status indicator for irrigation scheduling of fruit trees (Noar, 1999; Schakel *et al*., 2000; Chone *et al*., 2001, Noar, 2001). An indirectly relationship exists with LWP (Klepper, 1971).	
Mode of operation	Measurement of diameter
Advantages: ❑ It is fairly easy to install and must be connected to a logging system (Schackel *et al*., 2000)	
Shortcomings: ❑ The main problem encountered seems to be that the same responses are sometimes obtained with both excess and shortage of water. Small diurnal changes are observed in the case of high water stress conditions (as a result of stomatal closure). For mild water stress conditions, diurnal changes depend on species and varieties. ❑ This procedure does not detect water stress as rapidly as the leaf water potential method, but provides a more integrated measurement of conditions being experienced by the entire tree.	
Users: Mainly used by researchers, but also by a few progressive commercial fruit growers and horticulturalists in the Western and south-western Cape.	

2.4.4.3 Leaf water potential (LWP)

Description Irrigation timing techniques that ensure attainment of the upper boundary values of water-yield relationships are important and leaf water potential measurement is one of these methods. LWP is a criterion for irrigation timing. A miniature sensor attached to the leaf is used to measure the reduction in leaf thickness, and thus turgor pressure, as water stress of the plant increases. The main interest in this method lies in the possibility to link values of pre-dawn leaf water potential to relative evapotranspiration. To operate effectively, the method requires careful selection of a fully exposed leaf, which accurately represents the average response for the entire plant throughout the day.	
Mode of operation	Measurement of plant reductions in leaf thickness and turgor pressure.
Advantages: ❑ It is claimed that such a system is capable of reacting, almost immediately, to the onset of plant water stress, thereby preventing stomatal closure.	
Shortcomings: ❑ Limitations, such as the sampling needs, are presented by this technique. These are relatively difficult for farmers to apply. ❑ Measurements must be taken before dawn to avoid meteorological effects. ❑ Measurements on many representative fields are required.	
Users: Researchers and a few commercial fruit and wine producers in the Western Cape with the help of consultants.	

2.4.4.4 Sap flow

Description It measures how rapidly a pulse of heat is transported by the sap flow up the trunk. Relative ET values are obtained by measuring sap flow along the trunk and comparing trees under water shortage to well irrigated trees using both steady heat flux or heat pulse technology. Two techniques are available: ❑ Sap flux density technique: limited by the need to determine the cross-sectional area of the water conducting tissue. ❑ Mass flux technique.

Mode of operation	Sap flow measurements
Advantages: ❑ Direct measurements of plant water status can be used in conjunction with ET models to provide feedback data on crop water deficits.	
Shortcomings: ❑ Problems such as sampling range of instruments needed for a complete crop season (differing stem sizes) or sensor movement from plant to plant, besides the physical problems of instrumentation, make sap flow gauges mainly useful for research. ❑ Both sap flux and mass flux techniques require tree sampling and lead to necrosis of the trunk. This is why it is necessary to change sampling site frequently.	
Users: Researchers, progressive commercial fruit growers and wine producers in the Western Cape with the help of consultants.	

2.4.4.5 Canopy measurements (Temperature and radiation)

Description
Since the 1980's, a new technology was developed to remotely sense crop or plant temperature (Jackson *et al.,* 1981). Surface temperature measurements are performed by infrared radiometers, and infrared gun, and used to determine the degree of water stress. Measurements are based on the principle that objects emit radiation in proportion to their surface temperature. When the surface of the leaf is warmer than the air, evaporation is reduced. Change in leaf temperature is closely related to the availability of water, which indicates critical soil-water content when stress becomes detrimental to crop growth. Remote sensing of a plant canopy includes both reflected and emitted radiation. Remote sensing methods evaluate evaporation (in conjunction with meteorological methods) by determining certain reflective properties of the soil or crop, as viewed from a great distance. The spread of modelling techniques has encouraged use of input data from remote sensing with the support of GIS for manipulating large data sets. Spectral radiation as seen by reflected wavebands does follow the leaf area of the crop and under full cover, the changes in crop canopies caused by leaf rolling

can be depicted with the vegetative index. Information is used to support decision-making in water management of large districts that involves correct schematisation of the areas of interest and of water transport processes in each part of the system. By means of appropriate interpretation, digital images can be used to produce multi-temporal maps of crop requirements over large areas.	
Mode of operation	Measurement of plant and canopy temperature.
Advantages: ❑ Rapid assessment of large areas is possible. ❑ A portable device that is relatively easy to use and could easily be moved from one site to another. ❑ It is stable in a wide range of ambient temperatures.	
Shortcomings: ❑ Problems are experienced regarding the index threshold values, which need to be adjusted for each crop. ❑ Although the measurement of temperature is accurate, the translation of this measurement into plant water status requires additional information such as the net solar radiation, air temperature, humidity, etc. To be able to do this, calibration for a specific crop and site is required unless a theoretical model is used. ❑ It can only be used if weather conditions are not rapidly changing (wind and radiation) and only for fully developed crops (in order to avoid soil surface temperature influence on measurements). ❑ Accurate measurement of crop temperature is not useful on its own without supplementary environmental data rendering the technique difficult to apply using satellites (Howell, 1996). ❑ Relative expensive.	
Users: Limited to advisors and researchers.	

2.4.4.6 Phytomonitoring

Description
This technique was developed in Israel as a tool for direct monitoring of actual growth of plants and the environment. It is aimed at improvement of the controllable crop factors, as part of the worldwide change to precision agriculture. Plant-sensing

techniques, sampling rules, measurements protocols, data interpretation and crop-specific application techniques are incorporated. This serves as an interpreter between the plant and grower. It is a specialized real time information system for horticulture and crop production. The purpose is to derive new crop–related information for supporting decision-making and irrigation control. The phytomonitoring system combines:

- A data acquisition system based on a number of specifically designed sensors (up to 64 different sensors that can be allocated around a central unit). Remote sensors that can be selected with their own data loggers are:
  - *A. Plant sensor*: stem diameter, trunk diameter, leaf temperature, sap flow rate, and a variety of dendrometers and fruit growth sensors for different plant types.
  - *B. Environmental sensors*: solar radiation, air temperature and humidity.
- Data processing software is used to display measured data in terms of plant physiology (Kopmyt *et al.*, 2001).

Phytomonitoring involves more than just irrigation scheduling. It is by definition a management information system for crop production. This information system helps to monitor soil characteristics, weather patterns (air temperature, humidity) and provides measurement of leaf temperature, sap flow relative rate, stem micro-variations and fruit growth. It can identify plant physiological disorders at early stages of their development as well as disclose the crop physiological response to any environmental changes in a short time (Ton & Nilov, 1996). It helps the grower to monitor climate, irrigation and fertigation regimes and treatments in a trial-and-error approach. Three functions of phytomonitoring as a management information system are:

- Standard reporting: the system can generate a customized set of measured values and their derivatives, used in daily control practice.
- Exception reporting (watch-dog): the system enables clear detection of unexpected disorders in plants, and this function is based on a variety of phytomonitoring indicators of plant physiological disorder.
- Decision-support system: it enables the monitoring of climate and irrigation regimes though a trial-and error approach (Ton *et al.*, 2001).

Mode of operation	Management information system making use of plant sensing techniques.

Advantages:

- The system is tailored to specific growers and is simple to operate and maintain.

It can be installed by using simple building blocks: remote sensors; data connector and communication channels. Three options of communication channels are available direct cable or GSM cellular modem or web server.

- It can be configured for each grower's demands by making use of the trial-and-error regime. Graphic software presents the information in clear and easy to use way to the user.
- It helps to disclose hardly detectable, accumulated physiological disorders. Only a few examples are necessary for effective monitoring of plants.
- It is a convenient tool for comparative examination of different treatments and materials.
- It allows continuous monitoring of physiological parameters of the plants.
- Extremely high sensitivity and short response time of phytomonitoring channels eliminate the risk of crop damage.

Shortcomings:

- It is rather expensive.
- It needs extensive technical support with the start up of the system.

Users:

Greenhouses, vineyards, and progressive fruit growers in the Western and south-western Cape.

2.4.4.7 Remote sensing methods

Remote sensing can also be used for plant based monitoring to estimate crop biomass and study crop growing on scales ranging from individual field to scheme level (See 2.4.2.2.4 Remote sensing).

2.4.5 Integrated soil water balance methods

Irrigation scheduling by the integrated soil water balance approach is based upon using either soil water balance models and/or crop growth models to calculate evapotranspiration. The soil water balance approach is analogous with the use of the checkbook method where daily withdrawals are subtracted from the checkbook balance and deposits are added. This method requires tedious calculations if done by hand. Irrigation scheduling approaches based on soil water balance calculations imply that irrigation should start when a threshold value of water content in the soil is reached. To facilitate its use, several computer programs and models are available that could assist the irrigation consultant and farmer with decision-making. Many of the computer programs and models allow the user to choose the method of ET calculation. The data required are weather, crop and soil and management information. The crop growth models often calculate soil water evaporation (E) and crop transpiration (T) separately (Ritchie, 1972) for daily periods using leaf area index (LAI) to partition ET into the T and E components.

Two approaches of integrated soil water balance irrigation scheduling, namely *pre-programmed irrigation scheduling* and *real time irrigation scheduling*. With a pre-programmed irrigation scheduling approach, the decision on how much to irrigate and when to irrigate is determined in advance and a few corrections usually dependent on rainfall are made during the season. A real time irrigation scheduling approach is where the decisions on when and how much to irrigate is based on actual daily conditions, usually the soil water content or atmospheric demand. In real time irrigation scheduling, the ETref for the forthcoming days is sometimes directly estimated from meteorological services or forecasts.

Models can either be physically based or empirical mathematical equations and can be used either for strategic planning or tactical purposes. The use of computer programs to help with irrigation scheduling was introduced in the 1970's, however only recently with the introduction of fast, personal computers have they begun to gain wider acceptance. Strategically one may wish to indicate what area to irrigate, which crops to plant, and how to distribute the available water supply during the season (water delivery), for evaluation of irrigation strategies, and support to regional agro-meteorological information. Irrigation scheduling models can also be used for tactical decisions regarding when and how much irrigation to apply.

2.4.5.1 Pre-programmed irrigation scheduling methods

The following irrigation scheduling methods and models are applied by irrigators for pre-programmed irrigation scheduling:

- Seasonal calendar for irrigation (fixed or flexible).
- Checkbook scheduling with the help of computer programs like the GWK program.
- Models like BEWAB, CROPWAT, SAPWAT, SWB and VINET 1.1. These models are suited for estimating crop water requirements and for planning irrigation strategies. A calendar of expected irrigation dates can be provided through the use of these models.

2.4.5.1.1 Seasonal calendar

Description
Irrigation strategies make use of long-term historical data for full season irrigation scheduling programmes. The intention with calendars is to promote easy and ready adoption of improved water management practices by farmers by presenting simple, non-technical scheduling guidelines. It is the intention to prepare a schedule of anticipated weekly crop water requirements. Calendars are developed using daily soil water balance crop yield models to express most appropriate dates of irrigation. Therefore, following a soil water budget based on weather data and/or pan evaporation does this. The selected value for the fixed net application depth depends on the soil type, crop type, irrigation method and local irrigation practices at farmers' fields (Hillel & Allen, 1995). Once developed, the calendars require little updating and input by technical personnel, but the farmer needs to keep record of the water applied (must ensure water applications are on schedule). Rain is usually treated as if it was an irrigation event. Within this pre-programmed irrigation scheduling approach, irrigators often use two strategies: Fixed irrigation schedule: where farmers use the pre-programmed irrigation schedule without any seasonal adjustments for pertinent reasons like the lack of flexibility in terms of irrigation systems or delivery of bulk water.

Semi-fixed or flexible irrigation schedule: where irrigators use a pre-programmed irrigation schedule with in-season adjustments made as needed.	
Mode of operation	Compilation of schedule using historic weather data.
Advantages: ❑ Calendars are usually developed for several planting dates, crop varieties, soil types and initial water contents. ❑ This is a simple approach of assisting farmers in their decision-making process. ❑ It is ideal for small-scale farmers and commercial farmers without high value crops, and is also applicable to relatively low rainfall areas. ❑ Usually, this scheduling package is developed for flood or sprinkler irrigation where the irrigation cycle varies from one to two weekly applications. ❑ The availability of estimates of irrigation water usage during the season on a weekly basis enables the farmer to edit the original programme. These estimates are usually based on automatic weather data and crop coefficients.	
Shortcomings: ❑ The biggest problem is to account for rainfall in calendars based on long-term data. This makes calculations very uncertain. To solve this problem, one can either assume average rainfall or no rainfall, or utilize probable rainfall during the crop-growing season.	
Users: Farmers, extensionists and consultants.	

2.4.5.1.2 Checkbook method

Description
Checkbook irrigation scheduling enables irrigation farmers to estimate a field's daily soil water balance (in terms of soil water deficit), which can be used to plan the next irrigation. The checkbook method is a record-keeping model, which accounts for all water inputs and outputs. This method requires the irrigator to monitor: ❑ The growth stage of the crop. ❑ Maximum daily temperature. ❑ Relative humidity. ❑ Rainfall or irrigation applied to the field. ❑ Select the daily ET estimation from the crop water use table. ❑ Calculate the new soil water deficit.

<table>
<tr><td colspan="2">Usually, estimates of water use have been developed for average climatic conditions for a particular area based on expected crop growth stage and environmental conditions. Soil water can be measured or estimated in a variety of ways including the low cost “feel” method to more accurate, expensive neutron probe units. This helps to provide an accurate starting point as well as makes provision for corrections or adjustments to the soil water deficit throughout the season. A computer spreadsheet version or hand keeping of records can be followed. This water balance worksheet is operated like a “checkbook” - the irrigation manager maintains a rainfall and irrigation record and mathematically determines a net water balance. To decide when to start irrigating, farm managers should compare the latest soil water deficit in relationship to selected irrigation water management strategies for a crop, the crop’s projected water needs, and the weather forecast. The irrigation management strategy will depend either on factors like crop development (critical growth period) or the irrigation system’s normal net application amount (Shock, 2000).</td></tr>
<tr><td>Mode of operation</td><td>Calculation of soil water balance.</td></tr>
<tr><td colspan="2">Advantages:
❑ It is relatively easy to operate. If, for any reason, the soil water balance sheet is interrupted and a period elapses, the balance sheet can be restarted anytime whenever the irrigator has installed soil water instruments or irrigation is anticipated (Trimmer & Hansen, 1994).
❑ Several fields can be scheduled in a very short period of time depending on the number of crops and field locations.
❑ If properly maintained and occasionally verified by soil water measurements the checkbook can be highly successful.
❑ It is handy for daily record keeping of crop water use, soil water deficits along with dates, crop stage, rainfall and irrigation.</td></tr>
<tr><td colspan="2">Shortcomings:
❑ Effectiveness of checkbook depends on the accuracy and regularity of the in-field observations and measurements by the irrigator.
❑ Since the crop water use is influenced by more climatic factors than considered in this method, regular field visits and observations are necessary to determine the existing soil water deficit in the field and comparisons to the soil water balance sheet prediction.
❑ To set-up and operate an effective soil water accounting system like this, several field characteristics and soil-water-plant factors need to be understood and quantified by the irrigator.</td></tr>
<tr><td colspan="2">Users:
Cooperative extensionists (viz. GWK program), consultants and farmers.</td></tr>
</table>

Models	Developed	Principles of the model	Application
2.4.5.1.2.1 GWK program	1994, Dup Haarhof, GWK Ltd (Griekwaland Wes Cooperative)	❑ The GWK computer program is a typical checkbook scheduling method where the farmer receives information once week on the current level of the soil water content of the profile, and then based on checks and balances, decides whether he should step up or reduce the irrigation applications during the subsequent week. ❑ Applies checkbook-scheduling principles through the use of a simple, user-friendly spreadsheet computer program based on ETref and crop factors. This software programme that was developed in 1994 uses data from soil water sensors (mainly from neutron probes) and calculates the crop water use. ❑ This software creates a spreadsheet-like working file for each field that reflects the different soil types and depth, available water holding capacity, crop type and emergence date. It is expected of farmers to monitor rainfall and irrigation amounts on a daily basis, while the relative humidity, maximum and minimum daily temperatures, and ETref is collected from representative automatic weather stations. Farmers can use this meteorological data either from automatic weather stations situated on their farms or from weather stations in the specific area. ❑ The software generates a water depletion graph (depth and time graph) for each field for any date, which is printed to take to the field or is filed with other seasonal information on performance and input records. ❑ The program is designed to run in Lotus but is also available in Microsoft Excel. Farmers can either receive information e-mailed to them or just receive the printed information prepared by GWK irrigation expert's hand delivered or fax to them. ❑ *Advantages:* ➢ Quick method of observation by the farmer on the current rate of depletion. The programme incorporates farmer observation, meteorological data of the site and soil water content monitoring to decide on the amount of water to be applied. ➢ The farmer takes ownership of irrigation scheduling decisions based on the information (depth-time graph) provided. ❑ *Shortcoming:* ➢ It needs a sophisticated soil water instrument like neutron probe, Diviner or Enviroscan to monitor the of soil water content status. ➢ An irrigation consultant or expert needs to interpret the data.	❑ Crops: Potatoes, wheat, maize, onions, cotton. ❑ Areas: Northern Cape (Vaalharts, Douglas, Prieska, Barkley-Wes, Rietrivier, Taung). ❑ Commercial and small-scale farmers, consultants.

Models	Developed	Principles of the model	Application
2.4. 5.1.3 BEWAB **(***Besproeiingswater Bestuursprogram***)**	ATP Bennie, MJ Coetzee, R van Antwerpen, LD v Rensburg & R du T Burger (UOVS) 1988	❑ Pre-programmed scheduling model for a specific range of crops in the relatively dry areas of RSA (<600mm/annum). ❑ Scheduling is done by applying predetermined amounts at prescribed times or intervals. ❑ The pre-scheduling irrigation water management program is based on soil water budgeting principles and used under low rainfall conditions (< 600 mm/annum), deep soils with plant available water capacity (PAWC) higher than 800 mm. ❑ Maintenance of relatively full profile from early season to provide for the peak demand periods of ET during mid season is an important principle. ❑ BEWAB provides options for profile water status at planting – either 100%, 50% and 0% of PAWC. The upper limit of PAWC is estimated from the silt plus clay content and the lower limit is estimated through simulation of the root water uptake. ❑ Written in Turbo Pascal and GW Basic. Water balance model used for calculation of water use. ❑ Inputs needed to run programme: type of crop, length of growing season, target yield, depth of soil, silt plus clay content for 200 mm depth intervals, rain storage capacity. ❑ Estimating crop water requirements: an output is produced in terms of the number of days after planting and pre-scheduled water application programme for the different options. ❑ *Advantages:* ➢ User-friendly program and logical to implement. ➢ A calendar of expected irrigation dates is provided. ❑ *Shortcomings:* ➢ Initial support with the introduction and set up of the program is needed.	❑ On farm irrigation scheduling and irrigation planning at farm level. ❑ Planners, developers, consultants, irrigation board for calculations of water need and planning of irrigation strategies. ❑ Applicable for mechanised (sprinkler) and flood irrigation. ❑ The program can also be used to design water application requirements of irrigation systems. ❑ This program makes provision for wheat, maize, cotton, peanuts, soybeans, peas and potatoes. ❑ Users in semi-arid regions like Sandvet, Vaalharts, Ramah, Kalkfontein, vd Kloof, Scholtzburg, Petrusburg, Modderrivier, Northwest areas like Brits, Koedoeskop.

Models	Developed	Principles of the model	Application
2.4. 5.1.4 CROPWAT (Crop Water Requirements)	Smith , 1992	❑ FAO computer program for irrigation planning and management (FAO 46) that is accepted as international standard. ❑ Calculations of crop water requirements and irrigation requirements are carried out with inputs of climatic and crop data. Standard crop data are included in the program and the climatic data for 144 countries can be obtained through the CLIMWAT database. ❑ Furthermore, the development of irrigation schedules and evaluation of rain fed and irrigation practices are based on a daily soil-water balance using various options for water supply and irrigation management conditions. Scheme water supply is calculated according to the cropping pattern provided. ❑ Procedures for calculation of the crop water requirements and irrigation requirements are based on methodologies presented in FAO Irrigation and Drainage Papers No 24 “Crop water requirements” and No 33 “Yield response to water” ❑ The new version of CROPWAT, CROPWAT version 7, contains a completely new version in Pascal, and can be run in the MS-Windows environments. ❑ CROPWAT includes a revised method for estimating reference crop evapotranspiration, adopting the approach of Penman-Monteith as recommended by the FAO Expert Consultation held in May 1990 in Rome. Further details on the methodology are provided in the Irrigation and Drainage Paper No 56: “Crop Evapotranspiration". ❑ Main functions: ➢ To calculate: o Reference evapotranspiration. o Crop water requirements. ➢ To develop: o Irrigation schedules under various management conditions. o Scheme water supply. ➢ To evaluate: o Rain fed production and drought effects. o Efficiency of irrigation practices.	❑ Used for estimation of irrigation requirements by irrigation planners, designers and agronomists. ❑ CROPWAT is meant as a practical tool to help agro-meteorologists, agronomists and irrigation engineers to: ➢ Carry out standard calculations for evapotranspiration and crop water use studies. ➢ Design and manage irrigation schemes. ❑ It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rain fed conditions or deficit irrigation (Smith, 1992).

<table>
<tr><th>Models</th><th>Developed</th><th>Principles of the model</th><th>Application</th></tr>
<tr>
<td>2.4. 5.1.5 SAPWAT
(South African Procedure For Estimating Irrigation Water Requirements)</td>
<td>Crosby & Crosby, 1999

Van Heerden, Crosby & Crosby, 2001</td>
<td>
❑ A computer program that enables the planner, water manager and designer to develop realistic estimates that reflect the complex factors that determine crop water requirements. This planning and management aid is supported by an extensive South African climate and crop database.
❑ The methodology employed is based on atmospheric demand utilising the Penman-Monteith calculated evapotranspiration. The advantage of the FAO procedure is that crop factors can be developed to cater for regional variations, different varieties, management practices and irrigation methods.
❑ The purpose of SAPWAT is to satisfy the needs for a user-friendly aid to help with the planning and scheme management, and is therefore seen as a component of the decision support system.
❑ More suited for estimating crop water requirements and for planning irrigation strategies than for actual irrigation scheduling although some irrigators are using it for actual irrigation scheduling.
❑ SAPWAT takes the user through a process from the selection of up to six weather stations out of 350, which are shown on a map, comparative evaporation graphs, crop factors for a selected crop and a screen that shows the water requirements for that specific crop, effective rainfall and irrigation requirement. Several options are provided, enabling the user to replicate a specific situation. These include choice of growing periods, planting dates, geographic regions, basic irrigation management options, and changeable irrigation efficiency levels.
❑ SAPWAT conforms to the principles embodied in FAO 24.
❑ Advantages:
➢ Users, as they gain experience, can contribute to improving and up-dating the databases and develop new techniques for approaching local and specialised situations.
➢ A website has recently been created to promote a two-way communication between the SAPWAT authors and the diverse users of the program, as well as between the users themselves and the irrigation scientists, in order to develop specific applicable instruction sheets, which could also be updated periodically (Crosby, 2004).
➢ A calendar of expected irrigation dates is provided.
❑ Shortcomings:
➢ Initial professional support with the introduction and set up of the program is needed.
</td>
<td>Users:
❑ DWAF encourage designers, planners, farmers and scheme managers of WUAs and irrigation schemes to use it as a planning aid. SAPWAT is used by irrigation scheme managers to make certain inputs for the development of a water management plan by the WUA.
❑ Some commercial farmers also use it for irrigation scheduling.
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Models	Developed	Principles of the model	Application
2.4.5.1.6 *Vinet 1.1* **(Estimating Vineyard Evaporation for Irrigation System Design and Scheduling)**	PA Myburgh and C Beukes (ARC Infruitec Nietvoorbij) 1999	❑ This is a water consumption prediction model that takes into account the unique qualities and variation between different vineyards. ❑ This computer program makes use of an empirical model to simulate the water use of plants (ET). ❑ Traditional irrigation scheduling practices of farmers in vineyards usually only take one or two crop factors together with the ETo into account, and ignore the variation between vineyards in terms of leaf layer, trellis systems, cultivar characteristics, plant density, and climatic factors. The program takes into consideration conditions that have an influence on transpiration and evaporation. ❑ The heat pulse velocity technique was calibrated for measuring sap flow over short periods of time in grapevine trunks. A calibration curve of sap flux against time was developed. ❑ A Li Cor LAI 2000 Plant Canopy Analyser (PCA) was calibrated to measure leaf area index (LAI) in selected vineyards. Leaf area development was measured in eight vineyards varying in cultivars, vine spacing, and trellising system in five grape growing regions of Limpopo, Western Cape and Northern Cape. Seasonal leaf area development could be predicted by means of a third order polynomial equation-using day of season as the independent variable. Based on these predictions, potential growth curves were developed for the respective summer and winter rainfall regions. ❑ Transpiration and surface evaporation models are combined with this model to serve as basis for the prediction of evapotranspiration. The Boesten & Stroosnijder evaporation model was evaluated and adaptations were necessary to account for canopy shading effects viz. horizontal canopies vs. vertical canopies. ❑ Parameters like vine spacing, soil type, trellising system, leaf area, ETo and a constant factor that represents evaporation losses from different soil types were used as input parameters in this model. ❑ *Advantages:* ➢ This model takes into consideration different vineyard sites and conditions. ➢ The program is user-friendly and logical to implement. ❑ *Shortcomings:* ➢ Initial support by irrigation specialists with the introduction and set up of the program is needed.	❑ Commercial wine and table grape growers, consultants, engineers and small-scale table grape farmers. ❑ Areas: ➢ Summer rainfall region: o Northern Cape o Limpopo o Mpumalanga o Northwest Province o Gauteng o Northern Cape: Eksteenskuil ➢ Winter rainfall region: o Western Cape

2.4.5.2 Real time irrigation scheduling approach

In the context of this discussion, real time irrigation scheduling comprises of three main elements:

i) Soil water content as determined through regular measurement of the soil water status

ii) The use and availability of weather data and

iii) A decision support system which relies on field soil water content, weather forecast and crop cultural practises to select the most appropriate course of action in the scheduling of crops.

Models	Developed	Principles of the model	Application
2.4. 5.2.1 Irricheck (BBP17)	AJ vd Westhuizen & T Daldorf ,1994.	❑ Management program with the aim of real- time irrigation scheduling. ❑ This is the final product of a program initially called: BBP17 (Beste Besproeiings Praktyke). This program started as BBP 3 and was upgraded through feedback from farmers and field experience. ❑ It uses weather, soil, crop and management data to simulate daily water balance and daily real time irrigation scheduling. ❑ Crop factors are used to simulate growth and development of crops ❑ Crop coefficient together with grass reference daily evapotranspiration is used to calculate the water requirements of a plant. The crop coefficient can change according to local conditions. ❑ Evapotranspiration is calculated by taking into account the crop coefficient and weather data. ❑ Soil water balance is used to simulate the available soil water. ❑ Soil water balance can be crosschecked with the use of soil water measurement devices (neutron probe and gravimetric measurement of soil water). ❑ Both the original BBP17 and Irricheck are used in the field. ❑ *Shortcomings:* ➢ Support with the introduction and set up of the program is needed. ❑ *Advantages:* ➢ This program is used by commercial farmers and is relatively user friendly. ➢ This program is very much a bottom-up initiative, where farmers and their experiences in the field were included in the development of the program.	❑ Applicable to different regions in RSA – commercial farmers, consultants. ❑ Areas used: Limpopo, Mpumalanga Northwest, Gauteng, Vanderkloof, Petrusburg and KwaZulu Natal. ❑ Irrigation consultants in the Limpopo, Mpumalanga and Northwest Provinces use the BBP 17 version. ❑ This program makes provision for: ➢ Agronomic crops: maize, popcorn, sugarcane, sweet corn, wheat, tobacco, cotton, potatoes, groundnuts, soybeans, dry beans. ➢ Pastures: lucerne, rye grass ➢ Vegetables like: tomatoes, onions, green pepper, garlic, cabbage, pumpkins, sweet melons, carrots, beetroot, peas, ➢ Citrus and table grapes., ➢ Subtropical crops: bananas, avocado, mangoes, tea and coffee.

Models	Developed	Principles of the model	Application
2.4.5.2.2 PUTU	De Jager, Van Zyl, Kelbe & Singels,1987 De Jager, Singels & Kennedy, 2001	❑ PUTU is a crop growth model that attempts to arrive at a specific yield using water use predictions for specific conditions. ❑ The PUTU model was created for maize in 1973, with the initial development described by de Jager and King (1974) and de Jager (1979). A version for wheat (PUTU 6) followed in 1981 as described by de Jager, Botha and van Vuuren (1981). ❑ PUTU 6 was modified for irrigation scheduling and re-named PUTU 9 (1984/85). While PUTU 9 utilizes most of the functions of PUTU 6 it computes hourly time steps. It became subsequently apparent that daily time steps are more adequate and necessary for irrigation scheduling. So, the daily irrigation version PUTU 9.86 was developed in 1987 and further developed to PUTIRRI as a generalised application model. ❑ This is a simulation model for scheduling irrigation of wheat and maize on individual farms using weather data received from an automatic weather station. It calculates the daily values of Em (maximum total evaporation from a specific crop surface in a given growth stage) and ETref (reference evaporation) from the hourly data obtained from an automatic weather station (de Jager, 1992). ❑ Hourly values of crop total evaporation (Em) are calculated from the weather data, while daily values of Em are found by integrating these over the daylight period. ❑ This model provides accurate simulations of water use and the onset of crop water stress. ❑ Farmers receive the following information: ➢ Indication of the danger of the onset of water stress ➢ The daily water use over the past seven days ➢ The percolation of water out of the root zone ➢ The expected timing of the next irrigation ➢ The current plant available water in the root zone and assessment of the managers performance ❑ *Shortcomings:* ➢ The program is not that user-friendly, and therefore only a few farmers can use the program without support rendered by irrigation professionals. ❑ *Advantages*: ➢ Graphical presentations offer a simple way of communicating information to managers. ➢ It is expected that operators of the weather service should regularly visit the clients, and apart from meeting the needs of the manager, this acts as a valuable source of information to the weather service operator.	❑ Commercial farmers all over the country and in certain African countries like Tanzania, Swaziland and Lesotho. ❑ This service comprised of advisors in Bloemfontein and Pietermaritzburg who telephonically and /or with computers link to various clients in South Africa and some countries in Africa. ❑ Adapted for the following crops: pastures, maize, soybeans, wheat, peas, dry beans, potatoes, runner beans, sugarcane, barley, cotton and vegetables.

Models	Developed	Principles of the model	Application
2.4.5.2.3 Probe for Windows (PRWIN)	Trevor Finch, Research Services, New England, Australia, 1998	❑ Computer program that uses data from soil water sensors and schedules irrigation and the management of crops. The data on soil water content are derived from measurements by neutron probes and other instruments like the Diviner 2000 and Enviroscan at different depths down the soil profile. The program uses direct soil water measurements instead of atmospheric climate data or crop parameters to simulate plant growth. ❑ The prediction of irrigation requirement is based on the soil water measurement of a specific locality and the rate of soil water depletion and historic data on the depletion of soil water. Schedules are calculated using three different values of crop water use: ➢ Calculated from the soil water status. ➢ Calculated from ETo. ➢ Calculated from crop factors or models or historical data. ❑ This program outputs various reports that constitute the basis for a water audit: ➢ Gains report: printed at the end of the season, it shows the total amount of water delivered to each site by rain/irrigation, together with effective amount retained in the soil profile. ➢ Site history report: it shows each irrigation and rainfall in the season. ➢ Season summary report: time graph showing the root zone water content, the actual crop water use, and a "standard" crop water use curve as a comparison, total delivered and efficient irrigation and rainfall together with yield efficiency per mm of water. ➢ Scheduling report: it lays out the scheduled irrigation for each site together with total farm water requirements on a day-by-day basis for the next two weeks. ➢ Irrigation request report: simplified output designed to help valve operators or for export as a comma delimited text to automatic control systems (Motorola). ➢ Calculate water use report: it shows the amount of water used by the plant during the season – calculated by adding the daily water use each day. ❑ *Advantages:* ➢ This program does not simulate crop growth and therefore doesn't distinguish between crops - applicable to all types of crops. ➢ It provides information for planning of irrigation scheduling. ❑ *Shortcomings:* ➢ It needs intensive soil water measurements because of spatial variability. ➢ Initial support by irrigation specialists with the introduction and set up of the program is needed.	❑ It is used for irrigation scheduling purposes, based on intensive soil measurements. The soil water measurements are used for real time irrigation scheduling. ❑ It is widely applied throughout the country: irrigation consultants, commercial farmers and researchers

Models	Developed	Principles of the model	Application
2.4.5.2.4 Donkerhoek Data Irrigation Scheduling Program	Donkerhoek data Pty Ltd , Tienie du Preez & D Mercker (DFM Software Solutions) (1991)	❑ It uses real time weather data in the prediction of daily irrigation requirements. ❑ The program offers information on scheduling irrigation, automated control, fertiliser management and logging of fruit or plant growth. (Koch, 1996). ❑ The irrigation scheduling program offered is driven by: ➢ Crop factors together with Class A pan evaporation figures used to simulate the crop water need (and the prospects are very good that Penman-Monteith figures could be used in future). ➢ The user needs to enter on a daily basis figures on evapotranspiration, rainfall and irrigation for the previous 24 hours. With this information, the program calculates the soil water status of each locality and makes the necessary irrigation scheduling recommendation. ❑ Through soil measurement, the actual soil water contents are compared to estimates. If the calculated figures differ from the actual readings, the model can be corrected. ❑ *Advantages:* ➢ The program offers the option of full irrigation automation if required, where the figures are then automatically transferred to the control software that will control the pumps and blocks. ➢ The program does have the function to calculate the irrigation recommendations for a complete season or only a part of it, based on historical data. ➢ Apart from effective irrigation scheduling, an efficient communication program between the program operator and the irrigators is offered with this program. ➢ It is user friendly – although daily record keeping of E_0 is needed. ➢ It provides automatic control of irrigation systems, taking system capacity into account. ➢ It is adaptable to the use of Penman-Monteith evaporation figures if data from a meteorological weather station are available. ➢ The recommendations on irrigation scheduling are automatically transferred to the control software that controls the blocks and pumps. The inputs of the farmer are therefore minimal. ❑ *Shortcomings:* ➢ Initial support by irrigation specialists with the introduction and set up of the program is needed.	❑ Commercial farmers, consultants in the Western Cape and Orange River. ❑ Crops: Wine and table grapes, deciduous fruit (like: pears, apples, plums); citrus; sugarcane.

Models	Developed	Principles of the model	Application
2.4.5.2.5 SWB (Soil Water Balance)	Annandale, Benadé, Jovanovic, Steyn & Du Sautoy 1999	❑ It is a mechanistic daily time step, generic crop real time, and irrigation scheduling model. ❑ It is based on the improved crop version of the New Soil Water Balance (NEWSWB) model of Campbell & Diaz, 1988. ❑ SWB gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data. ❑ SWB is a generic crop growth model, where parameters specific for each crop have to be determined using weather, soil and crop growth data analysis. Each field to be irrigated is set up in the model and all users need to do is to enter the weather data. ❑ The SWB model calculates the FAO Penman-Monteith grass reference evapotranspiration. ❑ This model has a very well designed water uptake procedure that estimates crop water as a process that can be limited by water supply or atmospheric demand. ❑ SWB simulates crop growth in two ways: ➢ Crop growth model ➢ FAO model: The FAO model is commonly used where specific crop growth parameters are not available ❑ Although SWB model is written in Delphi 4,a Windows version of the SWB model is available. ❑ Extensive use is made of database graphics, with the soil water balance presented at the end of a simulation. ❑ *Advantages:* ➢ It can be used for crop growth and water consumption under saline conditions. ➢ Long-term water and salt balance simulations with generated weather data can be run (suitable for planning purposes). ➢ Site-specific irrigation calendars can be generated for users unable to schedule irrigations real-time. ➢ The mechanistic approach to estimating crop water has advantages over the use of more empirical methods. ➢ It is possible to update the layer water content and/or canopy cover at any stage during the season, should the simulation be out of line. ➢ Several fields can be simulated simultaneously. ❑ *Shortcomings* ➢ Professionals are needed to initially set up the program and to assist in the interpretation of the results.	❑ Irrigation consultants, commercial farmers and researchers in the RSA. ❑ Deficit irrigation strategies can be accurately described. where water supply is limited

Models	Developed	Principles of the model	Application
2.4.5.2.6 Probe schedule (Neutron probe) **Add schedule** (Diviner) **Waterman** (Neutron probe) (du Plessis, 2000)	J le Roux, Bokkeveld Besproeiing BK, 1996	❑ These are software programs used to calculate the theoretical soil water balance and the schedule for the next irrigations in a printable report taking prevailing weather, rainfall and irrigation into account. ❑ This integrates the principles of climate-driven water balance simulation accounting actual soil water measurements by the neutron probe (program can handle any soil water sensor) and direct soil water probing through the Probe Scheduling Program. ❑ The soil water information is used to correct the soil water balance of the simulation and to refine the simulation model. ❑ For each field or locality, a specific database is set up for the specific crop and weather data set. This is cross-validated by direct measurement of soil water. ❑ The necessary management and soil parameters are also entered in the program to run the simulation. ❑ Readings of actual soil water content by a neutron probe (or any other soil water sensor) provide soil water information measured every week or fortnight to correct the soil water balance of the simulation and to refine the simulation of the crop model. ❑ The ETo is calculated with data from the automatic weather station and the Penman-Monteith formula. ❑ The relevant information is displayed in full colour graphics, to give a farmer an instant overview of the irrigation status of his fields. ❑ *Advantages*: ➢ The synthesis of calculation and measurement enables farmers to determine the actual soil water absorption of the plants and the efficacy of rain and irrigation. ➢ It is a time effective and quick way of monitoring of soil water content and adjustment of irrigation scheduling is possible. ➢ Data could be collected by farmer or irrigation manager and sent *via* Internet to the irrigation expert for interpretation. ❑ *Shortcomings* ➢ The help and support of irrigation experts is needed especially during the initial stages to help with the interpretation of data and any adjustments to the model.	❑ Any generic crop of which crop factors are available can be entered. ❑ It is user friendly and easy to use by irrigators. (vd Merwe, 2000) ❑ Commercial farmers, consultants are needed for the initial stages. ❑ Western Cape commercial fruit growers.

Models	Developed	Principles of the model	Application
2.4.5.2.7 CANESIM & CANEGRO (South Africa) APSIM (International)	Inman–Bamber (1990) SA Sugar Association & University Natal (1990) DSSAT format (1997) (Univ Wageningen, Kiker & Inman-Bamber)	❑ The CANEGRO model was developed in response to questions put to scientists by growers and millers of the SA Sugar Industry. This model simulates on a daily basis the mass of the leaves, stalks, roots, leaf area, and root density and tiller population of sugarcane. It simulates processes like soil water movement, crop water use, radiation interception, photosynthesis and dry matter portioning. It requires daily weather data and management input factors. ❑ SQR-CANESIM is a computer program to support general agronomic management. This program was developed from IRRICANE (French program) and a Windows version is available. Precursor to CANEGRO, SQR-CANESIM was developed around the CERES-Maize water balance, which utilised a simple radiation based evaporation model (Inman-Bamber, 1990). ❑ The CANEGRO simulation model helps to predict optimum harvest age for sugarcane. At the same time, this model offers the development of a field record system, which provides growers with summaries of their field records of averages of yields, and sucrose content across soil types, varieties and harvest age, among other factors. ❑ The largest effort in CANEGRO was to develop the capability to simulate water stress. Up to 1991 the soil water balance and root water use based on algorithms of the CERES-Maize model was used. Subsequently, the Penman-Monteith evaporation method is used. ❑ The SQR-CANESIM model is a PC software program that fits in within the DDSAT system. ❑ *Advantages:* ➢ This is a simple computer program that utilises weather data to calculate crop water use and generates irrigation advice and yield information for sugarcane crops. The model used is a robust evaporation model capable of coping with a relatively wide range of conditions. ➢ This model predicts the stalk and sucrose yields of the sugarcane crop. ❑ *Shortcomings:* ➢ Over prediction of the stalk biomass yield (over estimation of yields). ➢ Not applicable to all the cultivars since more parameters are needed. The biggest need is to determine CANEGRO parameters for local cultivars. ➢ It is not a user-friendly program and it is perceived to be high technology, which will need the support of irrigation specialists with the initial set up and interpretation of results. Currently officials from SASRI are working on possibilities to address this concern of farmers.	❑ Since 1997, with the adaptation for the Decision Support System for Agrotechnology Transfer (DSSAT), this model is also used for many other sugar growing regions world- wide: ➢ South Africa ➢ Thailand ➢ Australia ➢ Swaziland ➢ Mauritius **Users:** ➢ *CANEGRO*: researchers from SASRI, which forms an integral part of the agronomic research programme with sugarcane production. ➢ *SQR-CANESIM:* Commercial and small-scale sugarcane growers with the help of the sugar industry's extension personnel. Recently an irrigation scheduling service was initiated for small-scale growers where CANESIM is used to provide the grower with real-time information via a SMS on when to start, stop or continue to irrigate.

2.4.6 Irrigation control or automation

Description	
Automated control of irrigation requires the use of soil, plant or atmospheric sensors to determine the need for irrigation (Younger *et al.* 1981; Phene *et al.,* 1990; Singh *et al.*, 1995) and then either a logic-type controller or a computer to control the irrigation sequence. The automated controller may need to use various control modules to properly manage the irrigation system. These control modules measure pressure and/or flow or other parameters at selected points and control pumps, filters, chemical injectors, etc. It is important for the controllers to have a safety shut down mode. Either pre-programmed or real-time irrigation schedules could be used for the determination of the irrigation schedules programmed in the controller.	
Mode of operation	Automation through soil-plant-atmosphere measurements
Advantages: ❑ Most control systems are designed for unattended operation with periodic operator intervention. ❑ Irrigation management automation can reduce peak electric loads. Since in many areas power costs are the main costs for irrigation, it represents one way to impact costs directly.	
Shortcomings: ❑ Irrigation control systems that use either soil or plant water sensors, in general, are affected by sensor location and field placement.	
Users: Farmers and irrigation consultants.	

2.5 SUMMARY

The timing and application depth criteria for irrigation scheduling can be established using several approaches based on soil water measurements, use of integrated soil water balance estimates and plant stress indicators in combination with simple rules, observations or very sophisticated models. Some of these methods as indicated in this report were found to be "transferable " to farmers while others will only be considered as research tools, or "sophisticated gadgets". These methods can range from very subjective as in intuition, to very objective measurements, where technical assistance is usually required.

Some farmers are not prepared to deal with real time scheduling and therefore use simple irrigation scheduling methods like an irrigation calendar or a “pegboard” to help them with decision-making. Others, however, will opt for more sophisticated and high technology methods, as they are willing to perform field measurements.