IMPROVEMENT OF SAPWAT AS AN IRRIGATION PLANNING TOOL

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Irrigation Management

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DECLARATION

I declare that the thesis hereby submitted by me for the degree of Doctor of Philosophy at the University of the Free State is my own independent work and has not been previously submitted by me at another University or Faculty. I furthermore cede copyright of the thesis in favour of the University of the Free State.

Pieter Schalk van Heerden   Signature: ………………………………

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ABSTRACT

IMPROVEMENT OF SAPWAT AS AN IRRIGATION PLANNING TOOL

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In a world with a continuous reduction in *per capita* availability of fresh water, the increase in the efficiency of irrigation water use becomes more important as a means to postpone the time when water shortages will restrict crop production. Irrigation uses 62% of South Africa's fresh water resources; therefore a saving in irrigation water through an increase in efficiency could have a large impact on total water use. Informed irrigation requirement planning is one way in which irrigation water use efficiency could be increased.

Associated to efficient irrigation water use, is the effective use of irrigation soil as a resource. Problems such as waterlogging and salinity are found on 19% of irrigated soil in South Africa. Increasing the efficiency of irrigation water use could reduce the rate of increase of these problems and it might even decrease the occurrence.

With the eye on the efficient planning of irrigation areas, research in crop irrigation water requirements has been done over time. Various approaches and planning aids have been developed for the estimation of irrigation requirements. During the second half of the 20th century products like the FAO's CROPWAT and the South African SAPWAT were developed. Both these programs had shortcomings which made their use somewhat difficult. Development of SAPWAT3 followed with the objective to develop a user-friendly program that could be used as widely as possible.

The estimation of irrigation water requirements by SAPWAT3 is based on the internationally accepted Penman-Monteith approach. The former links the climate data of a specific weather station with crop characteristics to determine a water requirement for a specified place and time.

The growth and development of crops are influenced by temperature; therefore the crop growth characteristics have been linked to the Köppen climate system as a means of growth and development periods for warm and cool areas. About 5 100 weather stations in 144 countries with either daily or monthly values are included in SAPWAT3. A large number of crops are also included in the data files.

If enough daily climate data are included, SAPWAT3 does consecutive year-on-year irrigation requirement calculations, which are then used to determine different levels of non-exceedance of the irrigation requirement. This enables the designer of systems or the water use planners to plan for different levels of risk.

A linkage between enterprise budgets and estimated irrigation requirements is also built into SAPWAT3. This enables the user to plan crop combinations which will provide a potential income while also considering water supply constraints.

The crop growth characteristics included in SAPWAT3 and in similar programs, are the weak point of such programs because they are based on calendar time and not on thermal time. A computerised methodology has been developed that uses measured crop water requirements and temperature data to link crop growth and development to thermal time. This methodology will be included as a module in the next version of SAPWAT3.

SAPWAT was accepted by the South African irrigation fraternity. To determine why this was so, and to determine future upgrade approaches that need to be considered, the level of adoption of SAPWAT was investigated. Good and bad points about SAPWAT which had been identified through verbal feed-back from users were kept in mind and confirmed during the development of SAPWAT3. The feedback on SAPWAT indicated the need to improve the functionality of SAPWAT as an irrigation planning tool, to evaluate and to verify its output and to test its potential for adoption by users. The feedback also indicated that SAPWAT3 is easy to use and that it gives credible results, two aspects that enhance adoption. Therefore it can be expected that future improved versions will also be well received, acceptable and used by the irrigation planning community.

Key words: irrigation requirement; planning; Penman-Monteith; soil; crop; water use; SAPWAT; diffusion; adoption; TAM

OPSOMMING

IMPROVEMENT OF SAPWAT AS AN IRRIGATION PLANNING TOOL

Pieter Schalk van Heerden

In ŉ wêreld met ŉ voortdurende vermindering in *per capita* beskikbaarheid van vars water, word doeltreffende watergebruik in die besproeiings-landbou al hoe belangriker om die dag uit te stel wanneer watertekorte gewasproduksie gaan beperk. Besproeiings-landbou gebruik 62% van Suid-Afrika se vars water, dus sal ŉ besparing deur verhoogde doeltreffendheid ŉ groot impak op totale watergebruik hê. Goeie besproeiingswaterbehoeftebeplanning is een manier om besproeiingsdoeltreffendheid te verhoog.

Parallel aan effektiewe besproeiingswatergebruik, gaan die doeltreffende gebruik van besproeiingsgrond as hulpbron. Probleme soos versuiping en verbrakking kom op ongeveer 19% van besproeiingsgrond voor. ŉ Verbetering in die doeltreffendheid van besproeiingswatergebruik kan die uitbreiding van hierdie probleemgebiede vertraag en selfs verklein.

Met die oog op die doeltreffende beplanning van besproeiingsgebiede, is daar met verloop van tyd ondersoek na waterbehoefte van gewasse gedoen. Verskeie benaderings en hulpmiddels is ontwikkel om waterbehoeftebeplanning mee te doen. In die tweede helfte van die 20ste eeu is produkte soos die FAO se CROPWAT en SAPWAT vir Suid-Afrika ontwikkel. Beide hierdie programme het tekortkominge gehad wat die gebruik daarvan ietwat bemoeilik het. Ontwikkeling van SAPWAT3 het gevolg met die uitsluitlike doel om ŉ gebruikersvriendelike program daar te stel wat so wyd as moontlik gebruik sal kan word.

SAPWAT3 is gebaseer op die internasionaal-erkende Penman-Monteith benadering. Hierdie benadering koppel ŉ spesifieke weerstasie se klimaatsdata en gewasgroeikenmerke met mekaar om ŉ waterbehoefte vir ŉ spesifieke plek en tyd te bepaal. Die berekende gewaswaterbehoefte is een van die insette in die grondwaterbalansvergelyking waarmee besproeiingsbehoeftes bepaal word.

Gewasse se groei en ontwikkeling word deur temperatuur beïnvloed, daarom is gewasgroeikenmerke aan Köppen-klimaatsones gekoppel om vir gewasgroei in warm en koeler gebiede voorsiening te maak. Ongeveer 5 100 weerstasies van hoofsaaklik derde-

wêreldse lande met daaglikse of maandelikse data is ingesluit. 'n Groot aantal gewasse is ook in die datalêers ingesluit.

As voldoende daaglikse klimaatsdata beskikbaar is, doen SAPWAT3 herhalende jaar-na-jaar besproeiingsbehoefteberamings wat gebruik word om besproeiingsbehoeftes vir verskillende vlakke van nie-oorskryding mee te beraam. Hierdie vermoë stel die ontwerper van stelsels of waterbehoeftebeplanners in staat om vir verskillende vlakke van risiko te beplan.

Koppeling tussen bedryfstakbegrotings en beraamde waterbehoefte is ook ingebou. Dit stel die gebruiker in staat om gewaskombinasies saam te stel wat binne beperking van beskikbare water en potensiële inkomste moontlik is.

In SAPWAT3, en ook ander soortgelyke programme, is die korrektheid van gewasse se groeikenmerke 'n swak punt omdat gewasgroei en ontwikkeling aan kalendertyd en nie aan termiese tyd, gekoppel word. 'n Gerekenariseerde metodiek wat bestaande gemete gewaswatergebruik en temperatuurdata gebruik om gewasgroei en –ontwikkeling aan termiese tyd te koppel word beskryf. Hierdie module sal in 'n volgende weergawe van SAPWAT3 ingesluit word.

SAPWAT is aanvaar en gebruik deur die besproeiingsgemeenskap in Suid Afrika. Om die redes daarvoor vas te stel en om te bepaal wat in die toekoms met verdere opgraderings van SAPWAT in ag geneem moet word, is die aanvaarding van SAPWAT deur die besproeiingsgemeenskap nagevors. Mondelinge terugvoer het aangedui dat die funksionaliteit van SAPWAT as 'n besproeiingsbeplanningsmodel verbeter moet word, dat die uitset geëvalueer en geverifieer moet word en dat die potensiaal vir aanvaarding getoets moet word. Die terugvoer het ook goeie en swak punte wat mondeling voor ontwikkeling van SAPWAT3 verkry is en wat ook met SAPWAT3 se ontwikkeling in ag geneem is, is deur die navorsing bevestig. Die resultate dui op 'n program wat redelik maklik is om te gebruik en wat betroubare resultate gee, twee aspekte wat aanvaarding bevorder.

CHAPTER 1.
INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Earth has so much water that it covers two-thirds of its surface area. Yet, only a very small portion of this vast quantity of water can be used by man, because most of it is saline. The fresh, usable water must satisfy all man's personal needs; for producing food and fibre (FAO, 2002); for industrial production and for maintaining the environment (Wikipedia, 2012a). Water, through its scarcity, especially in water stressed countries, has the potential to become a reason for conflict. This potential problem is aggravated by the world-wide exponential increase in human population and the resultant ever increasing pressure on fresh water resources (Alois, 2007).

Water cannot be created or destroyed, but good management could ensure its sustainable use as long as possible. It can also be mismanaged and misused to such an extent as to become virtually unavailable or impossible to use for human requirements. Such problems include over-use, siltation, salinization and pollution (Wikipedia, 2012a). Water is always present around us in one or other of its phases; as a vapour, as a liquid and/or as a solid. The movement of water in the soil-plant-atmosphere continuum is described as follows by the water cycle: The sun's rays heat the surface of oceans, lakes and smaller water bodies, which causes the water to evaporate or change from liquid phase to vapour phase. This evaporated water enters the atmosphere as water vapour, much of which is carried over land areas by wind. Given the right conditions, some of the water vapour, after undergoing phase change, return to earth as precipitation (rain, snow, hail or sleet). On the earth's surface a proportion of the water infiltrates into the soil within the root zone of plants, where it becomes available for plant growth and development. Most of the water taken up by plants is transpired as water vapour into the atmosphere. Some soil water seeps into the soil below plant roots and into deeper subsurface strata, becoming part of the ground water, some of which eventually becoming available to humans through wells, springs or surface seepage. Water that does not infiltrate the soil runs off into streams and rivers that flow into the lakes and oceans (Figure 1-1) (United States Geological Survey, 2014). In some arid countries ground water is the main source of water and is extracted through the sinking of boreholes and/or wells. However, if ground water extraction is not well managed, over-use can take place and wells could eventually dry up. The key to the sustainable use of fresh water is to plan and to manage its use as effectively as possible (Alois, 2007; Gleeson et al., 2012).

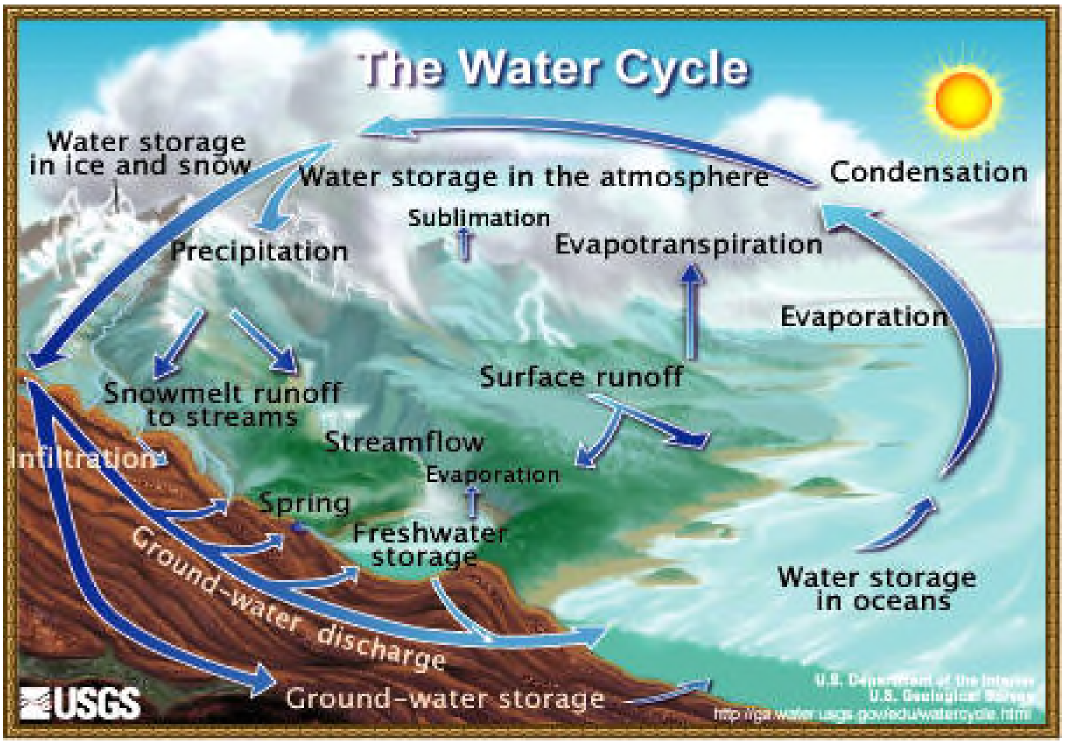


Figure 1-1 The water cycle (United States Geological Survey, 2014)

More than 60% of water used by mankind is used for irrigation; the South African figure is about 62% (Department of Water Affairs and Forestry, 2012). As the biggest water user, irrigated agriculture is always in the public eye and is often accused of being a wasteful user of water; an accusation that is not always justified (Backeberg, 2005) as this water produces food and fibre crops. However, with losses of water from irrigation canals (Wachyan and Rushton, 1987), design efficiencies varying from 60% to 95% (Brouwer and Prins, 1989), and obvious surface water outflow from irrigation fields, the general public cannot be blamed for developing a perception that irrigators waste water.

South Africa, with its relatively dry climate, reflects similar water situations to that of many countries world-wide where arid and semi-arid climates dominate the landscape. Adequate food, fodder and fibre production is not possible without irrigated agriculture and, where fresh water resources are limited, the effective use of irrigation water becomes much more important.

Due to the large volumes of irrigation water required, any improvement in irrigation water management and application efficiency could lead to a reduction in the overall water requirement. This in turn could have a large influence on water availability and could delay the expected time a country would "run out of water". Good irrigation water management implies sound estimation of irrigation water requirements, which could lead to properly designed irrigation and irrigation water conveyance systems. Furthermore, the planning of allocation of fresh water resources for urban, commercial and industrial needs, as well as mining and irrigated agriculture could be improved, if the irrigation water requirement can be estimated with a high degree of accuracy. Good irrigation water requirement estimation allows for good irrigation planning and real time water management, where the ideal is to give the crop the right amount of water at the right time to ensure optimum crop production and yield (Ali, 2010).

The methods of estimating irrigation water requirements for planning purposes have developed over time from values based on observation and experience to sophisticated approaches that use weather data and link that to a crop's growth and development. However, the more sophisticated the approaches have become, the more complicated the calculations and the more variables that have needed to be considered. SAPWAT3, an upgrade of SAPWAT, based on FAO Irrigation and Drainage Paper No 56 (Allen *et al.*, 1998), is such a development. The building of the computer program was done because of the complicated calculation of reference evapotranspiration (ET_0) and linking that to a crop at a specific growth stage through the crop coefficient (K_c) to get a good estimation of crop evapotranspiration (ET_c) ($ET_c = ET_0 \times K_c$). Reference evapotranspiration is calculated from temperature, radiation, wind and humidity. User requirement, user-friendliness and the production of credible results were main considerations during the development of SAPWAT3.

1.2 A perspective on water resources and irrigated agriculture

1.2.1 The international scene

Water resources are sources of fresh water that are useful or potentially useful to man. It is the essential ingredient for life on earth and is used for agricultural, industrial, mining and for household requirements. About 97% of the earth's water is unfit for human, animal and plant consumption in its raw form because of its high salt content (Figure 1-2). About 0.3% of fresh water resources on earth are unfrozen surface water and about 2% of this is found in rivers and streams, which are the main sources of water used by mankind (FAO, 2002; United States Geological Survey, 2014). Irrigated agriculture uses more than 60% of the fresh water resources available to mankind (Alois, 2007).

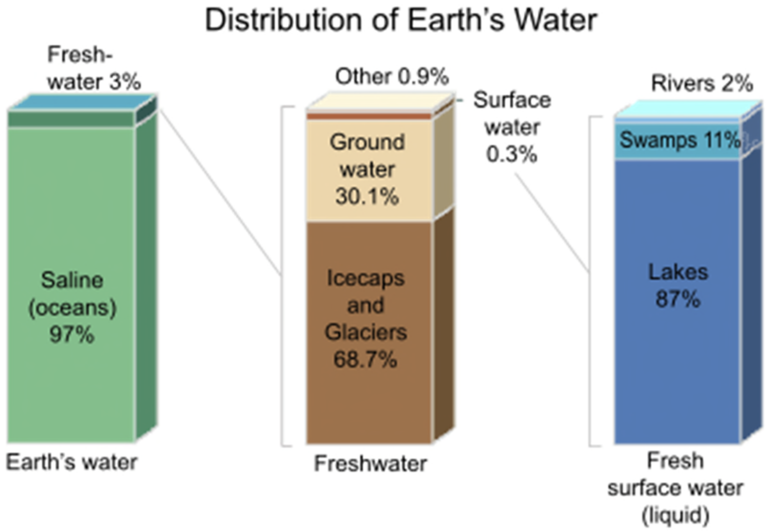


Figure 1-2 Distribution of the earth's water (United States Geological Survey, 2014)

The earth's fresh water resources are renewed through precipitation and therefore the potential supply is linked to total precipitation. However, precipitation is not evenly distributed across the globe. Countries where per capita precipitation is less than 1 700 m^3 a^{-1} (170 mm a^{-1}) are considered to be water-stressed. These countries include South Africa, Namibia, Botswana, Zimbabwe, most of Africa north of the Sahel and the Middle-East through Afghanistan to the Indian subcontinent (Alois, 2007; FAO, 2002).

In many water-stressed countries water is withdrawn from aquifers at a faster rate than refilling can take place, a situation referred to as mining of ground water (Alois, 2007, Gleeson et al., 2012). Recent studies of ground water resources in Africa (MacDonald *et al.*, 2012) have shown that some of these countries have very large ground water reserves, but that recharge could be limited and that over-use could very easily result if intensive extraction for irrigation on a scale larger than household requirements takes place. Ground water can only be abstracted in a sustainable manner at a rate less than, or equal to, the long term average recharge of the source through infiltration from precipitation (Basson and Van Niekerk, 1997). It is estimated that little or no recharge takes places in areas where rainfall is less than 200 mm. In areas with a rainfall of 300 – 500 mm, annual recharge is estimated at 5% of precipitation (15 – 25 mm a^{-1} recharge), while it is estimated to be 5 – 10% of precipitation in areas with a rainfall over 500 mm. Using ground water in low rainfall areas for domestic purposes only seems to be safe enough, as the delivery of hand pumps at 0.1 – 0.3 l s^{-1} does not seem to have the capacity to endanger existing ground water reserves (Calow and MacDonald, 2009; MacDonald *et al*., 2012). Should more water be abstracted over prolonged periods, ground water levels will drop and springs and boreholes will run dry. The estimated annual depletion of ground water resources in water deficit countries adds up to about 160 km^3 a^{-1} (Calow and MacDonald, 2009; FAO, 2002), which has resulted in a drop in ground water levels from 10 to 50 m at cities such as Bangkok, Beijing, Madras, Manila, Mexico City and Shanghai because of over-extraction (Wikipedia, 2012a).

The supply of clean, fresh water is steadily decreasing in many parts of the world because a growing population (Wikipedia, 2012b) results in a steadily increasing demand for water while over-use (Alois, 2007), pollution, wastage, salinization and siltation (Jensen *et al*., 1987) reduces the supply of clean, fresh water. One of the most conspicuous results of overuse is that some large rivers now periodically dry up before reaching the sea. Good examples are the Colorado (United States of America - Mexico), Shebelle (Ethiopia - Somalia) and Yellow (China) rivers (Alois, 2007; FAO, 2002; Wikipedia, 2012a).

Pollution of water resources reduces the amount of clean, fresh water available for human consumption; about 1.2 x 10^9 people are affected by this and in 2000 about 15 x 10^6 child deaths could be attributed to dirty water (Alois, 2007; FAO, 2002; Wikipedia, 2012b). Return flows out of irrigation areas are often contaminated with salts, pesticides and herbicides, which could limit crop choice for downstream users or influence production practices by enforced leaching or liming (Alois, 2007; McMahon *et al*., 2002). Industrial and urban centres with undeveloped or under-developed sewerage systems also return contaminated water to both surface and underground water resources, often polluting water resources with pathogens. In the United States 40% of the lakes and rivers are considered to be too polluted for normal use and in China 80% of rivers are so polluted that fish cannot survive. The most polluted river in the world is considered to be the Ganges River (India - Bangladesh), which supports an estimated 500 million people (Alois, 2007; FAO, 2002; Wikipedia, 2012a).

Irrigation has a reputation of wasting water because water is wasted at almost every point in the cycle. Losses occur from leaking canals to the huge tracts of land that are irrigated, even without crops growing (FAO, 2002). Incorrectly designed and managed irrigation systems (Reinders, 2010) waste water because application rates can be higher than soil infiltration rates resulting in runoff. Application in excess of crop requirements results in percolation to below rooting depth (Jensen *et al*., 1987). Improving irrigation efficiency - currently at less than 40% level (global average) - is a key goal for the future (Wikipedia, 2012a).

Sedimentation, the result of soil erosion, which in turn is often a result of ill-considered logging, farming or construction practices, is reducing the approximate 6 000 km^3 capacity of the world's major water reservoirs by an estimated 1% per year. An added problem is the increased sedimentation of downstream areas which could lead to flooding or reduced stream flow (FAO, 2002; International Rivers, 2012).

The water supply in a region is variable because of the annual variability in rainfall. Of the world population of 6.7 x 10^9 in 2008, 2 x 10^9 lacked access to clean water while another 1 x 10^9 did not have enough water to satisfy their daily needs. With a projected world population of 8 x 10^9 by 2025, the problem of water shortages can only be expected to increase because of demand exceeding supply by an ever-growing margin. As demand for fresh water increases, so the per capita available volume of fresh water decreases. Currently, about 3 600 km^3 (or about 0.01% of total fresh water resource) is withdrawn for human use - the equivalent of 580 m^3 per capita per year. It is estimated that 69% of total fresh water is used for transpiration by plants and evaporation from soil surfaces. However, all withdrawals are not necessarily beneficial; it is estimated that 15-35% of irrigation withdrawals are unsustainable in the long term because of over-use (FAO, 2002; Wikipedia, 2012a).

Satisfying a person's daily dietary need requires about 3 000 litres of water – this is the quantity of water required to produce the food for a normal diet. This is considerable, when compared to the per capita daily drinking water requirement of two to five litres – actual quantities depending on inclusion or exclusion of beverages and water contained in food (Wikipedia, 2015a). Well-managed irrigated agriculture uses considerable amounts of rainwater to partially meet the total water requirement of crops. The water needed for crop production amounts to 1 000 - 3 000 m^3 per tonne of cereal harvested. Put another way, it takes 1 000 - 3 000 l of water to grow 1 kg of rice, wheat or maize. For comparison, the quantity of water required to produce one unit of some agricultural products is depicted in Table 1-1. Good land and irrigation water management can significantly reduce the amount of water needed to produce a tonne of cereal by increasing efficiency and reducing waste (Alois, 2007; FAO, 2002; Reinders, 2008; Wikipedia, 2012a). What is not often said clearly when reference is made to the quantity of water required to produce a unit of food, is that it is beneficial consumptive water use (Bureau of Reclamation Glossary, 2012; Stam, 1987), and that it eventually goes back into the hydrological cycle to become available for precipitation. At a moisture content of about 80% at marketing, a 300g potato contains about 0.24 l of water compared to the about 25 l required (Table 1-1) to produce it. Thus the consumptive use of irrigation water required to produce a crop is often quoted out of context as wasteful (Stolts, 2009).

Table 1-1 The quantity of water required to produce one unit of selected agricultural products (FAO, 2002)

Product	litre water required
Tomato	13
Potato	25
Cup of tea	35
Slice of bread	40
Orange	50
Apple	70
Egg	135
Cup of coffee	140
Glass apple juice	190
Glass milk	200
Hamburger	2 400

A lot of attention is currently being given to irrigated agriculture which relies mainly on water from rivers, streams and aquifers. An FAO analysis of 93 developing countries found that 18 of them irrigate more than 40% of their cultivated land and that a further 18 irrigate between 20% and 40% of their cultivated area. Twenty countries are deemed to be in a critical water resource condition because more than 40% of their renewable water resources are used for irrigated agriculture. Such an intensive use of water for agriculture can strain the water resources. Countries that abstract more than 20% of their renewable water resources are defined as water stressed, and by this definition, 36 of 159 countries (23%) were water stressed in 1998 (FAO, 2002).

Irrigated agriculture changes the environment in its immediate vicinity because of its impact on microclimate. In addition, the over-abstraction of irrigation water from rivers and lakes can jeopardize aquatic ecosystems, leading to loss of their biodiversity. This has important implications for human populations that were dependant on the major inland fisheries previously supported by such areas and on the natural filtering action of wetlands, which have historically been responsible for cleaning much of the world's wastewater. In cases of over-irrigation, the agricultural chemicals used can contaminate surface runoff and ground water. Potassium and nitrogen from fertilizer applications may be washed into ground water or surface water where they can lead to algal blooms and eutrophication (FAO, 2002; Wikipedia, 2012a).

Irrigation tends to concentrate naturally occurring salts in the soil and water. These salts, dissolved in ground water are then carried with return flows into water resources, and if toxic, could make the water unusable for downstream users. Over-irrigation can lead to waterlogging which could increase the salt content of the surface soil layers and reduce yields substantially (FAO, 2002; Wikipedia, 2012e; Wilcox and Durum, 1987).

1.2.2 The South African scene

South Africa's average annual rainfall is about 450 mm a^{-1}, compared to the world average of about 860 mm a^{-1}, ranging from less than 100 mm in the dry western arid areas to about 1 200 mm a^{-1} in the eastern and Cape mountain ranges of the country. Only 35% of South Africa has a precipitation of 500 mm a^{-1} or more, while 44% has a precipitation of 200-500 mm a^{-1} and 21% has a precipitation of less than 200 mm a^{-1} (Frenken, 2005; Reader's Digest, 1984a). Therefore, 65% of the country does not receive enough rainfall for successful rain-fed crop production; crop production in those areas is therefore dependent upon irrigation. Except for the Western Cape, with its Mediterranean climate, the rest of the country is a summer rainfall area (Reader's Digest, 1984a; SouthAfrica.info, 2012; Wikipedia, 2012d).

River flows reflect the rainfall pattern. Rivers that have their origin in the high rainfall areas of the mountains of the eastern escarpment and the mountains of Western Cape normally have perennial flows. Rivers that originate in the drier, adjoining areas have periodic flows, whereas rivers that originate on the dry, western great plateau have episodic flows (Frenken, 2005). The total annual surface runoff is estimated at 49 $km^3\ a^{-1}$, or approximately 9% of annual rainfall. About 5 $km^3\ a^{-1}$ comes from Lesotho and Swaziland. This value is included in the South African surface water budget as these rivers run through South Africa. However, much of the total runoff volume is lost through flood spillage and evaporation, so that in the year 2000 the available yield was estimated at 13.2 $km^3\ a^{-1}$. The total dam capacity is estimated at 32.4 km^3. The dams can store virtually all the runoff from the plateau, while untapped resources are concentrated along the east and south coasts of the country (Department of Water Affairs and Forestry, 2012; Wikipedia, 2012c).

An estimated 9.5 $km^3\ a^{-1}$ is assumed to be required for the ecological reserve. Total water withdrawal was estimated at 12.5 $km^3\ a^{-1}$, or 26% of total runoff, in the year 2000, with irrigation using 62%, industry, mining and power generation using 8%, afforestation using 3% and human use being 27% (Department of Water Affairs and Forestry, 2012).

The best estimate of ground water storage for South Africa is 17 400 km^3 (MacDonald *et al*., 2012). About 4.8 $km^3\ a^{-1}$ of ground water is delivered annually from fountains, springs and boreholes, of which an estimated 3 $km^3\ a^{-1}$ is in turn drained by the rivers (Frenken, 2005). Even though ground water availability is limited and borehole productivity is generally classed as low to moderate because of the geology of the country, it is extensively utilized in the rural and more arid areas. Large, porous aquifers occur only in a few areas. Available yields for household and irrigation used from these resources were estimated at 1 $km^3\ a^{-1}$ in 2000; however existing extraction is not adequately monitored. It is foreseen that ground water use for human consumption will increase, especially in the western part of the country which lacks perennial rivers (Department of Water Affairs and Forestry, 2012; Wikipedia, 2012c).

Estimates of still undeveloped resource potential indicate that approximately 5.6 $km^3\ a^{-1}$ will be available by 2025. Potential also exists for further ground water development, although on a smaller scale. A projection for 2025 by the Department of Water Affairs and Forestry shows that the total annual water withdrawal is expected to increase from 12.5 $km^3\ a^{-1}$ to 14.5 $km^3\ a^{-1}$ by then (Department of Water Affairs and Forestry, 2012).

Desalination of seawater offers future opportunities for public and industrial use in the coastal areas. In 1990, desalination plants had a total capacity of 18 million $m^3\ a^{-1}$. Some industries have demineralization plants, but these are used on reticulated municipal or borehole water and their capacities are usually relatively small (Frenken, 2005; Department of Water Affairs and Forestry, 2012). Although expensive, desalination power requirement can vary from 30 to 620 Kwh t^{-1} of distilled water depending on the technology applied; however the expected trend is that desalination will become more competitive due to continuous technological advances (PC Cell, 2005).

It is not foreseen that importing water or other unconventional options will be economically viable in the near future (Department of Water Affairs and Forestry, 2012).

Surface and ground water resources are nearly fully developed and utilized in the northern parts of the country (Limpopo, Gauteng and Mpumalanga provinces). Some over-exploitation occurs in localized areas, with little undeveloped resource potential remaining. In contrast, in the well-watered south-eastern regions of the country (Kwazulu-Natal, Eastern Cape and the south coast areas of Western Cape provinces) significant undeveloped and little-used resources exist (Basson and Van Niekerk 1997; Department of Water Affairs and Forestry, 2012).

Basson and Van Niekerk (1997) reported on the water balances of South Africa, comparing 1996 values with estimates for 2030. In 1996, seven of the 19 major drainage basins were over-utilised and it is expected that this will increase to eight by 2030 (Table 1-2). Basins that are over-utilised are: Crocodile/Limpopo, Olifants (Limpopo Province), Great Fish, Sundays, Buffels, Orange downstream of Lesotho and the Vaal Basin. It is expected that by 2030 the Breë/Berg basin will join these. At present shortages in river basins are cancelled by 19 inter-basin transfers. The following inter-basin transfers shift more than $100 \times 10^6\ m^3\ a^{-1}$ water from the first-mentioned to the second-mentioned basin; transfer volume ($10^6\ m^3\ a^{-1}$) is shown in brackets: Orange-Fish (643), Tugela-Vaal (630), Vaal-Crocodile (615), Orange (Senqu River)-Vaal (574), Fish-Sundays (200), Orange-Riet (189), Vaal-Olifants (150), Komati-Olifants (111). Of these, the Tugela-Vaal is unique in South Africa as it is a pumped-storage scheme that shifts $630 \times 10^6\ m^3$ of Tugela River water annually into the Sterkfontein Dam. The pumps were designed to be reversible between electric motor and electric generating functionality; during peak electricity demand periods, the water flow is reversed, and hydro-electricity is generated and fed into the national grid. The Orange (Senqu River)-Vaal transfer scheme, better known as the Lesotho Highlands project, transfers water between two countries, from Lesotho into South Africa. Construction of inter-basin transfer projects is expensive, which in turn increases the cost of the water to such an extent that irrigation with inter-basin transferred water can become prohibitively expensive (Department of Water Affairs and Forestry, 2012).

Overuse of ground water is found in various parts of the country, the best indicators probably being the drying up of many of the streams which existed when man first started to develop the country. Ground water failure commonly occurs in some of the denser populated areas as experienced in the Limpopo and Mpumalanga provinces because of the over-use of ground water resources. This in turn caused the ground water level to drop, similar to the situation found internationally where overuse occurs (Basson and Van Niekerk, 1997; GSSA, 2014).

Table 1-2 Water balances of the main river basins of South Africa showing balances for 1996 and expected balances for 2030 (Basson and Van Niekerk, 1997). Negative balances are coloured yellow

Province	River/Basin	Maximum yield (10^6 m^3 a^{-1})	1996		2030	
			Water requirements (10^6 m^3 a^{-1})	Balance available (10^6 m^3 a^{-1})	Water requirements (10^6 m^3 a^{-1})	Balance available (10^6 m^3 a^{-1})
Gauteng, Limpopo	Crocodile/Limpopo	1117	1732	-615	3169	-2052
Gauteng, Limpopo, Mpumalanga	Olifants basin	1449	1641	-192	2393	-944
Mpumalanga, Limpopo	Inkomati basin	2252	1401	851	1943	309
Mpumalanga, KwaZulu-Natal	Maputo basin	2582	919	1663	1225	1357
KwaZulu-Natal	Mfolozi basin	1351	933	418	1253	98
KwaZulu-Natal	Thukela basin	2900	813	2087	1302	1598
KwaZulu-Natal	Mgeni/Mzimkulu basin	4122	1941	2181	3372	750
KwaZulu-Natal, Eastern Cape	Mzimvubu basin	2635	934	1701	1430	1205
Eastern Cape	Mbashe/Kei basin	2191	983	1208	1503	688
Eastern Cape	Great Fish basin	263	580	-317	806	-543
Eastern Cape	Sundays basin	164	407	-243	656	-492
Eastern Cape	Gamtoos basin	801	347	454	474	327
Western Cape	Gouritz basin	565	434	131	506	59
Western Cape	Breë/Berg basin	2508	1891	617	3342	-834
Western Cape, North Cape	Olifants/Doring	585	491	94	525	60
Western Cape	Buffels basin	2	14	-12	17	-15
Lesotho	Orange river (Lesotho)	4481	21	4460	31	4450
Free State, Eastern Cape, Northern Cape	Orange below Lesotho	1553	2534	-981	2638	-1085
Mpumalanga, Gauteng, Free State, North West, North Cape	Vaal River basin	1789	2029	-240	3830	-2041
	Total	33310	20045	13265	30415	2895

In a study by Reinders and project team (2010), irrigation water conveyance losses were found to vary between 4.3% and 57%. Irrigation system efficiencies varied from 38% to 77%. Extremely bad cases within the above rivers are isolated, but these are indicative of inefficiency levels that can be expected in worst-case scenarios. Rand Water, which supplies the Pretoria-Witwatersrand-Vereeniging area of Gauteng with mainly industrial and public water, states in its 2011 annual report that water loss out of their system for that year was 30% of the 40 000 m^3 water distributed (Rand Water, 2011) - the equivalent of 12 000 m^3 of water or 12 000 t of water that was lost.

Large parts of South Africa are characterised by steep topography, long slope lengths and shallow, eroded soils. The eroded soils are usually the result of misuse of the natural resources. Sediment production from large catchments is as high as 1 000 t km^{-2} a^{-1}. It is estimated that more than 120 million t of sediment enters South African rivers annually. This has serious negative consequences on the downstream water environment and leads to siltation of dams. The average loss on the reservoir capacity of large dams in South Africa is under 10% per decade, although there are indications that this problem has been declining lately through conservation farming practices (Department of Water Affairs, 1986).

Biodiversity in South Africa is under pressure, and could put aspects of our economy and quality of life at risk. It also reduces socio-economic options for future generations. Loss of biodiversity could influence stream flow, which in turn could affect irrigation in downstream areas. An assessment of the vulnerability of South Africa's 120 mainstream rivers regarding biodiversity indicates that 44% are critically endangered, 27% are endangered and 11% are vulnerable. In South Africa, mainstream rivers are heavily utilised, and depend quite substantially on intact tributaries for conserving biodiversity patterns. In many instances, these tributaries could be viewed as climatically stable areas for aquatic biodiversity (Nel *et al*., 2005).

Salinization of irrigated soils is probably the biggest soil problem in South Africa. The sources of salts that cause this problem can be salts contained in the parent material of the soil, salts dissolved in irrigation water, salts dissolved in shallow ground water or from fertiliser and soil amendments. All irrigation waters contain salts, which tend to concentrate in the crop root zone as water is extracted by the plant for transpiration and is evaporated from the soil surface. Good quality irrigation water could add from 5 000 to 10 000 kg salt ha^{-1} a^{-1} to the crop root zone, unless it is removed through leaching by the addition of irrigation water in excess of the crop requirement. The salt content of irrigation water tends to increase from upstream to downstream areas because return flows from upstream irrigation areas, tend to have higher dissolved salt concentrations, increasing the danger of salinization of downstream irrigation areas. Return flows from industrial areas and areas of population concentration also tend to increased salt load of water sources. In this regard it was found that the large-scale urban, industrial and mining developments in the Vaal River catchment have led to the salinization of the Vaal River (Backeberg *et al*., 1996; Du Preez *et al*., 2000; Ehlers *et al*., 2007; Frenken, 2005).

The salts contained in the soil within the crop root zone tend to move towards the soil surface where it is often noticeable as a whitish deposit (Wikipedia, 2012e). This movement is the result of the redistribution of salts towards the soil surface through the upward capillary flux of water and can be severe in cases where shallow, saline water tables are found. Shallow water tables usually develop in the lower lying downslope positions of irrigated fields in cases where water application exceeds the extraction through evapotranspiration, where soil hydraulic conductivity is low and where impermeable strata are found below the root zone. Soils with a water table need to be artificially drained and irrigation water management needs to be at a high level of efficiency to alleviate this problem. The area in South Africa affected by a combination of water logging and salinity is not accurately known, but estimates based on surveys in the past indicate that about 19% of irrigation soils are affected. Of this area about 6% is severely affected (Backeberg *et al*., 1996; Ehlers *et al*., 2007; Frenken, 2005).

The effects of high levels of salinity on crops are seen as: reduced plant growth rate, reduced yield, lower plant densities and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential and thus the total water potential of the soil solution. Some salts may be specifically toxic to plants or may upset the nutritional balance when present in excessive concentrations. The salt composition of the soil affects the exchangeable cation composition of the soil colloids, which has a negative effect on soil permeability and tilth (Ehlers *et al*., 2007; Wikipedia, 2012e).

Floods are a regular occurrence in South Africa. Floods, rather than base flows, provide most of the inflow to and storage by most of South Africa's dams. Only the major floods cause concern because of their potential for causing structural damage. The size of a flood of a given probability of occurrence can be estimated from an analysis of the historical record at a particular site on a river, or by using one or more of a number of alternative methods if no records are available. Minimising damage to irrigation farms along rivers through flood regulation by dams is generally only effective for moderate floods, as regulation by dams of extreme floods is usually non-effective (Department of Water Affairs, 1986). Flood history in South Africa is of short duration. However, a research project on the occurrence of paleo floods showed that the Lower Orange River has experienced 13 paleo floods with discharges in the range of approximately 10 200 to 14 660 $m^3 s^{-1}$ during the last 5 500 years. These discharges are considerably larger than the largest historically documented gauged discharge of 8 330 $m^3 s^{-1}$ in 1974 at Vioolsdrift and therefore represents additional flood information for the Lower Orange River. Evidence of a catastrophic flood that had occurred more than 5 500 years ago with a discharge of approximately 28 000 $m^3 s^{-1}$, over three times the discharge of the largest historically recorded gauged flood, was found. Flood frequency analysis based on paleo flood evidence of the lower Orange River yield a return period of approximately 1 000 years for floods of approximately 15 000 $m^3 s^{-1}$ (Zawada *et al*., 1996).

More sophisticated drought management strategies are required when the simple flow regulating advantages of storage dams in a river system become inadequate because of an increase in demand. Advanced methods of hydrological and systems analysis have been developed for this purpose in recent years (De Waal and Verster, 2012; Ghile and Schulze, 2008), supported by the increasing availability of computers and large databases. These include modelling approaches for managing spillway losses from large dams (De Waal and Verster, 2009). Accordingly, the Department of Water Affairs and Forestry is improving on earlier management methods, which were based on simple storage capacity/yield relationships and which were adequate for the utilisation levels and assurance requirements of the past. Current drought management methods include the imposition of continuously variable, progressive increases in the degree of restrictions on water use as the drought worsens and a progressive lifting of restrictions as the situation improves. Present management strategies take account of relationships between storage capacity, yield, risk and economic optimisation. Financing requirements, development and operating policies and cooperation with water distributors and users can also be taken into account (Department of Water Affairs and Forestry, 2012).

Water restrictions on a planned and more regular basis will become an increasing necessity once the economic limits of the exploitation of water resources and the inter-basin transfer of water are reached. Restrictions have demonstrated the ability of many user groups to curtail their consumption substantially. If reduced use becomes a permanent feature, it will limit the extent to which users can adapt to subsequent restrictions. Close cooperation between the Department of Water Affairs and users is essential to minimize the impact of restrictions

(Department of Water Affairs, 1986). Against this background, the George Municipality drought disaster plan is a good example where step-wise water use restrictions are defined for different low water levels of dams that supply water to the town (George Municipality Drought Policy, 2010).

1.2.3 Irrigation development in South Africa

Irrigation development was sporadic before the first Irrigation and Water Conservation Act was passed in 1912. Descriptions exist of irrigation development along the Liesbeeck River shortly after Jan van Riebeeck landed at the Cape during 1652. Further descriptions of irrigation development in the late 18th and early 19th century are found in writings of that period. The founding of an Irrigation Department in the Cape Colony and in the Transvaal during 1904 provided impetus to more ordered irrigation development (Department of Water Affairs, 1986; Van Heerden and De Kock, 1980).

Soon after Jan van Riebeeck landed in the Cape, reference is made to irrigation out of the Liesbeeck River, presumable in order to grow vegetables to supply the ships. The granting of farmland along the Berg River in the days of Simon van der Stel, who arrived at the Cape in 1679, is also found in historical records (Getting Home Executive Services, 2012). Further evidence that irrigation farming was historically part of South Africa is from references to high yields of wheat and exceptional fruit produced under irrigation along the Great Fish River towards the end of the 18th century in the travel writings of Paravicini di Capelli, an aide to Governor De Mist, in 1803 (De Kock, 1965, as referenced by Van Heerden and De Kock, 1980). Records of the building of the first weir in the Great Fish River during 1816 and crops produced also exist. By 1921, 23 643 ha was irrigated along the Great Fish River in the Cradock - Cookhouse - Somerset East - Bedford areas of the river. Records also exist of irrigation development during 1867 - 1888 at Backhouse along the lower reaches of the Vaal River, where Douglas is now situated (Van der Merwe, 1997), as well as other irrigation development projects elsewhere. Another example is at Kakamas where an irrigation development was initiated by the Dutch Reformed Church as a settlement for poor whites. In 1897, the Cape Government granted two farms on the left bank of the Orange River to the church for this project. Development soon started and the first settlers were given plots in 1899. Canal construction was completed during 1912 and by 1945, 574 families were settled there. The Goedemoed Irrigation Scheme, a part of the larger Kakamas irrigation development, was started during 1896. Development work of the 513 ha scheme was completed in 1912 and each settler received an entitlement of 3.5 ha (Van Vuuren, 2011).

During the years 1921 – 1922 construction on a number of large dams for irrigation and urban water supply was in progress. These include: Hartebeespoort (Crocodile River), Lake Mentz (now Darlington Dam, Lower Sundays River), Grassridge and Lake Arthur (Great Fish River) (Van Heerden and De Kock, 1980). Between 1912 and the 1940s, irrigation development took place at a level that has never been reached again. Much of the development in the 1930s and 1940s was done in an effort to alleviate the poverty problem that followed the great depression of the early 1930s and to accommodate soldiers returning after the Second World War by creating jobs for them during construction as well as for settlement on the farms. Vaalharts, Loskop and Riet River schemes are examples (Department of Agriculture, Forestry and Fisheries, 2012; Department of Water Affairs, 1986) where some of the small, square houses that were built to accommodate the settlers could still be seen at the end of the 20th century (Van Heerden, 1989).

Some schemes developed a history of not being able to supply enough water for their allocated irrigation areas, probably because of a combination of an over-estimation of water delivery potential and an under-estimation of irrigation water requirement. This problem was partly solved by the development of inter-basin transfers, mainly between the 1960s and 1980s (Department of Water Affairs, 1986; Frenken, 2005; Reinders, 2008; Van Heerden and De Kock, 1980). Thus over time, norms and standards have been defined for the development and re-development of irrigation areas in order to make better use of the country's limited water resources. These include soil and water norms (Backeberg *et al*., 1996), as well as irrigation system design standards (ARC-IAE, 1996). This was done to ensure that irrigation in South Africa is practised at a high level of efficiency.

The potential across South Africa for full or partial irrigation development, based on water availability and land suitability, is estimated at 1.5 x 10^6 ha (Table 1-3). In the central and western parts of the country, suitable soils are available for an increase in the irrigated area, but the expansion potential is limited by lack of water (Backeberg *et al*., 1996). In the eastern parts of the country steep slopes and a lack of suitable soils restrict expansion of irrigable areas. Soils are classified for irrigation suitability on the basis of soil depth, clay content, structural development and chemical characteristics. However, the importance of soil classification for irrigation purposes is somewhat reduced due the application of more recent highly sophisticated irrigation technologies (Backeberg *et al*., 1996; Frenken, 2005).

In 2005, an area of almost 1.5 million ha was equipped for full or partial controlled irrigation, comprising surface irrigation on approximately 500 000 ha, mechanized and non-mechanized sprinkler irrigation on approximately 820 000 ha, and localized irrigation on approximately 178 000 ha (Table 1-3). Actual efficiencies seem to deviate from the default design values, although very little reported data are available to substantiate this. Surface (border strip) irrigation system efficiencies have been measured at 40%, but efficiencies of up to 95% have been found in isolated cases (Reinders, 2010). One study indicated an overall efficiency of about 63% on some of the larger irrigation schemes (Frenken, 2005).

Table 1-3 Land under agricultural water management for South Africa (after Frenken, 2005)

Irrigation and drainage	**Value**	**Unit**
Land with potential for use under irrigation	1 500 000	ha
Water management		
Full or partial control irrigation: equipped area	1 498 000	ha
- surface irrigation	500 000	ha
- sprinkler irrigation	820 000	ha
- localized irrigation	178 000	ha
Area irrigated from ground water	8.5	%
Area irrigated from surface water	91.5	%
Total area equipped for irrigation	1 498 000	ha
- as percentage of the cultivated area across South Africa	10	%
- average increase per year for the period 1994 – 2000	2.8	%
-total area equipped that is actually irrigated	100	%
Total water-managed area	1 498 000	ha
Drainage		
Total drained area	54 000	ha
- part of the area equipped for irrigation drained 1990 – 2000 as area	54 000	ha
- part of the area equipped for irrigation drained 1990 – 2000 as percentage	3.6	%

Drainage systems cover approximately 54 000 ha. These are mostly open, lined ditches in already existing government irrigation schemes, built in such a way that farmers could link their subsurface drainage systems to them. In virtually all cases, drainage water is released into the river systems and becomes part of the supply of irrigation water to other users downstream as return flow. The salt content of this drainage water is usually higher than the salt content of the water that was abstracted upstream for purposes of irrigation (Frenken, 2005; Department of Water Affairs, 1986).

1.3 Crop production under irrigation

Intensive production under irrigation can sustain about 10 people per hectare, compared to rain fed agriculture's 0.4 to 0.6 people per hectare. It is calculated that irrigation in South Africa can sustain 10 to 15 million people, thus adding to food security in the country. Only about 12.5% of the arable land of the country is irrigated, yet it produces approximately 30% of the national crop production (Backeberg *et al*., 1996). Comparing individual components of the irrigated agricultural basket to total country production (Table 1-4); the high relative value of irrigated agriculture to total agriculture produced in South Africa becomes apparent. The data itself are old, but the expectation is that the relative values would still be similar (Kennon, 2014).

Table 1-4 1994 estimated contribution of irrigation to commercial crop production in South Africa (Backeberg et al., 1996)

Crop	Irrigated Area		Production	
	Area Ha	**% of total area planted to this crop in South Africa**	**Amount (t) (1994)**	**% of national production**
Maize	110 000	3	660 000	10
Wheat	170 000	12	74 000	30
Other small grains	52 000	3	200 000	6
Potatoes	39 000	70	1 200 000	80
Vegetables	108 000	66	1 330 000	90
Grapes	103 000	90	1 300 000	90
Citrus	35 000	85	1 100 000	90
Other fruit	95 000	80	1 200 000	90
Oilseeds	54 000	10	108 000	15
Sugarcane	60 000	15	4 000 000	25
Cotton (lint)	18 000	17	17 000	42
Tobacco	12 000	85	20 000	90
Lucerne	203 000	70	1 600 000	80
Other pasture	104 000	15	800 000	25

Crops grown under irrigation reflect a pattern that is related to a combination of farming enterprises, availability of water, climate, soil and access to markets (Dhillon, 2004). This holds true for the primary drainage regions of South Africa (Table 1-5) (Backeberg, 1996). Most of primary drainage regions C, D, E, F, J, K, L, M, P, Q, S, T, U, and V are in the drier (Figure 1-3; Figure 1-4; Figure 1-5) sheep and cattle grazing areas of the country and the production of pastures and forage crops under irrigation ensure a stable fodder flow. Summer and small grain crops are important components in conjunction with pasture and forage crops (Regions C, D, Q) and especially summer grains can be used as a component in ensuring a good fodder flow (Meadow Feeds, 2011; Mulwale *et al*., 2014). This is a natural extension of the surrounding animal production farming patterns (Figure 1-5). However, this does not stop the production of pasture and forages in higher rainfall areas; these are found under the first four most important crops in 19 of the 22 primary drainage regions. Outside of irrigation scheme areas, such as Vaalharts, Riet River, Douglas, Great Fish River and Lower Orange River where water supply is continuous and relatively assured, irrigation is sporadic and happens when rivers flow during and immediately after rainy seasons (Frenken, 2005). Forage crops, like lucerne (*Medicago sativa*), and some perennial pasture grasses, for example, Giant Bermuda (*Cynodon dactylon*), Weeping Love Grass (*Eragrostis curvula*) and Smuts Finger Grass (*Digitaria eriantha*), become dormant as a survival mechanism under severe water stress situations and can survive long periods of drought in this state, only to recover and produce again once the drought is broken during the next rainy season (Dickinson, and Hyam, 1984; Erice *et al*., 2010; Undersander *et al*., 2011). In conjunction with the consideration of producing fodder for the farm livestock enterprise, this is probably one of the reasons for the high levels of pasture and forage crops found in the drier areas of the country.

Vegetables are found under the first four most important crops in 17 of the primary drainage regions, although it is mostly at importance level two or three. The only primary drainage regions where it does not figure under the first four are D, E, Q, V and W. These areas are mostly farther away from the metropolitan markets of South Africa and this could be a major reason for this phenomenon. Summer and small grains are mostly grown under irrigation in the more northern and eastern parts of the country where these crops are also gown under dryland conditions (Figure 1-5), while vineyards and deciduous fruit are dominant crops under irrigation in the south-western part of the country with its Mediterranean climate (regions G, H, J and K) (Figure 1-3; Figure 1-5). Sugarcane and subtropical fruit are amongst the four most important crops along the KwaZulu-Natal coast and in the Lowveld of Mpumalanga (regions U, V, W and X) (Figure 1-3), where subtropical fruit also appears as an important irrigated crop (Figure 1-5).

Table 1-5 Most important crop types produced under irrigation in the different drainage regions (see Figure 1-3) of South Africa (Backeberg *et al*., 1996)

Drainage Region A		**Drainage Region B**		**Drainage Region C**	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Vegetables	42 400	Small grain	20 700	Pasture and forages	74 400
Small grain	29 600	Fibre crops	15 600	Small grain	61 300
Fibre crops	20 900	Vegetables	13 100	Summer grain	46 200
Summer grain	17 100	Summer grain	12 000	Vegetables	21 100
Pasture and forages	11 600	Citrus	8 600	Oil and protein seed	17 400
Subtropical fruit	7 900	Oil an protein seed	8 200	Fib\re crops	10 800
Oil and protein seeds	6 300	Pasture and forages	4 700	Vineyards	1 500
Citrus	4 300	Subtropical fruit	3 100		
Drainage Region D		**Drainage Region E**		**Drainage Region F**	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Pasture and forages	55 700	Pasture and forages	11 300	Pasture and forages	1 500
Small grain	32 000	Small grain	11 200	Vineyards/grapes	700
Summer grain	11 000	Deciduous fruit	10 800	Vegetables	200
Vineyards/grapes	6 900	Vineyards/grapes	8 600	Oil and protein seed0	100
Fibre crops	6 800	Vegetables	6 500		
Oil and protein seed	3 100	Citrus	5 700		
Vegetables	3 000				
Drainage Region G		**Drainage Region H**		**Drainage Region J**	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Vineyards/grapes	46 400	Vineyards/grapes	36 500	Pasture and forages	30 000
Deciduous fruit	27 200	Pasture and forages	15 500	Vegetables	2 100
Pasture and forages	5 700	Deciduous fruit	9 800	Deciduous fruit	1 500
Vegetables	4 100	Vegetables	7 900	Vineyards/grapes	1 400
Subtropical fruit	3 000	Small grain	5 100	Small grain	1 200
Citrus	1 200				
Drainage Region K		**Drainage Region L**		**Drainage Region M**	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Pasture and forages	9 300	Pasture and forages	17 100	Pasture and forages	2 400
Vegetables	3 700	Deciduous fruit	5 300	Vegetables	700
Summer grain	400	Vegetables	4 700	Small grain	100
Deciduous fruit	200	Citrus	1 500	Citrus	100
Vineyards/grapes	100	Summer grain	1 300		
Drainage Region N		**Drainage Region P**		**Drainage Region Q**	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Citrus	7 700	Pasture and forages	2 600	Pasture and forages	53 800
Pasture and forages	6 900	Vegetables	1 000	Summer grain	4 800
Vegetables	600	Small grain	400	Small grain	2 300
Summer grain	400	Summer gran	300	Citrus	800
Small gran	300	Citrus	100	Vegetables	100

Drainage Region R		Drainage Region S		Drainage Region T	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Vegetables	1 200	Pasture and forages	11 600	Pasture and forages	9 600
Pasture and forages	800	Summer gran	600	Small grain	1 800
Summer grain	100	Vegetables	400	Subtropical fruit	600
				Vegetables	600
				Summer grain	200
Drainage Region U		**Drainage Region V**		**Drainage Region W**	
Crop	**Area (ha)**	**Crop**	**Area (ha)**	**Crop**	**Area (ha)**
Pastures and forages	23 100	Pasture and forages	22 500	Sugarcane	26 200
Sugarcane	10 200	Sugarcane	20 100	Fibre crops	4 200
Vegetables	7 900	Summer grain	81 00	Pasture and forages	3 100
Summer gran	1 400	Small grain	6 100	Summer grain	2 100
Oil and protein seed	900	Vegetables	5 000	Citrus	1 900
Citrus	600	Oil and protein seed	4 100	Vegetables	1 700
Subtropical, fruit	500	Subtropical fruit	700	Subtropical fruit	1 400
		Citrus	400	Oil and protein seed	1 100
Drainage Region X					
Crop	**Area (ha)**				
Subtropical fruit	34 200				
Citrus	23 200				
Vegetables	20 700				
Sugarcane	14 300				
Fibre crops	6 000				
Oil and protein seed	3 600				
Pasture and forages	2 600				
Small grain	1 700				
Summer grain	1 000				

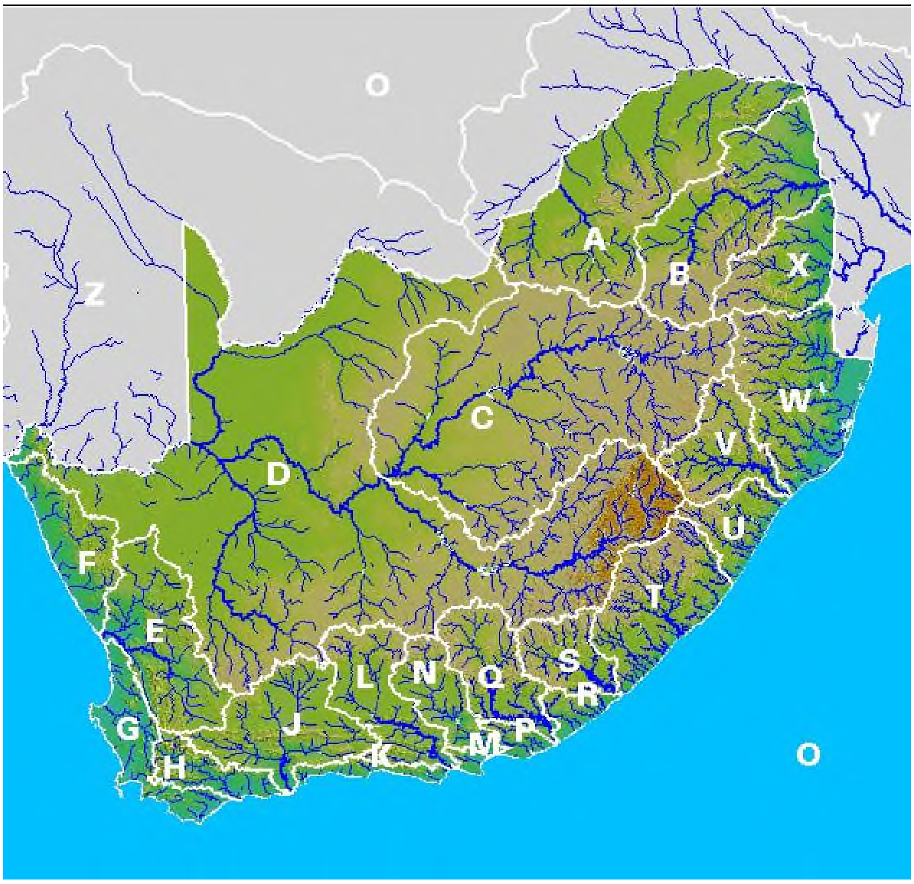


Figure 1-3 Primary drainage regions for South Africa (RQS, 2015)

Table 1-6 Primary drainage regions of South Africa showing the main rivers for each primary drainage region (Department of Water Affairs and Forestry, 2012)

Primary drainage region	Major rivers
A	Limpopo River
B	Olifants River
C	Vaal River
D	Orange River
E	Olifants River, Groot River
F	Buffels River
G	Berg River, Diep River, Eerste River, Verlorevlei River, Bot River, Klein River, Uilkraal River
H	Breede River
J	Touws River, Gamka River, Olifants River
K	Little Brak River, Great Brak River, Keurbooms River, Bloukrans River, Storms River, Groot River, Tsitsikamma River, Kromme River
L	Baviaanskloof River, Kouga River,
M	Maitland River, Van Stadens River
N	Sundays River
P	Bushmans River, Kowie River, Kariega River

Q	Great Fish River
R	Buffels River, Nahoon River
S	White Kei River, Klipplaat River, Thomas River, Tsomo River
T	Slang River, Mtata River, Tsitsa River
U	Mgeni River
V	Tugela River, Mooi River, Bushmans River
W	Mhlatuze River, Hluhluwe River
X	Nkomati River

Table 1-7 is a summary of field and horticultural crop production for South Africa for the year 2000. The irrigated area covered by these crops constitutes about 19% of total cultivated area on which these same crops are grown. The income from irrigated agriculture is about R16 711 per ha, compared to R3 159 per ha for dryland crops, a ratio of 5.3:1. These irrigated crops generated about 55% of the total income from their production, which is an indication of the importance of irrigated agriculture. The yield (t ha^{-1}) of irrigated agriculture is about 3.16 times that of dryland, while the income generated per ton of produce is about 1.67 times that of dryland, an indicator that higher value crops are grown under irrigation than on dryland as well as the importance that irrigation plays in the agricultural economy of South Africa (Agricultural Statistics in brief, 2014).

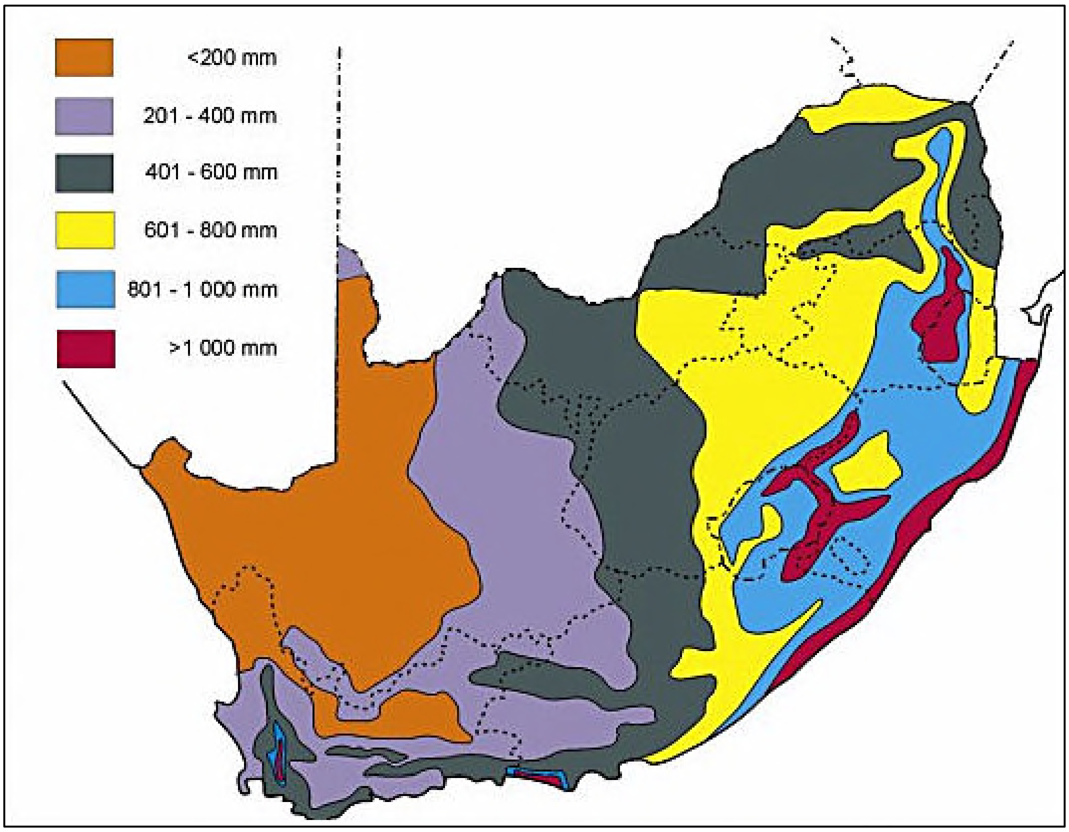


Figure 1-4 Rainfall map of South Africa (South Africa Tours and Travel.com, 2015)

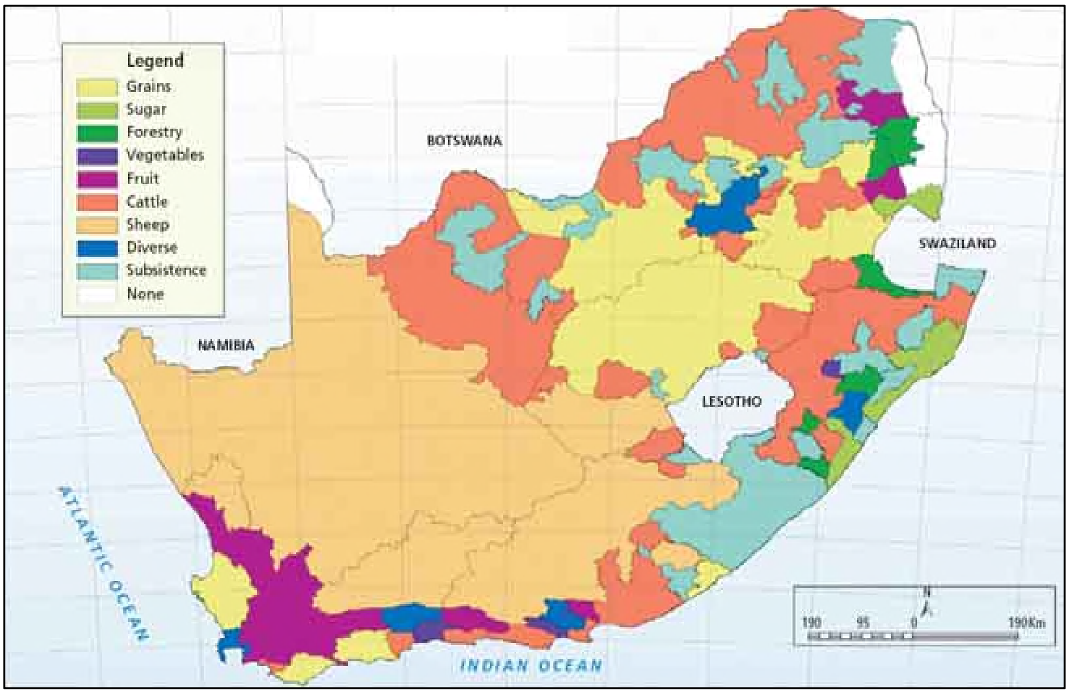


Figure 1-5 Agricultural regions of South Africa (FAO, 2005)

Table 1-7 Summary of agricultural production for South Africa for 2002 (Statistics South Africa, 2010)

Crops	Irrigation			Dryland			Total
	ha	tons	ZARand	ha	tons	ZARand	ZARand
Field crops	471 262	6 050 873	3 136 438 795	3 159 670	14 995 096	8 803 400 205	11 939 839 000
Horticultural crops	291 417	6 024 464	9 608 364 447	109 576	1 401 291	1 570 311 153	11 178 675 600
Total	762 679	12 075 337	12 744 803 242	3 269 246	16 396 387	10 373 711 358	23 118 514 600
Yield (t/ha or ZAR/ha)		15.8	16 711		5.0	3 173	
Income (ZAR/ton)			1 055			633	

1.4 Irrigation water management planning

An increase in the competition for water between different sectors of the economy is a given. This is the result of an ever increasing demand for water because of population growth. Added to this is the greater pressure on the irrigation farmer to become more efficient, to use irrigation water sustainably and to plan and manage his water in an environmentally friendly way (Clothier and Green, 1994). Sustainable irrigation water management should simultaneously satisfy the two objectives of food security and also of preserving the irrigated environment. A stable relationship should be maintained between these two objectives, while potential conflicts between these objectives should be mitigated through appropriate irrigation practices (Cai *et al*., 2003). In aiming for the maintenance of these objectives, the complete soil-plant-atmosphere continuum needs to be considered (Anderson *et al*., 2003). Suitable crops for the soil-atmosphere environment should be selected; the irrigation system should be suitable for the soil-crop environment and should be able to satisfy the crop's irrigation requirements. Irrigation management should be such that leaching of nutrients and potentially harmful salts into underground or downstream water resources does not take place (Cai *et al*., 2003). Irrigation management must be able to plan for and to supply the right amount of water at the right time to the crop (Reinders, 2010). Simultaneous to this, the irrigation management system must be such that even though unforeseen water restrictions might apply, the crop must still be able to yield at profitable levels and food security objectives must be satisfied.

Two distinct phases can be identified in irrigation water management. The first phase is an irrigation requirement planning phase, which is a precursor for the next phase, the real-time or day-to-day irrigation water management phase. This dissertation concentrates on the planning phase and will therefore *not* go into the detail of the day-to-day management of irrigation water.

1.4.1 Planning phase

The surest way of improving irrigation water requirement planning is to improve the estimation of irrigation water requirements by crops. Internationally these developments were through phases of rough irrigation water requirement estimates based on localised knowledge and experiments (Van Heerden and De Kock, 1980), to the use of data from evaporation pans, such as the Class A (Green, 1985) or Colorado sunken pan (Haise and Hagan, 1987), and the use of crop factors linked to evaporation data for improved irrigation water requirement estimates (Allen *et al*., 1998). This was followed by the use of weather data calculation approaches linked to crop coefficients (Doorenbos and Pruitt, 1977), of which the Penman-Monteith approach is presently the internationally accepted methodology (Allen *et al*., 1998).

Good climate data at monthly or shorter intervals were required and the FAO CLIMWAT climate data set provided a reference set of monthly average data that was applicable to virtually all developing countries (Smith, 1993). CLIMWAT data did not necessarily cover all irrigation areas in a country, which in turn led to extrapolation from the known to the unknown (Crosby and Crosby, 1999) which increased the risk of inaccuracy in crop irrigation requirement estimates. Using long-term, average monthly climate data does not allow the user to do repetitive, seasonal irrigation requirement estimates; therefore risk and variation in seasonal irrigation requirement could not be planned for (Van Heerden *et al*., 2008). Linked to this, the monthly data did not allow the estimation of rainfall use efficiency based on daily soil water balance calculations; therefore the inclusion of an effective rain water use was not necessarily accurate because it is based on equations used for estimating rain water use efficiency from monthly rainfall data (Crosby and Crosby, 1999; Smith, 1992; Van Heerden *et al*., 2008).

Published crop coefficients (referred to as crop factors when linking to evaporation pan data) and crop growth periods as published, did not provide for differences in rate of growth due to different climates, which in turn led to inaccurate irrigation requirement estimates, especially for crops grown in climates that differed significantly from the sub-humid climates used as a basis when compiling the K_c tables (Allen *et al*., 1998; Crosby and Crosby, 1999; Lazarra and Rana, 2012; Rohitashw *et al*., 2011; Van Heerden *et al*., 2008). This problem was partly solved by linking crop growth to geographic regions with different climates (Crosby and Crosby, 1999), and then linking to defined climates that could be linked to weather stations because of being defined in terms of temperature and rainfall combinations through the Köppen climate system (Van Heerden *et al*., 2008).

Approaches to the design of irrigation systems have become more sophisticated, leading to further developments in the estimation of irrigation water requirements which led to the development of sophisticated tools, such as computer models (Allen *et al*., 1998). Computer models provide cheaper and more feasible approaches to the estimation of irrigation requirements by replacing farm and local level experimental work (Le Gal *et al*., 2010). CROPWAT (Smith, 1992), a product of the United Nations Food and Agricultural Organisation (FAO), is probably the best-known example of computer models used for estimating irrigation water requirements used in the international field. Crosby (1996) realised that there were shortcomings in CROPWAT, e.g. it did not provide for differences in the rate of plant growth and development for crops planted in different climatic zones or at different planting dates. He started to develop SAPWAT as an easy to use and understandable alternative to CROPWAT for the South African irrigation system planner, designer and irrigation water manager (Paragraph 1.6) (Crosby and Crosby, 1999).

1.4.2 Real time water management phase

Approaches to irrigation water management at farm level went through different phases over time, from the simple guessing of soil water content through observation and touch, to soil water content measurement with probes such as the neutron water probe and capacitance probes (Haise and Hagan, 1987; Zerizghy *et al*., 2013); from direct observation of plant conditions to the sophisticated, above canopy estimates of ET using remote sensing, scintillometer and micrometeorological techniques (Fuchs, 1990; Mkhwanazi *et al*., 2012; Jarmain *et al*., 2014). Scheduling aids also included using evaporimeters approaches as indirect indicators, such as evaporation pans (Allen *et al*., 1998) and adapted evaporation pans (Scheepers, 1975). Alternative approaches include the use of data from automatic weather stations linked to crop growth and development models, of which the SWB computer model is an example (Annandale *et al*., 1999).

Some farmers in South Africa use scheduling tools as an aid to their irrigation water management. However, farmers seem to be reluctant to use technology where "they have to dig to install it"[1]; therefore there seem to be a limited number willing to invest in soil water measurement probes. On the other hand, electronic based scheduling aids seem to be acceptable, such as the MyCanesim system of the South African Sugar Research Institute (http://www.sasa.org.za/sasri/) where automatic weather station data is used to calculate crop water use and the information is then sent via mobile phone to sugar cane farmers with advice on irrigation management (Singels, 2008). A study by Stevens *et al*. (2005) found that 19% of irrigation farmers use soil water measurement approaches, 15% use models or model results and 81%[2] of irrigation farmers schedule by intuition, which is described as a combination of fixed or semi-fixed calendars based on experience, knowledge and observation. It was also found that 3% of respondents (Paragraph 5.7.1) use SAPWAT as an aid to scheduling, even though SAPWAT is aimed at the planning of irrigation water requirements and is not designed to be used as a scheduling aid. Management of the irrigation water distribution system in an irrigation area also influences the acceptability of irrigation scheduling. When farmers get their irrigation water on the basis of a fixed roster for a limited period of time, as is the system most commonly found on many irrigation

[1] Dup Haarhoff, Executive Manager: Research & Development, GWK Limited. Personal communication
[2] These values add up to more than 100% because farmers tend to use a combination of scheduling approaches and they have been asked to indicate all that are used by them.

schemes, they are less prone to apply irrigation scheduling in the fullest sense of the meaning than is the case where they have unrestricted access to water.

When available, good quality irrigation scheduling data can be used for purposes of irrigation water requirement planning. The biggest problem with the use of such data is that it is usually localised and therefore applicable for a specific geographic area and not necessarily applicable in a new area being planned. However, scheduling data could be used to verify SAPWAT crop growth and development characteristics data in order to improve its functionality as a water requirement planning tool.

1.5 Adoption of irrigation water requirement planning tools

The design and development of computer programs such as SAPWAT are innovations in their own right, even if the background science they are based on might not be new. In these cases the innovation is the packaging and integration of existing high-level scientific and local knowledge and experience into a tool that is easy to use and easy to understand by the potential user. SAPWAT is such a planning tool that links weather data, crop science, soil science, irrigation engineering and irrigation water management approaches into a single package through the development of a computer database management system. Based on Stevens and Van Heerden (2013) SAPWAT can be used with confidence by the irrigation design engineer, irrigation related researcher, extensionist, teacher, student and irrigation water manager as a planning tool. However, if such a model is not accepted as an easy-to-use tool it is of no real use to the potential user and the innovation value of it decreases (Rouse, 1991). Within the South African context, questions could be asked as to what has made SAPWAT an accepted tool, what are its strong and weak points that need to be strengthened or improved when building a revised and improved version. Part of the impact analysis that need to be done also needs to investigate the influence the direct marketing method, used in delivery to the potential clients, had on the adoption rate, using various diffusion and adoption theories.

1.5.1 The adoption process

Diffusion of an innovation is the result of communication there-of over time in a community. The end result is that people adopt an innovation and as a result gain new knowledge, change their behaviour, or change to a new product. The key to adoption is that the person must perceive the idea, behaviour or product as new or innovative, be to his or her advantage or must contribute to his or her comfort. However total rejection of the innovation is also a possible outcome if people do not perceive the innovation as potentially contributing to their knowledge or well-being (Rogers, 2003).

Adoption of an innovation is a process in which some people are more prone to adopt an innovation than others. People who adopt an innovation early have different characteristics to people who adopt an innovation later. The recognition of the differences in adoption by different members of a community, led to the defining of innovativeness as reflecting the degree to which an individual is earlier or later in adopting innovations relative to other members of a community (Rogers, 2003).

Some innovations diffuse relatively fast, while other innovations diffuse slowly. The characteristics of an innovation that determine its rate of adoption are its relative advantage, compatibility, complexity, ease of trying, observability (Rogers, 2003), ease of use and usefulness (Davis *et al*., 1989), while homophilous grouping, pace of innovation/re-innovation, norms, roles, social networks, and infrastructure can also play a role (Cain and Mittman, 2002). Overall, innovations that are perceived by individuals as having a greater relative advantage, are compatible with existing practices as well as with the norms and standards of the community are typically adopted quicker than others. If an innovation is perceived as being less complex, can be tested on a subset of applications rather than at the full application scale, and where positive results are readily noticeable, it will usually be adopted faster than other innovations (Cain and Mittman, 2002; Davis *et al*., 1989; Rogers, 2003; Wüstenhagen *et al.,* 2007).

The adoption of innovations generally depends on the availability or presence of infrastructure that can support it. If required infrastructure is available, it can be expected that diffusion will be so much quicker than in situations where infrastructure is lacking (Cain and Mittman, 2002).

The diffusion of an innovation through a population or a social system is a process that usually precedes the adoption or rejection there-of. The most generally accepted description of diffusion of an innovation is the process by which it is communicated through communication channels, over time, among the members of a community. The communication of innovations is of a special type; its main concern is the spreading of messages that are perceived as new ideas and which will probably be received with some degree of uncertainty (Analytictech, 2012; Poncet *et al*., 2010; Rogers, 2003).

Communication is the social process by which members of a community share information with one another while a communication channel is the means by which messages flow through the community. Mass media channels (TV, radio, newspapers and magazines) can be more effective in creating awareness of innovations; a large number of people can be reached at relatively low cost and the message can be repeated any number of times. Mass media channels are usually used as directed communication channel in advertising campaigns and are often found in diffusionist communication actions by government agencies (Rogers, 2003; Poncet *et al*., 2010), an example being a campaign for more efficient irrigation water use.

Opinion leaders are key elements in this type of communication. By nature, they are the people who look for information from outside sources and through their opinion leadership roles, spread the message in the rest of the community (Cain and Mittman, 2002; Rogers, 2003; Steinberg, 1994). Most individuals evaluate an innovation, not on the basis of scientific research by experts, but through the subjective evaluation of peers who have already adopted the innovation. So the diffusion process is essentially social in nature, driven by individuals talking to others and giving meaning to an innovation through a process of social intercourse (Rogers, 2003), a process which takes time.

Time is involved in the process of deciding on the acceptability and potential adoption of an innovation. This is the mental process that an individual goes through from coming across the first information of an innovation; to developing an attitude toward it and looking for more information about it; to deciding on adoption or rejection; to the implementation of the innovation; and then to confirm the decision to adopt or reject. An individual seeks information at various stages in the innovation-decision process, usually moving from mass media to personal contacts, in an effort to increase the understanding of the consequences of adopting it (Cain and Mittman, 2002; Rogers, 2003).

Adoption can further be described as a specific type of learning; the adopter needs to learn new approaches to solve his problems or to improve on his way of doing things. Learning is described as the relatively lasting change in the response to a specific stimulus. This goes to the heart of most learning theories, which is based on a stimulus-response relationship; a stimulus is interpreted by an individual and causes a response by him. Repeated reinforcement of the stimulus-response relationship results in a more or less permanent change in the individual's behaviour. Learning is not limited to classroom situations; it happens throughout life in which social structure interaction regarding learning and resultant skills development play an important role. The process of learning is generally similar, irrespective of the individual's training level or experience (Dessie *et al*., 2013; Learning Theories Knowledgebase, 2012; Mashavave *et al*., 2013; Rogers, 2003).

To adopt an innovation means to learn how to use a new product which can lead to a change in behaviour. It is the result of mental processes through which an individual passes from first hearing about an innovation, up to its final adoption. The decision to adopt an innovation is therefore an individual matter, which is influenced by the individual's characteristics, shaped by the social system in which that individual works and lives. This decision-making is the process by which an evaluation is made of the meaning and consequences of alternatives and it goes through the following steps: (1) observing the problem; (2) making an analysis of the problem; (3) deciding what available courses of action there are; (4) taking one course; and (5) accepting the consequences of the decision (Analytictech, 2012; Rogers, 2003).

1.5.2 Factors that influence the adoption process

A social system is characterised by its people, their culture, habits, social structure and interaction as well as lifestyle. In a similar way that a person can be characterised in terms of innovativeness, a community can be characterised in terms of its culture and social system. There is a reciprocal influence between social system and its population in the sense that one influences the other, or put slightly different, what happens in a community is mirrored in an individual. In a traditional social system the individuals will tend to be more traditional in outlook, will tend to look in their own social system for solutions to their problems and will be wary of outside influences. In a modern social system the individual members of the society will react in a more cosmopolitan way to stimuli from outside, will tend to look for solutions to their problems outside their own community, tend to be technologically developed and tend to accept innovations more readily. The reaction of a social system to an innovation is to a large extent based on the modern-traditional trend of its members. The social system, which can consist of individuals, informal groups, organizations, and/or subsystems of a community, constitutes a defined area within which an innovation diffuses.

Diffusion is affected by norms, which are the established behaviour patterns for the members of a social system, and by opinion leadership, which is the degree to which an individual is able to influence the attitudes or overt behaviour of other individuals in a desired way with relative frequency (Rogers, 2003).

The characteristics of the social system play a major role in the diffusion of innovations. In more homogeneous groups diffusion through the systems usually flows faster that in heterogeneous groups. Furthermore, the norms, roles, and social networks of a community have a great influence on the diffusion of an innovation through a community. Diffusion tends to be faster in communities where extensive interactive contacts between community members are found (Cain and Mittman, 2002).

Individual members of a social system progress through five steps in deciding to adopt an innovation. Each of these steps requires a conversion of tacit or explicit information to potential application information. This information either comes through external influences from outside the community or through influential members of the community. Individuals progress through these steps at different rates, often resulting in their differentiation into separate groups defined by their rate of adoption. These steps are (Rogers, 2003):

- Awareness: where the individual is simply made aware of the innovation. It is a passive stage where awareness is usually driven by sources outside the social system.
- Interest: where the individual becomes active and starts looking for more information regarding potential application in his situation.
- Evaluation: where the individual uses the information gathered to mentally examine the innovation in order to assess the impact that adoption of it will have on his situation. This is a critical stage and the first one where the voices of the community often have the largest influence on an individual.
- Trial: where the individual actually tests the innovation to see if it really matches expectations, usually with small-scale, experimental efforts. At this stage any source of information that could possibly be helpful in deciding will be used. Close community ties are the most important at this stage.
- Adoption: where the individual adopts the innovation.

The speed with which individuals pass through these five stages will vary depending on the particular innovation, its overall complexity, its costs, and how disruptive it is to current workflows (Rogers, 2003).

Adoption of innovations by individuals is influenced by the availability of funds. A lack of funds for inputs and the availability of supporting and complementary inputs will retard adoption. Furthermore, if funding is lacking, irrigation management will not be up to standard and agricultural production will be negatively affected by it. Adequate funding for application of an adoption is required to ensure adoption (Nmadu *et al*., 2015).

1.5.3 Adoption models or approaches

Ryan and Gross (1950) were probably the first to recognise that the adoption of a new idea consisted of stages. They distinguished between knowledge of hybrid seed corn (maize), conviction of its usefulness, implementation acceptance and complete adoption. Wilkening (1952) first pointed out that an individual's decision to adopt an innovation was a process composed of stages or steps. He described the adoption of an innovation as: "… a process composed of learning, deciding, and acting over a period of time. The adoption of a specific practice is not the result of a single decision to act or a series of actions and thought decisions". Wilkening proceeded to list four adoption stages: knowledge; obtaining information; conviction and trial; and then adoption. These stages, with slightly different titles, were highly publicized by a committee of rural sociologists (Iowa State University Cooperative Extension Service, undated) in the widely distributed bulletin "How farm people accept new ideas". Their five-stage adoption process, which is a further development of Wilkening's (1952) four stage approach, is basically the same, even if not in exact terminology, as described by Rogers (2003). It was also found that the Rogers description of adopter categories and innovativeness can be applied to the adoption of computer technological innovations (Hoerup, 2001).

1.5.3.1 Roger adoption model

Everett M. Rogers is best known for originating the diffusion of innovations theory and for introducing the term 'early adopter' (Wikipedia, 2014a). The paradigm that he so successfully used since 1961 typically is trying to identify what the stages are that people go through when considering the adoption of an innovation and how the characteristics of an innovation affects the rate of adoption. Rogers (2003) identified that variables like relative advantage, compatibility, complexity, ease of trying and observability determine and predict the rate of adoption. These variables, and their influence on adoption, have been described a half century ago, and have given the theoretical background upon which many agricultural extension research projects on adoption of innovations have been based. Adoption or uptake of innovations does not happen overnight, but is rather the final step in a sequence of stages and therefore part of the innovation process. The introduction of an innovation can lead to a wave of innovations (Röling, 2009) that was initially described as the diffusion curve by Rogers (2003). According to this theory, an innovation starts slowly and then gathers momentum as more farmers adopt it. Earlier research on the diffusion of innovations also suggests a prominent role for perceived ease of use. Researchers found that compatibility, relative advantage and complexity had the most significant relationships with adoption across a broad range of innovation types (Rogers, 2003). Research on adoption of innovations focused on the types and characteristics of innovations, communication channels and the influences of social or commercial systems on adoption (Leeuwis and Van den Ban, 2004).

1.5.3.1.1 Knowledge

At the knowledge stage the individual is exposed to the innovation but lacks complete information about it. The individual is aware of the innovation, but lacks the motivation to seek further information. The primary function of the knowledge stage is to initiate the sequence of later stages that lead to eventual adoption or rejection of the innovation (Rogers, 2003).

1.5.3.1.2 Persuasion

At the persuasion stage the individual becomes interested in the new idea and seeks additional information about it. The individual favours the innovation in a general way, but he has not yet judged its utility in terms of his own situation. The individual is more psychologically involved with the innovation at the persuasion stage than at the knowledge stage. Previously the individual listened or read about the innovation: at the persuasion stage he actively seeks information about the idea. His behaviour is now definitively purposeful, rather than non-purposeful. His personality and values, as well as the norms of his social system may affect where he seeks information, as well as how he interprets this information about the innovation (Rogers, 2003).

1.5.3.1.3 Decision

At the decision stage the individual mentally applies the innovation to his present and anticipated future situation, and then decides whether or not to try it. If the individual feels the advantages of the innovation outweigh the disadvantages, he will decide to try the innovation. This decision stage is conceptually distinct from the decision to try the new idea. The decision stage is probably the least distinct of the five adoption stages and empirically one of the most difficult about which to question respondents (Rogers, 2003).

The innovation carries a subjective risk to the individual. He is unsure of its results, and for this reason a reinforcement effect is needed at the decision stage to convince the individual that his thinking is on the right path. Information and advice from peers is likely to be sought at this point. The individual's decision can be made freely and implementation can be voluntary, or it can be influenced or even forced by community pressure, such as where a collective decision is made or where a decision is made for the community by individuals in authority (Rogers, 2003; Wikipedia, 2014b).

1.5.3.1.4 Implementation

At the implementation stage the individual uses the innovation on a small scale in order to determine its utility in his own situation, provided that the innovation is of such a nature that it can be tested on a small scale. The main function of the implementation stage is to demonstrate the new idea in the individual's own situation and determine its usefulness for possible complete adoption. It is thus a validity test or "dry run", such that the decision to use the idea on a trial basis can be made at the decision stage. The individual may seek specific information about the method of using the innovation at the implementation stage (Rogers, 2003).

Most people will not adopt an innovation without trying it first on a probationary basis. However clearly the advantages of hybrid corn had been demonstrated by community experience, most farmers insisted upon personal experimentation before they would adopt that innovation. Even the last Iowa farmers to adopt the innovation, although often surrounded by neighbours successfully using hybrid seed, planted only a portion of their acreage in hybrid seed during the first year. Industrial innovations during the nineteenth century were usually developed first on the smallest possible scale in order to demonstrate their utility (Rogers, 2003).

While the rejection of an innovation may occur at any stage in the adoption process, it sometimes happens when the results of the implementation stage are misinterpreted (Rogers, 2003).

1.5.3.1.5 Confirmation

At the confirmation stage the individual decides to continue the full use of the innovation. The main functions of the confirmation stage are consideration of the implementation results and the decision to ratify sustained use of the innovation. Confirmation implies continued use of the innovation in the future (Rogers, 2003).

1.5.3.2 TAM model

The Technology Acceptance Model (TAM) as described by Davis *et al*. (1989) was originally developed and tested for adoption of computer applications. It proposed that the use or adoption of innovations is mainly the response of what can be explained as the users' motivation. This motivation can be explained by three factors: (1) perceived ease of use; (2) perceived usefulness; and (3) general attitude of the user towards using a specific innovation. Perceived ease of use might be an antecedent to usefulness, rather than a parallel, a direct determinant of usage, with the proviso that the innovation must be useful (Davis *et al*., 1989; Gao, 2005; Rogers, 2003). This model differs from the traditional approach where adoption of innovations was mainly portrayed as relating to an individual in that the TAM model refers to the social system in which the potential adopter operates. Leeuwis and Van den Ban (2004) emphasized that innovations are constituted by the coordination between independent actors and are therefore defined as a package of new social and technical arrangements which may imply new forms of coordination between interrelated actors.

Perceived ease of use refers to the degree to which a person believes that using the particular innovation would be free of effort. This follows from the definition of "ease", which is: "freedom from difficulty or great effort". Effort is a finite resource that a person may allocate to the various activities for which he or she is responsible. All else being equal, an application perceived to be easier to use than another is more likely to be accepted by users (Davis *et al*., 1989; Goa, 2005).

Perceived usefulness and perceived ease of use influence a person's adoption of new or changed technology. The TAM model postulates that the use of new or changed technology is determined by behavioural intention and that behavioural intention is determined by a person's attitude and/or belief towards the use of a technology and also by his perception of the technology (Figure 1-6). The attitude of an individual is not the only factor that determines the use of an innovation, but also the impact which it may have on the output or performance judgement. Therefore, even if a person does not welcome a specific new technology, the probability that he/she will use it is high if a perception occurs that the technology will improve the valued outcomes. Besides, TAM hypothesizes a direct link between perceived usefulness and perceived ease of use. With two systems offering the same features, a user will find the one that is easier to use as being the more useful (Dillon and Morris, 1996).

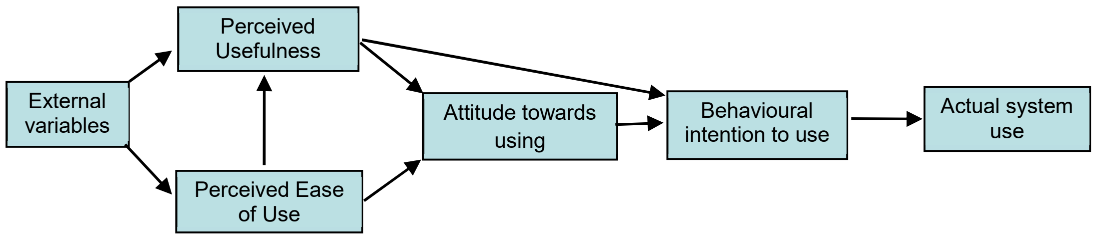


Figure 1-6 Technology Acceptance Model (Davis *et al.*, 1989)

Studies found in the literature provided strong evidence to support the use of the TAM model for predicting usage of innovations (Davis *et al.*, 1989; Goa, 2005). Research reports about how TAM itself is used have mainly addressed predicting and testing the acceptance of computer and related technology in the industrial sector.

1.6 Development of SAPWAT

The development of SAPWAT (Van Heerden *et al.*, 2008) had to take cognisance of international developments related to the function that SAPWAT tried to fulfil. The best thinking related to this is probably contained in FAO reports.

The development process of SAPWAT started with the Green Book of 1985 (Green, 1985) which linked crop factors to Class A pan evaporation for all irrigation areas in South Africa. For many years this was the accepted South African standard approach for the estimation of irrigation water requirements of crops for planning and design purposes.

1.6.1 The Green Book (Green, 1985)

In the introduction of this publication a summary of factors that influences the evapotranspiration process and the limitations of the accepted procedures to estimate crop water requirements are given. Applicable extracts are (Crosby and Crosby, 1999):

- The water requirement of different crops grown under the same environmental conditions might vary considerably, depending upon genetic factors, plant density and plant configuration. For a given crop, with a leaf canopy that provides complete ground cover, or which has a constant leaf area index, the rate of water use will depend mainly on external factors. These are, broadly speaking: atmospheric factors that provide the energy for the evapotranspiration process and soil factors that regulate the provision of water to the roots.

- At and above the soil surface, the leaf area index influences the ratio of the two processes that make up evapotranspiration, that is, transpiration of the crop itself and evaporation from the soil surface.
- Ideally speaking, there are a large number of meteorological, soil, water, crop and agronomic management and even economic factors that must be considered when crop irrigation requirements are estimated. At present (written in 1985 in Green Book) the ideal solution is out of reach as a result of a shortage of enough general mathematical models and because of a lack of input data.

The method that was still generally used (in South Africa) for the determination of daily water requirements is explained further (Crosby and Crosby, 1999):

- Of the empirical methods available for the estimation of evapotranspiration, the one that has been most widely tested and used in South Africa, is the method based on evaporation, specifically the American Class A evaporation pan;
- This method presupposes that over a given period, evapotranspiration (ET_c) is in direct relation with pan evaporation (E_{pan}). Stated otherwise, $ET_c = f.E_{pan}$, where f is the empirical ratio between pan evaporation and crop water use for a specific growth period, known as the crop factor.

However, there is a pertinent warning about the limitations of crop factor values (Crosby and Crosby, 1999):

- As a general rule crop factors, as used in the Green Book (Green, 1985), could not be adapted for differences in climate or growing season because of a lack of knowledge at that time. For example, the crop factors that were seen as applicable to deciduous fruit in the Western Cape were also used to estimate the water requirements for deciduous fruit in the Transvaal (now Gauteng, Mpumalanga, Limpopo and the eastern part of Northwest Province). Furthermore, estimates for a given vegetable crop were based on crop factors that stayed the same, irrespective of whether the crop was planted in summer, winter, autumn, or spring;

- This inability to adapt crop factors for specific seasonal and climatic situations is a shortcoming that cannot be ignored. Once decided upon, the crop factors were used unchanged in all production areas over all growing seasons;
- Because of this, estimates of evapotranspiration and irrigation requirements must still be seen as first approach working calculations, with a reasonable potential for refinement.

The accuracy of the evapotranspiration estimates are not only dependent upon the validity of crop factors, but also upon the use of strictly representative (pan) evaporation data (Crosby and Crosby, 1999).

1.6.2 The FAO Irrigation and Drainage Report No 24

This report "Guidelines for Predicting Crop Water Requirements" (Doorenbos and Pruitt, 1977) included two important concepts which had the potential to eliminate some of the shortcomings that were identified in the introduction to the Green Book. It recognized the limitations of the use of A-pan evaporation and recommended short grass as reference evapotranspiration, in association with the linked and less empirical four-stage approach for the development of crop factors. This reference evapotranspiration is in harmony with the growing plant, so that there is automatic compensation for climatic differences. When full effective ground cover is reached, the crop factor would be 1.0 (Crosby and Crosby, 1999).

The four stages of crop development are described as follows (Crosby and Crosby, 1999):

1. Initial stage: germination and early growth, when the ground surface is barely covered by the crop (ground cover <10%);
2. Crop development stage: from the end of the initial stage to the reaching of effective full ground cover (ground cover = 70 – 80%);
3. Mid-season stage: from reaching full effective ground cover, till the beginning of maturity, as indicated by colour change of leaves and start of leaf drop;
4. Late season stage: from the end of the mid-season stage to full maturity or harvest.

The basic approach for the estimation of crop water use did not change (Crosby and Crosby, 1999).

Now $ET_c = K_c \times ET_0$, where ET_0 is the short grass reference evapotranspiration and K_c is the equivalent of the crop factor, now called the 'crop coefficient'.

The value of ET_0 was calculated or determined by various methods (Blaney-Criddle, radiation, Priestly-Taylor, Penman, pan evaporation) from climate data (temperature, wind, humidity and radiation), the result of which was originally verified with the aid of weighing lysimeters (Doorenbos and Pruitt, 1977). Eventually the Penman-Monteith equation for the calculation of ET_0 were internationally recognized and published as the standard calculation method in the FAO Irrigation and Drainage Report No 56 (Allen *et al*., 1998).

1.6.3 FAO consultation / CROPWAT: The FAO Irrigation and Drainage Report No 46

Smith (1991) reported on the expert consultation with the aim of evaluating FAO No 24 (Doorenbos and Pruitt, 1977) that took place in Rome during 1990:

- In the series of Irrigation and Drainage reports the FAO methodology for the estimation of crop water requirements has proved itself as exceptional. FAO 24 became the international standard, and irrigation engineers, agronomists, hydrologists and environmentalists are using it on a worldwide scale. More than 200 000 copies have been distributed in four languages by 1991.

FAO 24 was adopted and adapted into a computer program, including information from FAO Irrigation and Drainage Report No 33 "Yield Responses to Water" (Doorenbos and Pruitt, 1979), and was published as a computer program CROPWAT (Smith, 1992). This program further enhanced the acceptance of the FAO procedures (Crosby and Crosby, 1999).

The consultation decided that crop coefficients were still valid, but that updating was justified and that the following should be considered (Smith, 1991):

- Review, with specific reference, crop coefficients for trees and fruit crops, as well as several of the perennial crops;
- Review crop coefficients, specifically during the initial stage, by evaluating soil evaporation and basal crop transpiration separately;
- Review the effect of climate and advective conditions on the crop coefficient;
- Review and update the length of the different growth stages, possibly also the incorporation of a growth function coupled to temperature and dry matter yield.

Since that consultation, progress has been made on these aspects. Recommended procedures and data were published in FAO No 56. As far as was known by 1999, this progress had not yet been directly integrated into computer program for irrigation design and planning programs (Crosby and Crosby, 1999).

1.6.4 SAPWAT and reference evapotranspiration (ET_0)

During the development of the pilot program SAPWAT, (replaced by the 1999 version of SAPWAT); Crosby (1996) made use of the estimated irrigation requirements of 712 climatic zones for specific crop coefficients, applied on equivalent A-pan evaporation, as calculated by Dent *et al*. (1988). Crosby (1996) converted the A-pan evaporation to short grass reference evaporation by adjusting the crop factor with a factor of $^5/_7$, derived from the Linacre equation (1977). This approach was recognized as being only of a temporary nature. It was generally believed that not enough data was available at that time to calculate the Penman-Monteith ET_0 values for a significant number of places in South Africa. This is the main reason why short grass reference evaporation had initially not been accepted in South Africa (Crosby and Crosby, 1999).

In the meantime, the FAO climate data set, CLIMWAT (Smith, 1993) was published and it contained monthly ET_0-data for several weather stations in South Africa. These stations were not necessarily situated in irrigation areas, but the monthly ET_0 values were compared to A-pan values. It was found that the ratio varied from month to month for the same station, as well as from one region to another. It was possible to derive reasonable values for ET_0 from these ratios, which made it possible to develop an extensive ET_0 network. Schulze (1997) refined this procedure further and ET_0 values were included in the "South African Atlas of Agrohydrology and -Climatology" (Crosby and Crosby, 1999).

Average monthly ET_0 values can be calculated directly for a station, provided maximum and minimum temperatures, relative humidity, wind and radiation data (which can be measured directly, or can be derived from hours of sunshine) are available. About 350 strategically situated weather stations with ten or more years of applicable data were identified. This eliminated the need to make use of indirect ET_0 data and monthly Penman-Monteith ET_0 values have been calculated for these stations using of the FAO recommended procedure. The availability of data over a reasonable time period allows for limited statistical output. An increasing number of automatic weather stations, with hourly and daily output, are now operational and it is possible to validate monthly values of conventional manual weather stations (Crosby and Crosby, 1999).

1.6.5 SAPWAT and crop factors

Smith (1994) strongly recommended that the four-stage FAO procedure (Figure 1-7) for the determination of crop coefficients be applied in SAPWAT to ensure a transparent and internationally comparable methodology. He acknowledged that the standard crop coefficients had to be adjusted to provide for the climatic conditions of regions, new cultivars, and deviations in planting density as well as for the full range of irrigation methods. One of the shortcomings of similar programmes was that they were designed in the days of long cycle flood and sprinkler irrigation and did not reflect techniques applied by developing farmers, such as wide spacing, short furrow, surface irrigation (Crosby and Crosby, 1999).

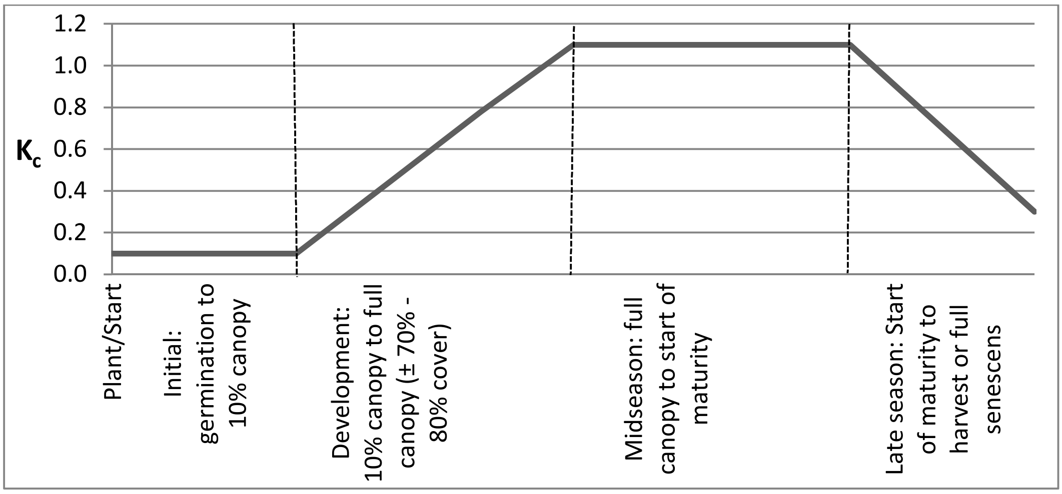


Figure 1-7 The FAO four stage crop growth curve as described by Allen *et al*. (1998)

Separate evaluation of soil evaporation and plant transpiration: The need for this was identified during the expert consultation (Smith, 1991), and a recommended methodology was published later (Allen *et al*, 1998). At about the same time a similar procedure was developed for SAPWAT, based on the work done by De Jager and Van Zyl (1989) and by Stroosnijder (1987). The SAPWAT procedure has the advantage that it is independent of soil texture (Crosby and Crosby, 1999).

If the soil evaporation and plant transpiration are considered, it becomes possible to manipulate the basic crop factors to provide for ground cover, wetted area, frequency of irrigation, cover crops, fruit trees, perennial crops, and different irrigation systems. SAPWAT was the first program to apply this possibility in a user-orientated crop irrigation program (Crosby and Crosby, 1999).

"Growing" crop coefficients: A lot of attention needed to be given to crop coefficient values, specifically mid-season values. There is a tendency to accept the default crop factor curve or table as a given physiological characteristic of a crop, even though these values might not be correct. Unrealistic or incorrectly applied crop coefficients are probably the main reasons for inaccurate estimates of irrigation requirements (Crosby and Crosby, 1999).

During the development of SAPWAT, specific attention was given to crop coefficients. The ideal would have been to let the crop grow, similar to growth models, so that stage length will react to planting date and climate. However, this is not possible in a program of this nature because of the comprehensive inputs required to simulate crop growth (Crosby and Crosby, 1999).

The solution was to subdivide South Africa into seven agro-climatic regions and to develop default crop coefficients for each of these regions. Default planting dates for each region and crop was also specified. Where planting date has a noticeable influence on growth stages, individual crop files were developed according to planting month per region. Where noticeable differences between cultivars (e.g. early or late) are found, each is handled as 'a separate crop' from the coding point of view. The crop coefficient file was developed according to "rules" derived with the help of crop scientists. Validation of these values takes place continuously and is based on practices in the field and on the experience of irrigation consultants. The default crop coefficient files provide for manipulations as discussed above (Crosby and Crosby, 1999).

SAPWAT contained about 100 individual crop files for each region and there are seven regions. Not all crops are grown in all the regions, but based on the tenet that crops are found in at least five regions, means that there are about 500 sets of default crop coefficients. This still does not cover the full need for the country, but the program allows the user to draw up one's own crop coefficient files for specific areas with the help of an editor (Crosby and Crosby, 1999).

1.6.6 ET_c, ET_0, effective rainfall and irrigation requirement

Monthly reference evaporation values for about 350 weather stations in RSA that were in use in 1999, have been calculated and are on file. The ET_c for each month was calculated by using FAO ET_0 and crop coefficients that were calculated by the program according to the parameters already discussed. Effective rainfall was calculated for every month by using of the Soil Conservation Service routine as described by Jensen *et al*. (1989). Subtracting the effective rainfall from evapotranspiration derived a monthly irrigation requirement (Crosby and Crosby, 1999).

As an aid to judgement, the monthly 20th percentile, median and 80th percentile evapotranspiration, effective rainfall and irrigation requirements were calculated. A similar calculation was done for the full season. This gave an indication of the situation of a favourable, normal and severe season (Crosby and Crosby, 1999).

1.6.7 Balance between a management and a planning aid

In a report Smith (1994) expresses the opinion that it is sometimes very difficult to differentiate between a planning and a management aid. To include all management options in a planning aid might make it too complicated for the user and a limit must be set somewhere. He makes the following recommendation (Crosby and Crosby, 1999):

- It is recommended that a careful evaluation be made of the different management options that must be standardized in a planning aid. The solution given in CROPWAT warrants possible further attention. A standard procedure for the calculation of irrigation requirement is based on the calculated crop water requirement and on effective rainfall only. In a separate water balance procedure, several management options are included, which indicate different irrigation (management) options.

SAPWAT was developed in accordance with these recommendations as a planning aid, whilst retaining compatibility with CROPWAT. However, field evaluations showed that the planning function is not complete if it was not integrated with management. It was possible to link SAPWAT to the CROPWAT management module and get good results. However, this linkage was awkward, and the user needs identified during field-testing of SAPWAT showed that the development of a management module for SAPWAT would be justified (Crosby and Crosby, 1999).

1.6.8 The application of SAPWAT in practice

During the course of the development and the field testing of SAPWAT, it became clear that the impact of the original objective, that is, updating and refining of the methodology for the estimation of crop irrigation requirements, was underestimated. The two most important aspects are the recognition of the Penman-Monteith based international standard for reference evapotranspiration in South Africa and the FAO four-stage crop coefficient methodology. For the first time there was the opportunity to develop crop irrigation requirement estimates on a countrywide scale, based on approaches which are both transparent and defendable. SAPWAT was an aid for this process (Crosby and Crosby, 1999). However, feedback by SAPWAT users indicated that irrigation requirement estimates were not always as good as expected. Cases of over or under-estimates were reported as well as growing periods that differed from the SAPWAT predictions. In a study done by Lazarra and Rana (2012) on the application of FAO 56 crop coefficient data, discrepancies of -20% for citrus ET_c grown in Morocco and +20% for apples ET_c grown in a cool, humid climate were found. The FAO 56 approach also gave underestimates of mustard evapotranspiration by 16.8% (Rohitashw *et al*., 2011). The implication is that crop irrigation requirements need to be verified and crop coefficients be adapted for a specific situation where required. By 2012, the crop characteristics of the following herbaceous crops had been extensively revised for use in AquaCrop (http://www.fao.org/nr/water/aquacrop.html): wheat (*Triticum spp.*), rice (*Oryza sativa*), maize (*Zea mays*), soybean (*Glycine max*), barley (*Hordeum vulgare*), sorghum (*Sorghum spp.*), cotton (*Gossypium spp.*), sunflower (*Helianthus annuus*), sugarcane (*Saccharum spp.*), potato (*Solanum tuberosum*), tomato (*Solanum lycopersicum*), sugar beet (*Beta vulgaris*), alfalfa (*Medicago sativa*), quinoa (*Chenopodium quinoa*), bambara groundnut (*Vigna subterranea*) and teff (*Eragrostis tef*) (Steduto *et al*., 2012). Therefore, this data could be used to update the SAPWAT crop characteristic files.

Three possible reasons for the problems observed by SAPWAT users exist:

- The wrong choice of climate regions by the user – as SAPWAT allows the user to select a climate region independently of weather station position;
- Incorrect crop coefficients and growth data included in the SAPWAT data tables; and,
- Selection of wrong weather station.

Possibly the most important shortcoming was that SAPWAT lacked facilities for saving and printing output data so that the calculation results had to be manually recorded. There were also no facilities for producing spread sheet type integration of monthly irrigation volume requirements that could be used to calculating field or farm monthly irrigation water requirements. This need was met by the program PLANWAT (Van Heerden, 2004) from which SAPWAT could be run and which then copied SAPWAT results to its data table for storage. The data stored in PLANWAT enabled the user to build an expected water requirement picture for fields, farms, water users associations and for drainage regions, as well as for backyard and community gardens. PLANWAT was addressing the need expressed by irrigation scheme designers for the integration of the crop and field level of calculation of water requirements, to a sum for each farm. Field irrigation requirement estimates were summed backward to also give estimated irrigation requirements for farms, for water user associations or for river drainage basins.

SAPWAT had practical shortcomings that required attention. It was a program in the process of development and consequently sections were programmed and reprogrammed in different versions of programming languages, which resulted in some instability. Crop growth and development was linked to South African geographic regions, which did not specifically link to climate regions. The boundaries of these regions are not necessarily based on identifiable topographic features and it was therefore difficult for the user to select the correct climate region.

As PLANWAT had a focus on water managers at an irrigation scheme level, it does not really help farmers. Therefore, the combination of SAPWAT and PLANWAT did not provide for interactively determining the best potential scenarios of irrigation water use coupled to gross crop margin to enable the farmer to select the best option for his circumstances. In discussions with clients this need has often been highlighted, as the amount of water needed is closely linked to the actual level of crop production of a specific field. PLANWAT also still only had limited data table export functionality. Requests were received for a more comprehensive export functionality of data tables that could be used as input data into other database programs and reports as well as to spreadsheets where the need for further calculation exists. The same was true to enable linkage of resultant data to GIS systems. A need was also identified for repetitive calculations of year on year irrigation requirements where differences in irrigation requirements due to annual weather variation can be used for risk assessment.

Informal feedback by SAPWAT users indicated the need for the integration of the programs SAPWAT and PLANWAT into a sensible unit. This upgrade could be a planning tool using irrigation requirements of crops as described by Allen *et al*. (1998) and incorporating the related economic scenarios. The developers aimed to make SAPWAT3.0 as interactive as possible so that by using the program, the users would develop a better understanding of the elements that are included in the irrigation requirement calculation and also develop a better understanding of the influence of each element. This would be in an effort to keep the "black box" effect found in some similar programs to a bare minimum so that the user could fully understand where the results come from.

SAPWAT3 is an irrigation-planning model that estimates irrigation requirements using published crop coefficients from the four-stage crop growth curve and the Penman-Monteith reference evapotranspiration (Van Heerden *et al*., 2008). Of the 104 main crops, and their 2 835 subgroups based on cultivar type, planting date and climate included in SAPWAT3, only the major crops grown under irrigation have had adequate research as far as K_c and/or K_{cb}[3] values are concerned (Doorenbos and Kassam, 1986). The SAPWAT3 development project team decided to follow a pragmatic approach, that is to include as many crops as possible, basing the crop growth and development characteristics on available data and to eventually update/improve crop coefficient data as better information became available. If K_{cb} values are correct for a specific crop, it would result in credible ET_c values for that crop. Despite there being little research on K_{cb} values for some crops grown under irrigation, one did not want to exclude them from SAPWAT3. Therefore, a routine was needed with which the correctness of K_{cb} values could be fairly easily verified, as long as the program was provided with reliable measured crop evapotranspiration data.

The users of FAO 56 K_c and K_{cb} values, and of SAPWAT3, are therefore warned about the acceptance of the default crop coefficients. Crop coefficients used in FAO 56 and applied by models such as SAPWAT3 need to be continuously verified; however, the verification means that research results need to be collected so that the relevant values can be changed. However, models such as CROPWAT and SAPWAT that uses the FAO four-stage crop growth curve do not have a routine that can use actual crop water use research data to adjust the K_c values. Such a routine needs to be able to compare K_c published values with those included in SAPWAT and suggest a scope and direction for adjustment.

A crop yield and irrigation water-planning model, AquaCrop, is available from FAO (http://www.fao.org/nr/water/aquacrop.html). Crops included are well researched and documented (Steduto *et al*., 2012) and the user has the choice of using either calendar time or thermal time for crop growth and development[4]. It has the added ability of not only estimating irrigation requirements, but also estimating biomass production (Raes *et al*., 2009;

[3] K_{cb} = basal crop coefficient. Crop coefficient K_c is split between the basal crop coefficient and a soil surface evaporation coefficient (K_e). The equation for crop evapotranspiration $ET_c = K_c.ET_0$ now becomes $ET_c = (K_{cb} + K_e).ET_0$.
[4] AquaCrop version 4.0, August 2012 (http://www.fao.org/nr/water/aquacrop.html).

Wikipedia, 2014c). Although total seasonal irrigation water required is shown, monthly requirements as needed by irrigation water managers and designers of irrigation systems are not immediately apparent.

1.7 Conclusions

The international and national picture clearly emerging is that limited water resources is a serious problem for countries in arid and semi-arid climates where irrigated agriculture is necessary to provide enough food for humans and animals. Water usage in these countries either currently exceeds, or will in the foreseeable future, exceed water resources. This problem can be managed by increasing the available resources by inter-basin transfers; desalinisation of seawater; and extraction from ground water reserves, provided that such steps do not exceed supply and are affordable for users. A first and probably cheaper option would be to improve the water use efficiency of all sectors of the economy and simultaneously reduce losses from water conveyance systems. Irrigation farming, as the largest water-using sector, can contribute significantly to water saving by improving its water management and planning efficiency.

The problem of potential and actual overuse of surface water resources could be alleviated or prevented with good irrigation water requirement planning. Irrigation requirement planning needs to be sensible, especially where surface water resources are over-utilised. Adaptations such as selection of hardy drought tolerant plant species or water saving irrigation water management strategies could be included. However where surface water resources are still adequate, good irrigation water management strategies could ensure the best possible use of existing surface water resources thus extending the time before water restrictions need to be introduced.

Salinity and water logging are perhaps the most visible result of poor irrigation practices. Its results can usually be seen by a lower crop production and/or quality of agricultural produce or even the loss of irrigation areas. Good irrigation crop water requirement planning can contribute to the alleviation of these problems by:

- Recommending the correct amount of water to be used for irrigation for a specific crop, in conjunction with soil water content measurements, for improved day-to-day management of irrigation water;

- Recommending the correct amount of irrigation water to be included in the water budget for leaching excessive salts out of the soil profile, or at least to below rooting depth; and
- Recommending a limit to the amount of irrigation water to be applied to a field to satisfy crop requirements plus leaching. Such a calculation would include the use of water rising by capillary action from existing water tables. This strategy would have the added advantage of reducing saline return flows from an irrigation area.

Irrigation water requirement planning in this situation would also include advice on the choice of crops that are more salt and drought tolerant as well as providing their irrigation water requirements through the season.

Irrigation farmers are first in line when water restrictions are imposed, and therefore are the first economic group to experience the effect of a drought. However, planning for water use during periods of water restrictions could alleviate this problem. Such planning would include the selection of crops and/or cultivars with a lower irrigation water requirement and irrigation strategies that could allow a degree of water stress even with an associated lower yield, while requiring substantially less water. A strategy like this can be associated with an increase in product quality and thus income, which could reduce the negative economic impact on farmers due to lower yields.

The potential impact of good water requirement planning is:

- A cheaper, and therefore preferable method of extending the time before more expensive options, such as inter-basin water transfers, need to be implemented to alleviate the effect of water shortages;
- Improvement of runoff water use in built-up areas by better planning of such water use in gardens and parks;
- Potentially reduction of waste water;
- Better use of limited water supplies from dams that have lost some of their capacity through siltation;
- Better water use planning and distribution between different sectors of the economy; and
- Reduce salinity and water logging problems and ensure a longer productive life of irrigation lands.

Over time approaches for the planning of irrigation water requirement have been developed. The first efforts were "rough and ready", but as time went by, these became more sophisticated. The use of evaporation pans, mainly the American Class A evaporation pan, linked to crop growth and development through crop factors, became widely used. In South Africa the best example of this application is probably the publication and use of the Green Book (Green, 1985) by the irrigation community. However, this approach was not without its inherent problems, the most common possibly being that it was not always locally calibrated before use, pans were not serviced as should be and placement of pans were not necessarily correct, which in turn resulted in incorrect irrigation requirement estimates. The next development was the Penman-Monteith approach (Allen *et al*., 1998), where calculated evapotranspiration from a defined grass surface was used as reference, and linked to crop growth and development through crop coefficients. This approach is similar to the Class A pan approach, with the major difference that the reference grass surface is self-calibrating. The Penman-Monteith approach is used in CROPWAT (Smith, 1992), a product of the FAO which is widely used for irrigation water requirement planning. With the development of the Penman-Monteith approach, which increased the accuracy of the reference evapotranspiration values, the hunt for accuracy of crop requirement estimates shifted to the accuracy of the crop coefficients linked to the FAO four-stage crop growth curve (Allen *et al*., 1998). Crop coefficients published by Allen *et al*. (1998) were based on well researched crop growth and development data, but in South Africa it was found that not enough differentiation was made for crops grown in different climates and, linked to this, for crops planted at different dates where temperature-crop relations shifted sideways. And therefore resulting in different growth characteristics. It was also found that the crop characteristics included in CROPWAT could not be easily adapted to local situations; therefore CROPWAT was adjudged as not being quite right for use in South Africa.

The next event in this sequence of development of irrigation water requirement planning approaches was the development of SAPWAT (Crosby and Crosby, 1999). Its design is based on that of CROPWAT, but provision was made for planting crops in different climates and at different planting dates and its output was based on data that the designers of irrigation system needed. Use of SAPWAT soon spread to more than 200 South African users because of its usefulness. Like its predecessors, it also had shortcomings, and in order to eliminate these, the next version, SAPWAT3 (Van Heerden *et al*., 2008) was developed. The development of SAPWAT3 and potential future improvements is the subject of this thesis.

The application of water use planning tools such as SAPWAT has been accepted by the irrigation community. Informal feedback was used as background in the upgrading of SAPWAT to SAPWAT3. However, no formal research had been done prior to 2010 to determine the reasons for the adoption of SAPWAT. Investigating methods used to assess the adoption of innovations could help give a scientific indication of the success of SAPWAT. It would also help to focus the upgrades of SAPWAT3 on specific aspects that enhance adoption and neutralise weak points that retard adoption, while making it more use-friendly.

1.8 Research questions

Seen overall, the world's available fresh water supplies are in short supply, even though there are countries that do not have a shortage of water, a large proportion of the developing world has such a shortage. If that water supply is not well looked after, the shortage could become unmanageable in the future. Irrigation water is seen as being at a lower priority level than water for human consumption and as the human population grows, pressure will be applied on irrigated agriculture to use less water. An obvious solution is that the irrigation farming community must aim to improve the efficiency of irrigation water use, which means that irrigation water use planning as well as real time management must be as effective as possible. This is over and above improvement to the water conveyance systems so that losses are minimised.

A range of approaches have been developed over time for the planning of crop irrigation water requirements. The best known of theses is the FAO's CROPWAT. The development of SAPWAT for the South African situation has been funded by the Water Research Commission and is locally perceived as an improvement on CROPWAT. However, SAPWAT, although generally accepted by the irrigation fraternity, does have some shortcomings and therein lays the question:

To what extent can SAPWAT be improved upon in order to eliminate at least some of the shortcomings and thus improve its functionality as an irrigation water requirement planning tool, and what made it acceptable in spite of its shortcomings?

This question can be broken down into the following:

1. Can a closer link between crop growth and development and the local climate be obtained and incorporated?
2. Can SAPWAT be rebuilt into a better tool that eliminates at least some of the shortcomings and at the same time be based on internationally accepted approaches?
3. Can the data management and calculation routines of SAPWAT be expanded and improved to the extent that risk levels can be determined through the use of consecutive year on year calculations of irrigation requirement?
4. Can crop coefficients be improved upon by including a routine that calculates crop coefficients based on measured water use?
5. What were the reasons for SAPWAT being evidently accepted within theirrigation community?

1.9 Objectives

An overall objective for this study is:

To improve the functionality of SAPWAT as an irrigation planning tool, to evaluate and to verify its output and to test its potential for adoption by users.

This overall objective can be broken down into the following specific objectives:

1. To link the SAPWAT crop coefficients that reflects growth and development to the internationally accepted Köppen climate system (chapter 2).

2. To build the decision support tool SAPWAT3 based on the split K_c (for transpiration and soil surface evaporation) approach as described in FAO 56 (chapter 3).

3. To include risk estimates of crop irrigation water requirements based on monthly means and standard deviations as well as medians and probabilities of non-exceedance (chapter 3)

4. To develop methodology to allow adjustment of crop coefficients and length of growth stages using existing crop water use field measurements (chapter 4)

5. To evaluate the adoption of SAPWAT by users (chapter 5).

CHAPTER 2.
LINKING CROP GROWTH AND DEVELOPMENT TO CLIMATE

2.1 Introduction

Equation Chapter (Next) Section 1Equation Chapter (Next) Section 1The crop coefficient (K_c), which is closely related to crop growth and development, provides a linkage between crop evapotranspiration (ET) and the reference evapotranspiration (ET_0) through a growing season. This linkage can be used to estimate crop irrigation requirements. This K_c formulation uses the FAO four-stage crop growth curve (Figure 2-1) described by Allen *et al*. (1998). This simplified way of depicting a crop's growth curve versus time and its influence on crop evapotranspiration (ET_c), has the advantage of approximating fairly easily on the basis of information received from farmers, researchers and research technicians. Guidelines based mainly on crop height and ground cover, exist for the level at which the mid-season K_c line (Figure 2-1) can be drawn parallel to the x-axis. Similarly, guidelines exist for the drawing of the initial growth stage line. What is required from crop growth observations, are the turning points, indicated in days after planting, for the changeover from the initial to the development growth stage; between the end of the development phase and the start of mid-season growth stage; and from the mid-season growth stage to the late season growth stage.

The three steps in the construction of the K_c curve (Figure 2-1) are described by Allen *et al*. (1998) as follows:

1. Divide the growing period into four general growth stages that describe crop phenology or development (initial, crop development, mid-season, and late season stage), determine the lengths of the growth stages, and identify the three K_c values that correspond to $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ from a K_c table (Table 12 in Allen *et al*., 1998).

2. Adjust the K_c values for the frequency of wetting and/or climatic conditions of the growth stages as outlined in chapter 6 of Allen *et al*. (1998).

3. Construct a curve by connecting straight line segments through each of the four growth stages. Horizontal lines are drawn through $K_{c\ ini}$ in the initial stage and through $K_{c\ mid}$ in the mid-season stage. Diagonal lines are drawn from $K_{c\ ini}$ to $K_{c\ mid}$ within the

course of the crop development stage and from $K_{c\ mid}$ to $K_{c\ end}$ within the course of the late season stage.

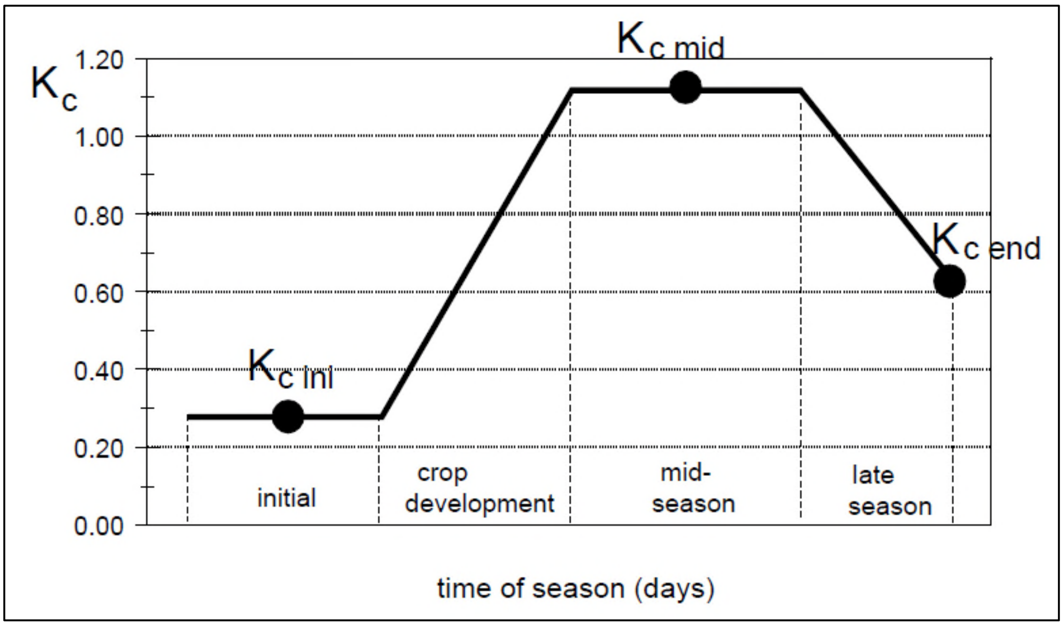


Figure 2-1 Construction of the Kc four-stage growth curve (Allen et al., 1998)

These growth periods and their turning points are defined by Allen *et al.* (1998) as:

- "Initial growth stage: From planting date to approximately 10% ground cover."
- "Crop development stage: From approximately 10% cover to effective full cover, interpreted to be at 70% to 80% ground cover for most crops."
- "Mid-season stage: From effective full cover to the start of maturity, usually indicated by the beginning of yellowing of leaves."
- "Late season stage: From the start of maturity to harvest or full senescence."

The length of the total growing period is genetically determined for a crop, but climate and weather also play a role in lengthening or shortening the growing period at a specific location (Sacks and Kucharik, 2011). Within the boundaries set by the crop's genetics and the temperatures at which optimal growth takes place, there is a general tendency that a crop will grow and develop faster at higher temperatures. The similar influence that temperature has on the whole length of the growing period of a crop, is also found for the different growth stages, i.e. higher temperatures will increase the rate of growth and development, and thus shorten the length of the period, while lower temperatures will retard it (McMahon *et al.*, 2002). It is necessary to make an accurate estimate of the length of each growth phase period

(Figure 2-1) in order to apply the FAO four-stage growth curve to estimate crop irrigation requirements.

Water loss from any vegetated surface to the atmosphere is determined by both environmental and plant factors. The environmental effect on evapotranspiration is called atmospheric or evaporative demand (De Jager and Van Zyl, 1989), and it forms the background to irrigation water requirement planning. The greater this demand, the higher evapotranspiration will be. Atmospheric demand is influenced by (Gardner *et al*., 1985):

- Solar radiation: Up to 5% of solar radiation absorbed by the leaf is used for photosynthesis and 75% to 80% is used to heat the leaf. At a higher temperature there is more energy available to be used as latent heat to evaporate water from the leaf surface. Solar radiation heats the leaf and this energy is then available to be used to evaporate water in the sub-stomatal cavity, therefore the transpiration rate increases. Increased solar radiation also increases atmospheric demand by increasing the air temperature, which in turn lowers the relative humidity of the surrounding air.

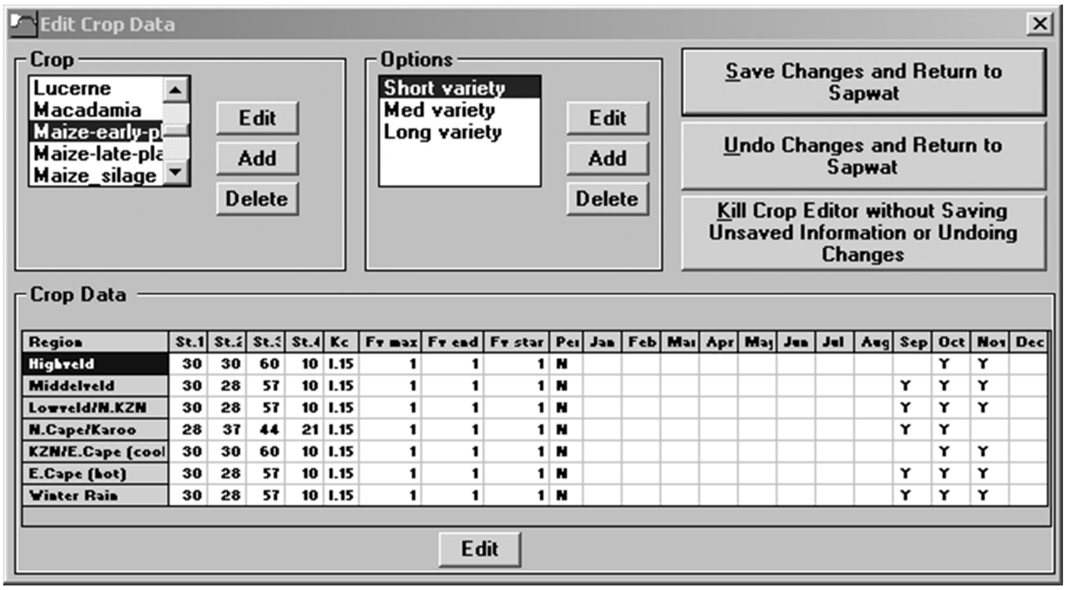
- Temperature: At higher temperatures, the air can hold more water as the saturated vapour pressure curve is curvilinear. At a higher temperature, there is also more energy available for latent heat of vaporisation.

- Relative humidity: The greater the water content of the air, the higher the water vapour pressure of the air and therefore the lower the atmospheric demand. High levels of relative humidity mean lower atmospheric demand while low levels of relative humidity have the opposite effect; it increases atmospheric demand, as there is a larger difference between the ambient humidity and saturated air as a driving force.

- Wind: Transpiration occurs when water diffuses through the stomata to the air surrounding the leaf because of a diffusion gradient that develops at the leaf surface. In wind-still situations, the diffusion gradient is reduced and transpiration slows down. Under windy conditions, the diffusion gradient is maintained high because saturated air immediately adjoining the leaf is removed, and transpiration can continue at a higher rate. The drier the wind, the higher the diffusion gradient will be and the more transpiration can take place.

The estimator of irrigation water requirements is faced with the problem that there is a general tendency to use regional names when referring to areas where crops are grown. These names do not necessarily indicate climate which could in turn be a determinant of crop irrigation requirements. Examples in South Africa are the use of, or references to, areas such as Lowveld, Highveld, Karoo, Eastern Free State and North Cape (Agricultural Research Council - Small Grain Institute, 2010; Mayford-Sakata seed, 2014; Pannar Seed, 2013; Reader's Digest, 1984b). A similar approach was used by Green (1985); in his memoire on irrigation requirements of crops with the agro-geographic regions (e.g. Karoo Region, Natal Region, and Winter Rainfall Region) used by the then Department of Agriculture and Water Supply as a basis. These agro-geographic regions were further subdivided into a combination of geographic regions (e.g. Highveld, Middleveld, and Lowveld) for purposes of crop growth and development. However, a somewhat closer linkage was created by linking irrigation requirement to specific localities such as towns and irrigation areas. On the international side, CROPWAT (Smith, 1992) and FAO 56 (Allen *et al.,* 1998) similarly use geographic regions to link crop growth and development for purposes of estimating irrigation water requirements. These references tend to be very wide in some cases, such as arid climate, East Africa, Spain or Nigeria for maize, Mediterranean for winter wheat and high or low latitudes for grapes. The user is expected to adapt these large area crop characteristics to their own area under investigation, an expected skill that might not be part of the user's training or experiential background (Van Heerden and Crosby, 2011).

SAPWAT tried to overcome this problem by including in its tables the K_c values and changes in values as influenced by different climates and planting times by linking crops to geographic regions with climatic implications (Figure 2-2) (Crosby and Crosby, 1999). The differences in growing periods shown in Figure 2-2 were based on the crop data tables contained in FAO 56 (Allen *et al*., 1998), adapted for the South African situation from information gleaned from seed catalogues, researchers, research technicians and farmers (Crosby and Crosby, 1999). Although not necessarily correct for newer cultivars, the more climatically based crop growth characteristic data made a large improvement in the previous values indicated for a wider, less well defined geographical region. The user of SAPWAT was expected to select the climatic region relevant to his area of interest, irrespective of whether the climate he selected is relevant to the selected weather station. However, soon after its publication, it became apparent that a noticeable number of SAPWAT users could not differentiate between the different geographic regions, especially in areas where there were no clearly defined geographic boundaries, such as an escarpment. Incorrect irrigation estimates could be the result of an incorrectly selected geographic area. However, this problem could be alleviated if the climate of the area the user is interested in could be automatically selected when a weather station is selected.



Region	St.1	St.2	St.3	St.4	Kc	Fv max	Fv end	Fv star	Pe	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Highveld	30	30	60	10	1.15	1	1	1	N										Y	Y	
Middelveld	30	28	57	10	1.15	1	1	1	N									Y	Y	Y	
Lowveld/N.KZN	30	28	57	10	1.15	1	1	1	N									Y	Y	Y	
N.Cape/Karoo	28	37	44	21	1.15	1	1	1	N									Y	Y		
KZN/E.Cape (cool	30	30	60	10	1.15	1	1	1	N										Y	Y	
E.Cape (hot)	30	28	57	10	1.15	1	1	1	N									Y	Y	Y	
Winter Rain	30	28	57	10	1.15	1	1	1	N									Y	Y	Y	

Figure 2-2 A screen shot of the SAPWAT crop editor screen form. SAPWAT growth stages for different geographic (by implication: climatic areas) regions in South Africa (shown in left-hand-side list) for short variety of maize planted in spring (Crosby and Crosby, 1999)

2.2 Objectives

The objective of this chapter is:

1. To find a suitable climate definition approach to be used in the upgraded SAPWAT3;
2. To describe the process of building the SAPWAT3 crop data tables;
3. To show the soundness of distinguishing between climate regions by comparing SAPWAT3 crop data to published crop data; and
4. To make a comparison of crop growth periods using a climate region approach versus growth periods based on thermal time for SAPWAT3 crop data.

2.3 Theoretical background

Against the background of the problem described above, the solution would be:

- To find a climate classification or zoning system suitable for use in SAPWAT3; and
- To link crop growth and development to climate.

2.3.1 Selection of a climate system suitable for SAPWAT3

SAPWAT3 uses weather data to calculate reference evapotranspiration, ET_0. Daily or monthly weather elements used are: maximum and minimum temperature, average or minimum humidity, average wind speed, net radiation or sunshine hours from which net radiation is calculated. Rainfall is also linked to these elements, because rainfall is included in the soil water balance equation as one of the variables that supplies water to the budget (Allen *et al.*, 1998). The ideal would be to find a climate classification system that uses at least some of these weather elements as part of its system, because then a weather station could be directly linked to a climate type. Furthermore, if such a climate system could be identified, crop growth and development could be linked to different climates for the application of the FAO four-stage crop growth curve (Allen *et al.*, 1998) for eventual use in SAPWAT3.

Generic and empirical approaches to describing climate have been investigated. While the generic classifications, such as air mass approaches are used to describe climate (Taylor, 2002), it was judged that such systems were too indeterminate to use for irrigation requirement estimation. An empirical classification approach, such as the Köppen system, uses weather parameters to classify climates (Encyclopædia Britannica, 2010). This system was developed in 1918 by Wladimir Köppen, a German botanist-climatologist. He defined climate boundaries in such a way that they coincided with vegetation zones. This classification is based on a subdivision of terrestrial climates into five major types, which are represented by the capital letters A, B, C, D and E (Figure 2-3). Each of the climate types, with the exception of B, is defined by temperature criteria. B climate types are dry types, where aridity is the controlling factor on vegetation. Aridity is defined by a precipitation-evaporation balance. In dry climates evaporation exceeds precipitation on the average throughout the year. Dry climates are divided into arid (BW) and semi-arid (BS) subtypes (Encyclopædia Britannica, 2010). Tropical rainy climates are indicated by the letter A; C are mild, humid (mesothermal) climates; D are snowy forest (microthermal) climates and E are polar climates (Strahler and Strahler, 2002). Over time, the Köppen climate system has undergone some revisions, the Köppen-Geiger revision is used in SAPWAT3. The world map of the Köppen-Geiger climate system is shown in Figure 2-3, while the South African map is shown in Figure 2-4. A description of the major climate regions and their sub-regions as used in the Köppen-Geiger climate system are defined in Table 2-1.

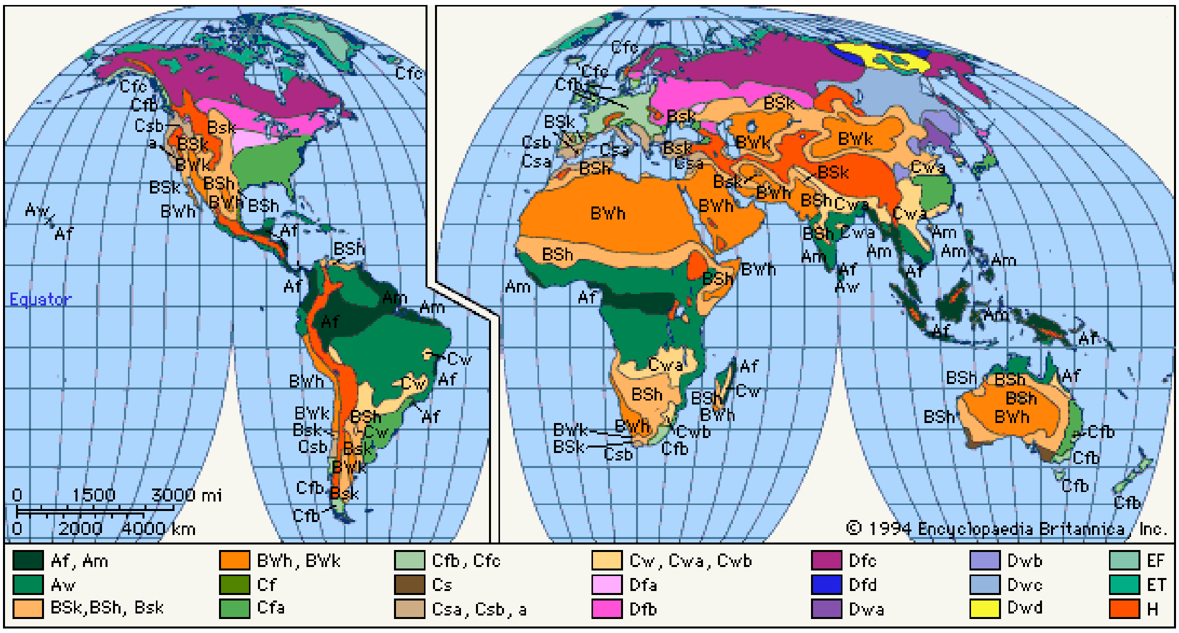


Figure 2-3 Köppen-Geiger climate map of the world (Encyclopaedia Britannica, 2010)

Table 2-1 The Köppen-Geiger climate system: Key to the map codes for Figure 2-3 and Figure 2-4 (Strahler and Strahler, 2002)

Code	Name	Description
First letter		
A, C, D		Sufficient heat and precipitation for growth of high-trunked trees
A	Tropical rainy climates	All months mean temperature over 18˚C
B	Dry Climates	Boundaries determined by equation using mean annual temperature and mean annual precipitation
C	Mild, humid climates	Mean temperature of coldest month: 18˚C down to –3˚C
D	Snowy-forest climates	Warmest month mean over 10˚C, coldest month mean under -3˚C
E	Polar climates	Warmest month mean under 10˚C
Second letter		
S	Semi-arid (steppe)	Boundaries determined by equation
W	Arid (desert)	
f		Sufficient precipitation in all months
m		Rainforest despite a dry season (i.e. monsoon cycle)
s		Dry season in summer in the respective hemisphere
w		Dry season in winter in the respective hemisphere
Third letter		
a		Warmest month mean temperature over 22˚C
b		Warmest month mean under 22˚C. At least four months have mean over 10˚C
c		Fewer than four months have a mean temperature over 10˚C
d		Same as c, but coldest month mean temperature under –38˚C
h		Dry and hot. Mean annual temperature over 18˚C: B climates only
k		Dry and cold. Mean annual temperature under 18˚C: B climates only
H		Highland climates

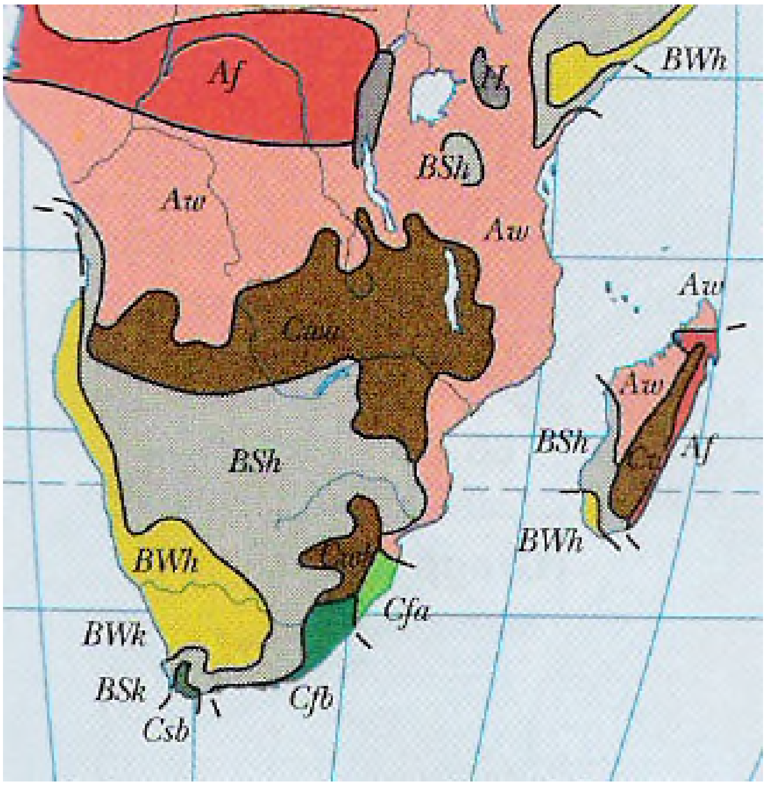


Figure 2-4 Köppen-Geiger climate map of Southern Africa (Strahler and Strahler, 2002)

The determination of boundaries between wetter and drier areas in Table 2-1 is based on equations that have the general format of (Strahler and Strahler, 2002):

$$P_{benchmark} = k_1(C + k_2) \qquad \text{Equation Section (Next)(2.1)}$$

where	$P_{benchmark}$	benchmark annual precipitation (cm), based on the calculation of C, k_1 and k_2
	C	average annual temperature (°C)
	k_1, k_2	constants: refer to Table 2-2 for values

If the actual precipitation measured at a locality is higher than the benchmark precipitation, the locality is situated in the wetter area; otherwise the locality is situated in the drier area. The values for the constants k_1 and k_2 are shown in Table 2-2:

Table 2-2 Values to be used for the constants k_1 and k_2 in Equation (2.1) (Strahler and Strahler, 2002)

Rainy season	**Boundary between wet and non-dry climates**		**Boundary between steppe and desert climates**	
	k_1	**k_2**	**k_1**	**k_2**
Precipitation distributed evenly during the year	2	7	1	7
Precipitation concentrated in summer	2	14	1	14
Precipitation concentrated in winter	2	0	1	0

These relationships can be easily applied to weather datasets to determine where the climate of a specific station should be classified. For application, the rainfall season of the weather station area is determined and the correct equation is then applied to determine the benchmark annual precipitation value that will be the boundary between dry and non-dry climates, as well as between steppe and desert climates.

2.3.2 Linking crop growth and development to climate

The rate of development of crops from planting to maturity is mainly dependent upon temperature (Parthasarathi *et al.*, 2013) within the scope of a genetically determined growing period (Sacks and Kucharik, 2011), and provided that extreme conditions such as unseasonal drought or disease do not occur (McMahon *et al.*, 2002). The heat driven rate of growth and development can be overridden by photoperiodism, vernalization (Kamran and Spaner, 2014), and earliness *per se* – under genetic influence regardless of environment (Košner and Žůrková, 1996). Therefore, these need to be considered when interpreting heat driven growth and development. Cool temperatures slow down and prolong the progress to maturity and warmer temperatures hasten maturity (Hardacre and Turnbull, 1986; Pessarakli, 2001). However, plant growth ceases when temperatures drop below a certain minimum or exceed a certain maximum. In between, an optimum temperature is found at which optimal growth takes place (Pessarakli, 2001). These three temperatures, also known as the cardinal temperatures, are known for most cultivated crops, although it seems to be common practice to use 10°C as a minimum cardinal temperature for the summer growing crops in calculations of thermal time (Miller *et al*., 2001). Minimum cardinal temperature is also referred to as base temperature (T_b). Thus, if the mean daily temperature for a particular day is 16°C, then 6 degree days are accumulated for that day on the Celsius scale (Miller *et al*., 2001). Budong *et al*. (2010) published three sets of cardinal temperatures for warm season, cool season and overwintering crop groups that can be used as general guideline (Table 2-3).

Table 2-3 Field crop types and their growing season cardinal temperatures for crops commonly grown in Canada (adapted from Budong *et al*., 2010)

Type of crop	**T_b (°C)**	**T_{opt} (°C)**	**$T_{cardinal\ max}$ (°C)**
Cool season crops (e.g. wheat, barley, canola, rye, oats, peas, potatoes)	5	25	30
Warm season crops (e.g. maize, soybeans, sweet potatoes)	10	30	35
Overwintering crops (e.g. biennial or perennial herbaceous and woody crops)	5	25	35

The cardinal temperatures need not be the same for different varieties of a crop, or for different crop growing stages. Furthermore, the cardinal minimum temperature can be different for a crop, depending on the thermal time calculation approach, e.g. when maize thermal time is calculated as described by Craufurd and Wheeler (2009), cardinal minimum or base temperatures are indicated as 6.6°C, or 8.2°C for the Ontario heat unit system (Eason and Fearnehough, 2003) or 8 to 10°C (Parthasarathi *et al*., 2013). The South African approach seems to use 10°C as base temperature for maize (Agricol, 2015, Monsanto, 2013, Pannar, 2013). Salazar-Gutierrez *et al*. (2013) found different estimated base temperatures for eight wheat cultivars which ranged from 3.1°C to 8.1°C for planting to heading and 10.6°C to 18.4°C for heading to maturity and/or harvest, an indication that base temperature is cultivar specific and that it is not a constant through the growing season of the crop. The implication is that the base temperature used should be stated when heat unit requirement of a crop is shown.

Temperature ranges for germination of crops show a similar pattern to that for mature crop growth and development: there is a minimum temperature below which seeds will not germinate, an optimum temperature at which germination will take place and a maximum temperature above which germination ceases. These also differ between different plant species (Table 2-4). The optimum temperature is the temperature at which the highest percentage of germination takes place in the shortest time (Pessarakli, 2001).

Table 2-4 Temperature ranges required for germination of different seeds (Pessarakli, 2001)

Crop	Cardinal Temperature Ranges (ºC air temperature)		
	Minimum	Optimum	Maximum
Maize	8 – 10	32 – 35	40 – 44
Rice	10 – 12	30 – 37	40 – 42
Wheat	3 – 5	15 – 31	30 – 43
Barley	3 – 5	19 – 27	30 – 40
Tobacco	10	24	30

The development rate from emergence to maturity for many plants depends upon the daily air temperature, provided that other environmental factors, such as soil water shortage, soil salinity or disease, do not stress the plant. It is possible to predict when developmental events of plants (and insects) should occur during a growing season, because these events are based on the accumulation of specific quantities of heat. Growing degree days (GDD or DD), also referred to as crop heat units (CHU) or heat units (HU) or thermal time (TT) is defined as the accumulation of the number of temperature degrees above a certain threshold base temperature, which is in turn linked to a crop (Equation 2.2) (Parthasarathi *et al*., 2013).

$$CHU=\sum_{n=1}^{365}\left[\left(\frac{\left(T_{max}+T_{min}\right)}{2}-T_b\right)\Delta t\right] \tag{2.2}$$

Where CHU crop heat units (˚C.d)
T_{max} maximum daily temperature ˚C)
T_{min} minimum daily temperature (˚C)
T_b threshold temperature of crop (˚C)
Δt time interval (day)

The base temperature is that air temperature below which plant growth is zero. CHU is calculated each day as the mean temperature minus the base temperature. CHU is accumulated by adding each day's CHU contribution as the season progresses (Parthasarathi *et al*., 2013). Crop heat units (CHU) measured in degree-days (˚C.d) provides a means of expressing the influence of temperature on crop growth and development (Parthasarathi *et al*., 2013). This concept holds that the growth of a plant is dependent on the total amount of heat to which it is subjected during its lifetime, accumulated as degree-days (Gardner *et al*., 1985). Table 2-5, shows the CHU values from planting to a specific growing stage of some crops (Miller *et al*., 2001; Parthasarathi *et al*., 2013). Care needs to be taken in interpreting these results, as for example with maize, differences in growth stage description are also found, such as reference to 50% silking (Lee, 2011; Miller *et al*., 2001; Parthasarathi *et al*., 2013) or 50% tassel (Monsanto, 2013; Pannar, 2013) by different authors and seed companies.

Table 2-5 Phenology and related heat units for some crops (Miller *et al*., 2001; Parthasarathi *et al*., 2013)

Stage	Description	Growth stage	CHU (°C.d)
BARLEY (Miller *et al*., 2001)			
Emergence	Leaf tip just emerging from above-ground coleoptile	1.0	109-145
Leaf development	Two leaves unfolded	1.2	145-184
Tillering	First tiller visible	2.1	308-360
Stem elongation	First node detectable	3.1	489-555
Anthesis	Flowering commences; first anthers of cereals are visible	6.1	738-936
Seed fill	Seed fill begins. Caryopsis of cereals watery ripe (first grains have reached half of their final size)	7.1	927-1145
Dough stage	Soft dough stage, grain contents soft but dry, fingernail impression does not hold	8.5	1193-1438
Maturity complete	Grain is fully mature and dry down begins. Ready for harvest when dry	8.9	1269-1522
WHEAT (Hard Red) (Miller *et al*., 2001)			
Emergence	Leaf tip just emerging from above-ground coleoptile	1.0	125-160
Leaf development	Two leaves unfolded	1.1	169-208
Tillering	First tiller visible (tillering of cereals may occur as early as stage 1.3, in this case continues with 2.1)	2.1	369-421
Stem elongation	First node detectable	3.1	592-659
Anthesis	Flowering commences; first anthers of cereals re visible	6.1	807-901
Seed fill	Seed fill begins. Caryopsis of cereals watery ripe (first grains have reached half of their final size)	7.1	1068-1174
Dough stage	Soft dough stage, grain contents soft but dry, fingernail impression does not hold	8.5	1434-1556
Maturity complete	Grain is fully mature and dry down begins. Ready for harvest when dry	8.9	1538-1665
OAT (Miller *et al*., 2001)			
Anthesis	Flowering commences; first anthers are visible	6.1	760-947
Seed fill	Seed fill begins. Caryopsis of cereals watery ripe (first grains have reached half of their final size)	7.1	1019-1229
Dough stage	Soft dough stage, grain contents soft but dry, fingernail impression does not hold	8.5	1380-1625
Maturity complete	Grain is fully mature and dry down begins. Ready for harvest when dry	8.9	1483-1738
FLAX (Miller *et al*., 2001)			
Emergence	Cotyledons completely unfolded	1.0	104-154
Leaf stages	First pair of true leaves unfolded	1.2	150-208
	Four true leaves unfolded	1.4	197-26z2
	Six true leaves unfolded	1.6	243-315
Flowering	Flowering begins. First flowers open on at least 50% of plants. Stage flax early in morning before flower petals fall off	6.0	582-706
Flowering	50% complete	6.5	758-895
Seed fill	Seed fill begins. 10% of seeds have reached final size	7.1	969-1121
Maturity	Seed begins to mature. 10% of seed has changed colour	8.1	1321-1499
Maturity complete	90% seed colour change. Seeds brown and rattle in capsules. Ready for swathing or wait until dry down complete for direct harvesting	8.9	1603-1801

Stage	Description	Growth stage	CHU (°C.d)
LENTIL (Miller *et al*., 2001)			
Leaf Stages	Two leaves unfolded	1.2	161-192
	Four leaves unfolded	1.4	248-285
	Six leaves unfolded	1.6	335-378
	Eight leaves unfolded	1.8	423-471
Flowering	Flowering begins. At least one open floret on 50% or more plants	6.0	762-853
	Flowering 50% complete	6.5	931-1030
Seed fill	Seed fill begins. 10% of seeds have reached final size	7.1	1133-1241
Maturity	Seed begins to mature. 10% of seed has changed colour	8.1	1470-1594
Swathing	70% of seed changed colour. Recommended stage for swathing	8.7	1673-1806
Maturity complete	90% of seed changed colour. Await completion of dry down for direct harvesting	8.9	1740-1876
PEA (Miller *et al*., 2001)			
Leaf Stages	Two leaves unfolded.	1.2	198-230
	Four leaves unfolded	1.4	301-340
	Six leaves unfolded	1.6	404-449
	Eight leaves unfolded.	1.8	507-558
Flowering	Flowering begins. At least one open floret on 50% or more plants	6.0	724-835
	Flowering 50% complete	6.5	862-982
Seed fill	Seed fill begins. 10% of seeds have reached final size	81	1028-1158
Maturity	Seed begins to mature. 10% of seed has changed colour	8.1	1305-1451
Maturity complete	90% of seed changed colour. Await completion of dry down for direct harvesting	8.9	1527-1686
SUNFLOWER (Early maturing, dwarf hybrid) **(**Miller *et al*., 2001)			
Emergence	Cotyledons completely unfolded	1.0	138-191
Leaf Stages	Two leaves unfolded	1.2	249-313
	Four leaves unfolded	1.4	359-435
	Six leaves unfolded	1.6	470-558
Flowering	Flowering begins. At least one open disc floret on 50% or more plants	6.0	935-1077
	Flowering 50% complete	6.5	1081-1232
Seed fill	Seed fill begins. 10% of seeds have reached final size	7.1	1255-1417
Maturity	Seed begins to mature. 10% of seed has changed colour	8.1	1547-1725
Maturity complete	90% of seed changed colour. Await completion of dry down for direct harvesting	8.9	1780-1972
MAIZE (Parthasarathi *et al*., 2013) (variety not specified by author)			
	Emergence	na	0
	2 leaves fully emerged	na	86
	4 leaves fully emerged	na	160
	6 leaves fully emerged	na	232
	8 leaves fully emerged	na	306
	10 leaves fully emerged	na	379
	12 leaves fully emerged	na	452
	14 leaves fully emerged	na	525
	16 leaves fully emerged	na	598
	Silking / Anthesis / Boot leaf	na	744
	Kernel in blister stage/half bloom	na	891
	Kernel in dough stage	na	1037
	Kernel begins to dent	na	1183
	Kernel fully dented	na	1329
	Physiological maturity	na	1475

2.4 Methodology

Köppen-Geiger climates that occur in southern Africa are variations of A, B and C, (Strahler and Strahler, 2002) and therefore crop growth data included in SAPWAT3 needs to be linked to these. Crop data has not been included in SAPWAT3 for climates D and E, although the place for it to be added is included. This is mainly because climates D and E are not found in South Africa. Furthermore the crop growth characteristics included in FAO 56, the basis of SAPWAT3, seems to refer to the warmer climates. Therefore, the applicability and correctness of the crop growth data included in SAPWAT3 need to be verified for the colder climates.

2.4.1 Adapting crop growth characteristics to climate regions in SAPWAT3

A comparison of the Köppen-Geiger climate system and the South African geographic regions that imply climate (Table 2-6), shows why it was necessary to change the climate reference approach for use in SAPWAT3. With the exception of small areas in Lowveld / Northern KwaZulu-Natal (KZN), which conform to a tropical climate, all other geographic regions contain more than one Köppen-Geiger climate region, for example Winter rainfall region encompasses climates BSh, BWh, BSk, BWk, Cfb, Csb, and Cwb. The overlap of geographic regions with the Köppen-Geiger climates makes the linkage between crop growth and development characteristics to a geographic region difficult. Wrong interpretations regarding climate could lead to errors in estimating irrigation water requirements.

Table 2-6 Comparison of South African geographic regional climate areas with the Köppen-Geiger climate system showing overlap

Köppen-Geiger climate codes	Annual T_{avg} (°C)	Hottest month T_{avg} (°C)	Coldest month T_{avg} (°C)	Months with T_{avg}> 10°C	South African geographic regions used in SAPWAT3
Aw			>18	12	Lowveld / N.KZN
BSh, BWh	>18			>4	N. Cape / Karoo, Middelveld, Winter Rainfall
BSk, BWk	=<18			>4	N. Cape / Karoo, Winter Rainfall
Cfa, Csa, Cwa		>22	>-3	>4	Lowveld / N.KZN, Middelveld
Cfb, Csb, Cwb		≤22	>-3	>4	Highveld, KZN / E. Cape (cool), E. Cape (hot), Winter Rainfall

The Köppen-Geiger climate at a weather station can be determined because the Köppen-Geiger climate system is based on long-term mean temperature-rainfall combinations, information usually included in a climate dataset (Encyclopædia Britannica, 2010; Strahler and Strahler, 2002). This fits into the SAPWAT3 concept, where weather station data is used as a basis for estimating crop water requirements. One adaptation was made to the Köppen-

Geiger climate codes, namely that the second letter of the three-letter climate code, which indicates rainfall seasonality, is not used because rainfall seasonality is neutralised by irrigation scheduling. The result, for inclusion in the SAPWAT3 climate data table is shown in Table 2-7 (Van Heerden *et al*., 2008). A climate classification was done for all the 3 053 worldwide CLIMWAT weather stations (Smith, 1993) and for the 1 925 virtual South African quaternary catchment hydro-climatic data points (Schulze and Maharaj, 2006) included in SAPWAT3 (Table 2-7, Figure 2-5).

Table 2-7 Table showing the adaptation of the Köppen-Geiger climate system for SAPWAT3 (Van Heerden *et al*., 2008)

Köppen-Geiger climate codes	SAPWAT3 data table codes	Annual T_{avg} (°C)	Hottest month T_{avg} (°C)	Coldest month T_{avg} (°C)	Months with T_{avg}> 10°C	Climate name used in SAPWAT3
Af, Am, Aw	A_			>18	12	Tropical
BSh, BWh	B_h	>18			>4	Dry, hot
BSk, BWk	B_k	≤18			>4	Dry, cold
Cfa, Csa, Cwa	C_a		>22	>-3	>4	Mild, humid, hot summers
Cfb, Csb, Cwb	C_b		≤22	>-3	>4	Mild, humid, warm summers
Cfc, Csc, Cwc	C_c		≤22	>-3	≤4	Mild, humid, cool summers
Dfa, Dsa, Dwa	D_a		>22	≤-3, >-38	>4	Snow, hot summers
Dfb, Dsb, Dwb	D_b		≤22	≤-3, >-38	>4	Snow, warm summers
Dfc, Dsc, Dwc	D_c		≤22	≤-3, >-38	≤4	Snow, cool summers
Dfd, Dsd, Dwd	D_d		≤22	≤-38	≤4	Snow, very cold winters
ET, EF	E_		≤10		≤4	Polar

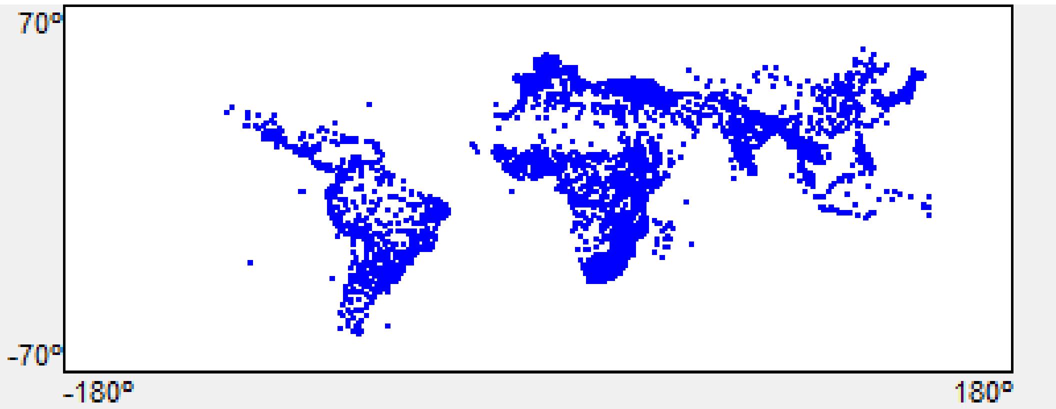


Figure 2-5 Distribution of weather stations included in SAPWAT3 (Smith, 1993; Schulze and Maharaj, 2006)

Selecting a weather station automatically selects the linked climate. The user will see the climate name as shown in the column "Climate names used in SAPWAT3" in Table 2-7. The definitions of the different climates can be seen in Table 2-1 and are available in the Climate data table that is included in SAPWAT3 (Van Heerden *et al*., 2008).

Figure 2-6 shows the application of the Köppen-Geiger climate system (Strahler and Strahler, 2002) in the crop data table of SAPWAT3. The total growing period for short grower maize planted in spring varies from 120 days for the warmer climate regions to 130 days for the cooler climate regions. Comparing the data content of the crop data table between SAPWAT3 (Figure 2-6) and SAPWAT (Figure 2-2) shows that the number of climatic regions have been reduced from seven to five. Furthermore, these five climate regions would be valid for most of the land area of the world between approximately 40°N and 40°S, and it is therefore a better system to use than the South African geographical regions which cannot be generally extrapolated beyond the borders of South Africa (Van Heerden *et al*., 2008).

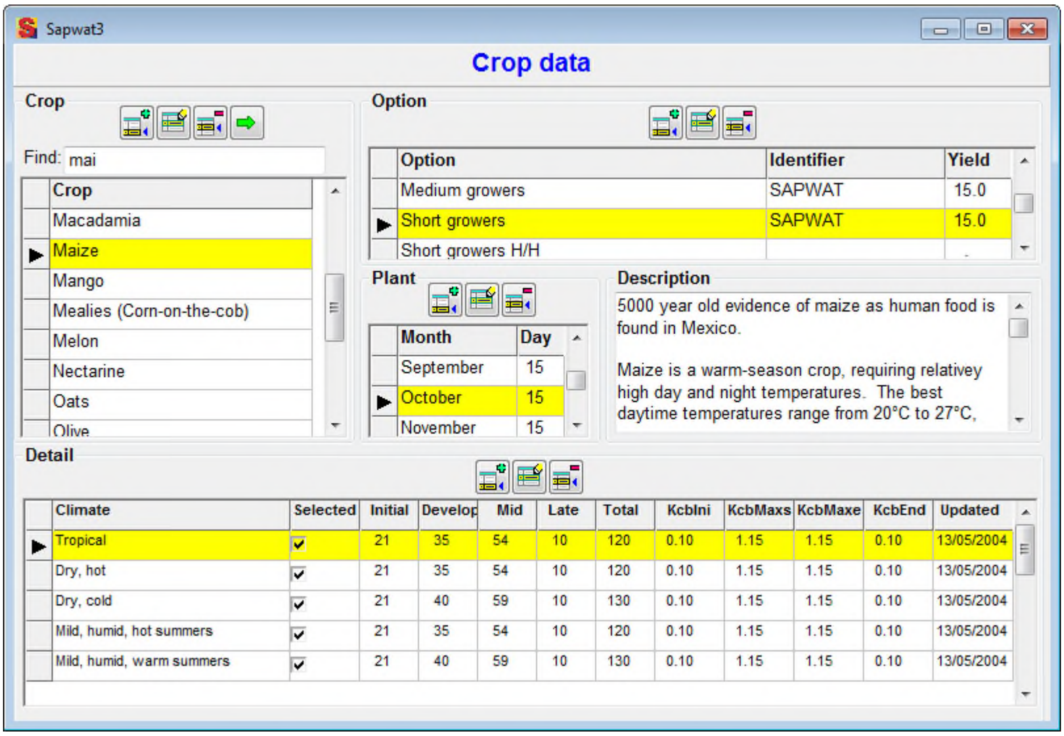


Figure 2-6 Crop characteristics of maize, short grower, planted middle of October showing the different stage lengths for warmer and colder areas (Van Heerden *et al*., 2008)

2.4.2 Fitting an ET_0 curve to weather station data

SAPWAT3 calculates reference evapotranspiration (ET_0) through the Penman-Monteith approach from the included weather data. This calculated ET_0 is linked to a crop coefficient (K_c) to calculate an expected daily crop evapotranspiration (ET_c) using the equation (Allen *et al*., 1998):

$$ET_c = ET_0 \times K_c \quad 2.3$$

Climate data follows a seasonal cycle; therefore, a cosine regression line is fitted through available ET_0 data to allow the derivation of daily values by interpolation in cases where only monthly average climate data is available. Daily weather data is highly variable, the fitting of a regression curve smooths out the data for calculation purposes. The coincidental high point between solar time and the cosine curve are expected to be on the southern hemisphere summer solstice, December 22 (Strahler and Strahler, 2002). However, experience has shown that high points rarely coincide and provision for lag time had to be made. Lag time is determined by doing a sequential sideways shift of the regression curve by making its starting date deviate from January 1 as starting day. Best fit is determined by the lowest standers deviation which is determined for each sequential calculation of fit. When that point is reached the number of days shift required is taken as the lag time. In Figure 2-7 a lag time of 14 days is indicated and is included as a constant in the regression equation. This lag time could be ascribed to the time required for atmospheric and earth surface temperatures to heat or cool as the seasons change (Strahler and Strahler, 2002). It is found to be relatively small at higher latitudes where significant differences between summer and winter sunshine hours are found (Figure 2-8) (Allen *et al.*, 1998).

At lower latitudes, and especially latitudes in close proximity of the equator, differences in winter and summer sunshine hours are small. When radiation interception through extended periods of cloud cover (Graham, 1999) during a monsoon or main rainy season become significant, the lag time could become large and the shift could go either way. Such a shift could change the shape of the regression curve. Figure 2-9 is an example where the lag time shift is a noticeable -67 days for a weather station situated close to the equator (9.5833˚N) and in a Köppen Geiger tropical monsoon climate in Sierra Leone. An analysis of the elements that influence ET_0 Penman-Monteith calculation in order to explain the large lag time shift in this case indicates that daily sunshine hours could be the major contributing factor (Figure 2-10). The average daily sunshine hours have decreased from 7.6 hours in the non-rainy season to 5.0 hours during the rainy season. Average relative humidity is higher during the rainy season at 85%, compared to the non-rainy average relative humidity of 65%. Wind run during the rainy season is 53 km/day compared to 76 km/day for the non-rainy season. Temperature differences are relatively small, rainy season average temperature being 24.7˚C compared to 25.9˚C for the non-rainy season (Figure 2-10).

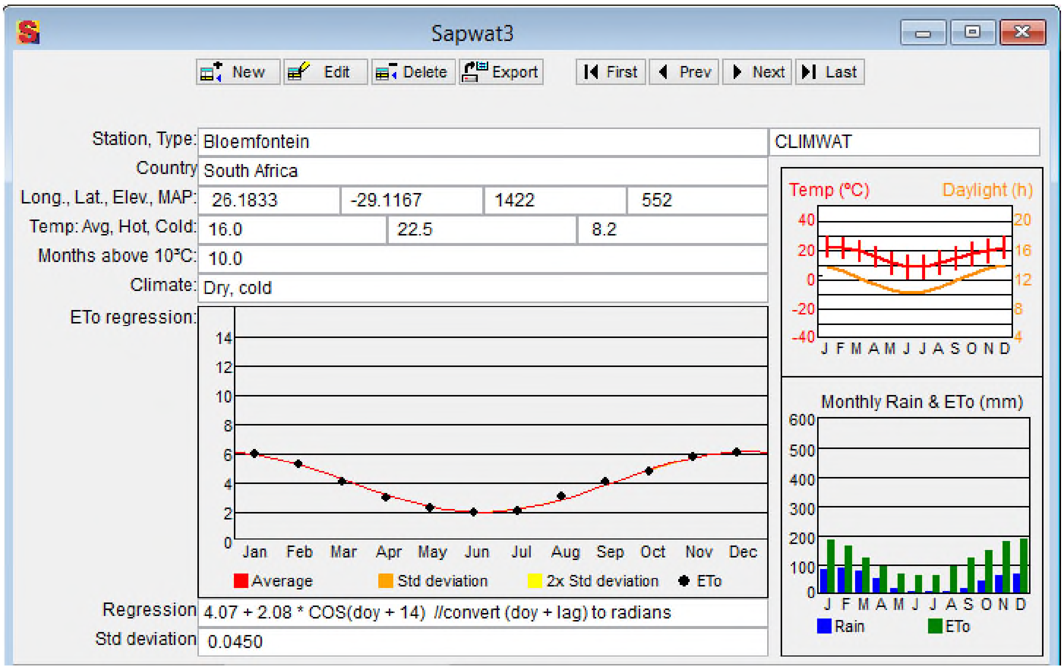
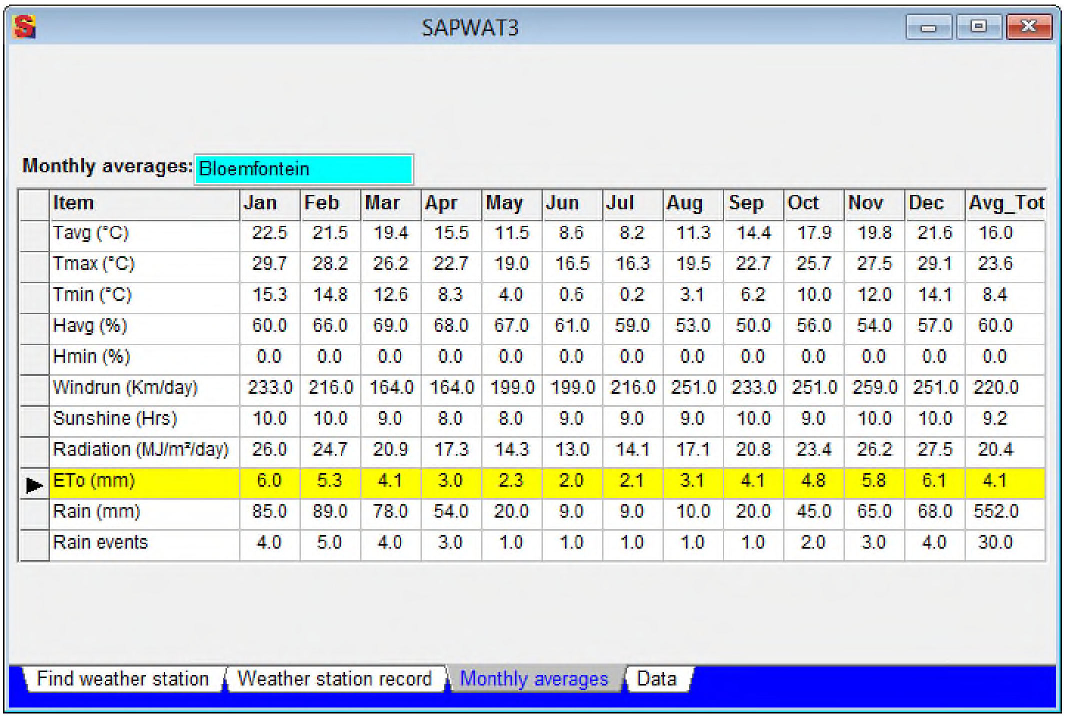


Figure 2-7 SAPWAT3 representation of the climate of the Bloemfontein CLIMWAT weather station (Smith, 1993) showing the cosine regression curve and its equation through monthly average ET_0 data – standard deviation values does not shown when a single set of monthly average values are used (Van Heerden *et al*., 2008)



SAPWAT3

Monthly averages: Bloemfontein

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	22.5	21.5	19.4	15.5	11.5	8.6	8.2	11.3	14.4	17.9	19.8	21.6	16.0
Tmax (°C)	29.7	28.2	26.2	22.7	19.0	16.5	16.3	19.5	22.7	25.7	27.5	29.1	23.6
Tmin (°C)	15.3	14.8	12.6	8.3	4.0	0.6	0.2	3.1	6.2	10.0	12.0	14.1	8.4
Havg (%)	60.0	66.0	69.0	68.0	67.0	61.0	59.0	53.0	50.0	56.0	54.0	57.0	60.0
Hmin (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Windrun (Km/day)	233.0	216.0	164.0	164.0	199.0	199.0	216.0	251.0	233.0	251.0	259.0	251.0	220.0
Sunshine (Hrs)	10.0	10.0	9.0	8.0	8.0	9.0	9.0	9.0	10.0	9.0	10.0	10.0	9.2
Radiation (MJ/m²/day)	26.0	24.7	20.9	17.3	14.3	13.0	14.1	17.1	20.8	23.4	26.2	27.5	20.4
ETo (mm)	6.0	5.3	4.1	3.0	2.3	2.0	2.1	3.1	4.1	4.8	5.8	6.1	4.1
Rain (mm)	85.0	89.0	78.0	54.0	20.0	9.0	9.0	10.0	20.0	45.0	65.0	68.0	552.0
Rain events	4.0	5.0	4.0	3.0	1.0	1.0	1.0	1.0	1.0	2.0	3.0	4.0	30.0

Find weather station | Weather station record | Monthly averages | Data

Figure 2-8 Monthly climate data of the Bloemfontein CLIMWAT weather station (Smith, 1993; Van Heerden et al., 2008)

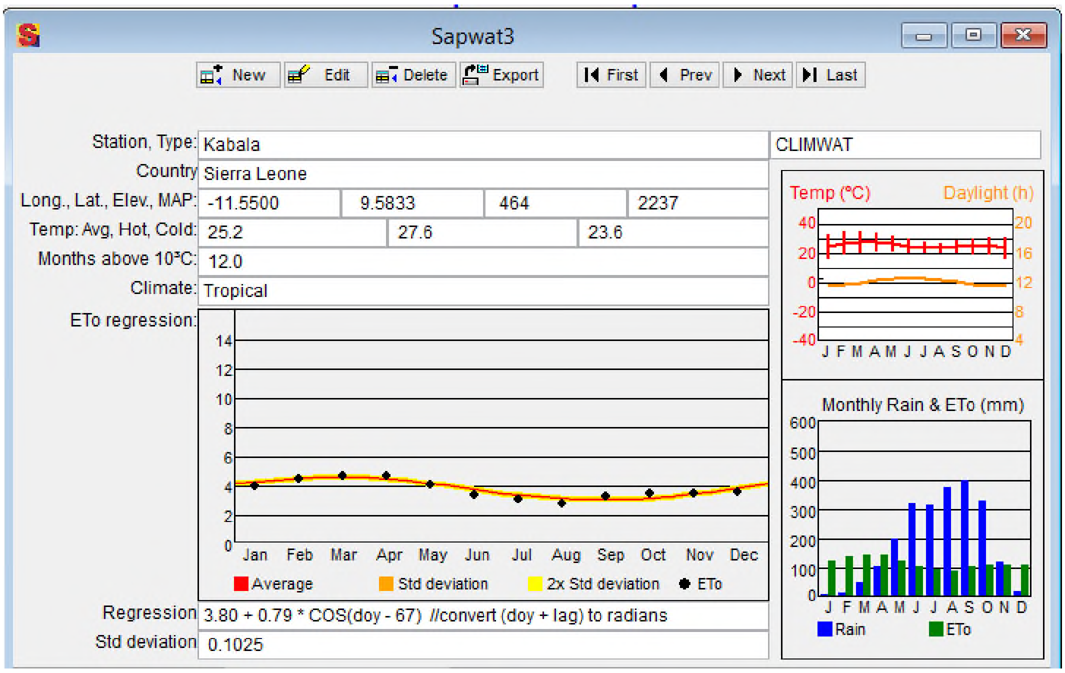
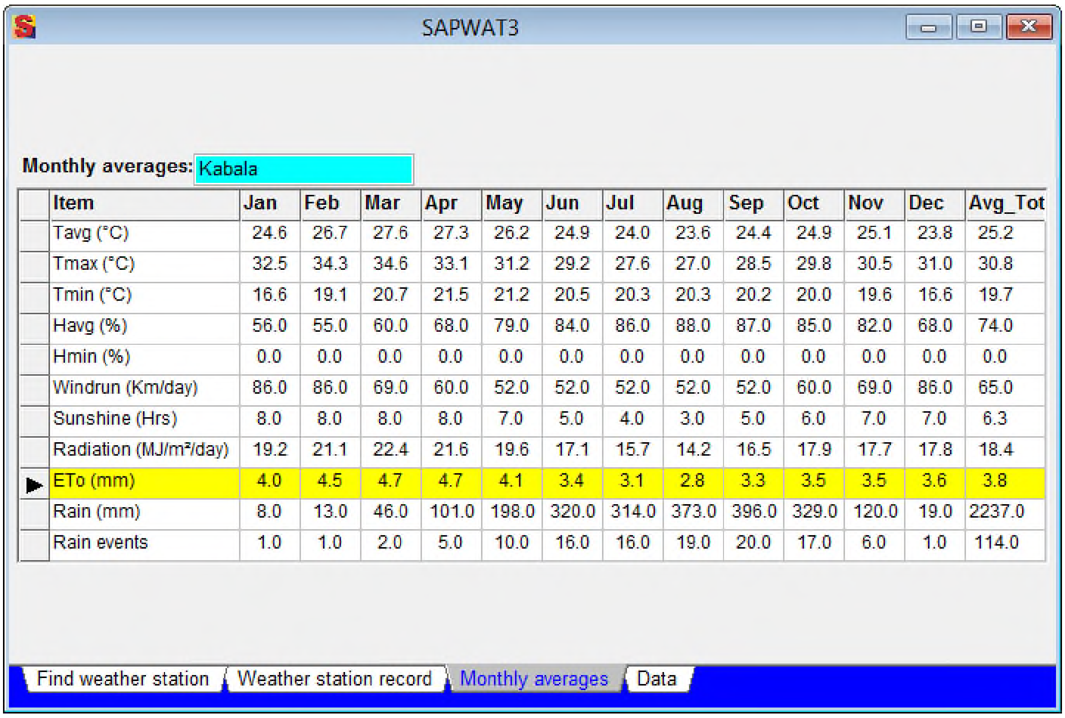


Figure 2-9 SAPWAT3 representation of the climate of the Kabala CLIMWAT weather station (Smith, 1993), situated in a rainy area, showing a significantly shifted cosine regression curve through monthly average ET_0 data relative to the solar time cosine curve (Van Heerden *et al*., 2008)


SAPWAT3

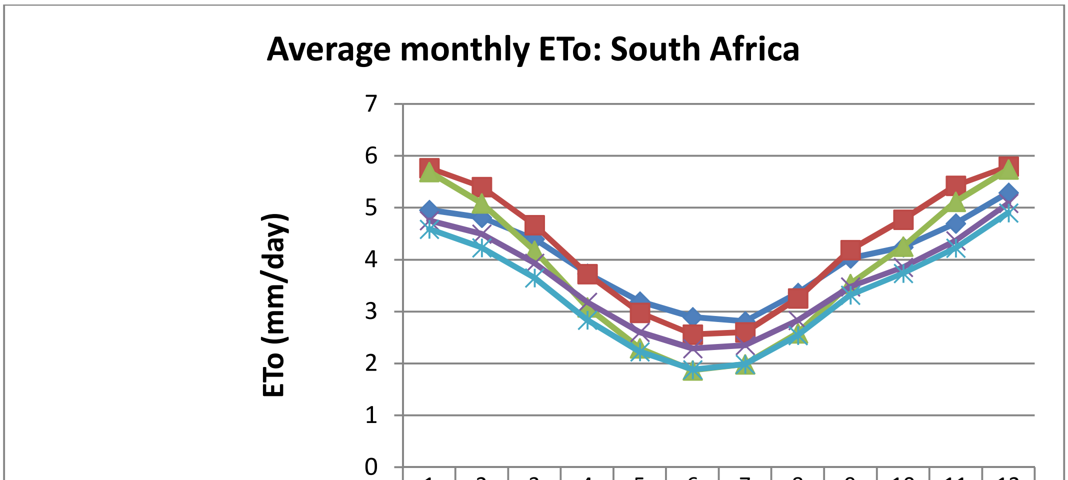
Monthly averages: Kabala

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	24.6	26.7	27.6	27.3	26.2	24.9	24.0	23.6	24.4	24.9	25.1	23.8	25.2
Tmax (°C)	32.5	34.3	34.6	33.1	31.2	29.2	27.6	27.0	28.5	29.8	30.5	31.0	30.8
Tmin (°C)	16.6	19.1	20.7	21.5	21.2	20.5	20.3	20.3	20.2	20.0	19.6	16.6	19.7
Havg (%)	56.0	55.0	60.0	68.0	79.0	84.0	86.0	88.0	87.0	85.0	82.0	68.0	74.0
Hmin (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Windrun (Km/day)	86.0	86.0	69.0	60.0	52.0	52.0	52.0	52.0	52.0	60.0	69.0	86.0	65.0
Sunshine (Hrs)	8.0	8.0	8.0	8.0	7.0	5.0	4.0	3.0	5.0	6.0	7.0	7.0	6.3
Radiation (MJ/m²/day)	19.2	21.1	22.4	21.6	19.6	17.1	15.7	14.2	16.5	17.9	17.7	17.8	18.4
ETo (mm)	4.0	4.5	4.7	4.7	4.1	3.4	3.1	2.8	3.3	3.5	3.5	3.6	3.8
Rain (mm)	8.0	13.0	46.0	101.0	198.0	320.0	314.0	373.0	396.0	329.0	120.0	19.0	2237.0
Rain events	1.0	1.0	2.0	5.0	10.0	16.0	16.0	19.0	20.0	17.0	6.0	1.0	114.0

Find weather station | Weather station record | Monthly averages | Data

Figure 2-10 Monthly climate data of the Kabala CLIMWAT weather station (Smith, 1993; Van Heerden *et al*., 2008)

SAPWAT links crop growth and development to climate, therefore a quick look at the climates of South Africa is needed. A comparison of average ET_0 values for the five Köppen-Geiger climates found in South Africa is shown in Figure 2-11. The difference in average monthly ET_0 values as well as the range of differences between winter and summer ET_0 values is noticeable across the climate types. In the tropical climate the seasonal difference in ET_0 is relatively small, ranging from a minimum of 2.8 mm/day in July to a maximum of 5.3 mm/day during December. In the case of the dry, hot climate the midsummer average monthly ET_0 can go as high as 5.8 mm/day, and drops to 2.6 mm/day during midwinter. In the dry, cold climate the range varies from 5.7 mm/day in summer to 1.9 mm/day in winter. A similar pattern emerges for the more humid climates, with ET_0 values lower than those of the dry climates.



	1	2	3	4	5	6	7	8	9	10	11	12
Tropical	5.0	4.8	4.4	3.7	3.2	2.9	2.8	3.4	4.0	4.2	4.7	5.3
Dry, hot	5.8	5.4	4.7	3.7	3.0	2.6	2.6	3.3	4.2	4.8	5.4	5.8
Dry, cold	5.7	5.1	4.2	3.1	2.3	1.9	2.0	2.6	3.5	4.3	5.1	5.7
Mild, humid, hot summers	4.8	4.5	3.9	3.2	2.6	2.3	2.4	2.8	3.5	3.9	4.4	5.1
Mild, humid, warm summers	4.6	4.2	3.7	2.8	2.2	1.9	2.0	2.5	3.3	3.7	4.2	4.9

Figure 2-11 Mean monthly ET_0 values (mm/day) for Köppen-Geiger climates found in South Africa weather stations included in the SAPWAT3 weather data table (Van Heerden *et al.*, 2008)

2.4.3 Temperatures of South African Köppen-Geiger climates

Temperature is an important determinant of crop growth and development that is used in SAPWAT3, therefore the temperatures of the five Köppen-Geiger climates found in South Africa need to be examined more closely. Average monthly temperatures for each climate were calculated for all South African weather stations included in the SAPWAT3 weather data table (Figure 2-12) (Van Heerden *et al.*, 2008). Average monthly temperatures for the tropical areas range from 18.3˚C in July to 26.2˚C during January. Average monthly temperatures show a larger variation in the dry and mesothermal climates, with average winter temperatures down to 9.8˚C and average summer maximum temperatures of 24.9˚C. These temperatures play a key role in determining the rate of growth and development of crops.

Average monthly temperatures as depicted in Figure 2-12 can be used to calculate CHU by using Equation 2.2. However, using these values to calculate monthly heat units would lead to a step-wise change in values every time the calculations move from one month to the next. The ideal would be to use daily T_{max} and T_{min} temperatures, but all CLIMWAT weather station data used in SAPWAT3 are given as monthly averages. This problem can be solved by fitting a cosine regression on the values and then using the resultant equation to calculate predicted daily temperatures. The lag time is determined by fitting a cos regression to temperature data starting with start day equivalent to southern solstice day. This regression calculation is recalculated with the cos start day shifting to later dates than solstice, until a best fit is found, i.e. where standard deviation is the smallest. Lag tine is then expressed as days after, or before, day of year (DOY) 1 which is January 1. The resultant equation has the format shown in Equation 2.4. Average monthly maximum and minimum temperatures were determined for each of the five Köppen-Geiger climates found in South Africa and a cosine regression was fitted to these[5]. The results are shown in Figure 2-12 to Figure 2-17.

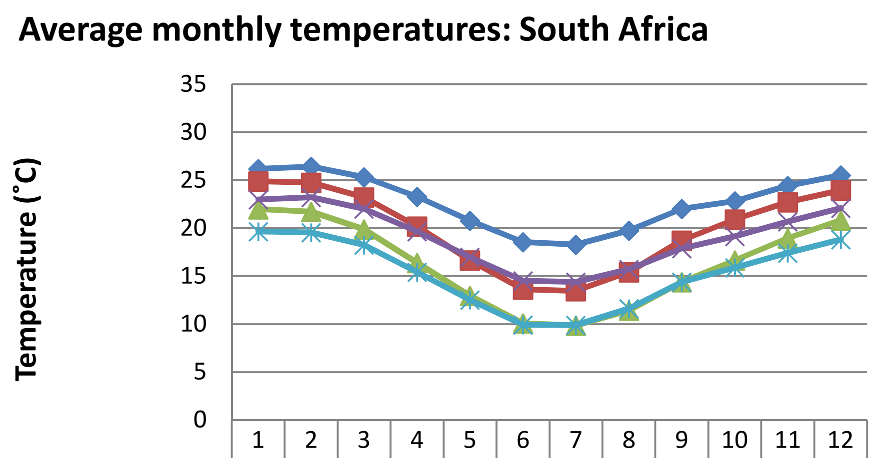
$$\overline{Y}=A+B.\cos\left\{\text{radians}\left[0.9863(DOY+lag)\right]\right\} \qquad 2.4$$

Where	$\overline{Y}$	expected temperature for DOY
	A	constant (y-axis value)
	B	constant (slope)
	cos	cosine function
	DOY	day of year: January 1 = DOY 1
	0.9863	conversion of 365 days to 360 degrees
	radians	(DOY + lag) degree angle converted to radians
	lag	sideways shift of cosine curve for best fit to data

[5] The cosine fit is not satisfactory; differences between actual and predicted winter temperatures are too big. A Fourier transformation would give a better fit, but the inclusion of a Fourier transformation in SAPWAT3 as an integral part of the program need further research.

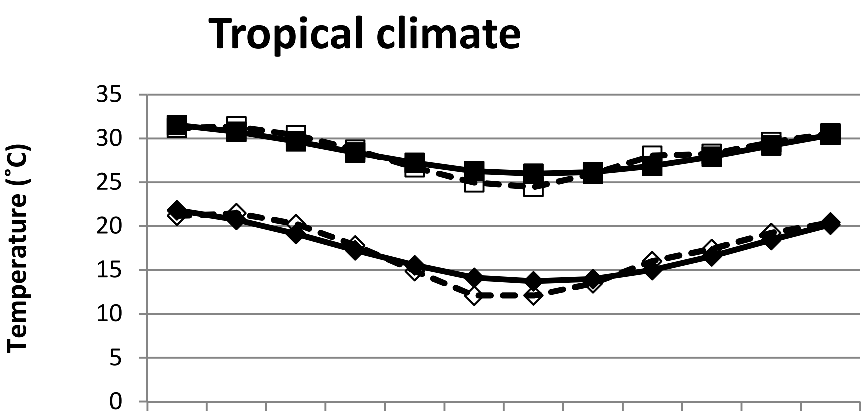
Table 2-8 Regression equations for average monthly maximum and minimum temperatures for all weather stations of Köppen-Geiger climates found in South Africa. Climate codes refer to SAPWAT3 climate codes described in Table 2-7. n = number of weather stations per climate

Climate	n	Parameter	Regression equation	r²	r
Tropical (A_)	29	T_{max}	$\overline{Y}$ = 28.90 + 2.93COS{radians[0.9863(DOY + 17)]}	0.7731	0.8793
		T_{min}	$\overline{Y}$ = 17.99 + 4.29COS{radians[0.9863(DOY + 17)]}	0.7858	0.8865
Dry, hot (B_h)	396	T_{max}	$\overline{Y}$ = 28.11 + 4.54COS{radians[0.9863(DOY + 26)]}	0.7677	0.8762
		T_{min}	$\overline{Y}$ = 13.61 + 5.97COS{radians[0.9863(DOY + 21)]}	0.7809	0.8837
Dry, cold (B_k)	598	T_{max}	$\overline{Y}$ = 24.67 + 5.54COS{radians[0.9863(DOY + 23)]}	0.8047	0.8971
		T_{min}	$\overline{Y}$ = 9.95 + 5.79COS{radians[0.9863(DOY + 16)]}	0.8140	0.9022
Mild, humid, hot summers (C_a)	290	T_{max}	$\overline{Y}$ = 25.80 + 3.24COS{radians[0.9863(DOY + 13)]}	0.8072	0.8984
		T_{min}	$\overline{Y}$ = 13.88 + 4.76COS{radians[0.9863(DOY + 16)]}	0.7931	0.8906
Mild, humid, warm summers (C_b)	712	T_{max}	$\overline{Y}$ = 22.61 + 3.76COS{radians[0.9863(DOY + 24)]}	0.7709	0.8781
		T_{min}	$\overline{Y}$ = 9.62 + 5.22COS{radians[0.9863(DOY + 20)]}	0.7908	0.8893



	1	2	3	4	5	6	7	8	9	10	11	12
Tropical	26.2	26.4	25.3	23.3	20.8	18.5	18.3	19.7	22.0	22.8	24.4	25.5
Dry, hot	24.9	24.8	23.2	20.2	16.7	13.6	13.4	15.4	18.7	20.9	22.7	23.9
Dry, cold	22.0	21.7	19.9	16.4	12.9	10.1	9.8	11.4	14.4	16.7	19.0	20.8
Mild, humid, hot summers	23.0	23.2	22.0	19.7	17.0	14.5	14.4	15.7	17.9	19.1	20.7	22.1
Mild, humid, warm summers	19.6	19.6	18.2	15.4	12.5	9.9	9.9	11.6	14.4	15.9	17.4	18.8

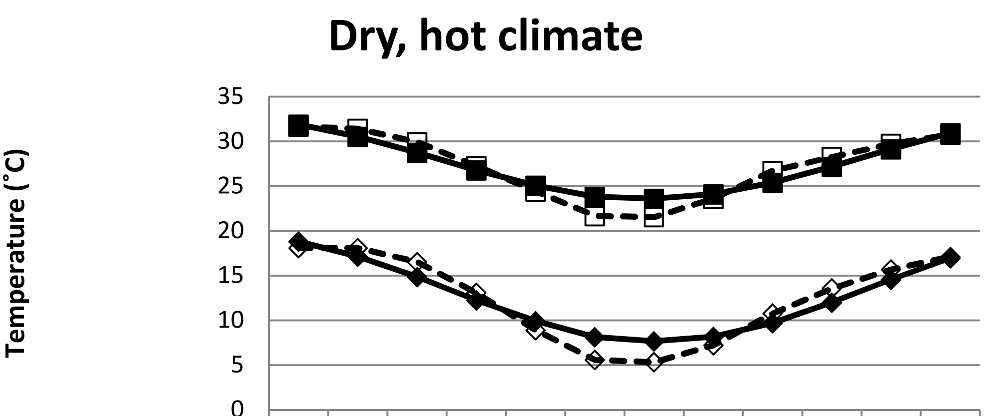
Figure 2-12 Average monthly temperatures for Köppen-Geiger climates for all South African weather stations included in the SAPWAT3 weather data table (Van Heerden *et al.*, 2008)



	1	2	3	4	5	6	7	8	9	10	11	12
Tmax observed	31.2	31.4	30.4	28.7	26.7	25.0	24.5	26.0	28.0	28.3	29.6	30.6
Tmax predicted	31.5	30.8	29.7	28.4	27.2	26.3	26.0	26.2	26.8	27.9	29.2	30.4
Tmin observed	21.2	21.5	20.3	17.8	14.9	12.1	12.1	13.5	16.0	17.4	19.2	20.4
Tmin predicted	21.8	20.7	19.1	17.3	15.5	14.1	13.7	14.0	15.0	16.6	18.4	20.2

Time (months)

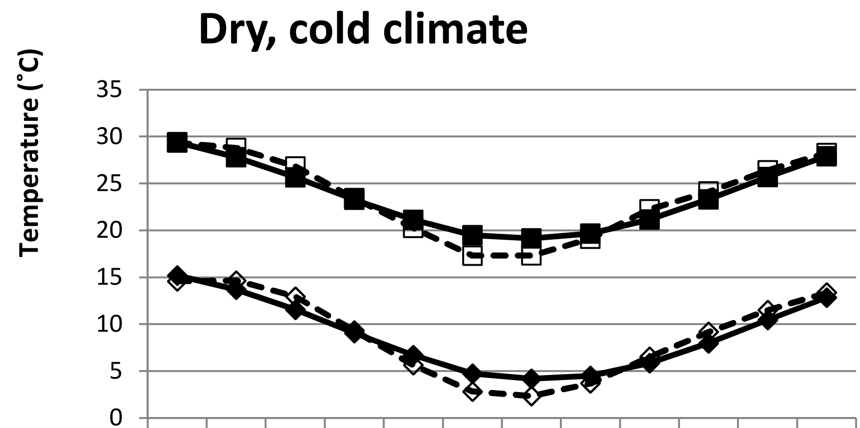
Figure 2-13 Comparison of actual and cosine regression predicted monthly temperatures for the tropical climate of South Africa based on weather data included in the SAPWAT3 program



	1	2	3	4	5	6	7	8	9	10	11	12
Tmax observed	31.7	31.4	29.9	27.3	24.4	21.7	21.6	23.6	26.7	28.3	29.7	30.8
Tmax predicted	31.9	30.5	28.7	26.8	25.1	23.8	23.6	24.1	25.4	27.2	29.1	30.9
Tmin observed	18.1	18.1	16.5	13.1	8.9	5.6	5.3	7.2	10.8	13.6	15.7	17.1
Tmin predicted	18.8	17.1	14.8	12.3	9.9	8.1	7.7	8.2	9.7	12.0	14.6	17.0

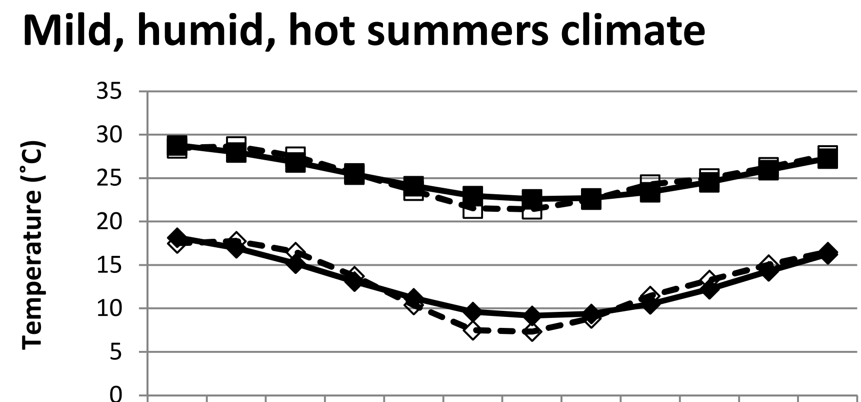
Time (months)

Figure 2-14 Comparison of actual and cosine regression predicted monthly temperatures for the dry, hot climate of South Africa based on weather data included in the SAPWAT3 program



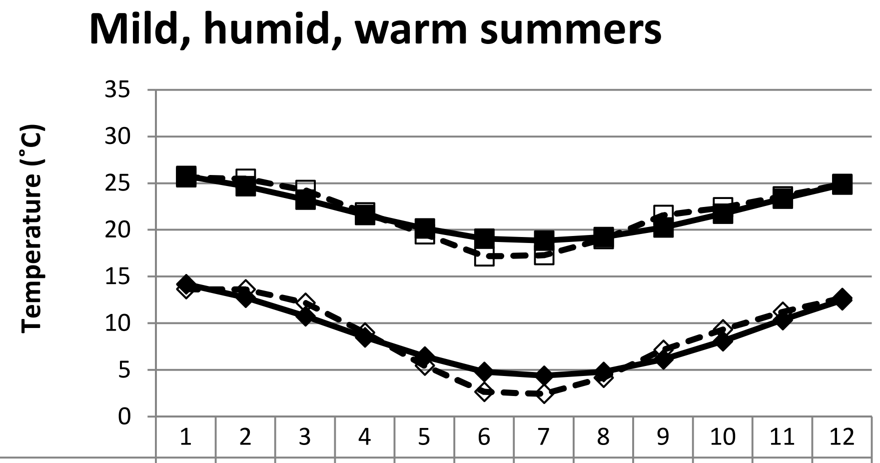
	1	2	3	4	5	6	7	8	9	10	11	12
Tmax observed	29.4	28.8	26.8	23.4	20.3	17.3	17.3	19.1	22.3	24.2	26.4	28.3
Tmax predicted	29.4	27.8	25.7	23.3	21.1	19.5	19.1	19.7	21.1	23.3	25.7	27.9
Tmin observed	14.6	14.7	12.9	9.3	5.6	2.8	2.4	3.7	6.5	9.2	11.5	13.4
Tmin predicted	15.2	13.7	11.6	9.0	6.7	4.7	4.2	4.5	5.8	8.0	10.4	12.8

Figure 2-15 Comparison of actual and cosine regression predicted monthly temperatures for the dry, cold climate of South Africa based on weather data included in the SAPWAT3 program



	1	2	3	4	5	6	7	8	9	10	11	12
Tmax observed	28.5	28.7	27.5	25.6	23.6	21.5	21.5	22.6	24.3	25.0	26.3	27.6
Tmax predicted	28.8	28.0	26.8	25.4	24.1	23.0	22.6	22.7	23.4	24.6	25.9	27.3
Tmin observed	17.5	17.8	16.5	13.7	10.4	7.5	7.4	8.9	11.5	13.3	15.1	16.5
Tmin predicted	18.2	17.0	15.2	13.1	11.2	9.6	9.2	9.4	10.5	12.2	14.3	16.3

Figure 2-16 Comparison of actual and cosine regression predicted monthly temperatures for the mild, humid, hot summers climate of South Africa based on weather data included in the SAPWAT3 program



	1	2	3	4	5	6	7	8	9	10	11	12
Tmax observed	25.6	25.5	24.3	21.9	19.6	17.2	17.3	19.0	21.6	22.4	23.6	24.9
Tmax predicted	25.8	24.7	23.2	21.6	20.2	19.1	18.9	19.2	20.3	21.7	23.4	24.8
Tmin observed	13.7	13.6	12.2	9.0	5.5	2.7	2.5	4.2	7.2	9.4	11.2	12.7
Tmin predicted	14.2	12.8	10.8	8.5	6.5	4.8	4.4	4.8	6.1	8.1	10.4	12.5

Figure 2-17 Comparison of actual and cosine regression predicted monthly temperatures for the mild, humid, warm summers climate of South Africa based on weather data included in the SAPWAT3

In all climate types found in South Africa, the predicted temperature values show a similarity with observed monthly values, although winter temperature differences between observed and predicted values are too big. Even so, sample correlation coefficient (r) values that fall between 0.8762 for T_{max} of the dry, hot climate and 0.9022 for T_{min} of the dry, cold climate (Table 2-8). These results show that the prediction equation could be used with care for doing daily heat unit calculations to provide a good approximation of length of each period (in days) of the FAO four-stage crop growth curve for describing crop growth and development for use in SAPWAT3.

2.5 Linking crop growth and development to the climate regions of SAPWAT3

Equation 2.2 was adapted to Equation 2.5 for computerised calculation of crop heat units in SAPWAT3. The adaptation ensures that:

- CHU calculated for a specific period will not be less than 0˚C.d;
- Maximum temperature included in the equation will be the smaller of maximum temperature or cardinal maximum temperature.

$$CHU=\sum_{n=1}^{365} max\left[0,\left(\frac{min\left(T_{cardinalmax},T_{max}\right)+T_{min}}{2}-T_{base}\right)\Delta t\right] \quad 2.5$$

Where CHU crop heat units (˚C.d)
$T_{cardinalmax}$ cardinal maximum temperature for the crop (°C)
T_{max} maximum daily temperature (˚C)
T_{min} minimum daily temperature (˚C)
T_b cardinal minimum or base temperature of crop (˚C)
Δt time interval (day)

2.5.1 Maize

The cosine regressions (Figure 2-13 to Figure 2-17) were used to calculate the growth period for maize as a summer grain crop planted on 15 October by using data shown in Table 2-5 from Miller *et al*. (2001). Canopy cover is not shown in Table 2-5; therefore the 4-leaf fully emerged growth stage was assumed to be equivalent to the 10% canopy cover turning point between the initial and the development growing staged. The 75% to 80% canopy cover turning point between the development and mid-season growing stage was assumed to be when the 12-leaf was fully emerged, while the beginning of maturity was assumed to be at the stage where the kernel begins to dent. Heat units required to reach each of these growth stages were: 160, 452, 1 329 and 1 475 (˚C.d) (Parthasarathi *et al*., 2013) with T_b = 10˚C. The resultant growing stage lengths were compared to data included in SAPWAT3 (Van Heerden *et al*., 2008) as well as data included in FAO 56 (Allen *et al*., 1998) (From **Error! Not a valid bookmark self-reference.** it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT3 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT3 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT3 crop data table, have been excluded because they are being phased out of the South African irrigation market.
- The total growing days for the medium growing types in SAPWAT3 shows a similarity in total growing days to four of the six examples indicated by the FAO 56 data. The two longest growing period maize included in the FAO 56 data could be for cultivars not grown in South Africa. The growth stage growing days as well as the total number of growing days indicated in both SAPWAT3 crop data tables and in

FAO 56 are not necessarily correct; to a large degree these values are based on general observations done by farmers and seed merchants and could also be the result of different cultivars with different growing periods. These can at best be seen as approximations.

Table 2-9).

From **Error! Not a valid bookmark self-reference.** it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT3 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT3 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT3 crop data table, have been excluded because they are being phased out of the South African irrigation market.
- The total growing days for the medium growing types in SAPWAT3 shows a similarity in total growing days to four of the six examples indicated by the FAO 56 data. The two longest growing period maize included in the FAO 56 data could be for cultivars not grown in South Africa. The growth stage growing days as well as the total number of growing days indicated in both SAPWAT3 crop data tables and in FAO 56 are not necessarily correct; to a large degree these values are based on general observations done by farmers and seed merchants and could also be the result of different cultivars with different growing periods. These can at best be seen as approximations.

Table 2-9 An example of a comparison of heat unit calculated growing periods for five climate regions found in South Africa, SAPWAT3 data (Van Heerden *et al*., 2008) for medium, short and ultra-short grower maize cultivars planted on 15 October, as well as data contained in FAO 56 (Allen *et al*., 1998)

Source	**Growth characteristics**	**Planting date**	**Climate or region**	**Days per growth stage**				
				Ini	**Dev**	**Mid**	**Late**	**Total**
Based on heat unit calculations	Maize CHU data calculation based on data contained in Table 2-5. T_b = 10˚C.	15-Oct	Tropical	11	19	59	9	89
			Dry, hot	11	21	53	10	95
			Dry, cold	15	26	68	14	123
			Mild, humid, hot summers	13	25	62	11	111
			Mild, humid, warm summers	17	32	90	25	164

SAPWAT3	Ultra-short	15-Oct	Tropical	21	37	42	10	110
			Dry, hot	21	37	42	10	110
			Dry, cold	21	42	47	10	120
			Mild, humid, hot summers	21	37	42	10	110
			Mild, humid, warm summers	21	42	47	10	120
	Short	15-Oct	Tropical	21	35	54	10	120
			Dry, hot	21	35	54	10	120
			Dry, cold	21	40	59	10	130
			Mild, humid, hot summers	21	35	54	10	120
			Mild, humid, warm summers	21	40	59	10	130
	Medium	15-Oct	Tropical	21	40	69	10	140
			Dry, hot	21	40	69	10	140
			Dry, cold	21	45	74	10	150
			Mild, humid, hot summers	21	40	69	10	140
			Mild, humid, warm summers	21	45	74	10	150
FAO 56		Apr	East Africa	30	50	60	40	180
		Dec/Jan	Arid climate	25	40	45	30	140
		Jun	Nigeria (humid)	35	40	30	30	135
		Oct	India (dry, cool)	35	40	30	30	135
		Apr	Spain (spring, summer)	30	40	50	30	150
		Apr	Idaho (USA)	30	40	50	50	170

The wide range of growing days between warmer and cooler areas seen in the heat unit calculated areas also reflected in some seed catalogues. Pannar (2013) seed catalogue indicates that expected days from plant to maturity varies from 103 to 115 days for warmer areas and from 140 to 162 days for cooler areas of South Africa. Similar differences in growth due to temperature differences are also reflected by other researchers but not for different climates as in the case of SAPWAT3, but for different planting dates which does alter the thermal time values for growth (Choukan, 2012; Parthasarathi, 2013; Tadeo-Robledo, 2015).

Seed catalogues differentiate between shorter and longer growing varieties (Monsanto, 2013; Pannar, 2013). In this sense, without giving detail about growth stages, one seed catalogue noted that maize cultivars should be divided at CHU of 1300˚C.d at T_b = 10˚C to differentiate between longer and shorter growing varieties for the South African market (Monsanto, 2013). This recommendation seems to be a more practical subdivision than that presently in use in SAPWAT3.

The interpretation of different growth periods for the individual growth stages of the FAO four-stage crop growth curve need to be carefully done. The assumption that 10% canopy cover is equivalent to the 4-leaf fully emerged growth stage, or that 75% to 80% canopy cover turning point is equivalent to the 12-leaf fully emerged growth stage need to be verified. Similarly, the assumption that the beginning of maturity is equivalent to the stage where the maize kernels begin to dent needs to be verified.

The Chi-squared test shows that homogeneity is high in all groups except in the data contained in the length of crop development stage table (FAO 56: Table 11) (Allen *et al*., 1998). The homogeneity found is irrespective of differences in total growing periods (Table 2-10) for different climate zones and types. This indicates consistency between the lengths of the growing periods of the crop development stages. The low level of homogeneity in the FAO 56 data could be the result of cultivar differences – cultivars are not indicated in either FAO 56 or in SAPWAT3. However, SAPWAT3 differentiates between ultra-short, short and medium cultivars based on total growing days. Ultra-short is taken as a growing period of 110 days, short at 120days, medium at 135 days; a rather arbitrary set of values that need to be re-investigated based on thermal time. In the paired groupings linking to the FAO 56 data show little to no homogeneity between the groups.

The results of applying the crop heat unit detail shown in From **Error! Not a valid bookmark self-reference.** it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT3 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT3 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT3 crop data table, have been excluded because they are being phased out of the South African irrigation market.
- The total growing days for the medium growing types in SAPWAT3 shows a similarity in total growing days to four of the six examples indicated by the FAO 56 data. The two longest growing period maize included in the FAO 56 data could be for cultivars not grown in South Africa. The growth stage growing days as well as the total number of growing days indicated in both SAPWAT3 crop data tables and in FAO 56 are not necessarily correct; to a large degree these values are based on general observations done by farmers and seed merchants and could also be the result of different cultivars with different growing periods. These can at best be seen as approximations.

Table 2-9 to estimate irrigation requirements are shown in Figure 2-18 to Figure 2-21 where the effect of different growth periods due to temperature differences becomes obviously apparent. In these figures the light blue histogram bars are the average (P50 = 50% level of non-exceedance) values, shown in the table below the histogram. The dark blue parts in the histogram represent different P-values, i.e. 90% level of non-exceedance indicated by P90, 80% level of non-exceedance (P80), and so forth. These levels of non-exceedance gives the designer and farmer an indication of the irrigation requirement at different levels of non-exceedance. At P90 the theory is that the water requirement indicated would be enough to satisfy the crop irrigation requirement 90% of the time.

Table 2-10 Chi-squared tests for homogeneity on maize groups (DF = degrees of freedom = (rows-1) x (columns-1) in From **Error! Not a valid bookmark self-reference.** it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT3 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT3 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT3 crop data table, have been excluded because they are being phased out of the South African irrigation market.
- The total growing days for the medium growing types in SAPWAT3 shows a similarity in total growing days to four of the six examples indicated by the FAO 56 data. The two longest growing period maize included in the FAO 56 data could be for cultivars not grown in South Africa. The growth stage growing days as well as the total number of growing days indicated in both SAPWAT3 crop data tables and in FAO 56 are not necessarily correct; to a large degree these values are based on general observations done by farmers and seed merchants and could also be the result of different cultivars with different growing periods. These can at best be seen as approximations.

Table 2-9 used for the Chi-squared test)

Group	DF	Required at P=0.95	Observed	Homogenous at P=0.95	Homogenous at P=?
Maize, Medium, SAPWAT3	12	5.226	0.300	Yes	0.99
Maize, Short, SAPWAT3	12	5.226	0.373	Yes	0.99
Maize, Ultra-short, SAPWAT3	12	5.226	0.392	Yes	0.99
Maize, HU	12	5.226	3.780	Yes	0.98
FAO 56, Table 11, p.104	12	5.226	14.122	No	0.20
Maize, Short, SAPWAT3/ Maize, Medium, SAPWAT3	27	16.151	2.003	Yes	0.99
Maize, Ultra-short, SAPWAT3 / Maize, Short, SAPWAT3	27	16.151	3.206	Yes	0.99
Maize, HU / Maize, Ultra-short	27	16.151	8.294	Yes	0.99
Maize, Ultra-short, SAPWAT3 / Maize, Medium, SAPWAT3	27	16.151	8.810	Yes	0.99
Maize, HU / Maize, Medium, SAPWAT3	27	16.151	16.800	No	0.90
Maize, HU/ Maize, Short, SAPWAT3	27	16.151	18.355	No	0.80
Maize, HU / Maize, Ultra-short, SAPWAT3	27	16.151	28.649	No	0.30
Maize, Ultra-short / Maize, FAO 56	28	16.151	33.928	No	0.20
Maize, Short, SAPWAT3 / Maize, FAO 56	28	16.151	44.569	No	0.01
Maize, Medium, SAPWAT3 / Maize, FAO 56	28	16.151	60.601	No	<0.01
Maize, HU / Maize, FAO 56	28	16.151	65.029	No	<0.01
Maize, all entries	75	16.151	47.943	No	<0.01

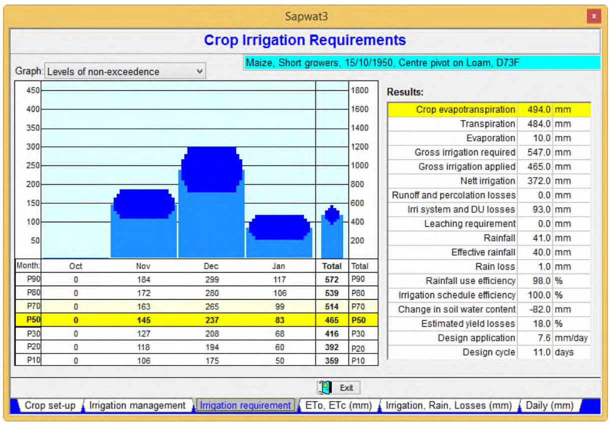


Figure 2-18 Maize planted 15 October in a dry, hot climate. Expected to reach maturity in the second week of January

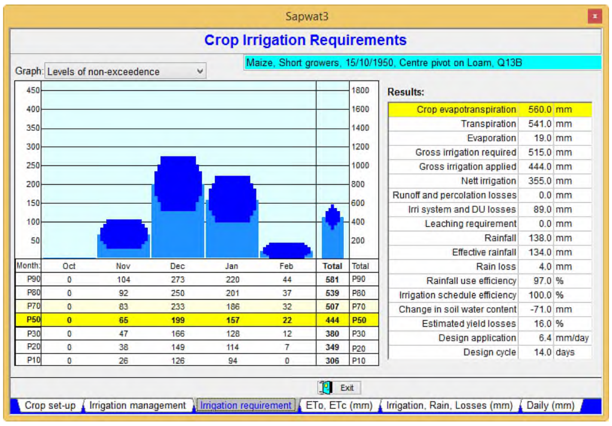


Figure 2-19 Maize planted 15 October in a dry, cold climate. Expected to reach maturity in the second week of February

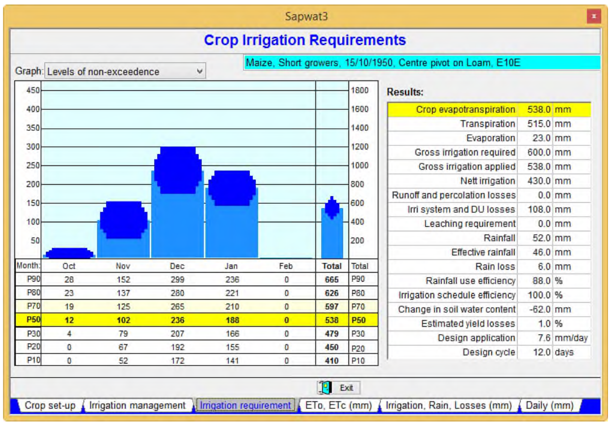


Figure 2-20 Maize planted 15 October in a mild, humid with hot summers climate. Expected to reach maturity in the last week of January

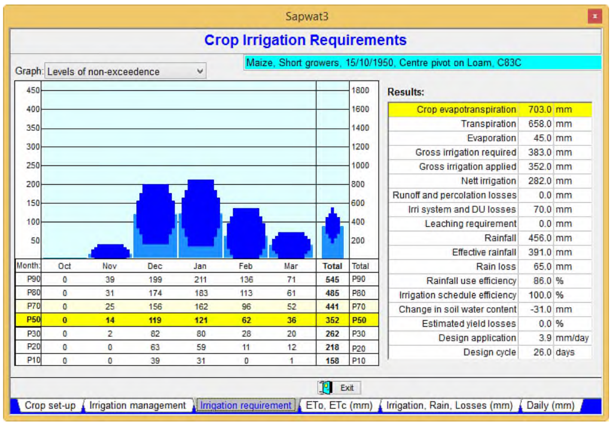


Figure 2-21 Maize planted 15 October in a mild, humid with warm summers climate. Expected to reach maturity in the second week of March

2.5.2 Wheat

Irrigated wheat in South Africa is referred to as spring wheat, but it is usually planted during the beginning of the winter season. According to Mr Robbie Lindeque[6] of the Agricultural Research Council - Small Grain Research Institute, the wheat grown in South Africa should rather be seen as an intermediate type, something between a winter and spring wheat. In the course of their spring wheat breeding research program, they continually notice traces of crop reaction that could be ascribed to combinations of cold requirement and photoperiodism. The prevalence of cold requirement and/or photoperiodism could complicate the interpretation of the wheat crop growth and development in terms of thermal time only as described by Parthasarathi *et al*. (2013).

The growth period for wheat planted on 25 June was calculated by using data shown in Table 2-5. Because canopy cover is not shown, the following assumptions regarding canopy cover were made: 10% cover was assumed to be at the two leaves fully unfolded stage at 208 ˚C.d; the 75% canopy cover was assumed to be equal to the beginning of anthesis appearance at 807 ˚C.d; beginning of maturity was assumed to be at the dough stage at 1 556 ˚C.d and full maturity was assumed to be at 1 665 ˚C.d (Parthasarathi *et al*., 2013). The assumption of 10% canopy cover at the two leaf stage might be earlier than actual 10% canopy cover, and the assumption of 75% canopy cover as equal to beginning of anthesis appearance might be later than when 75% canopy cover is actually reached. In both these cases intermediate

[6] Mr Robbie Lindeque, Personal communication, 3 July 2014, Wheat breeder, Agricultural Research Council - Small Grain Research Institute, Bethlehem.

growing stages are not provided in Table 2-5, therefore the closest possible approximations were used. This could shorten the initial period stage, increase the length of the development growth stage and shorten the length of the mid-season growth stage. The calculated growing stage lengths were compared to data included in SAPWAT3 (Van Heerden *et al*., 2008) as well as data included in FAO 56 (Allen *et al*., 1998) and are shown in Table 2-11.

Table 2-11 An example of a comparison of heat unit calculated growing periods, SAPWAT3 data for spring wheat cultivars for four climate regions found in South Africa, as well as spring and winter wheat data contained in FAO 56 (Allen et al., 1998)

Source	**Growth characteristics**	**Planting date**	**Climate or region**	**Days per growth stage**				
				Ini	**Dev**	**Mid**	**Late**	**Total**
Based on heat unit calculations	Wheat CHU data calculation based on data contained in Table 2-5. T_b = 4˚C.	25 Jun	Dry, hot	18	42	43	5	108
			Dry, cold	26	54	47	6	133
			Mild, humid, hot summers	18	45	46	6	115
			Mild, humid, warm summers	26	56	52	7	141
SAPWAT3	Spring types	25 Jun	Dry, hot	28	70	37	3	138
			Dry, cold	28	70	37	3	138
			Mild, humid, hot summers	28	63	37	3	131
			Mild, humid, warm summers	28	70	37	3	138
FAO 56 Spring wheat		Nov	Central India	15	25	50	30	120
		Jul	East Africa	15	30	65	40	150
		Dec	California desert, USA	20	50	60	30	160
FAO 56 Winter wheat		Dec	California, USA	20	60	70	30	180
		Nov	Mediterranean	30	140	40	30	240
		Oct	Idaho, USA	160	75	75	25	335
				Spike appearance				
Agricultural Research Council Small Grain Research Institute		25 Jun	Cooler areas	112		49		161
			Warmer areas	103		51		154

The following observations can be made:

- The Agricultural Research Council - Small Grain Research Institute (2010) shows days from plant to anthesis for wheat cultivars grown under irrigation and for different locations as 103 days for warmer areas and 112 days for cooler areas. This period should approximately be the sum of the initial and development periods. Comparing the CHU calculated growing periods of wheat where time to flowering is shown as 56 to 73 days for warmer areas and 80 to 82 days for coolers areas, the differences between expected periods according to the Agricultural Research Council - Small Grain Institute (2010) and that based on CHU calculations differ too much to be acceptable and need further investigation. These differences are also reflected in work done by some others (Parthasarathi, 2013) and are also influenced by stress situations (Sikder, 2009).
- Seed catalogues for wheat sold in South Africa indicate substantially longer growing periods to physiologically ripeness than CHU calculations with 144 to 154 days for warmer areas and 154 to 161 days for cooler areas (Monsanto, 2013, Pannar, 2013).

- The influence of photoperiodism overriding CHU calculations cannot be discounted (Kamran and Spaner, 2014). Increase in day length to 12 hours and beyond stimulates the wheat plant to change from its vegetative growth stage to its reproductive stage (Košner and Žůrková, 1996; McMahon *et al*., 2002). With the southern hemisphere spring solstice on 23 September (Strahler and Strahler, 2002), the period between planting time and the beginning of the reproductive phase is about 92 days, which is more in line with the time from plant to flowering indicated by the Agricultural Research Council - Small Grain Institute (2010) than the CHU calculations indicate.
- Farmer observations are that irrespective of whether wheat is planted during the period first week of June to the last week of July, harvesting takes place during the first half of December which gives a period from plant to harvest that varies between about 130 and about 180 days. The resultant growing period is comparable with the growing periods indicated by seed catalogues.
- The Agricultural Research Council - Small Grain Research Institute (2010) does advise different cultivars for early and late plantings, therefore cultivar differences do exist.
- The growth and development periods of SAPWAT3 and the FAO 56 spring and winter wheat planted in December (June in the southern hemisphere) show a similarity that could place these specific wheat types in the same category. The long growing FAO 56 winter wheat that shows very long initial or development growing stages could be the result of a combination of cold requirement or photoperiodism, both of which are naturally occurring phenomena in wheat. But this effect is not seen in South African wheat growing areas or across South African varieties, as none of them will grow some leaves and then go into a leaf growth dormant stage through the winter, such as those in North America and Europe.
- The initial and development growing stage lengths in SAPWAT3 for wheat are longer than that of the calculated data based on heat units. Because SAPWAT3 crop characteristics are described on the basis of field observations, the difference indicated for the initial and development growth stages might be caused by an underlying photoperiod influence. The lack of sufficient detail on growth stages that could be used to draw the FAO four stage crop growth curve for wheat could also play a role.

- The late season stage of the FAO 56 (Allen *et al.*, 1998) data is much longer than that of both the calculated and SAPWAT3 data cases, this could also be a case of poor definition of stages, as in the field the wheat does have a short flowering and grain filling period but a longer drying phase (Agricultural Research Council - Small Grain Institute, 2010).

Chi-squared analyses for homogeneity were done within and on paired groups to investigate consistency of crop growth periods (Table 2-12).

Table 2-12 Chi-squared tests form homogeneity on wheat groups

Group	DF	Required at P=0.95	Observed	Homogenous at P=0.95	Homogenous at P=?
Wheat, HU	9	3.325	1.278	Yes	0.99
Wheat SAPWAT3	9	3.325	0.276	Yes	0.99
Wheat FAO 56	9	3.325	42.519	No	0.01
Wheat, HU / Wheat SAPWAT3	21	11.591	15.696	No	0.70
Wheat, HU / Wheat FAO 56	22	12.338	60.494	No	<0.01
Wheat SAPWAT3 / Wheat FAO 56	22	12.338	114.928	No	<0.01
Wheat all entries	36	26.510	40.421	No	0.25

The chi-squared analysis shows a high level of homogeneity in the SAPWAT3 and in the thermal time calculated growth periods, but that there is virtually no homogeneity in the FAO 56 data. Linkage of the SAPWAT3 and heat unit data with the FAO 56 data also results in low or no levels of homogeneity. The suspicion that both photoperiodism and vernalisation requirement is present in spring wheat where it is supposed to have been eliminated by breeding programmes, could play havoc with thermal time calculations if these factors are not part of the consideration of wheat growth and development.

2.5.3 Sunflower

The cosine regressions shown in Figure 2-13 to Figure 2-17 were used to calculate the growing period for sunflower as an oil-seed crop planted on 15 October by using data shown in Table 2-5. Canopy cover is not shown; therefore the 4-leaf unfolded growth stage was assumed to be equivalent to the 10% canopy cover turning point between the initial and the development growing staged. The 75% to 80% canopy cover turning point between the development and mid-season growing stage was assumed to be at commencement of flowering, while the beginning of maturity was assumed to be at the stage where the seed begins to mature. Heat units required to reach these growth stages were: 359, 935, 1 547 and 1 780 CHU (˚C.d) (Parthasarathi *et al*., 2013) with T_b = 8˚C. The resultant growth stage lengths were compared to data included in SAPWAT3 (Van Heerden *et al*., 2008) as well as from FAO 56 (Allen *et al*., 1998) (Table 2-13).

Table 2-13 An example of a comparison of calculated heat unit growing periods for sunflower for climate regions found in South Africa, SAPWAT3 data, as well as data contained in FAO 56 (Allen et al., 1998)

Source	Growth characteristics	Planting date	Climate or region	Days per growth stage				
				Ini	Dev	Mid	Late	Total
Based on heat unit calculations	Sunflower CHU data calculation based on data contained in Table 2-5. Tb = 8˚C.	15 Oct	Tropical	21	30	34	13	96
			Dry, hot	22	32	34	14	102
			Dry, cold	27	39	43	19	128
			Mild, humid, hot summers	25	37	39	16	117
			Mild, humid, warm summers	31	46	56	29	162
SAPWAT3	Standard	15 Oct	Tropical	21	35	42	21	119
			Dry, hot	21	35	42	21	119
			Dry, cold	21	35	42	21	119
			Mild, humid, hot summers	21	35	42	21	119
			Mild, humid, warm summers	21	35	42	21	119
FAO 56		Apr/May	Mediterranean.; California	25	35	45	25	130

The growth periods for sunflowers grown in different climate zones (Table 2-13) show:

- Heat unit calculations show adaptation: warmer climate zones have a shorter growing period than colder climate zones.
- The growth data included in SAPWAT3 make no distinction in terms of growing periods for different climate zones because the differences in growing periods as influenced by thermal time were not available when the SAPWAT3 crop tables for sunflower were drawn up.

The consistency of growth periods were investigated by applying the Chi-squared analyses for homogeneity within and on paired groups to investigate consistency of crop growth periods (Table 2-14).

Table 2-14 Chi-square test for homogeneity of sunflowers grown in different climate zones

Group	DF	Required at P=0.95	Observed	Homogenous at P=0.95	Homogenous at P=?
Sunflower, HU	4	0.711	0.045	Yes	0.95
Sunflower, SAPWAT3	4	0.711	0.000	Yes	1.00
Sunflower, HU / Sunflower, SAPWAT3	27	16.151	1.659	Yes	0.99
Sunflower, HU / Sunflower, FAO 56	15	7.261	0.893	Yes	0.99
Sunflower, SAPWAT3 / Sunflower, FAO 56	15	7.261	0.039	Yes	0.99
Sunflower, All entries	30	18.493	4.728	Yes	0.99

The chi-square test for homogeneity (Table 2-14) on the growth periods for sunflowers grown in different climate zones (Table 2-13) show:

- The growing period analysis for SAPWAT3 data yields an overoptimistic Chi-squared value because no distinction between the growing periods of sunflower for the different climate zones is indicated.
- The growing periods for sunflower based on heat units is homogenous even though the growing periods differ. The homogeneity is because the ratios between the different growth stages for the different climate zones are similar enough to test positive for homogeneity.
- When comparing climate zone heat unit calculated growing periods with the SAPWAT3 growing periods the mild, humid, warm summer climate zones show homogeneity.

Applying the heat unit calculations shown in Table 2-13 in the calculation of irrigation requirement estimates by SAPWAT3 for the four most common climate regions in South Africa, yields the results shown in Figure 2-22 to Figure 2-25. The effect of temperature on growing periods to maturity can be seen – total growing period is longer in colder climates than in warmer climates, as indicated by the months for which water requirement planning is necessary.

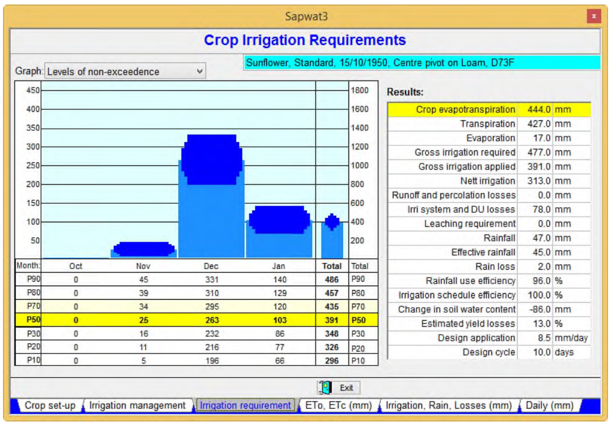


Figure 2-22 Sunflower planted 15 October in a dry, hot climate. Expected to reach maturity in the third week of January

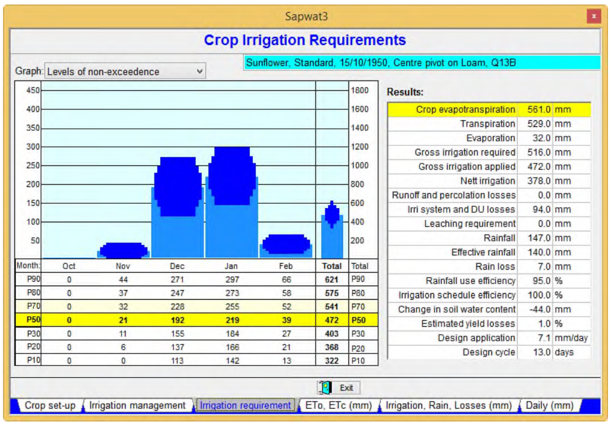


Figure 2-23 Sunflower planted 15 October in a dry, cold climate. Expected to reach maturity in the third week of February

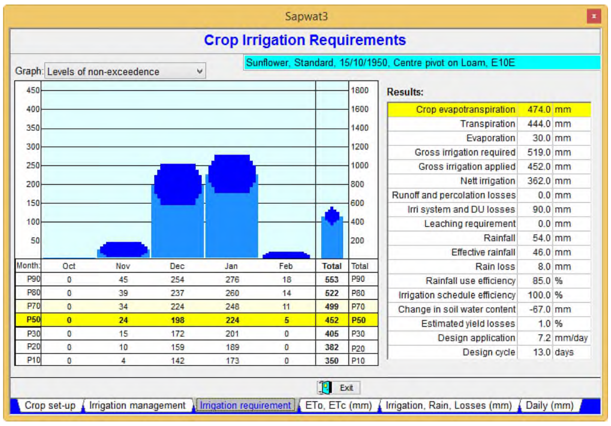


Figure 2-24 Sunflower planted 15 October in a mild, humid with hot summers climate. Expected to reach maturity in the first week of February

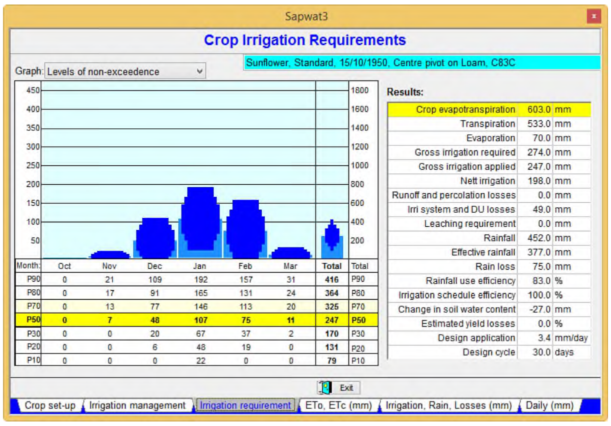


Figure 2-25 Sunflower planted 15 October in a mild, humid with warm summers climate. Expected to reach maturity in the third week of March

2.6 Conclusions

The weakest point in the SAPWAT3 crop irrigation requirement estimates is the crop coefficients and the lengths of the growth stages which are correct for some places, but incorrect at others. The main reason for this is that SAPWAT3 inherited its growth stage lengths from CROPWAT (Smith, 1992) and FAO 56 (Allen *et al*., 1998) where calendar time, and not thermal time, is used to define the duration of crop growth stages. The developers of SAPWAT3 tried to manage this problem for the South African situation by subdividing South Africa into seven geographic regions, each with implied climate characteristics, and linking crop growth and development to these areas. However, this did not work very well either, because geographic regions were not necessarily linked to only one climatic zone. A suitable climate classification system must be linkable to the SAPWAT3 weather stations and the climate must be definable on the basis of the weather data of the weather station. The climate definition must also be such that crop growth characteristics must be linkable to the defined climates. This led to the objectives listed at the beginning of the chapter, concerned with: a climate definition approach; reconstruction of the crop data tables; a methodology to compare crop growth data of these climatic zones to published data; as well as to growth data calculated using thermal time.

The Köppen climate system (Strahler and Strahler, 2002) was identified as a suitable system for use in SAPWAT3 because its climates are defined by temperature and rainfall combinations, data which are contained in the SAPWAT3 climate data tables. It was therefore possible to link each weather station location included in SAPWAT3 to a specific climate and then to link crop characteristics to each defined Köppen climate. Crop data tables were expanded from the single area-crop linkages as published in FAO 56 (Allen *et al*., 1998) to provide for crop growth and development data linked to the different Köppen climates. Where data to do the growth rate linkages to different climates were lacking, the current values were used across the different climates. This is a reflection of the pragmatic approach of the developers of SAPWAT3, which is to use available data and to update over time as more correct data becomes available.

However, the crop growth and development remained linked to calendar time and thus the problem of SAPWAT3 crops not necessarily growing at the same rate in different parts of the country persisted. A way still needs to be found to linking crop growth and development to thermal time and then translating those thermal time periods into calendar time for use in the SAPWAT3 irrigation requirement calculations. A thermal time calculator has been designed for use in SAPWAT3, in order to verify, and correct if necessary, crop growth stage times. However, this calculator is still under development and therefore not available for SAPWAT3 users as yet.

Thermal time research results are mostly defined in terms of crop growth stages, such as the number of leaves unfolded and also the change from vegetative to reproductive stages (Miller *et al*., 2001; Parthasarathi *et al*., 2013), none of which linked with the FAO four-stage crop growth curve. However, this problem can be managed by approximation and with field expertise. For example in maize, four leaves unfolded could be assumed to approximate 10% canopy cover and 12 leaves unfolded could approximate to 75% to 80% canopy cover. However, these assumptions need to be verified. In the case of maize the start of kernel denting could be assumed to approximate first sign of maturity, while full maturity is given from published thermal time data, and therefore presents no problem. These assumed approximations may not be perfectly correct, but on the positive side, it is at least better than what was available.

The newly designed and programmed evaluation and upgrading module for SAPWAT3 was tested on published thermal time data for maize, wheat and sunflower. After upgrading the SAPWAT3 data with thermal time based estimates, chi-squared testing showed that:

Maize: Heat unit calculated homogeneity is high (p=0.98) even though growth days were obviously different for different climate regions. This indicated that the heat unit approach was correct because temperature differences have comparable effects on crop growth and development. SAPWAT3 and FAO 56 data showed a high degree of similarity (p=0.99), but differences in crop growth periods is less pronounced than that of crop heat unit calculations and therefore possibly not correct.

Wheat: Comparing the SAPWAT3 spring wheat data with crop heat unit calculated data show a high degree of dissimilarity (P=0.70). FAO 56 data compared to crop heat unit calculations was even lower (P=0.01). For typical wheat planting date of late June, comparison of crop heat unit calculation to data published by the Agricultural Research Council - Small Grain Institute, show initial and development stages as too short by about 47 days for warmer areas and about 30 days for cooler areas of South Africa. This would imply flowering in middle September when frost danger is still high. The possibility that photoperiodism plays a role cannot be ignored (Mr Robbie Lindeque[7]). So in spite of heat units indicating anthesis, a "waiting" period should be included until day length reaches the correct number of hours and then the crop heat unit calculation should resume. Such an approach needs verification. It is foreseen that the newly developed crop heat unit calculator in SAPWAT3 needs to be expanded to also include photoperiodism requirements as part of its calculation routine.

Sunflower: Sunflower is perhaps not a very good example because it has only one entry in FAO 56, but the level of homogeneity is high.

Seen overall, it seems as if the newly designed heat unit calculator to be built into SAPWAT3 can provide useful results, provided that:

1. The linkage between crop growth stage – crop heat unit description be linked to the FAO four-stage crop growth curve; and,
2. The effect of photoperiodism and vernalisation, which influence crop growth and development, be fully researched for inclusion in the crop heat unit calculator of SAPWAT3 and then activated in the program.

The correcting of timing of crop growth stages has two very important implications:

[7] Mr Robbie Lindeque, Personal communication, 3 July 2014, Wheat breeder, Agricultural Research Council - Small Grain Institute, Bethlehem.

1. On the policy side, it affects the licensing of and registration for irrigation water use by the RSA Department of Water and Sanitation as too much or too little water might be allocated.
2. Incorrect irrigation water requirement estimates can have financial implications for the farmer. Systems that are under-designed because of incorrect irrigation water estimates, would not supply enough water and crop yield could be reduced due to water stress. If the irrigation requirement estimates are too large, unnecessary capital outlay for the farmer would result because the system would be over-designed and therefore with more capacity than required.

The incorporation of a fully-fledged heat unit calculator into SAPWAT3 to enable the user to improve crop growth stage periods, could improve the accuracy of SAPWAT3 results which will increase its usefulness and credibility.

CHAPTER 3
BUILDING SAPWAT3 INCLUDING UNDERLYING PRINCIPLES

3.1 Introduction

Equation Chapter (Next) Section 1Since the first SAPWAT (Crosby and Crosby, 1999) was developed in late 1990s, there have been major developments in computer technologies which are now also available to the general public. Although irrigation principles remain unchanged, the SAPWAT program needs some updating and improvements for it to be practically useful and to allow users to benefit from the integration and availability of many crops and varieties together with climate data in one simple programme. Therefore, the necessity for the actions described in this chapter. The following shortcomings were identified by users in both SAPWAT and its companion program PLANWAT (Van Heerden, 2004) and these required an upgrading of the program to rectify (Van Heerden *et al*., 2008). These included:

- SAPWAT did not save results data so the results had to be manually copied. PLANWAT was developed to address this problem, but the combination lacked sufficient interactivity; as a user could do a once-through crop irrigation requirement estimate, but could not do a rerun with different parameters without redoing a complete crop set-up.
- The SAPWAT-PLANWAT combination was awkward to use; the user had to start with PLANWAT and then run SAPWAT from within PLANWAT for this combination to work.
- SAPWAT-PLANWAT lacked the ability to link crop irrigation estimates to crop enterprise budgets in order to determine crop combinations suitable for an area under investigation that also made economic sense.
- SAPWAT-PLANWAT could not do consecutive year-on-year cycles for statistical analyses to determine long-term irrigation requirements with non-exceedance for different levels of assurance.

- SAPWAT-PLANWAT could not determine the ratio of water harvest area to planted area for in-field rainwater harvesting (Botha *et al*., 2003) purposes.
- Weather, crop, soil and irrigation system datasets in SAPWAT-PLANWAT were limited in scope and not easy to expand or adapt to provide for variations in local conditions.
- The SAPWAT-PLANWAT combination did not have the ability to export results datasets for use in other applications.

Therefore what was required was the combination of the programs SAPWAT and PLANWAT into a single, easily operated unit, and its upgrading to SAPWAT3 to fulfil the complete role as a planning aid for irrigation requirements of crops as described by Allen *et al*. (1998). Linked to this upgrading, identified shortcomings need to be addressed and overcome as far as practically possible.

3.2 Objectives

The following objectives were set for the development of SAPWAT3:

1. To integrate SAPWAT and PLANWAT into a user-friendly planning and teaching aid in relation to irrigation water requirements for use for the following applications: backyard and community gardens, crop fields, farms and water user associations.
2. To build an interactive module to calculate gross margin, based on the COMBUD approach, for use in conjunction with crop water requirements for selecting crop combinations.
3. To expand the PLANWAT water-harvesting module to include in-field rainwater harvesting calculations.
4. To provide comprehensive built-in datasets for crop, soil, irrigation systems and weather as required by SAPWAT to enable stand-alone operation or customisation.
5. To expand and upgrade climate and weather station data within SAPWAT to include the importation of both daily and monthly data from around the world.
6. To create data export capabilities in a variety of formats for use in other applications.

In the consideration of these objectives, the following should also be kept in mind:

- One of the objectives of the development of SAPWAT3 was that it should be used for teaching; therefore this chapter will also function as a user manual. The program therefore aimed at maximising user interaction as a means of increasing the user's understanding of the methodology of estimating irrigation water requirements, which includes easy access to the underlying theory. Therefore, the basic principles underlying the development of SAPWAT3 as described by Allen *et al*. (1998) are included instead of just being referred to as would otherwise be the case. The intention is that this chapter will be available and printed as a separate user manual.

- The level of accuracy of the results of the irrigation requirement estimations should be at a level that satisfies irrigation water use planning requirements, The whereas day-to-day irrigation water management (not the aim of SAPWAT3) usually requires a higher level of accuracy than that included in SAPWAT3 as a planning tool. Nevertheless, estimation correctness has not been compromised by this approach.

3.3 The SAPWAT3 programming approaches

The requirement at this stage for the development of SAPWAT3 was to satisfy these objectives and this work received funding from South African Water Research Commission (WRC Project No. K5/1578//4), as well as support from NRF Ph.D. student scholarship at the University of the Free State (2014-15). In order to accomplish the upgrade, some general principles and approaches need to be followed, including the importation and management of large volumes of data and to safeguard the data, resulting in a user-friendly program approach.

3.3.1 Reasons for changing the programming language

THE SAPWAT program was developed in stages and consequently sections were programmed and reprogrammed in different computer programming languages over time, which resulted in some instability and problems with future upgrading. SAPWAT3 is programmed in its entirety in dBase because of the program's data management capabilities and because it is a front-end data management programming language in its own right (Mayer, 2005; Mayer, 2007). dBase was one of the first and most successful database management systems for microcomputers. It includes a database engine, a query system, a forms engine, and a programming language. Its underlying file format, the `.dbf` file, is widely used in applications that use a simple format storage structure for data (Wikipedia, 2014d). A further consideration was that the resultant program, SAPWAT3, could be compiled into a program in its own right that do not need the installation of dBase on the user's computer.

3.3.2 Design overview

SAPWAT3 is designed as an interactive program, not one that would automatically do any number of recalculations in order to find an optimised design or management approach. The reasoning is that by making it interactive, it could contribute to the user's understanding of the underlying factors that influence irrigation efficiency, as well as the design and management of systems. It is furthermore designed as a shell that allows the user full functionality in the management of data. The motivation behind this approach is to give the user full control over the program and its data and to allow use of the program independent of the developer (Van Heerden *et al*., 2001; Van Heerden *et al*., 2008).

The structure of the program design is shown in Figure 3-1. Central to the design is the SAPWAT3 calculator which links weather data and crop data through the dual crop coefficient approach (K_{cb}+K_e) with reference evapotranspiration (ET_0) to calculate crop water requirement (ET_c) [$ET_c=(K_{cb}+K_e)\times ET_0$] (Allen *et al*., 1998). The result is then adapted to provide for the influence of irrigation system efficiency, soil water holding capacities, irrigation management strategy and rainfall to give an estimated irrigation requirement on a daily, weekly or monthly basis (Van Heerden *et al*., 2008).

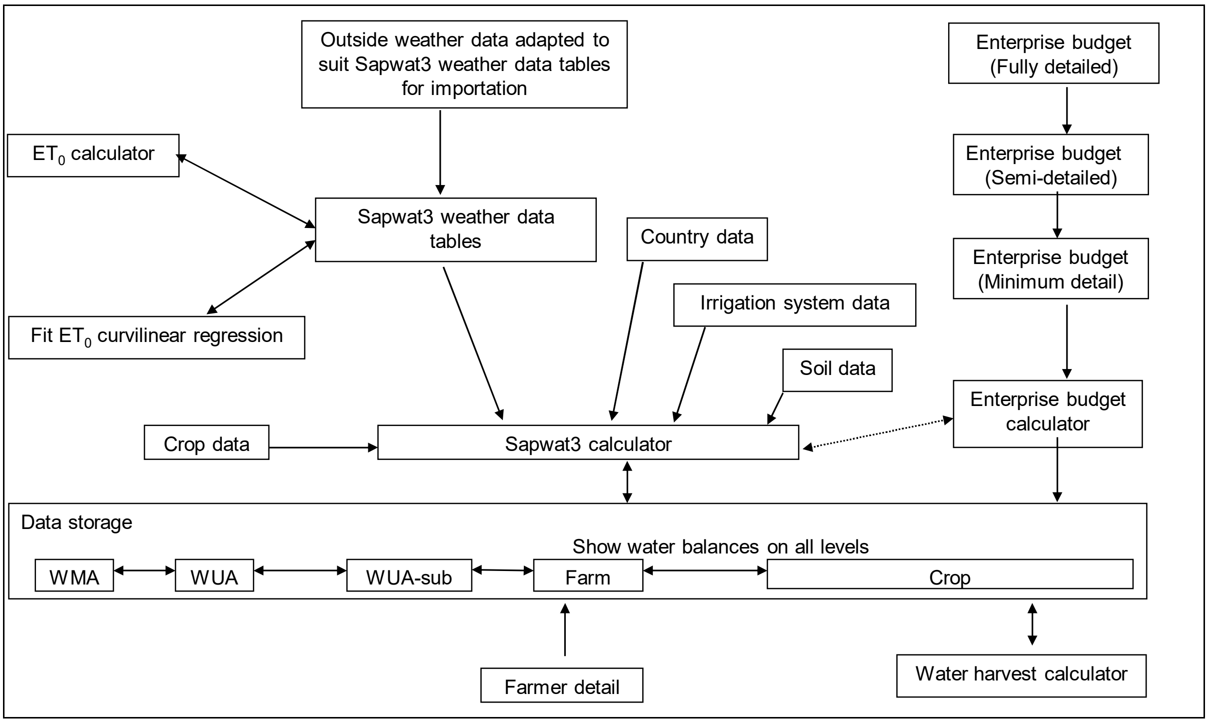


Figure 3-1 Diagrammatic layout of SAPWAT3 structure where WMA = water management area; WUA= water users association area; WUA-sub = water users association sub-area

Monthly and daily weather data can be imported or added manually. The ET_0 calculator calculates ET_0 values for the daily or monthly results and also fits a cosine curvilinear regression to the annual cycle of monthly ET_0 data (Snedecor and Cochran,1989) to enable the program to do daily water balance calculations, even in cases where available weather data are limited to monthly averages (Van Heerden *et al*., 2008).

Irrigation system data is incorporated, linking the default system efficiencies to the calculations so that the influence there-of can be incorporated into the irrigation requirement calculations (Reinders, 2010). Soil water holding capacities and leaching requirement also influence irrigation system design and irrigation water strategies, therefore a soils data table showing water holding capacities for different textured soils is included (Allen *et al*., 1998).

Parallel to the irrigation requirement estimates is a built-in ability to do crop enterprise budgets based on the COMBUD calculation scheme (DAEARD, 2011) so that the profitability of a crop can be estimated in conjunction with its irrigation water requirement as an aid to the farmer or adviser for crop selection within the framework of a specific irrigation water budget (Van Heerden *et al*., 2008).

For use on small plots of backyard garden scale, a water harvest calculator is included. It calculates water harvest sizes required, such as roof-tops, hard-packed earth or natural vegetation in order to determine required catchment size for a backyard vegetable patch. Linked to this is an indication of required storage volume of water and pumping hours with a low technology pump, such as a treadle pump (IPTRID, 2000) in order to supply water from storage to vegetables (Van Heerden *et al*., 2008).

Water user associations identified the need for storage and summation of crop irrigation requirement data to higher than farm-field levels. SAPWAT3 is therefore designed to not only store the estimated irrigation requirement of all crops, but also to sum data to a larger area so that the irrigation requirements of crops on the different fields of a farm would add up to a farm requirement. In the same way farm requirements would add up to the next higher level. This process is repeated up to the level of a central management agency area. In order to achieve this aim, the design levels were made on a hierarchical basis (Figure 3-2) which works well for the backward summation but does add to the complexity of the program for both developer and user. In many cases, the user is only interested in the irrigation requirement for a single crop for irrigation system design purposes, or for a single farm for purposes of irrigation water requirement planning.

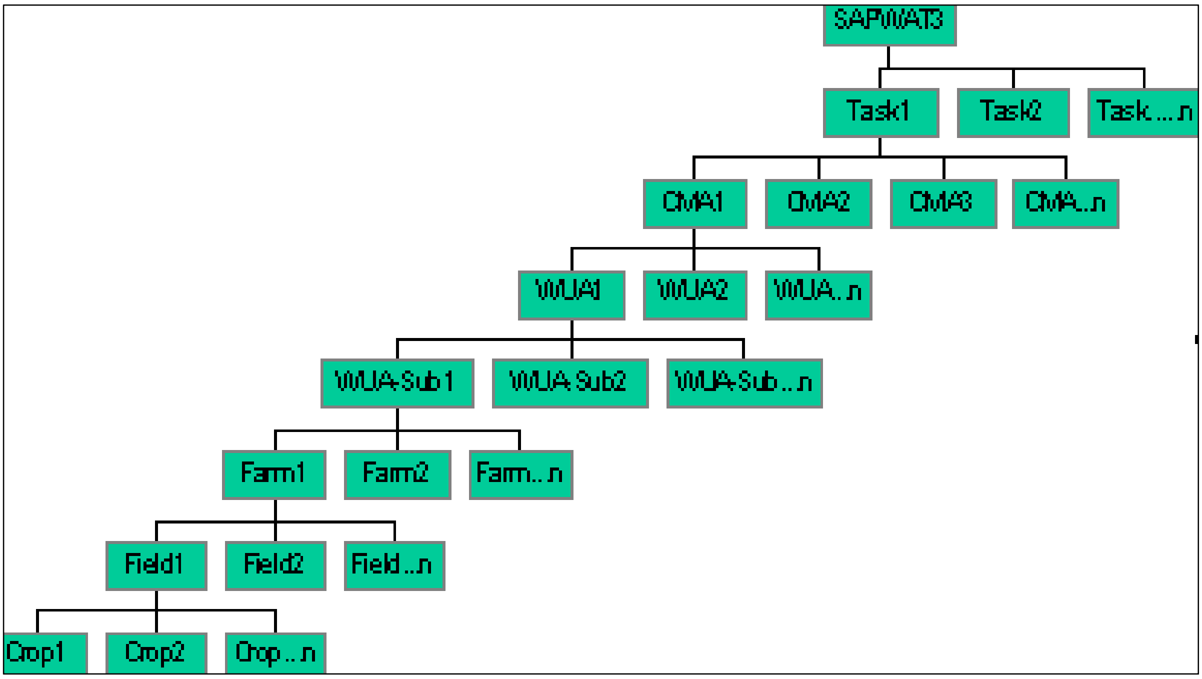


Figure 3-2 The hierarchical organisation of data in SAPWAT3 (CMA = catchment management agency; WUA= water users association area; WUA-sub = water users association sub-area)

The highest level, the 'Task#' plays the role of a container for keeping related projects together; from there the downward path through the hierarchy is through the central management agency (CMA#), water user association (WUA#), water user association sub-area (WUA-Sub#), through the farm to the field and the crop grown on a field (Van Heerden *et al*., 2008).

The hierarchical system CMA through WUA, WUA-sub to farm could be replaced by any other hierarchical system that suits a project. For example, in the South African case, it could be replaced by primary (Orange River basin), secondary (Hartbees River basin which drains into the Orange River), tertiary (Sak River basin which drains into the Hartbees River) and quaternary (Fish River basin which drains into the Sak River) drainage regions (Van Heerden *et al*., 2008).

3.4 Estimating crop irrigation requirements

It is generally assumed that if adequate rainfall is received during two-thirds of a growing season, the growing season would have enough water for most of the mesophytic crops usually grown by man. Otherwise at least some irrigation is required, although the amount required could vary, depending on the crops included in a crop production system (McMahon *et al*., 2002). However, the determination of the irrigation water requirement for each situation remains the main problem.

The approach for estimating crop water requirements is linking the crop through its crop coefficients to a reference evapotranspiration. Evapotranspiration refers to the combination of evaporation from soil surface and transpiration through the stomata of a leaf (Allen *et al*., 1998). The estimation of evapotranspiration has developed over time to the present acceptance of the FAO 56 Penman-Monteith equation, as the internationally accepted standard approach for determining reference evapotranspiration of a defined surface. The methodology has been published as FAO Irrigation and Drainage Paper No 56 with the evapotranspiration reference surface having been defined as (Allen *et al*., 1998):

> "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23."

In order to get the crop water requirement the calculated reference evapotranspiration (ET_0) needs to be linked to the crop for which a water requirement is to be determined. This is achieved through the use of a crop coefficient (K_c) that is defined for each of the four growth stages of the crop, then the sum gives an estimated crop water requirement or crop evapotranspiration (ET_c) (Equation 3.1) (Allen *et al*., 1998):

$$ET_c = K_c \times ET_0 \quad 3.1$$

where: ET_c crop evapotranspiration (mm d^{-1}),

K_c crop coefficient,

ET_0 reference evapotranspiration (mm d^{-1}).

SAPWAT3 makes use of the dual crop coefficient approach. The crop coefficient (K_c) is subdivided into smaller components; a basal crop coefficient (K_{cb}) and an evaporation coefficient (K_e) as has been identified by the expert consultation in Rome (Smith, 1991). Equation 3.1 then becomes Equation 3.2 (Allen *et al.*, 1998). This is this approach that is used in SAPWAT3 (Van Heerden *et al.*, 2008):

$$ET_c = \left(K_{cb} + K_e\right) ET_0 \quad 3.2$$

where: ET_c crop evapotranspiration (mm d^{-1}),

ET_0 reference evapotranspiration,

K_{cb} basal crop coefficient (lookup Cropdetail.dbf),

K_e soil evaporation coefficient (Equation 3.40).

The value of K_{cb} is read from a table (Cropdetail.dbf) which gives growing period lengths and K_{cb} values for different crops, while K_e is calculated from weather data. The total volume of water that can evaporate from a soil surface is influenced by soil water content, soil characteristics and canopy cover (Allen *et al.*, 1998).

Another equation that is central in the determination of crop irrigation requirements is the soil water balance equation. This equation balances the addition of water to a soil profile against the loss or extraction of water from the profile and can be used with either measured or calculated data – fully described in paragraph 3.4.5 (Allen *et al.*, 1998).

3.4.1 Irrigation strategy

SAPWAT3 provides the user with the possibility to define an irrigation strategy for each of the four crop growth stages. These can be any combination of fixed interval, such as weekly, or irrigation when a specified depletion of readily available soil water is reached, or to a fixed depth of irrigation or to refill the soil profile to a specific depth below field capacity. Refilling to a level below field capacity ensures space in the soil profile for the storage of rain water that may be received soon after an irrigation event (Table 3-1).

Table 3-1 Possible irrigation strategy combinations built into SAPWAT3

Growth stage	Irrigation cycle	Irrigation application
Initial	Fixed cycle (days)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
	Irrigate when depletion of readily available water (RAW) reaches specified level (%)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
Development	Fixed cycle (days)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
	Irrigate when depletion of RAW reaches specified level (%)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
Mid-season	Fixed cycle (days)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
	Irrigate when depletion of RAW reaches specified level (%)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
Late season	Fixed cycle (days)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)
	Irrigate when depletion of RAW reaches specified level (%)	Fixed application (mm)
		Refill to specified depth below field capacity (mm)

3.4.2 Calculating reference evapotranspiration (ET_0)

The Penman-Monteith equation for calculating reference evapotranspiration is (Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad 3.3$$

where:
- ET_0 reference evapotranspiration (mm d^{-1}),
- R_n net radiation at the crop surface (MJ m^{-2} d^{-1}) (Equation 3.32),
- G soil heat flux density (MJ m^{-2} d^{-1}) (Equation 3.33),
- T mean daily air temperature at 1.4 m height (˚C) (lookup Weatherdata.dbf, Equation 3.6),
- u_2 wind speed at 2 m height (m s^{-1}) (Equation 3.37),
- e_s saturated vapour pressure (kPa) (Equation 3.9),
- e_a actual vapour pressure (kPa) (Equation 3.11),
- e_s-e_a saturated vapour pressure deficit (kPa),
- Δ slope of vapour pressure curve (kPa ˚C^{-1}) (Equation 3.10),
- Υ psychrometric constant (kPa ˚C^{-1}) (Equation 3.4).

3.4.2.1 The psychrometric constant

The psychrometric constant (γ) relates the partial pressure of water in air to the air temperature (Wikipedia 2014e), which allows the interpolation of actual vapour pressure from paired dry and wet bulb temperature readings. The energy required to increase the temperature of a unit of air by one degree at constant pressure is referred to as its specific heat. The specific heat of the air is a variable, influenced by the humidity in the air. The psychrometric constant is kept constant for each selected weather station in SAPWAT3 because an average atmospheric pressure is used for each location (Allen *et al.*, 1998). The equation for calculating the psychrometric constant is:

$$\gamma=\frac{c_p P}{\varepsilon\lambda}=0.665\times10^{-3}P \qquad 3.4$$

where: Υ psychrometric constant (kPa°C^{-1}),

P atmospheric pressure (kPa) (Equation 3.5),

λ latent heat of vaporisation = 2.45 (MJ kg^{-1}),

c_p specific heat at constant pressure = 1.013 x 10^{-3} (MJ kg^{-1} °C^{-1}),

ε ratio molecular weight of water vapour / dry air = 0.622.

Atmospheric pressure (P) needs to be calculated before the psychrometric constant can be calculated, because it is an input into Equation 3.4. Atmospheric pressure is the pressure exerted by the weight of the earth's atmosphere at a specific location. As pressure declines with increased height above sea level, atmospheric pressure is directly related to elevation. It can be calculated as (Allen *et al.*, 1998):

$$P=101.3\left(\frac{293-0.0065z}{293}\right)^{5.26} \qquad 3.5$$

where: P atmospheric pressure (kPa),

z elevation above sea level (m) (lookup Weatherstations.dbf).

3.4.2.1.1 Application in SAPWAT3

SAPWAT3 calculates the psychrometric constant in the following sequence:

1. Read the elevation of the weather station from Weatherstations.dbf data table;
2. Uses the elevation of the weather station to calculate atmospheric pressure (Equation 3.5);

3. The psychrometric constant is then calculated using Equation 3.4.

3.4.2.2 Air temperature

Air temperature monitoring instruments are usually housed in Stevenson screens, 1.4 m above ground level. This places the thermometer at the height where the influence on crop growth and development can best be analysed. Thermographs or electronic data storage provides a record of maximum and minimum temperatures over time (Allen *et al*., 1998).

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \qquad 3.6$$

where: T_{mean} mean temperature (˚C),

T_{max} maximum temperature (˚C) (lookup Weatherdata.dbf),

T_{min} minimum temperature (˚C) (lookup Weatherdata.dbf).

3.4.2.2.1 SAPWAT3 use of this equation

SAPWAT3 applies Equation 3.6 to calculate mean temperature from recorded maximum and minimum daily temperature data contained in the SAPWAT3 weather data tables.

3.4.2.3 Air humidity

The water content of the air is usually expressed as vapour pressure, dew point, and/or relative humidity in agrometeorology. Water vapour is a gas and its pressure contributes to the total atmospheric pressure, which is measured in kPa. The amount of water in the air is directly related to the partial pressure exerted by the water vapour which is therefore a direct indicator of the water content of the air (Allen *et al*., 1998).

The humidity content of the atmosphere used by the Penman-Monteith equation is non-linear because of the non-linear nature of the changes in the capacity of the air to hold water vapour as temperature changes (Figure 3-3). The water vapour content of the air for a period should be computed as the mean between the vapour pressures at the daily maximum (T_{max}) and minimum (T_{min}) temperatures (Equation 3.6) (Allen *et al*., 1998).

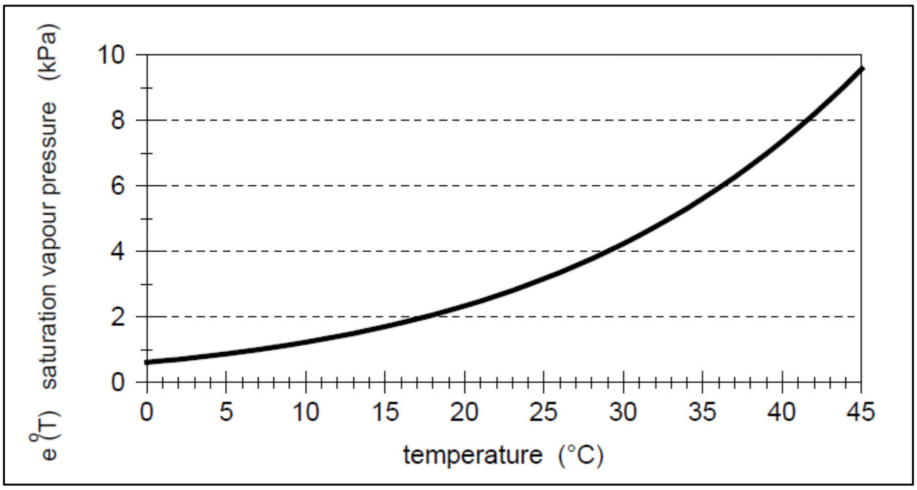


Figure 3-3 Saturated vapour pressure shown as a function of temperature (Allen *et al*., 1998)

Under still air conditions, air above an evaporative surface quickly reaches equilibrium between the water vapour contained in the air and the evaporative surface, a condition referred to as saturated vapour pressure. This results in a balance between the number of water molecules escaping from and those returning to the evaporative surface. The number of molecules that can be stored in the air depends on the temperature – the higher the air temperature, the more water molecules can be stored before the point of saturated vapour pressure is reached. The slope of the vapour pressure curve increases exponentially as the temperature increases. In the calculation of ET_0 from climate data, the slope of the saturated vapour pressure curve is an important parameter describing vaporisation (Allen *et al*., 1998).

The actual vapour pressure is the vapour pressure of the water vapour in the air. The difference between the saturated vapour pressure and the actual vapour pressure is called the vapour pressure deficit, which is an indicator of the evaporative capacity of the air. Dew point is the temperature to which the air temperature needs to be cooled to achieve saturated air conditions (Allen *et al*., 1998).

3.4.2.3.1 Relative humidity

The relative humidity expresses the degree to which the air is saturated with water vapour compared to saturated vapour pressure at that specific temperature. It is expressed as a ratio of saturated vapour pressure and is calculated with Equation 3.7 (Allen *et al*., 1998).

$$RH = 100 \frac{e_a}{e^0(T)} \qquad 3.7$$

where: RH relative humidity,

e_a actual vapour pressure (Equations 3.11, 3.12, 3.14, 3.15 or 3.16, depending on availability of data),

$e^0(T)$ saturated vapour pressure at the same temperature (Equation 3.8).

Relative humidity is dimensionless and is commonly indicated as a percentage. Although the actual vapour pressure might be fairly constant, throughout a day, the relative humidity fluctuates between a maximum at about sunrise when air temperature is usually at its lowest and reaches a minimum during early afternoon when temperature is usually at its highest (Figure 3-4) (Allen *et al*., 1998).

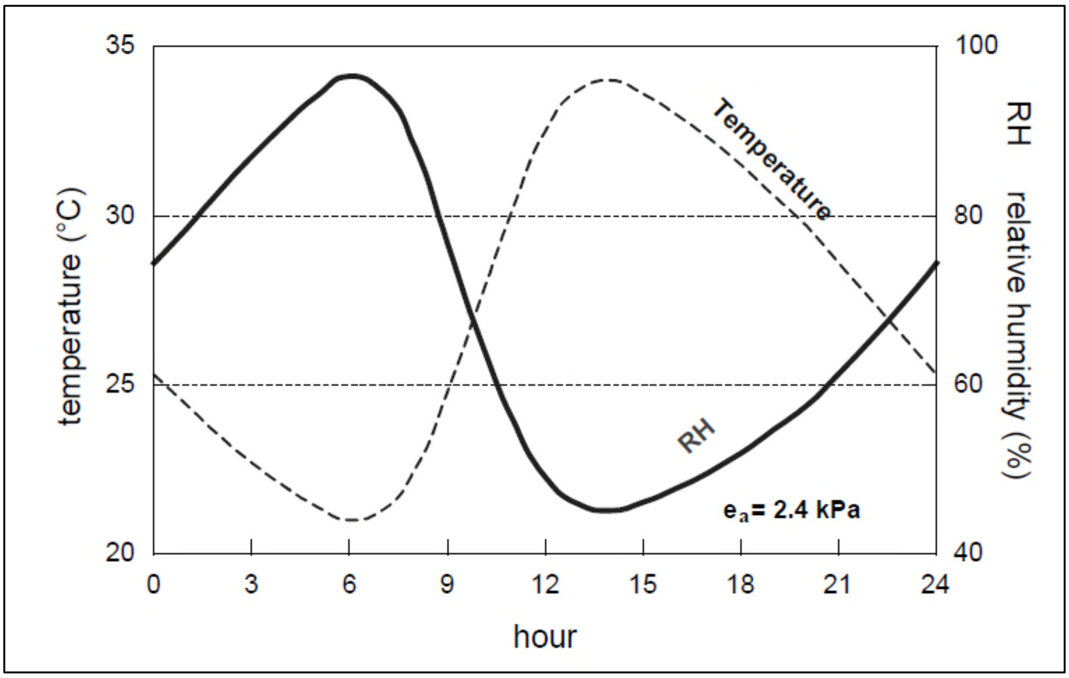


Figure 3-4 Variation of the relative humidity over 24 hours for a constant actual vapour pressure (e_a) of 2.4 kPa (Allen *et al*., 1998)

3.4.2.3.2 Mean saturated vapour pressure

The mean saturated vapour pressure is related to air temperature and can be calculated from the air temperature by Equation 3.8 (Allen *et al*., 1998):

$$e^0(T)=0.6108\exp\left(\frac{17.27T}{T+237.3}\right) \quad 3.8$$

where: $e^0(T)$ saturated vapour pressure at temperature T (kPa),

T air temperature (˚C) (lookup Weatherdata.dbf),

exp(..) 2.7183 (base of natural logarithm) raised to the power of (..).

Because of the non-linearity of the result of Equation 3.8 the mean saturated vapour pressure for a period needs to be calculated with Equation 3.9 (Allen *et al*., 1998):

$$e_s=\frac{e^0(T_{max})+e^0(T_{min})}{2} \quad 3.9$$

where: e_s mean saturated vapour pressure for period (kPa),

$e^0(T_{max})$ saturated vapour pressure at maximum temperature (kPa) (Equation 3.8),

$e^0(T_{min})$ saturated vapour pressure at minimum temperature (kPa) (Equating 3.8).

For the calculation of evapotranspiration the slope of the relationship between saturated vapour pressure and temperature is required. Equation 3.10 calculates the slope of the vapour pressure at temperature T (Allen *et al*., 1998).

$$\Delta=\frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \quad 3.10$$

where: Δ slope of the saturated vapour pressure curve at air temperature T (kPa ˚C^{-1}),

T air temperature (˚C) (lookup Weatherdata.dbf),

exp(..) 2.7183 (base of natural logarithm) raised to the power of (..).

3.4.2.3.3 Actual vapour pressure

The vapour pressure can be calculated by a number of different methods depending on the input data available. Actual vapour pressure can be derived from dew point; that is the temperature at which water vapour starts to condensate at ground level. Equation 3.11 uses dew point temperature to calculate actual vapour pressure (Allen *et al*., 1998).

$$e_a = e^0(T_{dew}) = 0.6108 \exp\left(\frac{17.27 T_{dew}}{T_{dew} + 237.3}\right) \quad 3.11$$

where: e_a actual vapour pressure (kPa),

$e^0(T_{dew})$ saturated vapour pressure at dew point temperature,

exp(..) 2.7183 (base of natural logarithm) raised to the power of (..).

An alternative approach for calculating actual vapour pressure is to use psychrometric data, as shown in Equation.3.12 (Allen *et al.*, 1998):

$$e_a = e^0(T_{wet}) - \gamma_{psy}(T_{dry} - T_{wet}) \quad 3.12$$

where: e_a actual vapour pressure (kPa),

$e^0(T_{wet})$ saturated vapour pressure at wet bulb temperature (kPa),

γ_{psy} psychrometric constant of the instrument (kPa˚C^{-1}),

$T_{dry} - T_{wet}$ wet bulb depression, with T_{dry} = dry bulb and T_{wet} = wet bulb temperature (˚C).

The psychrometric constant of the instrument is given by (Allen *et al.*, 1998):

$$\gamma_{psy} = a_{psy} P \quad 3.13$$

where: γ_{psy} psychrometric constant of the instrument (kPa˚C^{-1}),

P atmospheric pressure (kPa) (Equation 3.5),

a_{psy} coefficient depending on the type of ventilation of the wet bulb (˚C^{-1}).

a_{psy}= 0.000662 ventilated psychrometers: air movement of about 5 m s^{-1},

0.000800 ventilated psychrometer: air movement about 1 m s^{-1},

0.001200 non-ventilated psychrometers installed indoors.

A third alternative is to derive actual vapour pressure from relative humidity. Three approaches are possible, depending on availability of humidity data (Allen *et al.*, 1998).

- When RH_{max} and RH_{min} are available:

$$e_a = \frac{e^0\left(T_{min}\right)\frac{RH_{max}}{100} + e^0\left(T_{max}\right)\frac{RH_{min}}{100}}{2} \qquad 3.14$$

where: e_a actual vapour pressure (kPa),

$e^0(T_{min})$ saturated vapour pressure at daily minimum temperature (kPa) (Equation 3.8),

$e^0(T_{max})$ saturated vapour pressure at daily maximum temperature (kPa) (Equaiton 3.8),

RH_{max} maximum relative humidity (%) (lookup weatherdata.dbf),

RH_{min} minimum relative humidity (%) (lookup weatherdata.dbf).

For periods of days, RH_{max} and RH_{min} are obtained by dividing the sum of the daily values by the number of days.

- When RH_{min} is not available:

$$e_a = e^0(T_{min})\frac{RH_{max}}{100} \qquad 3.15$$

where: e_a actual vapour pressure (kPa),

$e^0(T_{min})$ saturated vapour pressure at daily minimum temperature (kPa) (Equation 3.8),

RH_{max} maximum relative humidity (%) (lookup weatherdata.dbf).

- When RH_{mean} is available:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^0\left(T_{max}\right) + e^0\left(T_{min}\right)}{2}\right] \qquad 3.16$$

where: e_a actual vapour pressure (kPa),

RH_{mean} mean relative humidity (%) (lookup weatherdata.dbf),

$e^0(T_{max})$ saturated vapour pressure at daily maximum temperature (kPa) (Equation 3.8),

$e^0(T_{min})$ saturated vapour pressure at daily minimum temperature (kPa) (Equation 3.8).

Once the actual vapour pressure is obtained, the vapour pressure deficit is calculated with Equation 3.17 (Allen *et al*., 1998):

$$\text{vapour pressure deficit} = e_s - e_a \qquad 3.17$$

where: e_s saturated vapour pressure (kPa) (Equation 3.9),
e_a actual vapour pressure (kPa) (Equation 3.16).

3.4.2.3.4 Application in SAPWAT3

SAPWAT3 goes through a series of steps to determine air humidity:

1. Saturated vapour pressure for maximum and minimum temperatures are calculated with Equation 3.8. Maximum and minimum temperatures are read from the weather data tables in SAPWAT3.
2. The mean saturated vapour pressure is then calculated with Equation 3.9.
3. The slope of the saturated pressure curve is calculated with Equation 3.10.
4. SAPWAT3 then calculates the actual vapour pressure from relative humidity which is available in the weather data table of SAPWAT3.
    a. If both RH_{max} data and RH_{min} data are available, actual vapour pressure is derived using Equation 3.14;
    b. If only RH_{max} data is available, Equation 3.15 is used;
    c. If only RH_{mean} data is available, Equation 3.16 is used.
5. The vapour pressure deficit is than calculated with Equation 3.17.

3.4.2.4 Radiation

Sunlight is a portion of the electromagnetic spectrum, in particular infrared, visible, and ultraviolet light. Sunlight is filtered through the earth's atmosphere, and when not blocked by clouds, it is experienced as sunshine, a combination of bright light and radiant heat. When it is blocked by clouds or reflects off other objects, it is experienced as diffused light. Sunlight is a key factor in photosynthesis by plants and other autotrophic organisms where radiant energy is converted into chemical energy that can be used to fuel the organisms' activities. The concept of radiation, originating at the sun as solar radiation, is made up of several sub-components (Figure 3-5) (Allen *et al*., 1998; Wikipedia, 2014f).

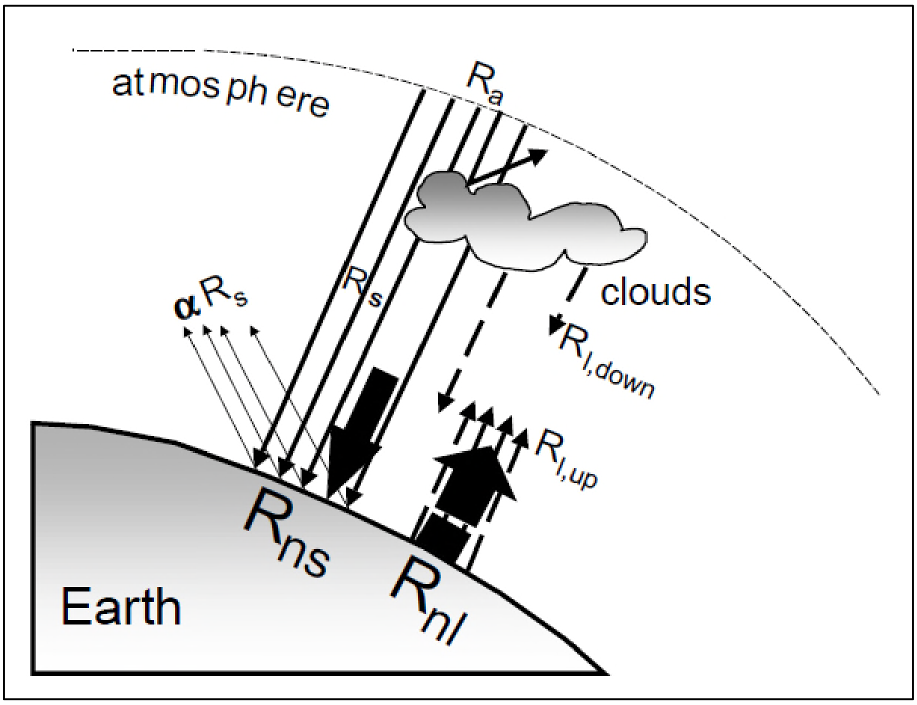


Figure 3-5 A diagrammatic representation of radiation, showing the sub-units that comprise it. (R_a = extra-terrestrial radiation; R_s = solar or shortwave radiation; R_{ns} net solar radiation; α = albedo; R_l = long wave radiation, with up and down components; R_{nl} = net long wave radiation) (Allen *et al*., 1998)

The standard unit to express energy received on a unit surface per unit time is usually indicated as mega-Joules per square metre per day (MJ m^{-2} d^{-1}). Extra-terrestrial radiation (R_a) is the reference amount to which actual solar energy measurements are compared. It is defined as the ideal amount of global horizontal radiation that a location would receive, provided that there is no atmosphere or cloud interception. The value of the extra-terrestrial solar radiation is 118 MJ m^{-2} d^{-1} (Allen *et al*., 1998; Wikipedia, 2014f).

Solar or shortwave radiation (R_s) is the radiation that reaches the earth's surface. During the process of atmospheric penetration, some of the incoming radiation is scattered, reflected or absorbed by the atmospheric gases, clouds and dust. On a cloudless day, solar radiation is approximately 75% of extra-terrestrial radiation, while it can be reduced to about 25% on a day with dense cloud cover. The ratio of the solar radiation that reaches a specific area of the earth's surface to the clear-sky solar radiation (R_{so}) is referred to as relative shortwave radiation (R_s/R_{so}). In the absence of a direct measurement of net radiation (R_n), the relative shortwave radiation is used in the computation of the net long wave radiation. Clear sky solar radiation is the radiation that would reach the same surface area during the same period, but under cloudless conditions. Relative shortwave radiation expresses the cloudiness of the atmosphere; the more clouds in the sky the smaller the ratio. Dense cloud cover would result in a value of about 0.33, while a clear sky would result in a ratio of one. Solar radiation is the sum of direct shortwave radiation from the sun and diffuse sky radiation (Allen *et al*., 1998).

Cloudiness of the atmosphere is expressed as relative sunshine duration (n/N) where n is the actual duration of sunshine on a specific day and N is the maximum possible duration of sunshine or daylight hours for that specific day (need date and latitude for calculation). In the absence of clouds the actual duration of sunshine is equal to the daylight hours (n = N) and the ratio is one. If R_s is not measured, the relative sunshine duration (n/N) is often used to derive solar radiation from extra-terrestrial radiation, using measured daylight hours and potential day light hours derived from the date and latitude of the place of interest (Allen *et al*., 1998). Sunshine duration may be measured or recorded using a sunshine recorder, pyranometer or pyrheliometer (Wikipedia, 2014f).

Not all solar radiation is absorbed by the earth's surface; some is reflected back into the atmosphere (α = albedo). Albedo is highly variable for different surfaces and with the slope of the ground surface. Freshly fallen snow, with a high reflectance, may reach an albedo value of 0.95, while the albedo of wet, bare soil may be as low as 0.05. A green canopy has an albedo of about 0.20 - 0.25. The defined green grass reference crop's albedo is 0.23. Net solar radiation (R_{ns}) is the fraction of the solar radiation that is not reflected from the surface. Its value is calculated as $(1-\alpha)R_s$ (Allen *et al*., 1998).

Solar radiation absorbed by the earth is converted to heat energy, which is eventually lost again to the atmosphere by several processes, including emission, as long wave radiation. Emitted long wave radiation ($R_{l,up}$) is lost into space or is absorbed by the atmosphere. The temperature of the atmosphere is increased by the absorbed long wave radiation and, as a consequence, the atmosphere radiates energy of its own, some of which is radiated back to the earth's surface ($R_{l,down}$). The surface of the earth is therefore both emitter and receiver of long wave radiation. The difference between outgoing and incoming long wave radiation is called the net long wave radiation (R_{nl}). The outgoing long wave radiation is almost always greater than the incoming long wave radiation; therefore net long wave radiation represents an energy loss (Allen *et al*., 1998).

Net radiation (R_n) is the balance between the energy absorbed, reflected and emitted by the surface of the earth or the difference between the incoming net short wave (R_{ns}) and the net outgoing long wave (R_{nl}) radiation. Net radiation is normally positive during the day and negative during the night. The total daily value for net radiation is almost always positive over a period of 24 hours, with the total amount (direct and indirect from the atmosphere) hitting the ground of approximately 97 MJ m^{-2} d^{-1}. However, in extreme conditions at high latitudes this position could be reversed, with the value of net radiation becoming negative (Allen *et al*., 1998; Wikipedia, 2014f).

In the estimation of evapotranspiration all terms of the energy balance should be considered. The soil heat flux (G) is the energy that is utilized to heat the soil and is positive when the soil is warming and negative when the soil is cooling down. Although the soil heat flux is small compared to net radiation (and may often be ignored), the amount of energy gained or lost by the soil in this process should be added to or subtracted from the net radiation when estimating evapotranspiration (Allen *et al*., 1998).

3.4.2.4.1 Extra-terrestrial radiation for daily periods

The extra-terrestrial radiation (R_a) for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by (Allen *et al*., 1998):

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s) \right] \qquad 3.18$$

where: R_a extra-terrestrial radiation (MJ m^{-2} d^{-2}),

G_{sc} solar constant (0.0820 MJ m^{-2} d^{-2}),

d_r inverse relative distance Earth-Sun (Equation 3.21),

ω_s sunset hour angle (rad) (Equation 3.23 or Equation 3.24),

φ latitude (rad) (Equation 3.20),

δ solar declination (rad) (Equation 3.22).

The corresponding equivalent evaporation in mm d^{-1} is obtained by (Allen *et al*., 1998):

$$\text{equivalent evaporation} = 0.408 \times R_a \qquad 3.19$$

where: Equivalent evaporation equivalent evaporation (mm d-1),

R_a extra-terrestrial radiation (MJ m^{-2} d^{-2}) (Equation 3.18).

Latitude (φ) expressed in radians, is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degrees to radians is given by (Allen *et al*., 1998):

$$\text{Rad}=\frac{\pi}{180}\left[\text{decimal degrees}\right] \qquad 3.20$$

where: Rad — radians,

Decimal degrees — degrees expressed in decimal format (lookup Weatherstations.dbf).

The inverse relative Earth-Sun distance is given by (Allen *et al*., 1998):

$$d_r=1+\cos\left(\frac{2\pi}{365}J\right) \qquad 3.21$$

where: d_r — inverse relative distance Earth-Sun,

J — number of the day of year (Jan1 = 1).

The solar declination is given by (Allen *et al*., 1998):

$$\delta=0.409\sin\left(\frac{2\pi}{365}J\text{-}1.39\right) \qquad 3.22$$

where: δ — solar declination (rad),

J — number of the day of year (Jan 1 = 1).

The sunset hour angle is given by:

$$\omega_s=\arccos\left[-\tan\left(\varphi\right)\tan\left(\delta\right)\right] \qquad 3.23$$

where: ω_s — sunset hour angle (rad),

φ — latitude (rad) (Equation 3.20),

δ — solar declination (rad) (Equation 3.22).

As the arcos function is not available in all computer languages, the sunset hour angle can also be computed, using the arctan function (Allen *et al*., 1998)

$$\omega_s = \frac{\pi}{2} - \left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}} \right] \qquad 3.24$$

where: ω_s sunset hour angle,

φ latitude (rad) (lookup Weatherstations.dbf, Equation 3.20),

δ solar declination (rad) (Equation 3.22),

X $\max\left(0.00001, \left\{1 - \left[\tan(\varphi)\right]^2 \left[\tan(\delta)\right]^2\right\}\right)$.

3.4.2.4.2 Maximum possible daylight hours

The maximum possible daylight hours for a given latitude on a specific day is given by (Allen *et al*., 1998):

$$N = \frac{24}{\pi} \omega_s \qquad 3.25$$

where: N maximum possible daylight hours,

ω_s sunset hour angle (rad) (Equation 3.24).

3.4.2.4.3 Solar radiation

Solar radiation can be calculated with the Angstrom equation which relates solar radiation to extra-terrestrial radiation and relative sunshine duration. This equation is to be used if solar radiation has not been measured (Allen *et al*., 1998).

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \qquad 3.26$$

where: R_s solar or shortwave radiation (MJ m^{-2} d^{-1}),

n actual duration of sunshine (hour) (lookup Weatherdata.dbf),

N maximum possible duration of sunshine or daylight hours (h) (Equation 3.25),

n/N relative sunshine duration,

R_a extra-terrestrial radiation (MJ m^{-2} d^{-1}) (Equation 3.27),

a_s regression constant, expressing fraction of extra-terrestrial radiation reaching earth on overcast days (n=0),

a_s+b_s fraction of extra-terrestrial radiation reaching earth on clear days (n=N).

In case data for the calculation of solar radiation is missing it can also be derived from air temperature differences by making use of the Hargreaves radiation equation (Allen *et al.*, 1998):

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}\,R_a \qquad 3.27$$

where: R_s solar or shortwave radiation (MJ m^{-2} d^{-1}),
R_a extra-terrestrial radiation (MJ m^{-2} d^{-1}) (Equation 3.18),
T_{max} maximum air temperature (˚C) (lookup Weatherdata.dbf),
T_{min} minimum air temperature (˚C) (lookup Weatherdata.dbf),
k_{Rs} adjustment coefficient (0.16 – 0.19).

Use of the k_{Rs} coefficient is advised as follows (Allen *et al.*, 1998):

- For interior locations where land mass dominates : $k_{Rs} \approx 0.16$;
- For locations on or adjacent to the coast of large land masses: $k_{Rs} \approx 0.19$.

3.4.2.4.4 Clear sky solar radiation

Clear sky radiation (R_{so}) calculation when n=N is required for the computation of long wave radiation. If values for a_s and b_s are available, R_{so} can be calculated with (Allen *et al.*, 1998):

$$R_{so} = (a_s + b_s)R_s \qquad 3.28$$

where: R_{so} clear sky solar radiation (MJ m^{-2} d^{-1}),
R_s solar or short wave radiation (MJ m^{-2} d^{-1}) (Equation 3.27),
a_s regression constant, expressing fraction of extra-terrestrial radiation reaching earth on overcast days (n-0),
a_s+b_s fraction of extra-terrestrial radiation reaching earth on clear days (n=N).

If values for a_s and b_s are not available, R_{so} can be calculated with (Allen *et al.*, 1998):

$$R_{so} = (0.75 + 2\times10^{-5}z)R_a \qquad 3.29$$

where: R_{so} clear sky solar radiation (MJ m^{-2} d^{-1}),
R_a extra-terrestrial radiation (MJ m^{-2} d^{-1}) (Equation 3.18),
z station elevation above sea level (m) (lookup Weatherstations.dbf).

3.4.2.4.5 Net solar or net short wave radiation

The net solar radiation resulting from the balance between incoming and reflected solar radiation is given by (Allen *et al*., 1998):

$$R_{ns}=\left(1\text{-}\alpha\right)R_s \qquad 3.30$$

where: R_{ns} net solar radiation (MJ m^{-2} d^{-1}),

R_s solar or short wave radiation (MJ m^{-2} d^{-1}) (Equation 3.27),

α albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop (dimensionless).

3.4.2.4.6 Net long wave radiation

The rate of long wave energy emission is proportional to the absolute temperature and is expressed quantitatively by the Stefan-Boltzmann law. The net energy flux leaving the earth's surface is less than that emitted and given by the Stefan-Boltzmann law due to the absorption and downward radiation from the sky. Net long wave radiation can be calculated by (Allen *et al*., 1998):

$$R_{nl}=\sigma\left[\frac{T_{max,K}{}^4+T_{min,K}{}^4}{2}\right]\left(0.34\text{-}0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}}\text{-}0.35\right) \qquad 3.31$$

where: R_{nl} net outgoing long wave radiation (MJ m^{-2} d^{-1}),

σ Stefan Boltzmann constant ($4.903*10^{-9}$ MJ K^{-4} m^{-2} d^{-1}),

$T_{max,K}$ maximum absolute temperature during the 24-hour period (K=°C+273.16) (lookup Weatherdata.dbf),

$T_{min,K}$ minimum absolute temperature during the 24-hour period (K=°C+273.16) (lookup Weatherdata.dbf),

e_a actual vapour pressure (kPa) (Equation 3.16),

R_s measured or calculated solar radiation (MJ m^{-2} d^{-1}) (Equation 3.27),

R_{so} calculated clear sky radiation (MJ m^{-2} d^{-1}) (Equation 3.29).

3.4.2.4.7 Net radiation

Net radiation (R_n) is the difference between the incoming net short wave radiation and the outgoing long wave radiation and can be calculated as follows (Allen *et al*., 1998):

$$R_n = R_{ns} - R_{nl} \qquad 3.32$$

where: R_n net radiation (MJ m^{-2} d^{-1}),

R_{ns} incoming net short wave radiation (MJ m^{-2} d^{-1}) (Equation 3.30),

R_{nl} net long wave radiation (MJ m^{-2} d^{-1}) (Equation 3.31).

3.4.2.4.8 Soil heat flux

Soil heat flux is small relative to net radiation, particularly when the surface is covered with vegetation. The equation for calculating soil heat flux is (Allen *et al*., 1998):

$$G = c_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z \qquad 3.33$$

where: G soil heat flux (MJ m^{-2} d^{-1}),

c_s soil heat capacity (MJ m^{-3} $°C^{-1}$),

T_i air temperature at time i (˚C) (lookup Weatherdata.dbf),

T_{i-1} air temperature at time i-1 (˚C) (lookup Weatherdata.dbf),

Δt length of time interval (day),

Δz effective soil depth (m) (0.1 – 0.15 m: SAPWAT3 uses 0.10 m).

As the magnitude of the daily soil heat flux beneath the grass reference surface is relatively small, it may be ignored and therefore (Allen *et al*., 1998):

$$G_{day} \approx 0 \qquad 3.34$$

If a constant soil heat capacity of 2.1 MJ m^{-3} $°C^{-1}$ and an appropriate soil depth and if $T_{month,i}$ is known, Equation 3.33 can be adapted to Equation 3.35 for monthly calculations (Allen *et al*., 1998):

$$G_{month,i} = 0.07\left(T_{month,i+1} - T_{month,i-1}\right) \qquad 3.35$$

where: $G_{month,i}$ soil heat flux for month i (MJ m^{-2} d^{-1}),

$T_{month,i+1}$ mean air temperature of month i+1 (˚C) (lookup Weatherdata.dbf),

$T_{month,i-1}$ mean air temperature of previous month (˚C) (lookup Weatherdata.dbf).

If $T_{month,I}$ is unknown, Equation 3.33 can be adapted to Equation 3.36 for monthly calculations (Allen *et al*., 1998):

$$G_{month,i} = 0.14\left(T_{month,i} - T_{month,i-1}\right) \qquad 3.36$$

where: $G_{month,i}$ soil heat flux for month i (MJ m^{-2} d^{-1}),

$T_{month,i}$ mean air temperature of month i (˚C) (lookup Weatherdata.dbf),

$T_{month,i-1}$ mean air temperature of previous month (˚C) (lookup Weatherdata.dbf).

3.4.2.4.9 Application in SAPWAT3

For the calculation of net radiation at the crop surface for inclusion in the reference evapotranspiration calculation (Equation 3.3), SAPWAT3 does the following (Allen *et al*., 1998):

1. Convert the latitude degrees decimal value of the weather station to radians with a built-in computer function (radians = dtor(degrees-decimal)).
2. Calculate the inverse relative distance earth- sun (Equation 3.21).
3. Calculate solar declination (Equation 3.22).
4. Calculate sunset hour angle (Equation 3.23).
5. Calculate daylight hours (Equation 3.25).
6. Calculate extra-terrestrial radiation (Equation 3.18).
7. Calculate solar radiation if not included in weather data table:
    a. If sunshine hours is given (Equation 3.26).
    b. If sunshine hours is not given (Equation 3.27).
8. Calculate clear sky radiation (Equation 3.28).
9. Calculate net shortwave radiation (Equation 3.30).
10. Calculate net long wave radiation (Equation 3.31).
11. Calculate the net radiation (Equation 3.32).
12. Soil heat flux is calculated as:
    a. If weather data interval is monthly (Equation 3.36);
    b. If weather data interval is daily, soil heat flux is assumed to be zero (Equation 3.34)

3.4.2.5 Wind

Wind is characterised by speed and direction. Both these characteristics can be highly variable during the course of a day, therefore it is necessary to indicate wind speed as an average over a time period. This is calculated from daily measured wind run passing a specific point, which is converted to a daily value in kilometre run per day or average wind speed in metres per second. Wind speed measured at different heights is also different, and in agriculture it is usual to measure wind speed above canopy level. A measurement height of 2 m is the accepted norm. Wind speeds measured at other heights needs to be converted to wind speed at 2 m height (Equation 3.37) (Allen *et al.*, 1998).

$$u_2 = u_z \frac{4.87}{\text{int}(67.8z - 5.42)} \tag{3.37}$$

where: u_2 wind speed at 2 m above ground surface (m s^{-1}),

u_z wind speed measured at z m above ground surface (m s^{-1}) (lookup Weatherdata.dbf),

z height of measurement above ground surface (m) (lookup Weatherstations.dbf).

3.4.2.5.1 Application in SAPWAT3

If wind speed is not given in the weather data tables an assumed average speed of 2 m s^{-1} is used as default (Allen *et al.*, 1998). In the case of South African weather stations the default is 1.6 m s^{-1} (Schulze and Maharaj, 2006).

3.4.3 Crop coefficients

SAPWAT3 makes use of the dual crop coefficient, where the crop coefficient (K_c) is split into its component parts, the basal crop coefficient (K_{cb}) and the evaporation coefficient (K_e) which is calculated with Equation 3.40. Lookup tables are used to get basal crop coefficients for crops planted in different climates and for different planting or regrowth dates.

A lot of attention needs to be given to crop coefficient values, specifically peak values. There is a tendency to accept the default crop coefficient curve or table value as a given physiological characteristic of a crop. Unrealistic or incorrectly applied crop coefficients are probably the main reason for inaccurate estimates of irrigation requirements. The ideal would have been to simulate crop grow with an appropriate model, so that stage length will react to planting date and climate. However, this is not possible in a program of this nature, because of the comprehensive inputs required to simulate crop growth. The use of short grass reference evapotranspiration reduces the impact of climatic variation on crop water use, but has no influence on the length of growth stages.

The solution applied in SAPWAT (Crosby and Crosby, 1999) was to subdivide South Africa into seven agro-climatic regions and to develop default crop coefficients for each of these regions, specifically with adapted growing periods for the four stages to reflect warmer or colder climates. Where knowledge of growth reaction or temperature was not known well enough, growth periods were accepted as being the same for the different regions, irrespective of warmer or colder climates. Default planting dates for each region and crop are also specified and where planting date has a noticeable influence on growth stages, individual crop files were developed according to planting month per region. Where noticeable differences between cultivars (e.g. early or late) are found, each is handled as a separate crop in SAPWAT3. The crop coefficient file was developed according to rules derived with the help of crop scientists. Validation of these values takes place continuously and is based on practices in the field and on the experience of irrigation consultants. The default crop coefficient files provide for manipulations as discussed. The seven agro-climatic regions for South Africa have now been superseded by the change to the Köppen-Geiger approach to standardized climatic regions (chapter 2) that form the background of the update of crop coefficient data for SAPWAT3.

The crop coefficients included in the SAPWAT3 crop data tables, (cropdetail.dbf), provide for crops that have different growing periods for the same crop type, such as early (Aug 15), medium (Sep 1) or late (Sep 21) bud break for deciduous fruit, short growing cultivars (about 110 days) or medium growing cultivars (about 140 days) for maize. Furthermore, it provides for different planting dates because temperatures experienced by late planted crops differ from those for early planted crops, or crops $K_{c\ max}$ period falls within a rainy period or outside a rainy period, which impacts on irrigation water requirement. The crop characteristic values for peaches and maize are shown as examples in Figure 3-6 and Figure 3-7.

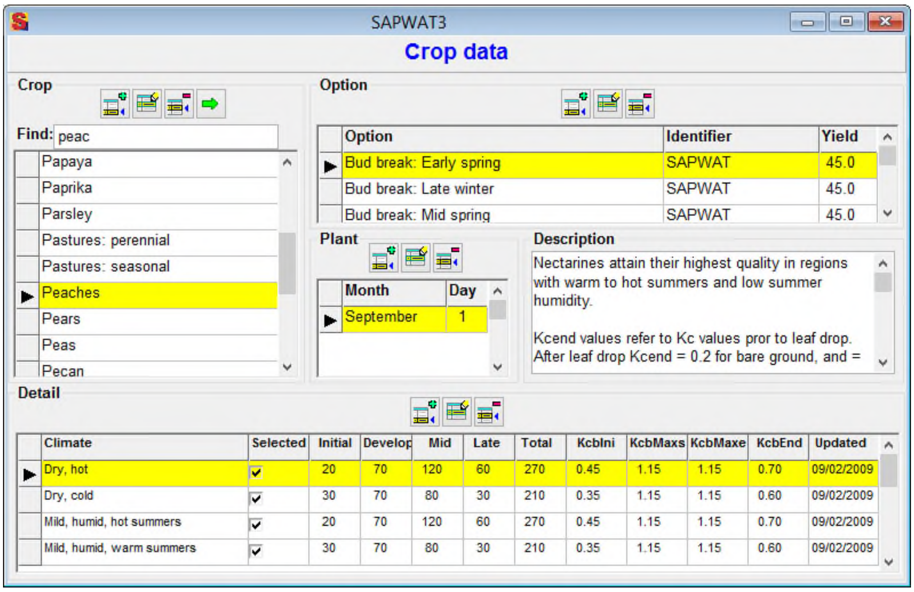


Figure 3-6 Crop data screen showing crop characteristics for peaches, early spring bud break, for different climates

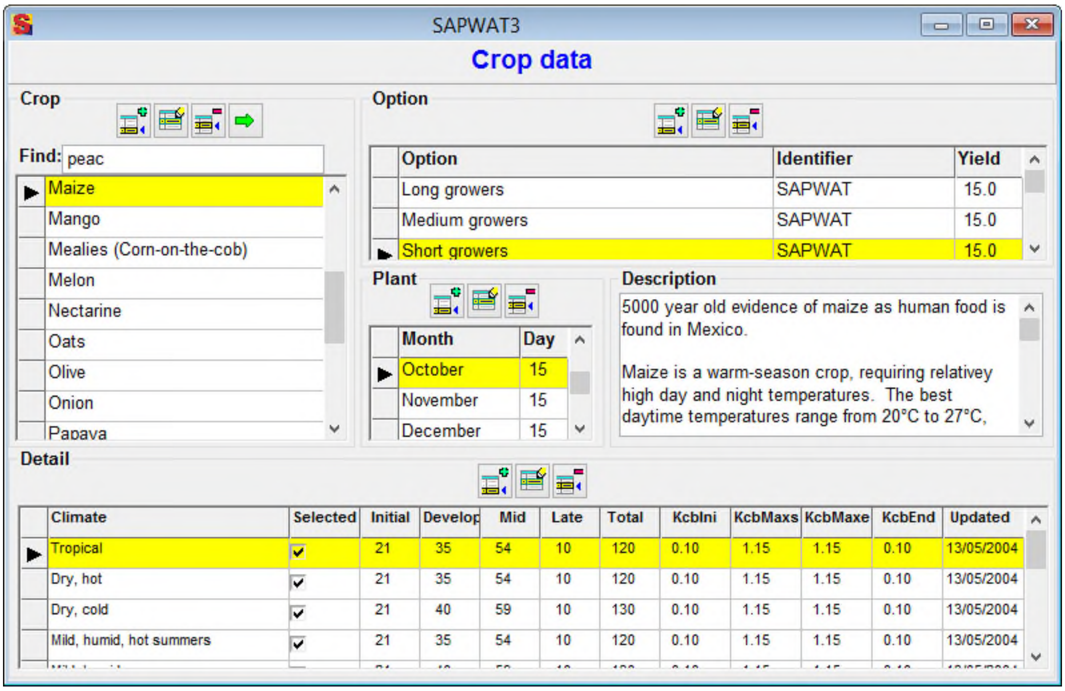


Figure 3-7 Crop data screen showing crop characteristics for maize, short grower, planted October 15, for different climates

A problem exists because the growth periods are expressed as calendar days and the full impact of temperatures on growing periods might not be adequately reflected in the FAO 56 crop characteristics tables (Allen *et al.*, 1998), a problem that has been inherited by both SAPWAT and SAPWAT3. This problem and possible ways of correcting it are more fully discussed in Chapter 2. In the interim, the authors of SAPWAT3 have decided to take a pragmatic approach to this problem; that is to use available data for the program and to refine the data as and when more correct crop characteristics become available, instead of omitting such data.

3.4.3.1 Application in SAPWAT3

While doing the crop set-up for calculating irrigation water requirements, the user selects a crop, a crop option and a planting date. SAPWAT3 does a look-up on the crop data and links it to a climate which is linked to the selected weather station. Relevant data concerning growing periods and crop coefficients are then looked up in the crop detail table by the program and used where required.

3.4.4 Soil surface evaporation

Where the topsoil is wet following rain or irrigation the evaporation component of the dual crop coefficient approach ($K_e.ET_0$) is at a maximum. As the soil surface becomes drier, soil surface evaporation is reduced until a level of no practically measurable evaporation is reached. Evaporation occurs predominantly from the exposed soil fraction. Hence, evaporation is restricted at any moment by the energy available at the exposed soil fraction; therefore K_e cannot exceed $f_{ew}.K_{c\ max}$, where f_{ew} is the fraction of soil from which most evaporation occurs, i.e. the fraction of the soil not covered by vegetation and wetted by irrigation or precipitation (Allen *et al*., 1998; Stroosnijder, 1987).

Evaporation from the soil surface can be assumed to take place in two stages: an energy limiting stage, and a falling rate stage (Ritchie 1972). When the soil surface is wet, K_r (dimensionless evaporation reduction coefficient) is 1. When the water content in the upper soil layer becomes limiting, K_r decreases and becomes zero when the total amount of water that can be evaporated from the topsoil is depleted (Allen *et al*., 1998).

In the simple evaporation procedure it is assumed that the water content of the evaporation layer of the soil is at field capacity (θ_{FC}), shortly following a major wetting event and that the soil can dry to a water content level that is halfway between oven dry (no water left) and wilting point (θ_{WP}). The amount of water that can be depleted by evaporation during a complete drying cycle can hence be estimated as (Allen *et al*., 1998):

$$TEW=1000(\theta_{FC}-0.5\theta_{WP})Z_e \qquad 3.38$$

where TEW total evaporable water = maximum depth of water that can be evaporated from the soil when the topsoil has been completely wetted (mm),

θ_{FC} soil water content at field capacity ($m^3\ m^{-3}$),

θ_{WP} soil water content at wilting point ($m^3\ m^{-3}$),

Z_e depth of surface soil layer that is subject to drying by way of evaporation (0.10 – 0.15 m).

When unknown, a value for Z_e, - the effective depth of the soil evaporation layer - of 0.1 to 0.15 m is recommended by Allen *et al*. (1988). SAPWAT3 uses 0.1 m as default soil evaporation layer for Z_e.

Figure 3-8 shows Kr as a function of cumulative soil surface evaporation (Allen *et al*., 1988).

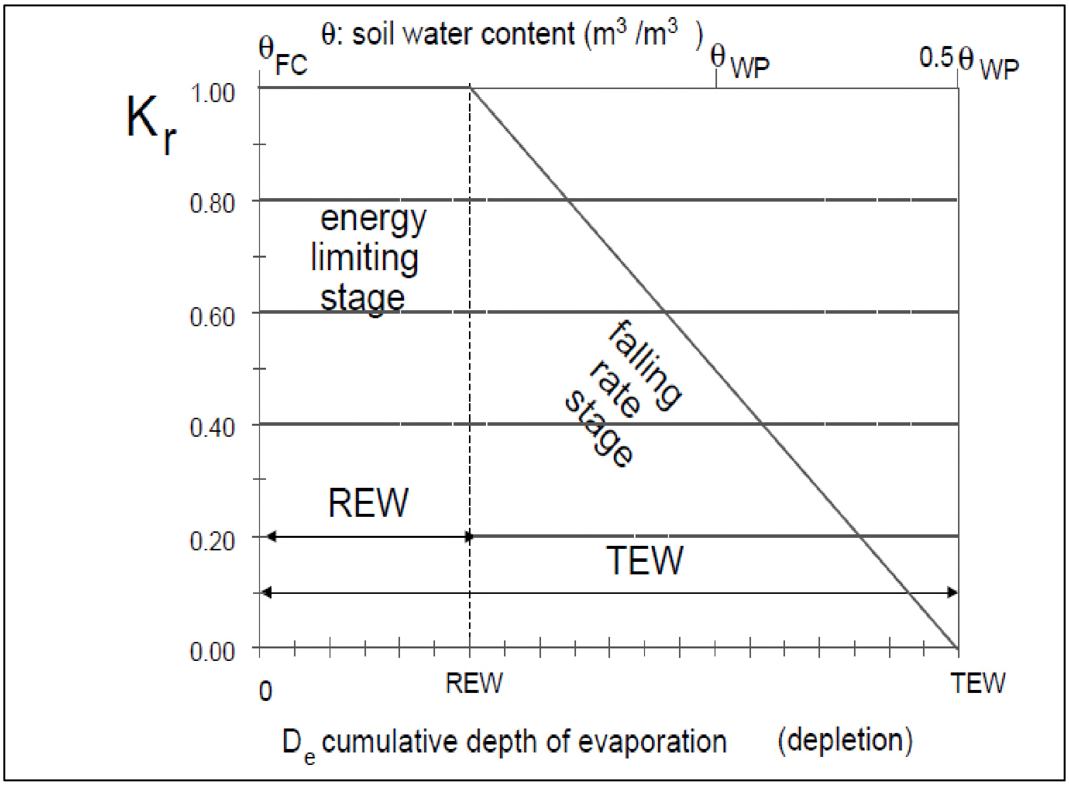


Figure 3-8 Soil evaporation reduction coefficient, K_r. The effect of the two stages, the energy limiting stage and the falling rate stage of soil surface evaporation (Allen et al., 1998) (REW = readily evaporable water; TEW = total evaporable water; K_r = dimensionless evaporation coefficient)

The evaporation reduction coefficient (K_r) can be calculated with (Allen *et al*., 1998):

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \qquad 3.39$$

Where K_r Dimensionless evaporation coefficient dependent on the soil water depletion (cumulative depth of evaporation) from the topsoil layer (K_r = 1 when $D_{e,i-1} \leq$ REW),

$D_{e,i-1}$ Cumulative depth of evaporation (depletion) from the soil surface layer at the end of day $_{i-1}$ (the previous day) (mm),

TEW Total Evaporative Water. Maximum cumulative depth of evaporation (depletion) from the soil surface layer when Kr = 0 (mm),

REW Readily Evaporative Water: Cumulative depth of evaporation (depletion) at the end of stage 1 soil surface evaporation (mm).

Following rain or irrigation K_r = 1 until the limit of the readily evaporative water content is reached, after which K_r decreases as the water content in the soil is lowered. The amount of evaporable water from different soils is indicated in Table 3-2 on page 129 (Allen *et al*., 1998).

The evaporation coefficient (K_e), which is linked to ET_0 to calculate soil surface evaporation, is calculated by SAPWAT3 with Equation 3.40 (Allen *et al*., 1998):

$$K_e = K_r (f_{ew} K_{c\,max} - K_{cb}) \leq f_{ew} K_{cmax} \qquad 3.40$$

where: K_e soil evaporation coefficient,

K_{cb} basal crop coefficient (lookup Cropdetail.dbf),

$K_{c\,max}$ maximum value of k_c following rain or irrigation (Equation 3.42),

K_r dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depletion (evaporated) from the top soil (Equation 3.39),

f_{ew} fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs (Equation 3.43).

$K_{c\ max}$ is the upper limit of evapotranspiration from a cropped surface and is imposed to reflect the natural constraint placed on available energy represented by the energy balance equation (Equation 3.41) (Allen *et al*., 1998).

$$\lambda ET = R_n - G - H \qquad 3.41$$

where: λET latent heat flux (MJ m^{-2} d^{-1}),
R_n net radiation (MJ m^{-2} d^{-1}),
G soil heat flux (MJ m^{-2} d^{-1}),
H sensible heat (MJ m^{-2} d^{-1}).

$K_{c\ max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_0 and is calculated with Equation 3.42 (Allen *et al*., 1998) by SAPWAT3 before calculating the evaporation coefficient with Equation 3.40 where its value is used as an input.

$$K_{c\ max} = \max\left(\left\{1.2 + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, \left\{K_{cb} + 0.05\right\}\right) \qquad 3.42$$

where: $K_{c\ max}$ maximum value of k_c following rain or irrigation,
K_{cb} basal crop coefficient from data table,
u_2 wind speed at 2 m height (m s^{-1}),
RH_{min} daily relative minimum humidity (%),
h mean maximum plant height during the period of calculation (initial, development, mid-season, or late season) (m).

Equation 3.42 ensures that $K_{c\ max}$ is always greater than or equal to the sum of (K_{cb} + 0.05). The result is that a wet soil will always increase the value of K_{cb} by 0.05 following a complete wetting of the soil by irrigation or rain, even under full canopy cover (Allen *et al*., 1998).

Soil surface evaporation takes place from exposed, wetted soil. In crops with partial canopy cover, such as found in orchards, evaporation is not uniform; it is more on the portion of the soil surface not covered by the crop canopy. This situation is complicated by situations where only partial wetting of the soil surface takes place, such as strip irrigation by micro or drip irrigation systems. Where the full surface is wetted, such as under full cover sprinkler systems, the fraction of the soil from which most evaporation takes place (f_{ew}) is defined as ($1-f_c$), where f_c is the average fraction of the soil covered by the crop canopy and ($1-f_c$) is the exposed soil surface. In this case f_{ew} must be limited to f_w the fraction wetted and $(1-f_{ew})$ is the fraction not wetted by irrigation. Considering both wetted area and area covered by canopy, the wetted area is calculated as (Allen *et al*., 1998):

$$f_{ew} = \min(1-f_c, f_w) \qquad 3.43$$

where: f_{ew} surface of the soil not wetted,

$1-f_c$ exposed soil fraction not covered by vegetation,

f_w fraction of soil wetted by irrigation.

The relationship between canopy cover and wetted area is illustrated in Figure 3-9 (Allen *et al*., 1998).

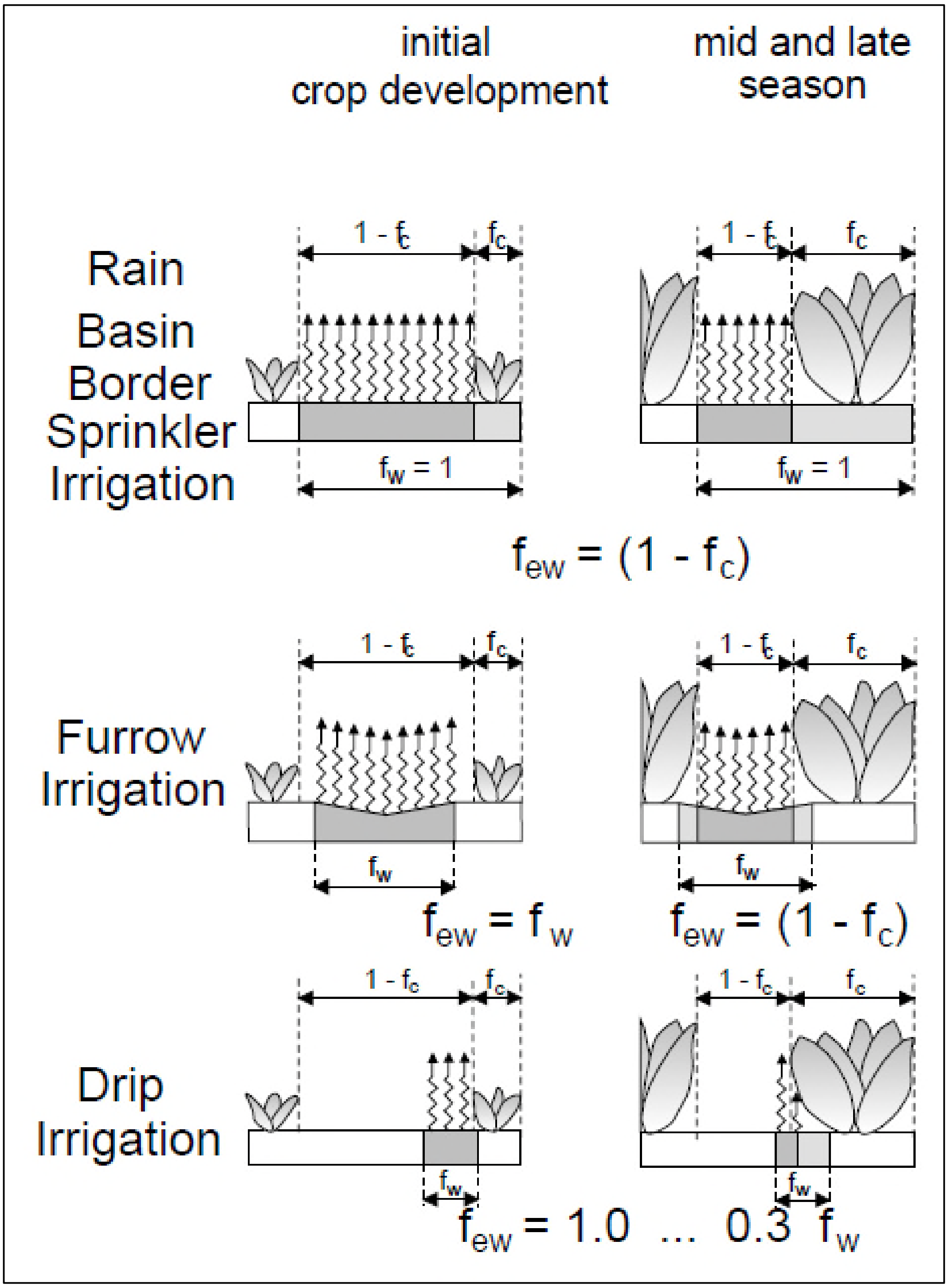


Figure 3-9 Determination of variable f_{ew} (cross hatched areas) as a function of the fraction of ground surface cover (f_c) and the fraction of the surface wetted (f_w) area (Allen *et al*., 1998)

Where f_c is not measured, it can be estimated with Equation 3.44 (Allen *et al*., 1998)

$$f_c = \left(\frac{K_{cb} - K_{cmin}}{K_{cmax} - K_{cmin}} \right)^{(1+0.5h)} \quad 3.44$$

where: f_c the effective fraction of soil surface covered by vegetation (0-0.99),

K_{cb} the value for the basal crop coefficient for the particular day,

$K_{c\,min}$ the minimum K_c for dry, bare soil with no ground cover (≈0.15),

$K_{c\,max}$ the maximum K_c immediately following wetting (Equation 3.42),

h mean plant height (m).

The estimation of K_e in the calculation process requires a daily water balance calculation for the surface layer of the soil to determine the cumulative evaporation or depletion from the wet condition.

3.4.5 Soil water balance

A thorough understanding of the soil water balance and the factors that influence it is essential if one is to understand irrigation. It can be mathematically described (Equation 3.45) and is diagrammatically represented in Figure 3-10 (Allen *et al*., 1998; Bennie *et al*., 1998):

$$\Delta D = I + (P - RO) - E - T + CR - DP \pm SF \quad 3.45$$

Where ΔD change in soil water content,

I irrigation,

P precipitation,

RO run-off,

E soil surface evaporation,

T crop transpiration,

CR capillary rise,

DP deep percolation,

SF sub-surface flow.

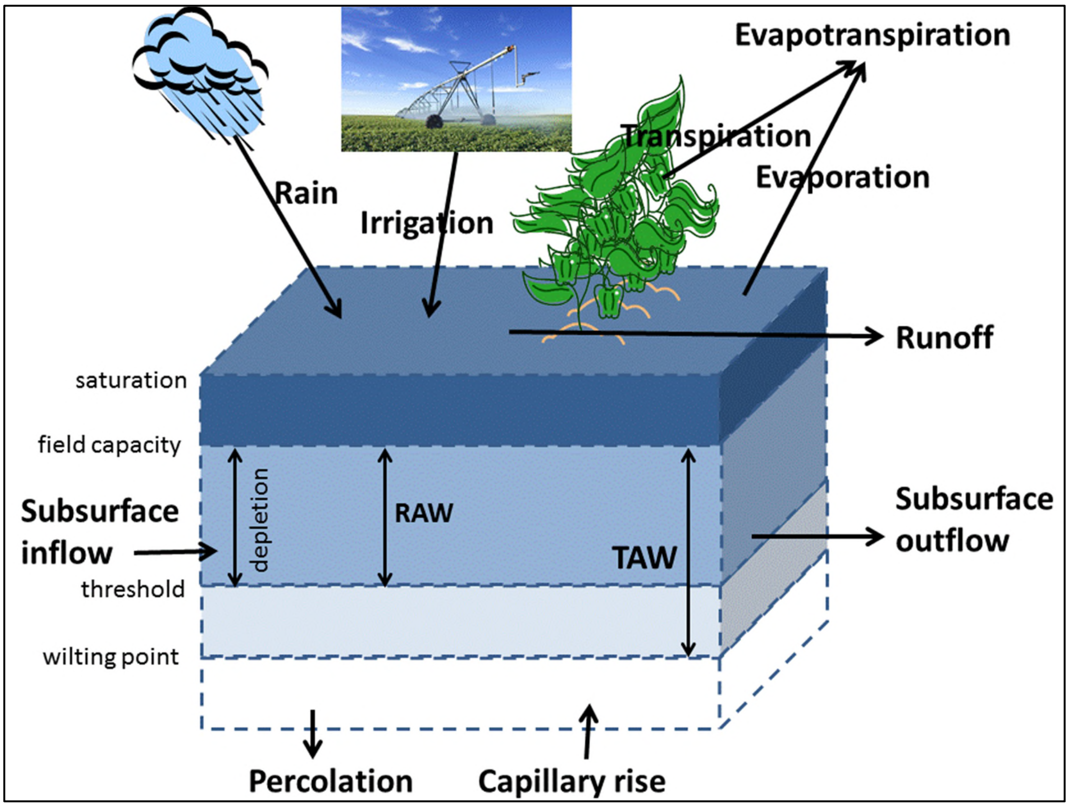


Figure 3-10 A diagrammatic representation of the soil water balance in the root zone of crop (Allen *et al*., 1998)

Figure 3-10 show that addition of water to a profile as coming from rain, irrigation and capillary rise, while the extraction of water is through evapotranspiration (transpiration and soil surface evaporation) and deep percolation. Runoff from soil surface does not add to the soil water content in this block of soil and is usually subtracted from rainfall. The amounts of rainfall, transpiration and soil surface evaporation are linked to the climate of the area, while capillary rise and deep percolation are mainly influenced by soil parameters and water management on the irrigated and surrounding areas. What are also diagrammatically shown are the concepts of:

Field capacity (θ_{FC})	The amount of water that a soil can hold after all free water has been allowed to drain out of the root zone. Also referred to as drained upper limit (Ratliff *et al*., 1982).
Wilting point (θ_{WP})	The water level in root zone at which plants will be permanently wilted.
Depletion	The amount of water depleted out of the root zone through evapotranspiration.
RAW	Readily available water – amount of water available to a crop without crop undergoing stress situations – indicated

as "threshold" in Figure 3-10 (mm);

TAW — Total available water – total amount of plant available water a soil can hold in root zone (UNITS mm)?

Typical values for θ_{FC}, θ_{WP} and TEW are given in Table 3-2.

Table 3-2: Typical soil water characteristics for different soil types (Allen *et al*., 1998) (TEW = total evaporable water; REW = readily evaporable water)

Soil type	Soil water characteristics			Evaporation parameters	
				Amount of water that can be depleted by evaporation	
	θ_{FC} (m^3/m^3)	θ_{WP} (m^3/m^3)	$\theta_{FC} - \theta_{WP}$ (m^3/m^3)	REW (mm)	TEW (Z_e = 0.1 m) (mm)
Sand	0.07 – 0.17	0.02 – 0.07	0.05 – 0.11	2 – 7	6 – 12
Loamy sand	0.11 – 0.19	0.03 – 0.10	0.06 – 0.12	4 – 8	9 – 14
Sandy loam	0.18 – 0.28	0.06 – 0.16	0.11 – 0.15	6 – 10	15 – 20
Loam	0.20 – 0.30	0.07 – 0.17	0.13 – 0.18	8 - 10	16 – 22
Silt loam	0.22 – 0.36	0.09 – 0.21	0.13 – 0.19	8 – 11	18 – 25
Silt	0.28 – 0.36	0.12 – 0.22	0.16 – 0.20	8 – 11	22 – 26
Silt clay loam	0.30 – 0.37	0.17 – 0.24	0.13 – 0.18	8 – 11	22 - 27
Silty clay	0.30 – 0.42	0.17 – 0.29	0.13 – 0.19	8 – 12	22 – 28
Clay	0.32 – 0.40	0.20 – 0.24	0.12 – 0.20	8 – 12	22 - 29

Allen *et al*. (1998) has refined the soil water balance equation (Equation 3.45) for the top soil layer (0.1 – 0.15 m) so that evaporation from this layer can also be taken into account (Figure 3-11; Equation 3.46). This adaptation allows for the fractional wetting of a soil such as found in soils under drip and micro irrigation systems, and the influence of evaporation from a fraction of the soil surface instead of from the complete surface. Capillary rise and subsurface flow have been left out of this equation, because both are difficult to measure at field level during short time spans. In order to calculate the water balance from the deeper soil layers, the value of soil surface evaporation (E_i/f_{ew}) in Equation 3.46 becomes zero. The value of f_{ew} also tends to become zero as canopy cover increases to full cover. A further element that limits the depth of evaporation is the limit set in Equation 3.46, where in the case of SAPWAT3, a limit of 0.10 m has been set (Allen *et al*., 1998).

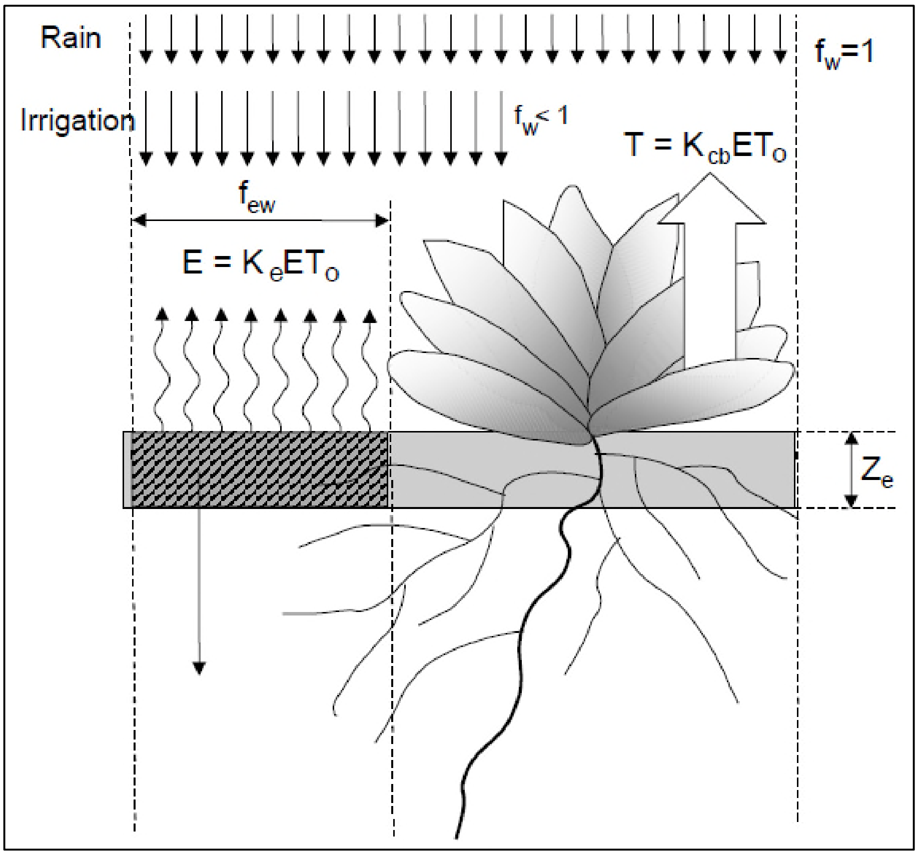


Figure 3-11 A graphic representation of the water balance of the topsoil layer, where Z_e = topsoil layer

$$D_{e,i}=D_{e,i-1}-(P_i-RO_i)-\frac{I_i}{f_w}+\frac{E_i}{f_{ew}}+T_{ew,i}+DP_{e,i} \quad 3.46$$

where:
- $D_{e,i}$ cumulative depth of evaporation (depletion) following complete wetting at the end of day i (mm),
- $D_{e,i-1}$ cumulative depth of evaporation (depletion) following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1 (mm),
- P_i precipitation on day i (mm),
- RO_i precipitation runoff from the soil surface on day i (mm),
- I_i irrigation depth on day i that infiltrates the soil (mm),
- f_w fraction of soil surface wetted by irrigation,
- E_i evaporation on day i (mm),
- f_{ew} exposed an wetted soil fraction,
- $T_{ew,i}$ depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i (mm),
- $DP_{e,i}$ deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity (mm).

Traditionally the level of allowed depletion has been given a default value of 50% of TAW for most crops (Green, 1985). This has been reviewed and the default depletion level varies from crop to crop, mainly depending on rooting depth. Default depletion levels are included in the crops data table (Table 3-16), but during calculation of irrigation requirement, these values are adapted for each daily calculation on the basis of atmospheric demand. The higher the atmospheric demand, the lower the allowed depletion level, and *vice versa*. In SAPWAT3 the allowed depletion level is calculated with Equation 3.47 with set outer boundaries of 0.1 and 0.8 (Equation 3.48) (Allen *et* al., 1998).

$$p=p_{table}+0.04(5-ET_c) \qquad 3.47$$

With

$$0.1 \le p \le 0.8 \qquad 3.48$$

Where p depletion fraction,

p_{table} data tables default depletion fraction for crop,

ET_c crop evapotranspiration.

3.4.5.1 Leaching requirement

One way of managing salinity problems in soil is to leach excess salts to below root zone by applying more water than the crop requirement. Excess salt is then removed and taken into the deeper soil layers in solution with the water that percolates to below root zone – a process referred to as leaching. The calculation approach is to determine a fraction of the irrigation water that would be needed to leach the salts (Equation 3.49) (Allen *et al.*, 1998):

$$LF=\frac{EC_{iw}}{5EC_e-EC_{iw}} \qquad 3.49$$

where LF leaching fraction = fraction of irrigation water required for leaching,

EC_e electrical conductivity threshold value of soil saturation extract where yield reduction due to salinity starts (Table 3-3) (dS m^{-1}),

EC_{iw} electrical conductivity of irrigation water (Irrifield.dbf) (dS m^{-1})

3.4.5.2 Application in SAPWAT3

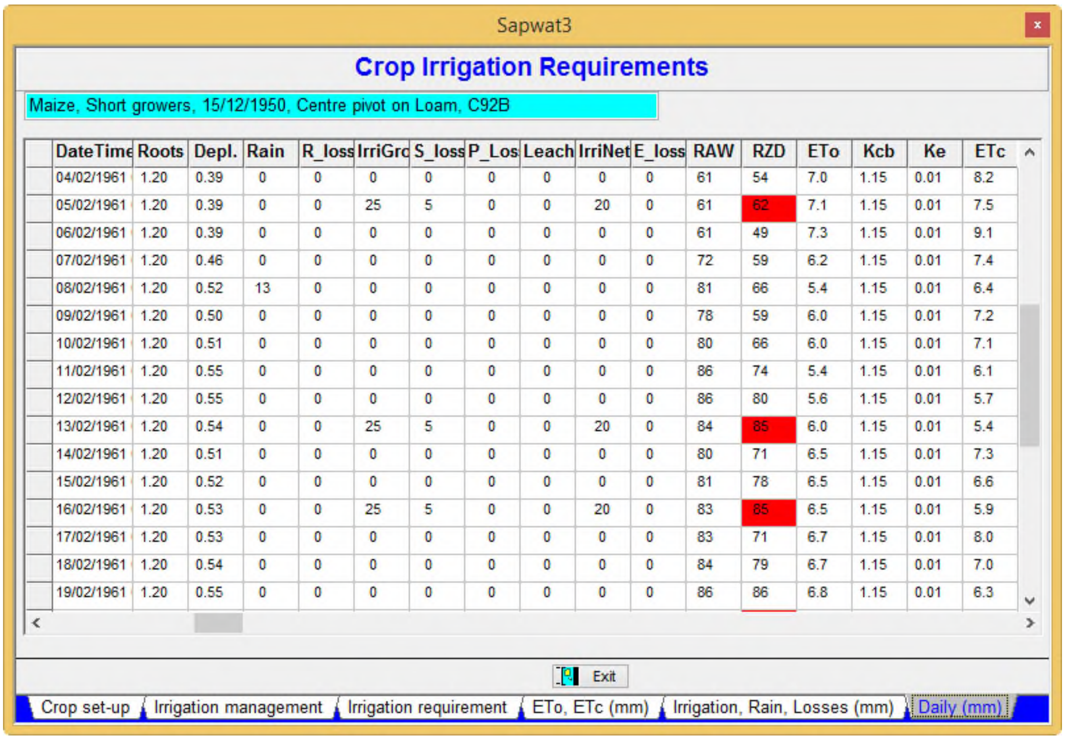
SAPWAT3 does a daily water balance calculation using the adapted soil water balance equation (Equation 3.46). During each daily cycle soil surface evaporation and transpiration calculations are done as follows:

- Calculate leaching fraction at start for application during each round of calculation;
- Canopy cover is increased linearly from zero to 10% during the initial stage and from 10% to maximum canopy cover as specified by the user in the crop set-up data table at the end of the development stage;
- Irrigation wetted fraction is read from the field data table – default value from the irrigation systems table, or as adapted by the user (Irrisystems.dbf);
- Calculate the exposed and wetted area from which evaporation takes place (Equation 3.43);
- Calculate the soil reduction coefficient (K_r):
    - If a value for evaporable water is available and greater than soil table readily evaporable water value: $K_r = 1$;
    - If a value for evaporable water is available and smaller than soil table readily evaporable water value: K_r is calculated (Equation 3.39);
    - If a value for evaporable water is not available: $K_r = 0$.
- Calculate the evaporation coefficient (Equation 3.40).

At the completion of the soil evaporation calculation, the rest of the water balance calculation is done during each daily calculation cycle:

- At the end of each daily calculation cycle is tests for satisfaction of the irrigation strategy definition (Table 3-1) for the growth stage relevant at that time. The values of variables of the soil water equation are noted and a new round is started with these values as starting values.

If the irrigation strategy definition is satisfied, an irrigation is simulated, the values of all relevant variables are tabled (Irricrop3.dbf) and a new irrigation cycle is started. Detail can be seen in Figure 3-12. Cells with a red background are days when soil water depletion puts the plant under stress. However, it will be noted that the soil water content does not seem to have the same value for stress situations, this is because the level at which stress appears, can vary with atmospheric demand; at high atmospheric demand levels stress will occur earlier that at lower atmospheric demand levels. As SAPWAT3 cycles through the daily soil water balance calculations, atmospheric demand for the specific day is used to determine depletion levels by using Equations 3.47 and 3.48 (Allen *et al*., 1998). On completion of the seasonal irrigation water requirement calculation all relevant data are totalled and shown on screen (Figure 3-24).



DateTime	Roots	Depl.	Rain	R_loss	IrriGro	S_loss	P_Los	Leach	IrriNet	E_loss	RAW	RZD	ETo	Kcb	Ke	ETc
04/02/1961	1.20	0.39	0	0	0	0	0	0	0	0	61	54	7.0	1.15	0.01	8.2
05/02/1961	1.20	0.39	0	0	25	5	0	0	20	0	61	62	7.1	1.15	0.01	7.5
06/02/1961	1.20	0.39	0	0	0	0	0	0	0	0	61	49	7.3	1.15	0.01	9.1
07/02/1961	1.20	0.46	0	0	0	0	0	0	0	0	72	59	6.2	1.15	0.01	7.4
08/02/1961	1.20	0.52	13	0	0	0	0	0	0	0	81	66	5.4	1.15	0.01	6.4
09/02/1961	1.20	0.50	0	0	0	0	0	0	0	0	78	59	6.0	1.15	0.01	7.2
10/02/1961	1.20	0.51	0	0	0	0	0	0	0	0	80	66	6.0	1.15	0.01	7.1
11/02/1961	1.20	0.55	0	0	0	0	0	0	0	0	86	74	5.4	1.15	0.01	6.1
12/02/1961	1.20	0.55	0	0	0	0	0	0	0	0	86	80	5.6	1.15	0.01	5.7
13/02/1961	1.20	0.54	0	0	25	5	0	0	20	0	84	85	6.0	1.15	0.01	5.4
14/02/1961	1.20	0.51	0	0	0	0	0	0	0	0	80	71	6.5	1.15	0.01	7.3
15/02/1961	1.20	0.52	0	0	0	0	0	0	0	0	81	78	6.5	1.15	0.01	6.6
16/02/1961	1.20	0.53	0	0	25	5	0	0	20	0	83	85	6.5	1.15	0.01	5.9
17/02/1961	1.20	0.53	0	0	0	0	0	0	0	0	83	71	6.7	1.15	0.01	8.0
18/02/1961	1.20	0.54	0	0	0	0	0	0	0	0	84	79	6.7	1.15	0.01	7.0
19/02/1961	1.20	0.55	0	0	0	0	0	0	0	0	86	86	6.8	1.15	0.01	6.3

Figure 3-12 Daily water balance table as shown in SAPWAT3

3.4.6 Managing stress situations

Stress situations can appear when soil water depletion has exceeded RAW in the soil, or when salinity levels of the soil or irrigation water exceed the levels at which it is safe for crop use, or crops can experience a combination of water stress and salinity stress. Stress reduces crop yield in direct relationship to the severity of the stress situation (Equation 3.53) – a relationship that varies from crop to crop and also between different growing periods of crops (Table 3-11). A yield response factor of more than one (K_y>1) indicates that the relative reduction in crop yield in response to stress is larger than the relative reduction in evapotranspiration. A response factor of smaller than one indicates a smaller level of sensitivity, the crop can undergo stress but yield will not be supressed to the same level as it would have been had the crop been sensitive (Smith and Steduto, 2012).

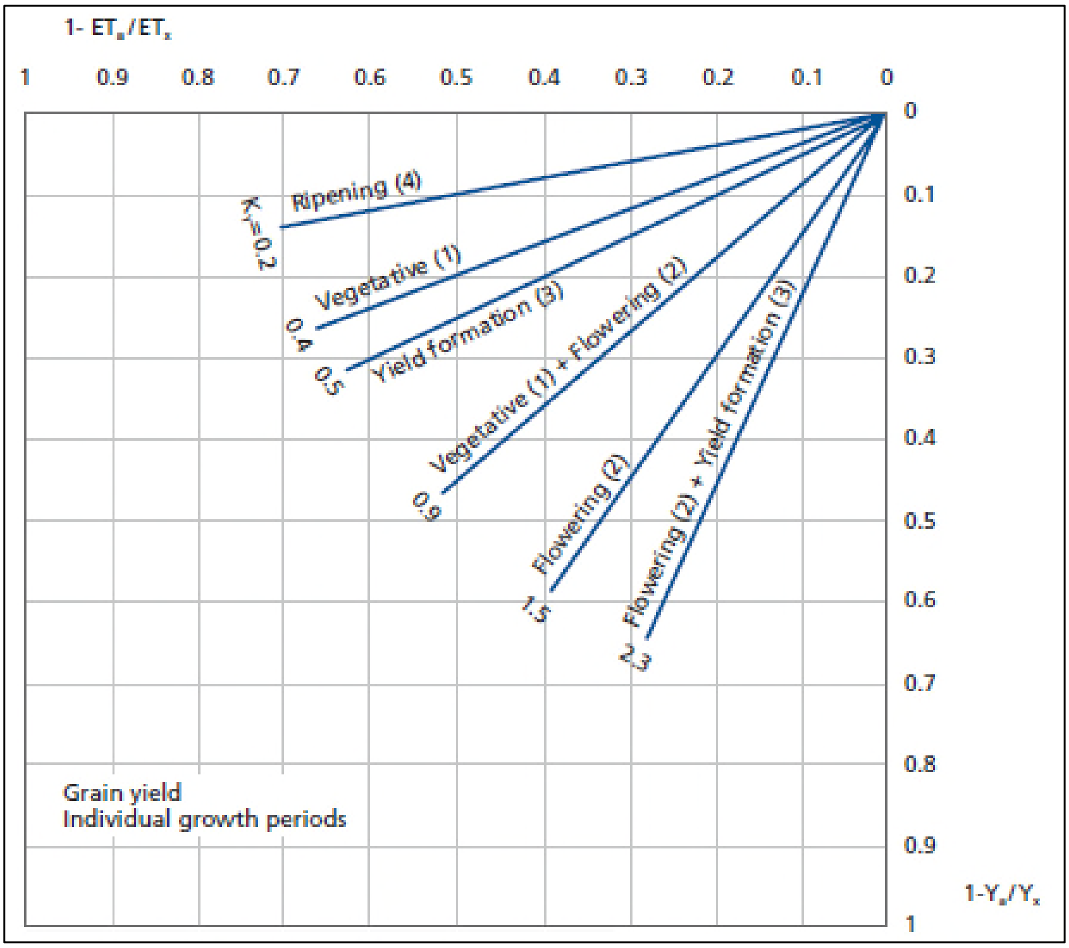


Figure 3-13 Yield response of maize to stress situations showing different sensitivities for different growth stages (k_y = yield response factor; ET_a = actual evapotranspiration; ET_x = maximum evapotranspiration; Y_a = actual yield and Y_x = maximum yield) (Smith and Steduto, 2012)

Under conditions of stress Equation 3.1 becomes (Allen *et al*., 1998):

$$ET_c = K_s \times K_c \times ET_0 \qquad 3.50$$

where: ET_c crop evapotranspiration,

K_s dimensionless transpiration reduction factor dependent on available soil water (0 - 1),

K_c crop coefficient,

ET_0 reference evapotranspiration.

3.4.6.1 Yield-water stress relation

If water stress is experienced by the crop, the transpiration reduction factor (K_s) can be described by (Allen *et al*., 1998):

$$K_s = \frac{TAW-D_r}{(1-p)TAW} \quad 3.51$$

where: K_s dimensionless transpiration reduction factor dependent on available soil water (0-1),

D_r root zone depletion (mm),

TAW total available water in root zone (mm m^{-1}),

p fraction of TAW that a crop can extract from root zone without suffering water stress.

3.4.6.2 Yield-salinity relationship

Crop yield is reduced when soil salinity exceeds safe levels for crops. Under such circumstances excessive salinity levels reduce crop evapotranspiration because the salts dissolved in the soil water compete with root water uptake and the crop evapotranspiration is reduced as a result. The equation for the yield salinity relationship is (Allen *et al*., 1998):

$$\frac{Y_a}{Y_m} = 1-\left(EC_e - EC_{e\ threshold}\right)\frac{b}{100} \quad 3.52$$

where: Y_a actual crop yield,

Y_m maximum expected crop yield when $EC_e < EC_{e\ threshold}$,

EC_e mean electrical conductivity of saturation extract for root zone (dS m^{-1}),

$EC_{e\ threshold}$ electrical conductivity of the saturation extract at threshold of EC_e when crop yield first reduces below Y_m (dS m^{-1}),

b reduction in yield per increase in EC_e (%).

The salinity tolerance and sensitivity classification of crops is shown in Table 3-3.

Table 3-3 Salinity sensitivity of crops showing the threshold level at which yield reduction will begin (EC Threshold), yield reduction rate when under stress (EC Reduction rate) and crop sensitivity to salinity (EC Rating) (Allen *et al*., 1998; McMahon *et al*., 2002; Ayers and Westcot, 1994; Reader's Digest, 1984b; Tanji and Kielen, 2002)

Crop	**EC Threshold (mS/m)**	**EC Reduction rate (mS/m)**	**EC Rating**
Almonds	150	19	Sensitive
Apples			Sensitive
Apricot	160	24	Sensitive
Artichokes			Moderately Tolerant
Asparagus	410	2	Tolerant
Avocado			Sensitive
Babala			Moderately Tolerant
Bananas			Moderately sensitive
Barley	800	5	Tolerant
Beans	100	19	Sensitive
Beetroot	400	9	Moderately Tolerant
Berries	150	22	Sensitive
Brinjals			Moderately sensitive
Broccoli	280	9.2	Moderately sensitive
Brussels sprouts	180	9.7	Moderately sensitive
Butternut squash	470	10	Moderately Tolerant
Cabbage	140	12	Sensitive
Canola			Moderately Tolerant
Carrots	100	14	Sensitive
Cassava			Moderately sensitive
Cauliflower	180	6.2	Moderately sensitive
Celery	210	9.6	Moderately sensitive
Cherries			Sensitive
Chicory			Moderately sensitive
Chillies			Moderately sensitive
Citrus	170	16	Sensitive
Coffee			Moderately sensitive
Coriander			Moderately sensitive
Cotton	770	5.2	Tolerant
Cow peas	490	12	Moderately Tolerant
Cucumber	180	10	Moderately sensitive
Cucurbits	120	13	Moderately sensitive
Cut flowers			Moderately sensitive
Date palm	400	3.6	Tolerant
Fig			Moderately Tolerant
Forage	390	5.8	Moderately Tolerant
Garlic			Sensitive
Ginger			Moderately sensitive

Crop	EC Threshold (mS/m)	EC Reduction rate (mS/m)	EC Rating
Gourds			Moderately sensitive
Grapes	150	9.6	Moderately sensitive
Granadillas			Moderately sensitive
Groundnuts	320	29	Moderately sensitive
Guava			Moderately sensitive
Herbs			Moderately sensitive
Hubbard squash	320	16	Moderately sensitive
Kiwifruit			Moderately sensitive
Lavender			Moderately Tolerant
Leeks			Sensitive
Lentils			Moderately Tolerant
Lettuce			Sensitive
Litchi			Moderately sensitive
Lucerne	200	7.3	Moderately sensitive
Macadamia			Moderately sensitive
Maize	170	12	Moderately sensitive
Mango			Moderately sensitive
Mealies (Corn-on-the-cob)	170	12	Moderately sensitive
Melon			Moderately sensitive
Nectarine	170	16	Sensitive
Oats			Moderately Tolerant
Olive			Moderately Tolerant
Onion	120	16	Sensitive
Papaya			Moderately sensitive
Paprika			Moderately sensitive
Parsley			Moderately sensitive
Pastures: perennial	560	7.6	Moderately Tolerant
Pastures: seasonal			Moderately Tolerant
Peaches	170	21	Sensitive
Pears			Sensitive
Peas	150	14	Sensitive
Pecan			Sensitive
Peppers			Moderately sensitive
Pineapple			Moderately sensitive
Pistachio			Moderately sensitive
Pomegranate			Moderately Tolerant
Potatoes	170	12	Moderately sensitive
Prunes	150	18	Sensitive
Pumpkin	120	13	Moderately sensitive
Quince			Moderately Tolerant
Radishes	160	10.3	Moderately sensitive
Rice	300	12	Sensitive
Rye			Moderately Tolerant

Crop	EC Threshold (mS/m)	EC Reduction rate (mS/m)	EC Rating
Saltbush			Tolerant
Sorghum	680	16	Moderately Tolerant
Soybeans	500	20	Moderately Tolerant
Spinach	260	12.8	Moderately sensitive
Spineless cactus			Moderately Tolerant
Squash	320	16	Moderately sensitive
Strawberry			Sensitive
Sugar-beet			Moderately sensitive
Sugarcane	170	5.9	Moderately sensitive
Sunflower			Moderately sensitive
Sweet potato	200	10	Moderately sensitive
Sweetcorn	170	12	Moderately sensitive
Swiss chard			Sensitive
Tea			Sensitive
Tobacco			Sensitive
Tomatoes	170	9	Moderately sensitive
Turnips	90	9	Tolerant
Vegetables			Moderately sensitive
Walnuts			Moderately sensitive
Watermelon			Moderately sensitive
Wheat	860	3	Tolerant

SAPWAT manages the lack of salinity sensitivity data in Table 3-3 as follows:

- If columns EC Threshold and EC Reduction rate are empty, and if column EC Rating indicates a sensitivity level, the following values are used as default (Ayers and Westcot, 1994):

Table 3-4 Default salinity sensitivity values used by SAPWAT3 in absence of data table values (Ayers and Westcot, 1994)

EC Rating	EC Threshold (mS/m)	EC Reduction rate (mS/m)
Sensitive	130	10
Moderately sensitive	300	10
Moderately tolerant	600	10
Tolerant	1200	10

- If columns EC Threshold, EC Reduction rate and EC Rating is empty, the following defaults are used:
  - EC Threshold = 300
  - EC Reduction rate = 10

- EC Rating = moderately sensitive

3.4.6.3 Yield-moisture stress relations

Moisture stress causes a reduction in expected yield because under moisture stress situations, a crop cannot produce its optimum yield for an area. The relationship between moisture stress and yield is described by (Allen *et al*., 1998):

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_{c\,adj}}{ET_c}\right) \qquad 3.53$$

where:
- Y_a — actual crop yield,
- Y_m — maximum expected crop yield when $EC_e<EC_{e\ threshold}$,
- K_y — yield response factor (-),
- $ET_{c\ adj}$ — adjusted (actual) crop evapotranspiration (mm d^{-1}),
- ET_c — crop evapotranspiration for standard conditions (no water stress) (mm d^{-1}).

K_y is a reduction factor published by Doorenbos and Kassam (1986) and revised by Steduto and Raes (2012). Values of K_y included in SAPWAT3 come from Allen *et al*. 1998 (Table 3-5):

Table 3-5 Seasonal yield response functions (Allen *et al*. 1998)

Crop	**Seasonal K_y**
Alfalfa	1.1
Banana	1.2-1.35
Beans	1.15
Cabbage	0.95
Citrus	1.1-1.3
Cotton	0.85
Grape	0.85
Groundnut	0.7
Maize	1.25
Onion	1.1
Peas	1.15
Pepper	
Potato	1.1
Safflower	0.8
Sorghum	0.9
Soybean	0.85

Crop	Seasonal K_y
Sugar beet	1.0
Sugarcane	1.2
Sunflower	0.95
Tomato	1.05
Watermelon	1.1
Wheat: spring	1.15
Wheat: winter	1.05

Stress situations need not arise as a result of water deficit only or excess salinity only; therefore Allen *at al*. (1998) provides equations for combined situations. When a new crop is added to the Crops.dbf data table, if the user does not enter a value for K_y, SAPWAT3 gives it a default value of 1.

- Salinity stress with no water stress:

$$K_s = 1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\ threshold}\right) \qquad 3.54$$

- Salinity stress with water stress:

$$K_s = \left[1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\ threshold}\right)\right]\left(\frac{TAW - D_r}{TAW - RAW}\right) \qquad 3.55$$

where:

K_s	dimensionless transpiration reduction factor dependent on available soil water (0 - 1),
b	reduction in yield per increase in EC_e (%),
K_y	yield response factor (-),
EC_e	mean electrical conductivity of the saturation extract for the root zone (dS m^{-1}),
$EC_{e\ threshold}$	electrical conductivity of the saturation extract at the threshold of EC_e when crop yield first reduces below Y_m (dS m^{-1}),
TAW	total available water in the root zone (mm),
D_r	allowed root zone depletion,
RAW	readily available water in the root zone (mm),

The combined stress factor can be displayed graphically as Figure 3-14 (Allen *et al.*, 1998):

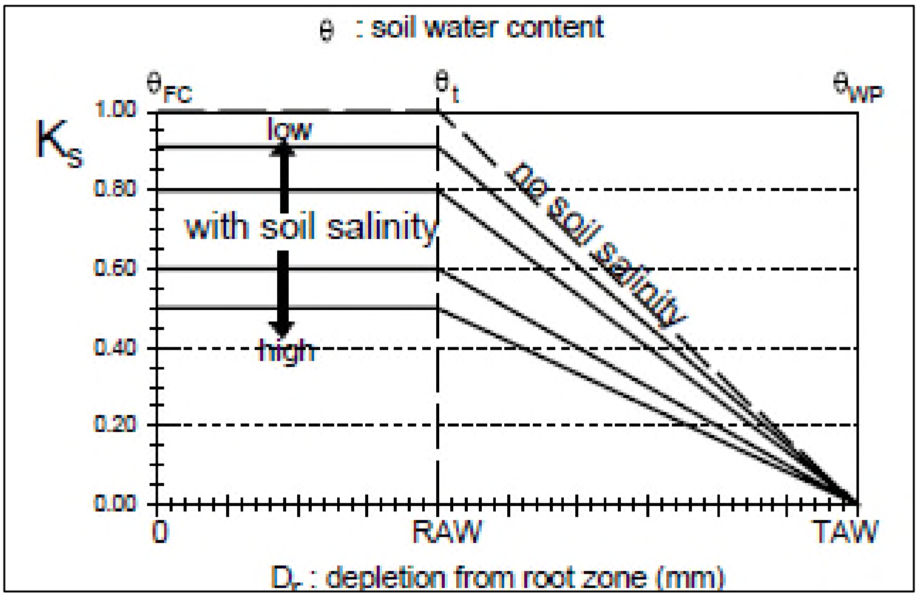


Figure 3-14 The effect of soil salinity on the water stress coefficient, K_s (Allen *et al.*, 1998)

3.4.6.4 Application in SAPWAT3

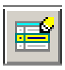
During irrigation requirement calculations, SAPWAT3 tests for salinity and water stress situations and applies:

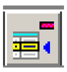
- Water stress only: Equation 3.51
- Salinity stress only: Equation 3.54
- Combined water and salinity stress: Equation 3.55

3.4.7 The irrigation requirement user interface

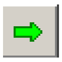
Control of the actions taken on the screen pages are through the use of press buttons. All data in SAPWAT3 is safeguarded to ensure data integrity; therefore no data can be changed unless the use specifically instructs the program through the use of these press buttons. Press buttons found on the screens and their meanings are the following:

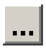
 Add a new record.

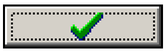
 Edit a record.

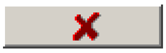
 Delete a record. All lower level linked records will also be deleted.

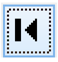
 Print a record and its lower level linked records.

 Export data for use in spread sheets of other data management programs.

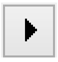
 Opens more detailed screen forms.

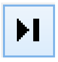
 Save changes and/or close the screen form.

 Cancel changes and/or close screen form.

 Go to first record

 Go to previous record

 Go to next record

 Go to last record

Colour codes used in the screen forms are:

- Yellow the selected record or field
- Cyan a read-only field for display of information or calculation result – the user cannot change the information in such a field
- Red: negative balance or stress situations

In order to illustrate how the SAPWAT3 interface works, step by step screen-shots will be shown in order to describe the process and at which stages certain values need to be verified or inserted. The example selected is based on data collected for a Water Research Commission project done in the Orange-Vaal and Orange-Riet Water Users Association area in the Jacobsdal-Douglas area of the North Cape (Van Heerden *et al*., 2001).

The user interface for the estimation of irrigation requirements is made up of several pages that follow the hierarchical structure shown in Figure 3-2. This section moves step by step from the page giving an overall picture of the area of interest and becomes more detailed through the following pages for farm and field data. It ends with the detailed crop irrigation requirement estimates page.

3.4.7.1 The task, WMA, WUA and WUA-sub page

This screen page (Figure 3-15) shows relational water requirement data at the higher management levels of the WMA, WUA and WUA-sub areas. Water balance fields in red indicate requirement that exceeds allowed water use. Entry fields coloured cyan are read-only fields and cannot be altered on-screen. Selected fields are yellow-coloured.

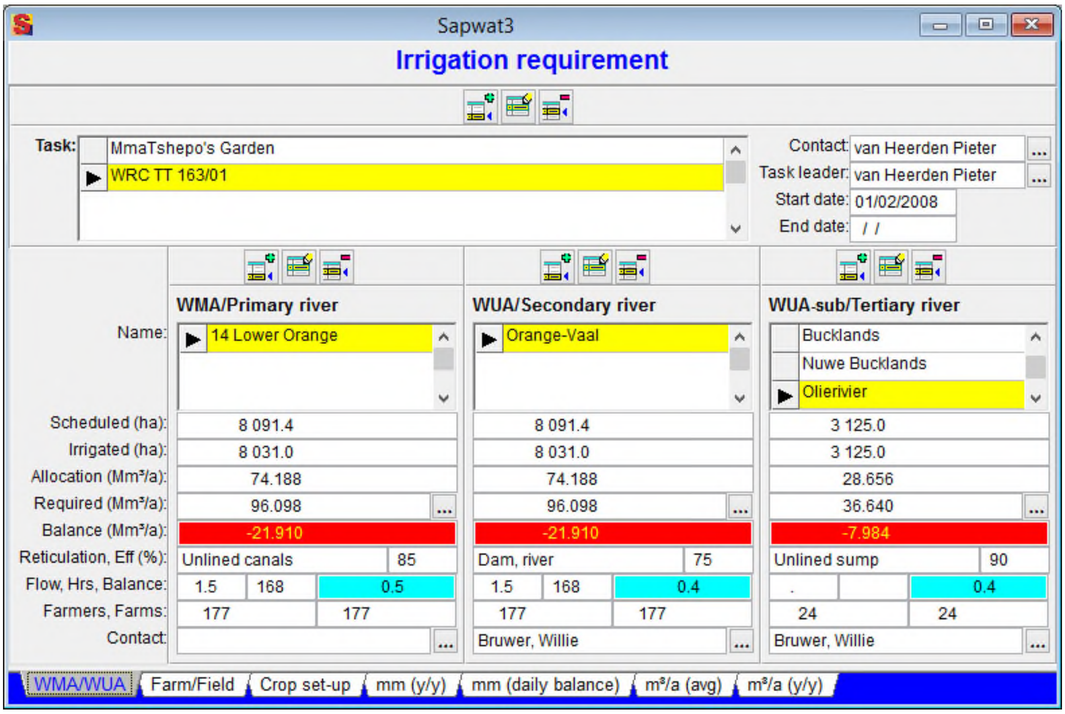


Figure 3-15 Page 1 of irrigation requirement routine of SAPWAT3 showing detail about task, water management area (WMA), water user association area (WUA) and water user association sub-area (WUA-sub)

3.4.7.2 The farm and field page

The farm-field screen page (Figure 3-16) shows linkages between farm and weather station and detail required, as well as field-soil-irrigation system linkage and related detail. In the case of the weather station, all data required by SAPWAT3 for the calculation of ET_c requirements is stored in the relevant weather station data table: the name of the weather station and its related climate are shown on screen. Other farm information is related to the area irrigated as well as information related to water use rights, such as scheduled area and water quota relevant under the previous Water Act, 1956 and total water use right as a volume of water required by the present Water Act (National Water Act, 1998). The total water use right is the product of scheduled area and quota. Information regarding on-farm water distribution system taking water from source to field edge and its management and efficiencies are also required in order to calculate the required volume of water at the source.

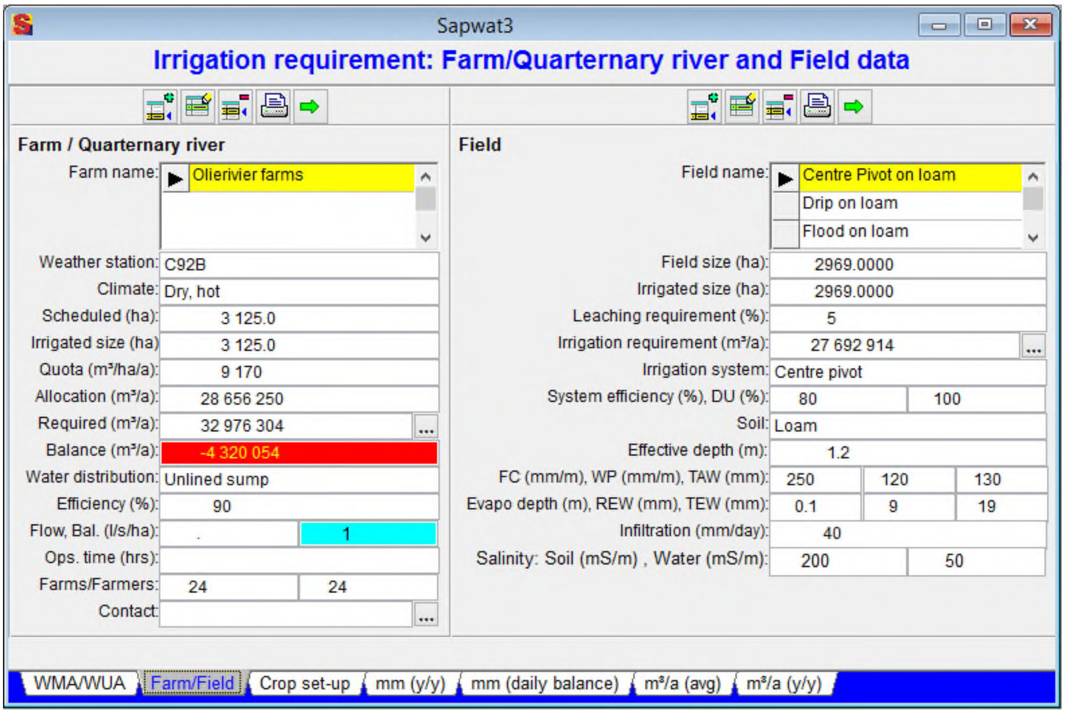


Figure 3-16 The farm-field screen page of SAPWAT3 showing the detail required in each case

The field part of the screen shows soil and irrigation system information, such as soil texture and its soil water holding capacities as well as the default efficiencies of the irrigation system. Most of this detail is read from the soil and irrigation system data tables and is displayed on this page for the user's verification – the user needs to select only soil and irrigation system and then the rest of the detail will be displayed as default values which could be altered as need be for a specific situation. Field and irrigated sizes shown in Figure 3-16 could be the size of an individual field, or if estimates for a geographic or administrative area are done, it could be the total sizes of the specified crop-soil-irrigation system combination of the area. Values shown in the soil and water salinity fields are default values based on a general pattern of salinity levels found in the central parts of South Africa.

3.4.7.3 The crop irrigation requirement and supplementary screen pages

This screen page (Figure 3-17) shows the monthly and total irrigation requirement for crops. The crop and its type and planting date are also shown on the same screen. Columns showing expected income, cost and gross margin values for each crop can be seen by shifting the cursor to the right. The year showed in the Start column relates to the weather data year and not the actual planting year, although the day and month of the data shown will reflect the day and month of planting or starting. Further details shown in read-only fields are weather station, soil and irrigation system information as well as the irrigation strategy. Addition of new crops or the editing of existing crops for the weather station – soil – irrigation system combination is done from this page by clicking on the append or edit buttons which will take the user to the relevant screen pages.

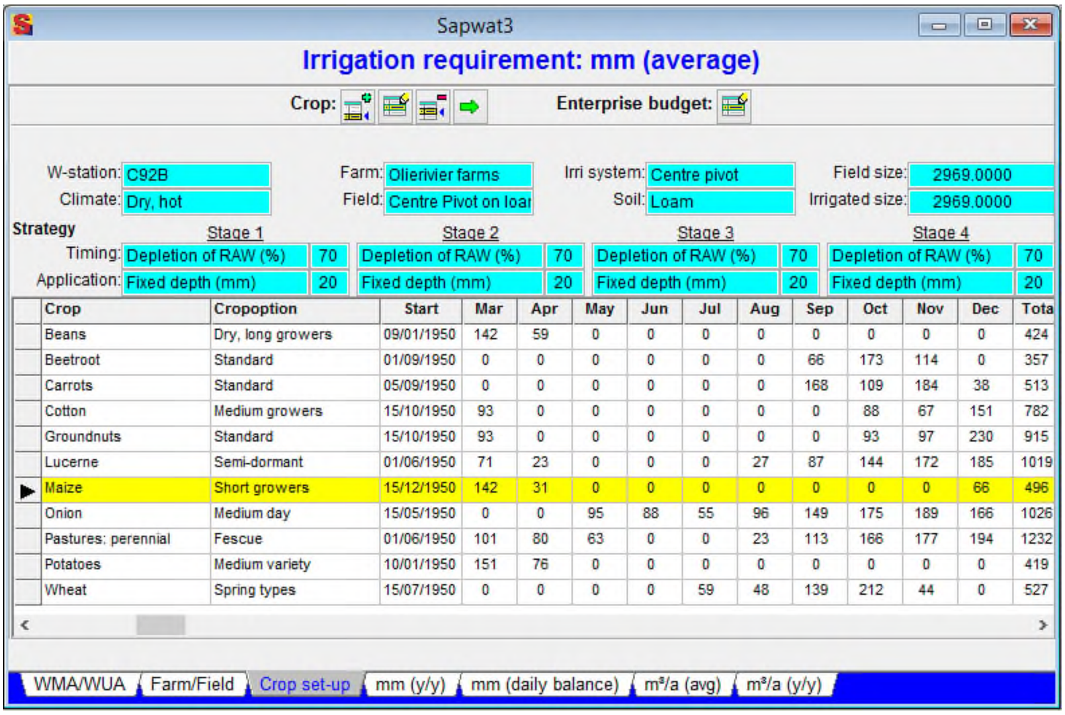
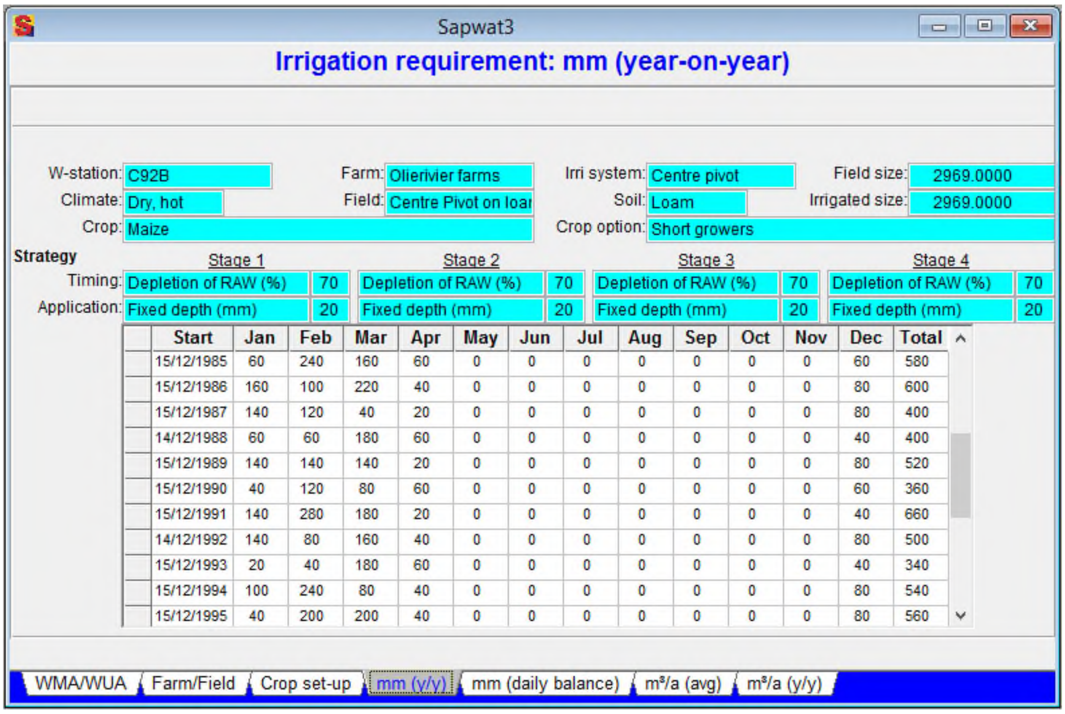


Figure 3-17 The amount of crop irrigation requirement (in mm) screen of SAPWAT3

The year-on-year irrigation requirement expressed as an amount in millimetres is shown in Figure 3-18. Noticeable is the variation in requirement, with totals varying from 340 mm for December 1993 planting date, to 660 mm for December 1991 planting date. This demonstrates the variation in estimated irrigation requirement that could result due to variation in weather from one year to another.

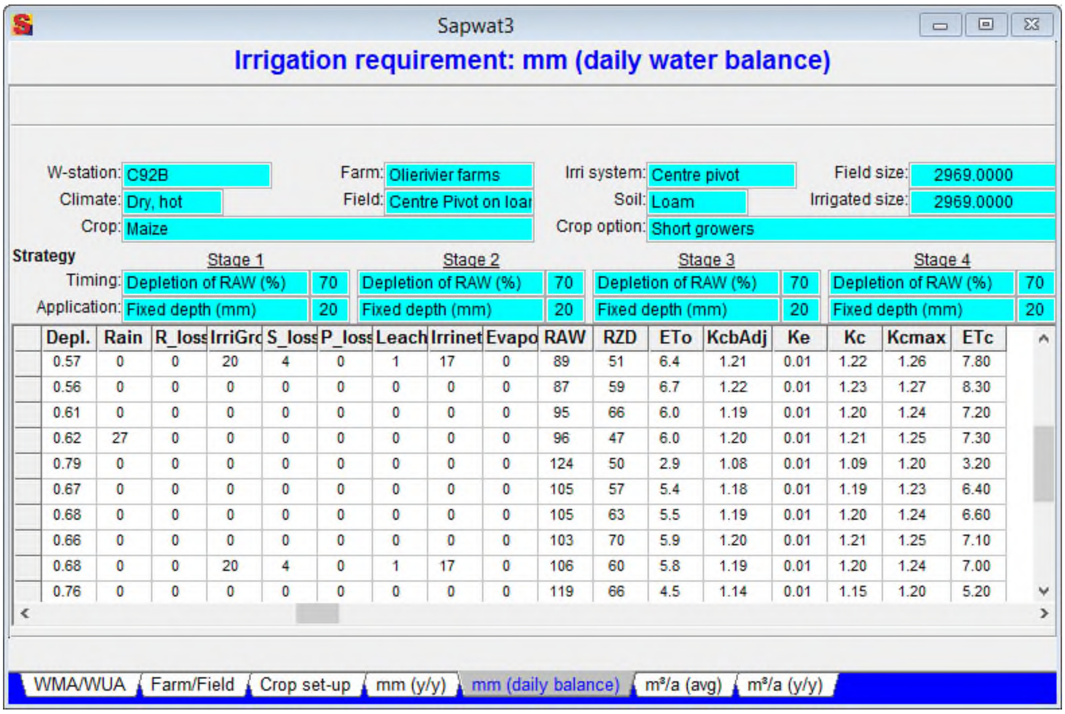


Start	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
15/12/1985	60	240	160	60	0	0	0	0	0	0	0	60	580
15/12/1986	160	100	220	40	0	0	0	0	0	0	0	80	600
15/12/1987	140	120	40	20	0	0	0	0	0	0	0	80	400
14/12/1988	60	60	180	60	0	0	0	0	0	0	0	40	400
15/12/1989	140	140	140	20	0	0	0	0	0	0	0	80	520
15/12/1990	40	120	80	60	0	0	0	0	0	0	0	60	360
15/12/1991	140	280	180	20	0	0	0	0	0	0	0	40	660
14/12/1992	140	80	160	40	0	0	0	0	0	0	0	80	500
15/12/1993	20	40	180	60	0	0	0	0	0	0	0	40	340
15/12/1994	100	240	80	40	0	0	0	0	0	0	0	80	540
15/12/1995	40	200	200	40	0	0	0	0	0	0	0	80	560

Figure 3-18 Year-on-year crop irrigation requirement screen of SAPWAT3, in mm

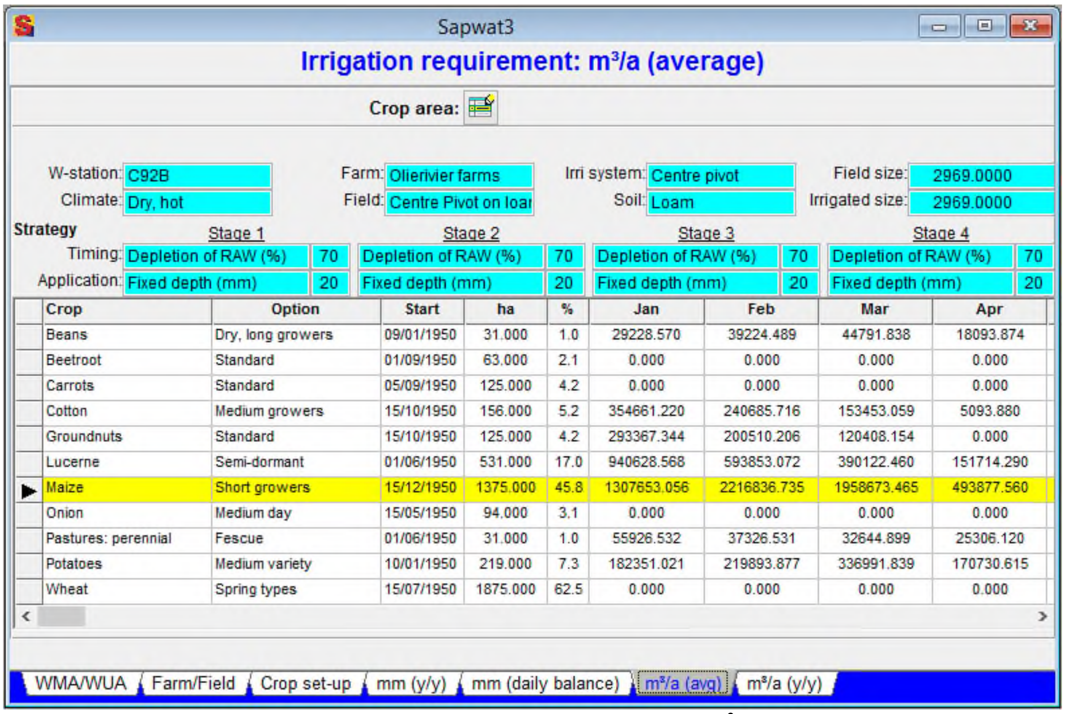
Figure 3-19 shows the results table of the daily soil water balance calculations and elements that influence it such as rain (Rain), rain loss (runoff when rain exceeds soil water holding capacity) (R_loss), gross irrigation (IrriGross), irrigation system losses (S_loss), percolation losses from irrigation (P_loss), leaching requirement (Leach), readily available water (RAW), root zone depletion (RZD), reference evapotranspiration (ET_0), basal crop coefficient adjusted for climate ($K_{cb\ Adj}$), evaporative coefficient (K_e), crop coefficient (K_c), maximum theoretical K_c value ($K_{c\ max}$) and crop evapotranspiration (ET_c).

Other tables include monthly and total irrigation water requirement in m^3 for the total area of the crop on the field (Figure 3-20), as well as year-on-year variation of total irrigation water requirement for a specific crop (Figure 3-21).



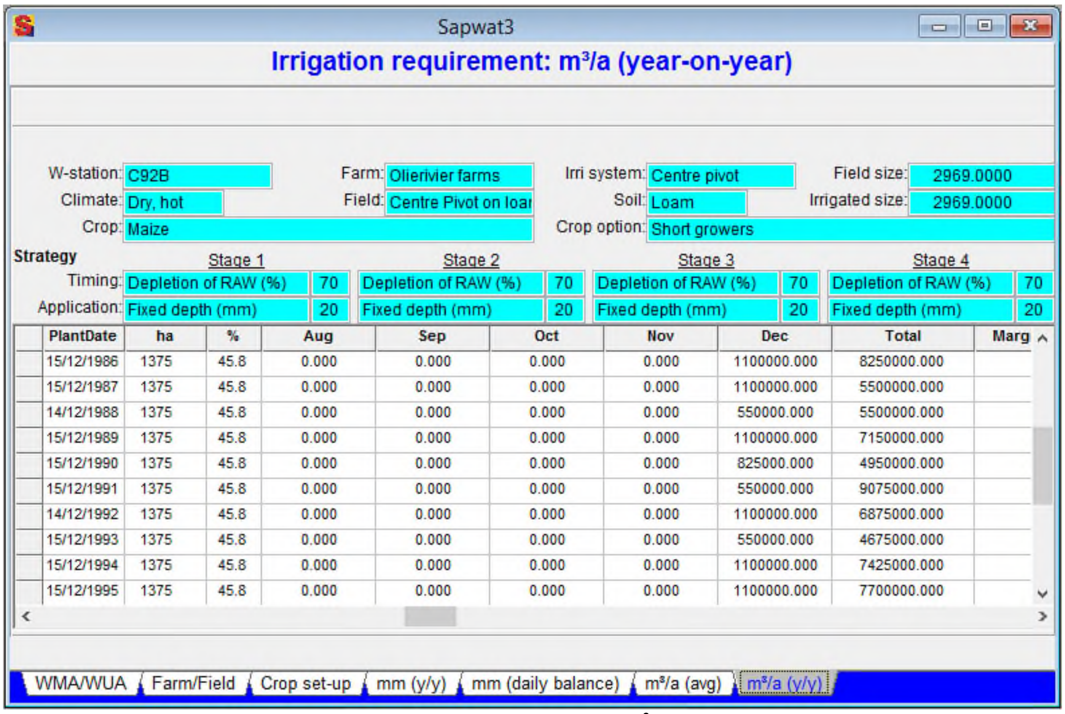
Depl.	Rain	R_loss	IrriGro	S_loss	P_loss	Leach	Irrinet	Evapo	RAW	RZD	ETo	KcbAdj	Ke	Kc	Kcmax	ETc
0.57	0	0	20	4	0	1	17	0	89	51	6.4	1.21	0.01	1.22	1.26	7.80
0.56	0	0	0	0	0	0	0	0	87	59	6.7	1.22	0.01	1.23	1.27	8.30
0.61	0	0	0	0	0	0	0	0	95	66	6.0	1.19	0.01	1.20	1.24	7.20
0.62	27	0	0	0	0	0	0	0	96	47	6.0	1.20	0.01	1.21	1.25	7.30
0.79	0	0	0	0	0	0	0	0	124	50	2.9	1.08	0.01	1.09	1.20	3.20
0.67	0	0	0	0	0	0	0	0	105	57	5.4	1.18	0.01	1.19	1.23	6.40
0.68	0	0	0	0	0	0	0	0	105	63	5.5	1.19	0.01	1.20	1.24	6.60
0.66	0	0	0	0	0	0	0	0	103	70	5.9	1.20	0.01	1.21	1.25	7.10
0.68	0	0	20	4	0	1	17	0	106	60	5.8	1.19	0.01	1.20	1.24	7.00
0.76	0	0	0	0	0	0	0	0	119	66	4.5	1.14	0.01	1.15	1.20	5.20

Figure 3-19 Daily soil water balance for a selected year



Crop	Option	Start	ha	%	Jan	Feb	Mar	Apr
Beans	Dry, long growers	09/01/1950	31.000	1.0	29228.570	39224.489	44791.838	18093.874
Beetroot	Standard	01/09/1950	63.000	2.1	0.000	0.000	0.000	0.000
Carrots	Standard	05/09/1950	125.000	4.2	0.000	0.000	0.000	0.000
Cotton	Medium growers	15/10/1950	156.000	5.2	354661.220	240685.716	153453.059	5093.880
Groundnuts	Standard	15/10/1950	125.000	4.2	293367.344	200510.206	120408.154	0.000
Lucerne	Semi-dormant	01/06/1950	531.000	17.0	940628.568	593853.072	390122.460	151714.290
Maize	Short growers	15/12/1950	1375.000	45.8	1307653.056	2216836.735	1958673.465	493877.560
Onion	Medium day	15/05/1950	94.000	3.1	0.000	0.000	0.000	0.000
Pastures: perennial	Fescue	01/06/1950	31.000	1.0	55926.532	37326.531	32644.899	25306.120
Potatoes	Medium variety	10/01/1950	219.000	7.3	182351.021	219893.877	336991.839	170730.615
Wheat	Spring types	15/07/1950	1875.000	62.5	0.000	0.000	0.000	0.000

Figure 3-20 Monthly and total irrigation requirement in m^3 for crops as estimated by SAPWAT3. The many decimal places in size and water requirement columns is to provide for backyard garden situations where both irrigated size and water requirement can be substantially less than unit values



PlantDate	ha	%	Aug	Sep	Oct	Nov	Dec	Total	Marg
15/12/1986	1375	45.8	0.000	0.000	0.000	0.000	1100000.000	8250000.000	
15/12/1987	1375	45.8	0.000	0.000	0.000	0.000	1100000.000	5500000.000	
14/12/1988	1375	45.8	0.000	0.000	0.000	0.000	550000.000	5500000.000	
15/12/1989	1375	45.8	0.000	0.000	0.000	0.000	1100000.000	7150000.000	
15/12/1990	1375	45.8	0.000	0.000	0.000	0.000	825000.000	4950000.000	
15/12/1991	1375	45.8	0.000	0.000	0.000	0.000	550000.000	9075000.000	
14/12/1992	1375	45.8	0.000	0.000	0.000	0.000	1100000.000	6875000.000	
15/12/1993	1375	45.8	0.000	0.000	0.000	0.000	550000.000	4675000.000	
15/12/1994	1375	45.8	0.000	0.000	0.000	0.000	1100000.000	7425000.000	
15/12/1995	1375	45.8	0.000	0.000	0.000	0.000	1100000.000	7700000.000	

Figure 3-21 Year-on-year irrigation requirement in m³ per month and total for a selected crop

3.4.7.4 The crop setup and irrigation water estimation screens

When one wants to add a new crop or edit an existing crop, then one needs to access an editing form from the screen shown in Figure 3-17, by clicking an "add new record" or "edit record" button at the top of the screen. Figure 3-22 shows the crop set-up screen. The crop, its growth characteristic option and the planting or starting date for perennial crops is selected. The user has the option of altering the data read from the crop data tables for the present situation, such as potential and actual yield, area planted, crop height and canopy cover. Planting date can also be altered, but the user is advised not to go beyond about one week either side of the given planting date because of the linkage between crop growth characteristics and the planting date for the specific climate. The year shown in the planting date field is linked to weather data range included in the weather station data. The planting month and day are important; the year is adjusted to available data.

If a number of years of daily weather data are available, the user can select any sub-period out of the available data, for example selecting a period that is known to deviate in terms of weather in order to study such effects on irrigation requirement. In Figure 3-22 the full available period of 50 years of daily weather data has been selected. This would result in 49 or 50 repeated seasonal irrigation water requirement calculations, depending on whether the growing season includes or excludes the change-over to a new year. If only long term average monthly data are available, this choice is not available and irrigation requirement is based on a single seasonal calculation.

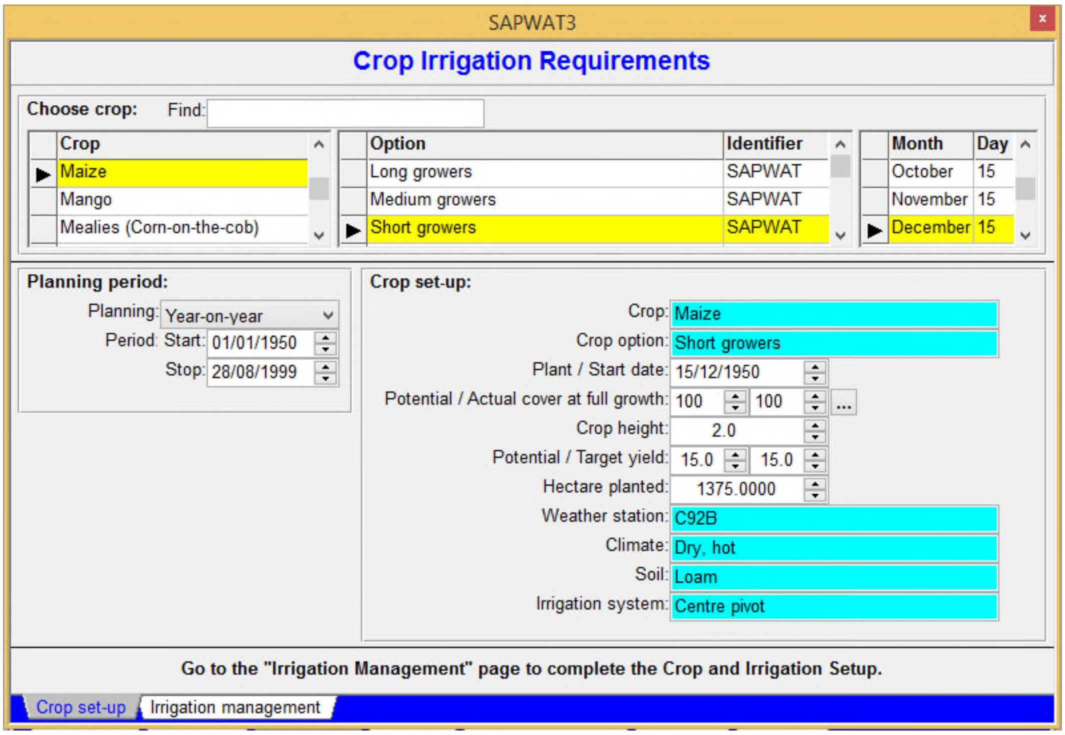


Figure 3-22 Page 1 of the crop set-up screen for estimating irrigation water requirement

Page 2 of this form (Figure 3-23) is where the user defines the irrigation strategy for each of the four crop growths stages. The choices are combinations of fixed period between irrigations; or irrigation when soil water depletion reaches a specified level; or fixed irrigation depth; or refill soil water content to a specified level below field capacity to leave space for rain water storage. There is also a choice of “no irrigation” to simulate rain-fed situations, but the use of this is not advised as it is not a purpose that SAPWAT3 was designed for and its accuracy for this function has not been adequately tested. The irrigation strategy shown in Figure 3-23 allows extraction of soil water to 70% of readily available water (approximately 45 mm for a loam soil of 1 m depth) and a refill depth of 20 mm per irrigation. This irrigation depth does not fill the soil profile to field capacity and space is therefore left for the storage of rain water.

The user can choose to exclude rainfall in the irrigation estimation calculations; this seems to be common practice by users in the dry, western parts of South Africa. Furthermore the user can choose to start the calculations with soil at different water content levels rather than the default of field capacity minus readily evaporative water.

When satisfied that the crop set-up is as close to the real situation that is found in practice for the area under investigation, the user clicks on the "Calculate" button and the program proceed with the water requirements estimation calculation. When complete, the average results of 49 years of yearly calculations will be shown graphically on page two (Figure 3-23) and graphically and/or tabulated on subsequent pages.

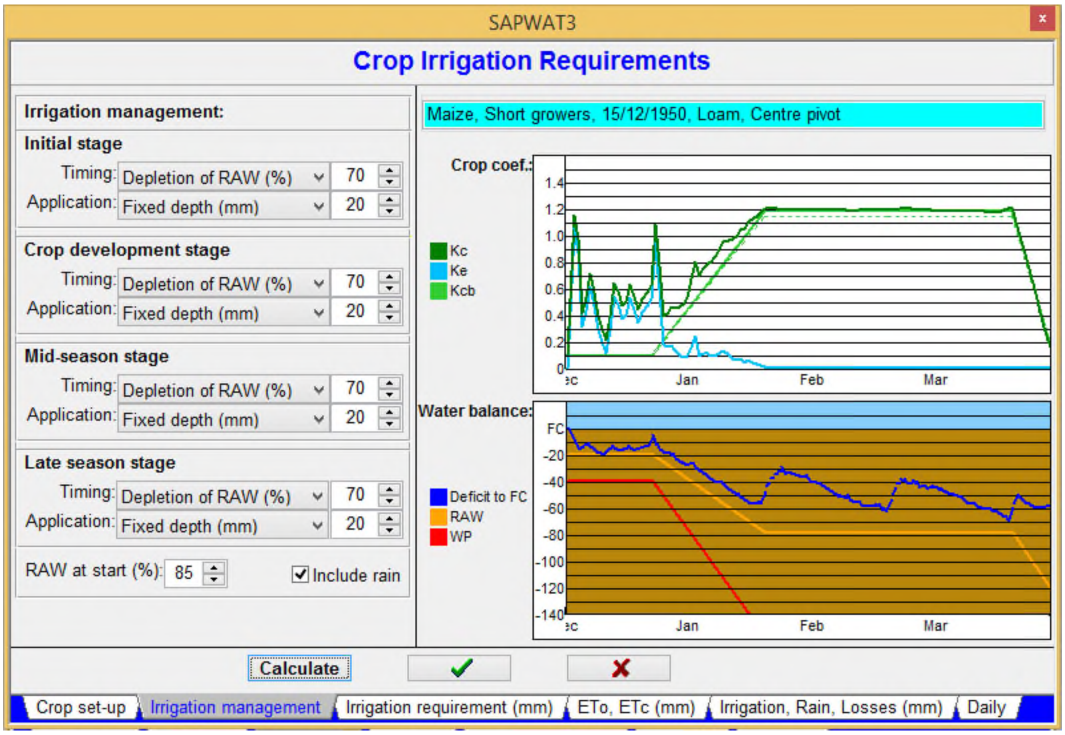
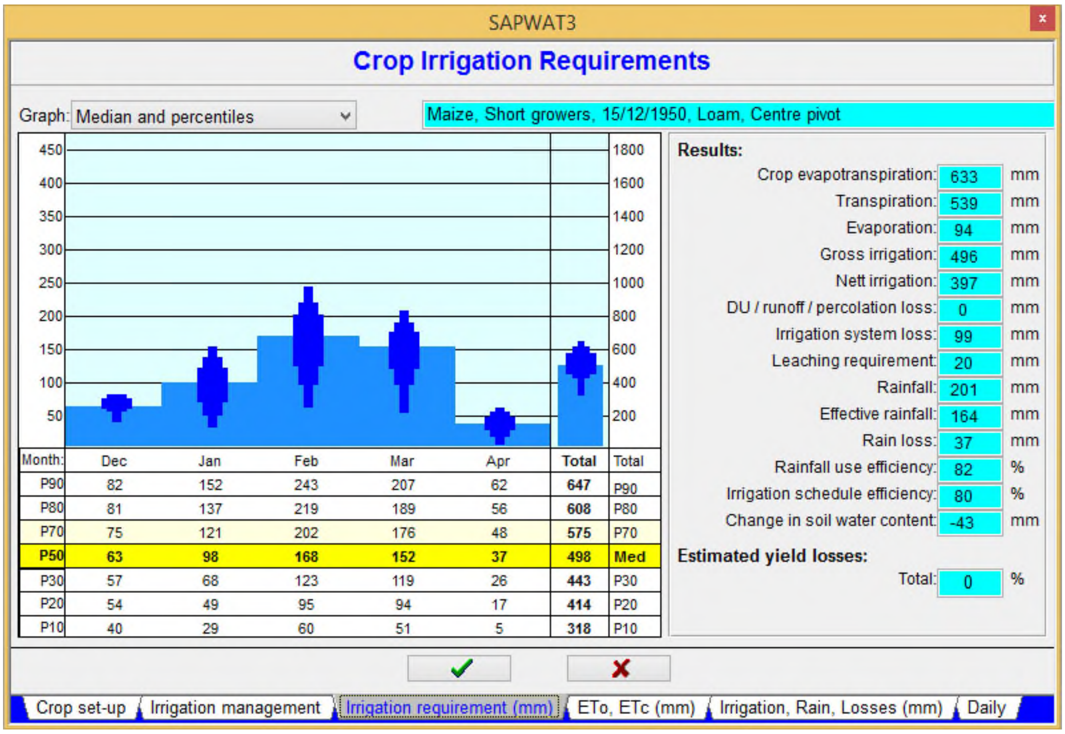


Figure 3-23 Page 2 of the crop set-up screen for estimating irrigation water requirement showing graphed results on completion of the calculation run

Two graphs are displayed on page 2 (Figure 3-23); the top graph shows the basal crop coefficient (K_{cb}), the evaporation coefficient (K_e) as well as the overall crop coefficient (K_c), which is the sum of the evaporative and basal coefficients. Noticeable is the reduction in the evaporative coefficient as canopy cover increases and soil water evaporation decreases accordingly.

The bottom graph shows the soil water content in relation to the level of readily available soil water (RAW) and wilting point (WP). The ideal is to aim for a soil water content that is between field capacity and readily available soil water. Soil water content is the mean for the number of repeated seasonal calculations, which has a smoothing effect on the line (Allen *et al.*, 1998).

Figure 3-24 show the results of the irrigation requirement calculations. The graph is a representation of the table immediately underneath it where median values and values required for non–exceedance are shown for both monthly and total seasonal requirement. The levels of P90, P80 and P70 show irrigation requirement estimates (in mm) for 90%, 80% and 70% levels of non-exceedance. At a non-exceedance level of 80% (P80) the crop would need 608 mm of irrigation water to ensure enough water for eight out of ten years, compared to the 498 mm required for the median value (5 out of ten years). It has been observed that irrigation water administrators plan and usually design on median values and not on various level of non-exceedance. The user needs to take note that monthly median values do not necessarily add up to seasonal median values.

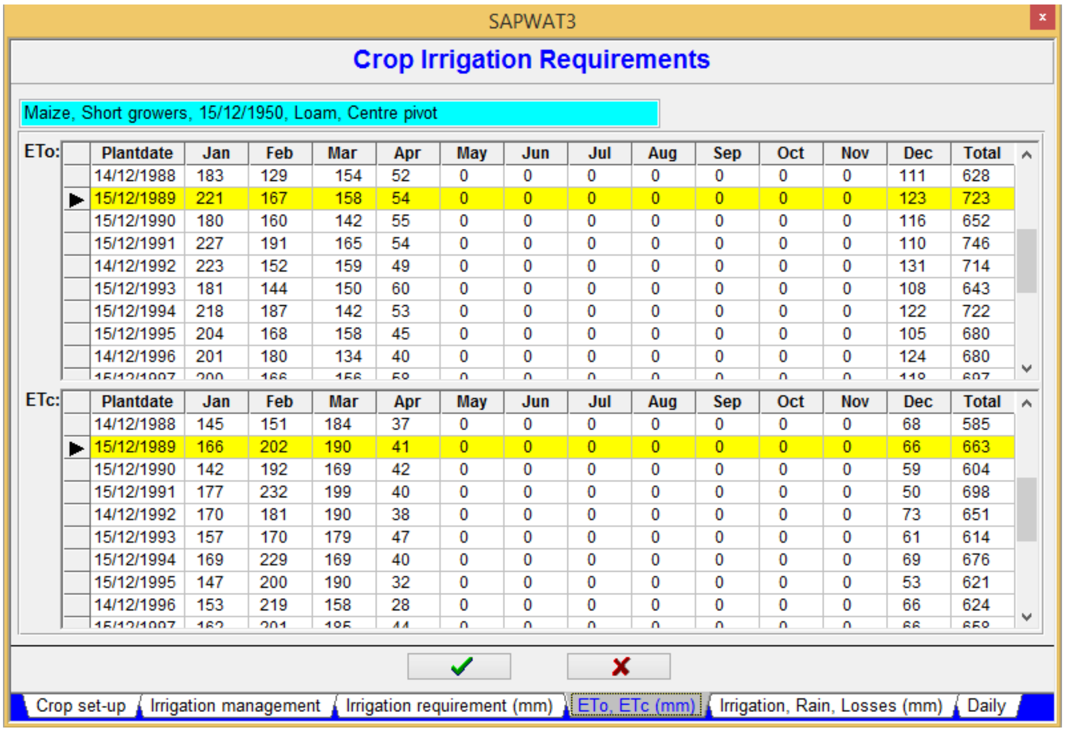


Month:	Dec	Jan	Feb	Mar	Apr	Total	Total
P90	82	152	243	207	62	647	P90
P80	81	137	219	189	56	608	P80
P70	75	121	202	176	48	575	P70
P50	63	98	168	152	37	498	Med
P30	57	68	123	119	26	443	P30
P20	54	49	95	94	17	414	P20
P10	40	29	60	51	5	318	P10

Figure 3-24 Irrigation requirement estimates result page showing median values (Med), values of non-exceedance at different percentage levels and water use efficiencies of the designed irrigation strategy

On the right-hand side of this screen different parts of the water balance and water use efficiencies are shown. From top to bottom it shows the mean crop evapotranspiration for the calculation period, as well as a split between transpiration and soil surface evaporation. Next in line is gross irrigation; the quantity of water "through the irrigation system pump", then the nett irrigation which is the quantity of water that reaches the root zone of the crop. This is followed by an indication of distribution uniformity (DU), runoff and percolation losses, followed by irrigation system losses (calculated from the system efficiency, the difference between water entering the irrigation system and that which enters the crop root zone), Next is an indication of leaching requirement, rainfall for the growing season, rainfall runoff losses and a rainfall use efficiency. The next line shows the irrigation scheduling efficiency followed by an indication of change in the soil water balance.

Following pages show variation across years in ET_0 and ET_c (Figure 3-25), variation in irrigation requirement, irrigation loss, rain, rain loss and evaporation (Figure 3-26) and the last page shows variation in daily ET_c as well as all elements that are taken into account for the water balance equation (Equation 3.45). Selection of a specific planting date in any of these tables would result in the screen cursor moving to the same date on all other related screen tables (Figure 3-25, Figure 3-26). Daily water balances for the selected season are shown in Figure 3-27.


SAPWAT3

Crop Irrigation Requirements

Maize, Short growers, 15/12/1950, Loam, Centre pivot

ETo:

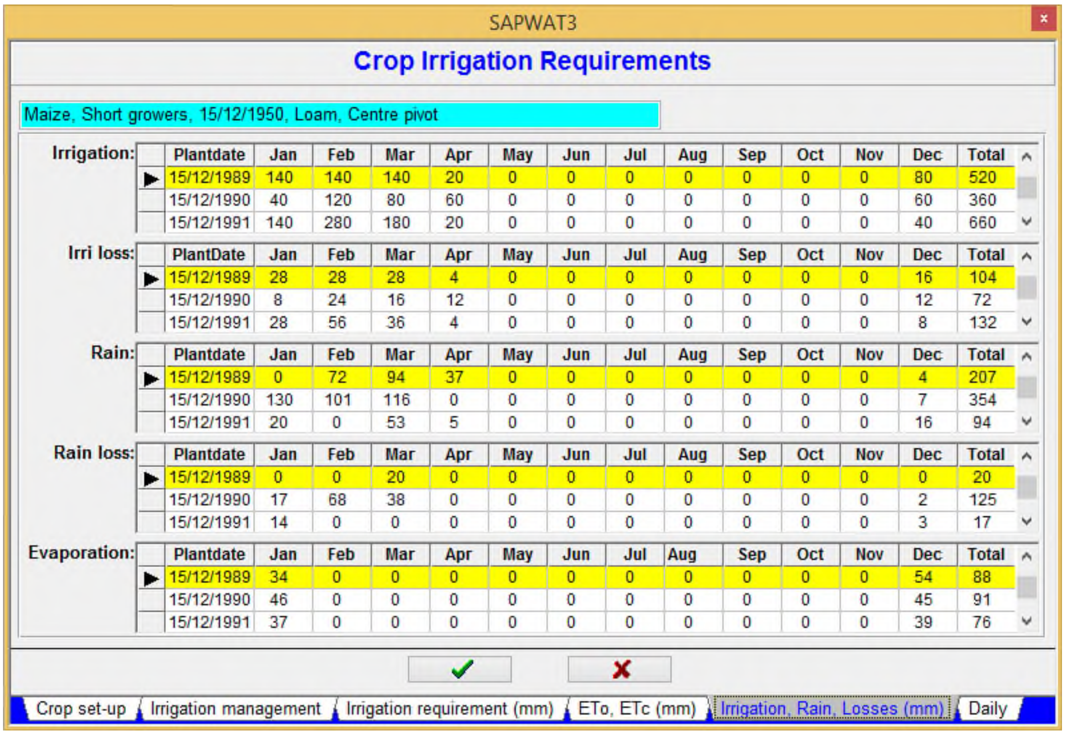
Plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
14/12/1988	183	129	154	52	0	0	0	0	0	0	0	111	628
15/12/1989	221	167	158	54	0	0	0	0	0	0	0	123	723
15/12/1990	180	160	142	55	0	0	0	0	0	0	0	116	652
15/12/1991	227	191	165	54	0	0	0	0	0	0	0	110	746
14/12/1992	223	152	159	49	0	0	0	0	0	0	0	131	714
15/12/1993	181	144	150	60	0	0	0	0	0	0	0	108	643
15/12/1994	218	187	142	53	0	0	0	0	0	0	0	122	722
15/12/1995	204	168	158	45	0	0	0	0	0	0	0	105	680
14/12/1996	201	180	134	40	0	0	0	0	0	0	0	124	680

ETc:

Plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
14/12/1988	145	151	184	37	0	0	0	0	0	0	0	68	585
15/12/1989	166	202	190	41	0	0	0	0	0	0	0	66	663
15/12/1990	142	192	169	42	0	0	0	0	0	0	0	59	604
15/12/1991	177	232	199	40	0	0	0	0	0	0	0	50	698
14/12/1992	170	181	190	38	0	0	0	0	0	0	0	73	651
15/12/1993	157	170	179	47	0	0	0	0	0	0	0	61	614
15/12/1994	169	229	169	40	0	0	0	0	0	0	0	69	676
15/12/1995	147	200	190	32	0	0	0	0	0	0	0	53	621
14/12/1996	153	219	158	28	0	0	0	0	0	0	0	66	624

Crop set-up | Irrigation management | Irrigation requirement (mm) | ETo, ETc (mm) | Irrigation, Rain, Losses (mm) | Daily

Figure 3-25 Tables showing variation in seasonal ET_0 and ET_c for months with crops on the field - Zero values indicate no crops on the field at that time or could also indicate no irrigation requirement in cases where rainfall is enough for crop requirements



Irrigation:

Plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
15/12/1989	140	140	140	20	0	0	0	0	0	0	0	80	520
15/12/1990	40	120	80	60	0	0	0	0	0	0	0	60	360
15/12/1991	140	280	180	20	0	0	0	0	0	0	0	40	660

Irri loss:

PlantDate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
15/12/1989	28	28	28	4	0	0	0	0	0	0	0	16	104
15/12/1990	8	24	16	12	0	0	0	0	0	0	0	12	72
15/12/1991	28	56	36	4	0	0	0	0	0	0	0	8	132

Rain:

Plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
15/12/1989	0	72	94	37	0	0	0	0	0	0	0	4	207
15/12/1990	130	101	116	0	0	0	0	0	0	0	0	7	354
15/12/1991	20	0	53	5	0	0	0	0	0	0	0	16	94

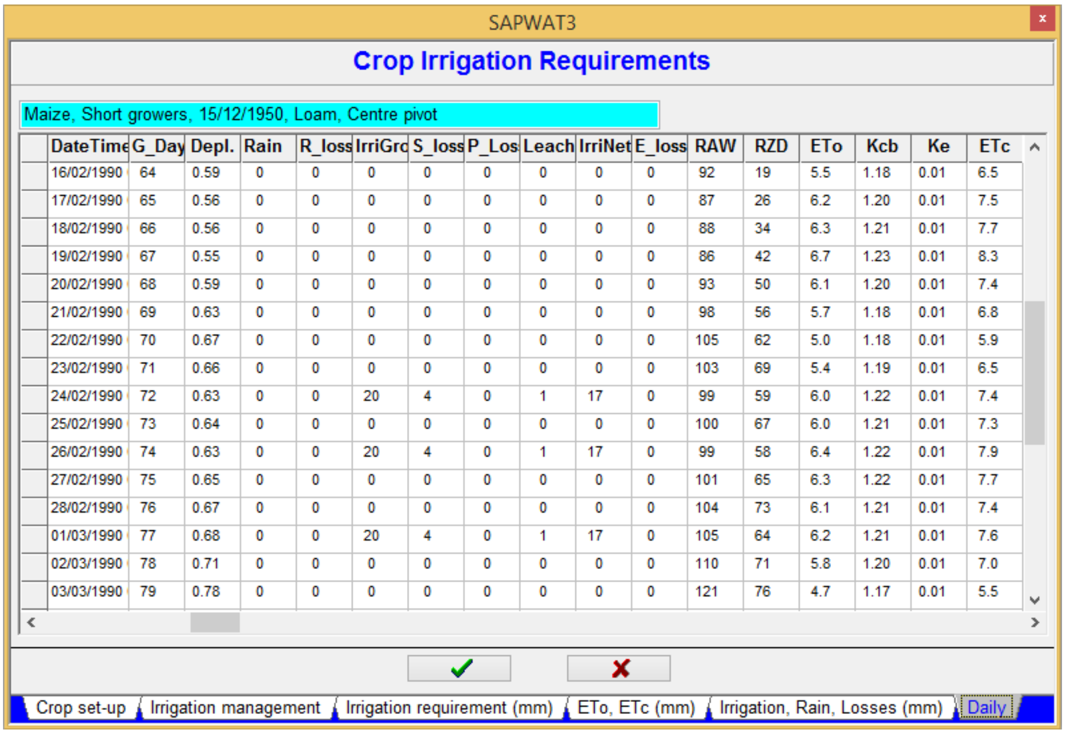
Rain loss:

Plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
15/12/1989	0	0	20	0	0	0	0	0	0	0	0	0	20
15/12/1990	17	68	38	0	0	0	0	0	0	0	0	2	125
15/12/1991	14	0	0	0	0	0	0	0	0	0	0	3	17

Evaporation:

Plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
15/12/1989	34	0	0	0	0	0	0	0	0	0	0	54	88
15/12/1990	46	0	0	0	0	0	0	0	0	0	0	45	91
15/12/1991	37	0	0	0	0	0	0	0	0	0	0	39	76

Figure 3-26 Irrigation, irrigation loss, rain, rain loss and evaporation from soil surface is shown on page 5 of the irrigation requirement calculation screen form. "Evaporation" refers to soil surface evaporation



DateTime	G_Day	Depl.	Rain	R_loss	IrriGrd	S_loss	P_Los	Leach	IrriNet	E_loss	RAW	RZD	ETo	Kcb	Ke	ETc
16/02/1990	64	0.59	0	0	0	0	0	0	0	0	92	19	5.5	1.18	0.01	6.5
17/02/1990	65	0.56	0	0	0	0	0	0	0	0	87	26	6.2	1.20	0.01	7.5
18/02/1990	66	0.56	0	0	0	0	0	0	0	0	88	34	6.3	1.21	0.01	7.7
19/02/1990	67	0.55	0	0	0	0	0	0	0	0	86	42	6.7	1.23	0.01	8.3
20/02/1990	68	0.59	0	0	0	0	0	0	0	0	93	50	6.1	1.20	0.01	7.4
21/02/1990	69	0.63	0	0	0	0	0	0	0	0	98	56	5.7	1.18	0.01	6.8
22/02/1990	70	0.67	0	0	0	0	0	0	0	0	105	62	5.0	1.18	0.01	5.9
23/02/1990	71	0.66	0	0	0	0	0	0	0	0	103	69	5.4	1.19	0.01	6.5
24/02/1990	72	0.63	0	0	20	4	0	1	17	0	99	59	6.0	1.22	0.01	7.4
25/02/1990	73	0.64	0	0	0	0	0	0	0	0	100	67	6.0	1.21	0.01	7.3
26/02/1990	74	0.63	0	0	20	4	0	1	17	0	99	58	6.4	1.22	0.01	7.9
27/02/1990	75	0.65	0	0	0	0	0	0	0	0	101	65	6.3	1.22	0.01	7.7
28/02/1990	76	0.67	0	0	0	0	0	0	0	0	104	73	6.1	1.21	0.01	7.4
01/03/1990	77	0.68	0	0	20	4	0	1	17	0	105	64	6.2	1.21	0.01	7.6
02/03/1990	78	0.71	0	0	0	0	0	0	0	0	110	71	5.8	1.20	0.01	7.0
03/03/1990	79	0.78	0	0	0	0	0	0	0	0	121	76	4.7	1.17	0.01	5.5

Figure 3-27 Daily data for ETc and the elements that influence its value through the soil water balance is shown on this page

3.5 Enterprise budgets

The ability to calculate basic enterprise budgets has been incorporated into SAPWAT3, as some users asked for such a facility, and it provides additional criteria in the decision making process. It is based on gross margin analyses that determine the relative profitability of different farm enterprises in order to optimise farming systems. In general terms, gross margin is described as the selling price of a product less its production cost. By comparing the gross margins of different farming enterprises, more profitable farming enterprise combinations can be identified (Accounting tools, 2015). The gross margin calculations included in SAPWAT3 is based on the COMBUD approach used by agricultural economists to compare relative potential profitability of farming enterprises. The COMBUD approach is used to calculate the gross margin of a farming enterprise as the difference between gross income of that enterprise minus its directly allocable costs and is usually expressed as a value per unit area – R ha^{-1} in the case of South Africa (Equation 3.56) (DAEARD, 2011).

$$GM = GI - DAC \qquad 3.56$$

where: GM gross margin (value per unit area),
GI gross income (value per unit area),
DAC direct allocable cost (value per unit area).

The module built into SAPWAT3 has three calculation levels which can be used in any combination to calculate gross margin. At its simplest it requires only total expected income and total expected directly allocable variable costs as inputs into Equation 3.56.

At the second and third levels of input detail, gross income is calculated as:

$$GI = \text{product volume} \times \text{unit price} \qquad 3.57$$

where: GI gross income (value per unit area),
product volume t ha^{-1}; kg ha^{-1}; l ha^{-1}; etc... ,
unit price R t^{-1}; R kg^{-1}; R l^{-1}; R ha^{-1}; etc...

At the second level of cost items are divided into two categories: cost items related to area planted, e.g. fertilizer, seed, irrigation cost; and cost related to yield, e.g. packaging material, product transport.

$$\text{DAC} = \text{area related cost} + \text{yield related cost} \qquad 3.58$$

where: DAC direct allocable cost (value per unit area).

At this level cost is grouped according to input type, e.g. total fertiliser cost, total pest and disease control cost.

$$\text{area related cost} = \text{fertiliser cost} + \text{pest and disease cost} + ... \qquad 3.59$$

At the third level gross income is calculated with Equation 3.57 and cost breakdown is done in detail to show every cost item as a separate entry:

$$\text{fertiliser cost} = \text{nitrogen cost} + \text{phosphate cost} + \text{potassium cost} + ... \qquad 3.60$$

The gross margin budget module is not directly linked to the irrigation water requirement estimate. It requires the user to physically link a budget result to an irrigation water requirement estimate. That budget result stays linked until such time as the user updates the result linkage manually. No automatic updating takes place if yield levels change, or if cost items or product prices change.

The result of a linked irrigation requirement and enterprise budget comparison is shown in Figure 3-28. At first glance sorghum requires the most water at 844 mm per season, compared to the 483 mm of maize. However, the irrigation requirement of the two crops cannot be compared without some further analysis. Maize is planted in December and most of its growing period is in the rainy season, while sorghum is planted in October, so that most of its growing period will be completed before the rainy season starts in late summer at this farm. Had these crops been planted on the same day, the irrigation requirement figures might have been closer. Of more significance is the gross margin per unit water, where maize seems to be by far the best, with R23.94 per unit (m^3) water. Sorghum is the worst, with only R0.89 per unit water. Thus in sequence of profitable use of water, maize is the best, followed by wheat, then soybeans and lastly sorghum. However, it must be kept in mind that water use and relative profitability alone do not necessarily decide which crops should be grown in an area. Adaptability to climate and the fitting in of a crop's growth pattern into a bigger farming system does play a significant role. Access to markets and farmer preferences could be the determining factor when deciding which crops to grow.

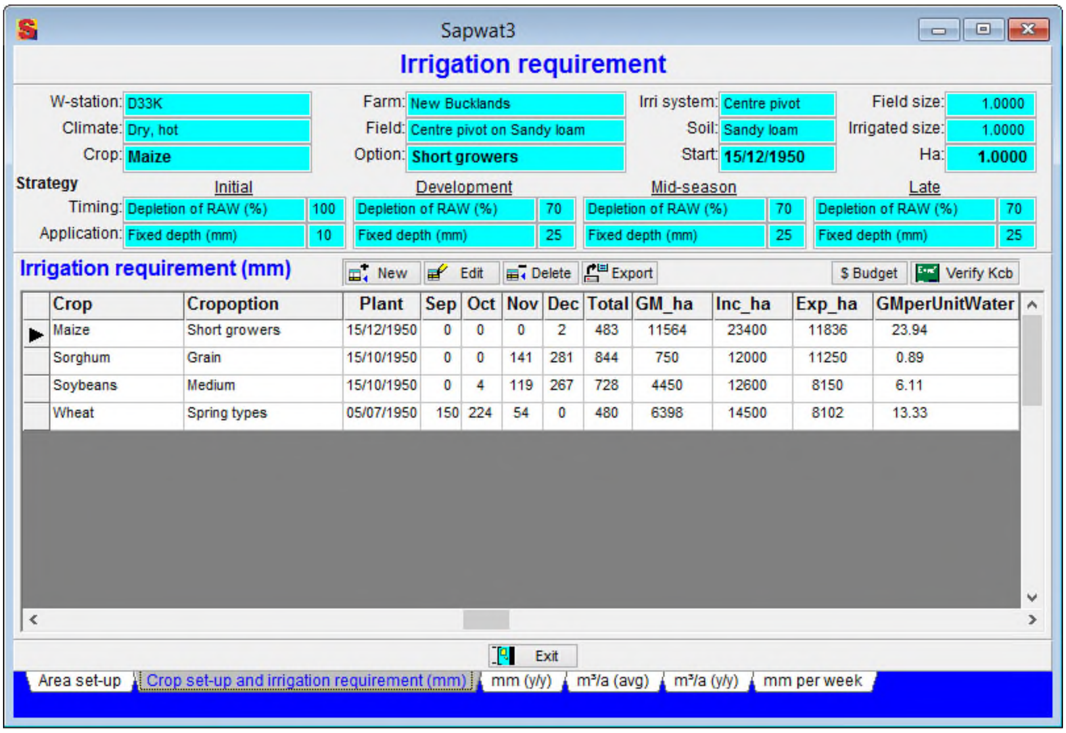


Figure 3-28 Irrigation requirement form showing irrigation requirement and gross margin (GM) results per hectare and per unit water.

3.5.1 Data structure

The data structure is made up of several tables that are relationally linked and are used in combination to give a single result. In the case of hierarchically linked tables, linkage between parent-child tables is thorough a common field in each of the tables, the proviso being that these fields have the same name and contain the same data type (Figure 3-29). The parent table is the controlling table; shifting from record to record in it resulting in the automatic selection of the correct results in the child table.

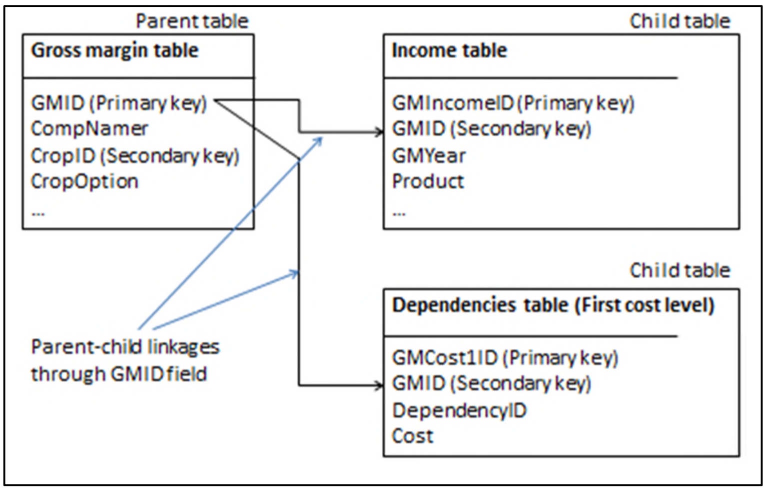


Figure 3-29 Linking hierarchical related data tables

3.5.1.1 The main gross margin data table

The main gross margin data table (Table 3-6) is the combined table that can be linked to the irrigation requirement estimation table so that irrigation requirements and potential profitability can be compared between different crops produced under irrigation.

Table 3-6 The main gross margin data table (Grossmargin.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	GMID	Autoincrement	4	0	Y	ID number - primary index
2	CompName	Character	60	0	Y	Compiled name for selection from a single field
3	CropID	Long	4	0	Y	Link to the Crops data table, show the crop name
4	Cropoption	Character	50	0	N	Description of growth characteristics
5	Cropplant	Gharavter	50	0	N	Month planted or start of growing season
6	Locality	Character	50	0	N	Area for which budget is relevant
7	SystemID	Long	4	0	N	Link to irrigation systems data table – shows irrigation system name
8	SoilID	Long	4	0	N	Link to soils data table – show soil name
9	GMYear	Numeric	4	0	N	Budget year
10	IncomeHa	Numeric	8	0	N	Gross income per hectare
11	ExpenseHa	Numeric	8	0	N	Allocable variable costs
12	GrossMarginHa	Numeric	8	0	N	Margin above directly allocable variable cost
13	Yieldratio	Numeric	4	2	N	

3.5.1.2 The gross margin income table

The income table (Table 3-7) is used for tabling income data related to enterprises budget.

Table 3-7 The income data table (Gmicome.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	GMIncomeID	Autoincrement	4	0	Y	ID number - primary index
2	GMid	Long	4	0	Y	Secondary index for linking to the gross margin table
3	GMYear	Numeric	4	0	N	Budget year
4	Product	Character	30	0	N	Product produced and marketed
5	Unit	Character	10	0	N	Weight/volume unit as marketed
6	U_Value	Numeric	9	3	N	Unit value
7	Quantity	Numeric	9	2	N	Yield
8	Income	Numeric	10	0	N	Gross income (yield * unit value)

3.5.1.3 The dependencies table

The function of the dependencies table (Table 3-8) is to divide all costs between those that can be linked to area, such as seed requirement, and costs that are influenced by yield, such as marketing costs. This table is the first level in the hierarchically structured cost data tables

Table 3-8 The dependencies table (Gmcost1.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	GmCost1ID	Autoincrement	4	0	N	ID number - primary index
2	GMId	Long	4	0	N	Secondary index for linking to the gross margin table
3	DependencyID	Long	4	0	N	ID code of the dependency (area, yield)
4	Cost	Numeric	10	0	N	Cost allocated to the dependency

3.5.1.4 The sub-dependency of cost group table

The sub-dependency table (Table 3-9) contains the cost groups, such as the expected cost for all fertilisers as a single cost item, without any breakdown of the cost according to individual nutrients groups.

Table 3-9 The sub-dependency of cost group table (Gmcost2.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	GMCost2ID	Autoincrement	4	0	Y	ID number - primary index
2	GMCost1ID	Long	4	0	Y	Secondary index for linking to the dependencies data table
3	Subdependencyid	Long	4	0	N	ID code of sub-dependency (fertiliser, weed control etc.)
4	Unit	Character	10	0	N	Unit in which production inputs are acquired
5	U_Value	Numeric	9	3	N	Production input unit cost
6	Quantity	Numeric	9	2	N	Quantity of production input required
7	Cost	Numeric	10	0	N	Cost of production input

3.5.1.5 The cost detail table

The cost detail table (Table 3-10) is the table in which production inputs are listed in detail. Costs are summed from child tables to parent tables.

Table 3-10 The cost detail table (Gmcost3.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	GMCost3ID	Autoincrement	4	0	Y	ID number - primary index
2	GMCost2ID	Long	4	0	Y	Secondary index for linking to the sub-dependencies data table
3	Description	Character	30	0	N	Description / name of cost item
4	Unit	Character	10	0	N	Unit in which production input is acquired
5	U_Value	Numeric	9	3	N	Production input unit cost
6	Quantity	Numeric	9	2	N	Quantity of production input required
7	Cost	Numeric	10	0	N	Cost of production input

3.5.2 Gross margin screen form

The gross margin screen form (Figure 3-30) is the key form for managing the filling in of data to estimate gross margins for crops (or any other agricultural enterprise) Three levels of cost input are provided for:

(i) where only the basic information regarding income and expenditure is added (Figure 3-30);

(ii) semi-detailed: where some cost breakdown in available, e.g. Fertiliser cost is available but not the cost of the individual components of the fertiliser, such as ammonium sulphate and super phosphate cost (Figure 3-31);

(iii) detailed: where the cost of each and every cost component is known (Figure 3-32).

Enterprise budgets are calculated per unit area, usually based on information from the previous financial year, but actually for a specific year if budgetary information is required for such a year. The heading of the screen indicates either per ha or per acre, so that the user should feel free to use the system relevant for his area – "per unit area" might have been better wording for this screen form.

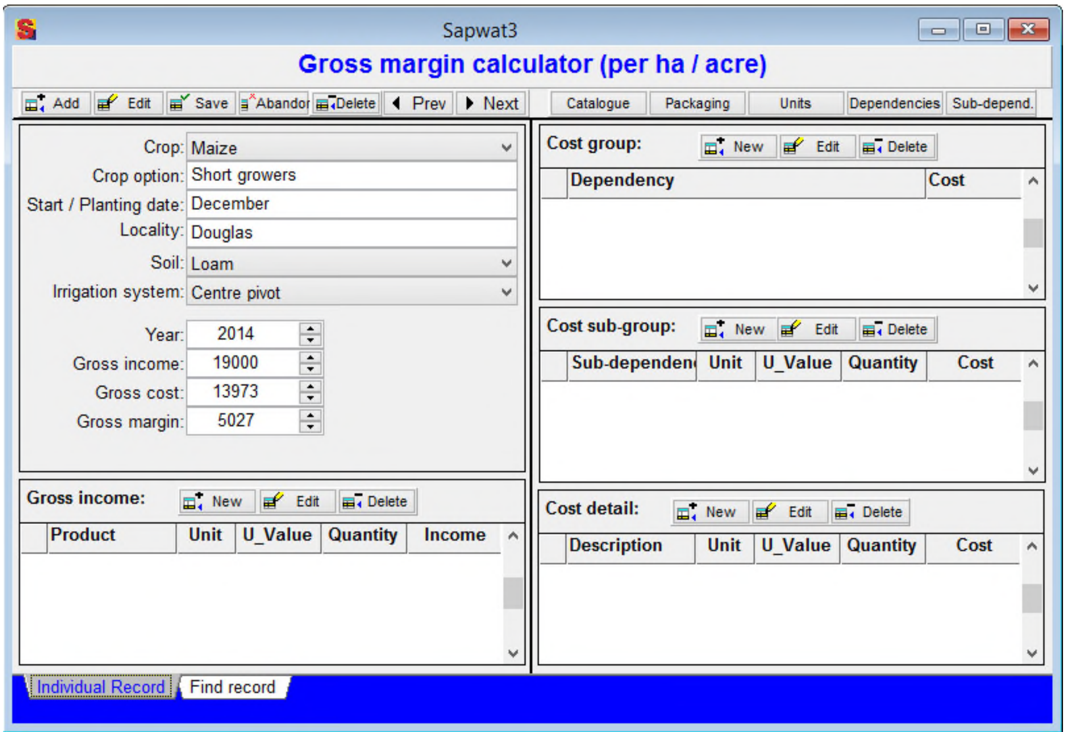


Figure 3-30 The gross margin screen form when inputting the minimum data required for doing an enterprise budget – data required has been filled in. In this case blank parts of the form do not contain or need to contain data.

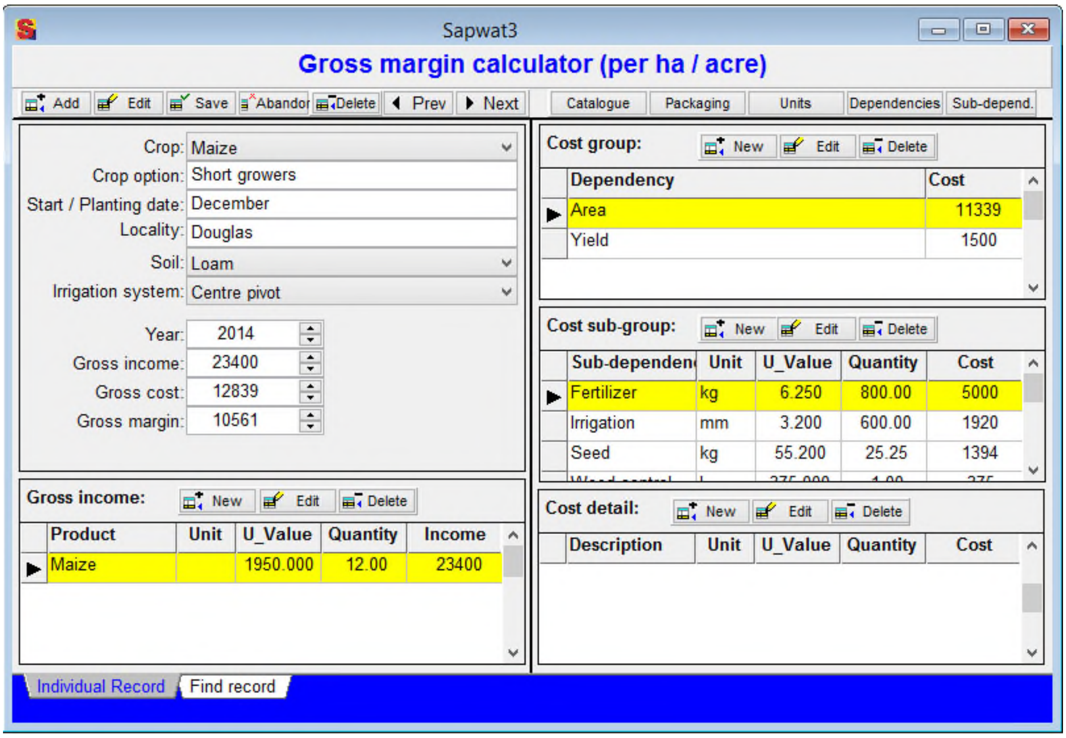


Figure 3-31 The gross margin screen form showing semi-detailed or cost sub-dependency data input for doing an enterprise budget – data has been entered.

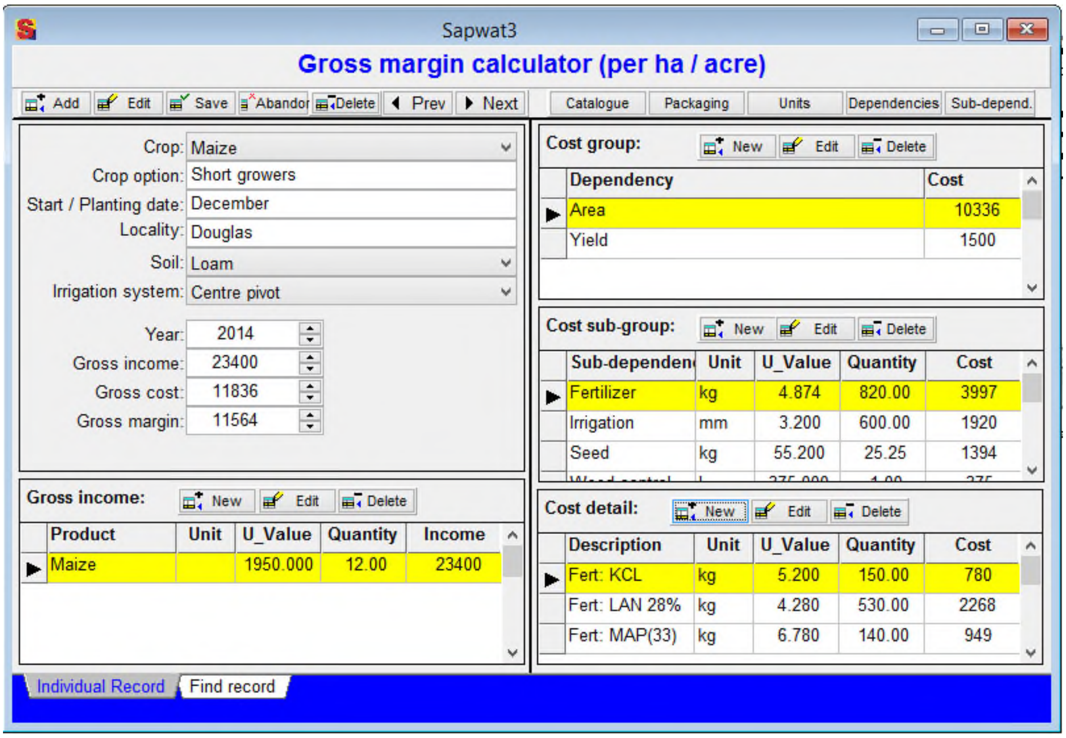


Figure 3-32 The gross margin screen form showing detailed data input for doing an enterprise budget – data already filled in. Detailed cost data is automatically summed to the relevant semi-dependency field, then summed from there to the relevant dependency field and finally summed from there to the gross cost field

3.6 Water harvesting.

SAPWAT3 includes a module on water harvesting and storage of water on a small scale which does water balances for one season only meant for the back-yard garden or similar situations. The opening screen is seen in Figure 3-33, with the volume of water required having been calculated in the normal SAPWAT3 way as described in 3.4. The opening screen provides for input in terms of grey water, well delivery, domestic requirement and whether more than one month's water supply is required at the beginning of the season. The water harvest module in SAPWAT3 is based on an empty start – empty finish approach, except when a balance is required at the beginning of the season , in which case that will be carried over from the end of the period.

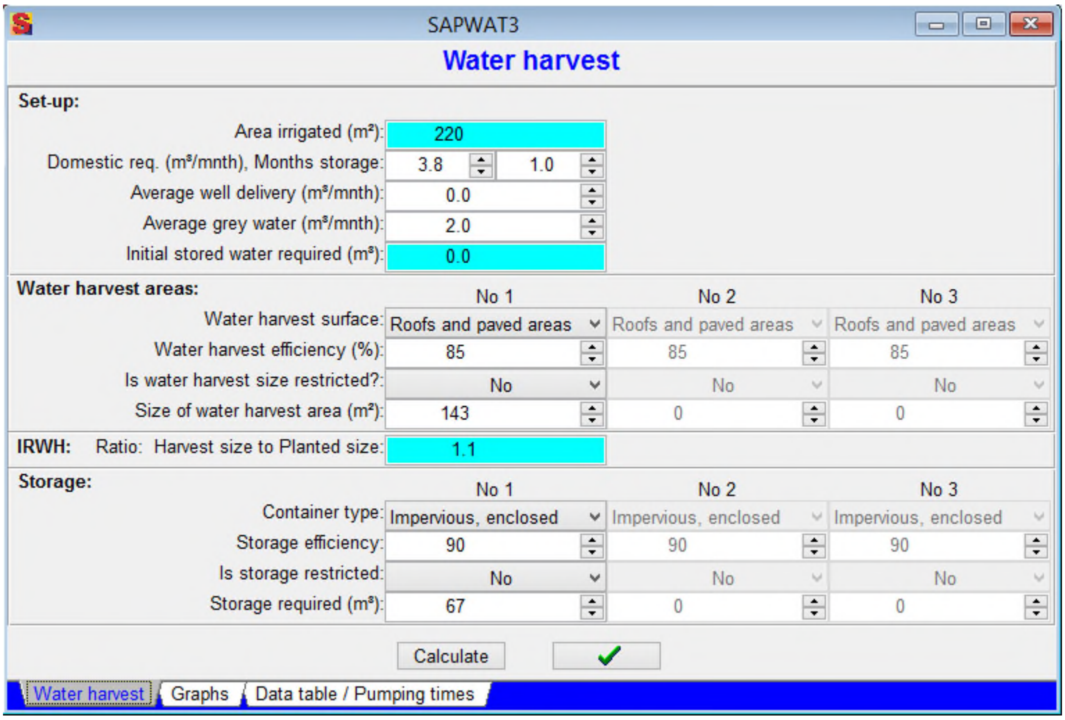


Figure 3-33 The water harvesting setup form.

Provision is made for the selection of up to three sources of water in combination and up to three means of water storage. Harvest area options are:

- Roofs and paved areas;
- Hard packed soil;
- Natural vegetation;

And storage options are:

- Impervious, enclosed;
- Impervious, open;
- Pond.

A water harvest area is calculated for each type of surface, each with its own harvesting efficiency and similarly, storage requirement is calculated for each type of storage separately. In the case shown in Figure 3-33, the assumption was that there is no limitation on both roof harvesting area, i.e. the total roof area is assumed to be big enough to supply the garden with all the extra water required. As a first round, the roof harvest area is usually indicated as unrestricted to give the user an idea of what is really needed. The usual practice is to put in the area of the roof, and if the roof is not big enough, the program will tell the user, in which case the options are a smaller garden, a different crop combination, or to expand the harvest area by also including say, an area of hard-packed earth such as a road surface from which to harvest water. In a similar approach the storage could be an impervious tank with a limited capacity – if the tank is too small, an additional storage must be planned for. Alternatively, the garden size need to be reduced or planning need to be done for a different crop combination. The results show a harvesting area requirement of 143 m^2 and a storage requirement of 67 m^3. In this particular case the large harvest area and storage requirement is because the owner insisted on producing vegetables after the rainy season had ended and all water required for that purpose had to be harvested and then stored for use during the dry season. The best option cost-wise for backyard gardens is to produce vegetables during the rainy season and use the harvested water for supplementary irrigation – this will usually require the smallest harvest area and smallest storage volume, but will not necessarily provide water for vegetable production throughout the year because no or very little vegetables will be produced outside the rainy season. It is the home owner's choice which approach he or she wants to follow – the designer can merely advise.

If harvest area or storage is limited, the limited area or volume is input in the size of water harvest area field or in the storage required field. In these cases the limited area of storage is subtracted from the total and the balance is carried over to the next option. If limited harvest area or storage is indicated and the calculated size or volume is smaller, then the calculation results ara indicated under the relevant options.

Figure 3-34 show the monthly and total water balances graphically. Figure 3-35 shows the tabulated results of the water harvest situation depicted in Figure 3-33. Included in this table, is detail about expected pumping time when using a low technology pump, such as a treadle pump (IPTRID, 2000), to pump water from storage to garden. In this case the longest pumping time required is 29 minutes per day for August. The water balance for August itself is negative, but the cumulative balance from start of storage in October is positive and provides the water for pumping.

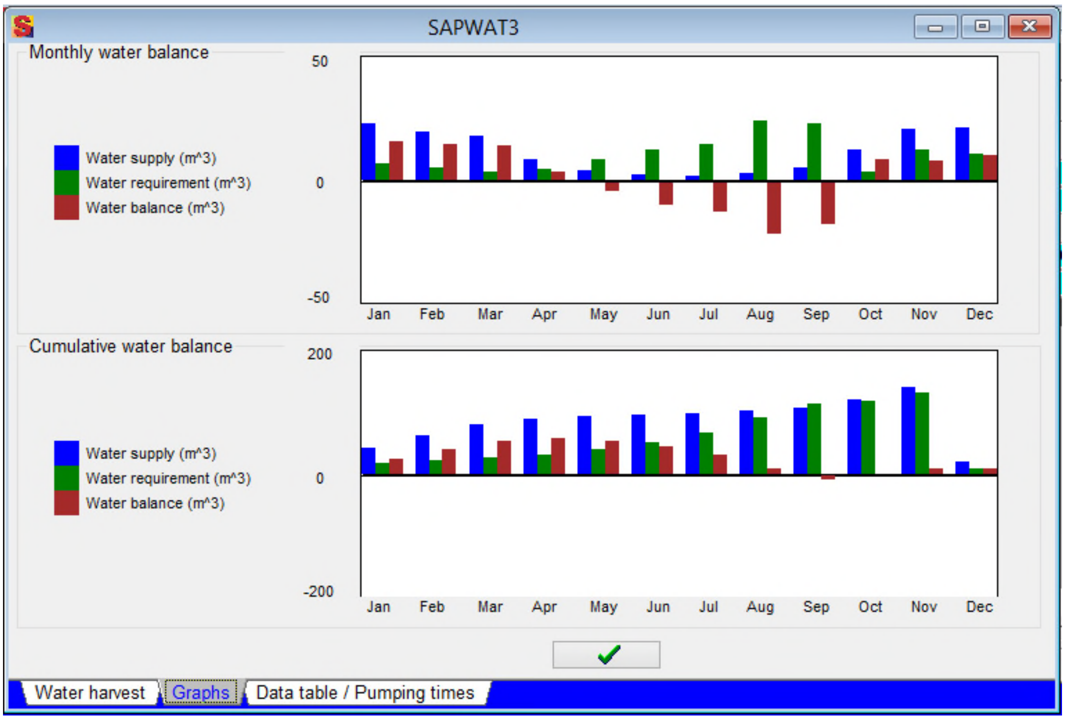
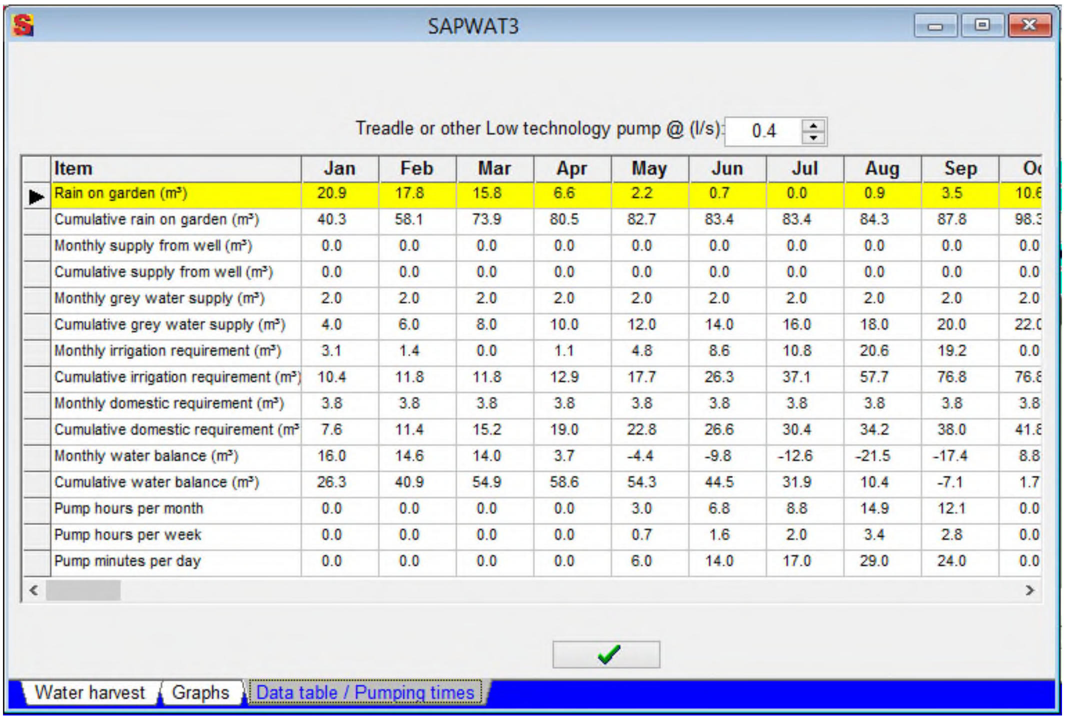


Figure 3-34 The water harvest monthly and total water balances.


SAPWAT3

Treadle or other Low technology pump @ (l/s): 0.4

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oc
Rain on garden (m³)	20.9	17.8	15.8	6.6	2.2	0.7	0.0	0.9	3.5	10.6
Cumulative rain on garden (m³)	40.3	58.1	73.9	80.5	82.7	83.4	83.4	84.3	87.8	98.3
Monthly supply from well (m³)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cumulative supply from well (m³)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Monthly grey water supply (m³)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Cumulative grey water supply (m³)	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0
Monthly irrigation requirement (m³)	3.1	1.4	0.0	1.1	4.8	8.6	10.8	20.6	19.2	0.0
Cumulative irrigation requirement (m³)	10.4	11.8	11.8	12.9	17.7	26.3	37.1	57.7	76.8	76.8
Monthly domestic requirement (m³)	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Cumulative domestic requirement (m³	7.6	11.4	15.2	19.0	22.8	26.6	30.4	34.2	38.0	41.8
Monthly water balance (m³)	16.0	14.6	14.0	3.7	-4.4	-9.8	-12.6	-21.5	-17.4	8.8
Cumulative water balance (m³)	26.3	40.9	54.9	58.6	54.3	44.5	31.9	10.4	-7.1	1.7
Pump hours per month	0.0	0.0	0.0	0.0	3.0	6.8	8.8	14.9	12.1	0.0
Pump hours per week	0.0	0.0	0.0	0.0	0.7	1.6	2.0	3.4	2.8	0.0
Pump minutes per day	0.0	0.0	0.0	0.0	6.0	14.0	17.0	29.0	24.0	0.0

Water harvest | Graphs | Data table / Pumping times

Figure 3-35 The water harvest water balances table.

3.7 Data volume, management and storage

SAPWAT3, being programmed in dBase with its full data management capabilities, has a large and trusted data management capability. Individual data tables are limited in size to 2 Gb or 1 x 10^9 records, whichever comes first. A combination of very large weather data files could slow-down computer speed, but a way of managing this problem – described in section 3.7.2.1 - has been incorporated into SAPWAT3 (Mayer, 2005; Van Heerden *et al*., 2008).

All data required by SAPWAT3 are stored on computer hard disc. The disadvantages of such a system are that there is no centralised data set that can be kept up to date by a single service provider, and that a large space (4.6 Gb) is required on the computer hard disc. The advantage is that the user can use SAPWAT3 to its fullest capabilities on site and irrespective of internet linkage deficiencies, which can be a limitation in rural Africa.

The reason for this approach goes back to the development of SAPWAT in 1999. Then the practical situation existed that a large proportion of irrigation system designers did not have country-wide access to the internet. These designers were the biggest potential user group of SAPWAT. The accepted work approach was then, and still is; to undertake design on the basis of crop irrigation requirement with the aid of a computer or laptop in the office. The proposed irrigation system design is then taken to the farmer and the implications discussed. With all data on board, the designer is able to implement desired changes by changing cropping patterns, or design specifications, and show the results to the farmer immediately on site. Thus designers is able to provide an efficient and interactive client-friendly service. Without on-line or on-board access to essential data, the designer would have to go back to his office, make the required changes and return to the farmer for further discussions. Having data on-board obviates this problem. The situation regarding internet access has improved substantially since then, but even so, SAPWAT3 has retained the principle of having all required data on board (Crosby and Crosby, 1999; Van Heerden *et al*., 2008). This aspect of the set-up could however be changed in future researchers where a server or internet access is readily available.

3.7.1 Safeguarding data

Data management in SAPWAT3 is designed to prevent accidental change of content. In all cases where the user interacts with data, SAPWAT3 must be instructed to add, change or delete data, otherwise no change will result. Backup of data is the responsibility of the user (Van Heerden *et al*., 2008).

3.7.2 Source data management

Source data required by SAPWAT3 is stored on computer. With the exception of climate definitions, all data is under control of the user, who gets full editing access on installation.

3.7.2.1 Weather stations and weather data

SAPWAT3 uses monthly or daily weather data as basis for calculating daily Penman-Monteith reference evapotranspiration (ET_0) values for a site as described by Allen *et al.* (1998). A cosine regression curve is fitted (Snedecor and Cochran, 1989) to ET_0 values and the regression equation is used to determine the daily ET_0 values used to calculate crop evapotranspiration (ET_c) values, except where sequential year-on-year calculations are done on daily weather data that covers a range of years.

Weather data for use by SAPWAT3 comes from three possible sources; CLIMWAT (Smith, 1993), manual weather stations and automatic weather stations. Data can be added manually or can be imported from external sources provided that it is organised in a way that is compatible with the SAPWAT3 data tables. SAPWAT3 includes the full set of CLIMWAT (Smith, 1993) data files as well as 50 years' daily hydro-climatic data for each quaternary drainage region of South Africa (Schulze & Maharaj, 2006).

The copyright notice in the CLIMWAT report (Smith, 1993) states that, while the program itself cannot be distributed by a third party, free use of the data may be made, provided that the Food and Agricultural Organisation of the United Nations (FAO) is cited as the source. This is seen as a tacit approval for the use of the data in programs such as SAPWAT3 and is also the condition under which the previous version of SAPWAT (Crosby and Crosby, 1999) had CLIMWAT (Smith, 1993) weather data included as part of its weather database.

3.7.2.2 Weather station data structure

The structure of the weather station data file is shown in Table 3-11. This table includes monthly values of the following weather variables: average air temperature, maximum temperature, minimum temperature, average humidity, minimum humidity, wind run, sunshine hours, solar radiation, reference evapotranspiration, rain and rainfall events. Monthly averages are calculated from all data included in the weather data tables, irrespective of the time period included concerned.

Table 3-11 Structure of the weather station data table (Weatherstations.dbf): numerals in column names refer to months; 13 refers to annual total or average.

Field	Field Name	Type	Length	Decimals	Index	Notes need units! For many
1	StationID	Character	9		Y	Primary index
2	WSFilename	Character	9		Y	Weather station file name
3	CountryID	Character	3		Y	Country id for linking to country
4	Wstation	Character	40		N	Weather station common name
5	Type	Character	9		N	Type of station (manual, automatic, derived, CLIMWAT)
6	Maptype	Character	11		N	Outline or topographic map
7	Longitude	Numeric	9	4	Y	Decimal notation, western longitudes are negative
8	Latitude	Numeric	9	4	Y	Decimal notation, southern latitudes are negative
9	Elevation	Long	4		N	Meters above sea level
10	MAP	Long	4		N	Mean annual precipitation (mm)
11	TAvg	Numeric	5	1	N	Annual average temperature (˚C)
12	TAvgHotMnth	Numeric	5	1	N	Average temperature of the hottest month
13	TAvgColdMnth	Numeric	5	1	N	Average temperature of coldest month
14	MnthsAbove10	Long	4		N	Number of month above 10˚C
15	RainSeason	Character	6		N	Time rainy season (summer, winter, year)
16	YearsData	Numeric	4		N	Number of years of data
17	ClimateID	Character	3		N	Climate ID for linking to climate table
18	AvgA	Numeric	8	4	N	Y-axis intercept
19	AvgB	Numeric	8	4	N	Slope
20	AvgLag	Numeric	4		N	Lag days – sideways shift of cosine regression for best fit
21	AvgRR	Numeric	6	4	N	r^2 value
22	AvgSyx	Numeric	7	4	N	Standard error value for y(ETo) on x (DOY)
23	Calc	Logical	1		N	Confirmed calculation of ET_0 – presently not used
24	Selected	Logical	1		N	Station selected for calculations – presently nor used
25	Colour	Character	10		N	Colour code for station type for display on outline map
26	GraphColour	Character	20		N	Colour for graphing data – presently not used
27	WindSpeedHeight	Numeric	2		N	Wind speed height measurement
28	Interval	Numeric	6	2	N	Interval between measurements (days)
29	Tavg01	Numeric	5	1	N	Average temperature Jan (˚C)
30	Tavg02	Numeric	5	1	N	Average temperature Feb (˚C)
31	Tavg03	Numeric	5	1	N	Average temperature Mar (˚C)
32	Tavg04	Numeric	5	1	N	Average temperature Apr (˚C)
33	Tavg05	Numeric	5	1	N	Average temperature May (˚C)
34	Tavg06	Numeric	5	1	N	Average temperature Jun (˚C)
35	Tavg07	Numeric	5	1	N	Average temperature Jul (˚C)
36	Tavg08	Numeric	5	1	N	Average temperature Aug (˚C)
37	Tavg09	Numeric	5	1	N	Average temperature Sep (˚C)
38	Tavg10	Numeric	5	1	N	Average temperature Oct (˚C)

Field	Field Name	Type	Length	Decimals	Index	Notes need units! For many
39	Tavg11	Numeric	5	1	N	Average temperature Nov (˚C)
40	Tavg12	Numeric	5	1	N	Average temperature Dec (˚C)
41	Tavg13	Numeric	5	1	N	Average temperature year (˚C)
42	Tmax01	Numeric	5	1	N	Average maximum temperature Jan (˚C)
43	Tmax02	Numeric	5	1	N	Average maximum temperature Feb (˚C)
44	Tmax03	Numeric	5	1	N	Average maximum temperature Mar (˚C)
45	Tmax04	Numeric	5	1	N	Average maximum temperature Apr (˚C)
46	Tmax05	Numeric	5	1	N	Average maximum temperature May (˚C)
47	Tmax06	Numeric	5	1	N	Average maximum temperature Jun (˚C)
48	Tmax07	Numeric	5	1	N	Average maximum temperature Jul (˚C)
49	Tmax08	Numeric	5	1	N	Average maximum temperature Aug (˚C)
50	Tmax09	Numeric	5	1	N	Average maximum temperature Sep (˚C)
51	Tmax10	Numeric	5	1	N	Average maximum temperature Oct (˚C)
52	Tmax11	Numeric	5	1	N	Average maximum temperature Nov (˚C)
53	Tmax12	Numeric	5	1	N	Average maximum temperature Dec (˚C)
54	Tmax13	Numeric	5	1	N	Average maximum temperature year (˚C)
55	Tmin01	Numeric	5	1	N	Average minimum temperature Jan (˚C)
56	Tmin02	Numeric	5	1	N	Average minimum temperature Feb (˚C)
57	Tmin03	Numeric	5	1	N	Average minimum temperature Mar (˚C)
58	Tmin04	Numeric	5	1	N	Average minimum temperature Apr (˚C)
59	Tmin05	Numeric	5	1	N	Average minimum temperature May (˚C)
60	Tmin06	Numeric	5	1	N	Average minimum temperature Jun (˚C)
61	Tmin07	Numeric	5	1	N	Average minimum temperature Jul (˚C)
62	Tmin08	Numeric	5	1	N	Average minimum temperature Aug (˚C)
63	Tmin09	Numeric	5	1	N	Average minimum temperature Sep (˚C)
64	Tmin10	Numeric	5	1	N	Average minimum temperature Oct (˚C)
65	Tmin11	Numeric	5	1	N	Average minimum temperature Nov (˚C)
66	Tmin12	Numeric	5	1	N	Average minimum temperature Dec (˚C)
67	Tmin13	Numeric	5	1	N	Average minimum temperature year (˚C)
68	Havg01	Numeric	3		N	Average humidity Jan (%)
69	Havg02	Numeric	3		N	Average humidity Feb (%)
70	Havg03	Numeric	3		N	Average humidity Mar (%)
71	Havg04	Numeric	3		N	Average humidity Apr (%)
72	Havg05	Numeric	3		N	Average humidity May (%)
73	Havg06	Numeric	3		N	Average humidity Jun (%)
74	Havg07	Numeric	3		N	Average humidity Jul (%)
75	Havg08	Numeric	3		N	Average humidity Aug (%)
76	Havg09	Numeric	3		N	Average humidity Sep (%)
77	Havg10	Numeric	3		N	Average humidity Oct (%)
78	Havg11	Numeric	3		N	Average humidity Nov (%)
79	Havg12	Numeric	3		N	Average humidity Dec (%)
80	Havg13	Numeric	3		N	Average humidity year (%)
81	Hmin01	Numeric	3		N	Average minimum humidity Jan (%)

Field	Field Name	Type	Length	Decimals	Index	Notes need units! For many
82	Hmin02	Numeric	3		N	Average minimum humidity Feb (%)
83	Hmin03	Numeric	3		N	Average minimum humidity Mar (%)
84	Hmin04	Numeric	3		N	Average minimum humidity Apr (%)
85	Hmin05	Numeric	3		N	Average minimum humidity May (%)
86	Hmin06	Numeric	3		N	Average minimum humidity Jun (%)
87	Hmin07	Numeric	3		N	Average minimum humidity Jul (%)
88	Hmin08	Numeric	3		N	Average minimum humidity Aug (%)
89	Hmin09	Numeric	3		N	Average minimum humidity Sep (%)
90	Hmin10	Numeric	3		N	Average minimum humidity Oct (%)
91	Hmin11	Numeric	3		N	Average minimum humidity Nov (%)
92	Hmin12	Numeric	3		N	Average minimum humidity Dec (%)
93	Hmin13	Numeric	3		N	Average minimum humidity year (%)
94	Windrun01	Numeric	5		N	Average wind run Jan (km)
95	Windrun02	Numeric	5		N	Average wind run Feb (km)
96	Windrun03	Numeric	5		N	Average wind run Mar (km)
97	Windrun04	Numeric	5		N	Average wind run Apr (km)
98	Windrun05	Numeric	5		N	Average wind run May (km)
99	Windrun06	Numeric	5		N	Average wind run Jun (km)
100	Windrun07	Numeric	5		N	Average wind run Jul (km)
101	Windrun08	Numeric	5		N	Average wind run Aug (km)
102	Windrun09	Numeric	5		N	Average wind run Sep (km)
103	Windrun10	Numeric	5		N	Average wind run Oct (km)
104	Windrun11	Numeric	5		N	Average wind run Nov (km)
105	Windrun12	Numeric	5		N	Average wind run Dec (km)
106	Windrun13	Numeric	5		N	Average wind run year (km)
107	Sun01	Numeric	4	1	N	Average sunshine Jan (hours)
108	Sun02	Numeric	4	1	N	Average sunshine Feb (hours)
109	Sun03	Numeric	4	1	N	Average sunshine Mar (hours)
110	Sun04	Numeric	4	1	N	Average sunshine Apr (hours)
111	Sun05	Numeric	4	1	N	Average sunshine May (hours)
112	Sun06	Numeric	4	1	N	Average sunshine Jun (hours)
113	Sun07	Numeric	4	1	N	Average sunshine Jul (hours)
114	Sun08	Numeric	4	1	N	Average sunshine Aug (hours)
115	Sun09	Numeric	4	1	N	Average sunshine Sep (hours)
116	Sun10	Numeric	4	1	N	Average sunshine Oct (hours)
117	Sun11	Numeric	4	1	N	Average sunshine Nov (hours)
118	Sun12	Numeric	4	1	N	Average sunshine Dec (hours)
119	Sun13	Numeric	4	1	N	Average sunshine total (hours)
120	Rad01	Numeric	4	1	N	Average radiation Jan (MJ/m^2/day)
121	Rad02	Numeric	5	2	N	Average radiation Feb (MJ/m^2/day)
122	Rad03	Numeric	5	2	N	Average radiation Mar (MJ/m^2/day)
123	Rad04	Numeric	5	2	N	Average radiation Apr (MJ/m^2/day)
124	Rad05	Numeric	5	2	N	Average radiation May (MJ/m^2/day)

Field	Field Name	Type	Length	Decimals	Index	Notes need units! For many
125	Rad06	Numeric	5	2	N	Average radiation Jun (MJ/m^2/day)
126	Rad07	Numeric	5	2	N	Average radiation Jul (MJ/m^2/day)
127	Rad08	Numeric	5	2	N	Average radiation Aug (MJ/m^2/day)
128	Rad09	Numeric	5	2	N	Average radiation Sep (MJ/m^2/day)
129	Rad10	Numeric	5	2	N	Average radiation Oct (MJ/m^2/day)
130	Rad11	Numeric	5	2	N	Average radiation Nov (MJ/m^2/day)
131	Rad12	Numeric	5	2	N	Average radiation Dec (MJ/m^2/day)
132	Rad13	Numeric	5	2	N	Average radiation year(MJ/m^2/day)
133	ET001	Numeric	4	1	N	Average ET_0 Jan (mm/day)
134	ET002	Numeric	4	1	N	Average ET_0 Feb (mm/day)
135	ET003	Numeric	4	1	N	Average ET_0 Mar (mm/day)
136	ET004	Numeric	4	1	N	Average ET_0 Apr (mm/day)
137	ET005	Numeric	4	1	N	Average ET_0 May (mm/day)
138	ET006	Numeric	4	1	N	Average ET_0 Jun (mm/day)
139	ET007	Numeric	4	1	N	Average ET_0 Jul (mm/day)
140	ET008	Numeric	4	1	N	Average ET_0 Aug (mm/day)
141	ET009	Numeric	4	1	N	Average ET_0 Sep (mm/day)
142	ET010	Numeric	4	1	N	Average ET_0 Oct (mm/day)
143	ET011	Numeric	4	1	N	Average ET_0 Nov (mm/day)
144	ET012	Numeric	4	1	N	Average ET_0 Dec (mm/day)
145	ET013	Numeric	4	1	N	Average ET_0 year (mm/day)
146	Rain01	Numeric	5		N	Average rain Jan (mm)
147	Rain02	Numeric	5		N	Average rain Feb (mm)
148	Rain03	Numeric	5		N	Average rain Mar (mm)
149	Rain04	Numeric	5		N	Average rain Apr (mm)
150	Rain05	Numeric	5		N	Average rain May (mm)
151	Rain06	Numeric	5		N	Average rain Jun (mm)
152	Rain07	Numeric	5		N	Average rain Jul (mm)
153	Rain08	Numeric	5		N	Average rain Aug (mm)
154	Rain09	Numeric	5		N	Average rain Sep (mm)
155	Rain10	Numeric	6		N	Average rain Oct (mm)
156	Rain11	Numeric	5		N	Average rain Nov (mm)
157	Rain12	Numeric	5		N	Average rain Dec (mm)
158	Rain13	Numeric	5		N	Average rain year (mm)
159	Events01	Numeric	3		N	Average number of rain events Jan
160	Events02	Numeric	3		N	Average number of rain events Feb
161	Events03	Numeric	3		N	Average number of rain events Mar
162	Events04	Numeric	3		N	Average number of rain events Apr
163	Events05	Numeric	3		N	Average number of rain events May
164	Events06	Numeric	3		N	Average number of rain events Jun
165	Events07	Numeric	3		N	Average number of rain events Jul
166	Events08	Numeric	3		N	Average number of rain events Aug
167	Events09	Numeric	3		N	Average number of rain events Sep

Field	Field Name	Type	Length	Decimals	Index	Notes need units! For many
168	Events10	Numeric	3		N	Average number of rain events Oct
169	Events11	Numeric	3		N	Average number of rain events Nov
170	Events12	Numeric	3		N	Average number of rain events Dec
171	Events13	Numeric	3		N	Average number of rain events year

The weather data table (Table 3-12) reflects all data that are required for calculating a reference evapotranspiration (ET_0) value (Equation 3.3), as well as rainfall. The table is designed to accept automatic weather station data at hourly or multiples of hourly intervals, manual weather station data at daily intervals, or long term averaged values, usually at 10-day or monthly intervals.

Table 3-12 Data structure of the detail weather data table (Weatherdata.dbf)

Field	Field Name	Type	Length	Decimals	Index	Notes
1	WeatherdataID	Character	21		Y	Primary index
2	Stationid	Character	9		N	Weather station ID for linkage
3	Wsfilename	Character	40		N	Weather station file name
4	rDateTime	Timestamp	8		Y	Date-time (CCYYMMDD:hh:ss)
5	YearMnth	Character	6		N	Year-month ID (YYMM)
6	MonthID	Numeric	2		Y	Month number
7	DOY	Numeric	6	2	N	Day of year (Jan 1 = 1)
8	TMax	Numeric	6	1	N	Maximum temperature(˚C)
9	Tmin	Numeric	6	1	N	Minimum temperature(˚C)
10	HMax	Numeric	6	1	N	Maximum humidity (%)
11	HMin	Numeric	6	1	N	Minimum humidity (%)
12	Havg	Numeric	6	1	N	Average humidity (%)
13	Windrun	Numeric	6	1	N	Wind run (km/day)
14	Sunshine	Numeric	4	1	N	Sunshine hours
15	Radiation	Numeric	5	1	N	Radiation (MJ/m^2/day)
16	ET0Given	Numeric	4	1	N	Given ET_0 (mm/day) (control for correctness of SAPWAT calculated ET_0)
17	ET0	Numeric	4	1	N	SAPWAT calculated ET_0 (mm/day)
18	Rain	Numeric	6	1	N	Rain (mm)
19	RainEvents	Numeric	3		N	Rain events (number)
20	Interval	Numeric	6	2	N	Interval between measurements

The weather stations and weather data tables are relationally linked in a parent-child linkage through a common field in both tables; in this case the field is StationID. When a weather station is selected, this linkage ensures that all weather data that are relevant to the weather station are linked and become visible as that weather station's data.

3.7.2.3 Weather station screen forms

The weather station screen form is composed of four pages. Page 1 (Figure 3-36) is the look-up table for selection of a station from the complete list available in SAPWAT3. The world-wide placements of weather stations show the relative position of all station included in SAPWAT3. Double clicking on any station, automatically shifts to that station for inspection of its data. Pop-up name tags could not be given to the stations included in the map; experience has shown that hardware capacity can become over-extended, leading to a program crash, if such a facility is included.

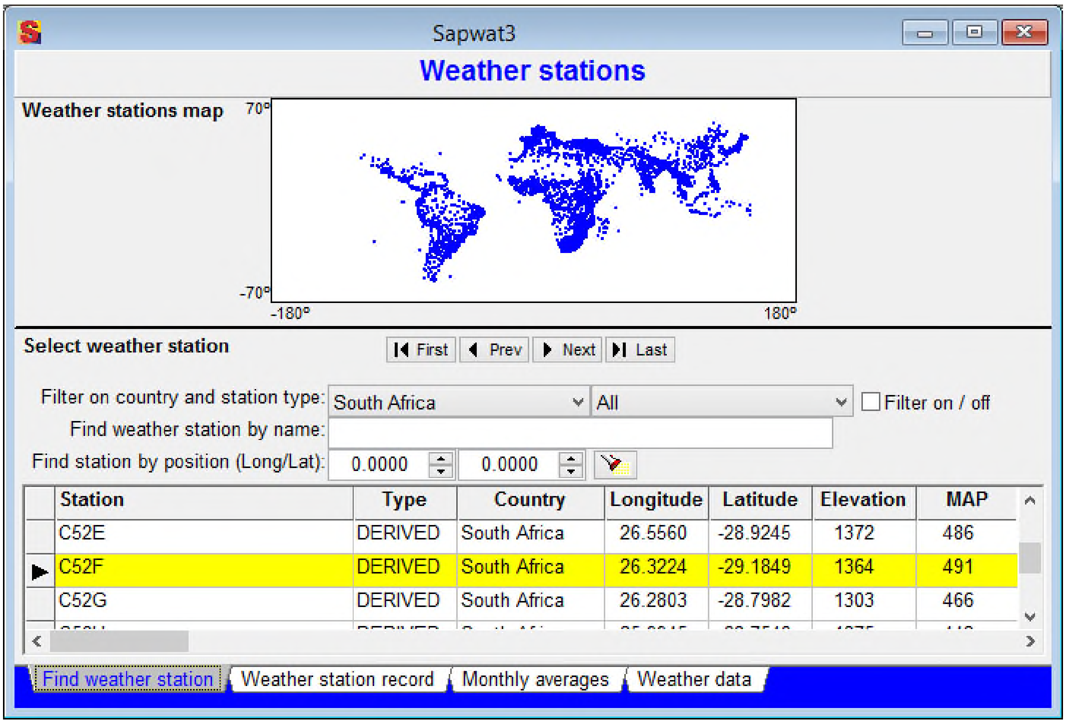


Figure 3-36 Page 1 of the weather stations screen form: a weather station is selected on this screen

Page two shows the summarised detail of the selected weather station (Figure 3-37). The ET_0 as well as monthly average ET_0 values are shown. Added to this are graphic representations of average, maximum and minimum temperatures, sunshine hours and overall water balance. Further information shown include geographic position, long term average temperatures, as well as hottest month and coldest month average temperatures and the number of months with average temperatures above 10°C. The Köppen-Geiger climate of the station is derived from the station's weather data and is also shown.

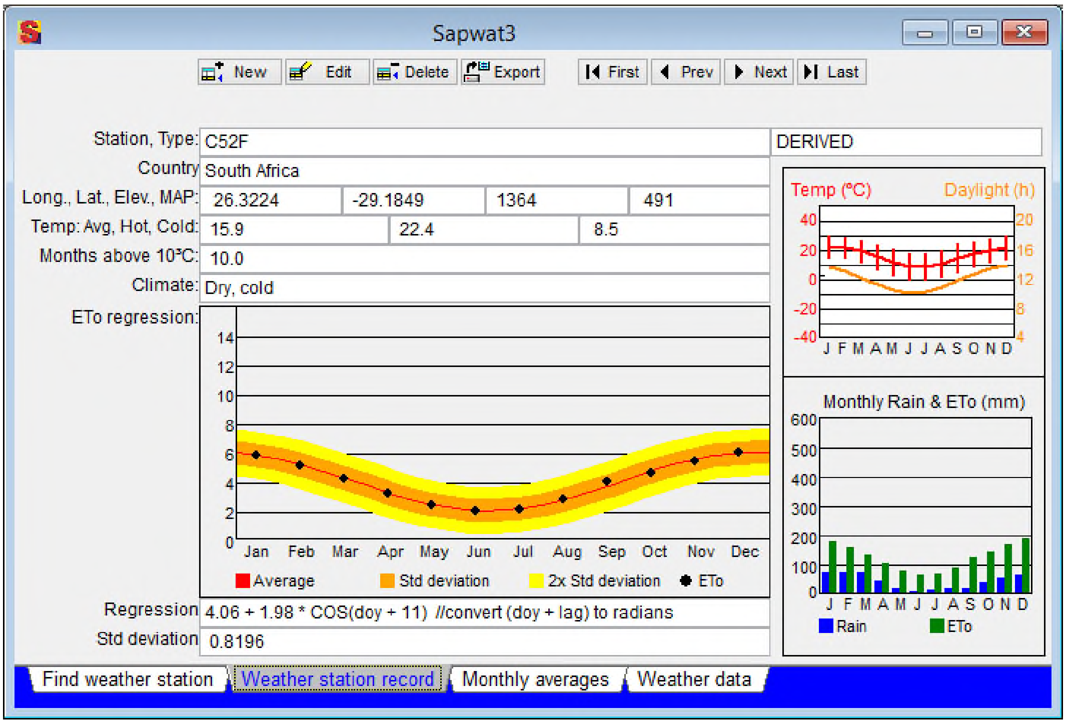
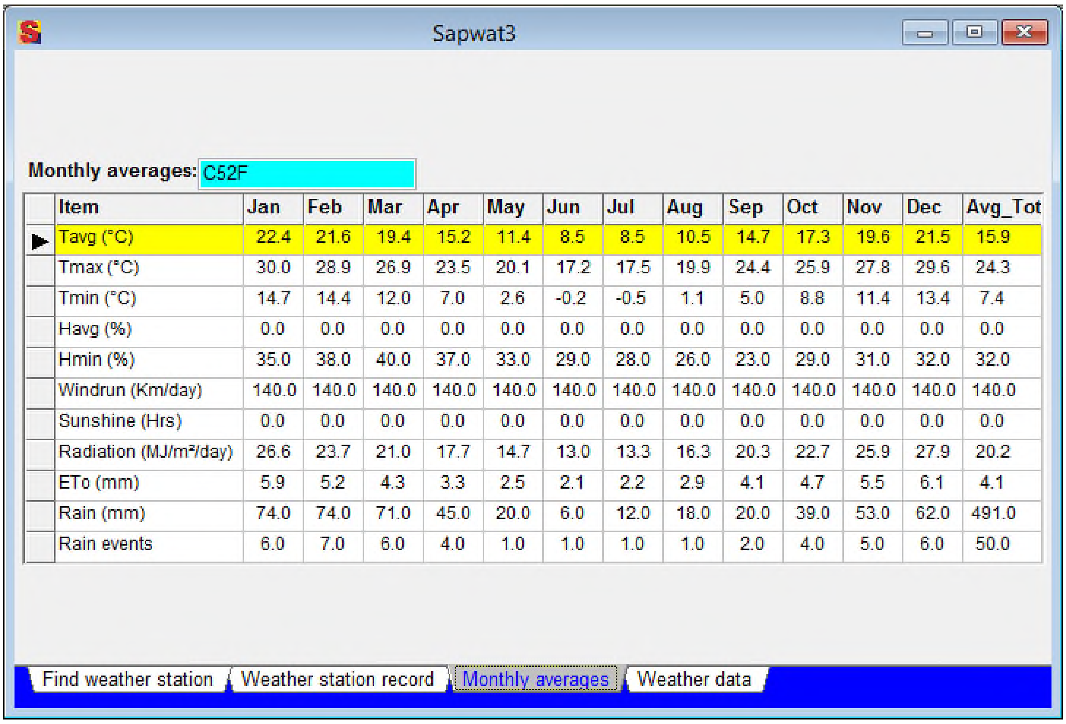


Figure 3-37 Page 2 of the weather stations screen showing screen detail

Average monthly weather data are shown on page 3 of the form (Figure 3-38). These average values are calculated by SAPWAT3 from weather data stored in the detailed weather data table (Figure 3-39). Weather data of a station can be added manually or can be imported when a weather station is added to the SAPWAT3 weather data table or when weather station data is updated.



Monthly averages: C52F

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	22.4	21.6	19.4	15.2	11.4	8.5	8.5	10.5	14.7	17.3	19.6	21.5	15.9
Tmax (°C)	30.0	28.9	26.9	23.5	20.1	17.2	17.5	19.9	24.4	25.9	27.8	29.6	24.3
Tmin (°C)	14.7	14.4	12.0	7.0	2.6	-0.2	-0.5	1.1	5.0	8.8	11.4	13.4	7.4
Havg (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hmin (%)	35.0	38.0	40.0	37.0	33.0	29.0	28.0	26.0	23.0	29.0	31.0	32.0	32.0
Windrun (Km/day)	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0	140.0
Sunshine (Hrs)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radiation (MJ/m²/day)	26.6	23.7	21.0	17.7	14.7	13.0	13.3	16.3	20.3	22.7	25.9	27.9	20.2
ETo (mm)	5.9	5.2	4.3	3.3	2.5	2.1	2.2	2.9	4.1	4.7	5.5	6.1	4.1
Rain (mm)	74.0	74.0	71.0	45.0	20.0	6.0	12.0	18.0	20.0	39.0	53.0	62.0	491.0
Rain events	6.0	7.0	6.0	4.0	1.0	1.0	1.0	1.0	2.0	4.0	5.0	6.0	50.0

Figure 3-38 Page 3 of the weather station screens showing monthly average values

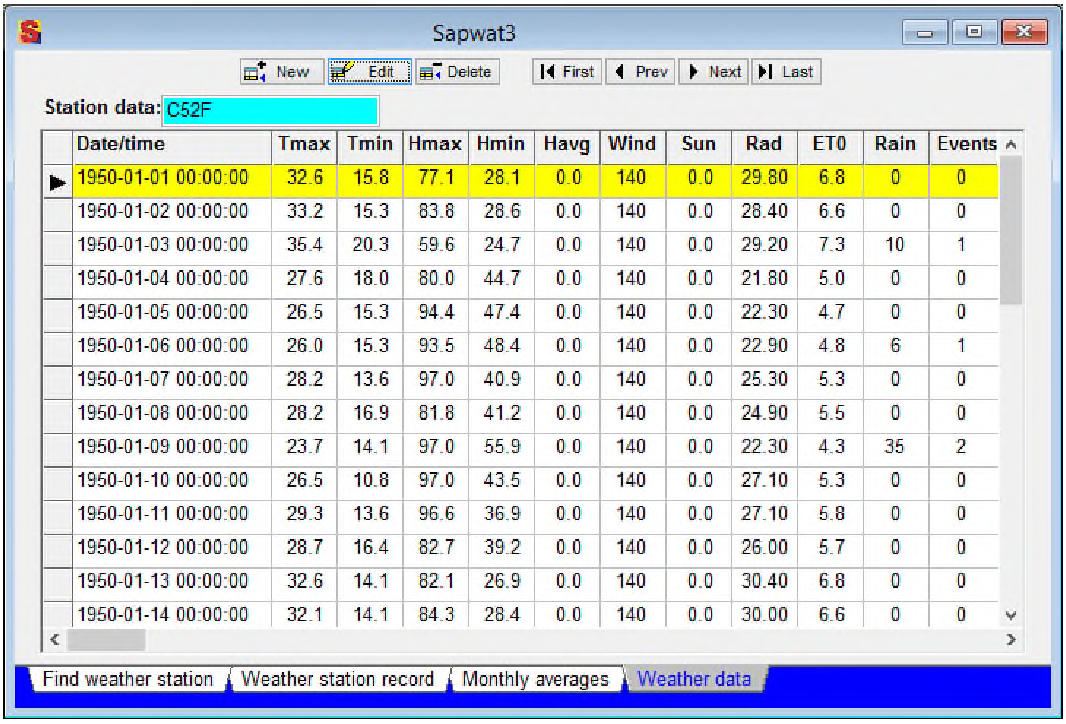


Figure 3-39 Page 4 of the weather stations screen showing daily weather data

3.7.2.4 Appending new weather station data

Weather station data can be added manually or by importation from outside sources. When the user chooses to add a new weather station, a screen form for the selection of weather station type and data source is shown (Figure 3-40).

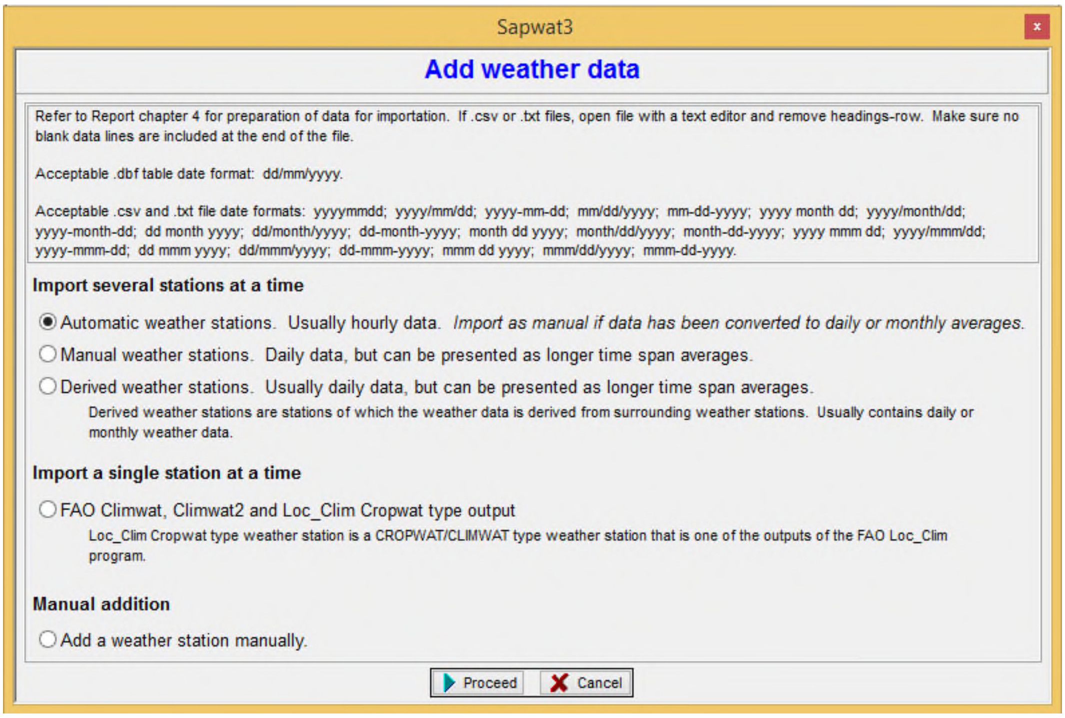


Figure 3-40 Adding a weather station, the screen form on which the users selects the type of input when adding a weather station

The manual addition of weather station data is feasible where average monthly data is available, such as CLIMWAT (Smith, 1993) data, but when daily data are added the volume of data makes manual addition impractical.

3.7.2.4.1 Manual appending of monthly data

Manual appending of average monthly data takes place in two steps: first a weather station is added to the data set, and secondly, the weather data for that station is added. Screen forms designed for this purpose are shown in Figure 3-41 and Figure 3-42. The weather station data requested as input must be included for correct calculation of ET_0 through Equation 3.3 and its sub-units. Of the weather data, maximum and minimum temperature and sunlight or radiation must be included. If humidity data are not provided saturated vapour pressure is calculated by assuming minimum temperature as equivalent to dew point temperature (Equation 3.11) (Allen *et al.*, 1998). If wind run is excluded, wind speed is assumed to be 2 $m\ s^{-1}$, based on the average wind speed of more than 2 000 weather stations (Allen *et al.*, 1998). For South Africa an average wind speed of 1.6 $m\ s^{-1}$ has been approximated by Schulz and Maharaj (2006) and is used as such where required.

Both the forms used for the manual appending of weather station data are used for editing this data, irrespective of whether the weather station and its data have originally been added manually or imported electronically.

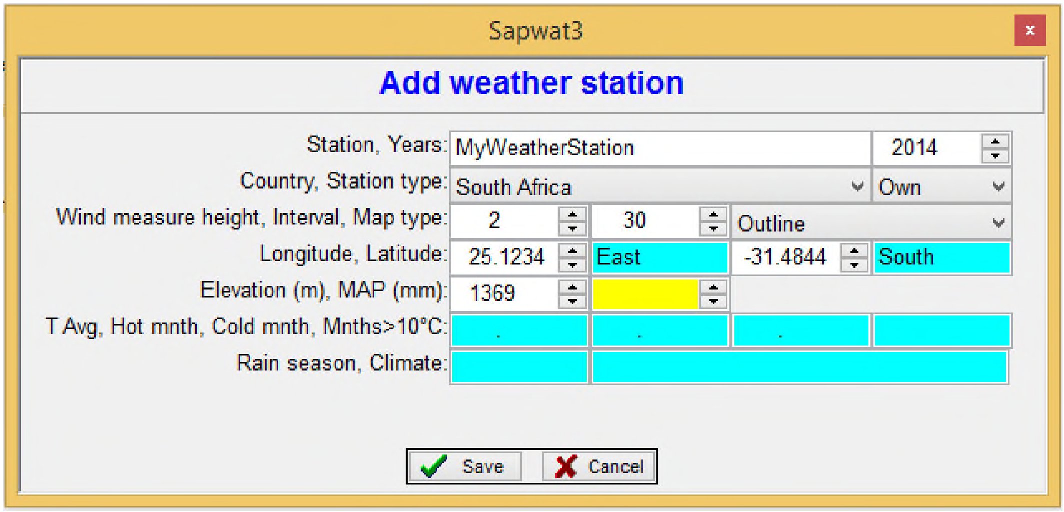


Figure 3-41 Screen form for adding or editing weather station data.

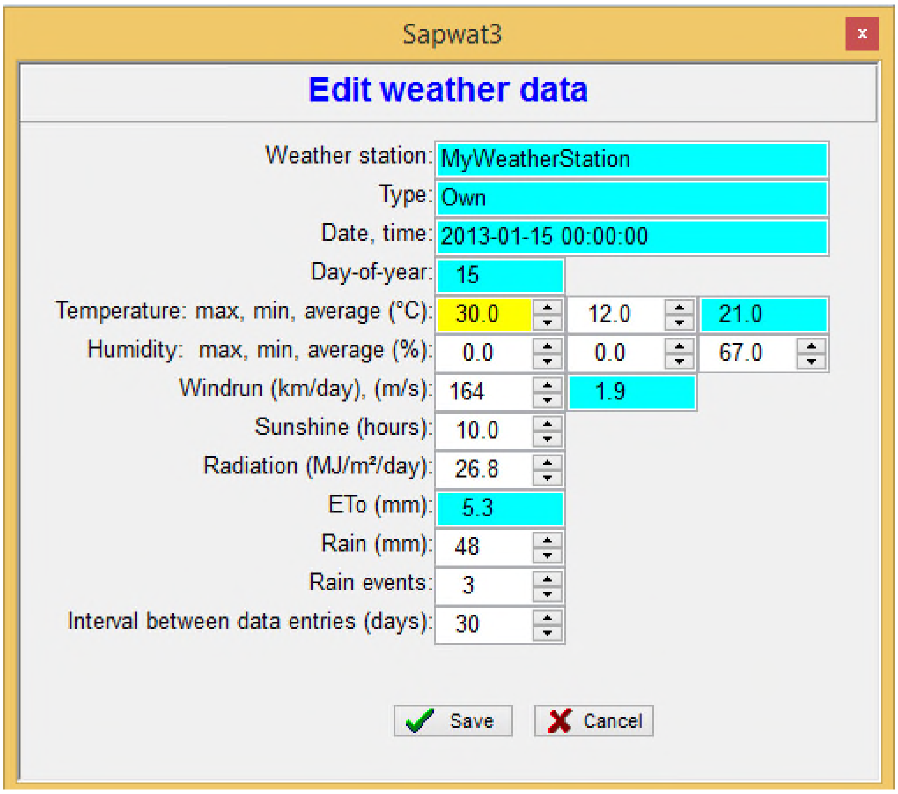


Figure 3-42 Screen form for adding or editing a specific date in the weather station weather data records.

3.7.2.4.2 Importation of weather station data

Provision is made for the importation of data from outside sources in the form of DBF tables or comma delimited text (CSV) files. Minimum data required for successful importation are: weather station name, longitude and latitude (both in decimal degrees), height above sea level (m), date, maximum and minimum temperatures (˚C), sunshine hours or radiation (MJ m^{-2} d^{-1}). Longitude degrees west and latitude degrees south are indicated with a negative sign.

Similarly to the manual addition of weather station data, SAPWAT3 manages missing data as follows:

- Wind speed measurement height is assumed to be at 2 m (Allen *et al*., 1998);
- Saturated vapour pressure is calculated on the assumption that minimum temperature equates to dew point by using Equation 3.11 (Allen *et al*., 1998).
- Wind speed is assumed to be 2 m s^{-1} for non-South African weather stations and 1.6 m s^{-1} for South African weather stations (Allen *et al*., 1998; Schulz and Maharaj, 2006).

Importation of weather station data files requires some preparation before importation can start. The main reason for this is that weather data files from different sources have been observed to have different configurations and a standard configuration is required for importation into the SAPWAT3 weather station data tables (Van Heerden *et al*., 2008). The structure of manual and automatic weather station data differs and therefore preparation for importation needs to be different.

3.7.2.4.2.1 Importation of manual weather station data

The required preparation for the importation of manual weather station data into the SAPWAT3 weather data tables is shown in Table 3-13. The prepared import file type must either be a DBF or comma separated value (CSV) text file. If it is a CSV text file, the user must make sure that no column headings appear, as these are sometimes included in CSV files.

Table 3-13 Prepared data table structure for importation of manual weather station into SAP-WAT3

Field name	Data type	Field width	Decimals	Remarks
WSFilename	Character	9		The locally used file name or file reference for a particular station, e.g., 345671, GB54370WD. **Must be included and must be unique.**
Wstation	Character	40		Weather station common name, e.g. Jonestown railway. Must be unique for each type of station per country. **Must be included.**
Longitude	Numeric	9	4	Degrees decimal, longitude west is shown as negative. **Must be included.**
Latitude	Numeric	9	4	Degrees decimal, latitude south is shown as negative. **Must be included.**
Elevation	Numeric	6	0	Height above sea level in meters. **Must be included.**
Yearsdata	Numeric	4	0	Number of years of records included.
rDate	Date	8		Record date in mm/dd/yyyy format. Date or (Year and DOY) must be included.
rYear	Numeric	4	0	Year. Date or (Year and DOY) must be included.
DOY	Numeric	3	0	The Day of Year, (January 1 = DOY 1). **Date or (Year and DOY) must be included**
rTime	Numeric	4	0	Daily time of weather station visit, in 24 hour format, e.g. 0700 for seven in the morning.
Tmax	Numeric	6	1	Maximum temperature (°C). **Must be included**
Tmin	Numeric	6	1	Minimum temperature (°C). **Must be included**
Hmax	Numeric	6	1	Maximum humidity (%).
Hmin	Numeric	6	1	Minimum humidity (%).
Havg	Numeric	6	1	Average humidity (%).
Wind	Numeric	4	1	Average m s^{-1}. Program uses default of 2 m s^{-1} if omitted. Measurement height assumed to be at 2 m.

Field name	Data type	Field width	Decimals	Remarks
Windrun	Numeric	6	1	Wind distance for day (Km). Program calculates from default, if omitted.
Sunshine	Numeric	4	1	Hours of sunshine. One of Sunshine or Radiation or RadWatt must be included.
Radiation	Numeric	5	1	Average radiation (MJ m^{-2} d^{-1}). One of Sunshine or Radiation or RadWatt must be included.
RadWatt	Numeric	8	3	Average radiation (Watts m^{-2}). Not normally part of daily data, but seems to be included in some cases. **One of Sunshine or Radiation or RadWatt must be included.**
Rain	Numeric	6	1	mm. Should be included.

3.7.2.4.2.2 Automatic station data

Table 3-14 shows the required structure for the importation of automatic weather station data into SAPWAT3. The data are stored in a different format than that for manual weather stations. SAPWAT3 converts automatic weather station data to the same format as used for manual weather station. Automatic weather station data that haveas been pre-converted to the same format as used for manual weather stations must be imported as if it is a manual weather station.

Table 3-14 Prepared data table structure for importation of automatic weather station data into SAPWAT3

Field name	Data type	Field width	Decimals	Remarks
WSFilename	Character	9		The locally used file name or file reference for a particular station, e.g., 345671, GB54370WD. **Must be included and must be unique.**
Wstation	Character	40		Weather station common name, e.g. Jonestown. Must be unique for each type of station per country. **Must be included**
Longitude	Numeric	9	4	Degrees decimal, longitude west is shown as negative. **Must be included**
Latitude	Numeric	9	4	Degrees decimal, latitude south is shown as negative. **Must be included**
Elevation	Numeric	6	0	Height above sea level in meters. **Must be included**
Yearsdata	Numeric	4	0	Number of years of records included.
rDate	Date	8		Record date in mm/dd/yyyy format. Date or (Year and DOY) must be included.
rYear	Numeric	4	0	Year. Date or (Year and DOY) must be included.
DOY	Numeric	3	0	The Day of Year, (January 1 = DOY 1). **Date or (Year and DOY) must be included.**
rTime	Numeric	4	0	Time of data record, in 24 hour format, e.g. 0700 for seven in the morning.
Temperature	Numeric	6	1	Average temperature of recording period (°C). **Must be included.**
Humidity	Numeric	6	1	Average humidity of recording period (%). Program estimates of omitted.
Wind	Numeric	4	1	Average m s^{-1}. Program uses default of 2 m s^{-1} if omitted.
Sunshine	Numeric	4	1	Time during recording period. One of Sunshine or Radiation or RadWatt must be included.
Radiation	Numeric	5	1	Average radiation for period (MJ m^{-2}). One of Sunshine or Radiation or RadWatt must be included.
RadWatt	Numeric	8	3	Average radiation for recording period (Watts m^{-2}). One of Sunshine or Radiation or RadWatt must be included.
Rain	Numeric	6	1	mm. Should be included.

3.7.2.4.2.3 Screen form for electronic importation

The screen form for setting up electronic importation of weather station data is shown in Figure 3-43. Selection between automatic and manual station has been done in the selection form for importation action (Figure 3-40), therefore the setup screen form directs SAPWAT3 to the file for importation as 'Data source:'.

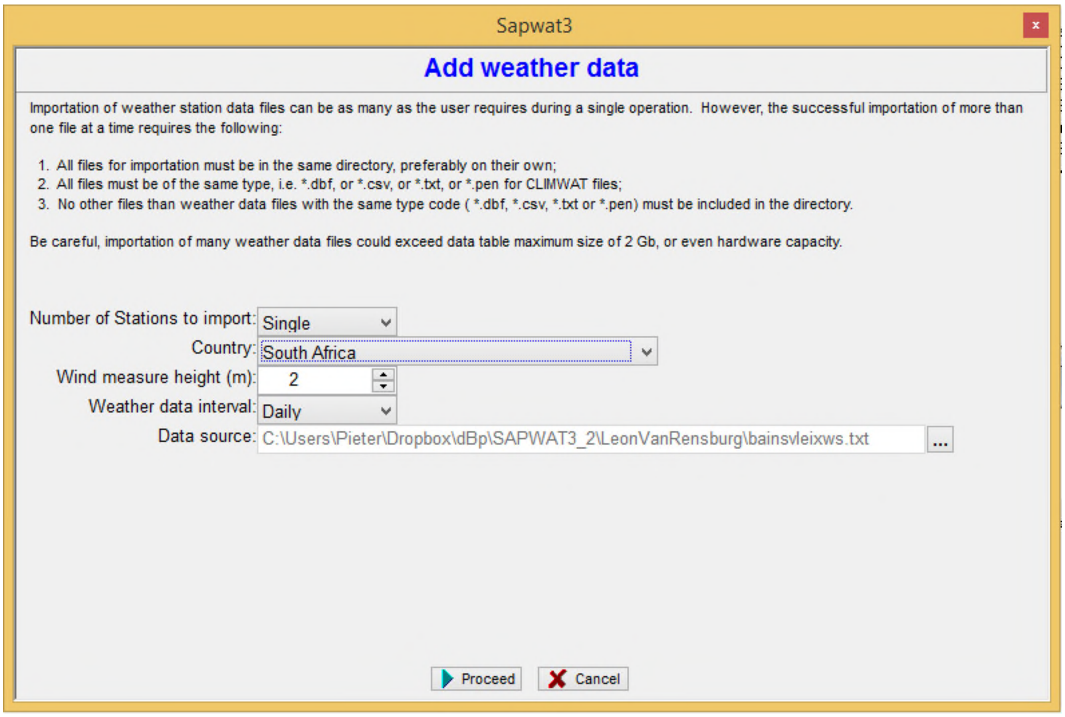


Figure 3-43 The set-up screen for electronic importation of weather station data

3.7.2.5 Climate

One of the strengths of CROPWAT and the associated climatic program CLIMWAT is that they are universally applicable. SAPWAT3 has incorporated CLIMWAT weather data but has gone further by adopting an international classification of climates, the Köppen-Geiger system (Strahler & Strahler, 2002), and linking these to crop coefficient values. In addition, maps of all countries showing the location of weather stations are included.

Note: *Climate detail is discussed in Chapter 2*

3.7.2.6 Structure of the climate data table

Table 3-15 Structure of the climate data table (Climate.dbf) centre numbers columns

Field	Field Name	Type	Length	Decimals	Index	Notes
1	ClimateID	Character	3		Y	Primary index (Köppen code)
2	Climate	Character	35		N	Climate name used by SAPWAT3
3	Description	Character	150		N	Climate definition

3.7.2.7 Climate screen form

The three pages of the climate screen forms giving visual information are shown in Figure 3-44 (the world climate map), Figure 3-45 (the Southern African climate map) and Figure 3-46 (map legend). The Köppen-Geiger climate (Chapter 2) is important for SAPWAT3 because it is based on combinations of rainfall and temperature and crop growth and development is also linked to temperature. The station's weather data can therefore be used to determine which climate the station is situated in. Care must be taken when interpreting the maps and linking mapped climates to localities because of the small scale used in most reference material, thus detailed boundaries of smaller climate areas are not shown (Strahler & Strahler, 2002; Encyclopaedia Britannica, 2002).

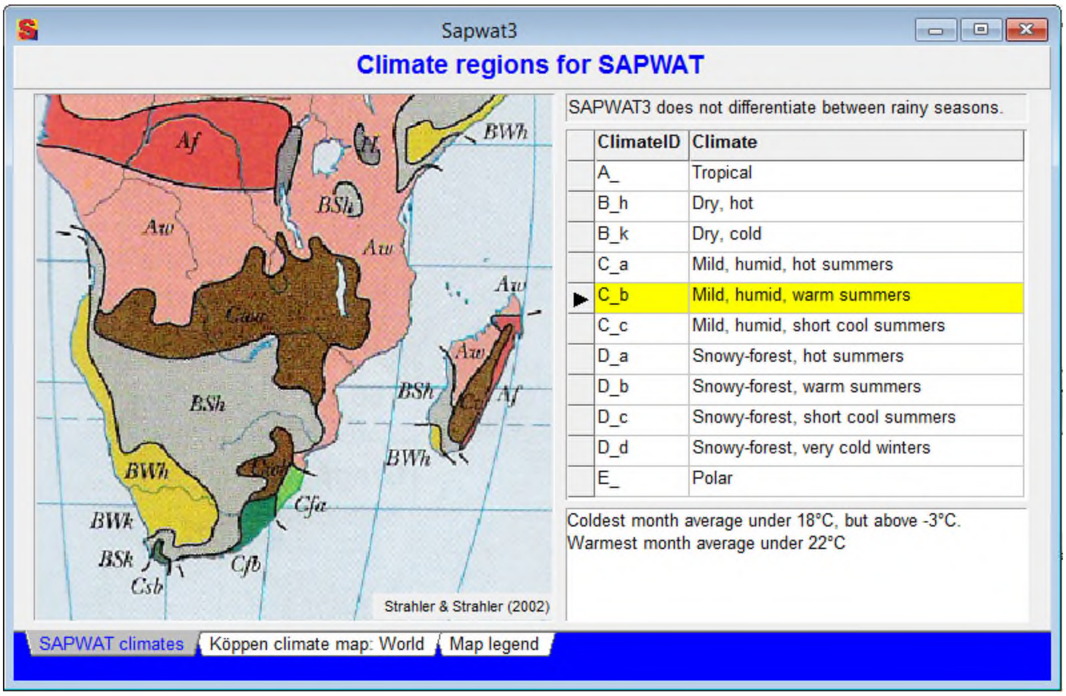


Figure 3-44 Screen form page 1: Köppen-Geiger climate map of Southern Africa and major climates

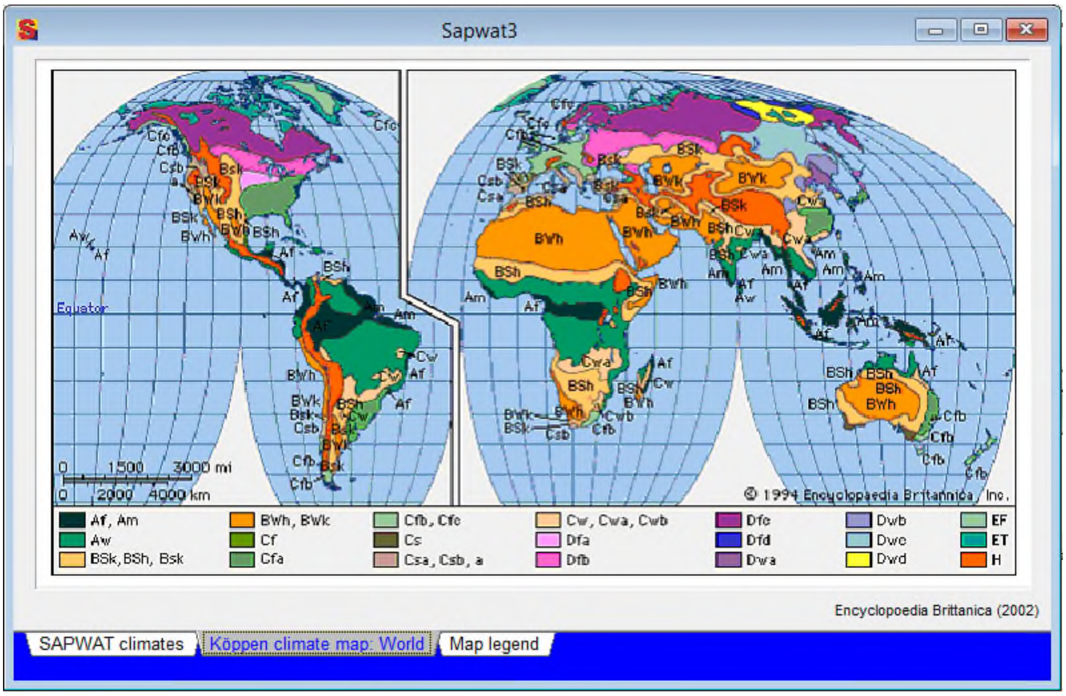
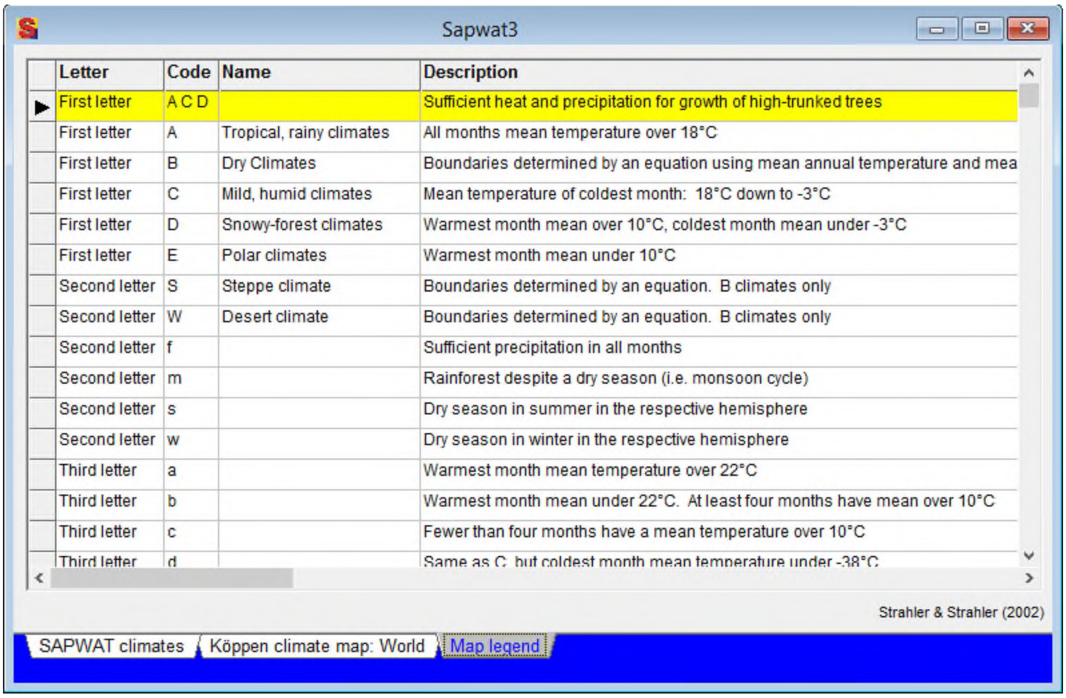


Figure 3-45 Screen form page 2: Köppen-Geiger climate map of the world



Letter	Code	Name	Description
First letter	A C D		Sufficient heat and precipitation for growth of high-trunked trees
First letter	A	Tropical, rainy climates	All months mean temperature over 18°C
First letter	B	Dry Climates	Boundaries determined by an equation using mean annual temperature and mea
First letter	C	Mild, humid climates	Mean temperature of coldest month: 18°C down to -3°C
First letter	D	Snowy-forest climates	Warmest month mean over 10°C, coldest month mean under -3°C
First letter	E	Polar climates	Warmest month mean under 10°C
Second letter	S	Steppe climate	Boundaries determined by an equation. B climates only
Second letter	W	Desert climate	Boundaries determined by an equation. B climates only
Second letter	f		Sufficient precipitation in all months
Second letter	m		Rainforest despite a dry season (i.e. monsoon cycle)
Second letter	s		Dry season in summer in the respective hemisphere
Second letter	w		Dry season in winter in the respective hemisphere
Third letter	a		Warmest month mean temperature over 22°C
Third letter	b		Warmest month mean under 22°C. At least four months have mean over 10°C
Third letter	c		Fewer than four months have a mean temperature over 10°C
Third letter	d		Same as C but coldest month mean temperature under -38°C

Figure 3-46 Screen form page 3: Köppen-Geiger climate map legend

3.7.2.8 Crops

Annual and deciduous crops have a similar growth and development pattern, i.e. new growth starts at the beginning of the season with seeds germinating or bud break and new canopy developing. As the crops grow, the canopy develops until the soil surface is mostly or fully overshadowed by the canopy. Following this plants go into a reproductive phase where fruit and seed are formed. These usually ripen towards the end of the season, the canopy begins senescence or leaves die and at the end of the season bare ground is again exposed to full sunlight. A similar pattern is found in perennial evergreen crops or trees grown in non-tropical areas, in that even though the canopy stays intact (green) and active, a decline in photosynthesis is usually observed during the off-season (cool season) period. Fitting of the four-stage crop growth curve is complicated by out-of-season growth flushes found in some of these crops (Allen *et al*., 1998; McMahon *et al.*, 2002).

A problem faced by the irrigation water requirement planner and designer was how to describe this rather complex physiology and phenology in terms that are easily understood by the layman or semi-skilled practitioner, while still retaining credibility. This problem was solved by adopting the four-stage growth curve approach to describe the growth and development of crops (Allen *et al*., 1998).

Crop characteristics for application by SAPWAT3 were mainly based on the data included in FAO 56 (Allen *et al*., 1998). This data was verified for South Africa by means of surveys of researchers, technicians and farmers who grow the crops and, where possible, evaluated against existing published data (Crosby and Crosby, 1999; see also chapter 5). One of the unfortunate things about the four-stage FAO crop growth curve is that the specific data required to derive it, are not necessarily included in the data that agronomists usually collect. The usual dataset collected relating to growth and development is as follows: planting date, day of emergence, commencement of flowering or tasseling day when the crop is physiologically ripe, harvest date(s) and production levels. However, the four-stage curve requires dates for: planting, 10% canopy cover, 70% to 80% canopy cover (usually when leaf area index (LAI) reaches a value of about 3 in agronomic crops), beginning of maturity (first signs of the discolouration of leaves, the last day of growth (Allen *et al*, 1998). As some of these events occur in between those that are usually noted by agronomists, one has to rely on the observation capacity and knowledge of crop growth and development stages of the researcher, technician and farmer to deduce applicable dates or periods for the various stages of the four-stage growth curve. This task can be approached in several ways, one of which is to visit knowledgeable scientists, scheduling consultants and farmers in different irrigation areas and to reproduce what they are doing in practice in the field with SAPWAT3 simulations. This is successful where there are data available as was the case in the Orange-Riet and Orange-Vaal river areas through the offices of the Orange-Vaal and Orange-Riet

WUAs and of GWK Ltd (Van Heerden *et al.*, 2001). However, in other areas around the world it may not be the case and so perhaps other methods need to be investigated.

SAPWAT introduced a new flexibility into the four-stage FAO crop factor approach, particularly for the perennial crops. It was observed that the generally accepted assumption that the dominant third stage of the crop coefficient curve does not seem to be horizontal for some tree crops. This is especially true for tree crops with long midseason growth periods, and specifically those which cross seasonal boundaries– the crop growth starts in spring and it continues growing through summer, autumn and sometimes also into winter. Therefore, SAPWAT3 makes provision for adjusting the slope of this stage by allowing the user to add different K_{cb} values as the start and end of this stage.

The references and personal communications used for the purpose of verifying crop growth and development as well as soil properties are detailed as follows and included in the reference list. The data thus collected are compared to data published in FAO 56 (Allen *et al.*, 1998. The four-stage crop coefficient curve, its influence on crop irrigation requirements, soil water balances and irrigation strategies were reviewed over an extended period of time. This led to the confirmation or adaptation of the crop characteristics of those crops included in the SAPWAT3 data files:

Bananas: Morse, Robinson and Ferreira, 1996.

Chicory: Aucamp, 1978; Luckman, 2002[8].

Citrus and Subtropical crops: Tolmay and Kruger, undated.

Dates: Ziad, 1999.

Deciduous fruit: Volschenk *et al*., 2003.

Field crops: McMahon *et al*., 2002; Otto, 2004[9];

Fodder crops and Pastures: Dickinson and Hyam (Ed), 1984; Marais, Rethman and Annandale, 2002; Meredith, 1959.

[8] Luckman, B. (2002) Field agriculturalist, Chicory SA. Alexandria, South Africa.

[9] Otto, W. (2004) Researcher, ARC – Small Grain Institute, Bethlehem, South Africa.

Grapes: Myburgh, 2004a; Myburgh, 2004b; Myburgh and Howell, 2007.

Groundnuts: Jansen, 2004[10].

Irrigation scheduling, soil water balance and crop reaction: Annandale *et al*., 1999; Bennie *et al*., 1998; Bennie *et al*., 1997; De Jager *et al*., 2001; Doorenbos and Kassam, 1986; Garg, 1992; Smith, 1992.

Irrigation systems and adaptation to crops: Hoffman *et al*., 1990; Sanmugnathan *et al*., 2000; USWRC, 1976.

Oil seeds: Liebenberg, 2002[11].

Olives: Malan, 2003.

Sugar Beet: Cooke and Scott, 1993.

Sugar cane: Inman-Bamber and McGlinchey, 2003.

Vegetables: Annandale *et al*., 1996; Jovanovic and Annandale, 1999; McMahon *et al*., 2002; Reader's Digest 1984b; Van Wyk, 1992.

The present K_c calculating system, where a four stage crop growth curve is drawn for each combination of crop, crop option, planting date and climate, is time consuming and many records are generated which increases the possibility of data errors. This leads one to agree with Allen *et al*. (1998) that different approaches of constructing a crop growth curve need to be investigated. One of the possibilities is the construction of a basic curve and possible mathematical or statistical adjustments of that basic curve to reflect changes due to heat units, cold units and day length and other climatic parameter that could influence crop growth and development. AquaCrop uses an approach similar to this for drawing its crop growth curves (Steduto and Raes, 2012). The initial and development stages are replaced by a sigmoid growth curve with the slope adapted for fast, medium and slow developers. The late season stage is replaced by an inverse logarithmic regression or similar curve, the slope also being adapted for fast, medium or slow maturing crops. However, it was found during surveys on crop growth and development that the responder (researcher, technician and farmer) could

[10] Jansen, W. (2004) Research Technician, Vaalharts Experimental Farm, Jankempdorp, South Africa.

[11] Liebenberg A, (2002) Researcher, ARC – Grain Crops Institute, Potchefstroom, South Africa.

very easily understand the concept of the four-stage approach and could in most cases, give usable answers for the time periods observed in the field situation for each stage. The traditional FAO-56 four stage curve is also very easy to adapt, if the need should arise.

3.7.2.9 Crops data structure

In order to make the crop information useable and be stored systematically, a four-level relational set of data tables has been developed for use in SAPWAT3. The four levels are: crop, crop option, planting date and detail. These tables interlink in such a way that relevant data is always kept together. Crops similar in type are also linked to crop groups, which are used for group updating of data.

3.7.2.9.1 The crop data table

Information in this data table (Table 3-16) includes crop height, rooting depth, allowed depletion, yield response to stress (K_y) (Doorenbos and Kassam, 1986; Steduto and Raes, 2012) values, salinity threshold and sensitivity values (Allen *et al*., 1998; McMahon *et al*., 2002; Ayers and Westcot, 1994; Reader's Digest, 1984b; Tanji and Kielen, 2002) and leaf resistance (O'Toole, and Cruz, 1980). Yield response values, salinity threshold and sensitivity values are used to estimate irrigation water requirement under non-standard and stress situations, while leaf resistance values can possibly be used to estimate irrigation water requirement under non-standard and stress situations.

Table 3-16 Structure of the crops data table (Crops.dbf)

Field	Field Name	Type	Length	Decimals	Index	Notes
1	CropID	Autoincrement	4		Y	Primary index
2	Crop	Character	30		N	Crop name
3	CropAlias	Character	30		N	Local crop name
4	BotanicalName	Character	30		N	Crop botanical name
5	CropGroupID	Long	4		N	Crop group index (e.g. pulses, forage etc.)
6	PotentialYield	Numeric	5	1	N	Potential yield for area fraction? Or %?
7	CropHeight	Numeric	5	2	N	Average crop height (m)
8	RootDepthInit	Numeric	6	2	N	Initial stage rooting depth (m)
9	RootDepthMid	Numeric	6	2	N	Mid-season stage rooting depth (m)
10	DepletionInit	Numeric	5	2	N	Initial stage allowed depletion (fraction)
11	DepletionMid	Numeric	5	2	N	Mid-season stage allowed depletion (fraction)
12	DepletionLate	Numeric	5	2	N	Late season stage allowed depletion (fraction)
13	KyInit	Numeric	5	2	N	Initial stage yield response factor (fraction)
14	KyDev	Numeric	5	2	N	Development stage yield response factor (fraction)
15	KyMid	Numeric	5	2	N	Mid-season stage yield response factor (fraction)
16	KyLate	Numeric	5	2	N	Late season stage yield response factor (fraction)

Field	Field Name	Type	Length	Decimals	Index	Notes
17	KySeason	Numeric	5	2	N	Growing season yield response factor (fraction)
18	ECThreshold	Numeric	5		N	Threshold where salinity stress starts
19	ECReductionRate	Numeric	4	1	N	Yield reduction rate on saline soils
20	ECRating	Character	2		N	Sensitivity classes to salinity (tolerant, moderately tolerant, moderately sensitive, sensitive)
21	LeafResistance	Numeric	5		N	Stomatal resistance (%? default = 100)
22	Description	Memo	10		N	Memo file to describe crop or Add? Other detail?.

3.7.2.9.2 The crop option data table

This file is the linkage between the crop and differences in growth and development found in early or late varieties and long or short growers (Table 3-17).

Table 3-17 Structure of the crop option data table (CropOption.dbf)

Field	Field Name	Type	Length	Decimals	Index	Notes
1	CropOptionID	Autoincrement	4		Y	Primary crop option index
2	CropID	Long	4		Y	Index for linking to crops data table (Table 3-16)
3	Cropoption	Character	50		N	Crop option e.g. early bud break, long growers etc.
4	PotentialYield	Numeric	5	1	N	Potential harvest yield
5	Identifier	Character	30		N	Identifies source data e.g. FAO 56, SAPWAT etc.,

3.7.2.9.3 The planting date data table

This data (Table 3-18) is the link between the different crop options and the detail file. It provides the scope to differentiate between growth and development reactions of the crop because of different planting dates.

Table 3-18 Structure of the crop plant data table (CropPlant.dbf)

Field	Field Name	Type	Length	Decimals	Index	Notes
1	cropplantid	Autoincrement	4		Y	Primary crop plant date index
2	cropoptionid	Long	4		Y	Index for linking to crop option data table (Table 3-17)
3	plantmonth	Numeric	3		N	Month when crop is planted
4	plantday	Numeric	2		N	Day of month when crop is planted

3.7.2.9.4 The crop detail table

This file contains the detailed information about the crop relevant to the crop options and the planting date related to a specific climate (Table 3-19). The growing periods of the four development stages, as well as the K_{cb}-values for each of the stages are included in this file.

Table 3-19 Structure of the crop detail data table (Cropdetail.dbf)

Field	Field Name	Type	Length	Decimals	Index	Notes
1	CropDetailID	Autoincrement	4		Y	Primary crop detail index
2	CropPlantID	Long	4		Y	Index for linking to crop plant data table (Table 3-18)
3	cSelected	Logical	1		N	Marker for selecting crop detail to display for selection
4	ClimateID	Character	3		N	Climate index key to link to climate data table
5	DaysInit	Numeric	3		N	Length of initial period (days)
6	DaysDev	Numeric	3		N	Length of development period (days)
7	DaysMid	Numeric	3		N	Length of mid-season period (days)
8	DaysLate	Numeric	3		N	Length of late season period (days)
9	Total	Numeric	3		N	Total days growing season
10	KcbInit	Numeric	4	2	N	Kcb value for initial period
11	KcbMaxs	Numeric	4	2	N	Kcb value for mid-season start
12	KcbMaxe	Numeric	4	2	N	Kcb value for mid-season end
13	KcbEnd	Numeric	4	2	N	Kcb value for late season end
14	Description	Memo	10		N	Memo field for describing detail data of crop
15	Updated	Date	8		N	Date of last update

3.7.2.9.5 The crop group table

The crops data table (Table 3-16) is linked to a crop group data table (Table 3-21) in which the crop groups used by Allen *et al*. (1998) and Frenken (2005) (Table 3-20) have been included.

Table 3-20 Crop groups included in SAPWAT3 (Allen *et al*., 1998); Frenken, (2005)

CropGroupID	CropGroup	CropCover
1	Vegetables - Small	100
2	Vegetables - Solanum family	100
3	Vegetables - Cucurbits	100
4	Roots and Tubers	100
5	Legumes	100
6	Vegetables - Perennial	100
7	Fibre Crops	100
8	Oil Crops	100
9	Cereals	100
10	Forages	100
11	Sugar Cane	100
12	Tropical Fruits and Trees	75
13	Grapes and Berries	100
14	Fruit Trees	75
16	Wetlands - Temperate Climates	100
17	Special	100

Table 3-21 Structure of the crop group data table (Cropgroup.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	CropGroupID	Autoincrement	4		Y	Primary index
2	CropGroup	Character	30		N	Group name
3	CropCover	Numeric	3	0	N	Default canopy cover (%)

3.7.2.10 Crops screen forms

Screen forms consist of a control screen (Figure 3-47) from which all editing related to the relational crop data tables are controlled through screen forms shown in Figure 3-48, Figure 3-49, Figure 3-50, Figure 3-51 and Figure 3-52. The user-data interaction screen forms are obvious. However, the user should note that provision is also made to input potential yield, a figure on which reduction in yield is based and therefore influences the gross margin calculation in the enterprise budget part (3.5) of the program. The user can also add as many detail data records as required, but mark only those to be used. The addition of references linked to records is handy, as it has been found that information regarding crop growth and development varies across regions and therefore sources.

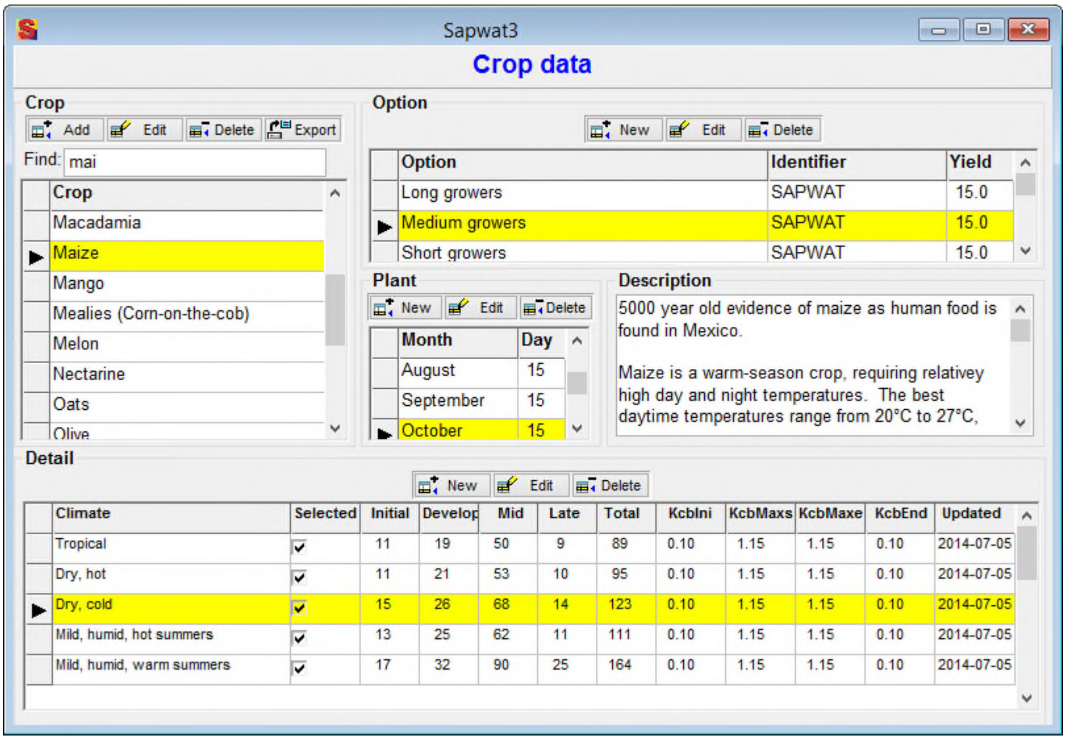


Figure 3-47 The crop data screen from which the different relational data tables are managed

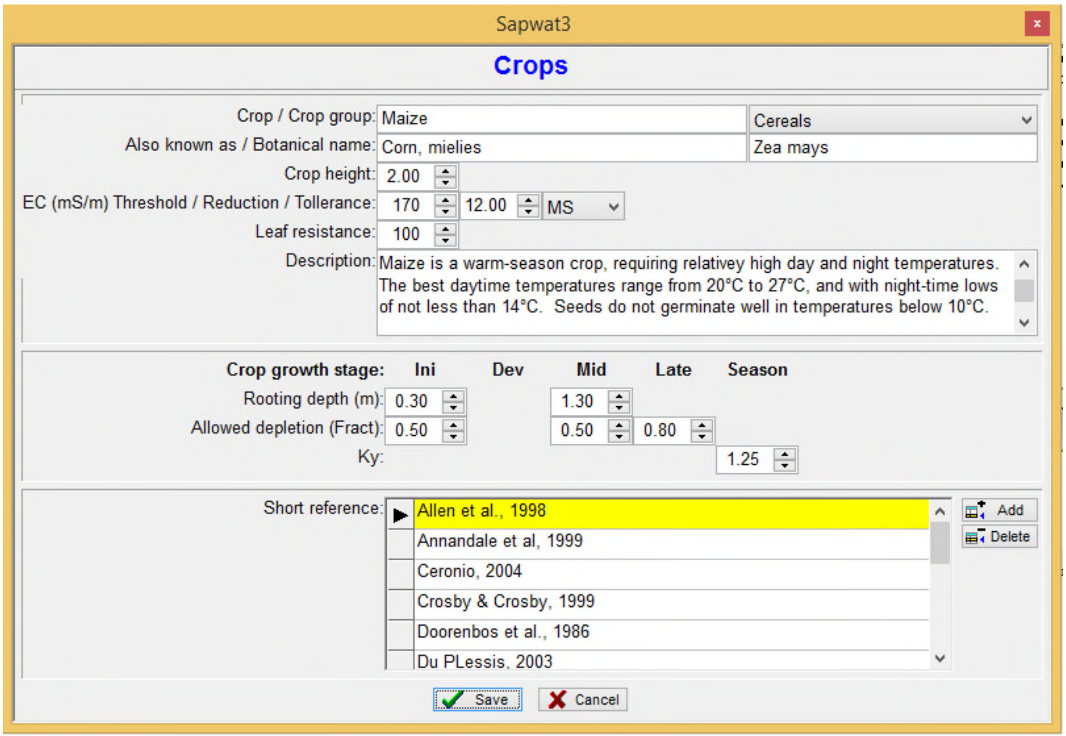


Figure 3-48 The crop edit screen

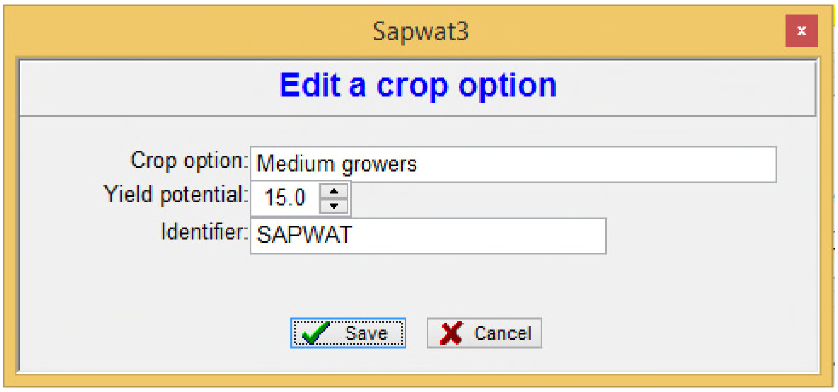


Figure 3-49 The crop option edit screen

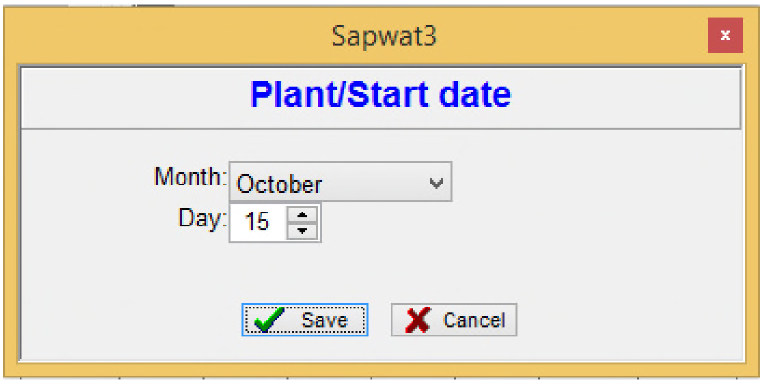


Figure 3-50 The crop plant edit screen.

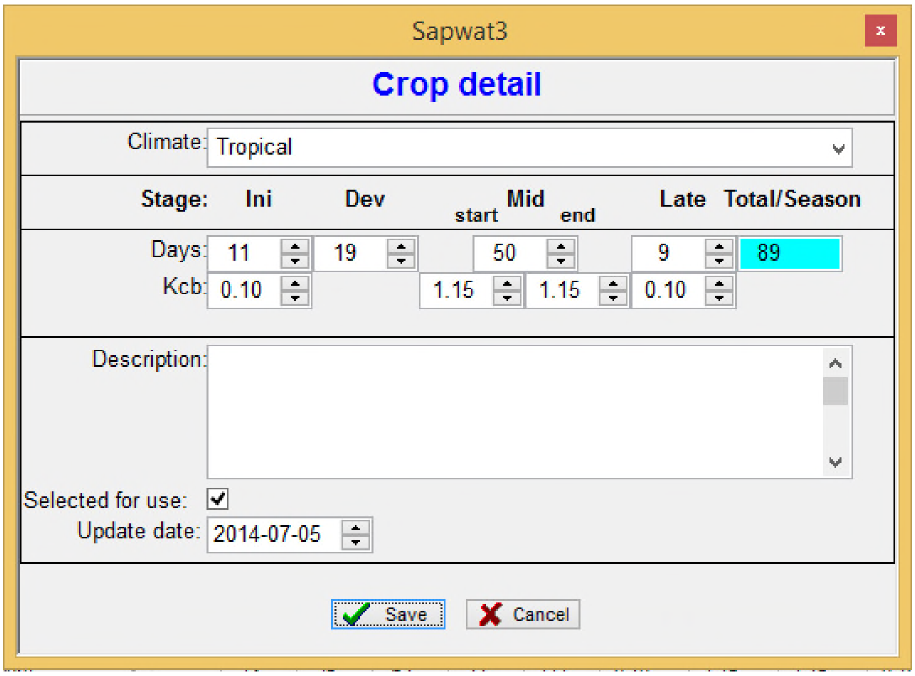


Figure 3-51 The crop detail edit screen

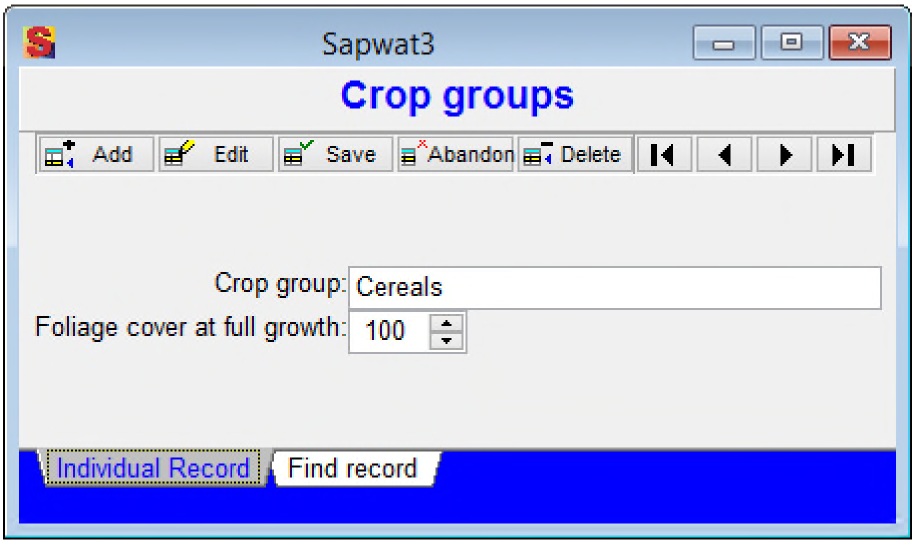


Figure 3-52 The crop group edit

3.7.2.11 Soil

Broadly speaking, soil is defined as unconsolidated inorganic and organic material on the immediate surface of the earth that contains water and air and acts as a natural medium for the growth of plants and all other soil-living creatures. It is an integral part of the landscape and its characteristics; appearance and distribution is determined by climate, parent material, topography, flora, fauna and time. The parent material as an unconsolidated mass that later differentiates into characteristic layers called horizons. Differentiation occurs by means of chemical differentiation and/or dissolution of the parent material. As the process continues, the horizons generally become more distinguishable and finally develop into a soil profile (McMahon *et al.*, 2002).

Soil can be highly variable in a landscape with observable differences in depth, texture, structure, colour and slope. The effect of differences in chemical content is sometimes obvious and changes can sometimes be predicted for specific land use activities. Not all soils are suitable for irrigation. Irrigation induces changes in the physical, chemical and biological characteristics of a soil; therefore land classification for irrigation should consider the various potential changes and use this as a background for delineating lands on the basis of suitability for irrigation use. Land classification for irrigation should provide a sound basis for fitting land resources into a plan of irrigation development (Maletic and Hutchins, 1987).

3.7.2.12 Soil in irrigation

The irrigator is interested in a soil that can be economically developed, is easy to cultivate, will allow full potential root development, will be chemically suitable for the crops to be grown and will be stable over time (Maletic and Hutchins, 1987). Of special interest to the planner of irrigation water requirements and a scheduling service is the water holding capacity of a soil and the factors that influence it, the ease with which a crop can access that water and the related osmotic forces, the hydraulic conductivity of soil and potential changes that could occur because of irrigation or that can influence irrigation type and strategy over time (Day *et al.*, 1987). Present irrigation technology enables man to irrigate virtually any soil – hydroponics is a case in point, where no soil is used. However soils that are irrigable without some form of constraint, such as the need for physical or chemical manipulation, would, in broad terms, have the properties shown in Table 3-22 and can also be mapped (Dohse and Turner, undated; NRCS, 2015). Soils selected for irrigation that do not satisfy these properties, usually need some form of adaptation of the irrigation system design, soil manipulation or amelioration, actions that have a cost implication. Cost of developing such soil for irrigation could add up to such an amount that the development is not economically feasible.

Table 3-22 Soil properties for selection of irrigation soils that can be irrigated without undergoing chemical or physical manipulation.

Physical properties	
Soil depth to impervious layer Soil depth to semi-impervious layer	1.2m 0.9m
Texture	6% < clay < 35%
Structure development	No structure, weak developed block (dry), Medium developed block (dry)
Stones (>75 mm) Gravel (2-75mm)	< 15% < 35%
Slope	< 5%
Risk of flooding	Low. Safeguarding at reasonable cost ought to be effective
Probability that artificial drainage might be required • Top soil • Subsoil • Feasibility of installing subsurface drains	 Low – high Low Easy
Chemical properties	
Top soil • ESP • SAR • Salinity (mS/m)	 < 5 < 5 < 800
Subsoil • ESP • SAR • Salinity (mS/m)	 < 8 < 8 < 800

3.7.2.13 Application in SAPWAT3

A data table that can be used as a lookup table has been constructed. The data table provides for all the elements required for irrigation water estimates, i.e. soil type, field capacity, wilting point, total evaporative water and readily evaporative water, as well as effective depth, evaporation depth and infiltration rate (Table 3-23). The values shown are either default values for the soil type, or are values that satisfy the norms of irrigation classification. In the set-up of a particular field, the user selects a soil and these default values are imported. The user is then free to change these values to values that imitate the field values, i.e. if the soil is shallower; the user changes the soil depth for that field. Similarly, if laboratory results show soil water holding capacities that differ from the default values, the user can change those. Soil water holding capacities are shown in both of commonly used units, namely m^3/m^3 and mm/m depth. This is just to make things easier for the user, because automatic conversion takes place from the input data unit to data unit. Evaporation depth has been discussed in 3.4.4.

Table 3-23 Soil water holding capacities included as default values in SAPWAT3 (Allen *et al*., 1998) (FC = field capacity; WP = wilting point; TAM =total available moisture; REW = readily evaporable water; TEW = total evaporable water)

Soil type	**Soil depth (m)**	**FC (m^3/m^3)**	**WP (m^3/m^3)**	**Available (m^3/m^3)**	**FC (mm/m)**	**WP (mm/m)**	**TAM (mm/m)**	**Evapo Depth (m)**	**REW (mm)**	**TEW (mm)**	**Infiltration (mm/h)**	**Comments**	**Default**
Sand	1.2	0.12	0.05	0.07	120	50	70	0.1	5	9	40		
Loamy sand	1.2	0.15	0.07	**0**.08	150	70	80	0.1	6	11	40		
Sandy loam	1.2	0.23	0.11	0.12	230	110	120	0.1	8	17	40		
Loam	1.2	0.25	0.12	0.13	250	120	130	0.1	9	19	40		T
Silt loam	1.2	0.29	0.15	0.14	290	150	140	0.1	10	21	40		
Silt	1.2	0.32	0.17	0.15	320	170	150	0.1	10	23	40		
Silt clay loam	1.2	0.34	0.21	0.13	342	210	132	0.1	10	23	40		
Silt clay	1.2	0.36	0.22	0.14	360	220	140	0.1	10	25	40		
Clay	1.2	0.36	0.22	0.14	360	220	140	0.1	10	25	40		

3.7.2.13.1 Soil data table structure

The structure provides for soil water content to be managed in both m^3/m and mm/m unit format because it was found that different publications used these approaches and data input was deemed to be easier and potentially more accurate if it takes place in the originally given unit. SAPWAT3 converts from one unit to the other on data input or data editing.

Table 3-24 Structure of the soil data table (Soil.dbf)

Field	Field Name	Type	Length	Decimal	Index	Notes
1	SoilID	Auto increment	4		Y	Primary index
2	SoilType	Character	30		Y	Name of soil
3	SoilDepth	Numeric	6	2		Soil depth (m)
4	FCm3	Numeric	4	2		Field capacity (m^3/m^3)
5	WPm3	Numeric	4	2		Wilting point (m^3/m^3)
6	Availablem3	Numeric	4	2		Plant available soil water capacity (m^3/m^3)
7	FCmm	Numeric	3	0		Field capacity (mm/m)
8	WPmm	Numeric	3	0		Wilting point (mm/m)
9	TAM	Numeric	3	0		Plant available soil water capacity (m^3/m)
10	EvapoDepth	Numeric	4	2		Soil evaporation depth (m)
11	REW	Numeric	2	0		Readily evaporative soil water (mm)
12	TEW	Numeric	2	0		Total evaporative soil water (mm)
13	Infiltration	Numeric	3	0		Soil infiltration rate (mm/day)
14	Comments	Memo	10			User can add notes
15	Default	Logical	1			Select a default soil for new estimates

3.7.2.14 Soil screen forms

The soils screen form is shown in Figure 3-53 and the soil texture triangle, which is available in the soils screen form, as Figure 3-54.

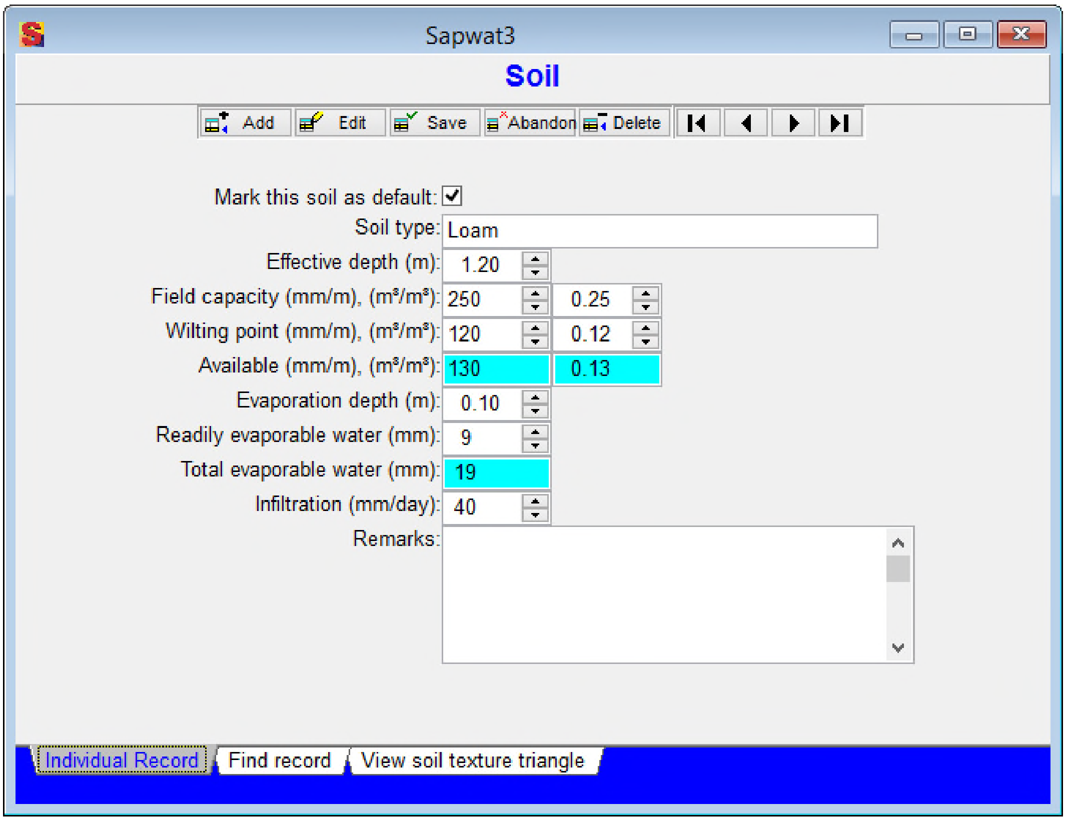


Figure 3-53 The soils screen form

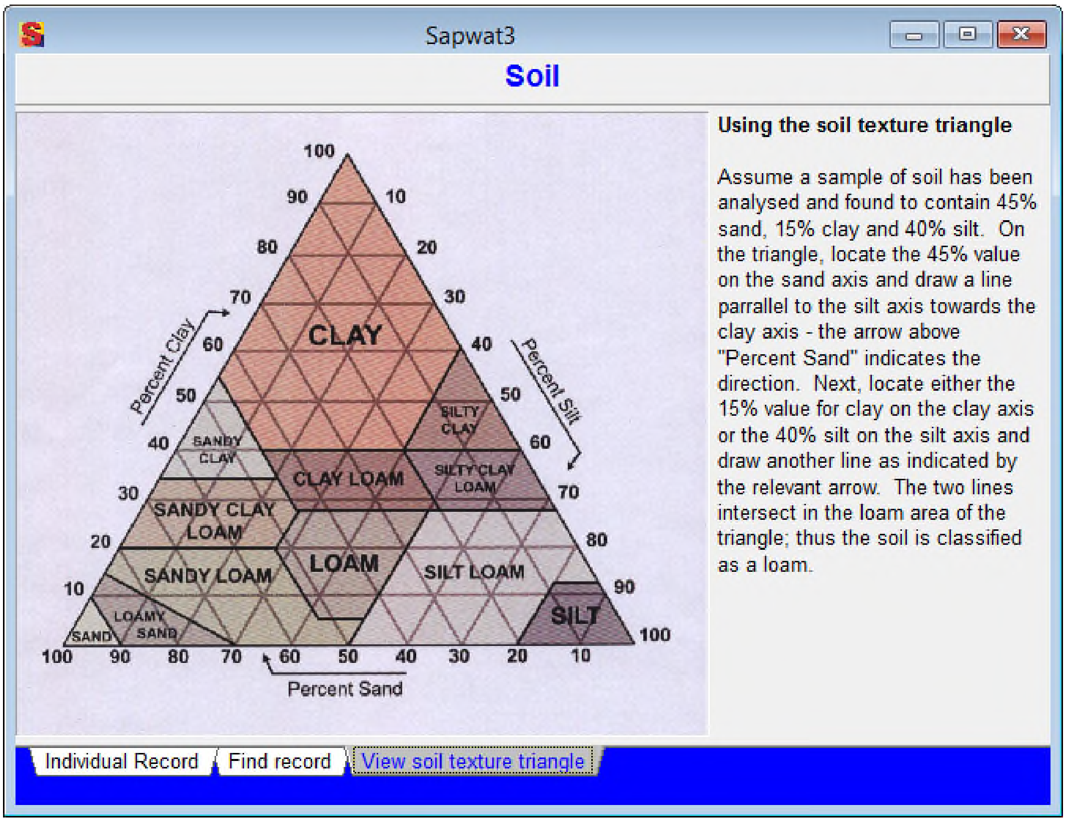


Figure 3-54 The soils texture triangle, page 3 of the soils screen form (Soilsensor.com, 2015)

3.7.2.15 Irrigation systems

Irrigation systems, consisting of surface, sprinkler and micro systems, are the means to distribute water over the field that needs to be irrigated. Each system has its own inherent efficiency, expressed as a default percentage (Table 3-25), and taken from the SABI[12] design manual which has been generally accepted by designers and planners (ARC-IAE, 1996). The Stamm (1987) definition of irrigation efficiency is the percentage of total irrigation water supplied to a given area which is made available within the root zone for beneficial consumptive use by crops. Reinders (2010) defines it as: the ratio between net and gross irrigation requirement, where nett irrigation is the quantity of water that reaches the root zone for beneficial use and gross irrigation is the quantity of water that enters the irrigation system. In neither of these two definitions does the distribution efficiency (DU) appear which was in the past wrongly assumed to form part of the in-field irrigation efficiency (Jensen *et* al., 1987; Reinders, 2010).

Table 3-25 Irrigation systems and their traditional efficiencies as used by irrigation system designers and irrigation planners (Reinders, 2010; ARC-IAE, 1996)

System	System efficiency (%)
Drip (surface and sub-surface)	90
Micro spray	80
Centre pivot, linear move	80
Centre pivot: LEPA sprinklers	80
Flood: piped supply	80
Flood: lined canal	60
Sprinkler: permanent	75
Sprinkler: movable	70
Traveling gun	75

In the original SAPWAT, system efficiency and DU were combined to give an in-field level efficiency (Table 3-26) (Crosby and Crosby, 1999). These values were used to estimate irrigation requirement, which, when compared to Table 3-25, would result in a big increase in irrigation water requirement because of a lower efficiency.

[12] South African Irrigation Institute

Table 3-26 Field level efficiencies as used by Crosby and Crosby (1999) in SAPWAT

Irrigation system	Application efficiency (%)	Distribution uniformity (%)	In-field efficiency (%)
Drip	90	85	77
Micro	80	85	68
Centre pivot	80	75	60
Spray permanent	75	75	56
Spray movable	70	75	53
Spray travelling	65	70	46
Flood piped supply	80	65	52
Flood canal supply	60	60	36

Using the efficiency values shown in Table 3-26 would result in over-design of irrigation systems, but arguments for this approach exist. An example is Li (1998), who argued that on small-scale water distribution in a field under irrigation is not uniform. This is because micro-topography unevenness causes some water to move sideways on the soil surface, or small pockets of soil may have a different infiltration rates than adjoining pockets of soil. Based on this argument, it is expected that under sprinkler irrigation about 50% of an irrigated area would get slightly more and 50% slightly less than the required amount of water. The crop on the areas that get slightly less water would have a smaller yield than the average. The approach is that the area that gets less water than required should be reduced from the expected 50% to about 25% to ensure optimum production. This argument can be illustrated with Figure 3-55 where H_R = required depth, H_G = gross depth, H_{max} = maximum depth, H_{min} = minimum depth, H_D = less than required irrigation depth, x_i = fraction of the total area receiving more than the required irrigation depth.

However, there is also a warning related to this where Li (1998) states: "The results from this work and other researchers demonstrate that the sprinkler water is more uniformly distributed within the root zone than that measured on the surface because of sideways water movement in the soil. Further research is obviously necessary to develop a quantified relationship between the uniformity of soil water content and the uniformity of sprinkler water application, and to add this quantified relationship to the crop water production function. Optimal sprinkler irrigation uniformity should be determined by considering crop yield, deep percolation, and initial sprinkler irrigation cost."

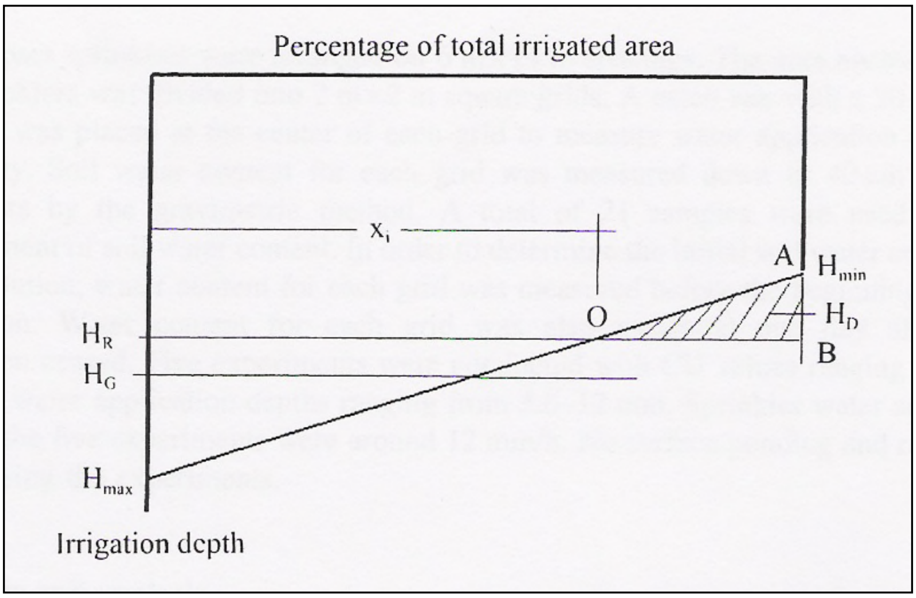


Figure 3-55: Distribution of irrigation depths in the field assuming a uniform distribution (Li, 1998)

Reinders (2010) recommends that the single figure irrigation system efficiency be replaced by two efficiency values consisting of system efficiency for the design of systems and a DU as a separate entity. This will bring the way efficiency of irrigation systems are defined and applied more in line with the ICID[13] (Reinders, 2010) recommended approach which is aimed at reducing the confusion surrounding the terms "irrigation efficiency", especially where irrigation systems are concerned. Recommended system efficiencies are mostly higher than the presently accepted default values for most irrigation systems (Table 3-27). These are based on analyses done for the publication of the Reinders (2010) report. In this report it is argued that the default irrigation efficiencies result in too much water that is lost through deep percolation or runoff and that the recommended values are a truer reflection of system efficiencies. It is further recommended that the Reinders (2010) efficiencies should be applied in system design and irrigation requirement planning and that the problem of poor uniformity (DU) should be specifically dealt with as a separate issue. It is also recommended that the DU component in SAPWAT3 irrigation system data table be kept at 100%, unless specifically determined. User reaction tested informally was against the change of the default irrigation system efficiencies to that recommended by Reinders (2010).

In SAPWAT3 irrigation systems and their efficiencies are included in a data table that is used as a lookup table by the program (Van Heerden *et al*., 2008). This gives the user the ability to add, edit or delete data or to adapt values to suit local conditions or to reflect newer

[13] International Commission on Irrigation and Drainage

research results. Irrigation systems included in the look-up table as well as their default system efficiencies are shown in Table 3-27.

Table 3-27 Irrigation systems and efficiencies included as default values in SAPWAT3

System	Distribution uniformity (%)	System efficiency used in SAPWAT3 (based on ARC-IAE, 1996) (%)	System efficiency recommended by Reinders (2010) (%)
Centre pivot	100	80	90
Drip	100	95	95
Flood: basin	100	75	86
Flood: border	100	50	86
Flood: furrow	100	55	86
Linear	100	85	98
Micro spray	100	90	85
Micro sprinkler	100	85	85
Sprinkler: big gun	100	70	78
Sprinkler: boom	100	75	83
Sprinkler: dragline	100	75	83
Sprinkler: hop-along	100	75	83
Sprinkler: permanent	100	85	90
Sprinkler: quick-coupling	100	75	83
Sprinkler: side roll	100	75	83
Sprinkler: travelling boom	100	80	83
Sprinkler: travelling gun	100	75	78
Subsurface	100	95	95
Sprinkler: permanent (floppy)	100	85	90

The combination of soil type, crop and farmer preference usually determines which irrigation system is best suited.

3.7.2.16 Irrigation system data structure

The data structure of the irrigation systems data table is shown in Table 3-28.

Table 3-28 Structure of irrigation system data table (Irrisys.dbf)

Field	Field Name	Type	Length	Decimal	Index	Notes
1	SystemID	Autoincrement	4		Y	Primary index.
2	System	Character	40		N	Irrigation system name.
3	IrriSysAppl	Numeric	3		N	Default design application.
4	Efficiency	Numeric	3		N	Default system efficiency (%).
5	DU	Numeric	3		N	Default distribution uniformity (%).
6	WettedArea	Numeric	3		N	Default percentage area wetted by system, e.g. 100% for centre pivot, 3% for drippers (%).
7	Default	Logical	1		N	Select a system to appear as default for system designs.

3.7.2.17 Screen forms

The irrigation system screen form is shown in Figure 3-56.

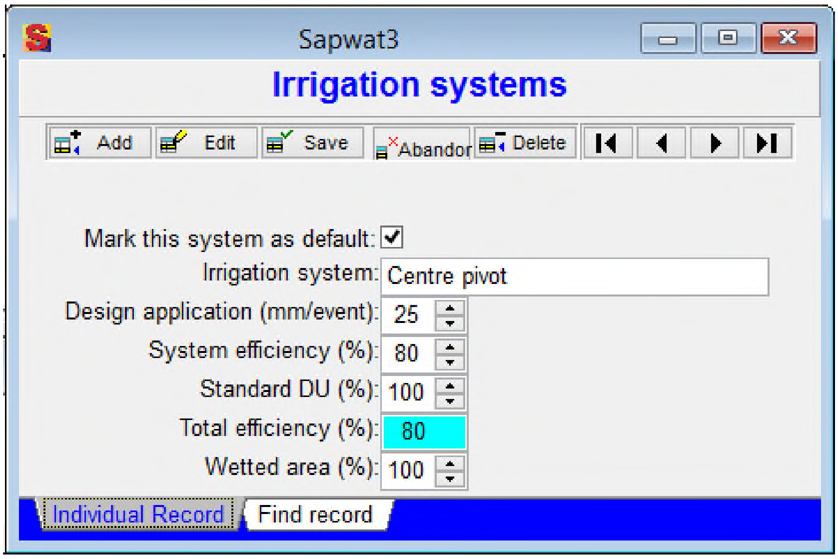


Figure 3-56 Irrigation system screen form

3.7.2.18 Irrigation water conveyance systems

Water conveyance systems are systems taking water from a source to the edge of the field on a farm or in a water management area and could be any combination of river, canal or pipeline. The irrigation system is the in-field distribution system. Potential irrigation water is lost from most conveyance systems and provision must be made to incorporate such losses in irrigation water requirement estimates for areas such as farms, water user management areas and central management agencies or for drainage regions. A problem encountered was that no default efficiency values for water conveyance systems relevant to South Africa could be found. An informal consultation group[14] made up of specialists, most of whom were eventually also involved in the Reinders (2010) project, were asked for advice. They reached consensus that the values shown in Table 3-29 should be used as default values.

Table 3-29 Conveyance system efficiencies included as default values in SAPWAT3 where WMA = water management area; WUA = water users association

Conveyance system	**Farm (%)**	**Sub WUA (%)**	**WUA (%)**	**WMA (%)**
Piped supply	100	100	100	100
Piped supply from lined sump	95	95	95	95
Piped supply from unlined sump	90	90	90	90
Lined dam, lined canals	90	90	90	90

[14] PS van Heerden of PICWAT; FB Reinders and F H Koegelenberg of the ARC – IAE; Isabel van der Stoep of Bioresources Consulting; Dr N Lecler of the South African Sugar Research Institute; Dr N Benade of NB Systems; Mr FJ du Plessis of MBB Consulting Services.

Lined dam, unlined canals	85	85	85	85
Unlined dam, lined canals	80	80	80	80
Unlined dam, unlined canals	75	75	75	75
Lined canals	95	95	95	95
Unlined canals	85	85	85	85
Dam, river	75	75	75	75

3.7.2.19 Data structure

The structure of the water conveyance efficiency table is shown in Table 3-30.

Table 3-30 Structure of the water conveyance efficiency data table (Disteff.dbf) explain / define terms?

Field	Field Name	Type	Length	Dec	Index	Notes
1	DEID	Autoincrement	4	0	Y	Primary index.
2	System	Character	30	0	Y	System descriptive name.
3	FarmDE	Numeric	3	0	N	Farm level efficiency.
4	WUASubDE	Numeric	3	0	N	WUA sub-area level efficiency.
5	WUADE	Numeric	3	0	N	WUA level efficiency.
6	CMADE	Numeric	3	0	N	CMA level efficiency.

3.7.2.20 Screen forms

The water conveyance system screen form is shown in Figure 3-57.

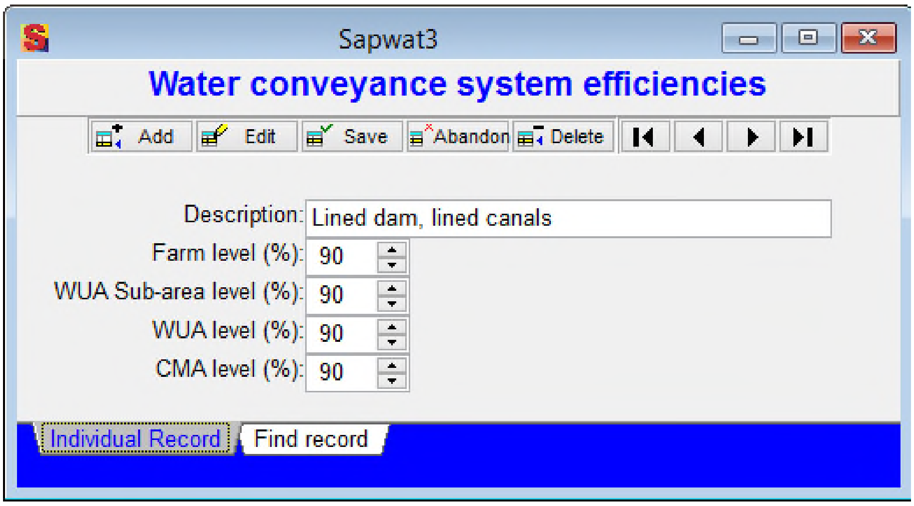


Figure 3-57 Water conveyance system efficiencies screen form

3.7.2.21 Countries

Countries are included to enable the user to select a country of interest and to pick a weather station from a position on a map. Data is stored in two tables, a controlling table (Countries.dbf) and a detail table (Countrymaps.dbf) which include information such as the extreme northern, eastern, southern and western boundaries as these define longitude and latitude references to which weather stations placed on the maps are linked. The three letter country identification code and country names included in the table are defined by ISO 3166[15]. These country maps are used for selecting weather stations for use in SAPWAT3. As many map types or subdivision maps of a country as required can be linked to the country data table.

On the opening of the program the country identified in the operating system files of the computer is selected as a default. The user can change this by selecting another country to work with.

3.7.2.22 Data structure

Data is structured in two tables. Table 3-31 is the controlling table with Table 3-32 providing the detail for each different type of map or for subdivisions of the country map. Linkage between the tables is through the CountryID field.

Table 3-31 Structure of countries data table (Countries.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	CountryID	Character	3	0	Y	Primary index
2	Country	Character	40	0	N	Name of country
3	Show	Logical	1	0	N	Select “True” for showing in SAPWAT3; “False” for not showing

Table 3-32 Structure of countrymaps detail data table (Countrymaps.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	CountryID	Character	3	0	Y	Index for linking with countries table
2	State	Character	40	0	N	Subdivision, such as state or province of a country
3	LatN	Numeric	9	4	N	Extreme northern latitude
4	LatS	Numeric	9	4	N	Extreme southern latitude
5	LongW	Numeric	9	4	N	Extreme western latitude
6	LongE	Numeric	9	4	N	Extreme eastern latitude
7	MapType	Character	15	0	N	Differentiate between outline and topographic maps
8	Map	Binary	10	0	N	Map graphic[16]

3.7.2.23 Countries screen forms

The countries screen form is shown in Figure 3-58 and the detail country form in Figure 3-59. Placing the pointer onto a weather station, shows its name and double clicking on it will open the weather station screen for that station.

[15] ISO 3166, 1993

[16] Maps and map detail provided by Dr Charles Barker, Department of Geography, University of the Free State.

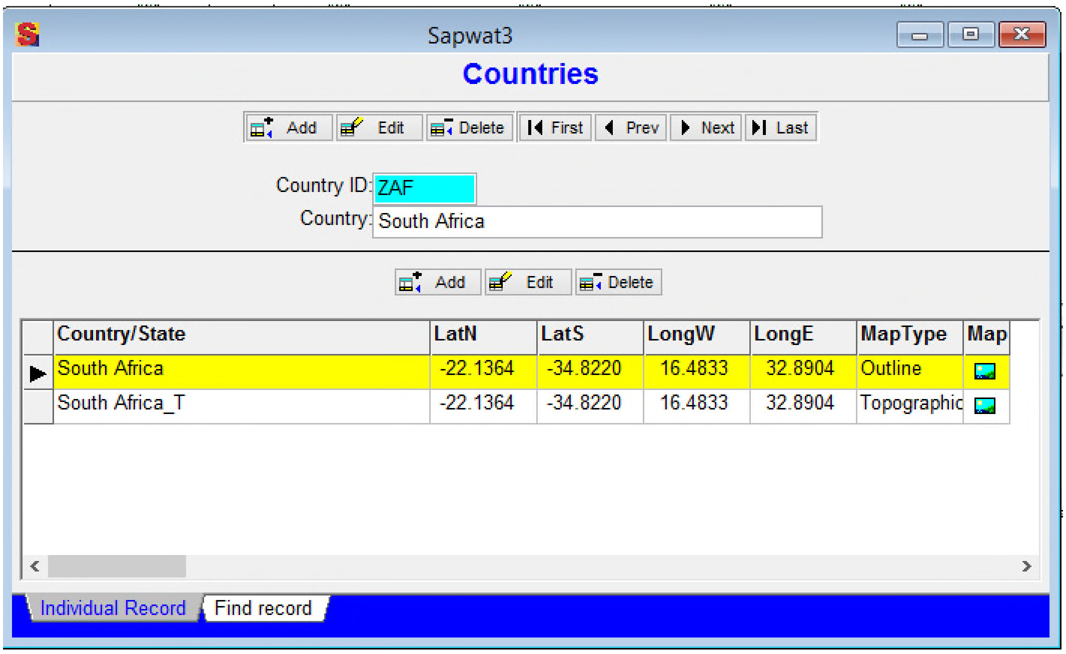


Figure 3-58 Screen form for countries, showing South Africa with choice of topographic and outline maps

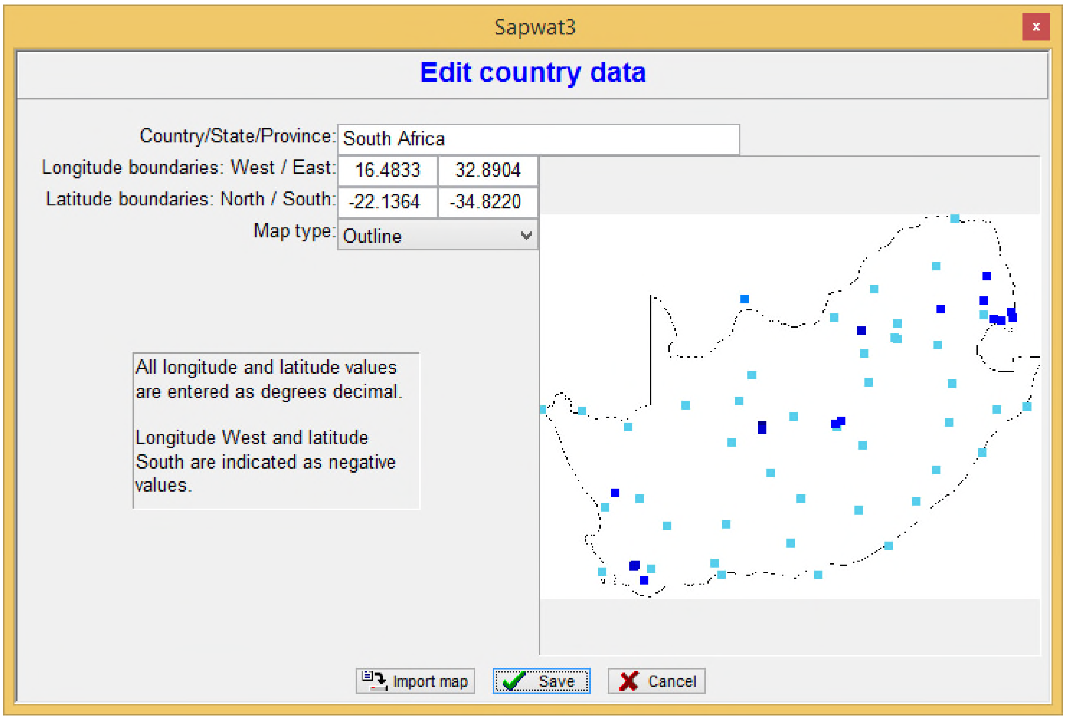


Figure 3-59 Detail map of South Africa showing CLIMWAT weather stations (light blue) and own weather stations (dark blue)

3.7.3 Address list

An address list is included for users who might want to make use of such a facility.

The addresses on the list cannot be used for anything but keeping track of people; there is no linkage to address lists of other computer programs. The data structure is shown in Table 3-33 and the screen form layout in Figure 3-60.

Table 3-33 The structure of the address list data table (Irricontact.dbf)

Field	Field Name	Type	Length	Dec	Index	Notes
1	ContactID	Autoincrement	4		Y	Primary index key
2	Seekname	Character	40		N	Compiled name to enable one-field seeking
3	Title	Character	7		N	
4	Firstname	Character	15		N	
5	Lastname	Character	30		N	
6	Position	Character	40		N	
7	Company	Character	40		N	
8	Postal1	Character	40		N	
9	Postal2	Character	40		N	
10	PostCode	Character	10		N	
11	PostOffice	Character	40		N	
12	PostProvince	Character	40		N	
13	PostCountryID	Character	3		N	
14	Residence1	Character	40		N	
15	Residence2	Character	40		N	
16	City	Character	40		N	
17	ResidenceProvince	Character	40		N	
18	ResidenceCountryID	Character	3		N	
19	Tel	Character	15		N	
20	Fax	Character	15		N	
21	Cel	Character	15		N	
22	eMail	Character	40		N	

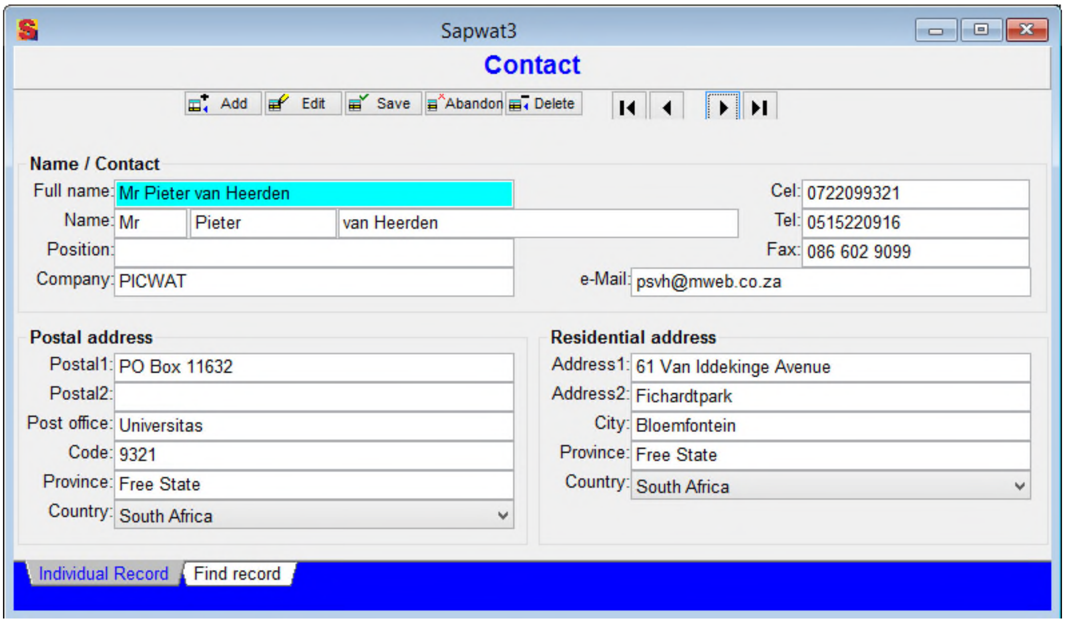


Figure 3-60 The screen form of the address list

3.8 Data exchange

Some data, mainly the result of irrigation water requirement estimates, can be exported as CSV (comma separated values) type files for further use in spreadsheet programs. The advanced graphing capabilities found in spreadsheet programs can then be utilised to demonstrate tendencies in irrigation water requirements over time, or because of changes in cropping patterns (Van Heerden *et al*., 2008).

The importation of weather data into SAPWAT3 from external sources requires the preparation of the data in either CSV or DBF format (Van Heerden *et al*., 2008).

3.9 Conclusions

SAPWAT (Crosby and Crosby, 1999) was developed because programs available at that time did not satisfy the South African requirements. During use, it became clear that SAPWAT itself had some unforeseen shortcomings, such as the inability to store estimation results and the inability to print results. PLANWAT (Van Heerden, 2004) was built as an interim solution to overcome these shortcomings. SAPWAT had other problems that PLANWAT did not solve, like crop growth and development that are based on the same calendar time approach used in CROPWAT (Smith, 1992) and FAO 56 (Allen *et al*., 1998). This resulted in it not able to adjust crop growth and development for warmer or colder areas, with the result that the SAPWAT crop growth and development was often out of phase with actual growth. The end result was that the estimated irrigation water requirement estimates were sometimes seen as incorrect.

It was decided to upgrade SAPWAT to SAPWAT3 and in that process to attempt to solve as many of the shortcomings experienced. This led to the objectives listed at the beginning of the chapter: integrating SAPWAT and PLANWAT; building a gross margin module; including rain water harvest size for in-field rainwater harvesting; provision of comprehensive built-in datasets; importation of weather data; and, exporting data to other file formats

SAPWAT and PLANWAT were integrated into a single program that had all the combined capabilities that the original SAPWAT and PLANWAT provided. Apart from the basic functions of estimating irrigation requirements it can store and print results, it can also sum results backwards so that not only the estimated irrigation requirements of a crop would be shown, but irrigation requirements of farm, water user association or even of primary drainage regions could be shown. This added functionality expanded the capabilities of the program, but at the same time made it somewhat more complicated to use. However, once the user is comfortable with the use of SAPWAT3, this no longer seems to be a problem.

Enterprise budget functionality was included in SAPWAT3 at the request of users who also wanted to look at the potential gross margin parallel to crop irrigation water requirements for planning purposes. This function is based on the COMBUD enterprise budget approach used by agricultural economists when planning for and advising farmers on the potential profitability of their farming enterprises.

The water harvesting module for back-yard type situations was designed and built to use estimated crop irrigation water requirement estimates to calculate both water harvest area needed and water storage capacity required. Water harvesting at this scale is not seen as irrigation in the full sense of the word, but rather to have water available for supplementary irrigation. The user has three choices of harvest area (roof, hard packed earth and natural vegetation) and three possible storage facilities (closed impervious; open impervious and ponds), which can be used in any combination. For in-field rainwater harvesting it also shows the ration between harvest area and production area.

Data include a full set of soil texture classes and a complete set of Köppen climates. Weather data is included for most of the third-world countries and more than 100 crops are included.

All data are on-board, and even though present day broadband connectivity makes it possible to allow data access from a centrally managed database, the situation at the time of development was such that a good proportion of potential users of SAPWAT did not have, or only had limited, electronic connectivity. It was decided to maintain this approach, because there are still problems with connectivity in places, and as SAPWAT3 is now used in at least 10 African countries, plus a few in central Europe and in the east, this decision still seems to be the right one.

All results are stored and the user can return to selected data at any time in the future for inspection or for recalculations. This data can be selectively exported to spreadsheet type programs. The extra functionality those programs provide, can then be used to include SAPWAT3 results as tables and graphs in reports.

SAPWAT3 has not completely solved the problem of crop growth and development that is out of phase with that actually found. This problem was reduced by linking crop growth and development to Köppen climates so that crops grow slower in cooler areas and faster in warmer area – that is where enough crop growth data were found to enable this improvement. Methods to solve this problem are being sought, as described in chapters 2 and 4, and will be included in future versions of SAPWAT3.

CHAPTER 4.
EVALUATION OF SAPWAT3 KCB VALUES

4.1 Introduction

Equation Chapter (Next) Section 1Plants contain water, up to about 90% of their total weight; with the exact water content being dependent upon their anatomy, physiology, and weather conditions as well as available soil water content. This water is stored in various tissues of the plant and is also used as one of the main raw materials in the photosynthesis process. During the process of transpiration a plant can extract a total amount of water from the soil that is usually many times the volume of water contained in its tissues at maturity (Allen *et al*., 1998; Gardiner *et al*., 1985). For example, at Bloemfontein an unstressed, short season maize crop planted during October at 100 000 plants per hectare will contain a standing mass of about 200 tons water per hectare as a mature crop, but during its growing period it will evapotranspire about 600 mm or 6 000 tons of water per hectare (Van Heerden *et al*., 2008). If the required water is not available through seasonal rain plus water stored in the soil profile, water should be made available by irrigation. In order to ensure that scarce water resources are used to the best advantage, the irrigation water requirement needs to be estimated as accurately as possible and managed to the best of the farmers' ability with available technology (Allen *et al*., 1998; Alois, 2007; Department of Water Affairs, 2012; Fairweather *et al*., undated).

The developers of models to be used as tools in the estimation or prediction of irrigation water requirements are faced with the problem of varying degrees of credibility. In South Africa, the Green Book (Green, 1985) used Class A-pan based crop factors. Irrigation estimates were reasonable as long as these crop factors were calibrated for the area and the crop. However, these practices were not necessarily possible, often resulting in incorrect estimates, which in turn led to a lack of credibility (Du Plessis and Wittwer, 1991; Green, 1985; Tanner, 1987). It is relatively easy to obtain manual measurements from evaporation pans, but there are several shortcomings, the main ones being the following (Lazarra and Rana, 2012):

1. The heat exchange between pan and soil is not negligible;
2. The sensitivity of partially buried pans to the surrounding environment;

3. The need to maintain sufficient freeboard can cause a wind turbulence effect which can influence the evaporation, the effect of which is difficult to estimate; and,

4. During the night the water usually cools on the surface, causing convective flow with the warm water rising to the surface, which in turn influences the amount of water that evaporates.

Using the energy-balance and mass-transfer approaches, the potential for shorter-term verification of crop coefficient became more of an option; although credibility problems were still present (Doorenbos and Pruitt, 1977).

Models used for the estimation of irrigation requirements, such as CROPWAT (Smith, 1992); SWB (Annandale *et al*., 1999); SAPWAT3 version 1.0 (Van Heerden *et al*., 2008) and AquaCrop (Raes *et al*., 2009) do not have subroutines that could simplify the verification of crop coefficients based on the FAO four-stage crop growth curve. Aggravating the problem of potentially incorrect crop coefficients is the fact that the FAO 56 crop coefficients for use with the Penman-Monteith equation were derived from mean K_c values of Doorenbos and Pruitt (1977) (Allen *et al*., 1998). Furthermore, the smooth surface of a short grass reference crop tends to lose its similarity in aerodynamic exchange and leaf area to tall vegetation, especially in arid and semi-arid climates. In these cases, lucerne (alfalfa) as a reference crop seems to provide a better choice (Allen *et al*., 2011), but the K_c and K_{cb} tables included in FAO 56 are based on short grass only, and that is the basis for the crop coefficients used in SAPWAT3. The users of FAO 56 K_c and K_{cb} values and of SAPWAT3 are therefore warned that the acceptance of default crop coefficients without considering the influence of climate, planting date, cultivar characteristics, agronomic practices and irrigation strategy on crop growth and development, could lead to incorrect irrigation requirement estimates (Allen *et al*., 1998; Smith, 1994, quoted by Van Heerden *et al*., 2001; Van Heerden *et al*., 2008). Crop coefficients used in FAO 56 and applied by models such as SAPWAT3 need to be adapted if so required, however the adaptation means that research results need to be collected in order to change the relevant values. None of the models mentioned above have a module that can take actual crop water use research data, and compare those to the published or included crop coefficients, and then suggest a scope and direction of adjustment.

SAPWAT3 is an irrigation-planning model that estimates irrigation requirements using published crop coefficients that link the four-stage crop growth curve to the Penman-Monteith based reference evapotranspiration. Of the 104 main crops, and their 2 835 subgroups based on cultivar type, planting date and climate that are included in SAPWAT3, only the major crops grown under irrigation have had adequate research as far as K_c values are concerned (Doorenbos and Kassam, 1986; Allen *et al*., 1998; Steduto *et al*., 2012). If K_{cb} values are correct for a specific crop, it would result in credible ET_c values for that crop. Because of the lack of research on K_{cb} values for some crops included in SAPWAT3 that are grown under irrigation, it was deemed necessary to include a module with which the correctness of K_{cb} values could be fairly easily verified, provided that reliable measured crop evapotranspiration data are available.

4.1 Objectives

The objectives of this chapter concerning the verification of K_{cb} values included in SAPWAT3 and the resultant correctness of calculated ET_c are:

1. to describe the theoretical basis underlying the verification calculation procedure;
2. to describe the application of the theoretical background in the verification module; and,
3. to evaluate the K_{cb} and ET_c verification outputs based on lysimeter measurements of crop evapotranspiration.

4.2 Theoretical background

Discrepancies were found between FAO 56 (Allen *et al*., 1998) crop coefficients (K_c) and those actually determined on site through a variety of methods including micrometeorological eddy covariance methods, weighing lysimeter measurements, soil water balance approaches, plant physiological approaches and remote sensing data (Lazarra and Rana, 2012). K_c values that differ from those in FAO 56 were also recommended by Fereres *et al*. (2012). K_c is affected by all the factors that influence soil water status e.g. irrigation method and frequency; the weather; soil characteristics and agronomic practices that affect crop growth. Therefore crop coefficient values reported in literature can vary significantly from actual values if growing conditions differ from those where the cited coefficients were obtained.

Furthermore, low soil water content, high air temperatures and water vapour deficit could lead to stomatal closure (Allen *et al*., 1998), resulting in lower than potential transpiration and thus a deviation from crop coefficient values (Lazarra and Rana, 2012; Steduto *et al*., 2012).

The problem of correct K_c and K_{cb} values could be alleviated if relevant research results were available at all sites where programs like SAPWAT3, CROPWAT (Smith, 1992), AquaCrop (Raes *et al*., 2009) or similar models are to be used. This is understandably the case, since research on such a scale would be impossible. A model will therefore always be needed to extrapolate results from research sites to application sites. Therefore, K_c values are given as generalised values valid for specific areas and/or climates which are stipulated. For example, the K_c values included in FAO 56 are valid for *sub-humid climates* and a warning is also given to the user that these K_c values: "…. should be verified or validated for the local area or for a specific crop variety using local observations". FAO 56 includes an adjustment equation to transform the tabulated data for all other climates through the use of average values for wind speed and relative humidity (Allen *et al*., 1998). The Penman-Monteith approach of calculating reference evapotranspiration is accepted as being correct and deviations in calculated evapotranspiration from that actually measured in a specific area could mostly be ascribed to incorrect crop coefficients (Allen *et al*., 1998; Lazarra and Rana, 2012).

The predicted or estimated output of a model such as SAPWAT3 needs to be verified against actual measured data (Willmott, 1981). While some researchers use only Pearson's product-moment correlation coefficient (r), because it describes colinearity between observed (x) and predicted (y) variates, others use the coefficient of determination (r^2) which could be a better measure of a model's worth because it describes the proportion of the total variance explained by the model. However, the ability of a model to simulate "truth" could be too elusive to be adequately represented by these standardised coefficients of agreement or association (Willmott, 1981). Willmott (1981) and Snedecor and Cochran (1989) recommend that the following also be computed and reported:

1. Observed and predicted means ($\bar{x}$ and $\bar{y}$, respectively) and standard deviations (s_x and s_y, respectively);

2. Slope (b) and intercept (a) of least squares correlation between the predicted (dependent variable) and observed (independent variable);
3. Mean percentage error (MPE);
4. Root mean squared error (RMSE) and its components, the systematic (RMSEs) and unsystematic (RMSEu) root mean square errors; and
5. Index of agreement (d).

Even if complex processes are perfectly understood, computational procedures used in manageable management models are at best numerical approximations that make extensive use of parameterisation. Under such circumstances statistical testing would continue to be needed. Willmott (1981) states that tests of statistical significance should be enhanced by data plots which lend visual credibility to quantitative comparisons and which could also point to possible erroneous computations. In addition to statistical tests of significance, he recommends that the predictive worth of models should also be assessed on the basis of the modeller's knowledge of the processes the model describes, the accuracy of the input and test data and the numerical computational scheme employed.

4.3 Materials and methods

The verification of SAPWAT3 K_{cb} and growth period data entails the comparison of the SAPWAT3 table data with field measured data. The SAPWAT3 table data should then be adapted to closely reflect measured crop water requirement over its growing period so that future predicted water requirement by the crop can be estimated more closely. Then the improvement in ET_c predictions can be evaluated.

4.3.1 Data used

The development of the verification module is based on lysimeter experiments (Ehlers *et al*., 2003; Ehlers *et al*., 2007) that were done at Kenilworth Experimental Farm (29°01'00"S, 26°85'50"E) of the Department of Soil, Crop and Climate Sciences of the University of the Free State near Bloemfontein in the Free State Province of South Africa. Two lysimeter banks were constructed in a field so that the crops planted in the lysimeter could be surrounded by the same crop at field scale. One lysimeter bank contained a yellow sandy soil (Soil A: Clovelly soil form, Setlagole family (Soil Classification Working Group, 1991)) and the other a red loamy sand soil (Soil B; Bainsvlei soil form, Amalia family (Soil Classification Working Group, 1991)).

The aim of the two series of experiments were to determine the quantity of water that could be extracted from a soil water table by the crop (Ehlers *et al*., 2003) and to investigate the influence of different levels of salinity on water table crop water use (Ehlers *et al*., 2007). In both these cases the control lysimeters did not have either a water table or a higher than normal salt content in order to simulate normal situations. The water use results of the control lysimeters were used to develop and evaluate the K_{cb} verification module of SAPWAT3 in this chapter.

Agronomic practices during the experiments were managed to create optimum-conditions for crop growth, allowing for maximum root water uptake and yield during all experiments. The area around the lysimeter was treated in a manner identical to the lysimeter to eliminate possible island effect on crop growth and development. Crop evapotranspiration was measured at more or less weekly intervals and a comprehensive water balance sheet was used to calculate crop evapotranspiration. Irrigation was on a weekly basis and calculated to refill the 0-600 mm layer to its drained upper limit value. Water extraction was determined through lysimeter measurement (Ehlers *et al*., 2003; Ehlers *et al*., 2007). These experiments provide good measured data for calibrating crop characteristics used in SAPWAT3 to construct the four-stage FAO crop K_{cb} curve (Allen *et al*., 1998) for maize, wheat and peas.

4.3.2 Soil water balance

Irrigation requirement and related calculations by SAPWAT3 are based on the soil water balance equation. In the verification module Equation 4.1 (Allen *et al*., 1998) is used to calculate the observed evapotranspiration from measured data - adaptable to coincide with the actual measurement periods - represented in the equation. In the case of a lysimeter, all the variables are either measured or eliminated, with the result that ET can be accurately determined (Jia *et al*., 2006). Use of this equation to determine crop evapotranspiration at field level is possible, provided that all variables in the equation are determined *in situ* (Bennie *et al*., 1998).

$$ET=I+P-RO-DP+CR\pm\Delta SF\pm\Delta SW \quad 4.1$$

Where
- ET evapotranspiration
- I irrigation
- P precipitation
- RO run-off
- DP deep percolation
- CR capillary rise
- ΔSF change in subsurface flow
- ΔSW change in soil water content

4.3.3 The SAPWAT3 verification module

The verification module is an adaptation of the approach described by Allen *et al*. (1998) for the construction of the crop coefficient (K_c) curve. The adaptation is based on the SAPWAT3 approach that uses basal crop coefficient (K_{cb}) and not K_c, as used by Allen *et al*. (1998), therefore K_c was adjusted to its K_{cb} component by subtracting the value of the soil surface evaporation coefficient (K_e) (Equation 3.40) from the Kc value. The K_c equation $K_c=K_{cb}+K_e$ is therefore changed to:

$$K_{cb}=K_c-K_e \quad 4.2$$

The approach described by Allen *et al*. (1998), is to graph K_c data, calculated from field measured evapotranspiration (ET_c) through the equation $K_c=\frac{ET_c}{ET_0}$, where ET_0 is the Penman-Monteith reference evaporation calculated from the weather station data. The basal crop coefficient is determined by adapting this equation to $K_{cb}=\frac{ET_c}{ET_0}-K_e$. In the case of SAPWAT3 the K_{cb} values are graphed. Allen *et al*. (1998) describes the approach to determine the crop coefficient (K_c) in four steps:

1. Plot the observed K_c data on graph paper with growth days (growth day 1 = day of planting) on the x-axis and K_c values on the y-axis.

2. Divide the graphed growing period visually into four general growing stages that will best describe the crop phenological stages initial ($K_{c\ ini}$), development ($K_{c\ dev}$), mid-season ($K_{c\ mid}$) and late season ($K_{c\ late}$) based on the picture presented by the graphed data.

3. Adjust the K_c values to the frequency of wetting and climate conditions.

4. Construct a curve by connecting straight line segments through the four stages. The $K_{c\ ini}$ and $K_{c\ mid}$ line segments must be drawn parallel to the x-axis. Diagonal lines are drawn linking $K_{c\ ini}$ to $K_{c\ mid}$ and from $K_{c\ mid}$ to $K_{c\ end}$.

The Allen *et al*. (1998) approach described above is applied in the SAPWAT3 verification module by taking K_e out of the K_c equation, and therefore working with the K_{cb} values. The application is as follows:

1. The user lets SAPWAT3 calculate the estimated irrigation requirement using the existing K_{cb} table values contained in SAPWAT3.

2. The verification module is then called, the source of the observed data is given and the following graphic iteration method is followed by SAPWAT3:

   i. Determine the mean for all observed K_{cb} data;

   ii. Divide the K_{cb} data into two groups, an upper group made up of all observed K_{cb} values larger than the mean and a lower group made up of all K_{cb} values smaller than the overall mean.

   iii. The mean of the upper group will be the first approximation of $K_{cb\ mid}$, and the mean of the lower group will be the first approximation of $K_{cb\ ini}$. Lines are drawn through these mean points parallel to the x-axis.

   iv. Move from left to right along the lower values mean line – this is the approximation of $K_{cb\ ini}$ – until the last K_{cb} value is found that is equal to or smaller than the approximated $K_{cb\ ini}$ value. (If values exist at the end of the growing period that is equal to or smaller than the approximated $K_{cb\ ini}$ value, they are ignored as being end values of $K_{cb\ late}$). The growing day at which this point appears, is the approximation of the first day of the development growing period.

   v. Start at the first day of the development stage on the upper values mean line and move from left to right along that line until a K_{cb} value is reached that is equal to or larger in value to the upper mean value. This is an approximation of the first day of the mid-season growth stage.

vi. The next step is too look further along the upper values mean line for the last K_{cb} value that is larger than or equal to the upper mean value. This is the first day of the late season growth stage. The last day of measurement as taken as the last day of growth (unless otherwise stated in the experimental data).

vii. A linear regression equation is calculated between growth days and the observed K_{cb} data between and including the first and last days of the development growth stage.

viii. The intersects of lower mean values line, the development stage regression line and the upper mean values line are the new approximations of the first day of the development stage and the first day of the mid-season stage.

ix. A linear regression equation is calculated between growth days and the observed K_c data between and including the first and last days of the late season growth stage.

x. The intersect of the upper mean values line and the late season regression line is the new approximation of the first day of the late season stage.

xi. Recalculate the mean value of K_{cb} values for days before the approximated first day of the development stage. This value is a new approximation for $K_{cb\ ini}$.

xii. Recalculate the mean value of K_{cb} values for days between the first day of the mid-season stage and the first day of the late season stage. This value is a new approximation for $K_{cb\ mid}$.

xiii. Do an RMSE analysis (paragraph 4.3.4) at the end of each repeat as an aid to interpretation of goodness of a new fit. The program recommends grow days and K_{cb} values to be applied for a rerun. These values are used to update the crop data in the data table.

xiv. The user lets SAPWAT3 recalculate the estimated irrigation requirement on the updated K_{cb} table values contained in SAPWAT3.

xv. Repeat the process, starting at #2.i until the difference between determined values and recommended values become small enough to indicate that further updates will be of no or very little consequence.

3. The approximate number of days for each growth stage and value for K_{cb} thus reached would then be those to use for the crop at this location.

The approach described above, based on Allen *et al*. (1998) has a problem in that when determining the basal crop coefficient for the initial period ($K_{cb\ ini}$), the calculation includes the zero K_{cb} values between planting and emergence and would therefore result in a bias towards a lower than correct value. $K_{cb\ ini}$ should therefore be determined for the period after emergence with the resultant higher $K_{cb\ ini}$ then relevant to the days between planting and emergence. This problem of having a non-zero K_{cb} value for a short period during the initial growing stage is mitigated by the irrigation requirement equation that also included canopy cover – at this early stage canopy cover is zero and the non-zero $K_{cb\ ini}$ valued during this period is then cancelled because a zero value for canopy cover results in a zero value for transpiration for the very beginning period of the initial growth stage. The recommended K_{cb} value of 0.1 to 0.15 for the initial period as per FAO 56 tabled data is to provide for diffusive evaporation from tilled soil, a condition usually found in seeded soils before and during germination (Allen *et al*., 1998).

The present definition of the initial period of the four-stage crop growth curve does not include the dividing of the initial stage into before and after emergence values, as when considered as a percentage of the crop water use over the whole growing season, this period will account for a very low amount.

4.3.3.1 Applying the verification module

Out of the SAPWAT3 crop data a crop, crop option and planting date that best resembles the crop to be used for analysis is selected. The planting data is changed to exactly match that of the crop of which measured data is obtained. An irrigation estimate is run in SAPWAT3 and the evaluation module called up. Estimated crop data related to growth periods of the four-stage crop growth period is than compared to the measured data. An RMSE analysis is done (Willmott, 1981) and the data and results are graphed. By comparing the graphic representation as well as the results of the statistical analysis, the user can decide on doing a rerun or stopping the process.

4.3.4 Statistical analyses

Model evaluation consists of two components. One is a component where the output of the model is evaluated visually through graphic representation. The other is also a statistical analyses component where the aim is to search for the existence of compensatory errors, to determine the causes of failure, and to provide additional insight into model performance (Willmott, 1981). The use of both graphic and statistical presentation of results in the verification module is based on Willmott (1981): "Data plots ought to accompany any comparison between observed and simulated variables as such graphic aids lend visual credibility to quantities comparisons as well as point to possible erroneous computations". The graphic representation of the data should be a correlation graph showing the predicted results against the observed results. An ideal slope of 1 is expected, but because the ideal is seldom reached, a slope between 0.7 and 1.3 is acceptable (Willmott, 1981).

Willmott (1981) and Snedecor and Cochran (1989) recommend that in addition to Pearson's product-moment correlation coefficient (r) or the coefficient of determination (r^2) the following descriptors are also computed and reported:

MPE: The mean percentage error, Equation 4.3, is the average of the percentage errors of estimate compared to observed data, which also indicates the bias of the error. Estimates that are unbiased are desirable, but bias could also be useful by indicating a positive or negative deviation from an observed mean, which in turn could indicate the direction of potential adaptation – a positive bias indicates predicted values that are too high and a negative bias indicate predicted values that are too low (Snedecor and Cochran, 1989; Wikipedia, 2013a; Willmott, 1981).

$$MPE=\frac{100\%}{n}\sum_{i=1}^{n}\frac{y_i - x_i}{x_i} \qquad 4.3$$

Where:	MPE	mean percentage error
	y_i	y-values (predicted values)
	x_i	x values (observed values)
	n	number of data pairs

RMSE: Root mean square error. Willmott (1981) makes a strong case for doing a mean square error analysis because the average error produced by a model is encapsulated in the mean square error (MSE), or its square root, the root mean square error (RMSE). The root mean square error is easy to interpret since it has the same metric as the observed and predicted values. It is an important statistical tool in that it informs the modeller and reader about the actual size of the error produced by the model, unlike r or r^2 in which a large error may be masked by high values of standard deviations. The MSE is further broken down in its sub-units, the systematic mean square error (MSEs) and unsystematic mean square error (MSEu) as an indication of how good a fit the model provides. Willmott (1981) also indicates that the roots of these values should preferably be used. RMSEs should be minimised in order for the model to predict at its maximum possible accuracy. If RMSE consists of mainly unsystematic root mean square error (RMSEu), it is an indication that the model is as good as can be and that further refinement might not be necessary.

The root mean square error, (Equation 4.4), is a measure of the differences between values predicted by a model and the values actually observed. It is a good measure of accuracy, but only to compare different forecasting errors within a dataset and not between different data sets. These individual differences are aggregated into a single measure of predictive power. In the case of SAPWAT3, it determines the closeness of both predicted ET_c and K_{cb} values when compared to observed ET_c and K_{cb} values. RMSE values that are small when expressed as a percentage of the observed average indicate a good comparison between predicted and observed values (Willmott, 1981).

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(y_i-x_i\right)^2}{n}} \qquad 4.4$$

Where: RMSE root mean square error

y_i y values (predicted values)

x_i x values (observed values)

n number of data pairs

$RMSE_s$: The systematic root mean square error (Equation 4.5) is a measure of the model's linear or systematic bias. A low value indicates that a model, such as SAPWAT3, is predicting at its maximum possible accuracy (Willmott, 1981).

$$RMSEs=\sqrt{\frac{\sum_{i=1}^{n}\left(\bar{y}_i-x_i\right)^2}{n}} \quad 4.5$$

Where: $RMSE_s$ root mean square error - systematic

$\bar{y}_i$ y values (expected or predicted values)

x_i x values (observed values)

N number of data pairs

$RMSE_u$: The unsystematic root mean square error (Equation 4.6) is a measure of the model's predictive bias (Willmott, 1981).

$$RMSEu=\sqrt{\frac{\sum_{i=1}^{n}\left(y_i-\bar{y}_i\right)^2}{n}} \quad 4.6$$

Where: $RMSE_u$ root mean square error - unsystematic

$\bar{y}_i$ y values (expected values)

y_i y values (predicted values)

N number of data pairs

d: Index of agreement. Equation 4.7 reflects the degree to which the observed variate is accurately estimated by the simulated variate. It is not a measure of the correlation or association in the formal sense of the word, but is rather a measure of the degree to which a model's predictions are error-free. At the same time, d is a standardised measure in order that (i) it may be easily interpreted, and (ii) cross-comparisons of its magnitudes for variety of models, regardless of units, can readily be made. It varies between 0.0 and 1.0 where a computed value of 1.0 indicates perfect agreement between observed and predicted observations, and 0.0 indicates one of a variety of complete disagreements. Owing to the dimensionless nature, relationships described by d, tend to complement the information contained in RMSE, $RMSE_s$ and $RMSE_u$ (Willmott, 1981).

$$d=1-\frac{\sum_{i=1}^{n}\left(y_i-x_i\right)^2}{\sum_{i=1}^{n}\left(\left|y_i-\bar{x}\right|+\left|x_i-\bar{x}\right|\right)^2} \quad 4.7$$

Where d index of agreement

y_i y values (predicted values)

x_i x values (observed values)

$\bar{x}_i$ x- average (average of observed values)

n number of data pairs

4.4 Results and discussion

The aim of verifying crop coefficients is to enable the coefficients of the FAO four-stage crop growth curve to be used to simulate the pattern of observed water requirement data as closely as is possible (Allen *et al*., 1998). A precise fit is seldom achieved; therefore Willmott (1981) advises that judgement of correctness should be based on a combination of the judgement of someone who knows the subject matter, as well as graphic presentation and statistical analyses. Statistical analyses should not be the only criterion for judgement of fit.

4.4.1 Selecting adapted crop coefficients

A problem linked to RMSE analyses and the eventual selection of the best set of recommended crop characteristics for use in SAPWAT3 is that several repeats of testing could satisfy statistical analysis acceptance norms, such as when the slope of the tabulated versus observed data regression falls within an accepted range of 0.7 to 1.3 (Willmott, 1981), or the RMSE expressed as a percentage of the observed data mean is less than 30% (Willmott, 1981). One possibility is to accept the crop characteristics with the lowest RMSE value as the correct characteristics, but experience in testing such analyses for SAPWAT3 purposes did not necessarily give the best observed fit of K_{cb} table values when compared to observed values. This duplicates an observation by Willmott (1981) who recommended that a combination of statistical analyses and visual evaluation should be done by a person or persons who know the subject matter. Thus this is the approach used in SAPWAT3: repeats of testing tabulated data against observed data with an update of tabulated data after each analysis cycle. The analysis cycle is repeated until a good fit between tabulated and observed data is seen, and these values then accepted as the final adaptation provided that the specifications of slope and RMSE value are satisfied.

4.4.2 Crop evapotranspiration data

Data from wheat planted 3 July 2003 were initially used to develop the basal crop coefficient verification module of SAPWAT3. Data are duplicated because data of two replications of the original work done by Ehlers *et al*. (2007) were used together and have been incorporated into one table for computation purposes. An interesting phenomenon is that from day 104 to day 118, the observed K_c values exceeded $K_{c\ max}$, which is the upper limit on evapotranspiration from a cropped surface (Allen *et al*., 1998). This upper limit is a natural constraint placed on energy available for evaporation by the energy balance difference $R_n - G - H$: where R_n is net radiation, G is soil heat flux and H is sensible heat. $K_{c\ max}$, based on the grass reference evapotranspiration generally ranges from about 1.05 to about 1.30 for different crop types, but the influence of climate could change these values substantially. Lower than tabulated value are found for humid, calm climates and higher than the tabulated value are found in arid and windy climates (Figure 4-1) (Allen *et al*., 1998). The $K_{c\ max}$ values shown in Table 4-1 have been calculated (Equation 3.42) using the measured Kenilworth weather station data for 2003 (Allen *et al*., 1998). No reason for $K_{c\ obs}$ exceeding $K_{c\ max}$ during the latter half of the growing season is apparent.

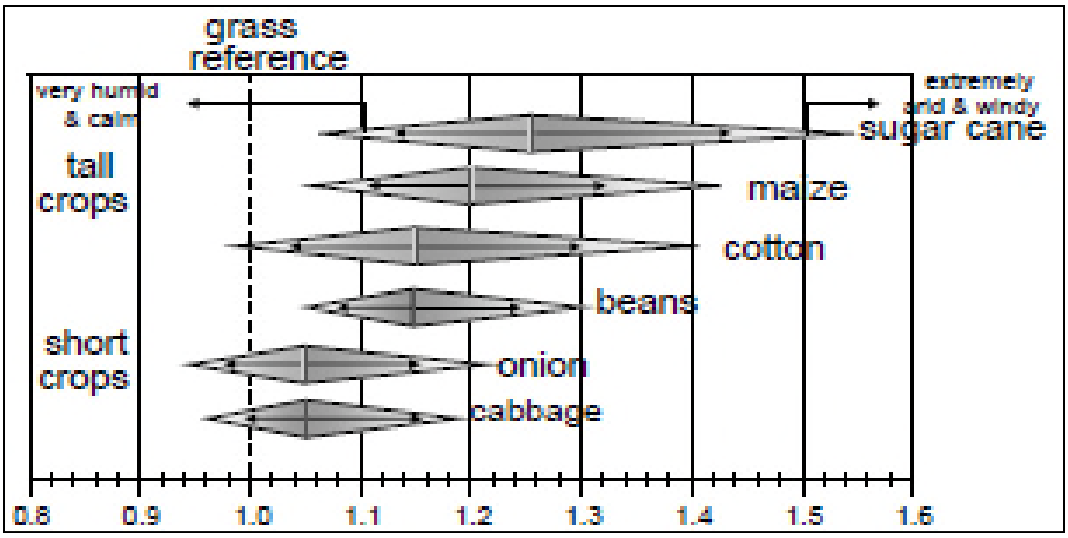


Figure 4-1 K_c ranges of some crops as influenced by climate (Allen *et al*., 1998)

Table 4-1 Data used for the verification of SAPWAT3 basal crop coefficients for two repetitions of wheat planted in lysimeters at Kenilworth near Bloemfontein on 3 July 2003. Average values for the indicated periods for K_e[17], ET_c, K_{cb}, K_c are shown for values based on K_{cb} lookup table values ($_{tab}$) and values observed during the course of the experiment ($_{obs}$)

GrowDay	Growstage	ET_0	K_e	ET_{c_obs}	ET_{c_tab}	K_{cb_obs}	K_{cb_tab}	$K_{c\ max}$	K_{c_obs}	K_{c_tab}
1	Ini	1.9	1.11	1.0	2.3	0.00	0.09	1.21	0.53	1.21
1	Ini	1.9	1.11	1.0	2.3	0.00	0.09	1.21	0.53	1.21
12	Ini	2.4	0.39	1.1	1.2	0.07	0.09	1.22	0.46	0.49
12	Ini	2.4	0.39	1.2	1.2	0.11	0.09	1.22	0.50	0.49
20	Ini	2.8	0.45	1.1	1.6	0.00	0.09	1.22	0.39	0.55
20	Ini	2.8	0.45	1.2	1.6	0.00	0.09	1.22	0.43	0.55
29	Ini	3.3	0.48	1.2	1.8	0.00	0.09	1.22	0.36	0.58
29	Ini	3.3	0.48	1.0	1.8	0.00	0.09	1.22	0.30	0.58
34	Ini	3.4	0.32	2.4	1.5	0.39	0.09	1.23	0.71	0.42
34	Ini	3.4	0.32	2.0	1.5	0.27	0.09	1.23	0.59	0.42
47	Ini	3.4	0.51	2.1	2.0	0.11	0.09	1.23	0.62	0.61
47	Ini	3.4	0.51	1.5	2.0	0.00	0.09	1.23	0.44	0.61
55	Ini	3.5	0.37	1.5	1.7	0.06	0.09	1.24	0.43	0.47
55	Ini	3.5	0.37	2.0	1.7	0.20	0.09	1.24	0.57	0.47
62	Ini	4.9	0.36	2.7	2.0	0.19	0.09	1.24	0.55	0.46
62	Ini	4.9	0.36	2.3	2.0	0.11	0.09	1.24	0.47	0.46
68	Dev	5.0	0.28	2.5	2.9	0.22	0.27	1.26	0.50	0.55
68	Dev	5.0	0.28	3.2	2.9	0.36	0.27	1.26	0.64	0.55
76	Dev	4.3	0.13	3.8	3.5	0.75	0.63	1.25	0.88	0.82
76	Dev	4.3	0.13	3.5	3.5	0.68	0.63	1.25	0.81	0.82
82	Dev	4.3	0.08	5.7	4.9	1.25	0.99	1.25	1.33	1.13
82	Dev	4.3	0.08	5.3	4.9	1.15	0.99	1.25	1.23	1.13
90	Mid	5.5	0.01	6.4	7.1	1.15	1.28	1.34	1.16	1.37
90	Mid	5.5	0.01	6.5	7.1	1.17	1.28	1.34	1.18	1.37
97	Mid	6.0	0.01	6.7	7.0	1.11	1.32	1.37	1.12	1.40
97	Mid	6.0	0.01	6.7	7.0	1.11	1.32	1.37	1.12	1.40
104	Mid	6.0	0.01	8.4	6.8	1.39	1.32	1.37	1.40	1.41
104	Mid	6.0	0.01	8.4	6.8	1.39	1.32	1.37	1.40	1.41
111	Mid	5.4	0.01	8.6	6.7	1.58	1.32	1.37	1.59	1.41
111	Mid	5.4	0.01	8.3	6.7	1.53	1.32	1.37	1.54	1.41
118	Mid	6.6	0.01	9.3	7.4	1.40	1.32	1.37	1.41	1.41
118	Mid	6.6	0.01	8.9	7.4	1.34	1.32	1.37	1.35	1.41
125	Mid	6.7	0.01	9.1	7.7	1.35	1.32	1.37	1.36	1.41
125	Mid	6.7	0.01	8.7	7.7	1.29	1.32	1.37	1.30	1.41
132	Mid	6.8	0.01	8.9	7.2	1.30	1.24	1.30	1.31	1.32
132	Mid	6.8	0.01	8.4	7.2	1.23	1.24	1.30	1.24	1.32
139	Late	7.0	0.01	4.4	7.0	0.62	1.00	1.27	0.63	1.08
139	Late	7.0	0.01	4.6	7.0	0.65	1.00	1.27	0.66	1.08
146	Late	5.5	0.01	3.9	4.1	0.70	0.75	1.21	0.71	0.77
146	Late	5.5	0.01	4.7	4.1	0.84	0.75	1.21	0.85	0.77

K_{cb} values for the mid-season growth stage are higher than expected (above 1.37) (Table 4-1). This is higher than the 1.10 for small grain cereals found in the FAO 56 $K_{cb\ mid}$ tables of

[17] K_e: evaporation coefficient; ET_c: crop evapotranspiration; K_{cb}: basal crop coefficient; K_c: crop coefficient

Allen *et al*. (1998). However, values higher than FAO 56 and SAPWAT3 $K_{c\ mid}$ table values were found in a number of other cited cases, e.g.:

- Using remote imagery and related analyses techniques Farg *et al*. (2012) found K_c values that varied between 1.6126 and 1.8777 (FAO 56 = 1.15) for wheat grown in the south Nile Delta in Egypt.
- Yang *et al*. (2008) reported K_c values for winter wheat ranging from 1.1 to 1.35 and 1.14 to 1.23 for two consecutive seasons (FAO 56 = 1.15).
- High $K_{c\ mid}$ values of 1.28 (FAO 56 = not specifically given, but 1.05 for members of the same family (*Brasicca spp*.)) for mustard grown in the non-monsoon period at Himachal Pradesh, India was found by Rohitashw *et al*. (2011).
- Abyaneh *et al.* (2011) found $K_{c\ mid}$ values of 1.4 (FAO 56 = 1.0) for garlic grown at Hamedan in Iran.

Some doubt could be placed on K_c values that exceed the $K_{c\ max}$ values (Table 4-1) because an energy constraint exist that should not be exceeded (Allen, *et al.*, 2011)). Such exceedance could be the result of plants growing more densely in the lysimeter than in the surrounding field or if the surrounding soil is drier than that contained in the lysimeter. In such cases an island effect would result which would lead to over-estimates of crop evaporation (Perkins, 1996).

4.4.3 Crop coefficients

Crop data of a winter cereal, a summer cereal and a non-cereal legume were used to develop and test the evaluation module built into SAPWAT3.

4.4.3.1 Spring wheat: 2003 data

The wheat cultivar SST 806 was planted on 3 July 2003 for the salinity experiment (Ehlers *et al*., 2007). Only data from the control (non-saline) treatment were used.

4.4.3.1.1 K_{cb} predicted and observed

The initial run with original K_{cb} data from the SAPWAT3 table and the comparative result of the observed data are shown in Figure 4-2 (repetition 1). The SAPWAT3 table data used as recommended values for a next repetition of analysis calculations is shown in the bottom right side of the screen. Figure 4-3 shows the related RMSE analysis for repetition 1 of the SAPWAT3 evaluation module. The crop data were updated with recommended changes by pressing the "Update" button; a crop irrigation water requirement rerun was done and again compared to the observed data. This process was repeated four times until the situation shown in Figure 4-4 and Figure 4-5 was reached. Both evaluation of the graphic representation through inspection and the statistical analysis indicate this as a good point to stop further updates (Figure 4-4, Table 4-2 and Table 4-3).

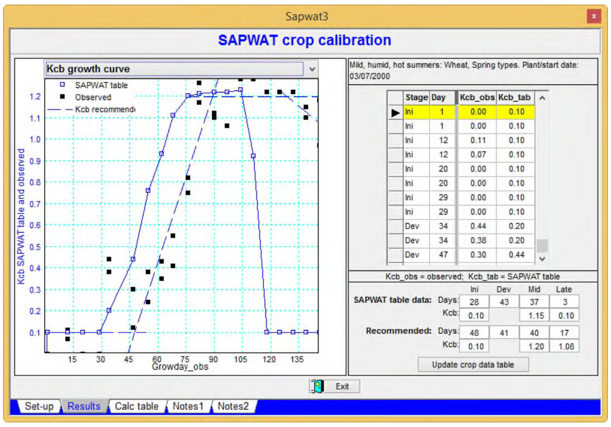


Figure 4-2 The SAPWAT3 table K_{cb} data curve, the observed data and the first repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

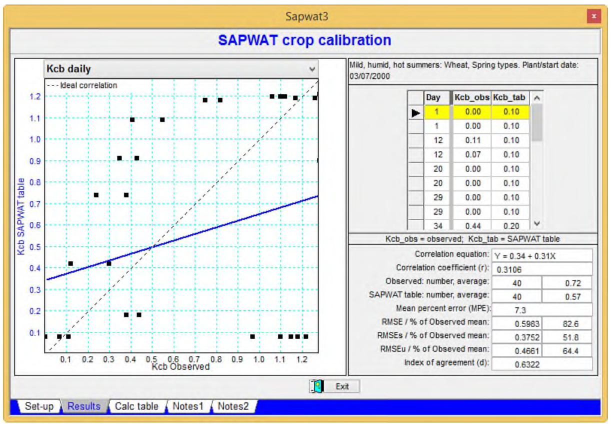


Figure 4-3 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

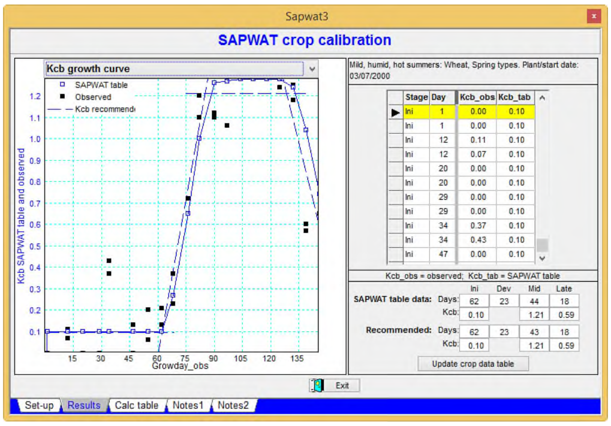


Figure 4-4 The SAPWAT3 table K_{cb} data curve, the observed data and the fourth repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

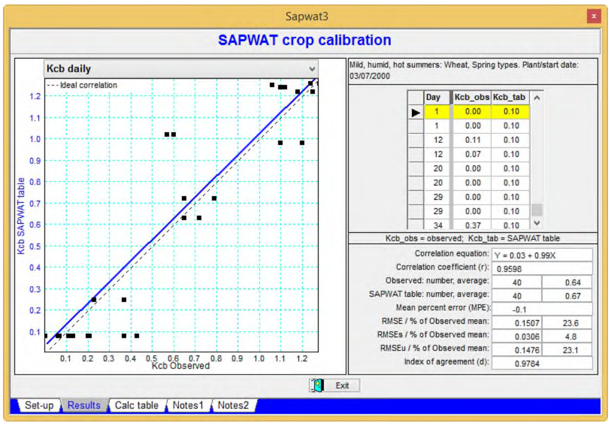


Figure 4-5 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the fourth repeat for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

Table 4-2 Changes in successive repeats of calibrating basal crop coefficients for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

Verification repeat	Crop growth stages						
	Initial		Development	Mid-season		Late season	
	Days	$K_{cb\ ini}$	Days	Days	$K_{cb\ mid}$	Days	$K_{cb\ end}$
Repeat 1: Lookup table values	28	0.15	43	37	1.15	3	0.10
Repeat 2	48	0.10	41	40	1.20	17	1.08
Repeat 3	56	0.09	31	41	1.21	18	0.59
Repeat 4	62	0.09	23	43	1.21	18	0.59
Recommended for repeat 5	61	0.09	23	43	1.21	18	0.59

Table 4-3 Statistical analyses of consecutive repeats of verification of the K_{cb} values of wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

Element		Repeat 1: Lookup table values	Repeat 2	Repeat 3	Repeat 4
Regression slope		0.31	0.95	0.97	0.99
r^2		0.3106	0.9303	0.9628	0.9598
Average of observed K_{cb}		0.72	0.65	0.64	0.64
MPE		7.3	15.8	5.9	-0.1
RMSE	Value	0.5983	0.2103	0.1458	0.1507
	% of observed mean	82.6	32.3	22.7	23.6
RMSEs	Value	0.3752	0.0948	0.0454	0.0306
	% of observed mean	51.8	14.5	7.1	4.8
RMSEu	Value	0.4664	0.1878	0.1386	0.1476
	% of observed mean	64.1	28.8	21.6	23.1
d		0.6322	0.9559	0.9792	0.9784

Figure 4-3 and Figure 4-5 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeats while Figure 4-2 and Figure 4-4 show the improvement of fit in the four-stage crop growth K_{cb} curve. In the situation indicated in the figures, the slope of the correlation line has improved from a non-acceptable 0.31 to an acceptable 0.99, which is mainly the result of the growth rate periods that were improved to coincide with actual plant growth rates for each of the four stages. The RMSE expressed as a percentage of the average of observed data improved from 82.6% to 23.6% (Table 4-3). The RMSEs is smaller than the RMSEu at 4.8% compared to 23.1% (Repeat 4) which is an indicator that the model works as expected and further development of the model itself might not be necessary (Willmott, 1981). The index of agreement (d) has also improved from 0.6322 to 0.9784 with a value of 0 indicating no agreement and a value of 1 showing perfect agreement.

4.4.3.1.2 Irrigation requirement

The SAPWAT3 estimated gross irrigation requirements are shown in Table 4-4. Part of the calculation of irrigation water requirement is the inclusion of rainfall as part of the soil water balance equation. The calculation of rainfall use efficiency is the comparison of the rain water that can be stored in the soil because storage space is available when it rains, compared to total seasonal rain. Rainfall use efficiency is calculated as the percentage of rain water that can be stored in the soil. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 4-4 Gross irrigation requirements of wheat planted on 3 July 2003 at Kenilworth near Bloemfontein as estimated by SAPWT3

Verification repeat	Gross irrigation requirement (mm)						Rainfall use efficiency (%)
	Jul	Aug	Sep	Oct	Nov	Total	
Repeat 1: Lookup table values	42	70	145	126	0	384	27
Repeat 2	42	46	115	204	123	530	40
Repeat 3	42	45	105	205	118	515	38
Repeat 4	42	45	95	205	144	532	39

Differences between all repeats of estimated irrigation requirements is significant (Chi-squared test $p<0.01$) while there is no significant difference between repeats 2, 3 and 4 ($p=1.00$), therefore the tabulated values differ significantly from all updates.

4.4.3.2 Spring wheat: 2000 data

The wheat cultivar SST 825 was planted on 6 June 2000 for the water table experiment (Ehlers *et al*., 2003). Only data from the control treatment (no water table influence) were used.

4.4.3.2.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT3 table and the comparison of the observed data are shown in Figure 4-6. Figure 4-7 show the related RMSE analyses for repetition 1. The crop data were updated with recommended changes and six crop irrigation water requirement reruns were done and compared to the measured data until the situation shown in Figure 4-8 and Figure 4-9 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 4-8, Table 4-5 and Table 4-6).

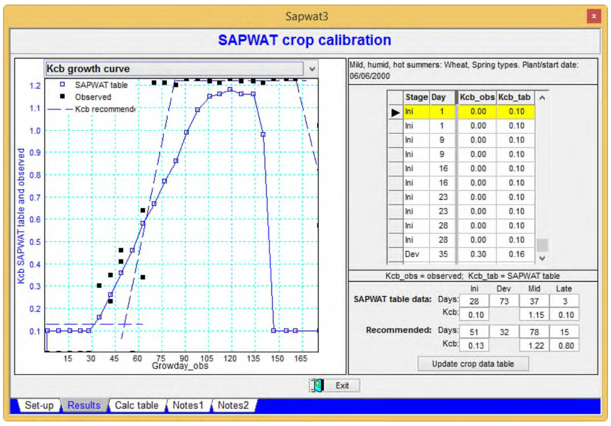


Figure 4-6 The SAPWAT3 table K_{cb} data curve, the observed data and the first repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

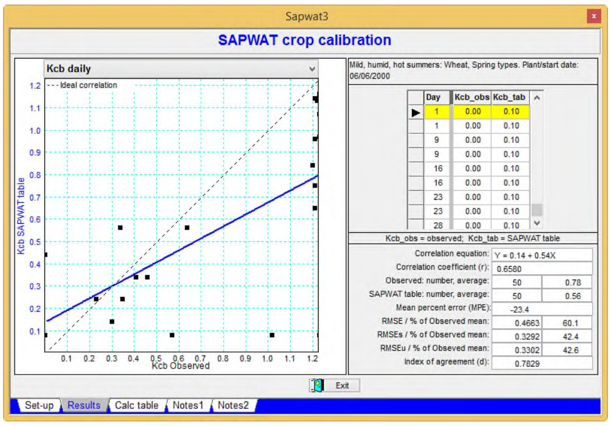


Figure 4-7 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

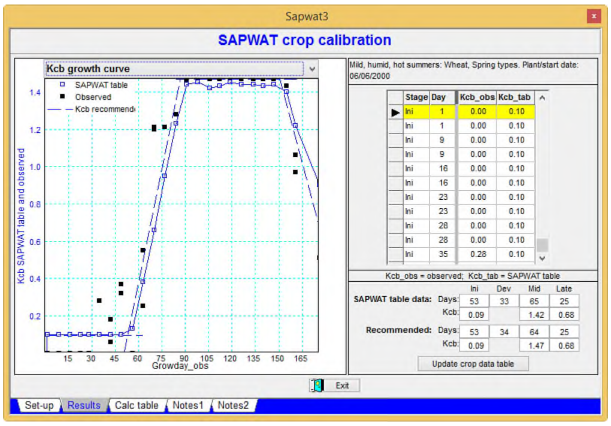


Figure 4-8 The SAPWAT3 table K_{cb} data curve, the observed data and the sixth repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

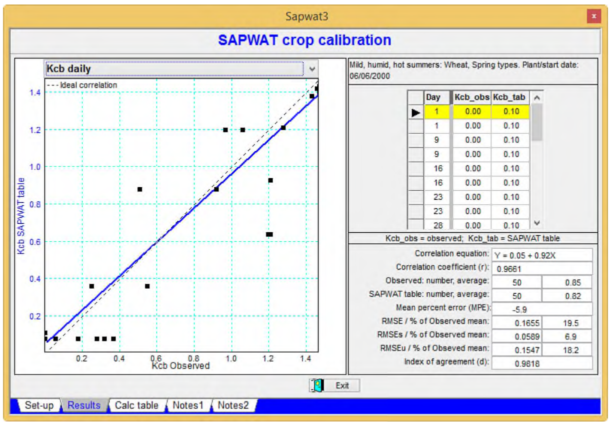


Figure 4-9 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the sixth repeat for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

Table 4-5 Changes in successive repeats of calibrating basal crop coefficients for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

Verification repeat	**Crop growth stages**						
	Initial		**Development**	**Mid-season**		**Late season**	
	Days	**$K_{cb\ ini}$**	**Days**	**Days**	**$K_{cb\ mid}$**	**Days**	**$K_{cb\ end}$**
Repeat 1: Lookup table values	28	0.1	73	37	1.15	3	0.1
Repeat 2	51	0.13	32	78	1.22	15	0.8
Repeat 3	51	0.10	33	69	1.27	23	0.70
Repeat 4	52	0.09	33	68	1.32	23	0.69
Repeat 5	52	0.09	33	66	1.37	25	0.69
Repeat 6	53	0.09	33	65	1.42	25	0.68
Recommended for repeat 7	53	0.09	34	64	1.47	25	0.68

Table 4-6 Statistical analyses of consecutive repeats of verification of the K_{cb} values of wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

Element		Repeat 1: Lookup table values	Repeat 2	Repeat 3	Repeat 4	Repeat 5	Repeat 6
Regression slope		0.54	0.86	0.89	0.90	0.91	0.92
r^2		0.6580	0.9491	0.9591	0.9613	0.9654	0.9661
Average of observed K_{cb}		0.78	0.77	0.79	0.81	0.83	0.85
MPE		-23.4	-4.2	-6.2	-6.2	-5.9	-5.9
RMSE	Value	0.4663	0.1765	0.1649	0.1665	0.1625	0.1655
	% of observed mean	60.1	22.9	20.9	20.6	19.6	19.5
RMSEs	Value	0.3292	0.0773	0.0689	0.0650	0.0620	0.0589
	% of observed mean	42.4	10.0	8.7	8.0	7.5	6.9
RMSEu	Value	0.3302	0.1587	0.1498	0.1532	0.1502	0.1547
	% of observed mean	42.6	20.6	19.0	18.9	18.1	18.2
d		0.7829	0.9718	0.9776	0.9788	0.9812	0.9818

Figure 4-7 and Figure 4-9 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeat. In the situation indicated in the figures, the slope of the correlation line has improved from an unacceptable 0.54 to an acceptable 0.92. The RMSE expressed as a percentage of the average of observed data improved from 60.1% (unacceptably high) to 19.5% (Table 4-6), well within the acceptance boundary of 30% (Willmott, 1981). The RMSEs is substantially smaller than the RMSEu at 6.9% compared to 18.2% which is an indicator that the model works as expected (Willmott, 1981). The index of agreement (d) has also improved from 0.7829 to 0.9812.

4.4.3.2.2 Irrigation requirement

The SAPWAT3 estimated gross irrigation requirements are shown in Table 4-7. The calculation of rainfall use efficiency is based on the rain water that can be stored in the soil because storage space is available when it rains, compared to total seasonal rain. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 4-7 Gross irrigation requirements of wheat planted on 6 June 2000 at Kenilworth near Bloemfontein as estimated by SAPWT3

Verification repeat	Gross irrigation requirement (mm)								Rainfall use efficiency (%)
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	
Repeat 1: Lookup table values	30	63	84	135	184	0	0	496	59
Repeat 2	31	57	90	147	224	171	0	719	61
Repeat 3	30	57	91	150	228	166	0	722	59
Repeat 4	30	57	90	155	233	169	0	733	60
Repeat 5	30	57	92	158	239	169	0	745	60
Repeat 6	30	56	91	162	245	171	0	754	62

Differences between all repeats of estimated irrigation requirements are significant (Chi-squared test $p<0.01$) while there is no significant difference between repeats 2, to 6 ($p=1.00$) , therefore the tabulated values differ significantly from all updates.

4.4.3.3 Spring wheat: Comparison of crop growth stages and crop coefficients

The crop growth periods estimated for spring wheat by SAPWAT3 and published in FAO 56 (Allen *et al.*, 1998) are compared in Table 4-8. Differences between all the rows are significant (Chi-squared p< 0.01), as are the differences between the SAPWAT3 estimated values (p=0.15). The big differences between the SAPWAT3 estimates could possibly be because two different cultivars were used, planting dates differed nearly a month and differences in weather between the two growing seasons. A further possible reason could be too few replications – only two different years with only two replications per year.

Table 4-8 Comparison of crop growth stage lengths for spring wheat between SAPWAT estimates and FAO 56 data

Source	**Initial growth stage (days**	**Development growth stage (days)**	**Mid-season growth stage (days)**	**Late season growth stage (days)**	**Total (days)**
SAPWAT3 (2003)	62	23	43	18	146
SAPWAT3 (2000)	53	33	65	25	176
East Africa (Allen *et al.*, 1998)	15	30	65	40	150
California, USA (Allen *et al.*, 1998)	20	50	60	30	160

The crop coefficients estimated for spring wheat by SAPWAT3 are compared to FAO 56 crop coefficients in Table 4-9 – FAO 56 includes only one set of K_{cb} values for spring wheat, regardless of where it is planted. Chi-squared tests indicate no significant differences between all row in the table, (p=0.99) as well as for the SAPWAT3 estimates (p=0.96).

Table 4-9 Comparison of crop coefficients for spring wheat between SAPWAT3 estimates and FAO 56 data

Source	**K_{cb}**		
	Initial	**Mid-season**	**Late season**
SAPWAT3 (salinity)	0.10	1.21	0.59
SAPWAT3 (water table)	0.09	1.42	0.68
FAO 56 (Allen *et al.*, 1998)	0.1	1.1	0.15

The SAPWAT3 mid-season K_{cb} values for the water table experiment are higher than expected. Farg *et al*. (2012) found K_c values that varied between 1.6126 and 1.8777 compared to the FAO values of 1.15 for wheat grown in the south Nile Delta in Egypt. This supports the high values found by SAPWAT3. Compared to this, Yang *et al*. (2008) reported K_c values for winter wheat ranging from 1.1 to 1.35 and 1.14 to 1.23 for two consecutive seasons for research done in China. On the other hand Howell *et al*. (2006) found K_c values of 0.9 for research done in Texas. The possibility of an island effect between the wheat planted in the lysimeter and the surrounding field that could have resulted in the higher than $K_{c\ max}$ values for the SAPWAT3 calculated data could not be excluded.

4.4.3.4 Peas: 2004

The pea cultivar Solara was planted on 20 July 2004 for the salinity experiment (Ehlers *et al.*, 2007). Only data from the control (non-saline) treatment were used.

4.4.3.4.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT3 table and the comparison of the observed data are shown in Figure 4-10. Figure 4-11 shows the related RMSE analyses for repetition 1. The crop data were updated with recommended changes; a crop irrigation water requirement rerun was done and again compared to the measured data. This process was repeated six times until the situation shown in Figure 4-12 and Figure 4-13 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 4-12, Table 4-10 and Table 4-11).

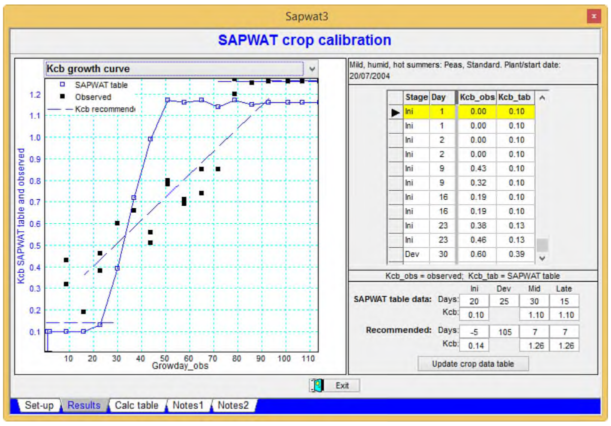


Figure 4-10 The SAPWAT3 table K_{cb} data curve, the observed data and the first repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

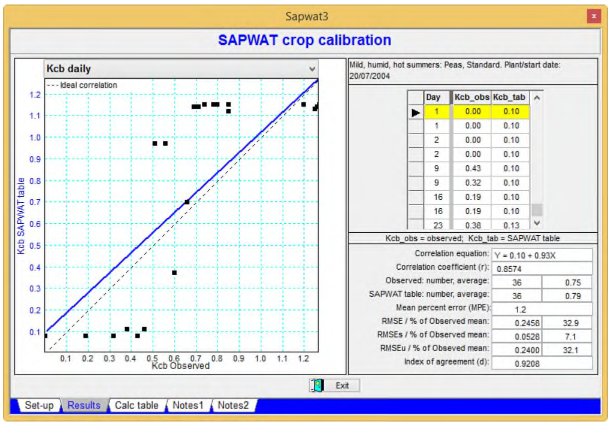


Figure 4-11 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

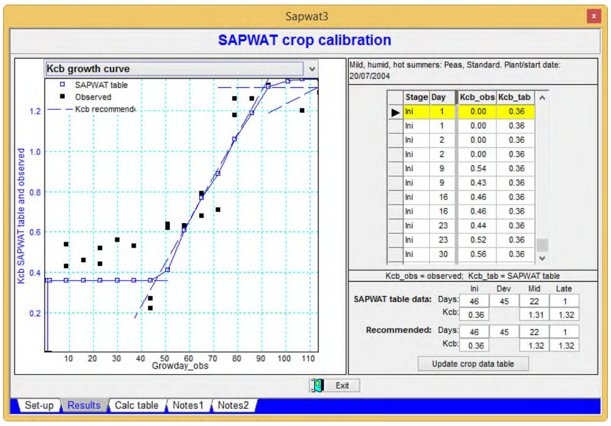


Figure 4-12 The SAPWAT3 table K_{cb} data curve, the observed data and the sixth repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

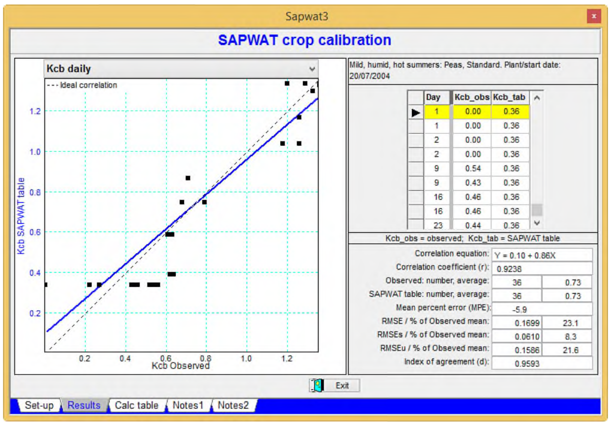


Figure 4-13 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the sixth repeat for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

Table 4-10 Changes in successive repeats of calibrating basal crop coefficients for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

Verification repeat	Crop growth stages						
	Initial		Development	Mid-season		Late season	
	Days	$K_{cb\ ini}$	Days	Days	$K_{cb\ mid}$	Days	$K_{cb\ end}$
Repeat 1: Lookup table values	20	0.10	25	30	1.10	15	1.10
Repeat 2	0	0.14	105	7	1.26	7	1.26
Repeat 3	40	0.37	51	17	1.26	7	1.30
Repeat 4	45	0.36	45	21	1.28	3	1.31
Repeat 5	46	0.36	44	22	1.30	2	1.31
Repeat 6	46	0.36	45	22	1.31	1	1.32
Recommended for repeat 7	46	0.36	45	22	1.32	1	1.32

Table 4-11 Statistical analyses of consecutive repeats of verification of the K_{cb} values of peas planted on 20 July 2004 at Kenilworth near Bloemfontein

Element		Repeat 1: Lookup table values	Repeat 2	Repeat 3	Repeat 4	Repeat 5	Repeat 6
Regression slope		0.93	0.86	0.83	0.85	0.85	0.86
r^2		0.8574	0.9787	0.9241	0.9249	0.9242	0.9238
Average of observed K_{cb}		0.75	0.75	0.73	0.73	0.73	0.73
MPE		1.2	2.5	-3.5	-5.5	-5.8	-5.9
RMSE	Value	0.2458	0.1478	0.1655	0.1665	0.1688	0.1699
	% of observed mean	32.9	19.8	22.6	22.8	23.0	23.1
RMSEs	Value	0.0528	0.0679	0.0732	0.0639	0.0610	0.0610
	% of observed mean	7.1	9.1	10.0	8.7	8.3	8.3
RMSEu	Value	0.2400	0.1313	0.1485	0.1537	0.1574	0.1586
	% of observed mean	32.1	17.6	20.3	21.0	21.4	21.6
d		0.9208	0.9648	0.9577	0.9595	0.9594	0.9593

Figure 4-11 and Figure 4-13 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeat. In the situation indicated in the figures, the slope of the correlation line has changed from 0.93 to 0.86, still well within the boundaries of acceptance of 0.7 to 1.3 defined by Willmott (1981). The RMSE expressed as a percentage of the average of observed data improved from 32.9% to an acceptable 23.1% (Table 4-11). The RMSEs is substantially smaller than the RMSEu at 8.3% compared to 21.6% which is an indicator that the model works as expected (Willmott, 1981). The index of agreement (d) has improved from 0.9208 to 0.9593. These results support the picture that emerged from Figure 4-10 and Figure 4-12 that the application of the SAPWAT3 verification module did improve the agreement between $K_{c\ tab}$ and $K_{cb\ obs}$. The apparent lower than observed Kcb value for the initial period in Figure 4-12 is the result of zero measured evapotranspiration before emergence and the relatively low values measured on day 42 which lowers the total average for that period.

4.4.3.4.2 Irrigation requirement

The SAPWAT3 estimated gross irrigation requirements are shown in Table 4-12. The calculation of rainfall use efficiency is based on the rain water that can be stored in the soil because storage space is available when it rains, compared to total seasonal rain. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 4-12 Gross irrigation requirements of peas planted on 20 July 2004 at Kenilworth near Bloemfontein as estimated by SAPWT3

Verification repeat	Gross irrigation requirement (mm)							Rainfall use efficiency (%)
	Jun	Jul	Aug	Sep	Oct	Nov	Total	
Repeat 1: Lookup table values	10	91	152	105	0	0	358	84
Repeat 2	11	93	127	186	123	0	540	83
Repeat 3	14	82	111	190	123	0	520	81
Repeat 4	14	81	103	191	124	0	513	81
Repeat 5	14	81	99	191	126	0	511	79
Repeat 6	14	81	99	191	126	0	511	79

Differences between all repeats of estimated irrigation requirements are significant (Chi-squared test $p<0.01$) while there are no significant difference between repeats 2, to 6 ($p=0.98$); therefore, the tabulated values differ significantly from all updates. Rainfall use efficiency did go down from 84% to 79%, which is still good if kept in mind that the aim of irrigation requirement planning is not necessarily to aim for 100% rainfall use efficiency, but but to plan for an efficient total water use.

4.4.3.5 Peas: 2001

The pea cultivar Solara was planted on 27 June 2001 for the water table experiment (Ehlers *et al*., 2003). Only the data from the non-water table control treatment were used.

4.4.3.5.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT3 table and the comparison with the observed data are shown in Figure 4-14. Figure 4-15 show the related RMSE analyses for repetition 1. The crop data were updated with recommended changes; a crop irrigation water requirement rerun was done and again compared to the measured data. This process was repeated seven times until the situation shown in Figure 4-16 and Figure 4-17 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 4-16, Table 4-13 and Table 4-14).

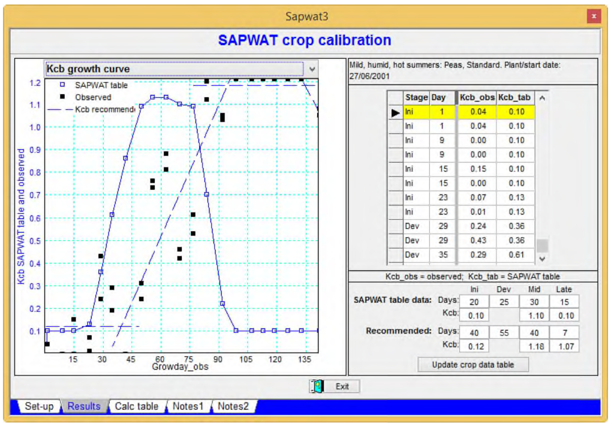


Figure 4-14 The SAPWAT3 table K_{cb} data curve, the observed data and the first repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

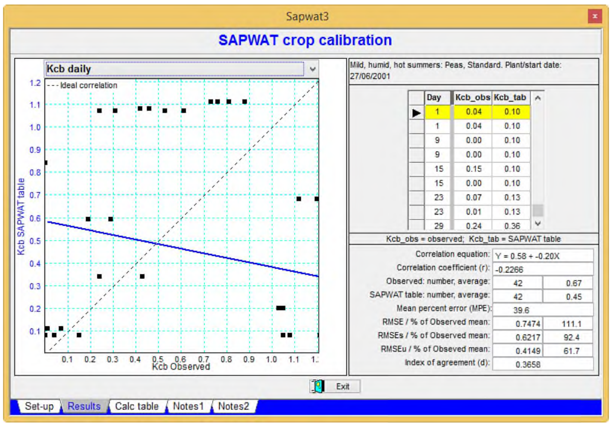


Figure 4-15 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

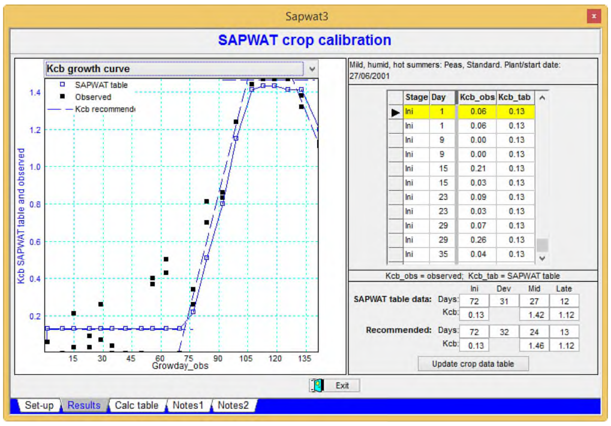


Figure 4-16 The SAPWAT3 table K_{cb} data curve, the observed data and the seventh repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

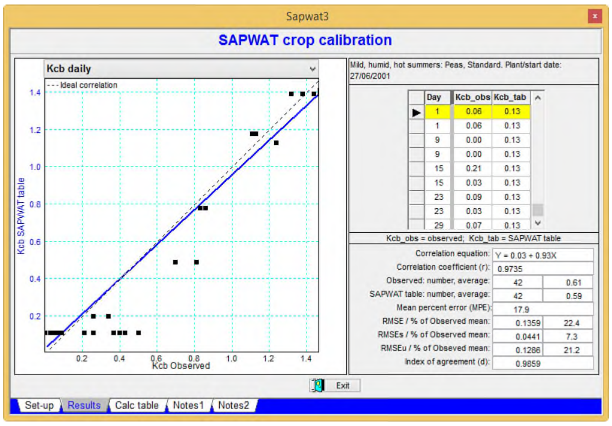


Figure 4-17 The comparison of adapted K_{cb} tab with lysimeter $K_{cb\ obs}$ data for the seventh repeat for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

Table 4-13 Changes in successive repeats of calibrating basal crop coefficients for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

Verification repeat	**Crop growth stages**						
	Initial		**Development**	**Mid-season**		**Late season**	
	Days	**$K_{cb\ ini}$**	**Days**	**Days**	**$K_{cb\ mid}$**	**Days**	**$K_{cb\ end}$**
Repeat 1: Lookup table values	20	0.1	25	30	1.10	15	0.1
Repeat 2	40	0.12	55	40	1.18	7	1.07
Repeat 3	47	0.06	55	31	1.23	9	1.12
Repeat 4	49	0.04	53	26	1.28	9	1.12
Repeat 5	70	0.12	31	33	1.32	9	1.12
Repeat 6	72	0.13	30	30	1.37	12	1.12
Repeat 7	72	0.13	31	27	1.42	12	1.12
Recommended for repeat 8	72	0.13	32	24	1.46	13	1.12

Table 4-14 Statistical analyses of consecutive repeats of verification of the K_{cb} values of peas planted on 27 June 2001 at Kenilworth near Bloemfontein

Element		**Repeat 1: Lookup table values**	**Repeat 2**	**Repeat 3**	**Repeat 4**	**Repeat 5**	**Repeat 6**	**Repeat 7**
Regression slope		-0.2	0.84	0.87	0.87	0.92	0.92	0.93
r^2		-0.2266	0.9578	0.9636	0.9653	0.9724	0.9725	0.9735
Average of observed K_{cb}		0.67	0.60	0.59	0.59	0.59	0.60	0.61
MPE		39.6	50.4	80.7	36.0	19.6	17.8	17.9
RMSE	Value	0.7474	0.1618	0.1488	0.1480	0.1338	0.1355	0.1355
	% of observed mean	111.1	26.8	25.3	25.1	22.7	22.7	22.4
RMSEs	Value	0.6217	0.0939	0.0720	0.0704	0.0491	0.0468	0.0441
	% of observed mean	92.4	15.8	12.3	11.9	8.3	7.8	7.3
RMSEu	Value	0.4149	0.1317	0.1302	0.1302	0.1244	0.1271	0.1286
	% of observed mean	61.7	21.8	22.1	22.1	21.1	21.3	21.2
d		0.3658	0.9724	0.9286	0.9798	0.9859	0.9852	0.9859

Figure 4-15 and Figure 4-17 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeat. In the situation indicated in the figures, the slope of the correlation line has improved from -0.2 to 0.93, which is well within the acceptance range of 0.7 to 1.3 (Willmott, 1981). The RMSE expressed as a percentage of the average of observed data improved from 111.1% to 22.4% (Table 4-14). The RMSEs is substantially smaller than the RMSEu at 7.3% compared to 21.2% which is an indicator that the model works as expected (Willmott, 1981). The index of agreement (d) has also improved from 0.3658 to 0.9859.

4.4.3.5.2 Irrigation requirement

The SAPWAT3 estimated gross irrigation requirements are shown in Table 4-15. The calculation of rainfall use efficiency is based on rain water that can be stored in the soil because storage space is available when it rains, compared to total seasonal rain. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 4-15 Gross irrigation requirements of peas planted on 27 June 2001 at Kenilworth near Bloemfontein as estimated by SAPWT3

Verification repeat	Gross irrigation requirement (mm)							Rainfall use efficiency (%)
	Jun	Jul	Aug	Sep	Oct	Nov	Total	
Repeat 1: Lookup table values	0	57	90	64	0	0	288	54
Repeat 2	0	53	50	81	176	69	599	59
Repeat 3	0	54	45	75	178	70	422	58
Repeat 4	0	54	43	72	180	72	421	58
Repeat 5	0	53	40	61	186	73	413	57
Repeat 6	0	53	41	60	191	74	419	57
Repeat 7	0	53	41	60	194	75	423	56

Differences between all repeats of estimated irrigation requirements are significant (Chi-squared test p<0.01) while there is no significant difference between repeats 2, to 7 (p=0.98); therefore, the tabulated values differ significantly from all updates.

4.4.3.6 Peas: Comparison of crop growth stages and crop coefficients

The crop growth periods estimated for peas by SAPWAT3 and published in FAO 56 (Allen *et al*., 1998) are compared in Table 4-16. Differences between all the rows are significant (Chi-squared p< 0.01). The differences between the FAO 56 values are also significant (p=0.17), as are the SAPWAT3 estimated values for (p<0.01). The big differences between the SAPWAT3 estimates are unexpected and no specific reason for that could be identified. A possible reason could be too few replications – only two different years with only two replications per year.

Table 4-16 Comparison of crop growth stage lengths for peas between SAPWAT estimates and FAO 56 data

Source	Initial growth stage (days	Development growth stage (days)	Mid-season growth stage (days)	Late season growth stage (days)	Total (days)
SAPWAT3 (2002)	46	45	22	1	114
SAPWAT3 (2001)	72	32	24	13	141
Europe (Allen *et al*., 1998)	15	25	35	15	90
Mediterranean (Allen *et al*., 1998)	20	30	35	15	100
Idaho, USA (Allen *et al*., 1998)	35	25	30	20	110

The crop coefficients estimated for peas by SAPWAT3 are compared to FAO 56 crop coefficients in Table 4-17. Chi-squared tests indicate no significant differences between all rows in the table, (p=0.99) as well as for the FAO 56 data (p=1.0) nor for the SAPWAT3 estimates (p=0.95): this, in spite of an obviously higher values for mid-season K_{cb} for the SAPWAT3 calculated values.

Table 4-17 Comparison of crop coefficients for peas between SAPWAT3 estimates and FAO 56 data

Source	K_{cb}		
	Initial	**Mid-season**	**Late season**
SAPWAT3 (salinity)	0.36	1.32	1.32
SAPWAT3 (water table)	0.13	1.46	1.12
Europe (Allen *et al.*, 1998)	0.5	1.15	1.1
Mediterranean (Allen *et al.*, 1998)	0.5	1.15	1.1
Idaho, USA (Allen *et al.*, 1998)	0.5	1.15	1.1

4.4.3.7 Maize: 2004

The maize cultivar PAN 6335 was planted on 17 December 2004 for the salinity experiment (Ehlers *et al*., 2007). Only the data from the non-saline control treatment were used.

4.4.3.7.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT3 table and the comparative result of the observed data are shown in Figure 4-18. Figure 4-19 shows the related RMSE analyses for repetition 1. The crop data were updated with recommended changes and crop irrigation water requirement reruns were done until the situation shown in Figure 4-20 and Figure 4-21was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 4-21, Table 4-18 and Table 4-19).

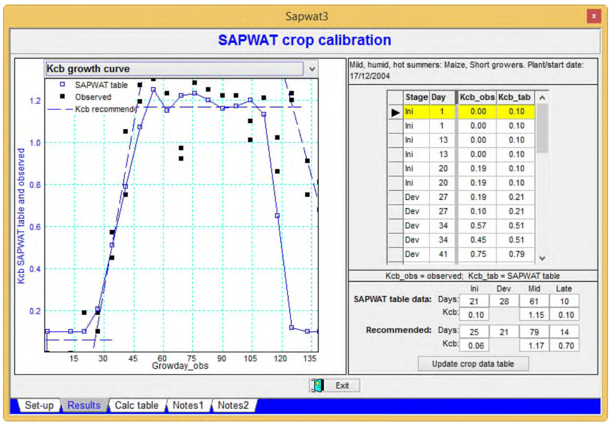


Figure 4-18 The SAPWAT3 table Kcb data curve, the observed data and the first repeat recommended Kcb growth curve based on observed data of lysimeter measured ETc data for maize planted on 17 December 2004 at Kenilworth near Bloemfontein

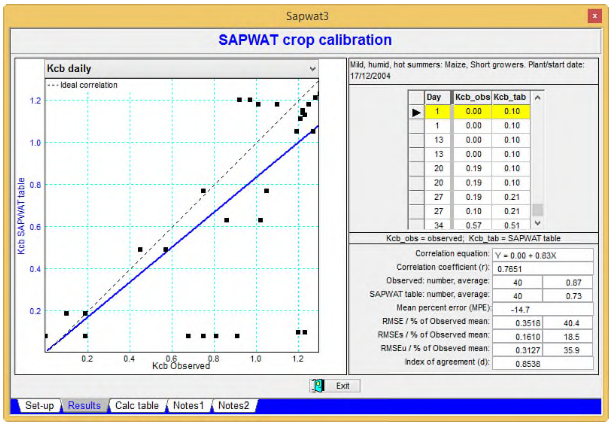


Figure 4-19 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for maize planted on 17 December 2004 at Kenilworth near Bloemfontein

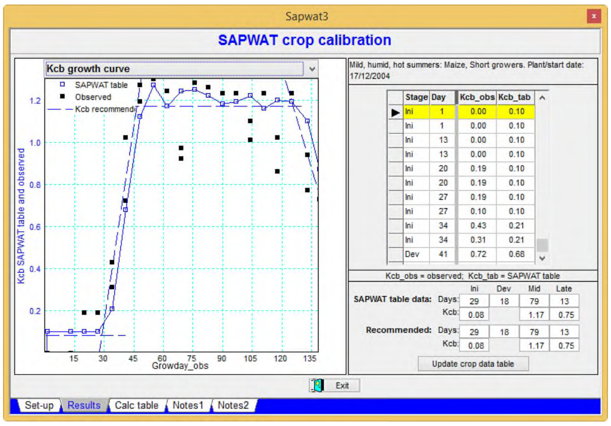


Figure 4-20 The SAPWAT3 table K_{cb} data curve, the observed data and the fifth repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for maize planted 17 on December 2004 at Kenilworth near Bloemfontein

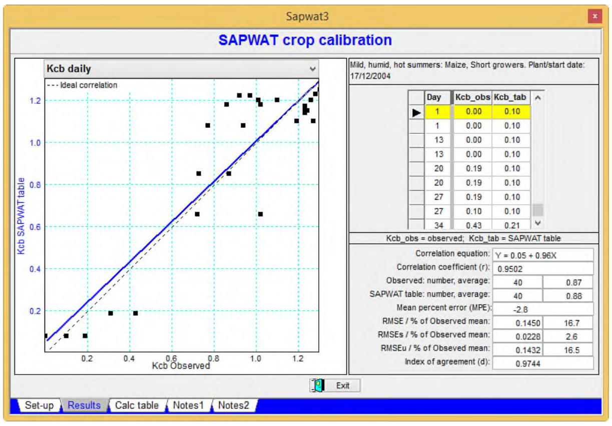


Figure 4-21 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the fifth repeat for maize planted on 17 December 2004 at Kenilworth near Bloemfontein

Table 4-18 Changes in successive repeats of calibrating basal crop coefficients for maize planted on 17 on December 2004 at Kenilworth near Bloemfontein

Verification repeat	Crop growth stages						
	Initial		Development	Mid-season		Late season	
	Days	$K_{cb\ ini}$	Days	Days	$K_{cb\ mid}$	Days	$K_{cb\ end}$
Repeat 1: Lookup table values	21	0.11	28	41	1.15	10	0.10
Repeat 2	25	0.06	21	79	1.17	14	0.70
Repeat 3	26	0.06	21	79	1.17	13	0.75
Repeat 4	28	0.08	19	79	1.17	13	0.75
Repeat 5	29	0.08	18	79	1.17	13	0.75
Recommended for repeat 6	25	0.12	27	54	1.57	33	0.74

Table 4-19 Statistical analyses of consecutive repeats of verification of the K_{cb} values of maize planted on 17 on December 2004 at Kenilworth near Bloemfontein

Element		Repeat 1: Lookup table values	Repeat 2	Repeat 3	Repeat 4	Repeat 5
Regression slope		0.83	0.95	0.95	0.96	0.96
r^2		0.7651	0.9586	0.9538	0.9514	0.9502
Average of observed K_{cb}		0.87	0.88	0.87	0.87	0.87
MPE		-14.7	-0.8	-1.3	-2.3	-2.8
RMSE	Value	0.3581	0.1307	0.1386	0.1427	0.1450
	% of observed mean	40.4	14.9	15.9	16.4	16.7
RMSEs	Value	0.1610	0.0310	0.0304	0.0253	0.0228
	% of observed mean	18.5	3.5	3.5	2.9	2.6
RMSEu	Value	0.3127	0.1269	0.1353	0.1404	0.1432
	% of observed mean	35.9	14.5	15.5	16.1	16.5
d		0.8538	0.9784	0.9760	0.9750	0.9744

Figure 4-19 and Figure 4-21 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeat. In the situation indicated in the figures, the slope of the correlation line has improved from 0.83 to 0.96. The RMSE expressed as a percentage of the average of observed data improved from 40.4% to 16.7% (Table 4-19). The RMSEs is substantially smaller than the RMSEu at 2.6% compared to 16.5% which is an indicator that the model works as expected (Willmott, 1981). The index of agreement (d) has also improved from 0.8538 to 0.9744.

4.4.3.7.2 Irrigation requirement

The SAPWAT3 estimated gross irrigation requirements are shown in Table 4-20. The calculation of rainfall use efficiency is based on the rain water that can be stored in the soil because storage space is available when it rains, compared to total seasonal rain. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 4-20 Gross irrigation requirements of maize planted on 17 on December 2004 at Kenilworth near Bloemfontein as estimated by SAPWT3

Verification repeat	**Gross irrigation requirement (mm)**							**Rainfall use efficiency (%)**
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total**	
Repeat 1: Lookup table values	34	87	164	188	29	0	502	78
Repeat 2	34	86	169	193	86	0	568	77
Repeat 3	34	82	167	193	86	0	562	78
Repeat 4	34	79	167	193	86	0	559	77
Repeat 5	34	77	167	193	86	0	557	77

Differences between all repeats of estimated irrigation requirements is significant (Chi-squared test $p<0.01$) while there is no significant difference between repeats 2, to 5 ($p=1.00$) , therefore the tabulated values differ significantly from all updates.

4.4.3.8 Maize: 2000

The maize cultivar PAN 6335 was planted on 6 December 2000 for the water table experiment (Ehlers *et al*., 2003). Only the data from the non-water table control treatment were used.

4.4.3.8.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT3 table and the comparison of the observed data are shown in Figure 4-22. Figure 4-23 show the related RMSE analyses for repetition 1. The crop data were updated with recommended changes; a crop irrigation water requirement rerun was done and again compared to the measured data. This process was repeated seven times until the situation shown in Figure 4-24 and Figure 4-25 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 4-24, Table 4-21 and Table 4-22).

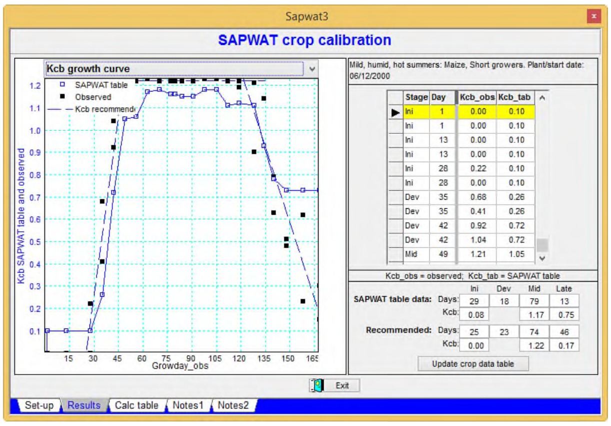


Figure 4-22 The SAPWAT3 table K_{cb} data curve, the observed data and the first repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

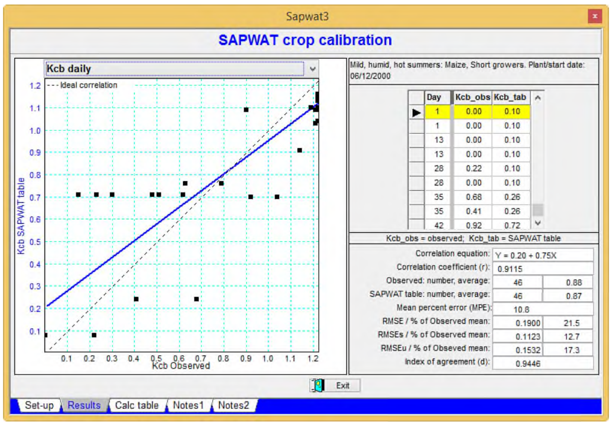


Figure 4-23 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

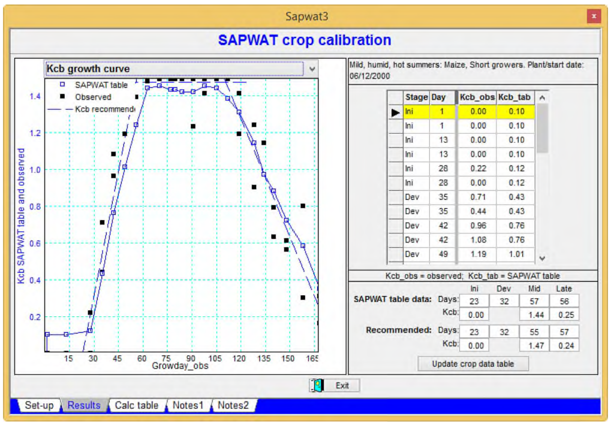


Figure 4-24 The SAPWAT3 table K_{cb} data curve, the observed data and the fourth repeat recommended K_{cb} growth curve based on observed data of lysimeter measured ET_c data for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

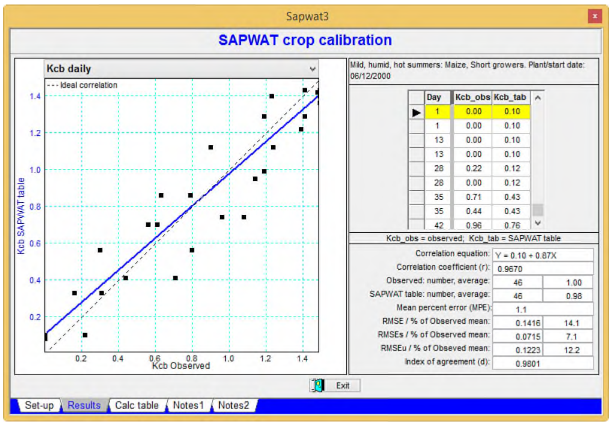


Figure 4-25 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the fourth repeat for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

Table 4-21 Changes in successive repeats of calibrating basal crop coefficients for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

Verification repeat	**Crop growth stages**						
	Initial		**Development**	**Mid-season**		**Late season**	
	Days	**$K_{cb\ ini}$**	**Days**	**Days**	**$K_{cb\ mid}$**	**Days**	**$K_{cb\ end}$**
Repeat 1: Lookup table values	29	0.08	18	79	1.17	13	0.75
Repeat 2	25	0	23	74	1.22	46	0.17
Repeat 3	22	0	30	67	1.27	49	0.26
Repeat 4	22	0	31	61	1.33	51	0.25
Repeat 5	22	0	32	61	1.36	53	0.25
Repeat 6	22	0	32	59	1.40	55	0.25
Repeat 7	23	0	32	57	1.44	56	0.24
Recommended for repeat 8	23	0	32	55	1.47	57	0.24

Table 4-22 Statistical analyses of consecutive repeats of verification of the K_{cb} values of maize planted on 6 December 2000 at Kenilworth near Bloemfontein

Element		Repeat 1: Lookup table values	Repeat 2	Repeat 3	Repeat 4	Repeat 5	Repeat 6	Repeat 7
Regression slope		0.75	0.86	0.84	0.85	0.86	0.87	0.87
r^2		0.9115	0.9652	0.9616	0.9643	0.9650	0.9677	0.9670
Average of observed K_{cb}		0.88	0.92	0.94	0.96	0.98	0.99	1.00
MPE		10.8	-3.3	-0.2	-0.3	-0.1	0.4	1.1
RMSE	Value	0.1900	0.1325	0.1408	0.1398	0.1412	0.1388	0.1416
	% of observed mean	21.5	14.4	15.0	14.6	14.5	14.0	14.1
RMSEs	Value	0.1123	0.0783	0.0833	0.0797	0.0781	0.0753	0.0715
	% of observed mean	12.7	8.5	8.9	8.3	8.0	7.6	7.1
RMSEu	Value	0.1532	0.1069	-.1135	0.1149	0.1176	0.1167	0.1223
	% of observed mean	17.3	11.6	12.1	12.0	12.0	11.8	12.2
d		0.9446	0.9764	0.9744	0.9678	0.9778	0.9797	0.9801

Figure 4-23 and Figure 4-25 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeat. In the situation indicated in the figures, the slope of the correlation line has improved from 0.75 to 0.87. The RMSE expressed as a percentage of the average of observed data improved from 21.5% to 14.1% (Table 4-22), well within the acceptance boundary of 30% (Willmott, 1981). The RMSEs is substantially smaller than the RMSEu at 7.1% compared to 12.2% which is an indicator that the model works as expected (Willmott, 1981). The index of agreement (d) has also improved from 0.9446 to 0.9801.

4.4.3.8.2 Irrigation requirement

The SAPWAT3 estimated gross irrigation requirements are shown in Table 4-23. The calculation of rainfall use efficiency is based on the rain water that can be stored in the soil because storage space is available when it rains, compared to total seasonal rain. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 4-23 Gross irrigation requirements of maize planted on 6 December 2000 at Kenilworth near Bloemfontein as estimated by SAPWT3

Verification repeat	Gross irrigation requirement (mm)							Rainfall use efficiency (%)
	Dec	Jan	Feb	Mar	Apr	May	Total	
Repeat 1: Lookup table values	31	170	159	161	27	0	548	61
Repeat 2	31	179	165	168	30	22	595	61
Repeat 3	31	181	169	174	32	26	613	63
Repeat 4	31	183	174	178	33	26	625	63
Repeat 5	31	184	180	184	33	26	638	63
Repeat 6	31	188	185	189	34	26	643	63
Repeat 7	31	185	186	192	34	26	656	64

Differences between all repeats of estimated irrigation requirements are significant (Chi-squared test p<0.73) while there is no significant difference between repeats 2, to 7 (p=1.00) , therefore the tabulated values differ significantly from all updates.

4.4.3.9 Maize: Comparison of crop growth stages and crop coefficients

The crop growth periods estimated for maize by SAPWAT3 and published in FAO 56 (Allen *et al*., 1998) are compared in Table 4-24. Differences between all the rows are significant (Chi-squared p< 0.01). The differences between the FAO 56 values are insignificant (p=0.98), and the difference between the SAPWAT3 rows are significant (p<0.01). A possible reason for the difference found in the SAPWAT3 estimates could be too few data sets – only two different years with only two repeats per year.

Table 4-24 Comparison of crop growth stage lengths for maize between SAPWAT estimates and FAO 56 data

Source	Initial growth stage (days	Development growth stage (days)	Mid-season growth stage (days)	Late season growth stage (days)	Total (days)
SAPWAT3 (2004)	25	18	79	13	135
SAPWAT3 (2000)	23	32	57	56	168
East Africa (Allen *et al*., 1998)	30	50	60	40	180
Arid climate (Allen *et al*., 1998)	25	40	45	30	140
Nigeria (humid) (Allen *et al*., 1998)	20	35	40	30	125
India (dry, cool) (Allen *et al*., 1998)	20	35	40	30	125
Spain (spring) (Allen *et al*., 1998)	30	40	50	30	150
Idaho, USA (Allen *et al*., 1998)	30	40	50	50	170

The crop coefficients estimated for maize by SAPWAT3 are compared to FAO 56 crop coefficients in Table 4-25. Chi-squared tests indicate no significant differences between all row in the table, (p=0.98). Differences between rows are significant for the SAPWAT3 estimates (p=0.81).

Table 4-25 Comparison of crop coefficients for maize between SAPWAT3 estimates and FAO 56 data

Source	K_{cb}		
	Initial	Mid-season	Late season
SAPWAT3 (salinity)	0.18	1.17	0.75
SAPWAT3 (water table)	0	1.44	0.24
Field FAO (Allen *et al*., 1998)	0.15	1.15	0.5

4.5 Conclusions

A problem encountered with models such as SAPWAT3 is that the crop coefficients do not necessarily indicate growing periods that agree with local crop growth and development. Added to this is the problem that such models do not have an easy to use module that could be used to verify and update the coefficient data (CROPWAT (Smith, 1992); SWB (Annandale *et al*., 1999); SAPWAT3 version 1.0 (Van Heerden *et al*., 2008) and AquaCrop (Raes *et al*., 2009). Aggravating the problem of potentially incorrect crop coefficients is the fact that the FAO 56 crop coefficients for use with the Penman-Monteith equation were determined for non-stressed, well-managed crops grown in sub-humid climates (Allen *et al*., 1998). Therefore, applying the Penman-Monteith equation to crops using such crop coefficients in different climates does not necessarily give the correct estimates of ET_0. Allen *et al*. (1998) has described a methodology for constructing the FAO four-stage crop growth curve from tabulated data and it was decided to include a module in SAPWAT3 that is based on that methodology and that could be used to verify and update crop coefficient values by using measured crop water use data. The objectives for attaining this goal were defined at the beginning of the chapter as: describing the theoretical background; describing the application of the theoretical background in the verification module; and, evaluating the K_{cb} and ET_c verification outputs.

The methodologies described by Allen *et al.* (1998) for the construction of the FAO four-stage crop growth curve and that of Willmott (1981) for testing goodness of fit between observed and model predicted values have been combined in the SAPWAT3 module for evaluating and improving crop growth characteristics. The results are displayed graphically and statistical test (RMSE) results are also shown on screen. The RMSE test serves the purpose of being both able to give direction to necessary changes and sets boundaries within which results are considered to be acceptable.

The module was tested with results of two non-consecutive years of lysimeter experiments done at the Kenilworth Experimental farm of the University of the Free State near Bloemfontein. The results show that this module worked for crops tested. However, it was found that the mid-season K_{cb} values are higher in all cases than expected. Higher than published FAO 56 data and reasons for this phenomenon are described by Allen *et al*. (1998). Furthermore, higher than expected mid-season K_c and K_{cb} values have also been reported by a number of authors (Abyaneh *et al*., 2011; Farg *et al*., 2012; Lazarra and Rana, 2012;

Rohitashw *et al*., 2011; Yang *et al*., 2008). Other factors that could influence the value of observed lysimeter based K_{cb} values are the possibility of an island effect, the lysimeter planted crop standing in a field of a different crop, or surrounded by a water-stressed crop, or the effect that an enclosed rooting volume in the lysimeter pot could have on crop water use (Perkins, 1996). In addition to this island effect which could lead to overestimations, there is also an energy constraint which places an upper limit on crop transpiration (Allen, *et al.*, 1998; Allen, *et al.*, 2011). Another possibility is that measurements are not taken at the exact intervals as reported; a supposed interval of seven days could become eight days if a measurement day is deferred for some reason and if not reported as such and thus influence the result of the calculation of daily evapotranspiration. Some differences in the growing period of the different stage of the same crop was also noticed, differences that could be the result of differences in planting dates.

An acceptable slope for the regression line between observed and theoretical values is between 0.7 and 1.3 (Willmott, 1981). In all cases the slope of the regression line improved: from 0.3 to 0.97 and from 0.54 to 0.92 for maize; from 0.93 to 0.86 and from -0.2 to 0.93 for peas; from 0.83 to 0.96 and from 0.75 to 0.87 for spring wheat. RMSE, expressed as a percentage of observed data must be less than 30% (Willmott, 1981). RMSE results improved from 82% to 23.6% and from 60.1% to 19.5% for maize; from 32.9% to 23.1% and from 111.1% to 22.4% for peas; from 40.4% to 16.7% and from 21.5% to 14.1% for spring wheat. Apart from these results, the fit of the recalculated K_{cb} curve was also evaluated visually as recommended by Willmott (1981). In all cases a good fit was observed (Figure 4-4, Figure 4-8, Figure 4-12, Figure 4-16, Figure 4-20, Figure 4-24).

In all cases the change in growth periods and K_{cb} values was noticeable. However from the second round of improvement change became relatively small, a chi-squared test between results of successive rounds confirmed this observed trend. The estimated irrigation requirement for each round also confirmed this trend, where total irrigation requirement changed very little after the second round of improvement. An unanswered question at present is “when should the successive rounds of improvement stop”; this should be further tested so that a program message can be displayed on screen advising the user that further testing for improvement will make no significant difference. Present thought is that once chi-squared tests of successive round for both the crop coefficients and for estimated irrigation requirements show no significant difference (P>0.95), further efforts at upgrading should stop.

In all cases tested the water table experiment resulted in mid-season K_{cb} values that were higher than those of the salinity experiments, and the values were also higher than $K_{c\ max}$ for the area. It seems that the water table contributed to an island effect in the lysimeter tested data that increased its water use to above expected values. This module needs the inclusion of an upper limit related to the $K_{c\ max}$ value that should not be exceeded, and if so, then the $K_{c\ max}$ value should replace the observed value.

SAPWAT3 is used to verify the application of water quantities by farmers for licensing and verification of water rights. As this is the implementation of a regulation based on the National Water Act of 1998, it is the users of SAPWAT3's responsibility to make sure that the estimation of irrigation water requirements is as accurate as possible. The methodology described here, if applied, will ensure that a more correct irrigation water quantity is estimated, and will result in a higher level of credibility being ascribed to the results of SAPWAT3. It should also decrease the potential conflict between farmers and the Department of Water and Sanitation on the matter of the correctness of the allocated water use right.

Acknowledgement:

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CHAPTER 5.
ADOPTION POTENTIAL OF SAPWAT3

5.1 Introduction

South Africa, with its large areas of low rainfall (Frenken, 2005), and its dependency on irrigation for agricultural production (SouthAfrica.info, 2012), need to manage irrigation water well (Alois, 2007). The management of irrigation water stands on two broadly defined legs: the one is the day-to-day water management; the other is the planning of irrigation water use. The main concern with irrigation water use planning is to answer the question of how much and when water will be required at a certain point for on-farm planning (Reinders, 2010). On a larger scale the planning of irrigation water requirements forms part of the planning of water use in drainage regions and in the country as a whole, where irrigation uses 62% of the total water resources of South Africa (Department of Water Affairs and Forestry, 2012). The planning of future water use by irrigation and the proportion of the total water resources that it will have, depends on how good the planning of irrigation water requirement for the future is.

Several tools for the estimation of irrigation water have been developed over time. Presently, the Penman-Monteith approach is the one that is internationally accepted (Allen *et al*., 1998). Computer models that use this approach include SAPWAT (Crosby and Crosby, 1999), which has been widely accepted by the South African irrigation industry (Van Heerden *et al*., 2008).

5.2 Literature overview

The need for approaches and tools to estimate irrigation requirements has for long been recognised exist. From the early days of irrigation development in South Africa it was realised that limited water required such planning to be done to enable government and private organisations to develop viable irrigation schemes with objectives such as food and fibre production, farmer development, settlement of poor whites during and after the great depression of the 1930s and the settlement of soldiers after the second world war which lasted from 1939 to 1945 (Department of Water Affairs, 1986; Van Heerden and De Kock,1980; Van Vuuren, 2011). Tools and approaches include the use of the A-pan evaporation data and crop factors (Green, 1985) and computer models such as CROPWAT (Smith, 1992) and SAPWAT (Crosby and Crosby, 1999). Such tools and approaches would not be of much use if potential users did not know about it and how to use it; therefore communication about its existence, capabilities and application potential is important (Rogers, 2003).

5.3 Overview of the directed communication strategy regarding the introduction and use of SAPWAT

A good communication strategy plays an important role in the spread of knowledge about innovations. The communicator of an innovation fulfils the role of a change agent and should plan a communication strategy around the promotion of the adoption of an innovation (Rogers, 2003). In the case of innovations for a specialised market, such as CROPWAT and SAPWAT, or older approaches, such as the use of an evaporation pan, user manuals or their equivalent were printed and distributed as hard copies (Crosby and Crosby, 1999; Green, 1985; Smith, 1992) and/or as electronic copies such as found on the FAO publications web site (http://www.fao.org/publications/en). Knowledge about the existence of such specialised publications needs to be spread (Rogers, 2003), this is usually done by electronic means, for example, as information on web sites of the FAO (http://www.fao.org/publications/en) or the Water Research Commission (http://www.wrc.org.za/) and in publications such as the Water Wheel magazine of the Water Research Commission. Knowledge dissemination such as in these examples, is also dependant on the communication behaviour of the potential user, i.e. would the potential user actively look for information (Rogers 2003). In the case of the cited examples the assumption is that the potential user, being a specialist in his field, would actively look for information, which would also include seeking contact with someone who knows the subject matter (Krikelas, 1983; Rogers, 2003). The developer of an innovation also need to plan and execute a communication strategy in which knowledge about the innovation is actively spread through publications in general and specialised magazines, presentations at group meetings and talks to individuals (Lee and O'Connor, 2003; Rogers 2003).

After the publication of SAPWAT in 1999, a directed communication strategy was launched with the aim of introducing it to the irrigation fraternity (Crosby and Crosby, 1999). During the period 1999 to 2002 the strategy consisted of:

- Building a web site to explain the working of SAPWAT and giving the address where it could be obtained;
- Discussions by the senior author (C.T. Crosby) with the then Department of Water Affairs and Forestry on the use of SAPWAT as reference for their irrigation water use registration and licencing – the Department agreed that this would in future be included in the policy;
- Discussions by the senior author with the Department of Agriculture and with the Agricultural Research Council - Institute of Agricultural Engineering on the application of SAPWAT for improvement of the planning of irrigation water requirements and for improved irrigation system design;
- Discussions by the senior author with the then Pretoria University of Technology concerning the inclusion of training in the use of SAPWAT in its syllabus for the higher diploma in irrigation system design;
- Demonstration of the use of SAPWAT at SABI (South African Irrigation Institute) conferences and branch meetings;
- Presentation of courses on its use for irrigation system designers, irrigation water use researchers, planners, managers and advisors in Gauteng (Pretoria), Western Cape (Elsenburg), Northern Cape (Upington) and Free State (Glen) – some irrigation farmers were sent invitations, but none attended these courses;
- Demonstration of the application of SAPWAT in the Orange-Vaal and Orange-Riet Water Users Association areas at Douglas and Jacobsdal (Van Heerden *et al*., 2001);
- Publication of an article on SAPWAT in the Water Wheel (Vol 3 No 1; January, 2004), a magazine of the Water Research Commission (WRC) in which articles related to WRC-funded water research is published (http://www.wrc.org.za/Pages/KH_WaterWheel.aspx?dt=12&ms=55%3B&start=61);
- Ongoing availability of the SAPWAT team to SAPWAT users for e-mail, telephonic and personal assistance in the use of SAPWAT.

The target audience at that stage was specialised, relatively small and relatively homogenous in that all members had an interest in irrigation water use planning, design of irrigation systems and irrigation water reticulation systems and management of irrigation water. Added to this was the need of an easy to use and reliable irrigation water requirement planning tool - SAPWAT. The shortcomings in CROPWAT (Smith, 1992) resulted in it not being used in

South Africa as a general planning tool and the reliance on historical irrigation requirement data and experiential knowledge was also not satisfactory for such a purpose.

5.4 Research question

SAPWAT was formally launched in 1999 with the publication of the relevant Water Research Commission report on it as well as the making available of the program through downloading (Crosby and Crosby, 1999). Users were requested to voluntarily register for downloading, but there was no copyright on the program that limited use or further redistribution, with the result that more people than those on the registration list might have used it. By 2008, nine years after its launch, 226 users were registered and informal feedback was that SAPWAT largely satisfied their needs and that its use seemed to be popular amongst the irrigation system designers and water use planners.

The main question is: what made SAPWAT popular and why, a question that can be elucidated by the following:

- who uses SAPWAT;
- what do they use it for;
- what is the frequency of use;
- why did it spread fairly quickly through a specialised user group;
- how did they perceive SAPWAT's usefulness; and,
- what is their perception of SAPWAT's ease of use.

5.5 Objective

The overall objective of this study is to evaluate the reason for adoption of SAPWAT by active users and the potential for adoption of SAPWAT3 by prospective users. This objective can be subdivided as follows:

- To determine who uses SAPWAT;
- To determine what do they use it for;
- To determine its frequency of use;
- To determine what characteristics of SAPWAT influenced its adoption;
- To determine the users' perception of its ease of use;

- To determine the users' perception of its usefulness.

5.6 Research methodology

SAPWAT users were identified through a user registration list which was updated with the help of regional South African Irrigation Institute (SABI) branches. These users were invited to attend training meetings in various localities between March and December 2010 where SAPWAT3 (a new version of SAPWAT) was introduced. The venues were selected for their proximity to concentrations of SAPWAT users in each of the nine provinces. 72 users attended these meetings as it turned out that quite a number of SAPWAT users had left the irrigation industry since the introduction of the program.

Data pertaining to the meeting of above-mentioned objectives were collected through the use of structured questionnaires that were distributed and explained at the training meetings (see Appendix A). The participants were asked to complete the questionnaires which included questions on their perceptions of important variables in SAPWAT as identified by the research team that could influence its acceptability. Perceptions were tested by using a 5-point Likert-type scale:

	Degree of negative perception or disagreement		**No perception differentiation or not applicable**	**Degree of positive perception or agreement**	
For questions that test attitude	Strong negative	Weak negative	Neutral	Weak positive	Strong positive
For questions that test agreement	Disagree fully	Disagree partially	Neutral	Agree partially	Agree fully
Five-point scale Values	1	2	3	4	5

To ensure reliability of the data, respondents were asked not to discuss the questionnaire amongst themselves during the time required for filling in the questionnaire.

5.7 Results and discussion

The attitude and motivation towards the adoption of new technology like SAPWAT3 is important for research and development. Factors like qualification, prior experience in adopting technology, compatibility with existing technology and enhanced value are important factors that will be discussed. In this study the Diffusion of Innovations (Rogers

2003) and Technology Acceptance Model (Davis, 1989) were used in parallel to analyse the perceptions of the target group.

5.7.1 Profile of respondents

Respondents originated from all nine provinces of South Africa. None of the respondents had more than 11 years of experience in the use of SAPWAT (SAPWAT was published in 1999), while 58% of them had less than 6 years' experience. 66% of the respondents have the equivalent of a B. Tech or higher qualification (Figure 5-1).

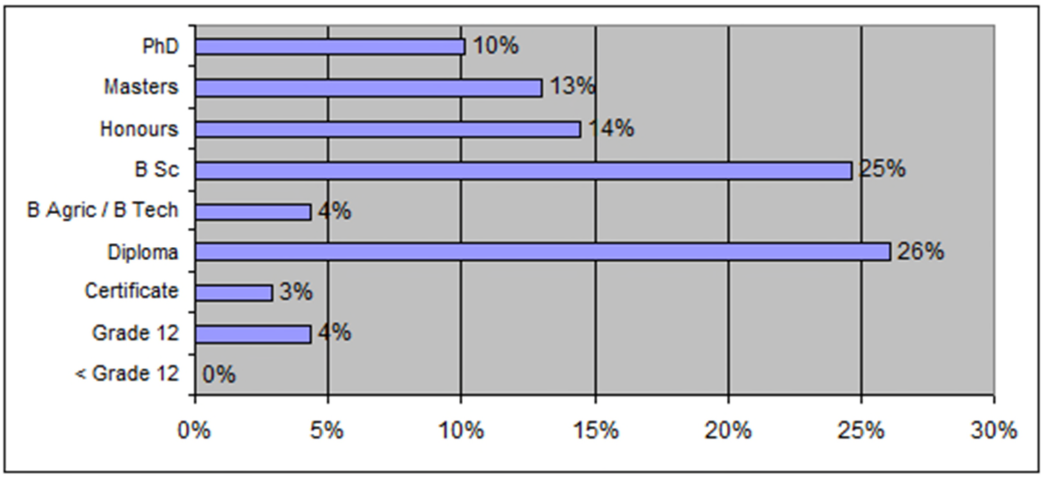

Figure 5-1 Education level of SAPWAT users in 2010

This finding not unexpected, because SAPWAT was originally designed and built as a tool for planning and design of irrigation and irrigation water reticulation systems. It can also be used for planning of the management of irrigation water. People who can potentially use SAPWAT are mostly water distribution managers, scientists, engineers or technicians, professions that require tertiary training.

5.7.2 Purpose and frequency of use of SAPWAT irrigation program

Irrigation water use planning is the biggest single application with 25% of the respondents using the program for this purpose (Figure 5-2). Furthermore SAPWAT is applied for the designing and planning at farm level (16%) and also for planning and designing of irrigation water use at catchment and Water Users Association (WUA) level. SAPWAT is also used by 11% of the respondents as a control system for administering the registration and licensing of water use by irrigators under the National Water Act of 1998.

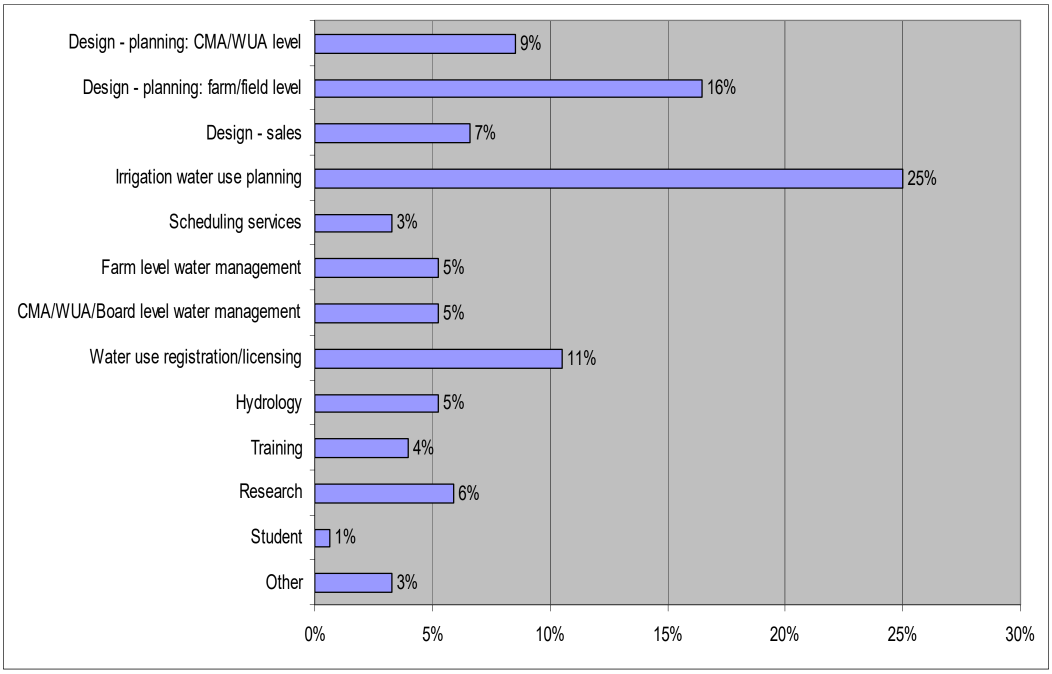

Figure 5-2 Frequency distribution of the use of SAPWAT by respondents in 2010. Student refers to mostly post graduate students who use SAPWAT in their studies.

Respondents were asked to indicate the frequency of use of SAPWAT for decision making, as, according to the literature, this is usually significantly related to both perceived ease of use and perceived usefulness (Davis *et al*., 1989; Dillon and Morris, 1996; Goa, 2005). 53% of the respondents used SAPWAT on a monthly basis, while 17% of the respondents used it on an annual basis (Figure 5-3). Designers and planners of irrigation systems are the main users of SAPWAT at a monthly frequency, while water use planners and managers of water at scheme or catchment level usually use it annually as an aid to review their water budget for the next water year. More frequent use than monthly is not expected to rise above 2010 levels, because, once a water requirement plan is complete, it stays valid until a farming system changes or until new crops or even cultivars are brought into the system, or the climate variability increases.

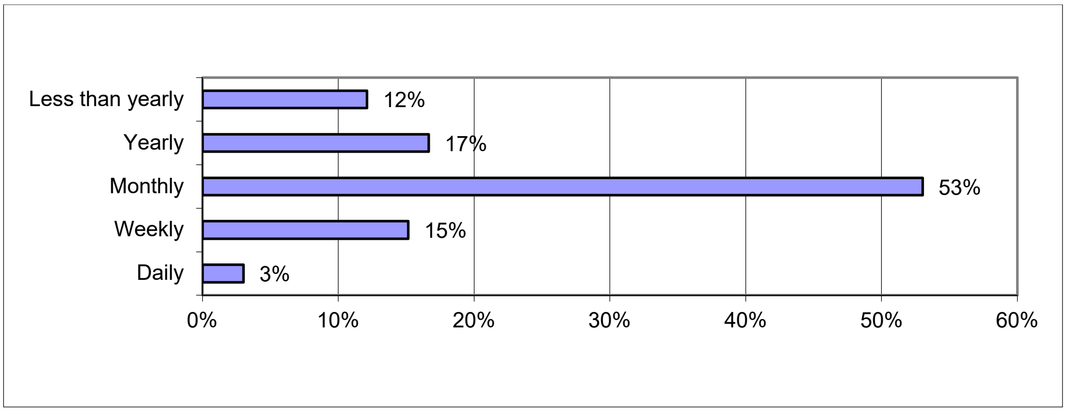

Figure 5-3 Frequency of use of SAPWAT

5.7.3 Perceived characteristics for adoption of SAPWAT

Respondents were asked to give an assessment of the characteristics of SAPWAT based on the work done by Rogers (2003) as well as work done on the Technology Acceptance Model (TAM) approach (Davis, 1989). The following variables were tested:

- Relative advantage: saving time and effort to make decisions in irrigation water requirement planning by using SAPWAT;
- Complexity: difficulty in understanding and using of SAPWAT in the workplace;
- Compatibility: the degree to which SAPWAT is compatible with the job, existing ways of planning and decision making;
- Ease of trying out: the degree to what SAPWAT can be used on a trial basis for planning and decision making;
- Observability: the relative easiness to explain and communicate the program and its results to others;
- Usefulness: the degree to which a person believes that using SAPWAT would improve his or her job performance;
- Ease of use: the degree to which a person believes that using SAPWAT would be free of effort.

Users' perceptions towards SAPWAT are positive for both the characteristic that promote diffusion and adoption as well as for usefulness and ease of use (Figure 5-4). Compatibility has the highest total positive value (87%), which is a strong indication that SAPWAT is compatible with the user's task and fits easily into the office work routine. Usefulness and ease of use, measures of how well a technology like SAPWAT will fit into the office routine and work space and be easy to learn and use by personnel are also strongly perceived with high positive values. Complexity, or the lack there-of, in applying and ease of trying out SAPWAT were lower than expected, probably due to some of the shortcomings of SAPWAT indicated by the respondents. These include the non-storage of results data, results which cannot be printed, high training levels expected and a measure of non user-friendliness experienced by some.

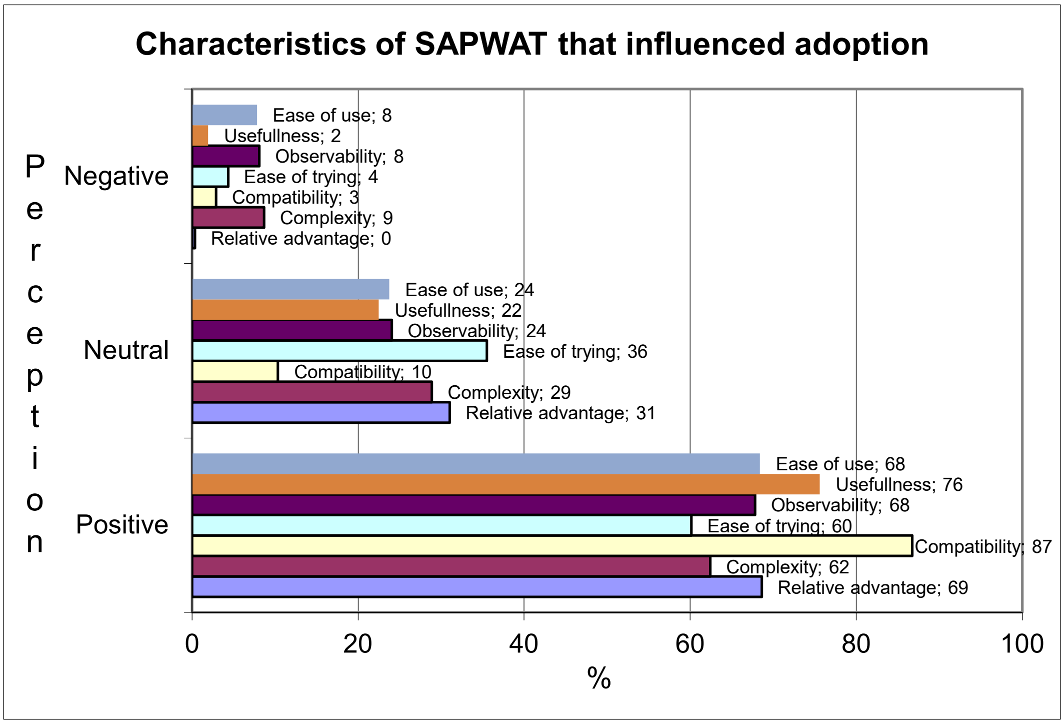

Figure 5-4 User's perceptions of important characteristics of SAPWAT that influence its adoption

Parallel to the influence of positive perceptions on the advantage of using SAPWAT and therefore on its adoption, Adrian *et al*. (2005) found that for farmers applying precision technologies, compatibility, attitudes of confidence towards such tools and their level of education had a positive influence on adoption. This tendency was also found by Ajili *et al.* (2012) among irrigation specialists in Iran, where observability was specifically mentioned as having had a positive influence on adoption.

5.7.4 Perceived relative advantages of SAPWAT

The respondents were asked to, in their own words, give their opinion on the benefits of using SAPWAT. The responses were translated to conceptual meaning and analysed (Figure 5-5). 33% of respondents perceived SAPWAT as a user-friendly irrigation requirement planning tool, 31% indicated that it is a good planning tool, and 18% perceived it as easy to apply.

These results support the results in Figure 5-4 and further explain the apparent ease with which SAPWAT has been adopted.

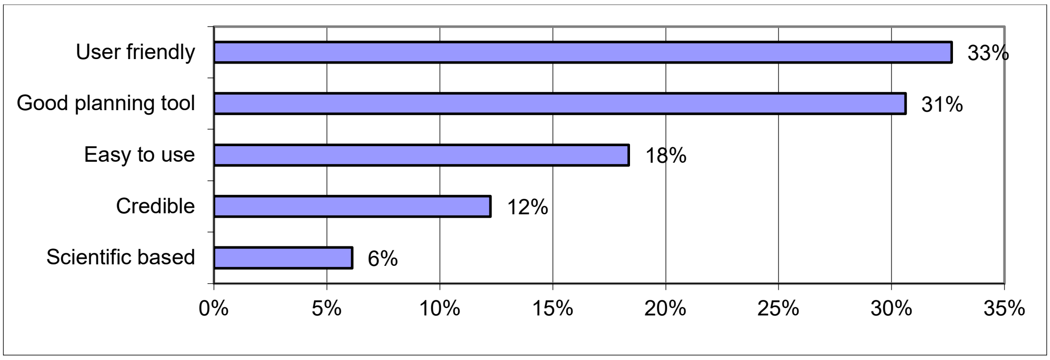

Figure 5-5 Perceived relative advantage (utility) of applying SAPWAT

5.7.5 Shortcomings of SAPWAT

In a similar way the respondents were asked in an open-ended question to describe the shortcomings or weak points of SAPWAT. The three most important shortcomings identified by users were: inadequate weather stations and weather data (15%); no data storage / printout facilities (13%) and that SAPWAT can be manipulated to get the answer the user wants (13%) (Figure 5-6). The survey results were a confirmation of the informal feedback received from SAPWAT users. These identified shortcomings were addressed by the developers of SAPWAT3 during the upgrading of SAPWAT to SAPWAT3.

5.7.6 Perceived usefulness and ease of use of SAPWAT

There is a high regard for the perceived usefulness (78 %) and ease of use (68 %) of SAPWAT by users, as assessed when doing a combination of all the different elements that make up these two characteristics (Figure 5-7). Disagreements to both ease of use (8%) and usefulness (2%) of SAPWAT was low. According to Davis (1989), perceived ease of use can be an antecedent to perceived usefulness rather than directly parallel to determinant of usage. 76% of the respondents adopted the use of SAPWAT on the basis of the task it can help perform and the impact on decision-making (usefulness). Respondents perceive SAPWAT especially useful for the planning of irrigation strategies and the calculation of crop water requirements.

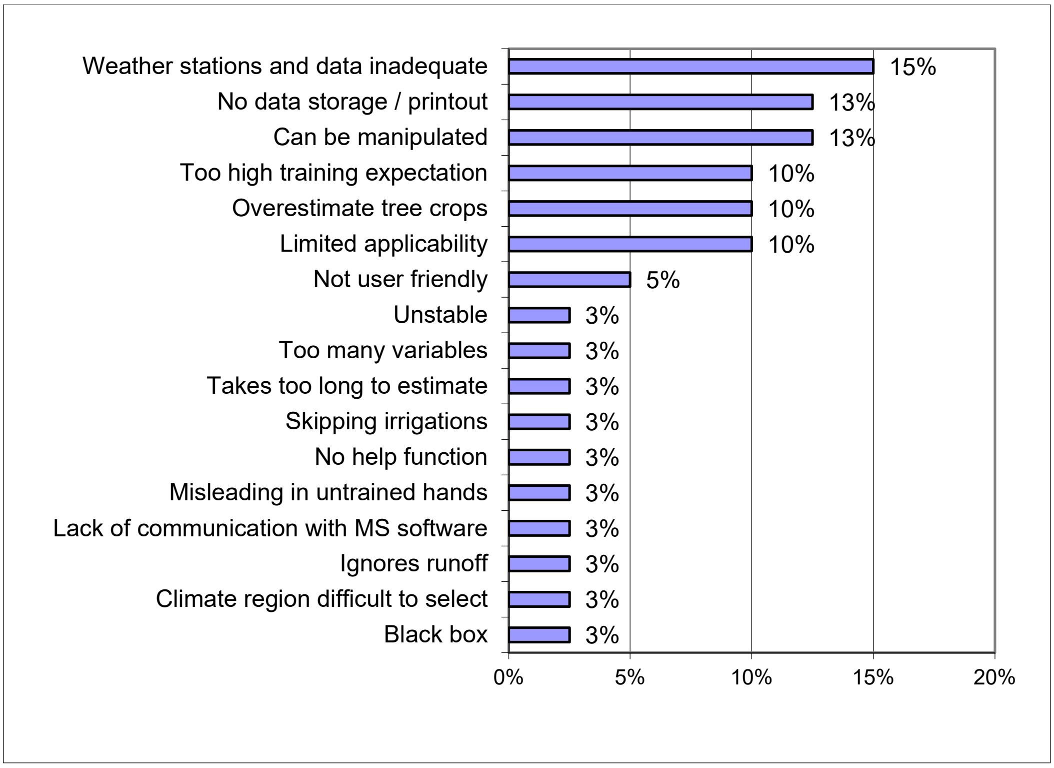

Figure 5-6 Perceived shortcomings of SAPWAT as identified by users

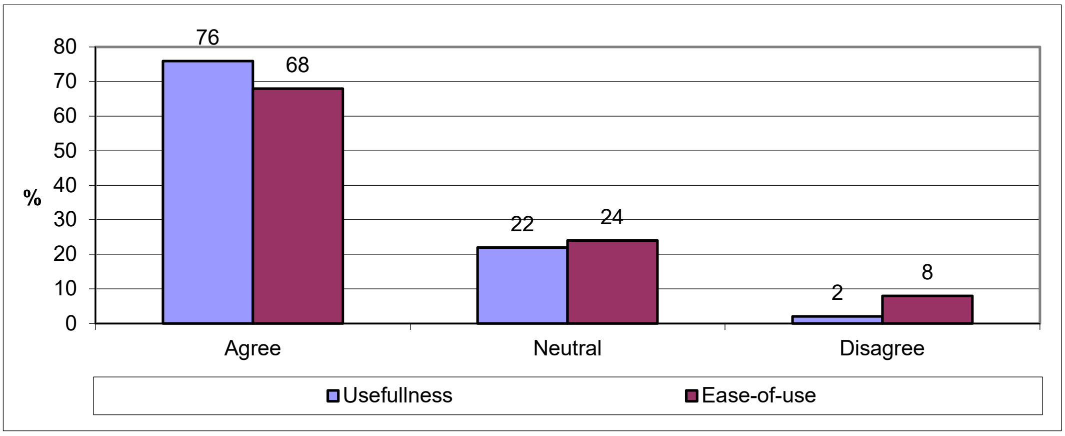

Figure 5-7 User's perceptions of the perceived usefulness and ease of use of SAPWAT

5.7.6.1 Perceived usefulness

The following variables were used to assess the perceived usefulness of SAPWAT:

- Quicker task completion;
- Improved job performance;
- Increased productivity;
- More effective job execution;
- Easier to do the job;
- Useful in the execution of the job; and,

- Addresses job related needs.

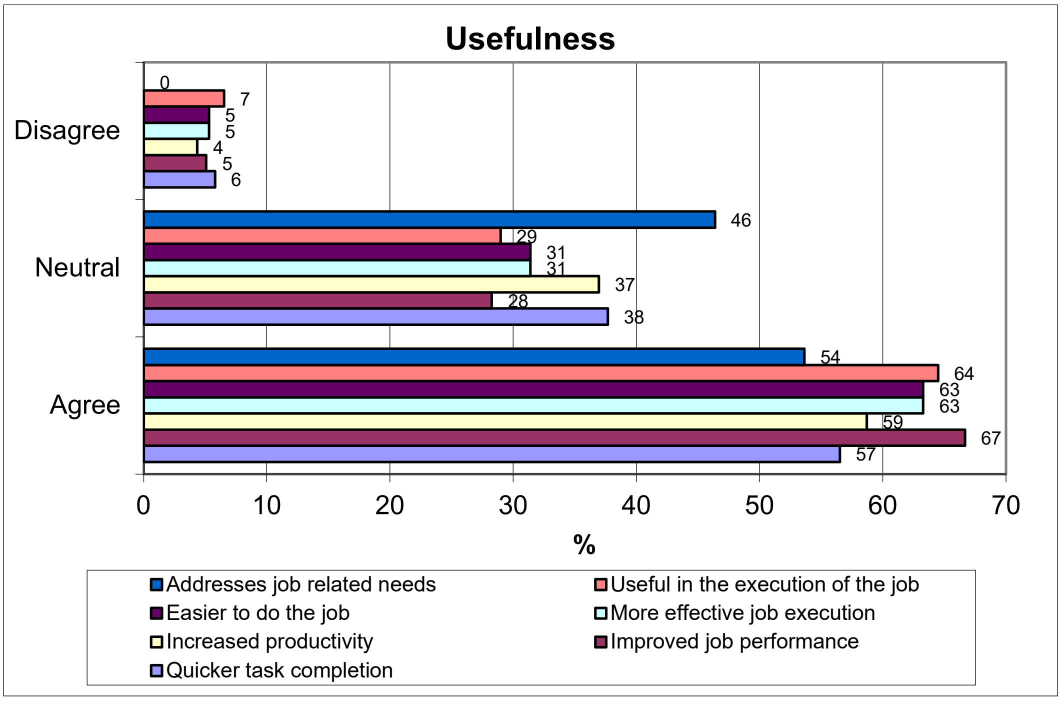

Figure 5-8 Assessment of the perceived usefulness of SAPWAT by respondents

Figure 5-8 illustrates the perceptions of respondents regarding the specific variables identified to measure perceived usefulness of SAPWAT. The majority of respondents perceived all these variables positively which therefore explains the positive attitude towards adopting SAPWAT. In a parallel research field where the use of high, for example, precision technologies for use in the farming sector was tested, it was found that perceived usefulness had a positive effect on the adoption of such technologies (Adrian *et al*., 2005). Ajili *et al*. (2012) confirmed this tendency that perceived usefulness stimulated adoption of variable rate irrigation technology amongst irrigation specialists. Porter and Donthu (2006) found in a study on acceptance of internet that even though demography and wealth played a role in acceptance, perceptions of both ease of use and usefulness were dominant.

The elements useful in the execution of the job; easier to do the job; more effective job execution and improved job performance have all scored more than 60%, while the elements addresses job related needs; increased productivity and quicker task completion scored in the high 50's. The weakest element is the one of addressing job-related tasks at a total of 50%, however, this element came out as a dominant element in the neutral group. No reason for this phenomenon could be identified.

5.7.6.2 Perceived ease of use

Perceived ease of use is the degree to which the prospective adopter expects the new technology adopted to be free of effort regarding its transfer and utilisation. The following variables were used to assess the perceived ease of use of SAPWAT:

- Ease of learning about how to operate the program;
- Ease with the use of the program - allows the user to do what is expected;
- Clear and understandable interaction with the program;
- Flexibility in the use of the program;
- Ease with which the user could become skilled in its use; and
- Overall ease to use.

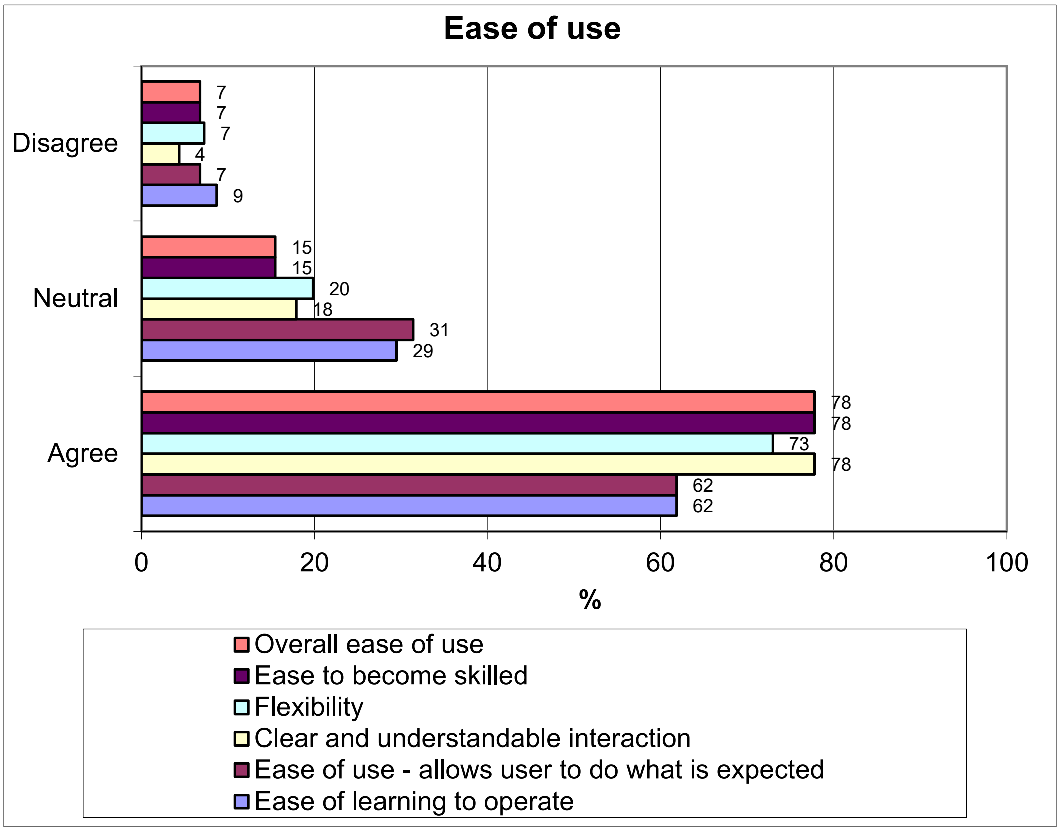

Figure 5-9 Assessment of the perceived ease of use of SAPWAT by respondents

The majority of respondents found SAPWAT relatively easy to use, which implies that the ease of application of SAPWAT a possible reason for the utilisation of the technology (Figure 5-9). Characteristics like relative easiness to learn and operate; a clear and understandable interaction with the program; that it is flexible; that it is easy to become skilled in its use and that it is overall easy to use were all positively acknowledged. At 78% agreement, clear and understandable interaction, easy to become skilled and overall ease of use were the highest positive evaluations. Perceived ease of use also had a positive influence on the adoption of variable rate irrigation technology amongst irrigation specialists in Iran (Ajili et al., 2012).

5.8 Conclusions

South Africa is on the verge of becoming a water stressed country, therefore good irrigation water use planning is essential in not only conserving the country's water resources, but also to extend the time before actually becoming water stressed. SAPWAT (Crosby and Crosby, 1999), a computer program aimed at assisting irrigation systems water use managers and designers to estimate irrigation water requirements, has been adopted within 11 years by at least 226 users within the relatively small irrigation planning, management and design community of South Africa. This study was done to determine which characteristics of SAPWAT contributed to its adoption as a tool to assist in the planning of irrigation water requirements, as a precursor of irrigation system design and good irrigation water management. To guide future development of the program, it is essential to know what characteristics made it acceptable to the irrigation community and who uses it for what.

86% of the users of SAPWAT have had post matric training; they are *managers* of irrigation scheme water, and *designers* of irrigation systems and scheme level water distribution systems. Use of SAPWAT is mostly for design purposes (57%), and a secondary use is for licensing and registration of irrigation water use (11%), or for water use management (10%). The balance is made up of use for hydrology, for research purposes, training students, and as an aid to irrigation scheduling.

SAPWAT scored high on all facets that enhance diffusion and adoption with a positive perception of more than 50%. Characteristics like its ease of use (68%) and usefulness (76%), ease of trying it out (60%) before committing to final adoption all give an even higher value. Its compatibility (87%) with the office environment and work to be done as well as the relative advantage (69%) it could give by simplifying the work environment and speeding up delivery of design are also highly positive. These high levels of positive perception are all factors that determine the rate of adoption (Davis *et al*., 1989; Gao, 2005; Rogers, 2003) and that enhanced the adoption of SAPWAT as a planning tool. A well designed and fairly intensive communication strategy was followed by the developers of SAPWAT in order to make potential users aware of its existence and what its capabilities are. The contribution of the communication programme to adoption was not tested separately, but it seems to have contributed in a similar way as that described by Leeuwis and Van den Ban (2004) and Rogers (2003).

On a policy level, SAPWAT is used by the South African Department of Water and Sanitation in their process of licensing and registering water use rights for irrigation farmers. In this respect the validity of the SAPWAT output needs to be acceptable to all parties, including the users and custodians of the water. Ease of use and usefulness enhance SAPWAT's acceptability as a tool for verifying irrigation water requirement estimation for registration purposes.

In general terms SAPWAT was described by respondents as: user friendly; a good planning tool; easy to use; useful; credible and scientifically based. The overall perception is that SAPWAT would make the job of the target community easier and therefore it was adopted as a tool for a specific task.

Respondents indicated some shortcomings in the use of SAPWAT. These are the inability to store result data or to print results, some instability when running the program and inadequate weather data. Some of these shortcomings have already been addressed in SAPWAT3 version 1.

The questionnaire was bulky because of its comprehensiveness for testing perceptions of SAPWAT as a tool for use by irrigation system designers and related users. Furthermore, training meetings before which the survey was administered made data collection expensive and limited the survey to those people who attended these advertised training meetings. However, an inspection of the consistency of the results indicates that it may have been adequate to test ease of use and usefulness only. Designing a questionnaire to test the elements of only these two characteristics would have simplified the design of the questionnaire and would have enabled it to be handled as a postal questionnaire at a lower cost, as well as possibly enabling a larger number of SAPWAT users to be reached.

SAPWAT was quickly adopted by the irrigation fraternity of South Africa as a working tool for designing irrigation systems and for planning of irrigation water requirements. The results of this research show that its quick adoption was promoted by the positive perceptions relating to ease of use, user friendliness, compatibility and simplicity to use. It is hoped that in the future, the new version of SAPWAT3 with additional capabilities and modules, will also be well accepted by the new up-coming generation of irrigation designers and managers.

Following the incorporation of global climate datasets, the usefulness of SAPWAT in designing and developing new irrigation schemes will be further extended in developing countries.

CHAPTER 6.
CONCLUSIONS

6.1 Introduction

South Africa is a water scarce country and therefore needs to use its water as efficiently as possible. Irrigated agriculture uses 62% of South Africa's water, and the sheer volume of water used means that even a small improvement in irrigation efficiency can save a noticeable amount of water and as a result delay the time when South Africa will become water stressed. Furthermore, it is accepted by the irrigation fraternity that the improvement of irrigation water use efficiency is one of the cheaper methods of extending the water life of a country. Improving irrigation water use efficiency means the application of planning, advisory and management tools specifically built for such a purpose. Some irrigation water planning tools have been developed locally, the best known and most widely used one in South Africa being SAPWAT (Crosby and Crosby, 1999). SAPWAT satisfied most of the requirements of, especially, the irrigation system designers, but it had shortcomings such as not saving, printing or exporting results data. Other shortcomings were a limited number of weather stations included and the inability of doing year-on-year consecutive irrigation requirement calculations in order to determine risk. A recognised problem of SAPWAT was that accepted crop growth days did not necessarily correspond with actual crop growth days, a result of temperature differences between weather station data to which crop growth and development were linked, and the climate of localities in which SAPWAT was used.

At about the same time that SAPWAT was published (Crosby and Crosby, 1999); the FAO in Rome published their internationally accepted manual on guidelines for computing crop water requirements – generally referred to in South Africa as FAO 56 (Allen *et al*., 1998). The shortcomings of SAPWAT and PLANWAT and the availability of FAO 56 led to the upgrading of SAPWAT to SAPWAT3, a computer program that applies the FAO 56 dual crop coefficient approach. This upgrade was aimed at eliminating shortcomings and improving the functionality of SAPWAT as an irrigation planning tool.

6.2 Linking crop growth and development to a recognised climate system

Crop growth and development are usually expressed in terms of calendar days, which is valid for a relatively small area within the same climate region and if the crop growth and development characteristics are defined for that area. Moving outside the climate area for which the crop's growing period has been defined could lead to a difference between the SAPWAT3 defined crop growth and that found at the locality of interest. The solution for this problem is to link crop growth and development to the climate of an area and to adjust the theoretical growth rate to the climate. This has been done for SAPWAT3, but has only partly solved the problem because differences between theoretical SAPWAT3 growth rates and those found at specific localities differed too much. A further step in the solving of this problem is to link crop growth and development through the calculation of thermal time to the different climates included in SAPWAT3. This improvement will be included in the next version of SAPWAT3.

The Köppen climate system (Strahler and Strahler, 2002) was incorporated into SAPWAT3 and because its climate definitions are based on combinations of temperature and rainfall, each weather station included could be linked to a specific climate. In order to automate this process, certain steps needed to be taken. A first step in the linking of crop growth and development to the temperature ranges of a climate region, or of a weather station, and to apply it in SAPWAT3, is to fit cosine curves to represent the seasonal cycle of daily maximum and minimum temperatures and use the parameters of the fitted curves in an equation for calculating daily heat units.

The second step would be the calculation of heat units of an area with the heat unit equation and to apply this to crop growth for the climate of the weather station. An application that does this has been developed for inclusion in SAPWAT3 and will be included in the next published version. This application will use weather station temperature data to get an improved growing period length for crops when estimating irrigation water requirements for specific areas.

The advantages of including a system whereby crop growth can be linked to the temperature of an area, is that the user of SAPWAT3 can be more assured of estimating crop irrigation requirements for a correct growth period.

A handicap for general application in SAPWAT3 at present is that thermal time data is not available for all crops and, perhaps more important, base temperatures are not necessarily indicated. This requires further basic agronomic research for each of the crops, and then in the application of the concept of thermal time to the SAPWAT3 crop data tables.

6.3 Building the SAPWAT3 program

SAPWAT has been expanded to include an internationally accepted worldwide climate system, to do computations at a daily time step, to complete an enterprise budget and enable risk assessment across the variation of climate and even climate change.

SAPWAT was originally designed using monthly values, as that seemed most appropriate at the time for a planning exercise. However, with time it became increasingly important to have a more accurate estimate of the crop irrigation water requirements, therefore SAPWAT shifted to a daily time step. This however, made all the computations more complicated with daily ET_0 and soil water balance calculations. Because of its complexity, the authors of FAO 56 recommended a computerised approach, resulting in the development of SAPWAT3 in South Africa. When SAPWAT was developed, most potential users, the designers of irrigation systems, did not have computer network access; therefore it was decided to include all required data as look-up tables. This approach was maintained for the development of SAPWAT3, even though a larger proportion of potential users in South Africa had internet access, but with a vision of SAPWAT3 expanding its service to developing countries, which probably still lacked good internet access.

The usefulness of SAPWAT3 has been greatly expanded by the inclusion of the FAO-CLIMWAT climate dataset (Smith, 1993) from around the world. This means that SAPWAT3 can be used by many users all over the world. So the technology developed and refined here in South Africa can be launched to the developing countries and used during this critical time when water is scarce and its availability is changing due to climate change. The expansion of capabilities and as a service to the whole of South Africa, the national database of derived South African quaternary weather stations is included in SAPWAT3 (Schulze and Maharaj, 2006). This will make it easy for future students and developers to use SAPWAT3 to generate irrigation requirements for a range of potential crops across a whole country. At the present time the total number of climate stations available in the current version of SAPWAT3 is about 5 100. The advantage of the availability of this large amount of climate data is that SAPWAT3 can now be used in nearly all third world countries. It can also be expanded world-wide for specific locations by the importation of climate data irrespective of where the station is situated. The possibility to add weather data is now a built-in function of the program; giving the user full control over all data included in the program. This will surely make the program more accessible to other users and able to be included into other computational databases or knowledge platforms in the future.

A method was developed in SAPWAT3, to expand the monthly climate datasets and generate daily input for the ET_0 and water balance calculations. A cosine function is fitted to the monthly climate data using linear regression to enable SAPWAT3 to do crop water requirement and soil water balance calculations on a daily basis. Calculations are done using the dual crop coefficient approach so that soil surface evaporation and crop transpiration are calculated as separate entities, then combined to give a daily crop evapotranspiration value. Usually for irrigation planning, one only needs the monthly and total seasonal values; this is how the output is now saved.

As the impact of climate change becomes more of a reality, it is important to be able to estimate the risk associated with the varying climate. Thus another additional module in SAPWAT3 is the ability to calculate and represent the data in the format of distribution charts. Examples of which are shown in Figures 2-18 to 2-21 in Chapter 2. Therefore, when sufficient daily weather data exists, irrigation requirements for different levels of probability of non-exceedance can be calculated. This enables the user to plan irrigation water reticulation and irrigation system capacities to provide capacity for other than mean requirement values. Thus the engineers and other water managers can now have an estimation of the range of values of the crop water requirements over the past 50 years of climate data. Thus the variation that can be expected can also be brought into the current calculations and planning for any new developments. In future, one could also do similar computations with data from climate projections for different scenarios using the global climate models.

SAPWAT3, as an irrigation water planning tool, is also aimed at the irrigation farming community. Apart from water requirement planning, they are also interested in the financial side of their irrigation farming. For that purpose, an enterprise budget module is included with the aim of letting the user not only balance a water budget, but to combine the water budget with an economic budget to enable the best possible choice of crop combinations. It must be stressed here that SAPWAT3 was not built to give an optimised result, it is built as an interactive model with the aim of also acting as a training tool. The interactivity with the user should lead to a better understanding of the parameters that are used in the program and the effect that changes in one parameter value has on an irrigation water requirement calculation at a specific location for a particular crop.

6.4 Verifying crop coefficients

SAPWAT3 uses crop coefficient data inherited from FAO 56 (Allen *et al*., 1998) which has been updated to reflect the South African agricultural situation. Even so, the crop coefficients and growing period length for each growth stage were not always relevant to specific areas, because of possible temperature deviations between current location and areas where the original crop characteristics have been defined. In the estimation of irrigation requirements as done in SAPWAT3, the value of the crop coefficient parameter is the most uncertain factor. To allay this doubt, a computerised methodology to evaluate the correctness of the crop coefficient data has been developed for SAPWAT3. The theory it is based on, is described in FAO 56 and the statistical testing approach by Willmott (1981) who said that the evaluation should be a combination of visual and statistical. This methodology makes use of measured crop water use and calendar days to update the crop coefficient data for the specific area. The relevance of the crop coefficient data could be further improved upon by using thermal time instead of calendar time when doing this evaluation.

The module was tested with results of two non-consecutive years of lysimeter experiments with three crops and the results were good, both visually and statistically. The slopes of the regression lines between observed and theoretical values were better than 0.82 and the RMSEs, expressed as percentages of observed averages, were less than 22.7%. However, it was found that the mid-season K_{cb} values are higher in all cases than expected. Higher than expected mid-season K_{cb} values have been reported by a number of authors (Abyaneh *et al*., 2011; Farg *et al*., 2012; Lazarra and Rana, 2012; Rohitashw *et al*., 2011; Yang *et al*., 2008), and possible reasons for such high values have been described in FAO 56. However, an island effect of the crop included in the lysimeter compared to surrounding crop could also lead to such a deviation. It was noticed that the lysimeter experiments with a water table consistently gave a higher K_{cb} value than $K_{c\ max}$. For that reason the module built into SAPWAT3 need to be adapted to limit maximum K_{cb} to $K_{c\ max}$.

The module tests fit of and recommends new crop coefficient values. If the user so decides, a retest with the recommended values is done. This cycle of testing/retesting can be repeated any number of times, but indications are that it would not be necessary to exceed four repetitions of refining crop coefficient values because chi-squared testing shows that at that stage changes becomes insignificant with P>0.95

SAPWAT3 is used to verify the application of water quantities by farmers for licensing and verification of water rights. As this is the implementation of a regulation based on the National Water Act of 1998, it is the users of SAPWAT3's responsibility to make sure that the estimation of irrigation water requirements is as accurate as is possible. The methodology described here, if applied, will ensure that a more correct irrigation water quantity is estimated, and will result in a higher level of credibility to be ascribed to the results of SAPWAT3.

This methodology will be included as a module in the next version of SAPWAT3.

6.5 Evaluation of the Adoption of SAPWAT

During the development of SAPWAT3 care had to be taken that the end product would be acceptable to the user (Rogers, 2003). This was done by obtaining feedback from users of SAPWAT about their likes, dislikes, as well as shortcomings and possible gaps in the program. The first round of distributing SAPWAT3 was during the series of meetings at different centres across the country where SAPWAT users were concentrated. At these meetings the attendees were asked what their perceptions of SAPWAT were in order to test its acceptability and to get confirmation of feedback received regarding potential improvements.

The acceptance of SAPWAT was evaluated by using a combination of Rogers' (2005) diffusion theory and the Technology Acceptance Model (TAM) as described by Davis (1989) and Davis *et al.* (1989). The main group targeted when SAPWAT was initially developed, were the people involved in irrigation water use planning and designers of irrigation systems. Many purpose built scheduling tools available, and SAPWAT was never intended to be used as a scheduling tool, as it uses historic data and not real-time data for its calculations. Even so, it was found that some people use SAPWAT as a scheduling tool. The majority of users found SAPWAT to be easy to understand and to learn to use, and a time saver, while its inability to store data, inadequate weather stations distribution and a tendency to over-estimate irrigation requirements were reported by some.

Evaluation using the TAM approach indicated positive points such as easier and more effective job completion, improved job performance, and that it is programmed in such a way that it is easy to become a skilled user. Proof that the attractiveness of SAPWAT has been carried over to SAPWAT3, by addressing most of the complaints received, despite making the program somewhat more complicated, is the fact that more than 600 copies of SAPWAT3 (2014 in 3rd reprint; 300 copies per reprint) have been distributed and as far as could be ascertained, to more than 15 countries. Regular (more or less weekly) requests for information and possibilities to acquire SAPWAT3 continue to be received. Requests for training in SAPWAT3 are also received from time to time.

These requests for training and advice include the Department of Water and Sanitation who uses SAPWAT3 results as a norm when deciding on water use registration and licensing as well as making policy decisions on irrigation water use.

6.6 Possible future developments

SAPWAT3 was developed because a need for it existed. It was readily accepted by the target community of irrigation system designers, water use planners, advisors and also the Department of Water and Sanitation for the administration of water use licensing and registration.

SAPWAT3 could be further developed by including a choice to work with thermal time instead of calendar time as at present. This has the potential of increasing the accuracy of irrigation requirement estimates and making the program even more universally acceptable than at present. This function is under development and will be included in a future version of SAPWAT3.

The fitting of a cosine regression on weather data to enable SAPWAT3 to do daily calculations even though the background data is monthly, gives a good fit in most cases, however, there are situations when the fit is not good enough, such as areas in extreme climates (Berbera in Somalia is a good example). The replacement of the cosine transformation with a Fourier transformation could alleviate this problem and need to be investigated. If it is found to be an improvement, the present cosine transformation need to be replaced with the Fourier transformation.

Some complaints have been received about the complexity of the program which is the result of a greater functionality. A redesign of the first two screen pages could alleviate this problem. Shifting forms with comprehensive data requirements to the background while keeping only absolutely required data in the foreground will reduce any remaining perception that SAPWAT3 is difficult to use. This program make use of default values that could be customised by the experienced user for his specific purposes.

Requests have been received for the development of a scheduling module in association with SAPWAT3 that makes use of real time weather data to predict the time and depth of the next irrigation. It is possible to do this. However, the funders of the development of SAPWAT3 have also funded the development of other irrigation scheduling tools over the years, and might not be agreeable to fund such a functionality in SAPWAT3, therefore funding might be a problem. Nevertheless if a group of irrigators or farmers or another organisation were willing to fund such a task, it could be expanded from irrigation design and planning to day-to-day operational irrigation scheduling with real time weather data.

At this stage there is no other irrigation water requirement planning tool than SAPWAT3 that satisfies the needs of the South African irrigation industry. To maintain this situation, continuous redevelopment and upgrading is necessary to ensure compatibility with new versions of computer operating systems, new crop varieties and potential climate change.

Looking at the reality of South Africa as a potentially water-stressed country in the near future, linked to a continuous increase in water demand because of population growth, the onset of water shortages for all sectors of the economy could be delayed by increasing the efficiency of irrigation water planning, use and management because the irrigation sector is the biggest user of water. As an irrigation water requirement planning tool the use of SAPWAT3 is important, but to maintain its credibility and its influence on efficient water use planning and policy (Department of Water and Sanitation) of water use, continuous upgrading and development is required.

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APPENDIX A
SURVEY QUESTIONNAIRE

At the time that the adoption potential of SAPWAT needed to be determined, a Water Research Commission project was started with the objective of doing the same test of adoption on all irrigation and related models and approaches funded by it – this included SAPWAT (Stevens and Van Heerden, 2013). This author and Dr Joe Stevens (project leader) of the University of Pretoria joined forces and designed a questionnaire that covered all the computer and related models. The questionnaire is therefore somewhat more comprehensive than would normally have been the case.

The results discussed in Chapter 5 are only those related to SAPWAT taken from this questionnaire.

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A. Personal Details

Respondent no:

A1 Title, Initials and Surname: …………………………………………….

A2 Contact details:

Telephone: ……………………………..……………

Cell no: ……………………………………………

E-mail: ……………………………………..………

Postal address: ……………………………………………...

……………………..……………………………

A3 Highest qualification:

- a <Grade 12 ☐
- b Grade 12 ☐
- c Certificate ☐
- d Diploma (2/3 years) ☐
- e B Agric / B Tech degree ☐
- f BSc ☐
- g Honours ☐
- h Masters ☐
- i PhD ☐

A4 Occupation: ………………………………..………………

A5 Years' experience in irrigation water management and planning

- a < 5 years ☐
- a 6-10 years ☐
- b 11-15 years ☐
- c 16-20 years ☐
- d >20 years ☐

A6 Prior experience in the use of computer programs for water use planning and irrigation management

- Yes ☐
- No ☐

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B. Irrigation tools and their use

B1 What **method or tool** did you, do you or will you use **for decision-making**, for what **purpose** and when did you **start using** it?

Method / tool	**Do/did yo use it?**		**Indicate purpose (x)**		**Starting dat (year)**	**Duration of us (years)**
	Yes	**No**	**Agriculture**	**Non-agriculture**		
SAPWAT						
BEWAB						
PUTU						
MyCanesim						
SWB						
ACRU **Mike Basin**						
Wetting Front Detecto (WFD)						

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B2	For what **purpose** did, do you or will you use the method or tool?	SAP WAT	BEWAB	PUTU	My Cane sim	SWB	ACRU Mike Basin	Wetting Front Detector (WFD)
a	Design and planning at CMA, WUA or Irrigation board level	☐	☐	☐	☐	☐	☐	☐
b	Irrigation water management at CMA, WUA or Irrigation board level	☐	☐	☐	☐	☐	☐	☐
c	Design and planning at field level	☐	☐	☐	☐	☐	☐	☐
d	Scheduling service	☐	☐	☐	☐	☐	☐	☐
e	Water use licensing or registration	☐	☐	☐	☐	☐	☐	☐
f	Hydrology planning	☐	☐	☐	☐	☐	☐	☐
g	Training (specify)	☐	☐	☐	☐	☐	☐	☐
h	Research (specify)	☐	☐	☐	☐	☐	☐	☐
i	Administration of Water Act	☐	☐	☐	☐	☐	☐	☐
j	Planning for irrigation water policy	☐	☐	☐	☐	☐	☐	☐
k	Other (specify)	☐	☐	☐	☐	☐	☐	☐

B3 Give the main reasons (at least TWO) why you use the methods or tools for **decision-making?** (Own words)

SAPWAT

………
………
……………………………………………

BEWAB

………
………
……………………………………………

PUTU

………
………
……………………………………………

MyCanesim

………
………
……………………………………………

SWB

………
………
……………………………………………

ACRU Mike Basin

………
………
……………………………………………

Wetting Front Detector

………
………

IMPACT OF WRC FUNDED RESEARCH ON THE APPLICATION OF IRRIGATION SCHEDULING METHODS

		SAP WAT	BEWAB	PUTU	My Cane sim	SWB	ACRU Mike Basin	WFD
B4	What **types of decision-making** is mainly influenced by the tool or method?							
	a Trouble shooting of irrigation water management	☐	☐	☐	☐	☐	☐	☐
	b Problem solving of irrigation water management problems	☐	☐	☐	☐	☐	☐	☐
	c Enlightenment of certain aspects of irrigation water management	☐	☐	☐	☐	☐	☐	☐
	d Confirmation of appropriateness of current irrigation management strategy followed	☐	☐	☐	☐	☐	☐	☐
	e Policy planning and implementation	☐	☐	☐	☐	☐	☐	☐
	f Planning and designing of irrigation management strategy	☐	☐	☐	☐	☐	☐	☐
	g Designing of irrigation systems	☐	☐	☐	☐	☐	☐	☐
	h Estimation of catchment water balances	☐	☐	☐	☐	☐	☐	☐
	i Others (specify) ………… …Investigating salinity aspects which can be further use to judge irrigation performance….	☐	☐	☐	☐	☐	☐	☐

		SAP WAT	BEWAB	PUTU	My Cane sim	SWB	ACRU Mike Basin	WFD
B5	At which **level of operation** are your decisions aimed?							
	a Field or farm level	☐	☐	☐	☐	☐	☐	☐
	b Scheme level	☐	☐	☐	☐	☐	☐	☐
	c Catchment level	☐	☐	☐	☐	☐	☐	☐
	d National level	☐	☐	☐	☐	☐	☐	☐

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B6	**How did you become aware** of the tool or method for the first time?	SAPWAT	BEWAB	PUTU	My Cane sim	SWB	ACRU Mike Basin	WFD
a	Research reports	☐	☐	☐	☐	☐	☐	☐
b	Scientific articles	☐	☐	☐	☐	☐	☐	☐
c	Popular articles	☐	☐	☐	☐	☐	☐	☐
d	Contact with researcher or specialist on your request	☐	☐	☐	☐	☐	☐	☐
e	Introduction through peer	☐	☐	☐	☐	☐	☐	☐
f	Introduction through advisor or extensionist	☐	☐	☐	☐	☐	☐	☐
g	Training session on specific research knowledge	☐	☐	☐	☐	☐	☐	☐
h	Advice of researcher or specialist	☐	☐	☐	☐	☐	☐	☐
i	Contact via website	☐	☐	☐	☐	☐	☐	☐
j	Conference or symposium	☐	☐	☐	☐	☐	☐	☐
k	Other (specify) …………………… ………………………………………	☐	☐	☐	☐	☐	☐	☐

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	Method tool	Frequency of use (x)		Decision-making importanc				
				1=Not important				5=Ve importa
B7 How **often** do you use the method or tool for **decision-making** and how **important** is it in your decision-making?	**SAPWAT**	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						
	BEWAB	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						
	PUTU	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						
	MyCanesim	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						
	SWB	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						
	ACRU Mik Basin	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						
	Wetting Fro Detector	Daily		1	2	3	4	5
		Weekly						
		Monthly						
		Yearly						
		Sporadically						
		Not at all						

IMPACT OF WRC FUNDED RESEARCH ON THE APPLICATION OF IRRIGATION SCHEDULING METHODS

C. Perceived usefulness

	Method or tool	Improve water use planning				
		No improvement ↓				Gre improveme ↓
C1 To what extent does the method or tool you use help you with the **planning of irrigation water use**?	SAPWAT	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Fro Detector (WFD)	1	2	3	4	5

	Method or tool	Improve water use evaluatio				
		No improvement ↓				Gre improveme ↓
C2 To what extent does the method or tool you use help you with the **evaluation** of **irrigation water use**?	SAPWAT	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Fro Detector (WFD)	1	2	3	4	5

	Method or tool	Improve planning of system desig				
		No improvement ↓				Gre improveme ↓
C3 To what extent does the method or tool you use help you with the **planning** of **system design**?	SAPWAT	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basi	1	2	3	4	5
	Wetting Fro Detector (WFD)	1	2	3	4	5

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		Method or tool	Improve evaluation of system design				
			No improvement ↓				Gre improveme ↓
C4	To what extent does the method or tool you use help you with the **evaluation** of **system design**?	**SAPWAT**	1	2	3	4	5
		BEWAB	1	2	3	4	5
		PUTU	1	2	3	4	5
		MyCanesim	1	2	3	4	5
		SWB	1	2	3	4	5
		ACRU Mike Basi	1	2	3	4	5
		Wetting Fro Detector (WFD)	1	2	3	4	5

		Method or tool	Improve catchment resource assessment				
			No improvement ↓				Gre improveme ↓
C5	To what extent does the method or tool you use help you with **water resource assessments** of **catchments**?	**SAPWAT**	1	2	3	4	5
		BEWAB	1	2	3	4	5
		PUTU	1	2	3	4	5
		MyCanesim	1	2	3	4	5
		SWB	1	2	3	4	5
		ACRU Mike Basin	1	2	3	4	5
		Wetting Fro Detector (WFD)	1	2	3	4	5

		Method or tool	Improve irrigation water demand and supply assessment				
			No improvement ↓				Gre improveme ↓
C6	To what extent does the method or tool you use help you with **water resource assessments** for **irrigation water demand and supply**?	**SAPWAT**	1	2	3	4	5
		BEWAB	1	2	3	4	5
		PUTU	1	2	3	4	5
		MyCanesim	1	2	3	4	5
		SWB	1	2	3	4	5
		ACRU Mike Basi	1	2	3	4	5
		Wetting Fro Detector	1	2	3	4	5

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C7

a To what extent does the tool or method of **irrigation scheduling** lead to **better-informed decision-making** in **irrigation management**?

Method or tool	**Better informed irrigation management decisions** No improvement ↓				Gre improveme ↓
SAPWAT	1	2	3	4	5
BEWAB	1	2	3	4	5
PUTU	1	2	3	4	5
MyCanesim	1	2	3	4	5
SWB	1	2	3	4	5
ACRU Mike Basir	1	2	3	4	5
Wetting Fro Detector	1	2	3	4	5

b Explain your answer (provide an example of **improvement** of **quality** of **decisions**):

……………………………………………………………………………………………

………

C8

a To what extent does the tool or method help you to have **better control** over the **implementation** of an **irrigation management strategy**?

Method or tool	**Improve implementation of irrigation strategy** No improvement ↓				Gre improveme ↓
SAPWAT	1	2	3	4	5
BEWAB	1	2	3	4	5
PUTU	1	2	3	4	5
MyCanesim	1	2	3	4	5
SWB	1	2	3	4	5
ACRU Mike Basin	1	2	3	4	5
Wetting Fro Detector	1	2	3	4	5

b Explain your answer (examples of better control over **implementation** of **irrigation management**):

………..

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	Method or tool	Quicker decisions for irrigation management				
		No improvement ↓				Gre improveme ↓
C9	SAPWAT	1	2	3	4	5
a To what extent does the method or tool help you to accomplish **quicker decisions** regarding **irrigation management**?	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basir	1	2	3	4	5
	Wetting Froi Detector (WFD)	1	2	3	4	5

b Explain your answer (examples of how it helps to make **quicker decisions**):

……
……
……..

	Method or tool	Easier decisions for irrigation management				
		No improvement ↓				Great improvement ↓
C10	SAPWAT	1	2	3	4	5
a To what extent does the method or tool help you to make **easier decisions** regarding the **implementation** of **irrigation management strategies**?	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basii	1	2	3	4	5
	Wetting Froi Detector	1	2	3	4	5

b Explain your answer (examples how the specific tool helps with **easier decision-making**):

………
………
………
………………………..

c Is this specific tool or method **useful** for **management** of **irrigation**?

Yes ☐

No ☐

	Method or tool	Increased productivity				
		No improvement ↓				Great improvement ↓
C11 a To what extent does the **output** produced by the specific method or tool help you to **increase productivity**?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Froı Detector	1	2	3	4	5

b Explain your answer (examples of increased productivity):

………
………
………
………..

	Method or tool	Included input data allow us at level				
		Basic ↓				Advance ↓
C12 a To what degree does the **input data** included in the tool or method **allow its use**?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detectoı	1	2	3	4	5

b Explain your answer:

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
………………………..

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	Method or tool	Input data availability				
		Not ↓				Free ↓
C13 How **available is the input data** required for effective operation of the selected method of tool?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detector	1	2	3	4	5

	Method or tool	Credibility of output				
		Low ↓				Hig ↓
C14 How **credible is the output** of the irrigation method or tool?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detector	1	2	3	4	5

	Method or tool	Need for addition information		Main reason for additional output information require	Importance of addition output information				
		Yes	No		Not				Free
C15 How important is **input information not** provided by the tool or method for decision making?	**SAPWAT**				1	2	3	4	5
	BEWAB				1	2	3	4	5
	PUTU				1	2	3	4	5
	MyCanesim				1	2	3	4	5
	SWB		x		1	2	3	4	5
	ACRU Mike Basin				1	2	3	4	5
	Wetting Fro Detector				1	2	3	4	5

	Method or tool	Barriers to information availability	Availability of addition information				
			Not				Free
C16 How **available** is **additional input information**?	**SAPWAT**		1	2	3	4	5
	BEWAB		1	2	3	4	5
	PUTU		1	2	3	4	5
	MyCanesim		1	2	3	4	5
	SWB	Difficult to obtain weather data and soil parameters in some cases	1	2	3	4	5
	ACRU Mike Basin		1	2	3	4	5
	Wetting Fro Detector	Limited experts on WFD application and use to guide irrigation scheduling	1	2	3	4	5

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D. Perceived ease of use

	Question	Method or tool	Ease of use				
			Not ↓				Ve ↓
D1	How **easy** did you find the **use** of the **tool or method**?	**SAPWAT**	1	2	3	4	5
		BEWAB	1	2	3	4	5
		PUTU	1	2	3	4	5
		MyCanesim	1	2	3	4	5
		SWB	1	2	3	4	5
		ACRU Mike Basin	1	2	3	4	5
		Wetting Fro Detector	1	2	3	4	5

	Question	Method or tool	Ease of understanding research report				
			Not ↓				Ve ↓
D2	How **easy** did you find the **understanding of** the **research report**?	**SAPWAT**	1	2	3	4	5
		BEWAB	1	2	3	4	5
		PUTU	1	2	3	4	5
		MyCanesim	1	2	3	4	5
		SWB	1	2	3	4	5
		ACRU Mike Basin	1	2	3	4	5
		Wetting Fro Detector	1	2	3	4	5

	Question	Method or tool	Ease of understanding and following of user manual				
			Not ↓				Ve ↓
D3	Was the **user manual easy to understand and follow**?	**SAPWAT**	1	2	3	4	5
		BEWAB	1	2	3	4	5
		PUTU	1	2	3	4	5
		MyCanesim	1	2	3	4	5
		SWB	1	2	3	4	5
		ACRU Mike Basin	1	2	3	4	5
		Wetting Fro Detector	1	2	3	4	5

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	Method or tool	Importance of user manual				
		Low ↓				Hig ↓
D4 How **important is a user manual** for the tool or method?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Fro Detector	1	2	3	4	5

	Method or tool	Ease of learning				
		Not ↓				Ve ↓
D5 How **easy is it to learn how to use** the tool or method?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Fro Detector	1	2	3	4	5

	Method or tool	Increase skills and knowledg				
		Not ↓				Great ↓
D6 Indicate to what extent the tool or method **increases your knowledge and skills** of **irrigation management**?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detecto	1	2	3	4	5

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	Method or tool	Flexibility				
		Not ↓				Ve ↓
D7 How **flexible** is the tool or method to **work with**?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Fro Detector	1	2	3	4	5

	Method or tool	Time saving				
		False ↓				Tru ↓
D8 The method or tool **saves you time** in **irrigation management decision-making**?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detecto	1	2	3	4	5

D9 What **type of user assistance** is favoured?

a Web linked system ☐

b E-mail / SMS ☐

c Back-up support by research team ☐

d Back-up support by dealer ☐

e Appropriate support of extensionists and advisors ☐

f Other (specify) ………………… ☐

D10 What **type of electronic mail support** system do you prefer?

a Website / E –mail ☐

b SMS messages ☐

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c Provide reasons for the preference indicated:

…………………………………………………………………………………………………As a researcher I have constant access to e-mail, but if I was in the field more I would prefer SMS contact… E-mailing also makes it easier to keep records.………………………………………………………………………………………………… …… ………………………

D11 Is it **important to meet the research team** responsible for the development of the specific irrigation-scheduling tool or method?

Yes ☐

No ☐

D12 How **satisfied** are you with **communication and support** by the **research team**?	**Method or tool**	**Satisfaction with support by research team** Not ↓				High ↓
	SAPWAT	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detecto	1	2	3	4	5

D13 How **satisfied** are you with **communication and support by extension staff or irrigation advisors**?	**Method or tool**	**Satisfaction with support by extension staff or advisors** Not ↓				High ↓
	SAPWAT	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Front Detecto	1	2	3	4	5

	Method or tool	Satisfaction with backup support by dealer				
		Not ↓				High ↓
D14 How **satisfied** are you with **back-up support by dealer**?	**SAPWAT**	1	2	3	4	5
	BEWAB	1	2	3	4	5
	PUTU	1	2	3	4	5
	MyCanesim	1	2	3	4	5
	SWB	1	2	3	4	5
	ACRU Mike Basin	1	2	3	4	5
	Wetting Froi Detector	1	2	3	4	5

D15 What are the major **hindrances** that influence the use of this specific **research knowledge** in **decision-making**?	
a Technical knowledge about soil-plant-atmosphere continuum is not adequate (WFD)	☐
a Lack of computer skills and knowledge	☐
b Lack of skills and knowledge to interact with the electronic mail system	☐
c Poor water administration and communication to farmers	☐
d Time availability (SWB)	☐
e Other (Specify) …………………………………………………	☐

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E. Attitude of user

		In agreement Not ↓ … Ful ↓				
E1	The National Water Act imposes necessary regulations on irrigation water users to apply efficient irrigation water management strategies.	1	2	3	4	5

		In agreement Not ↓ … Ful ↓				
E2	Irrigation scheduling methods and tools are developed for use by irrigation advisors and researchers.	1	2	3	4	5

		In agreement Not ↓ … Ful ↓				
E3	The refinement in irrigation management offered with the implementation of irrigation scheduling tools and methods is not cost effective.	1	2	3	4	5

		In agreement Not ↓ … Ful ↓				
E4	Variability (rainfall and climate) is too complex to accommodate in the irrigation scheduling computer models and programmes available.	1	2	3	4	5

		In agreement Not ↓ … Ful ↓				
E5	Irrigation scheduling could only be effectively applied once farmers have full control of the water supply.	1	2	3	4	5

E6 Are you familiar with the research done by the WRC?

- Yes ☐
- No ☐

E7 Are you a regular user of research knowledge generated by the WRC?

- Yes ☐
- No ☐

E8 Indicate the main purpose for using of WRC research knowledge in your business.

a Research ☐

b Training ☐

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c Planning and designing ☐

d Irrigation management ☐

e Policy designing and implementation ☐

f Water use administration ☐

g Other (specify) …………………………………..

	Importance				
	Not ↓				Ver ↓
E9 Rate the **importance of research knowledge** generated by the **WRC** as a source of information in your business?	1	2	3	4	5

	Needs addressed				
	Poorly ↓				Exceller ↓
E10 Rate whether the **needs** of **irrigation water users are appropriately addressed** in the **WRC** research (Thrust: Agricultural Water Management)?	1	2	3	4	5

E11 How important is the following **participation in the development** of specific tools and methods for irrigation management?	Importance				
	Not ↓				Ver ↓
a Active participation of potential users in the **designing of WRC research agendas**	1	2	3	4	5
b Active participation of potential users in the **planning of WRC research projects**	1	2	3	4	5
c Participation of potential users in the **execution of the WRC research**	1	2	3	4	5
d Participation of potential users in the **testing** and **fine-tuning of new innovations** derived from research	1	2	3	4	5
e Participation of users only with the **implementation** of the **specific method or tool**.	1	2	3	4	5

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F. Specific to SAPWAT

F1 Your impressions about the user-friendliness of SAPWAT

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F2 Functions and/or routines you would like to see added

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F3 Functions and/or routines that are superfluous

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