# Irrigation scheduling research: South African experiences and future prospects

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## Abstract

Many scheduling approaches have been developed with Water Research Commission funding over the past 4 decades and deployed with varying levels of success; 2 approaches have won prestigious international awards. Soil-based approaches which include measurement of matric potential (tensiometry), water content (neutron probes, capacitance sensors) and depth of wetting (wetting front detectors) have been relatively well accepted by farmers. Atmospheric-based approaches apply, through biophysical modelling of the soil-crop-atmosphere system, thermodynamic limits to the amount of water that can evaporate from a cropped surface under particular environmental conditions. Modelling approaches have been quite empirical or somewhat more mechanistic, generic or crop specific, with pre-programmed (e.g. irrigation calendars) or real-time output. Novel mechanisms have been developed to deliver recommendations to farmers, including resource-poor irrigators. Although general adoption of objective irrigation scheduling in South Africa is still low, the high cost of electricity and nitrogen, and scarcity of water is reviving the interest of consultants and irrigators in the application of these tools to use water more efficiently. Where adoption has been relatively high, intensive support and farmer-researcher-consultant interactions have been key contributing factors. We propose 4 avenues in the R&D domain to ensure responsible water utilisation. Firstly, there is a need to continue to advance existing soil-water measurement technology; and secondly, to further develop new and emerging technologies, like the use of remote sensing. Thirdly, the user-friendliness should be improved as should systems that support existing scheduling tools; and finally, we need to appreciate that farmers are intuitively adaptive managers, and we need to develop simple monitoring tools and conceptual frameworks that enable structured learning.

**Keywords:** BEWAB; CANESIM; PUTU; SWB; wetting front detector

## Introduction

South Africa receives an average rainfall of 495 mm, well below the global average of 860 mm/a. The total renewable water available per inhabitant is just 1 106 $m^3$/a, placing South Africa among the driest quintile of countries in the world (FAO, 2005). According to international criteria, over 90% of South Africa is classified as dryland, i.e. arid to sub-humid, with 82% being classified as arid to semi-arid (ARC-ISCW, 2005). Most of the country receives summer rain that is poorly distributed, with droughts being common phenomena (Bennie and Hensley, 2001). Most of the sub-humid to humid areas are non-arable due to steep slopes and/or poor quality soils. Thus, only around 13% (14 x $10^6$ ha) of the country is suitable for rain-fed cropping. Irrigation is practised on an estimated 1.5 x $10^6$ ha and approximately 0.26 x $10^6$ ha are affected by waterlogging and/or salinisation (FAO, 2005). A large proportion of irrigated land is in areas that are too dry for rain-fed cropping, and the area is limited mainly by water scarcity.

Irrigated agriculture is by far the biggest user of runoff water in South Africa. In 2000 irrigated agriculture used 7 900 x $10^6$ $m^3$ of runoff, around 61% of the 12 900 x $10^6$ $m^3$ runoff used by all sectors during that year or just under 40% of the estimated 20 x $10^9$ $m^3$ exploitable runoff (DWAF, 2004). Because of this large proportion of South Africa's blue water resources being used by irrigated agriculture, there is understandably a great deal of pressure to transfer water to other sectors. This could have major implications for food security, since a large proportion of several food crops is produced under irrigation, e.g. about 90% of all fruit and vegetables (Nieuwoudt et al., 2004). In view of the scarce water resources and the huge demand by irrigated agriculture, South Africa's Water Research Commission (WRC) has over its 40-year history continuously invested in developing tools that can assist water managers and growers to optimise irrigation water-use efficiency.

The primary aim of irrigation scheduling is to minimise wasteful losses of water (percolation beyond what is necessary for salt leaching, surface runoff and evaporation) and maximise transpiration, which is the beneficial loss of water due to its direct link with dry matter production (Tanner and Sinclair, 1983). Scheduling, therefore, plays a fundamental role in determining crop water productivity (CWP), which is a performance indicator used to describe the relationship between water applied and agricultural product output.

The pioneering work of, *inter alia*, Gardner (1960), Denmead and Shaw (1962) and Passioura (1988), set the fundamental theoretical framework of soil-plant-water relations. Much of the research over the past few decades has been to operationalise this framework, i.e. to make it useful to irrigation farmers. This has involved the characterisation of soil-water holding properties, the development of soil-water monitoring tools and methods to predict plant-water use. Although enormous progress has been made, and the scientific

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elements of the irrigation scheduling package appear to be in place, adoption by irrigators remains limited in South Africa and internationally (Leib et al., 2002; Stevens et al., 2005; Stirzaker, 2006). A survey of 332 irrigation schemes in South Africa by Stevens et al. (2005) indicated that objective scheduling was being applied by 18% of farmers only, with the rest relying on approaches based on 'instinct, knowledge, experience and confidence gained over many years of farming'. In practice, irrigators often irrigated with fixed amounts or at a constant interval with little regard to variability in weather conditions and actual crop-water requirements.

The objective of this review is to document irrigation scheduling-related research over the past 4 decades in South Africa, with the main emphasis on the advances made through WRC-funded irrigation scheduling research and technology-transfer projects. The aim is to highlight technical achievements of soil- and atmospheric-based scheduling approaches, to reflect on why adoption of new technology has been much lower than expected, and to consider possible approaches needed to take irrigation scheduling forward in the future.

## An overview of WRC-funded irrigation scheduling and related research in South Africa

During the late 1970s and early 80s, WRC-funded research focused on allowable depletion, or the so-called 'profile available water capacity' (PAWC) concept, and models to derive PAWC values for different crop-soil combinations. There was also research during this early period on irrigation scheduling of agronomic, vegetable and pasture crops. By the late 1980s, the focus had shifted to atmospheric-based soil-water balance modelling, with much of the results of this work put into practice by the late 1990s, with the development of a variety of computer-based scheduling approaches. The turn of the millennium saw the first of the social science research looking at technology adoption issues. Thereafter there was continued development of existing methods and their deployment in a variety of specific applications with greater focus on technology transfer. Lastly there was an attempt to develop irrigation-scheduling tools for the small-scale irrigation sector.

Table 1 shows a list of final reports emanating from WRC-sponsored research projects on irrigation scheduling published since the early 1980s, chronologically representing efforts and focus areas over the years. Most of these reports can be accessed and downloaded free of charge from the WRC's website (www.wrc.org.za). While a comprehensive review of this vast body of research is beyond the scope of this article, selected research that has enhanced our knowledge and the approach of researchers to assist irrigators in devising more effective scheduling programmes is discussed below.

## The concept of plant-available water

Knowing when to irrigate, i.e. the optimum stage in the drying cycle at which to apply water, and how much plant-available water the soil profile can hold, can assist an irrigator in improving irrigation water-use efficiency. For the determination of allowable depletion or 'PAWC', as it was defined by South African researchers, the correct determination of both the upper and lower limits is required (Bennie, 1995; Hensley and De Jager, 1982.)

Since the soil-water potential at 'field capacity' differs widely between soils, a single soil-water potential value cannot be used for all soils (Bennie, 1995; Hensley and De Jager, 1982; Ratliff et al., 1983). For the fine sandy soils at Vaalharts (about 8% to 10% clay and a sand fraction highly dominated by fine sand), 'field capacity' is, for example, at a soil-water potential of about -5 kPa and much of the plant-available water is held

**Table 1**
**Details of final reports of irrigation scheduling related research projects sponsored by the Water Research Commission**

| Year | Report Title | Report No. | Reference |
|---|---|---|---|
| 1982 | The Determination of the Profile Available Water Capacities of Soils | Univ. Fort Hare Report | Hensley and De Jager (1982) |
| 1983 | Water Use Efficiency of Irrigated Crops as Influenced by Varying Cultivation Practices and Root Configurations | UOFS Report | Botha et al. (1983) |
| 1985 | The Development of Profile Available Water Capacity Models | 98/1/85 | Boedt and Laker (1985) |
| 1987 | Research on a Weather Service for Scheduling the Irrigation of Winter Wheat in the OFS | 117/1/87 | De Jager et al. (1987) |
| 1987 | Evapotranspiration and Water Use Studies in Wheat and Soybeans with the Help of the Weighing Lysimeter Technique | H2/1/87 | Meyer et al. (1987) |
| 1988 | Water Balance Model for Irrigation Based on Soil Profile Water Supply Rate | 144/1/88 | Bennie et al. (1988) |
| 1989 | Research on Improving Irrigation Management based on Soil Water Monitoring and Detailed Knowledge of Profile Available Water Capacities | 166/1/89 | Vanassche and Laker (1989) |
| 1989 | Correction factors for evaporimeter coefficients used for scheduling irrigation of wheat | 151/1/89 | Van Zyl et al. (1989) |
| 1990 | Drupbesproeiing by Tamaties (Drip Irrigation of Tomatoes) | 185/1/90 | Fischer and Nel (1993) |
| 1993 | Practical Scheduling of Irrigation in the Northern Transvaal | 152/1/93 | Burgers and Kirk (1993) |
| 1994 | Research on the Climatic Dependence of Evaporation Coefficients | 260/1/94 | Van Zyl and De Jager (1994) |
| 1994 | Research on Maximising Irrigation Project Efficiency in Different Soil-Climate-Irrigation Situations | 226/1/94 | Mottram and De Jager (1994) |
| 1994 | Waterverbruik en Waterverbruiksdoeltreffendheid van Gematigde Aanplante Weidings onder Bespoeiing (Water Use and Water Use Efficiency of Temperate Planted Pastures under Irrigation) | 257/1/94 | Steynberg et al. (1994) |


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| Table 1 (continued) | | | |
|---|---|---|---|
| **Year** | **Report Title** | **Report No.** | **Reference** |
| 1995 | *Proceedings of the Southern African Irrigation Symposium*, Durban, 1991 | TT 71/95 | Water Research Commission (1995) |
| 1996 | The Response of Citrus Seedlings to Soil Compaction And Variations In Soil Water Potential In the Upper Range of Plant-Available-Water | 261/1/96 | Mkhize et al. (1996) |
| 1996 | Die Fasilitering van Tegnologie Oordrag deur Verbeterde Besproeiings-riglyne vir Groente en 'n Meganistiese Gewasmodelleringbenadering (Facilitating Technology Transfer through Improved Irrigation Guidelines of Vegetables and a Mechanistic Crop Modelling Approach) | 476/1/96 | Annandale et al. (1996) |
| 1997 | Reaksie van Gewasse op Voorafgeprogrammeerde Tekortbesproeiing (Reaction of Crops to Pre-Programmed Deficit Irrigation) | 423/1/97 | Bennie et al. (1997) |
| 1998 | Use of Computer Models for Agricultural Water Management on Ecotope Level | 102/98 | Bennie et al. (1998) |
| 1999 | SAPWAT: A Computer Program for Establishing Irrigation Requirements and Scheduling Strategies in South Africa | 624/1/99 | Crosby and Crosby (1999) |
| 1999 | Facilitating Irrigation Scheduling by Means of the Soil Water Balance model | 753/1/99 | Annandale et al. (1999a) |
| 2000 | Factors Which Influence the Acceptability of Irrigation Scheduling with Specific Reference to Scheduling Models | 893/1/00 | Botha et al. (2000) |
| 2000 | An investigation of the Stem Steady State Heat Energy Balance Technique in Determining Water Use by Trees | 348/1/00 | Savage et al. (2000) |
| 2000 | Irrigation Requirements of Selected Crops under Small-Scale Production: Linking On-Farm and On-Station Research | 689/1/00 | Walker (2000) |
| 2001 | Research on a Computerised Weather Based Irrigation Water Management System | 581/1/01 | De Jager et al. (2001) |
| 2002 | The Development of an Integrated Information System for Irrigation Water Management Using the WAS, SWB and RISKMAN Computer Models | 946/4/02 | Benadé et al. (2002) |
| 2002 | Water Use and Water Use Efficiency of Fodder Crops under Irrigation: Part 1 – Annual Subtropical Crops | 573/1/02 | Marais et al. (2002) |
| 2002 | Two Dimensional Energy Interception and Water Balance Model for Hedgerow Tree Crops | 945/1/02 | Annandale et al. (2002a) |
| 2003 | Optimization of Irrigation Management in Mango Trees by Determination of Water and Carbon Demands to Improve Water Use Efficiency and Fruit Quality | 1136/1/03 | Pavel et al. (2003) |
| 2003 | The Selection and Calibration of a Model for Irrigation Scheduling of Deciduous Fruit Orchards | 892/1/03 | Volschenk et al. (2003) |
| 2003 | Deficit Irrigation Studies to Improve Irrigation Scheduling in Deciduous Fruit Orchards | 892/2/03 | Beukes et al. (2003) |
| 2004 | Building Capacity in Irrigation Management with Wetting Front Detectors | TT 230/04 | Stirzaker et al. (2004) |
| 2005 | Technology Transfer of the Soil Water Balance (SWB) Model as a User-Friendly Irrigation Scheduling Tool | TT 251/05 | Annandale et al. (2005) |
| 2005 | The Range, Distribution and Implementation of Irrigation Scheduling Models and Methods in South Africa | 1137/1/05 | Stevens et al. (2005) |
| 2007 | Predicting the Environmental Impact and Sustainability of Irrigation with Coal Mine Water | 1149/1/07 | Annandale et al. (2007) |
| 2008 | Real Time Irrigation Advice for Small-Scale Sugarcane Production Using a Crop Model | 1576/1/08 | Singels and Smith (2008) |
| 2009 | Increasing Water Use Efficiency of Irrigated Sugarcane by Means of Specific Agronomic Practices | 1577/1/09 | Olivier et al. (2009) |
| 2010 | Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application: Guidelines | TT 466/10 | Reinders et al. (2010) |
| 2010 | Wetting Front Detector Transfer of Technology | K8/599/4 | Stevens and Stirzaker (2010) |
| 2010 | Adapting the Wetting Front Detector to Small-Scale Furrow Irrigation and Providing a Basis for the Interpretation of Salt and Nutrient Measurements from the Water Sample | 1574/1/10 | Stirzaker et al. (2010b) |

at high soil-water potentials, causing these soils to have unexpectedly high PAWC values of more than 100 mm·m$^{-1}$ for crops like maize and wheat, Thus, as in the USA and elsewhere, it was realised that *in situ* determined 'drained upper limits' (DUL) had to be used. Boedt and Laker (1985) and Bennie et al. (1988) carried out several DUL determinations from which they derived remarkably similar regression equations for estimating DUL from the silt plus clay contents of different depth intervals of a soil profile (Bennie, 1995).

Hensley and De Jager (1982) defined the lower limit of PAWC using plant parameters; a point Hensley termed 'first material stress' (FMS). This is not to be confused with the more commonly used international lower limit for plant-available water (PAW) of permanent wilting point, a much lower soil-water content, typically at a matric potential of around -1.5 MPa. Based on earlier work in KwaZulu-Natal, Hensley used wilting of maize between 10:00 and 10:30 as a visual indicator of stress (Hensley and De Jager, 1982). This worked well under the climatic conditions prevailing at Fort Hare, but during periods of extreme evaporative demand (Class A pan readings of up to 14 mm·d$^{-1}$) at Vaalharts, it could not be used. Under such conditions, maize wilted at 10:00 even on soils that were at field capacity (Boedt and Laker, 1985). Pre-dawn leaf-water potential, measured by means of a pressure chamber, was found to be a good indicator of FMS under normal conditions. Under conditions of extreme evaporative demand, however, its results also became very erratic (Boedt and Laker, 1985; Laker et al., 1987).

Using the results of Hensley and De Jager (1982), Laker (1982) developed a model by means of which PAWC could be estimated accurately for different soils, using very simple soil properties. Boedt and Laker (1985) followed this up with PAWC studies with maize, wheat, cotton and peas on an even wider range of soils in 3 different regions, i.e. at Fort Hare (Eastern Cape), Vaalharts (Northern Cape) and Loskop (Mpumalanga). All PAWC estimates were for plants at full canopy and full root-system development. Vanassche and Laker (1989) determined PAWC at various growth stages for wheat, durum wheat and maize. Bennie and his co-workers made use of these concepts in the development of the BEWAB irrigation model (Bennie, 1995; Bennie et al., 1988; Bennie et al., 1997).

A significant finding in the various PAWC studies was that field crops could extract water to great depths and that PAWC was larger than had been assumed previously, especially in the fine sandy soils of Vaalharts (Boedt and Laker, 1985). Consequently intervals between irrigations could be stretched and evaporation losses were less than with more frequent irrigations. Flood irrigation was used in the experiments, but Bennie and his co-workers developed strategies for using it under overhead systems as well (Bennie, 1995). Scheduling irrigation in this way increased irrigation water-use efficiency, without compromising crop yields, compared with controls that were irrigated at shorter intervals, maintaining higher levels of plant-available water in soils (Hensley and De Jager, 1982; Boedt and Laker, 1985; Vanassche and Laker, 1989). This was in line with the findings of similar studies in the USA at the same time (e.g. Buchheim and Ploss, 1977).

An additional innovation studied during the PAWC research by Vanassche and Laker (1989) was 'deficit high-frequency irrigation', an irrigation-scheduling approach that was pioneered in the USA (e.g. Miller, 1977; English and Nakamura, 1982). In this approach the water content of the soil is not allowed to drop below the point of first material stress, i.e. the crop is never stressed. With 'deficit' is meant that the entire soil profile soil is not filled to DUL during an irrigation event – after initially starting on a full profile. Reasons for improved irrigation water-use efficiencies were extraction of more water from the deep subsoil; and leaving room for effective use of rain water if a rainfall event occurred shortly (within a few days) after irrigation (this is not relevant to arid areas).

Vanassche and Laker (1989) studied different variations of this type of deficit irrigation with maize and wheat, e.g. irrigation is applied each time that 75% of PAWC has been extracted, i.e. leaving 25% of PAWC, but enough water is applied to replenish it up to only 75% of PAWC and not up to full DUL. This approach generally gave better irrigation water-use efficiencies than other approaches, as was also found in the USA.

Laker (1985) discussed how knowledge of PAWC could be used to reduce design peaks so that various irrigation systems and systems designed with smaller capacities (thus being less expensive) could cope with crop-water requirements during peak demand periods. He also indicated how this could be implemented under, for example, centre-pivot irrigation, where a soil profile cannot be filled with a single large irrigation event – as under flood irrigation. Starting with a dry profile, the soil-water content could be built up by 'over-irrigating' in the early part of the season to have a full profile at the start of the peak demand period. By means of 'deficit high frequency' irrigation the soil water would then be extracted gradually during the peak demand, to end with a profile at FMS at the end of the peak period. Bennie and his co-workers devised different variations of this suggested approach and had great success with it in practical irrigation scheduling of field crops (Bennie, 1995; Bennie et al., 1997).

It was also applied successfully to some horticultural crops, such as tomatoes (Fischer and Nel, 1990; Fischer, 1995), and at farm scale with grapevines (Nel, 1995b). The latter was introduced during a period of severe water restrictions. A computerised irrigation system was used. A 'start irrigation' level was set at a soil-water content halfway between the upper and lower limits of PAWC. A 'stop irrigation' level was at a deficit 30 mm below the upper limit. This left a reserve capacity of 30 mm for interception and effective storage of rainfall, 'a most important consideration when the effective use of available irrigation water is to be maximised' (Nel, 1995b).

It is important to keep in mind that in the case of leafy vegetables deficit irrigation usually leads to significant yield losses, as for example found by Van Averbeke and Netshithuthuni (2010) with Chinese cabbage in a WRC-sponsored study. The shallow root system and the fact that a high water supply is required for maximum leaf growth means that very frequent full irrigations are required for these crops, i.e. the water content of the soil must be kept close to DUL the whole time.

During the past decade or more 'regulated deficit irrigation' (RDI) and 'partial root zone drying' (PRD) approaches have been widely researched as deficit irrigation strategies aimed at increasing water-use efficiencies in areas with water scarcity (reviewed by e.g. Costa et al., 2007). These have also been implemented successfully in practice. RDI is a method of stressing a crop at a specific growth stage (or stages) to control excessive vegetative growth without affecting fruit yield (Grant, 2000; Costa et al., 2007), so as to improve water-use efficiency and/or crop quality. In PRD irrigation is applied to half the root zone, while the other half is allowed to dry (Grant, 2000; Costa et al., 2007). It is implemented by irrigating alternative inter-rows (e.g. in vineyards), whereupon the dry side is irrigated, and the previously irrigated side is allowed to dry.


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RDI and PRD are particularly effective practices for grapevines and various deciduous fruit crops (Grant, 2000; Costa et al., 2007). Water-use efficiency (WUE) increases of up to over 60% or 70% without harming crop yield or quality have been recorded in best-case scenarios (Costa et al., 2007). In South Africa the use of RDI in deciduous fruit crop irrigation has, *inter alia*, been studied by Beukes et al. (2003). PRD has recently been studied intensively at the ARC-Infruitec/Nietvoorbij as potential strategy for irrigating wine grapes in South Africa. This has been reported in several publications, including those by Lategan and Howell (2010) and Myburgh (2011a).

RDI and PRD give variable results with evergreen fruit crops (Costa et al., 2007). Mangoes are interesting in the sense that deficit irrigation not only achieved higher WUE (Pavel and De Villiers, 2004), but also produced larger and better quality fruit than full irrigation (Spreer et al., 2007).

Additional studies with deficit irrigation strategies have been conducted on various other types of crops (Costa et al., 2007). Potatoes, for example, generally gave negative results, because of the shallow root system, but in a best-case scenario irrigation water use was increased by 60% without lowering yield. Various types of vegetables generally gave negative responses to deficit irrigation.

There appears to be great scope and an urgent need for more research on deficit irrigation strategies in South Africa, considering different approaches and studying a variety of important crops.

## Measuring techniques for irrigation scheduling

In order to implement different irrigation-scheduling strategies efficiently, measurements need to be made. Types of measuring techniques can be broadly classified as plant, soil or atmospheric based.

### Plant-based techniques

Several plant-based measuring techniques have been studied for their potential use in irrigation scheduling. The 'pistol' type infrared thermometer for measuring canopy temperature received much attention as a potential practical tool for irrigation scheduling, because of its apparent ease of use (Reginato, 1995), but determining water stress from canopy and air temperatures proved problematic because of the effects of extreme atmospheric conditions, e.g. situations of very low vapour saturation deficit (VSD). A rather more complex 'crop water stress index' (CWSI) taking VSD into account had to be developed to complement this device (Idso et al., 1981; Jackson et al., 1981).

Measurement of leaf-water potential has received by far the most attention of the plant-based measurement techniques in irrigation scheduling. Savage and his co-workers at the University of KwaZulu-Natal are internationally renowned for their studies on thermocouple psychrometers as method to determine leaf-water potential (e.g. Savage and Wiebe, 1987). However, Scholander-type pressure chambers have been most widely used for determining leaf-water potential, including in South Africa (e.g. Hensley and De Jager, 1982; Boedt and Laker 1985; Vanassche and Laker, 1989; Nel, 1995a). Although midday determination of leaf-water potential has been used successfully (e.g. Nel, 1995a), pre-dawn leaf-water potential under normal conditions gives the best indication of the onset of water stress in plants (Hensley and De Jager, 1982; Boedt and Laker, 1985, Vanassche and Laker, 1989; Laker, 2004) because shortly before dawn, leaf-water potential equilibrates with soil-water potential (Laker, 2004). The exception is under extremely hot, dry conditions, such as often experienced in summer in the central irrigation areas of South Africa, conditions under which pre-dawn leaf-water potential measurements were shown to be unreliable (Boedt and Laker, 1985; Laker et al., 1987; Vanassche and Laker, 1989). Similar problems have been found with other plant-based measurements also under extreme conditions (Reginato, 1995). Research using pre-dawn leaf-water potential by means of Scholander-type pressure chambers has produced threshold values that have facilitated its use in practical irrigation scheduling on a limited scale, for example in the wine-grape industry in the Western Cape. Some irrigation scheduling consultants provide advice using pressure chambers, and a few wine estates also operate their own instruments (Myburgh, 2011b). Many other plant-based measurements have been researched in South Africa (e.g. stomatal conductance, $CO_2$ exchange rate, sap flow, leaf extension rate), but none of these have evolved into practical irrigation-scheduling methods.

## Soil-based techniques

Measurement of soil-water status has a long history, from the tensiometers developed in the 1930s (Richards and Neal, 1936), to the neutron probe in the 1950s (Gardner and Kirkham, 1952), through to a whole range of tools based on the measurement of the dielectric properties of water in soil (Charlesworth, 2005). Perhaps the most familiar tool to irrigators is the tensiometer, which measures matric potential (suction) at the wet end of the plant-available water spectrum, making it valuable for horticultural crops. Streutker (1978) used tensiometers to keep the top (0 cm to 45 cm) soil layer at a high water potential and the subsoil water at a low water potential, achieved through medium frequency irrigation. This early research demonstrated how objective scheduling could result in significant water savings with no loss of yield.

Streutker et al. (1981) promoted the use of **tensiometers** in the Loskop Irrigation District during the 1980s, and was very successful at improving irrigation management by, amongst other interventions, highlighting the contribution of shallow water tables to crop-water use. They developed water-yield functions for several crops enabling farmers to benchmark their water productivities and gauge whether or not they had room to improve.

The **neutron probe** has long been the standard instrument for measuring soil-water content. It has been used with great success in practical irrigation management, especially in orchards and vineyards (Mkhize et al., 1996; Nel, 1995b). On a large commercial citrus estate near Marble Hall, Mkhize et al. (1996) were able to demonstrate 24% water saving, while increasing yield and fruit quality through neutron-probe scheduling following a PAWC approach, thereby facilitating a significant saving in irrigation costs. The neutron probe is, however, being superseded by a range of logged capacitance-type sensors, such as DFM capacitance probes (Haarhoff, 2011). Although potentially not as representative as neutron probes because of their smaller volume of measurement, automated capacitance sensors are usually far easier to deploy in farmers' fields.

The **wetting front detector** (WFD) was conceived and developed against the background of poor adoption of commonly available technologies. Essentially the WFD reframed the age-old irrigation scheduling question from 'when to turn

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the water on' to 'when to turn it off' (Stirzaker, 2003). The focus of soil-based monitoring had been on specifying refill points, i.e. how dry the soil could be allowed to get without affecting production of the crop. Long intervals between irrigation events meant that sprinklers could be moved less often; however, the advent of micro-irrigation changed this perspective. Irrigation could occur at any time, and was often carried out daily or pulsed several times per day.

WFDs are based around the tipping-bucket analogy, where soil layers are viewed as a sequence of buckets that store water. As the upper bucket is filled by irrigation, it tips and spills excess water into the bucket below and so on down the profile. The WFD was designed to show when water moved from one layer to the next. It is comprised of a specially shaped funnel, a filter, and a float plus indicator mechanism. The funnel shape was designed so that the soil at its base reaches saturation when matric potential of the soil outside the funnel is around 2 kPa to 3 kPa (Stirzaker 2008), which corresponds to a relatively 'strong' wetting front. Once saturation occurs at the base of the funnel, free water flows through a filter into a small reservoir and activates a float. The float trips a magnetically latched indicator, visible to the irrigator. These detectors are often installed at different depths and used in a similar way to that for tensiometry, namely a shallow detector indicating water entering the root zone and a deeper detector possibly warning of over-irrigation (Stirzaker and Hutchinson 2005).

Fessehazion et al. (2011) used WFDs and the principles of adaptive management to manage excess nitrogen use in irrigated pastures. In this case, the depth of wetting and nitrate concentrations recorded in WFDs were measurements that broadly integrated many of the processes involved in the soil-water balance and N cycle. Even simple thresholds for action were able to reduce N application by up to one third, whilst retaining yield levels and improving the quality of the pasture in which this application was tested.

## Atmospheric-based approaches

Atmospheric-based approaches apply, through biophysical modelling of the soil-crop-atmosphere system, thermodynamic limits to the amount of water that can evaporate from a cropped surface under a particular set of environmental conditions. Early work was based on evaporation measured from a pan together with crop coefficients which were then used to estimate evapotranspiration (*ET*) (Doorenbos and Pruitt, 1977). The standard Class A-evaporation pan was most widely used in South Africa, and was reported by Stevens et al. (2005) still to be popular amongst commercial farmers and consultants in the Breede Water Management Area. Customised approaches, such as the Scheepers and Vaalharts pan, have also been successfully used in the past, but only a limited number of Northern Cape farmers still use the Vaalharts pan to measure evaporation (Stevens et al., 2005). The aptly named 'Green Book' (Green, 1985) made extensive use of crop factors and evaporation pan data to estimate crop-water requirements of several crops throughout South Africa and was widely used, particularly for planning purposes.

The evaporation pan/crop coefficient approach was later shown to have serious limitations (Van Zyl et al., 1989). Pan- and crop-evaporation coefficients depend strongly on climate, and the use of constant values can lead to inaccurate estimates of crop evaporation (De Jager and Van Zyl, 1989; Van Zyl and De Jager, 1992; Annandale and Stockle, 1994). De Jager and Van Zyl (1989) proposed a breakdown of the single crop coefficient into vegetation and soil sub-components. Each of these was further broken down to account for canopy cover and plant- and soil-water status.

De Jager and Van Zyl (1989) used evaporation from a reference crop to represent atmospheric evaporative demand. This theoretical formulation of crop evaporation provided the basis for weather-based water-balance models used in many irrigation-scheduling tools and crop models.

Van Zyl and De Jager (1987) and Van Zyl et al. (1990) demonstrated the accuracy of the Penman-Monteith equation (the energy balance of a cropped surface), for estimating evaporation from an unstressed wheat crop and determined typical values of canopy conductance, a key plant parameter in this equation. Although the Penman-Monteith equation requires detailed weather data as input, Van Zyl and De Jager (1987) demonstrated that a modified method using sunshine duration, temperature and a Piché evaporimeter produced reliable evaporation estimates as well. This, and the development of automated weather stations, paved the way for the Penman-Monteith method to replace the evaporation pan/crop coefficient approach as a standard method to estimate crop-water use in South Africa at the time.

As automated weather stations became more common, the high-frequency measurement (every few seconds) of air temperature, vapour pressure deficit, wind speed and solar radiation, made the calculation of the evaporation from a reference crop surface based on energy balance principles, commonplace. The international community has settled on a standardised version of the Penman-Monteith equation, that assumes a full cover, well-watered, 12 cm tall reference crop, with an albedo of 0.23 and canopy resistance of 70 $s \cdot m^{-1}$ (Allen et al., 1998), and this has also been adopted in South Africa.

## Modelling the soil-water balance

All approaches to modelling the soil-water balance have empirical and mechanistic aspects to them. Models are either crop-specific or can be described as 'generic' in nature if they can be used for several crops, with pre-programmed (e.g. irrigation calendars) or real-time output. Four WRC-supported irrigation-scheduling modelling efforts stand out. These are BEWAB, PUTU, SWB and MyCanesim.

Bennie et al. (1988) determined long-term average irrigation water requirements and efficient water-management strategies for various crops (wheat, maize, groundnuts, cotton and peas) for irrigation schemes in the semi-arid regions of South Africa (Vaalharts, Sandvet, Ramah). This new knowledge was incorporated into a software package named BEWAB (BEsproeiingsWAterBestuursprogram – Afrikaans for Irrigation Water Management Program) that was widely adopted by farmers. The package provided seasonal irrigation requirement and pre-plant schedules of irrigations for specific crop/site/soil/planting date scenarios. It also related irrigation requirements and schedules to a user-specified target yield through linear production functions derived from experimental data. Strydom (1998) incorporated transpiration efficiency concepts from Tanner and Sinclair (1983) into BEWAB, thus making it applicable to any site for which maximum biomass yield and maximum evapotranspiration information were available. The package suggested appropriate values for these inputs for different locations around South Africa.

The concepts developed by De Jager et al. (1987) were incorporated into the PUTU wheat model that was used to provide weekly irrigation scheduling advice to wheat farmers


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at Vaalharts. Electronically recorded weather data were downloaded via telephone modems and landlines. This was particularly impressive considering that these were manual telephone exchanges. The model was run by the research team to generate crop- and soil-water status information (e.g. expected onset of water stress, water use of the past 7 days, deep drainage out of the root zone, expected date of next irrigation and current soil-water status). This information was faxed to the local extension officer, who conveyed it to farmers when they phoned. This approach to advice dissemination was not very successful. The project highlighted the need for personal interaction with farmers and for marketing of the service to ensure better uptake.

The experience gained from this research also led to the development of a generic crop model (PUTU-anycrop) that was used to determine water and irrigation requirements of various crops (e.g. De Jager and Singels, 1994; De Jager et al., 2001). It was used by irrigation consultants and extension officers for weather-based irrigation scheduling at Bergville and Winterton in KwaZulu-Natal and on the Riet River and other Free State/Northern Cape irrigation schemes, as well as in Limpopo Province at ZZ2 on tomatoes and other crops (De Jager and Mottram, 1996; De Jager and Kennedy, 1996).

The SWB model is a mechanistic, generic crop model which was developed as a real-time irrigation-scheduling tool (Annandale et al., 1999a). Evapotranspiration is calculated according to the Penman-Monteith grass reference method as recommended by the Food and Agricultural Organization (FAO) (Allen et al., 1998). The soil-water balance can be modelled using either a cascading soil-water balance or a finite difference model (Annandale et al., 1999a). Daily crop dry matter accumulation was taken as the lower value of either radiation-limited growth (Monteith, 1977) or water-limited growth (Tanner and Sinclair, 1983). Thermal time was used to calculate phenology and partitioning with the effect of water stress accounted for through the use of a stress factor.

The crop- and soil-water components of the model have undergone extensive parameterisation and testing for commonly grown South African crops including potatoes, sunflower, maize, soybean, canola, fescue, lucerne and a wide range of vegetable crops (Jovanovic and Annandale 1999; Jovanovic et al., 1999; Annandale et al., 2000; Jovanovic and Annandale 2000a; Jovanovic et al., 2000b; Jovanovic et al., 2002; Tesfamariam, 2004; Annandale et al., 2007). An FAO-type crop factor approach was also included in the model to include crops for which limited data were available and for tree crops which cannot be 'grown' using the simple crop model (Jovanovic and Annandale, 1999).

Singels and Smith (2009) developed and implemented a weather-based irrigation scheduling advice service for sugarcane growers. The MyCanesim system (Fig. 1, described by Singels, 2007) was automatically executed daily on behalf of subscribers and advice was made available through web downloads for extension staff and commercial farmers, or by cellular text messages for small-scale farmers.

More details on the 4 irrigation-scheduling models described briefly above can be found in the references given.

## Adoption

The research projects described above produced many novel mechanisms that were successfully applied by the target end-users. Yet when the irrigation industry is viewed as a whole, the picture is not reassuring. Stevens et al. (2005) showed that

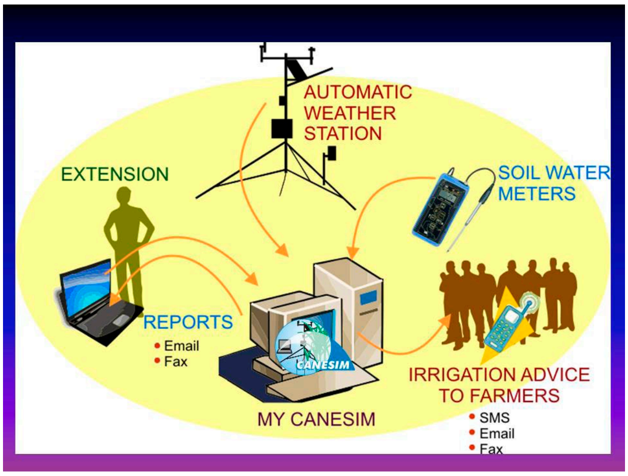


**Figure 1**
*Schematic presentation of MyCanesim irrigation-scheduling system*

only 18% of commercial irrigators used the products of science to help them schedule irrigation. Their national survey covered 332 irrigation schemes and included semi-structured interviews with irrigation professionals (consultants, advisors, industry experts and irrigation specialists), followed by a more quantitative survey of large- and small-scale farmers to better understand human factors influencing the adoption of objective scheduling.

Findings included that scheduling method was closely related to irrigation system, with users of mechanised systems (pivot, micro, drip) showing a positive view towards objective scheduling, and users of flood irrigation showing little interest. The technology level, size of the farm and value of crops grown were also found to influence adoption of more sophisticated scheduling methods. Flat-rate water tariffs on the majority of schemes provided little incentive to schedule objectively, while unreliable water delivery also hindered adoption. In many cases water was one of the cheapest inputs into the irrigation business, and so applying luxury quantities was considered a cheap form of insurance (Stirzaker, 1999). This could be an acceptable strategy in situations where over-irrigation is not considered problematic. However, in many situations injudicious over-irrigation can have serious negative impacts, such as, for example, raised water tables (often leading also to salinisation), high drainage costs, nutrient leaching, crop yield reductions and/or soil or human-health impacts.

In response to low adoption of the SWB model, the WRC commissioned a Technology Transfer project to train potential users at the national scale and to make software changes in order to improve user-friendliness. Annandale et al. (2005) reported that these training exercises were largely successful in general knowledge capacity building, but did not improve the adoption of the model itself. Many of the consultants were not irrigation advisors *per se*, but used the course to update and refresh their knowledge on plant/water relations. Others continued to use their own models or tools, and this was attributed to the fact that they were more familiar with their own systems and did not see enough benefit in changing over to another system. Some felt that the model was still too complex and required too many input parameters.

BEWAB, on the other hand, was used by around 500 growers. Its successful adoption was ascribed largely to the credibility of the developer, Alan Bennie, who is a well-respected

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academic, but with the uncanny ability to translate basic scientific findings into practical solutions for on-farm management. He grew up on an irrigation farm at Vaalharts and is also a successful farmer in the area where it was rolled out. It is probable that the intimate knowledge of the local conditions, including knowledge of the views and attitudes of the local farmers, was instrumental in developing a product that satisfied the particular needs of those farmers

In many ways, PUTU was a technology developed ahead of its time. Considering rapid development in communication and computer infrastructure, it might have been more successful had it come 10 years later.

The development of MyCanesim was focused on the difficulties of getting buy-in from farmers. It was first implemented in 2004 on a small-scale grower scheme in Pongola (Singels and Smith, 2006), and in 2007, advice via text message was provided to 45 small-scale growers. Most of the farmers indicated that they found the advice useful and that it helped them to better understand the value of scheduling. Frequent face-to-face interaction with farmers was observed to be essential in ensuring that advice was understood and implemented. Reliable feedback on irrigation actions and rainfall was also needed to ensure accurate simulation and relevant advice. The approach followed was to provide direct, simple advice and not to confront users with the complexity of the system. This work received recognition by being awarded the International Commission on Irrigation and Drainage (ICID) WATSAVE Award for Innovative Water Management in 2007. Additional work is envisaged to further improve as well as implement this system more widely in the South African sugar industry.

The wetting front detector (WFD) was essentially pioneered in South Africa and the research and development effort was framed by the ongoing problem of poor adoption. After a minimum of 12 months' evaluation of prototype detectors, 54 irrigators, or their advisors who participated in the study, were surveyed. All participants perceived the device as simple and intuitive, and based on their own experience, 82% believed it conferred a relative advantage over what they had been doing (Stirzaker et al., 2010a). Those experiencing problems were either using furrow or centre-pivot irrigation, methods not ideally suited to the WFD.

In 2003, the team that developed the WFD were awarded the ICID WATSAVE award for 'outstanding contribution to water saving and water conservation in agriculture'. The following year the commercial version was released by a South African irrigation company. Over 15 000 detectors were sold over the next 7 years, mostly in South Africa and Australia but also in Argentina, Chile, Peru, Spain and Greece. Yet the momentum of the early success has been difficult to maintain. Although a simple device, it turned out that a good deal of local knowledge was required to get the best out of the detectors. In particular, the depth of placement was crucial and the need to fit the soil type and irrigation method. Despite the sales volumes, the business model did not generate the returns that allowed advisors or consultants to learn and adapt and solve new problems as they arose. Successful adoption is far more than just the technology. The distribution network, back-up assistance and availability of spare parts are just as important.

Adoption of irrigation scheduling among the South African small-scale irrigation schemes has been particularly poor (Fanadzo et al., 2010). Water-limited crop productivity in small-scale irrigation schemes has been attributed to socio-economic, political, climatic, edaphic and design factors (Bembridge, 2000), and has been exacerbated by dilapidated irrigation equipment and poor farmer performance (e.g. poor weed and fertiliser management) (Crosby et al., 2000; Fanadzo et al., 2010). In such cases, it would be important to simultaneously address factors limiting primary production, whilst committing resources to irrigation-scheduling initiatives.

Poor adoption, therefore, remains a conundrum for those whose mandate it is to improve water-use efficiency. Eighteen years ago, Burgers and Kirk (1993) wrote '…computers are fast becoming an essential facility on farms, and a user-friendly program which computes the amount of water to be applied on each of the scheduled dates, may well be the answer to the farmer's scheduling problems'. This prediction has not materialised, and the use of computer models for irrigation scheduling, especially by farmers themselves, has remained low (Botha et al., 2000).

Similarly, it was expected that once soil-water monitoring equipment was more affordable and user-friendly, widespread adoption would follow naturally. Yet adoption seems to require a dedicated service as well. For example, the Orange-Vaal Water Users Association, managed by Griqualand Wes Kooperasie (GWK), includes around 91 000 ha of irrigated land (about 2 600 centre-pivots) of which more than two-thirds is objectively scheduled, 55% to 65 % by the GWK service, which makes use of 2 systems (Haarhoff, 2011). The older of the two is a simple neutron probe system on about 200 pivots, where farmers are sent weekly updates of soil-profile-water content via e-mail, fax or text message. The successful implementation of this system over many years is attributed to it being designed and customised around meeting the specific needs of farmers for the region (Crosby, 2004). The new technology used by GWK on about 1 300 pivots uses DFM capacitance probes and Irricheck software that enables the farmer to make his own scheduling decisions. However, a service is still provided in that GWK offers support through field observations for probe calibration (Haarhoff, 2011).

Lower than expected adoption does not, in itself, question the value of the research effort. For example, SWB was originally conceived as a tool for farmers, but had more positive spin-offs in other applications. The model has been effectively used as a teaching tool in undergraduate courses on irrigation management (Jovanovic and Annandale, 2000b) and crop physiology (Jovanovic et al., 2000b). Many postgraduate students have also been involved with the inclusion of new routines into the model for specific research purposes. For example, the chemical equilibrium routine of Robbins (1991) has been included to enable salt simulations and was used to study the feasibility of irrigating crops with gypsiferous mine water (Annandale et al., 1999b; Annandale et al., 2001; Annandale et al., 2002b). Carbon, nitrogen and phosphorus subroutines have also been included to enable the investigation of nutrient dynamics for the determination of responsible municipal sludge application rates and nitrogen and phosphorus pollution at the field scale (Tesfamariam, 2009; Van der Laan, 2009; Van der Laan et al., 2010).

## Future focus and opportunities

The emerging story of apparently successful research projects but only patchy adoption of its outputs by the industry remains the key challenge for the irrigation research community. Increases in population and wealth will only make the situation more urgent. On a global scale, it has been estimated that food production needs to double in the next 40 years (Godfray et al., 2010). This directly translates into a need for more irrigation water and more efficient irrigation practices. Already, water-balance studies in 2000 showed that 10 of the 19 water management areas investigated in South Africa could not meet demand (DWAF, 2004). In addition there remains much uncertainty on what the influence of changing weather patterns and elevated $CO_2$ will be on crop-growth processes and water availability, but it is generally agreed that projected climate-change scenarios will lead to additional challenges to the irrigation industry.

Prior to 2008, the cost of electricity in South Africa was rated amongst the cheapest in the world (Jumman, 2009). Increases in population and fossil-fuel prices, coupled with infrastructure difficulties, has meant that the country's energy supplier has struggled to meet demand and electricity prices have escalated dramatically. Additional increases of 25% in 2011 and another 25% in 2012 have already been approved, and are expected to further impact negatively on the profitability of irrigation farming Various cost-saving options are now available to irrigators, for example the 'Nightsave' and 'Ruraflex' options, which are being introduced to encourage electricity use for irrigation during off-peak periods (Jumman, 2009).

We envisage 4 responses to the above challenges. First, continued **advances in existing technology** related to the direct measurement of volumetric soil-water content coupled with advances in remote data access through radio communication or via cellular networks, may still develop a cost-effective, real-time system of irrigation. This scenario invokes the concept of 'embodied technology' whereby the data collection and processing is done automatically, and the user receives a daily recommendation without having to understand how any of the technology actually works.

Second, **new and emerging technology** may yet overcome the barriers that have plagued existing technology. For example, space-borne remote sensing can be used to provide regular hydrological information for large areas and though used for research purposes in the past (Bastiaanssen et al., 2000), it is now receiving increased application in irrigation-scheduling recommendations (e.g. Santos et al., 2008). Remote sensing is already being used in the Western Cape to assist table-grape and wine farmers to better manage scarce irrigation water resources and nitrogen fertiliser in a project sponsored by the Western Cape Department of Agriculture (see www.GrapeLook.co.za) (Posthumus, 2011). A second project using this technology in irrigated sugarcane production in the Mpumalanga Province, South Africa, has been launched and is co-funded by the WRC and the Department of Agriculture, Forestry and Fisheries. A third project is being planned for irrigated grain crops in the Middle-Orange River catchment (Van Vuuren, 2011). Such new and emerging technologies may, of course, also be very simple. For both highly sophisticated and simple technologies, proper field testing and validation under different environmental and socio-economic conditions should be a non-negotiable requirement.

Third, there are approaches that make **'user-friendliness'** the main focus. The MyCanesim system described above is one such example. There has been a trend to provide real-time and pre-programmed irrigation scheduling advice via the internet [e.g. Wateright (California State University, USA); Citrus MicroSprinkler Irrigation Scheduler (University of Florida, USA); PlanteInfo (Denmark)]. Many of these systems allow the use of text-messaging technology to deliver the results. Car et al. (2010) investigated the feasibility of using a photograph, taken with a cell-phone and sent to an internet server via MMS technology, to calculate canopy cover and to estimate a crop coefficient ($K_c$).

A fourth approach is to use simple tools and engage irrigators in a process of **adaptive learning** by combining the best of different methods. For example, various strands of information, such as the experiential knowledge of the irrigator, the crop factor, depth of wetting, salt build-up and soil tension are combined to give a more complete picture of the irrigation dilemma (see for example http://thescientistsgarden.blogspot.com). This approach recognises that farmers are intuitively adaptive managers and the use of a robust conceptualisation combined with simple monitoring presents a way to structure their learning (Stirzaker, 2011).

Whichever approach we follow, biophysical scientists will need to remember the words of caution of their social science colleagues who have pointed out that technology-driven approaches often fail to capture the specific goals of the farmers and to understand the constraints under which they operate (Vanclay, 2003) and that adoption is driven by the relative advantage over current practice, risk reduction and the compatibility with existing farm practices (Pannell et al., 2006).

## Conclusions

As an important food producer and the largest user of freshwater resources in South Africa, the irrigation industry has a vital role to play in achieving the country's water goal of 'Some, for all, forever'. WRC-funded research efforts over the past 4 decades to develop, improve and promote the use of irrigation-scheduling tools in South Africa have been impressive, but challenges remain and much work still needs to be done, especially to support the application of such tools.

No single method of irrigation scheduling has met with universal appeal. In most cases new developments have only taken root where long and consistent back-up was provided, either by the scientists involved themselves or by consultants. There is no simple way to measure water-use efficiency, but when the effort is made, the results invariably show that there is vast room for improvement. It is frustrating that uptake of novel technologies has been so slow.

This is not unique to South Africa, and begs the question of whether or not the approach by biophysicists has been somewhat naive? Irrigation is just one part of a profitable farm business, and researchers have perhaps often not always fully understood the constraints under which irrigators operate. Ultimately, together as water users, we will need to learn our way into the future and become better managers of water and the solutes it carries; this will involve a whole range of different technologies.

We propose 4 responses to these challenges worth pursuing. Firstly, continue to **advance existing technology** related to direct measurement of volumetric soil-water content coupled with advances in remote data access through radio communication or via cellular networks; secondly, **new and emerging technology** may yet overcome the barriers that have plagued existing technology; thirdly, approaches that make **'user-friendliness'** the main focus should receive attention; and finally, we need to develop simple monitoring tools and engage irrigators in a process of **adaptive learning** by combining the best that different methods have to offer.

Given the urgency of the need to save water, and the sound understanding of the physical principles governing the functioning of the soil-plant-atmosphere system developed by science over the years, more determined effort is needed to bridge the gap between science and the application of this knowledge on farm.

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