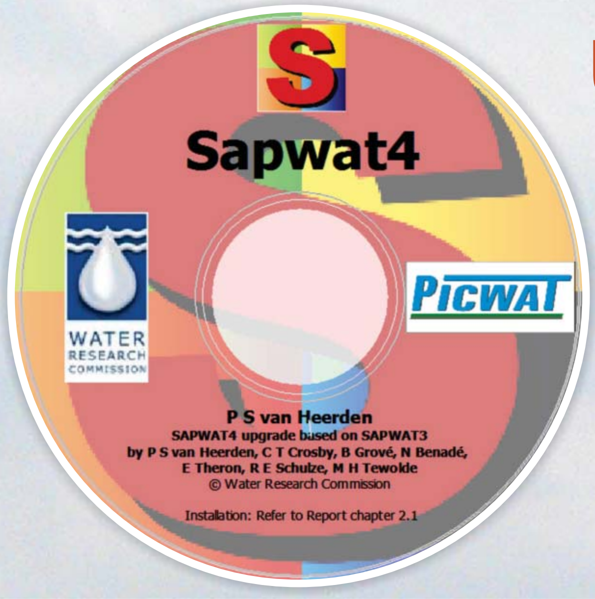
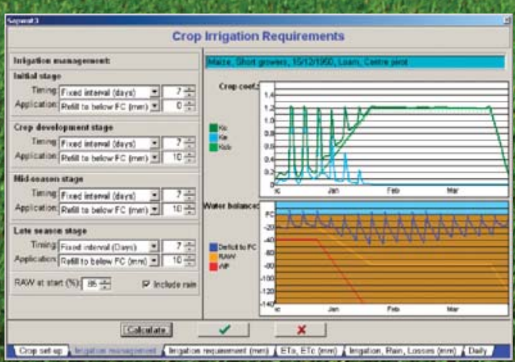
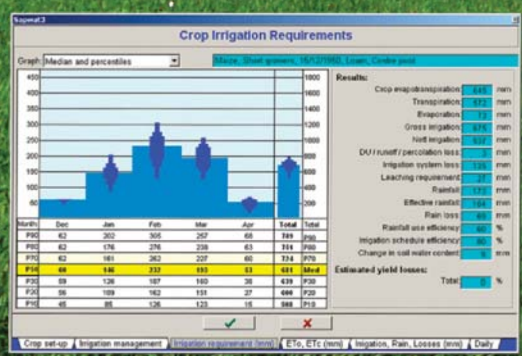


Upgrading of SAPWAT3 as a Management Tool to Estimate the Irrigation Water Use of Crops

Revised Edition SAPWAT4

PS van Heerden and S Walker





WATER RESEARCH COMMISSION

TT 662/16

UPGRADING OF SAPWAT3 AS A MANAGEMENT TOOL TO ESTIMATE THE IRRIGATION WATER USE OF CROPS

REVISED EDITION

SAPWAT4

Report to the

WATER RESEARCH COMMISSION

by

Pieter S. van Heerden and Sue Walker

WRC Report No. TT 662/16

May 2016

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The publication of this report emanates from a project entitled *Upgrading of SAPWAT3 as a Management Tool to Estimate the Irrigation Water Use of Crops* (WRC Project No K8/1115//4.

The upgraded SAPWAT4 program is on the CD inside the back cover of his report.

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This report and program update is an upgrade of the original SAPWAT3 report and program:

INTEGRATING AND UPGRADING OF SAPWAT AND PLANWAT

TO CREATE A POWERFUL AND USER-FRIENDLY IRRIGATION WATER PLANNING TOOL

by

P.S. van Heerden, C.T. Crosby, B Grové, N Benadé, E Pretorius, R.E. Schulze, M.H. Tewolde, S Nkumbule

WRC Report TT 391/08

Further development based on SAPWAT3 used for this upgrade to SAPWAT4

is contained in the PhD thesis

IMPROVEMENT OF SAPWAT AS AN IRRIGATION PLANNING TOOL

by

Pieter S. van Heerden

which was completed under guidance of

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Dr Joe Stevens of the University of Pretoria (acceptance as a planning tool).

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TABLE OF CONTENTS

Executive summary

SAPWAT4 Is an improved version of SAPWAT3, the program that is extensively applied in South Africa and internationally and was developed to establish a decision-making procedure for the estimation of crop irrigation requirements by irrigation engineers, planners, agriculturalists, administrators, teachers and students. The development of the current SAPWAT4 program, which, as in the case of SAPWAT3, is based on the FAO-published Irrigation and Drainage Report No. 56, *Crop evapotranspiration*. *Guidelines for computing crop water requirements.* This intuitive and comprehensive document is highly acclaimed and is accepted internationally. As the calculation of crop evapotranspiration is the first and essential element of any routine for estimating crop irrigation requirement, SAPWAT4 has at its core the computer procedures contained in FAO 56 and all recommendations have been applied strictly. Extensive use was also made of FAO Irrigation and Drainage Report No. 66, *Crop Yield Response to Water*.

The irrigation requirement of crops is dominated by climate, particularly in the yearly and seasonal variation in the evaporative demand of the atmosphere as well as precipitation. SAPWAT4 has included in its installed database comprehensive weather data that is immediately available to the user:

> Firstly, it includes the complete FAO CLIMWAT weather database encompassing not only South Africa, but many other countries in the world where there is irrigation development. CLIMWAT comprises 3262 weather stations from 144 countries, and contains long-term monthly average data for calculating Penman-Monteith ET_0 values as well as rainfall. While CLIMWAT weather data output is monthly averages, SAPWAT4 calculations are based on daily values requiring interpolation. This has been facilitated in SAPWAT4 by statistically fitting a cosine curve to the monthly ET_0 values.
>
> Secondly, the installed set of weather data in SAPWAT4 also includes derived weather stations, presently only applicable to South Africa. This database was developed from the South African Atlas of Climatology and Agrohydrology by the team from the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal. The derived weather stations are located at the centroid of the polygon that represents each quaternary drainage region of the country and provide not only comprehensive coverage, but also 50 years of historical (1950-1999) daily weather data. This capability has major implications when it comes to planning and strategy development. It is possible to select

any day during this period and access the maximum and minimum temperatures, humidity, rainfall, solar radiation and ET_0.

SAPWAT4 provides facilities for importing additional weather station data, including data produced by the New LocClim Climate Estimator, an FAO program that produces monthly climate data for any place on earth. If the weather station database consists of average monthly values, similar to CLIMWAT data, then manual importation is recommended, but if the data is more detailed there are facilities for formatting and importing the data files electronically.

SAPWAT4 has the built-in facility to export irrigation requirement data on crop, field or farm level, or on higher administrative levels to a variety of spreadsheets and similar facilities. Irrigation requirement output is provided in millimetres and cubic metres for the specified irrigated areas.

SAPWAT4 utilises the four-stage crop development curve procedure based on relating crop evapotranspiration in each stage to the short grass reference evapotranspiration (Penman-Monteith approach) by applying a crop coefficient. Typical values of expected average crop coefficients under a mild, standard climatic condition are published in FAO 56 and applied in SAPWAT4. FAO 56 makes provision for this and for making the necessary corrections. SAPWAT4 applies these corrections and also makes allowance for the effect of climate, planting date, management strategies or crop varieties on the individual crop development stage lengths or the total irrigation period. SAPWAT4 includes default stage length values for each of the crops listed for each of the five climatic zones found in South Africa and, in addition, has options for each crop where there are differing cultivars and modifies the stage lengths where these are influenced by planting dates. Further development in the use of crop heat units is included to enable the user to adjust growth periods to local climate temperature data. SAPWAT4 goes one step further by also including a module that can use measured crop water use data to adjust both K_{cb} value and stage lengths.

The crop coefficient files were developed according to rules derived with the help of crop scientists. Experience showed that it was necessary to modify the approach to suit irrigation as opposed to the normal rain-fed development stages. Editing has been simplified by the provision of options available on drop-down menus. It is envisaged that users concerned with groups of irrigators would develop their own sets of defaults tailored to their conditions.

SAPWAT4 incorporates the internationally recognised Köppen-Geiger climatic system. The system is based on temperature-rainfall combinations so that the climate of the weather station can be classified by using the temperature and rainfall data of a weather station record. One adaptation was made, that is the second letter of the three-letter code that indicates rainfall seasonality, is not used because rainfall seasonality is superseded by irrigation scheduling. In the case of South Africa this resulted in the number of climatic regions being reduced to five and it is no longer necessary for the user to have to decide in which climatic zone a weather station falls because this is determined by the program.

SAPWAT4 makes use of the FAO 56 procedure that separates soil evaporation from plant transpiration and, therefore, conforms to the FAO 56 defaults that determine soil water characteristics and evaporation parameters. Fortunately, FAO 56 specifies soils according to the familiar sand, silt and clay criterion into nine classes. The profile water balance during irrigation is also calculated and tabulated strictly in accordance with FAO 56 methodology.

The methodology for estimating crop evapotranspiration under standard conditions has been well researched and due allowance can be made for nonstandard conditions arising from unusual circumstances and the realities of practical management. In short, we can be reasonably confident that we can estimate the amount of water being used by the crop and thus the net irrigation requirement.

Water that evaporates in the air or is blown away from sprinkler systems is regarded as a loss, so is water that is applied to uncultivated areas of the field. In SAPWAT4 this is reflected by System Efficiency (%). If too much water is applied and penetrates below the roots this is also regarded as a loss, it is normally the result of an uneven distribution of water by the system or by lack of uniformity in the soil itself. In SAPWAT4 this is referred to as Standard DU (%). It is very difficult to provide standardised or even defensible defaults for these values. The approach that SAPWAT4 has followed is to provide a preliminary default value for System Efficiency and to set Standard DU at 100%. If, through measurement or judgement, the user can come up with real-life values, these should be substituted for the default values.

The inclusion of an enterprise budget module in SAPWAT3, and now further developed in SAPWAT4, had been requested by a number of users as the conviction grew that planning irrigation water use without considering the economic impact does not give enough of a picture on which to base future planning for crop production. Provision is made for the introduction of enterprise budgets as part of the irrigation water requirement planning process. Income, expenditure and gross margins are reflected in the crop irrigation requirement tables. There is a linkage between the economic factors and the crop irrigation requirements so that if there is a variation in crop irrigation requirements with altering strategies, the impact on costs will be reflected and should there be a depression in yield, the impact on income and gross profit margin will also be reflected.

SAPWAT4 provides a rainwater harvesting module aimed at small areas, typically small farms or household gardens, therefore the water harvesting module is only available if the cultivated and irrigated area is less than 1 ha. The 50 year daily weather records provided by the derived weather stations are particularly useful because a thorough understanding of the rainfall pattern is essential when assessing the viability and developing suitable systems for rainwater harvesting. A water balance is the background to this module. Total of water requirement is the sum of the irrigation and household requirements, while water gain on the irrigated area is the sum of the rain that falls directly on the garden beds and run-off from the roof and surrounding areas that can be augmented by borehole water and greywater from kitchen and bathroom waste. Run-off can be harvested from any combinations of roof, hard-packed soil around the homestead or adjoining roadways or from an adjoining area of natural vegetation. The storage to provide water for the dry season can be any combination of totally covered, impervious containers, open impervious containers or open ponds. The module can also be used to estimate the harvest width area of the infield rainwater harvesting techniques where runoff from an area of slow infiltration soil is stored in a shallow basin where the water can concentrate and infiltrate into the soil adjacent to the plant row.

CHAPTER 1.
Introduction

Earth has so much water that it covers two-thirds of its surface area. Yet, only a very small portion (0.00054%) of this vast quantity is found in rivers and is therefore readily accessible by man (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. This stresses the importance of efficient irrigation water use, because Irrigated agriculture uses more than 60% of the fresh water resources available to mankind (Alois, 2007; Gleeson *et al*., 2012). 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).

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 link to a crop's growth and development. However, the more sophisticated the approaches have become, the more complicated the calculations have become. 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. These considerations were also kept in mind for the upgrading of SAPWAT3 to SAPWAT4

1.1 A perspective on water resources and irrigated agriculture

1.1.1 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. (Alois, 2007).

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). 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. A drop in ground water levels from 10 to 50 m is found 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).

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 *et al*., 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).

The water supply in a region is variable because of the annual variability in rainfall. Of the world population of 6.7×10^9 in 2008, 2×10^9 lacked access to clean water while another 1×10^9 did not have enough water to satisfy their daily needs. With a projected world population of 8×10^9 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 300 g 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).

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).

1.1.2 The South African scene

South Africa's average 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 flowing 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).

Surface and ground water resources are nearly fully developed and utilized in the northern parts of the country (Limpopo, Gauteng, Mpumalanga, Free State and North Cape 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. 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 x 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 x 10^6 m^3 of Tugela River water annually into the Sterkfontein Dam. The pumps are 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).

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).

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).

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).

1.1.3 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).

Historic irrigation development and crop yields along the Berg River in the days of Simon van der Stel, the Great Fish River (middle 1800's), Lower Vaal River (late 1800's) and lower Orange River (early 1900's) are described (Getting Home Executive Services, 2012; De Kock, 1965, as referenced by Van Heerden and De Kock, 1980; Van der Merwe, 1997; 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: Hartbeespoort (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).

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 1-2). 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).

Table 1-2 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	%

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 1-2) (Frenken, 2005).

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).

1.2 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 1-3); 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 1-3 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**	**Harvest (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 1-4) (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 1-1; Figure 1-2; Figure 1-3) 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 1-3). 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.

Table 1-4 Most important crop types produced under irrigation in the different drainage regions (see Figure 1-1) 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

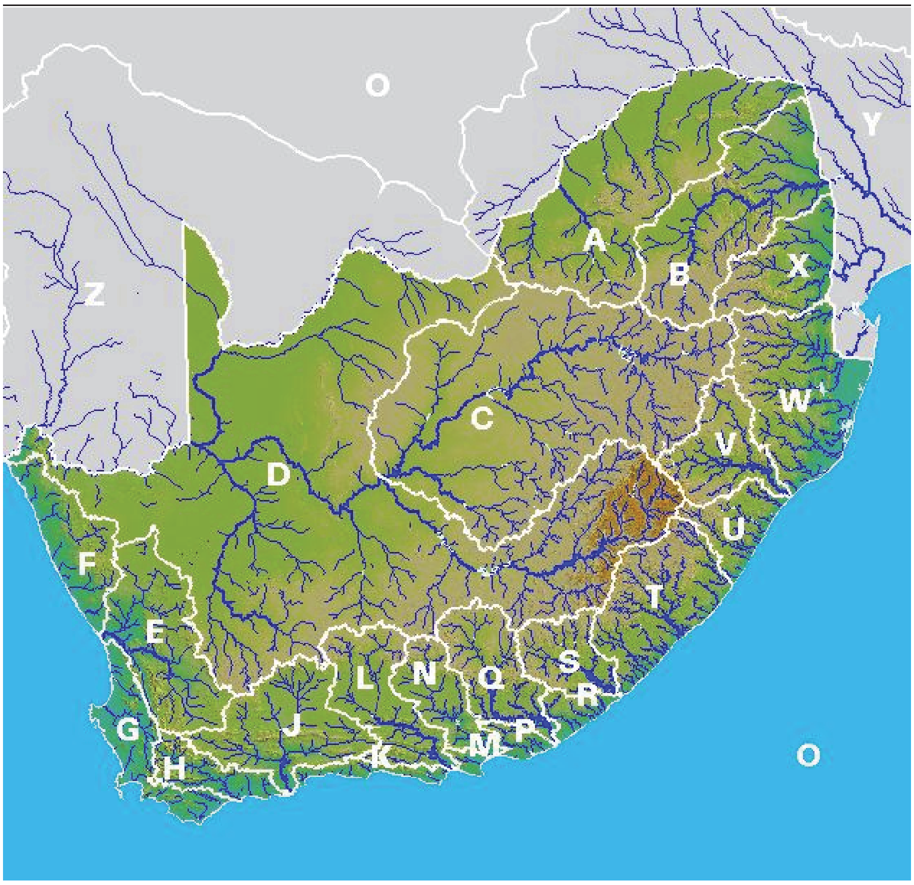


Figure 1-1 Primary drainage regions for South Africa (RQS, 2015)

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 1-3), 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 1-1; Figure 1-3). 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 1-1), where subtropical fruit also appears as an important irrigated crop (Figure 1-3).

Table 1-5 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 1-6 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).

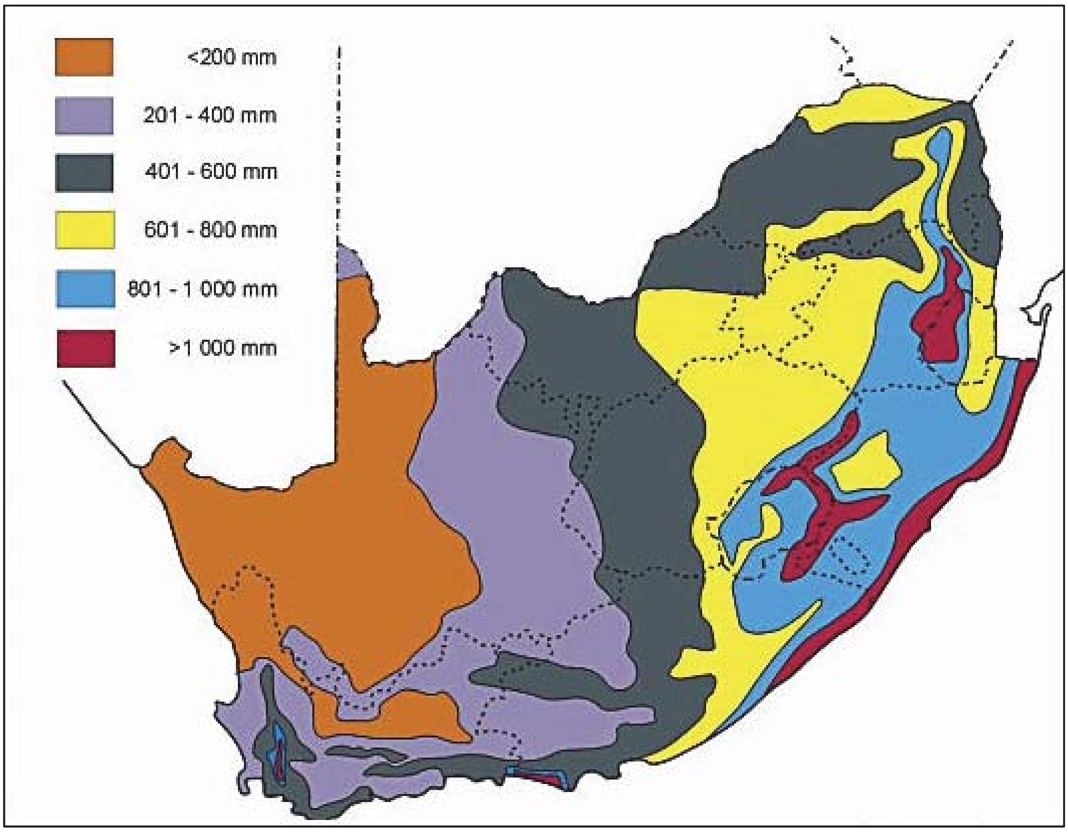


Figure 1-2 Rainfall map of South Africa (South Africa Tours and Travel.com, 2015)

Table 1-6 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	

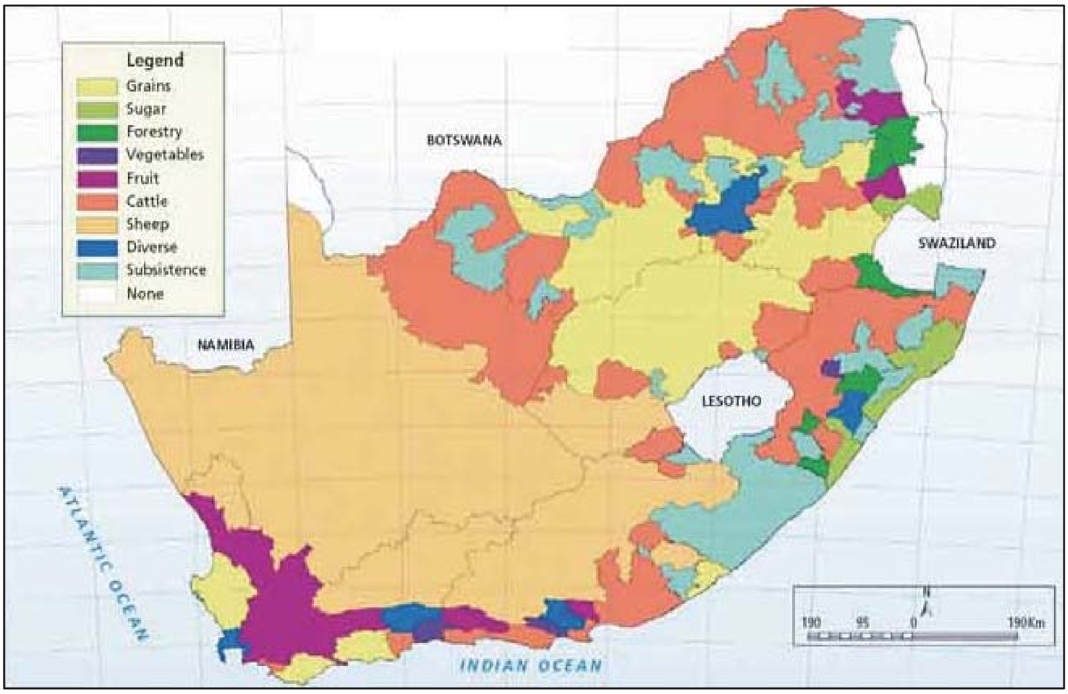


Figure 1-3 Agricultural regions of South Africa (FAO, 2005)

1.3 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 *et al.*, 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 report concentrates on the planning phase and will therefore *not* go into the detail of the day-to-day management of irrigation water.

1.3.1 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 (Crosby and Crosby, 1999).

1.3.2 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

[1] Dup Haarhoff, Executive Manager: Research & Development, GWK Limited. Personal communication

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 use SAPWAT3 as an aid to scheduling, even though SAPWAT3 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 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 SAPWAT3 and SAPWAT4 crop growth and development characteristics data in order to improve its functionality as a water requirement planning tool.

1.4 Adoption of irrigation water requirement planning tools

The design and development of computer programs such as SAPWAT3 and SAPWAT4 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. SAPWAT3 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) SAPWAT3 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

[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.

user and the innovation value of it decreases (Rouse, 1991). Within the South African context, questions could be asked as to what has made SAPWAT3 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 Development of SAPWAT3

The development of SAPWAT3 (Van Heerden *et al.*, 2008) had to take cognisance of international developments related to the function that SAPWAT3 tried to fulfil. The best thinking related to this is probably contained in FAO reports.

The development process of SAPWAT3 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.

1.5.1 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).

1.5.2 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).

1.5.3 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).

1.5.4 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).

1.5.5 SAPWAT and crop factors (crop coefficients)

Smith (1994) strongly recommended that the four-stage FAO procedure (Figure 1-4) 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 progems 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).

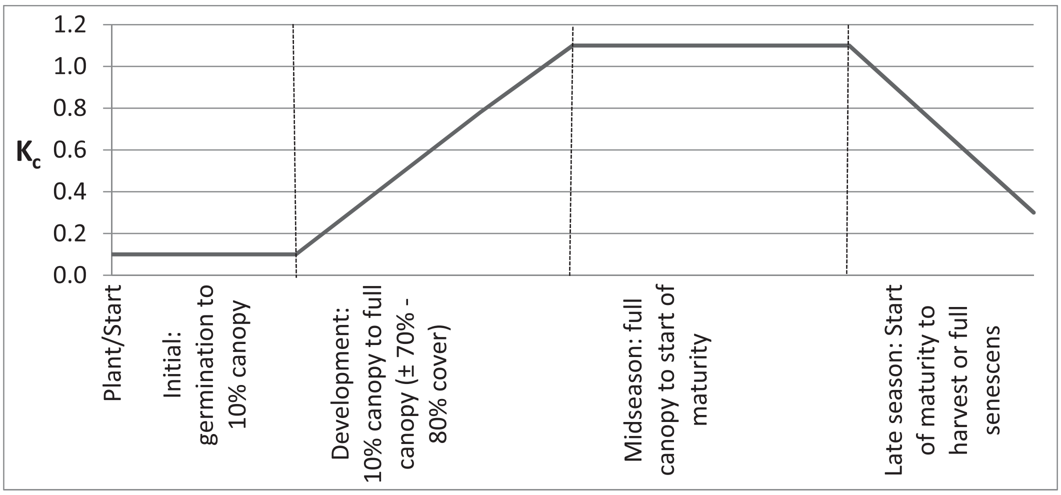


Figure 1-4 The FAO four stage crop growth curve as described by Allen *et al*. (1998)

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).

1.5.6 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 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).

1.5.7 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).

1.5.8 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 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; 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.

[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).

1.6 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, SAPWAT4 (Van Heerden *et al*., 2008) was developed. The development of SAPWAT4 and potential future improvements is the subject of this report.

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 SAPWAT4. 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 SAPWAT4 on specific aspects that enhance adoption and neutralise weak points that retard adoption, while making it more use-friendly.

1.7 Problem statement

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?

SAPWAT3 was published by the WRC in 2008 (TT 391/08). Since then more than 600 copies have been distributed and it has been used in at least 15 countries. It is used by irrigation advisors and designers of irrigation systems and irrigation water distribution systems as an input guide to determine the capacity and delivery volumes of irrigation systems, canal systems and irrigation water storage dams. SAPWAT4 has also proved itself as a useful planning tool for water conservation and demand management overviews and actions in pilot studies initiated by the Department of Water Affairs. In South Africa it is also the reference used by the Department of Water and Sanitation to confirm the correctness of irrigation water requirement application by potential users. Over and above this, SAPWAT4 is used as a training aid in several institutions of higher learning and has also been used as a data source tool for post-graduate studies. Overall comments from users are that it is an easy to use and credible tool for estimating irrigation water requirements.

Feedback from users include:

1. It needs special installation approaches for 64-bit computers and for Windows 8 systems, which, if not done, results in program failure;
2. Crop data included does not provide enough variation for growth periods as influenced by climate of an area so that over- or under estimates of irrigation water requirement is experienced in some cases;

3. Increased functionality related to updating of crop data tables have been requested;
4. First screen forms that appear are somewhat off-putting for the majority of users (increase the perception of complication to operate and unnecessary input requirement from the irrigation water use planner and system designer at farm or field level);
5. Important information needed by the program, re farm and field is shown on page 2 instead of on the first operational screen form;
6. Some complaints about operational speed being too slow;
7. Programming errors and omissions reported:
8. Export functions of results to spreadsheet type programs does not always work correctly (seem to be linked to 64-bit and Windows 8 systems);
9. Export functions not adequate to satisfy all export requirements;
10. Backward summation of irrigation water requirement from farm level to water user association level does not work correctly when editing data;
11. Information required from user and terms used not well enough defined or described;
12. Some data included needs updating e.g. irrigation system efficiencies as recommended by Reinders (WRC TT 465/10), crop coefficient data resulting in over- and under estimates in excess of 20% (various authors) and soil data not complete enough for the South African situation;
13. Requests for the inclusion of small irrigation dam water balances have been received.

1.8 Objectives

An overall objective for this project is:

1. To upgrade SAPWAT4 to make it 64-it and Windows 8 friendly, to update program data and to increase its functionality. This overall objective can be sub-divided into the following specific objectives:
2. To update included irrigation system, soil and crop data to reflect research results published after the publication of SAPWAT4 version 1;
3. To move farm and field information input screen to screen page 1;
4. To simplify data input screens by shifting lesser-used screen forms to the background;
5. To increase functionality by including a module or modules that can use research results to update crop data tables;
6. To give the user the choice of using thermal time or calendar time when estimating irrigation water requirements;

7. To increase operational speed by reprogramming the calculation modules;
8. To correct programming errors in the present version of SAPWAT4;
9. To eliminate reported programming omissions;
10. To attempt to include small irrigation dam water balances in SAPWAT4;
11. To make SAPWAT4 Windows 8 and 64-bit system friendly by reprogramming in a Windows 8 friendly version of dBase – dBase Plus 10;
12. To build and compile the complete the upgraded program, SAPWAT4, and to update the user manual to reflect the proposed changes.

CHAPTER 2.
Using SAPWAT4

2.1 Installing

2.1.1 Existing users

SAPWAT4 places its data tables in a different directory than that used by SAPWAT3. If you want to retain your data set, do the following **before installing SAPWAT4**:

> Copy all directories and files in the c:\program files\SAPWAT3\tables (or c:\program files (X86)\SAPWAT3\tables) to c:\users\public\sapwat4\tables

Then proceed as for new users.

2.1.2 New users

2.1.2.1 Single user installation

Install from the Install DVD and accept all default values. At the end of the install process a WinZip Unzip facility will be activated. Click "Unzip" to save the related weather data tables to the default directory. **The upgraded SAPWAT4 program is on the CD inside the back cover of his report.**

2.1.2.2 System requirements

SAPWAT4 requires about 5 GB disk space for its program and data files.

2.1.2.3 Data security and reinstallation

On reinstallation the user's data files are not overwritten as a means of retaining existing data.

2.2 Introduction to the program

SAPWAT4 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 2-1. Central to the design is the SAPWAT4 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 strategy and rainfall to give an estimated irrigation requirement on a daily, weekly or monthly basis (Van Heerden *et al*., 2008).

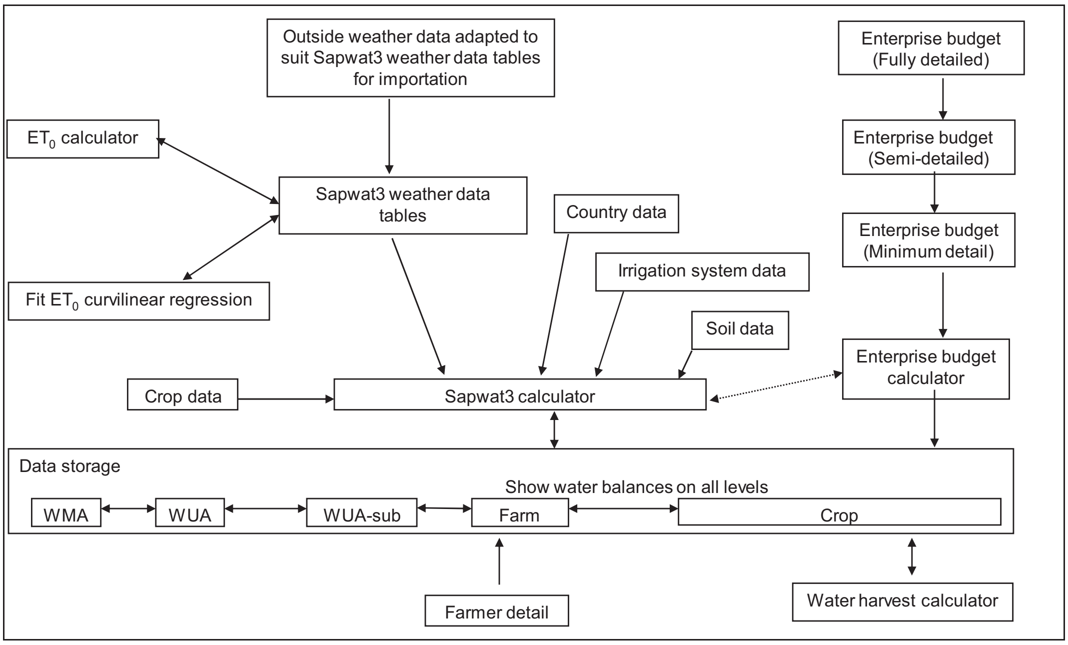


Figure 2-1 Diagrammatic layout of SAPWAT4 structure where WMA = water management area; WUA= water user's association area; WUA-sub = water user's association sub-area

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 ET_0 data (Snedecor and Cochran,1989) to enable the program to do daily water balance calculations, even in cases where available weather data is 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 *et al.*, 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. SAPWAT4 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 2-2) which works well for the backward summation but does add to the complicity 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.

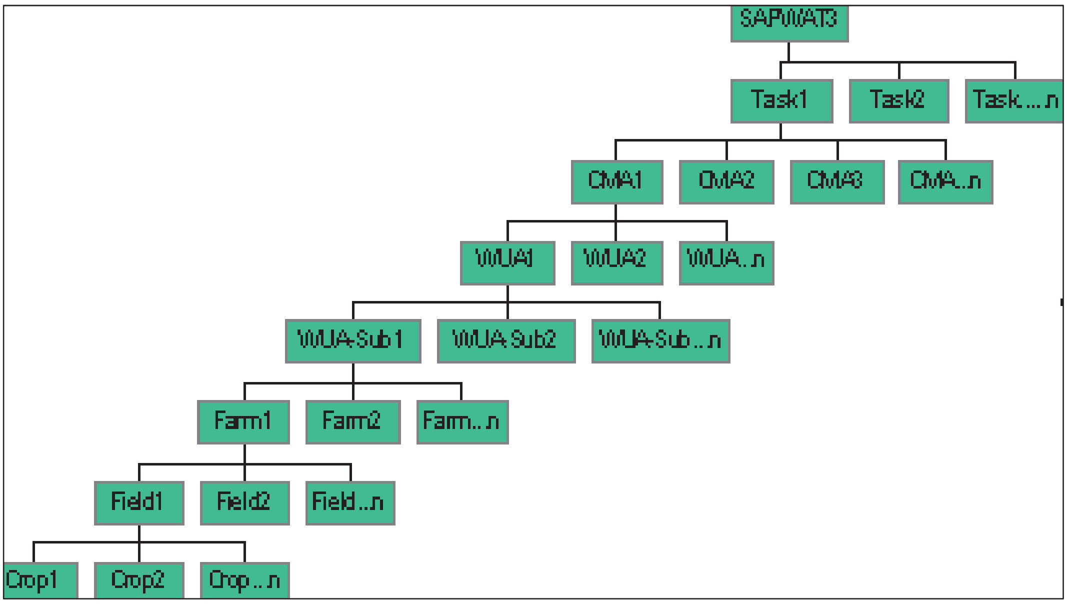


Figure 2-2 The hierarchical organisation of data in SAPWAT4 (CMA = catchment management agency; WUA= water users association area; WUA-sub = water users association sub-area)

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).

At start-up SAPWAT4 displays the screen shown in Figure 2-3.

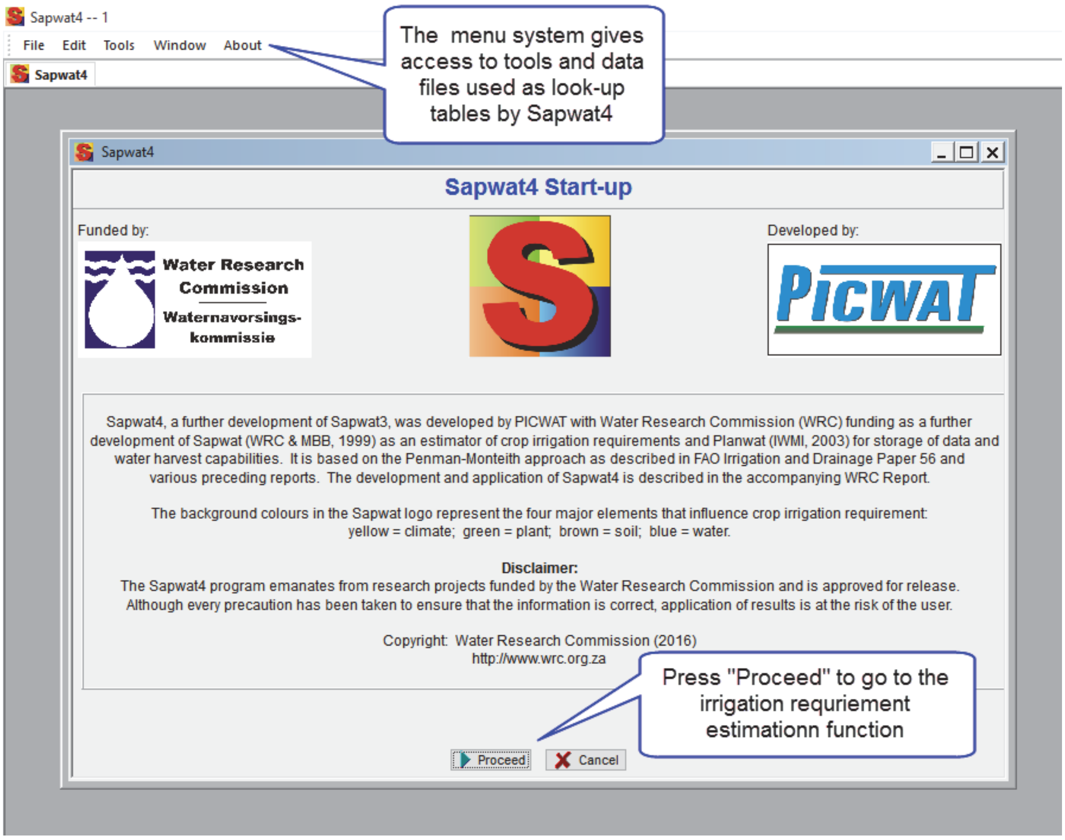


Figure 2-3 The SAPWAT4 Opening screen

Pushbuttons generally used in SAPWAT4 and their meanings are as follows:

Add a new record

Edit a record

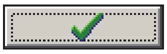
Save changes made to a record

Abandon changes made to a record

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

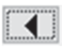
Export data for use in spread sheets or other data management programs


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

Selected record

2.3 The main program

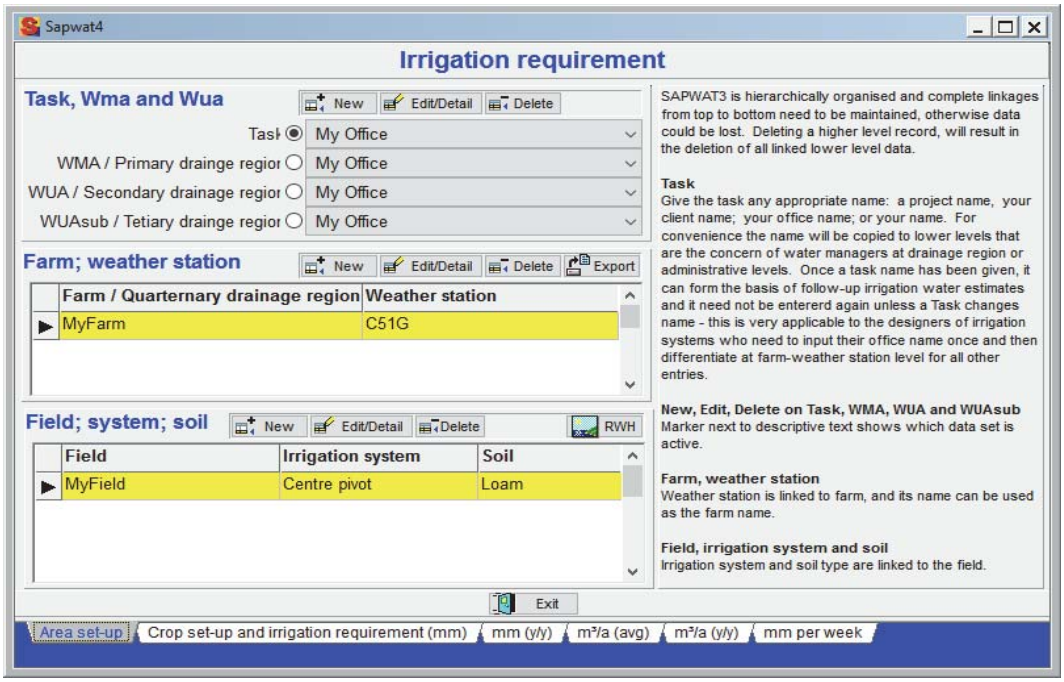


Figure 2-4 The area set-up screen of SAPWAT4. The detail of the task, WMA, WUA and WUA-sub areas are hidden in the background. Clicking on the "Edit/Detail" button will open the detail. The radio button (black dot) shows the selected level. RWH-button takes the user to the rainwater harvesting screen, only active for small areas.

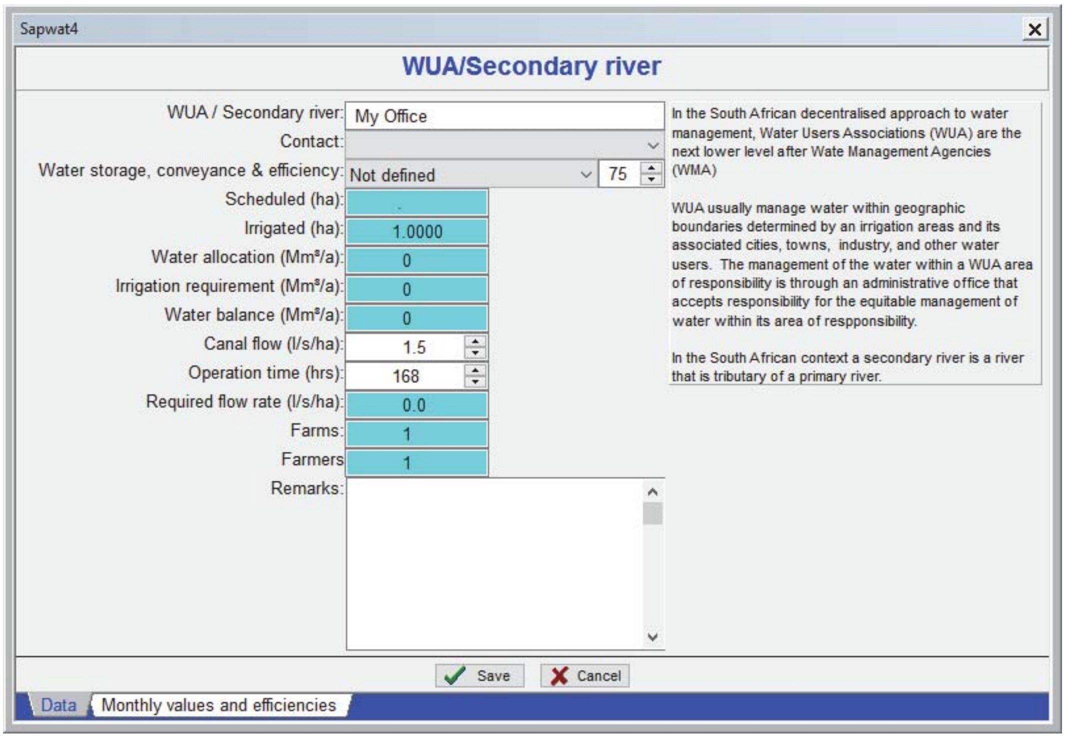


Figure 2-5 The detail screen for a WUA. WMA and WUA-sub areas screens are similar. The only data that the user can change on this screen relates to name, canal flow and remarks. All other numerical data is summed from lower levels.

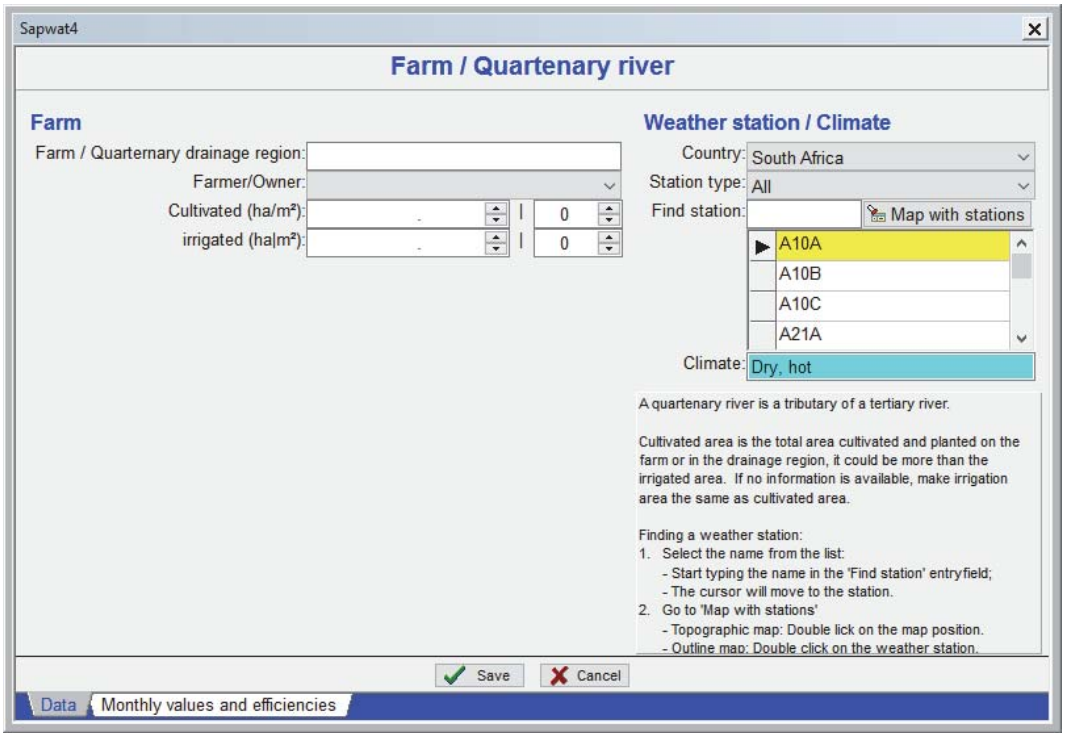


Figure 2-6 The add a new farm screen. Only necessary data input from the user is required. Cultivated ha must be bigger or the same as irrigated ha. Weather station can be selected from list, or the user can click on the "Map with stations" button to open a map from which weather stations can be selected.

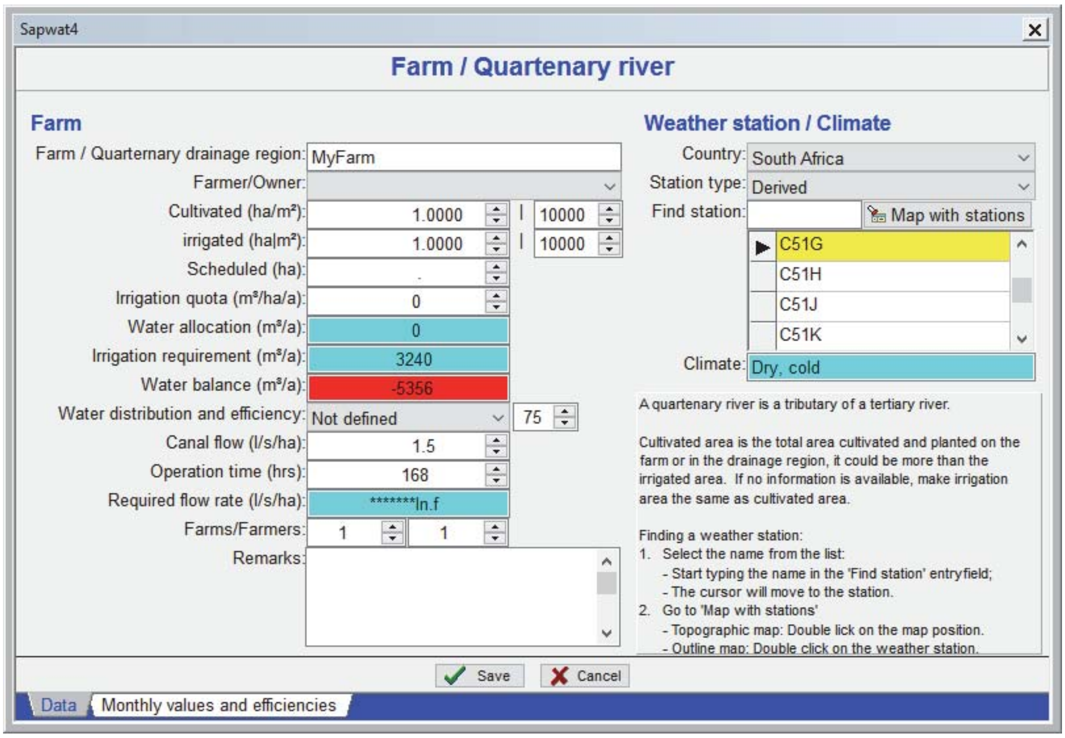


Figure 2-7 The farm detail screen with its more detail concerning the farm, including summed field data for total crop area and total water requirement. Values in red indicate over-use – not correct in this case because the farm irrigation quota (water use right) has not yet been entered. Selected weather station is the derived station for quaternary drainage region Q51G, which is situated in a dry, cold climate.

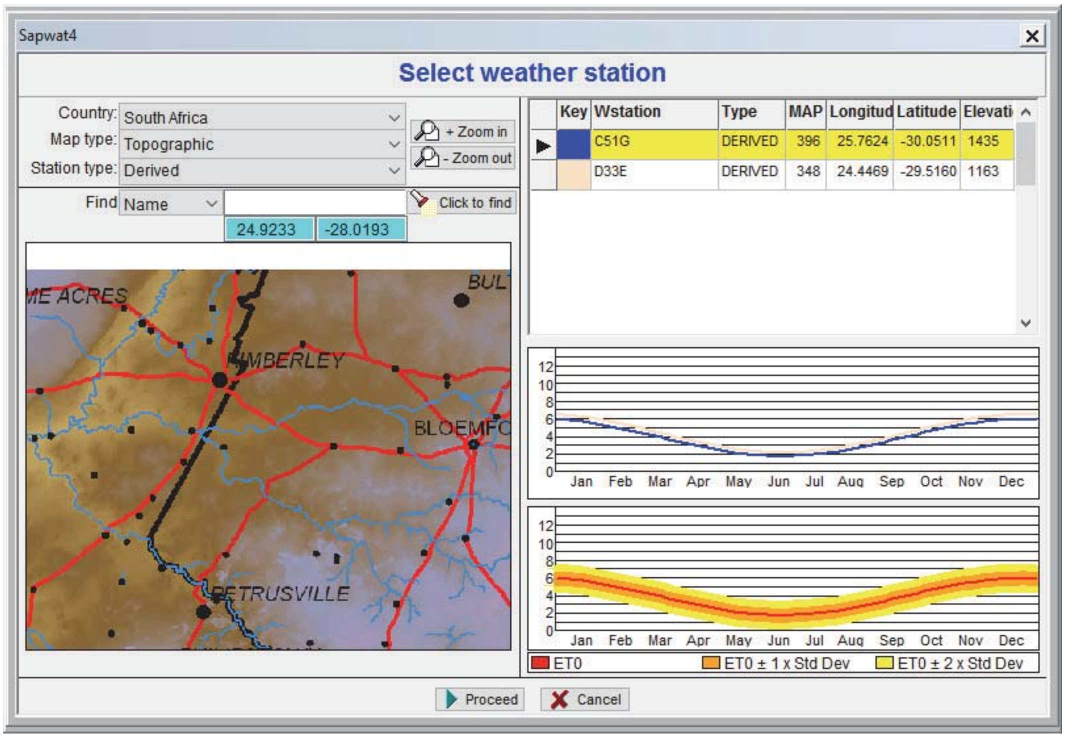


Figure 2-8 The select a weather station screen, showing an enlarged part of the South African map. Double clicking on a topographic map selects the nearest weather station, otherwise clicking on a weather station, selects it. The final selected station (marked in yellow) is linked to the farm data and is used for estimating irrigation requirement estimates.

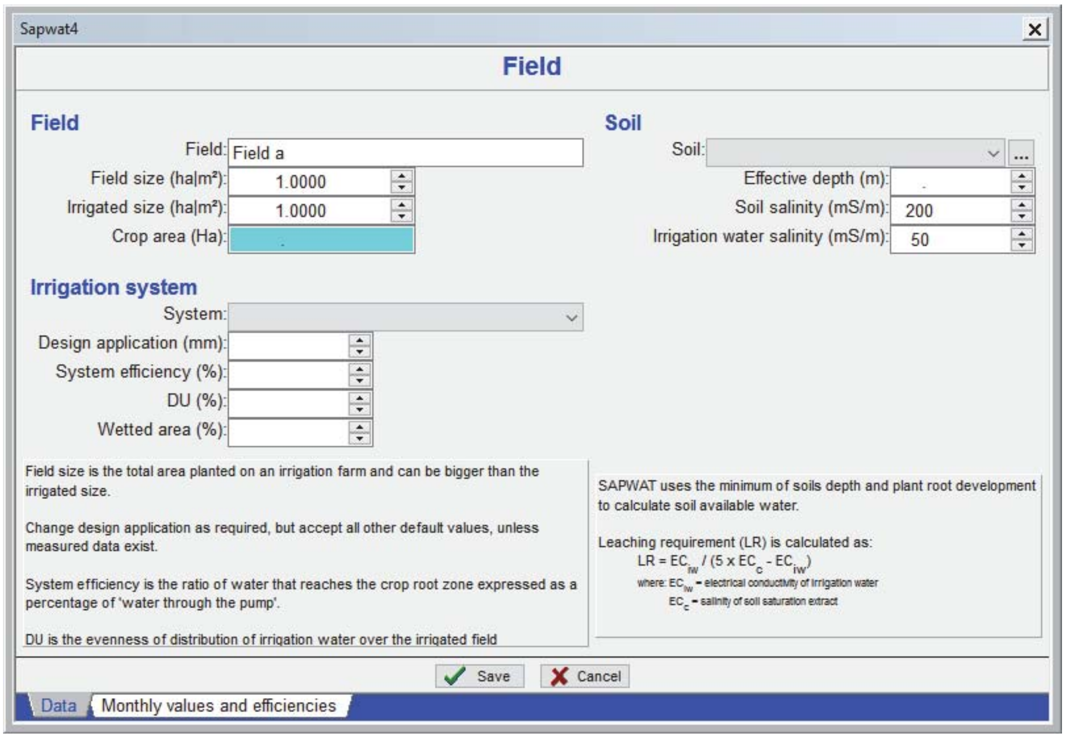


Figure 2-9 The new field screen. Basic irrigation system and soil data is required. Selecting a soil or an irrigation system will display the data contained in the look-up tables, so the user does not need to either know or input those values, unless the user has measured data for the specific field. If field name is cleared before saving, the field is named based on a combination of system on soil (e.g. "Centre pivot on loam"). Both irrigation system and soil type are selected from drop-down lists.

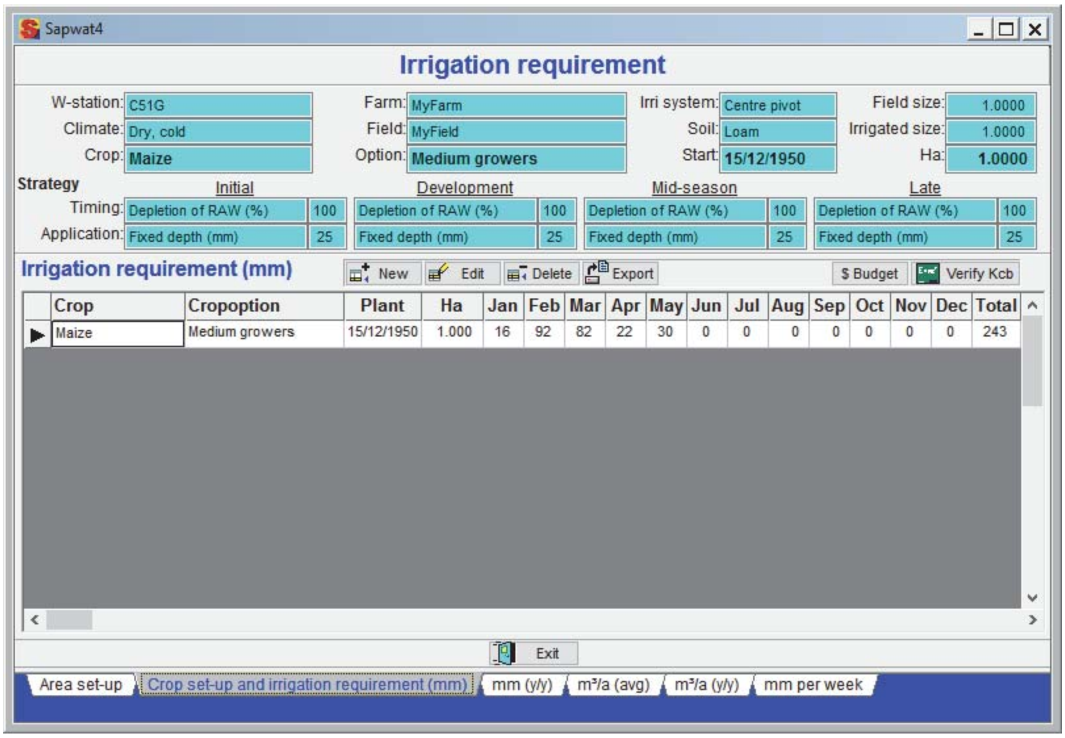


Figure 2-10 The irrigation requirement screen from which the irrigation requirement estimation function is accessed. Upper part of the screen shows farm and field information as well as crop and irrigation management information. Note pushbuttons for linking crop water use to budget and for verification of K_{cb} values. Crop area can be altered under m^3/a (avg) tab.

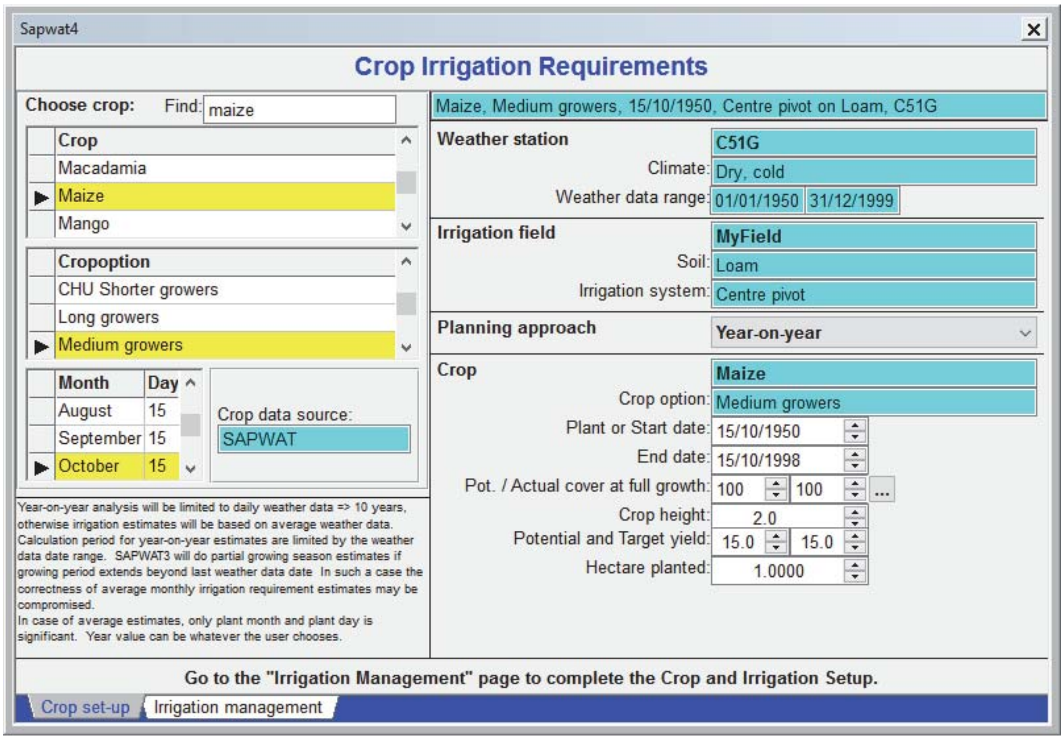


Figure 2-11 Page 1 of the crop set-up screen for doing an irrigation requirement estimation. The plant or start date on the right hand part of the screen can be altered to deviate from that selected on the left. The user is advised to limit such deviations to less than 10 days. If target yield is shown as lower than potential, a water stress situation will be simulated – irrigation requirement will be reduced so that yield reduction will approximate the target yield shown in this field (Paragraph 3.7.2.5).

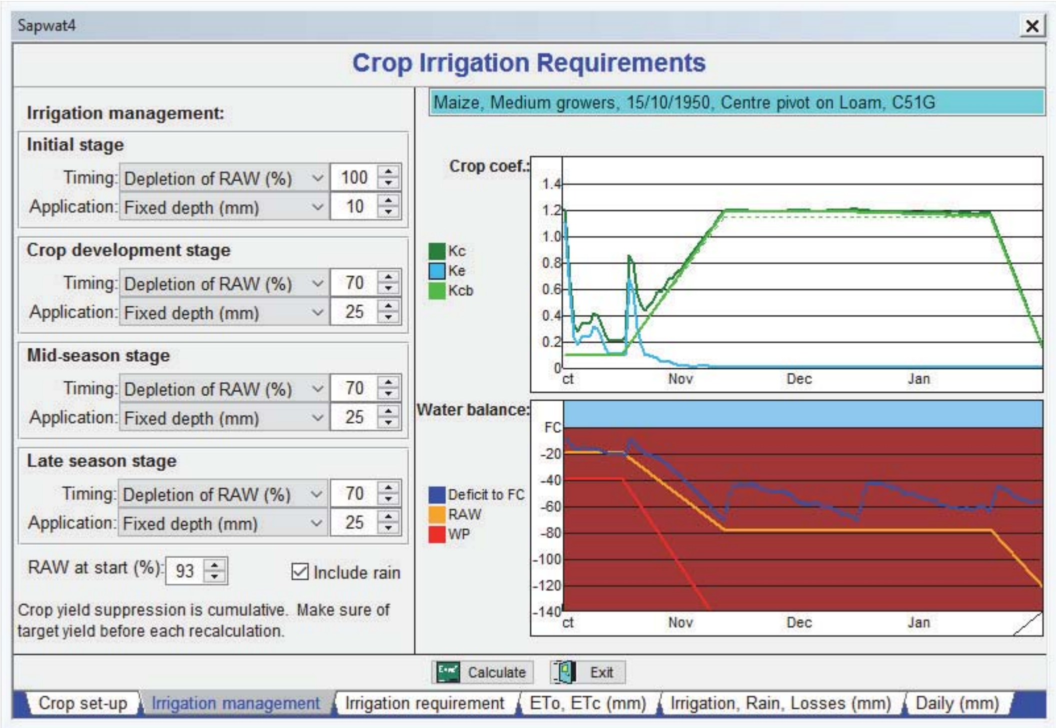


Figure 2-12 Page 2 of the crop set-up screen after doing an irrigation requirement estimation by clicking the calculate button. Irrigation scheduling approach is indicated, soil water balances and crop coefficient values are shown graphically.

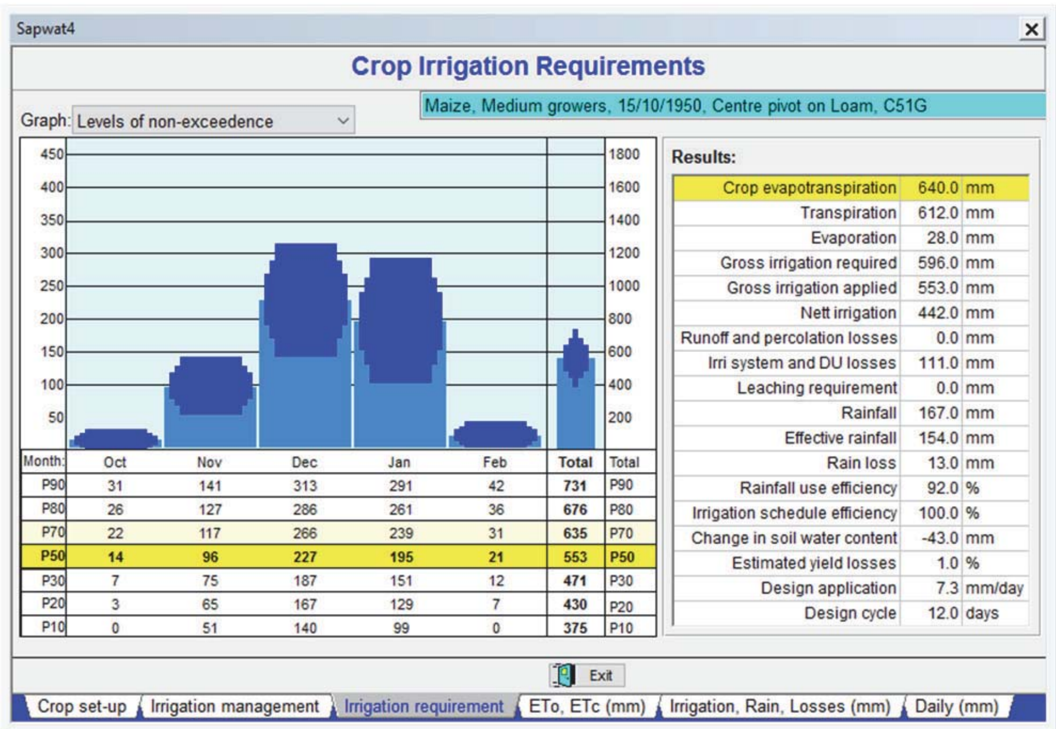


Figure 2-13 The crop irrigation requirement screen. P-values are levels of non-exceedance, with P50 = 50% non-exceedance (average) normally used for planning, design and administrative purposes. P80 means that in eight out of ten years (80% of time), the relevant value will probably not be exceeded; crop irrigation requirement aimed for in this case, should be 676 mm instead of the average of 553 mm. One of the aims is to get rainfall use efficiency as high as possible; 92% in this case, because that is free water. Total rainfall is rainfall during the growing season of the crop.

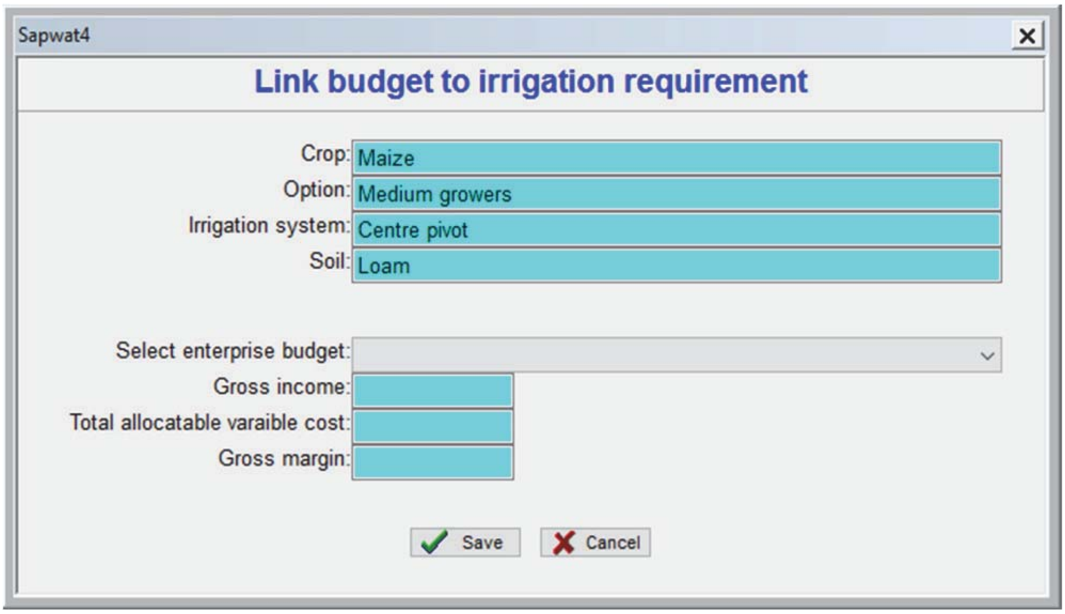


Figure 2-14 The screen form where the user selects the enterprise budget that should be linked to the irrigation water requirement estimate. The budget itself is built under the Files – > Budget function (Discussed in detail in paragraph 3.5).

2.4 Crop K_{cb} calibration

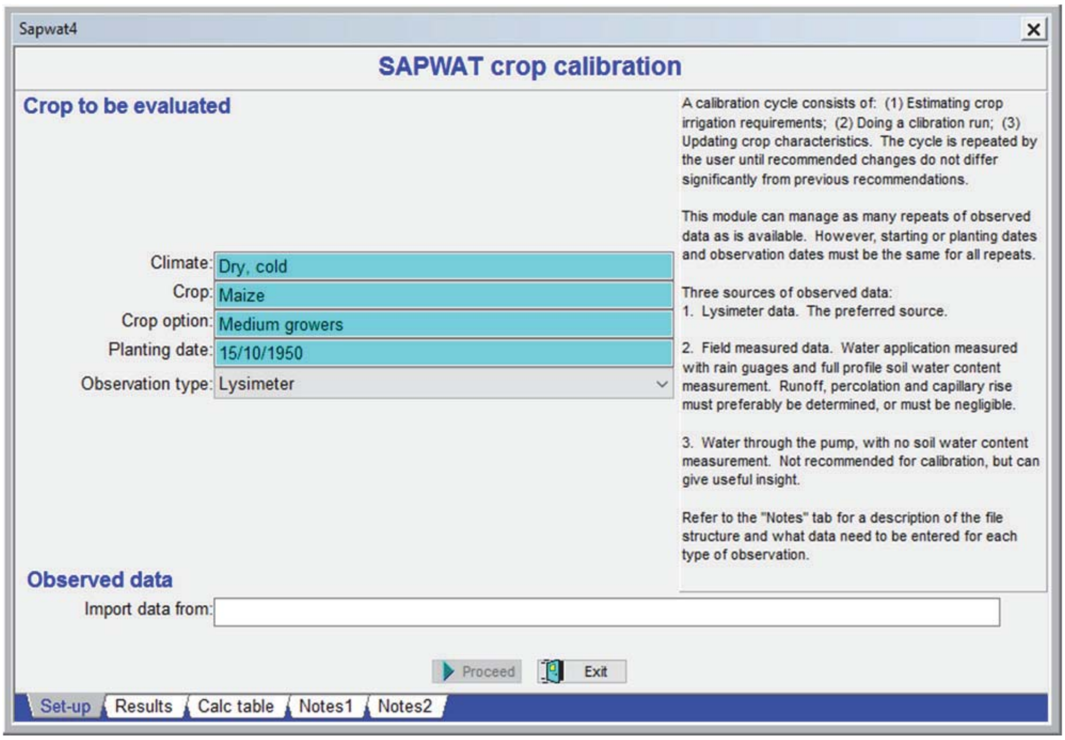


Figure 2-15 The set-up screen for calibrating K_{cb} values. An irrigation requirement estimate is done, exported to a CSV file which is linked to this module, it is statistically compared to observed data from the source file and adjustments in K_{cb} values and growth stages is recommended. If the user accepts the adjusted values, the crop detail table is updated, a rerun of irrigation requirement is done and the verification module called again. This process is repeated until recommended changes become small enough to be deemed as insignificant (Detailed discussion in Chapter 5).

2.5 Rainwater harvest

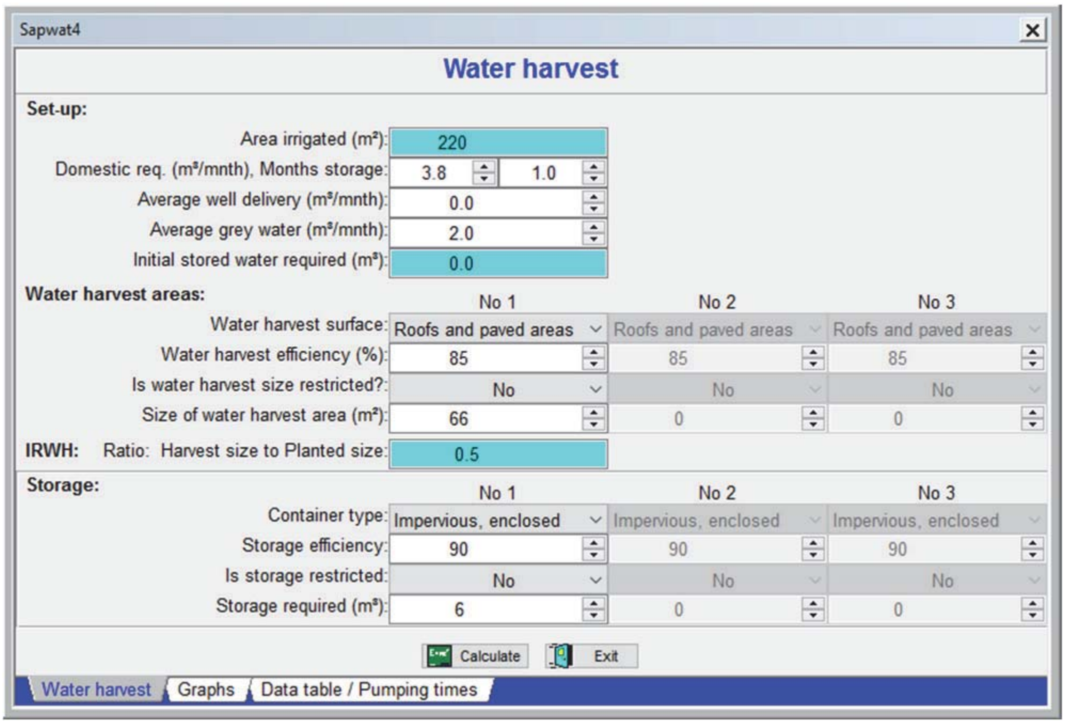


Figure 2-16 The set-up screen for rainwater harvesting (Discussed in paragraph 3.6).

2.5.1 The File Menu items

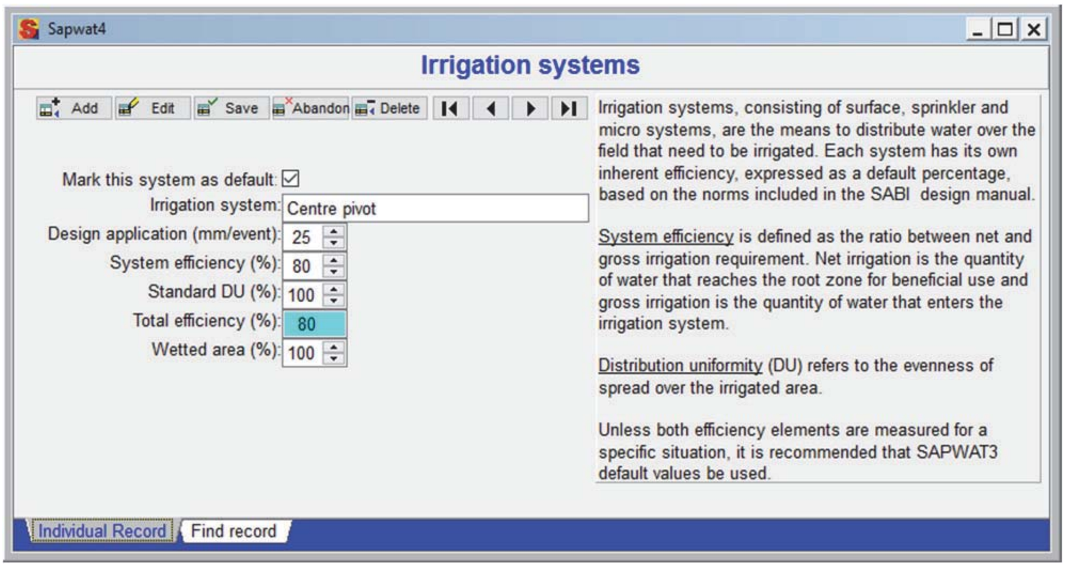


Figure 2-17 The irrigation systems screen.

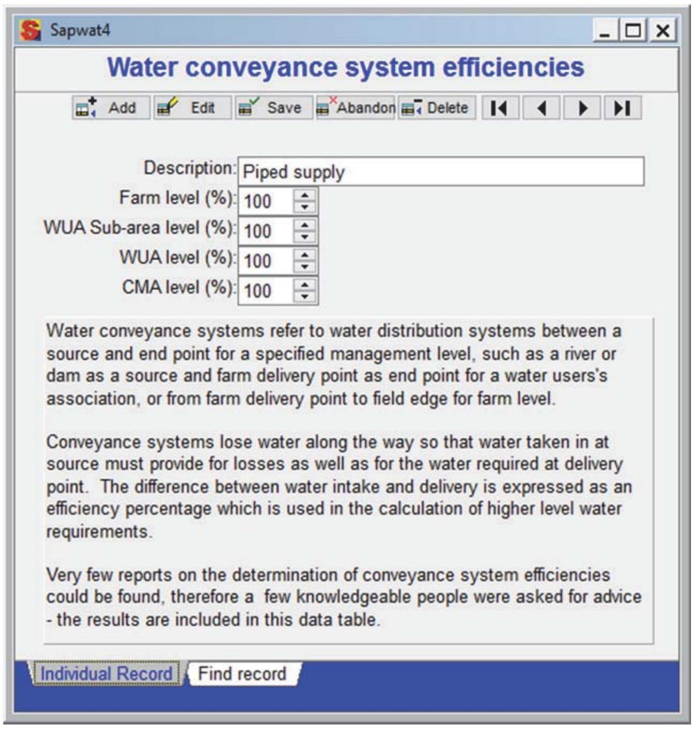


Figure 2-18 Distribution systems and efficiencies screen form.

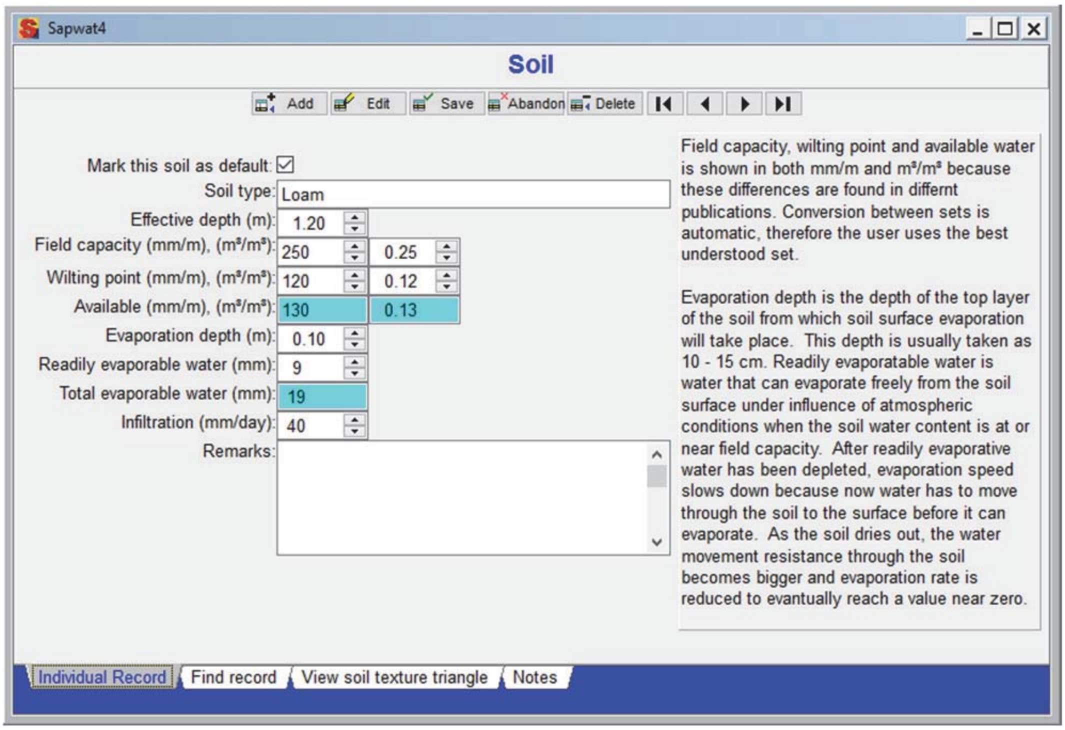


Figure 2-19 The soil screen form.

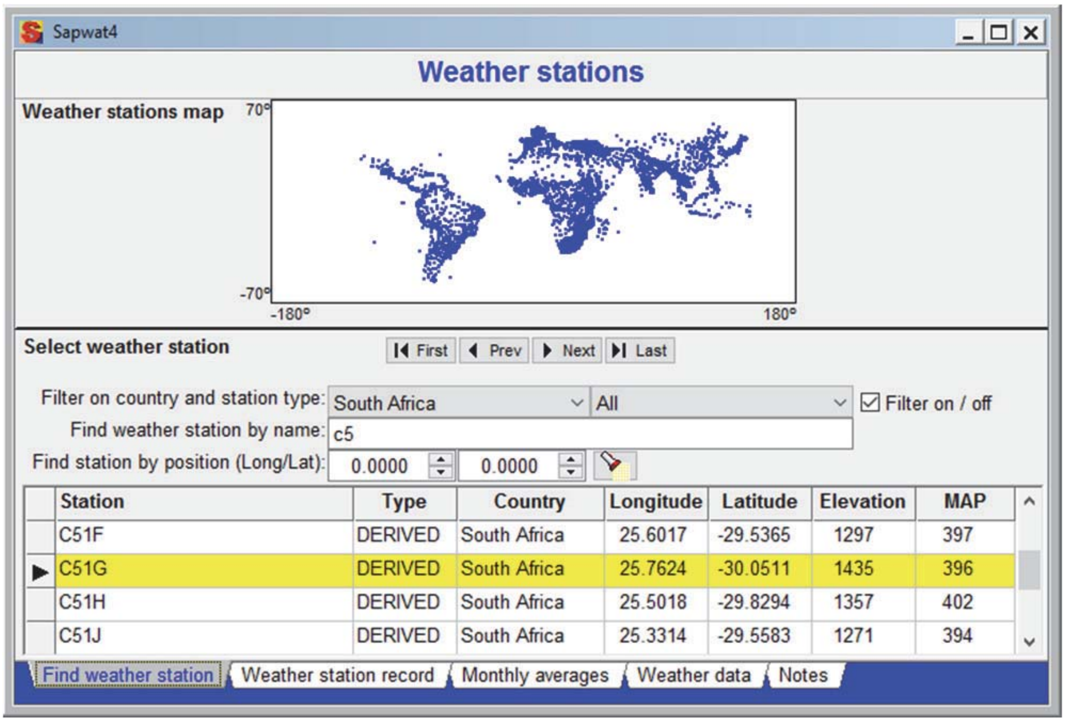


Figure 2-20 List of weather stations included from which a station can be selected (Detailed discussion in paragraph 3.7.2.1)

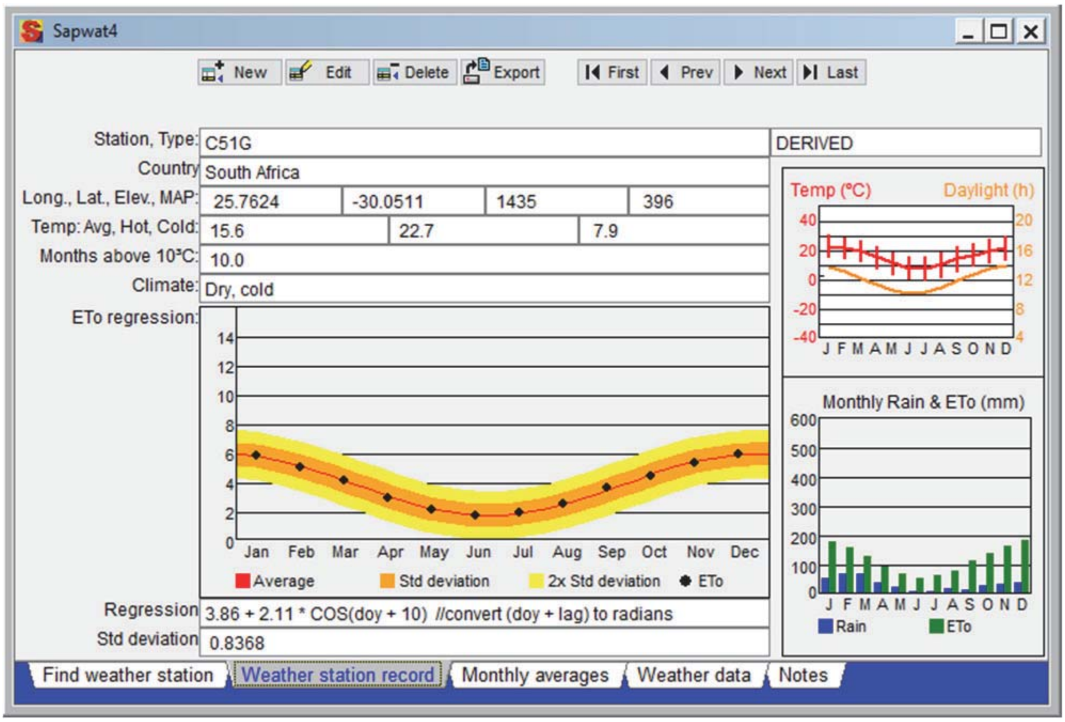


Figure 2-21 Weather station detail. The ET_0 graph shows the average line as well as 1- and 2-standard deviation to give an idea of the variability of the climate data. At the bottom right the precipitation is compared on a monthly basis with ET_0. Where ET_0 is more than rain, a water deficit situation occurs. Water deficit of the scope as seen in this figure, usually implies that crop production can only be successful if grown under irrigation.

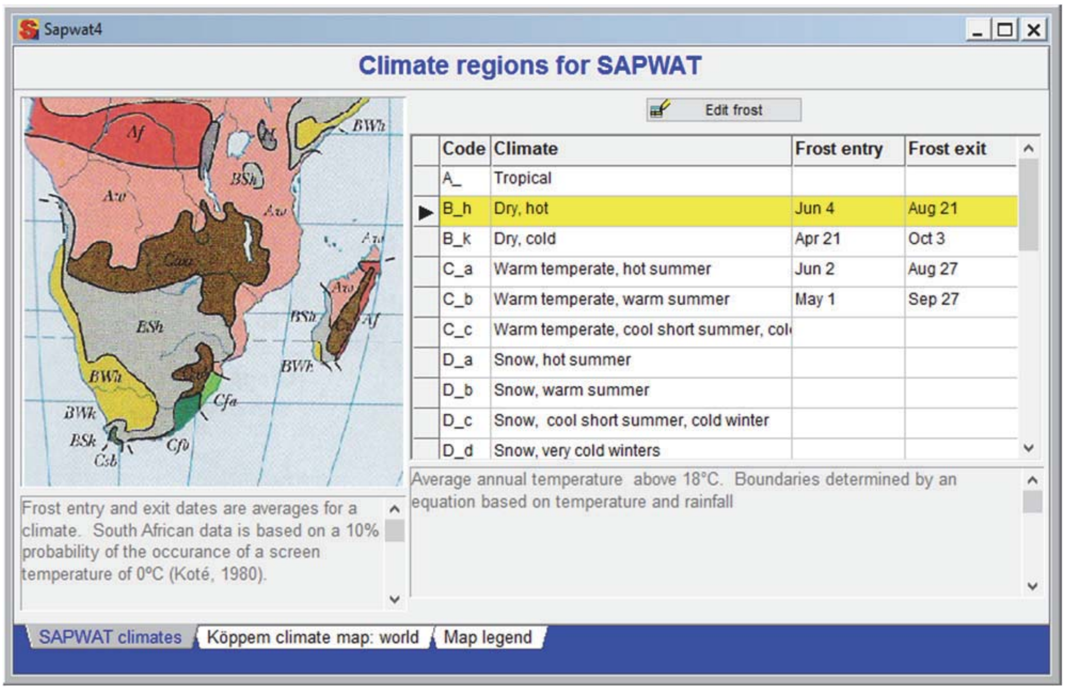


Figure 2-22 The Köppen-Geiger climates of Southern Africa (Discussed in 3.7.2.4)

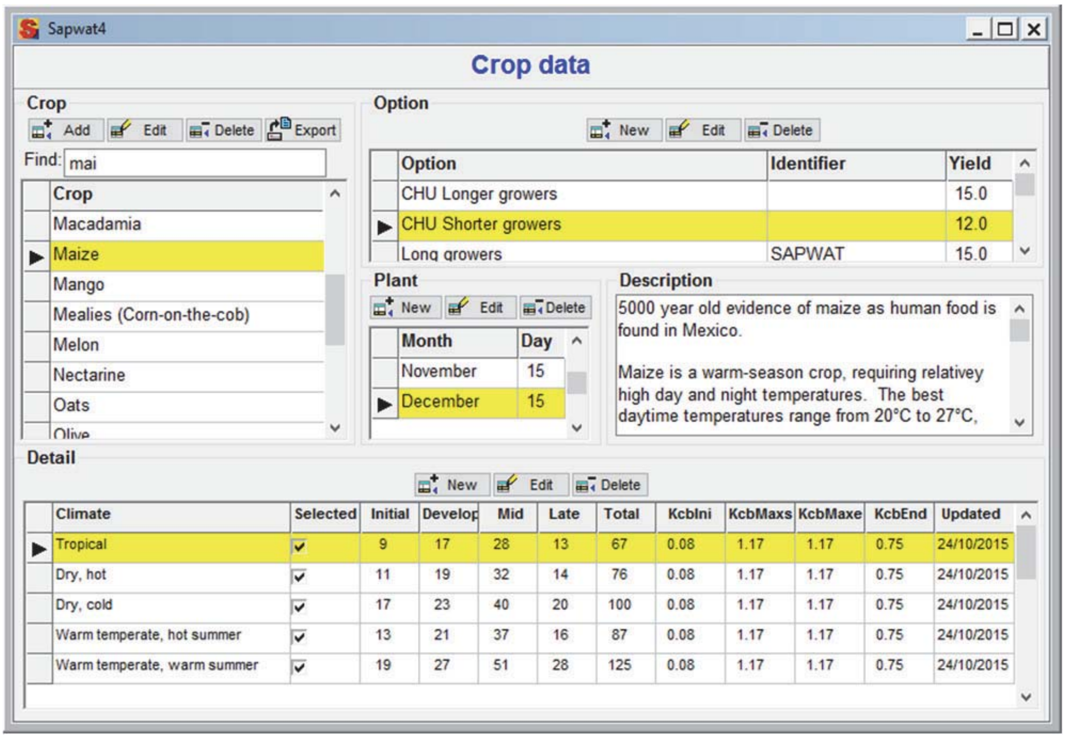


Figure 2-23 The crop data screen. Each of the four different elements, crop, option, plant and climate have their own editing screens where more detail than is shown, can be edited.

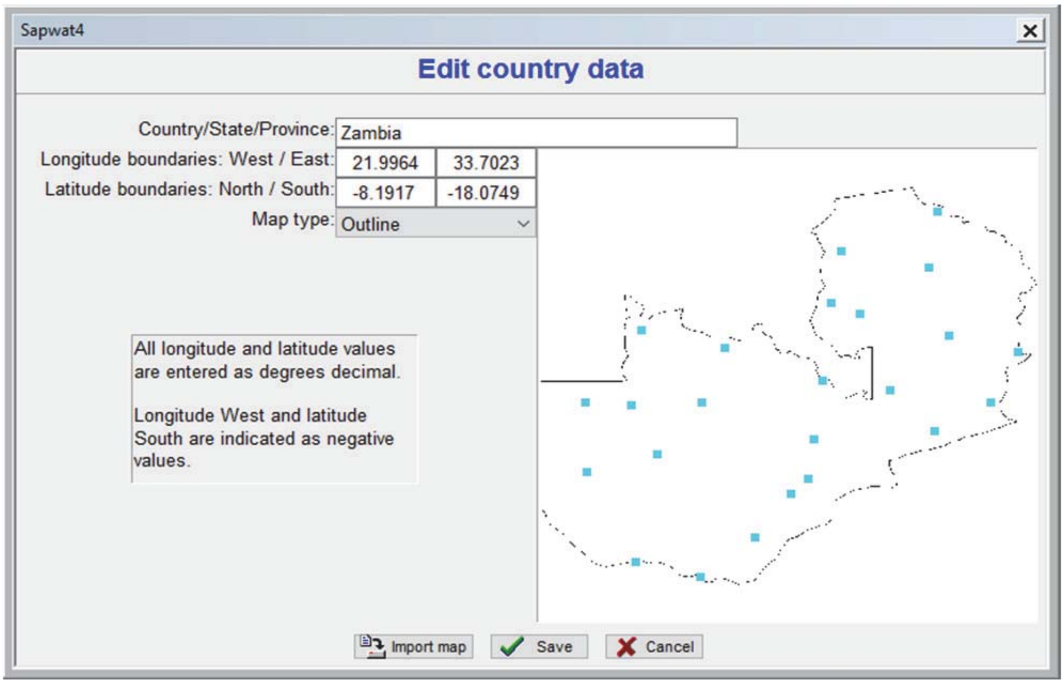


Figure 2-24 A country edit screen showing distribution of Climwat weather stations. Double click on a station will move to the weather data screen for the selected station.

2.5.2 The Tools Menu items

Only one of the items in this menu system needs discussion. The function to update crop data based on thermal time (CHU).

2.5.2.1 Crop growth based on thermal time

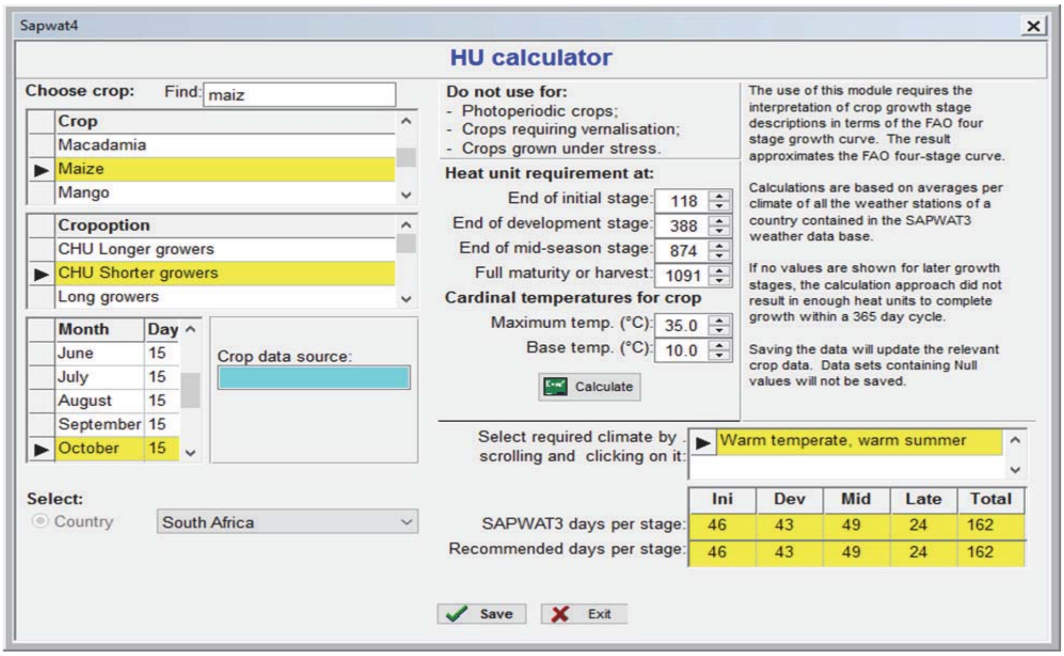


Figure 2-25 The Crop heat unit calculation screen. Clicking the Save pushbutton will update the crop data file (Discussed in Chapter 4).

CHAPTER 3.
Building SAPWAT4

3.1 Introduction

Since the first SAPWAT (Crosby and Crosby, 1999) was developed in late 1990s, and since the publication of its improved SAPWAT3 in 2008, there have been further developments in computer operation systems and programs. Although irrigation principles remain unchanged, the SAPWAT3 program needed 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 program on computers running under newer operating systems. Since its publication the following shortcomings and problems have been identified and needs attention in an upgrade:

- SAPWAT3 needs special installation approaches for 64-bit computers and for Windows 8 and later operating systems, which, if not done, results in program failure;
- Crop data included does not provide enough variation for growth periods as influenced by climate of an area so that over- or under estimates of irrigation water requirement is experienced in some cases;
- Increased functionality related to updating of crop data tables have been requested;
- First screen forms that appear are somewhat off-putting for the majority of users – these increase the perception of complicatedness and require inputs that are perceived as unnecessary by most of the users;
- Important information needed by the program, re farm and field is shown on page 2 instead of on the first operational screen form;
- Some complaints about operational speed being too slow;
- Export functions of results to spreadsheet type programs does not always work correctly – this problem seem to be linked to 64-bit computers and Windows 8 and later operating systems;
- Built-in export functions do not satisfy all export requirements;
- Backward summation of irrigation water requirement from farm level to water user association level does not work correctly when editing data;
- Information required from the user and terms used are not well enough defined or described;

- Some data included needs updating e.g. irrigation system efficiencies as recommended by Reinders (WRC TT 465/10), crop coefficient data resulting in over- and under estimates in excess of 20% (various authors) and soil data not complete enough for the South African situation;
- Requests for the inclusion of small irrigation dam water balances have been received.

Therefore, what is required is the upgrading of SAPWAT3 to a next version that will eliminate the identified shortcomings. This includes the upgrading to fulfil the complete role as a planning aid for irrigation requirements of crops as described by Allen *et al*. (1998). Linked to this, the identified shortcomings should be addressed and satisfied as far as practically possible.

3.2 Objectives

The following objectives were set for the upgrading of SAPWAT4:

To upgrade SAPWAT4 to make it 64-bit and Windows 8 friendly, to update program data and to increase its functionality. This overall objective can be sub-divided into the following specific objectives:

1. To update included irrigation system, soil and crop data to reflect research results published after the publication of SAPWAT4 version 1;
2. To move farm and field information input screen to screen page 1;
3. To simplify data input screens by shifting lesser-used screen forms to the background;
4. To increase functionality by including a module or modules that can use research results to update crop data tables;
5. To give the user the choice of using thermal time or calendar time when estimating irrigation water requirements;
6. To increase operational speed by reprogramming the calculation modules;
7. To correct programming errors in the present version of SAPWAT3;
8. To eliminate reported programming omissions;
9. To attempt to include small irrigation dam water balances in SAPWAT4;
10. To make SAPWAT4 Windows 8 and 64-bit system friendly by reprogramming in a Windows 8 friendly version of dBase;
11. To build and compile the complete program, SAPWAT4, and to update the user manual to reflect the proposed changes.

3.3 The SAPWAT4 programming approaches

The requirement at this stage for the development of SAPWAT4 is to satisfy these objectives and this work received funding from South African Water Research Commission (WRC Project No. K8/1154). 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. The programming is still done in dBase because of its data management capabilities and because it is a front-end data management 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, 2014e).

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 FAO56 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 (1)) (Allen *et al*., 1998):

$$ET_c = K_c \times ET_0 \tag{1}$$

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

K_c crop coefficient,

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

SAPWAT4 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 (1) then becomes Equation (2) (Allen *et al*., 1998). This is this approach that is used in SAPWAT3 (Van Heerden *et al.*, 2008) and is continued in SAPWAT4:

$$ET_c = \left(K_{cb} + K_e\right) ET_0 \tag{2}$$

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 (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 0 (Allen *et al*., 1998).

3.4.1 Irrigation strategy

SAPWAT4 provides the user with the possibility to define an irrigation strategy for each of the four crop growth stages. These can be any combinations 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 SAPWAT4

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):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where: ET_0 reference evapotranspiration (mm day^{-1}),

R_n net radiation at the crop surface (MJ m^{-2} day^{-1}) (Equation (32)),

G soil heat flux density (MJ m^{-2} day^{-1}) (Equation (33)),

T mean daily air temperature at 2 m height (˚C) (lookup Weatherdata.dbf, Equation (6)),

u_2 wind speed at 2 m height (m s^{-1}) (Equation (37)),

e_s saturated vapour pressure (kPa) (Equation (9)),

e_a actual vapour pressure (kPa) (Equation (11)),

e_s-e_a saturated vapour pressure deficit (kPa),

Δ slope of vapour pressure curve (kPa $˚C^{-1}$) (Equation (10)),

ϒ psychrometric constant (kPa $˚C^{-1}$) (Equation (4)).

3.4.2.1 The psychrometric constant

The psychrometric constant (γ) relates the partial pressure of water in air to the air temperature, 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 SAPWAT4 because an average atmospheric pressure is used for each location (Allen *et al.*, 1998). The equation for calculating the psychrometric constant is:

$$\gamma=\frac{c_p P}{\varepsilon\lambda}=0.665\times10^{-3}P \tag{4}$$

where: ϒ psychrometric constant ($kPa\,^{\circ}C^{-1}$),

P atmospheric pressure (kPa) (Equation (5)),

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

c_p specific heat at constant pressure = 1.013×10^{-3} ($MJ\ kg^{-1}\,^{\circ}C^{-1}$),

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 (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):

$$P=101.3\left(\frac{293-0.0065z}{293}\right)^{5.26} \tag{5}$$

where: P atmospheric pressure (kPa),

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

3.4.2.1.1 Application in SAPWAT4

SAPWAT4 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 (5));
3. The psychrometric constant is then calculated using Equation (4).

3.4.2.2 Air temperature

Air temperature monitoring instruments are usually housed in Stevenson screens, which is set up so that the height of the thermometer inside the screen is at a height of between 1.25 m and 2 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).

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \qquad (6)$$

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 SAPWAT4 use of this equation

SAPWAT4 applies Equation (6) to calculate mean temperature from recorded maximum and minimum daily temperature data contained in the SAPWAT4 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 3-1). 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 (6)) (Allen *et al*., 1998).

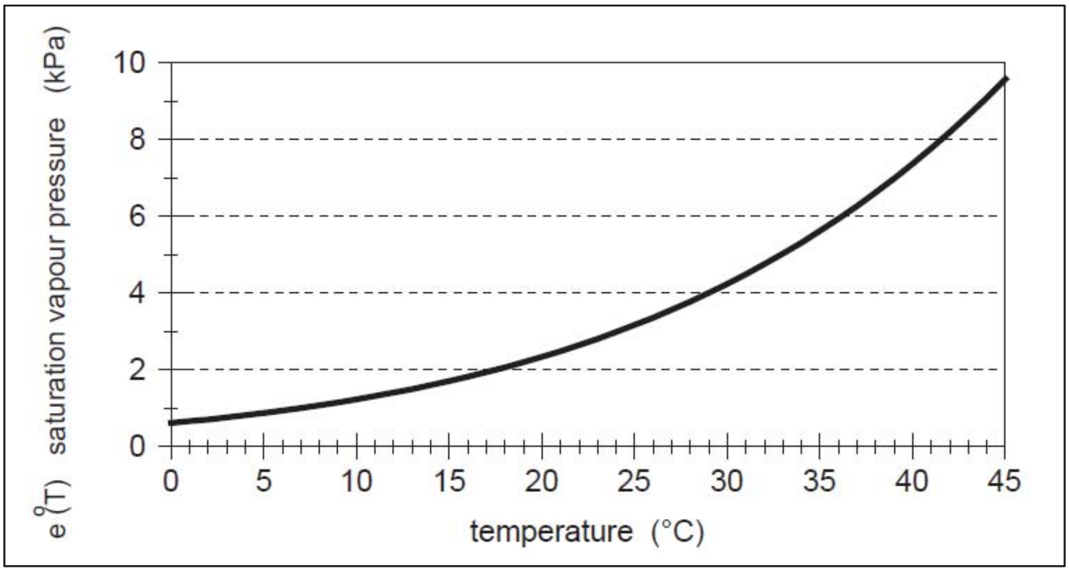


Figure 3-1 Saturated vapour pressure shown as a function of temperature (Allen *et al.*, 1998)

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 of 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 (7) (Allen *et al.*, 1998).

$$RH = 100 \frac{e_a}{e^0(T)} \qquad (7)$$

where: RH relative humidity,

e_a actual vapour pressure (Equations (11), (12), (14), (15) or (16), depending on availability of data),

$e^0(T)$ saturated vapour pressure at the same temperature (Equation (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 3-2) (Allen *et al*., 1998).

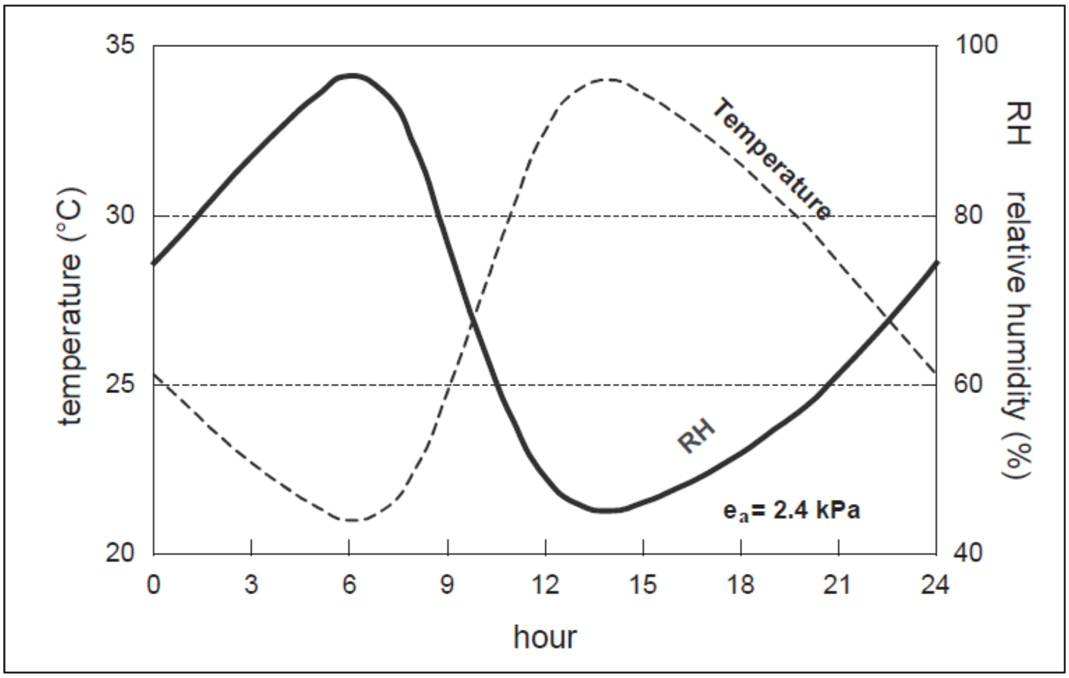


Figure 3-2 Variation of the relative humidity over 24 hours for a constant actual vapour pressure (e_a) of 2.4 kPa (Allen *et al*., 1998)

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 (8) (Allen *et al*., 1998):

$$e^0(T)=0.6108\exp\left(\frac{17.27T}{T+237.3}\right) \tag{8}$$

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 (8) the mean saturated vapour pressure for a period needs to be calculated with Equation (9) (Allen *et al*., 1998):

$$e_s=\frac{e^0(T_{max})+e^0(T_{min})}{2} \tag{9}$$

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

$e^0(T_{max})$ saturated vapour pressure at maximum temperature (kPa) (Equation (8)),

$e^0(T_{min})$ saturated vapour pressure at minimum temperature (kPa) (Equating (8)).

For the calculation of evapotranspiration, the slope of the relationship between saturated vapour pressure and temperature is required. Equation (10) calculates the slope of the vapour pressure at temperature T (Allen *et al*., 1998).

$$\Delta=\frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \tag{10}$$

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 (11) uses dew point temperature to calculate actual vapour pressure (Allen *et al*., 1998).

$$e_a = e^0(T_{dew}) = 0.6108 \exp\left(\frac{17.27 T_{dew}}{T_{dew} + 237.3}\right) \tag{11}$$

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.(12) (Allen *et al*., 1998):

$$e_a = e^0(T_{wet}) - \gamma_{psy}(T_{dry} - T_{wet}) \tag{12}$$

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):

$$\gamma_{psy} = a_{psy} P \tag{13}$$

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

P atmospheric pressure (kPa) (Equation (5)),

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

a_{psy}= 0.000662 ventilated psychrometers with 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:

$$e_a = \frac{e^0\left(T_{min}\right)\frac{RH_{max}}{100} + e^0\left(T_{max}\right)\frac{RH_{min}}{100}}{2} \tag{14}$$

where:	e_a	actual vapour pressure (kPa),
	$e^0(T_{min})$	saturated vapour pressure at daily minimum temperature (kPa) (Equation (8)),
	$e^0(T_{max})$	saturated vapour pressure at daily maximum temperature (kPa) (Equation (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:

$$e_a = e^0(T_{min})\frac{RH_{max}}{100} \tag{15}$$

where:	e_a	actual vapour pressure (kPa),
	$e^0(T_{min})$	saturated vapour pressure at daily minimum temperature (kPa) (Equation (8)),
	RH_{max}	maximum relative humidity (%) (lookup weatherdata.dbf).

- When RH_{mean} is available:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^0\left(T_{max}\right) + e^0\left(T_{min}\right)}{2}\right] \tag{16}$$

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 (8)),
	$e^0(T_{min})$	saturated vapour pressure at daily minimum temperature (kPa) (Equation (8)).

Once the actual vapour pressure is obtained, the vapour pressure deficit is calculated with Equation (17) (Allen *et al*., 1998):

$$\text{vapour pressure deficit} = e_s - e_a \tag{17}$$

where: e_s saturated vapour pressure (kPa) (Equation (9)),

e_a actual vapour pressure (kPa).

3.4.2.3.4 Application in SAPWAT4

SAPWAT4 goes through a series of steps to determine air humidity:

1. Saturated vapour pressure for maximum and minimum temperatures are calculated with Equation (8). Maximum and minimum temperatures are read from the weather data tables in SAPWAT4.
2. The mean saturated vapour pressure is then calculated with Equation (9).
3. The slope of the saturated pressure curve is calculated with Equation (10).
4. SAPWAT4 then calculates the actual vapour pressure from relative humidity; because this data is available in the weather data table of SAPWT3.
    a. If both RH_{max} data and RH_{min} data are available, actual vapour pressure is derived using Equation (14);
    b. If only RH_{max} data is available, Equation (15) is used;
    c. If only RH_{mean} data is available, Equation (16) is used.
5. The vapour pressure deficit is than calculated with Equation (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 3-3) (Allen *et al*., 1998; Wikipedia, 2014e).

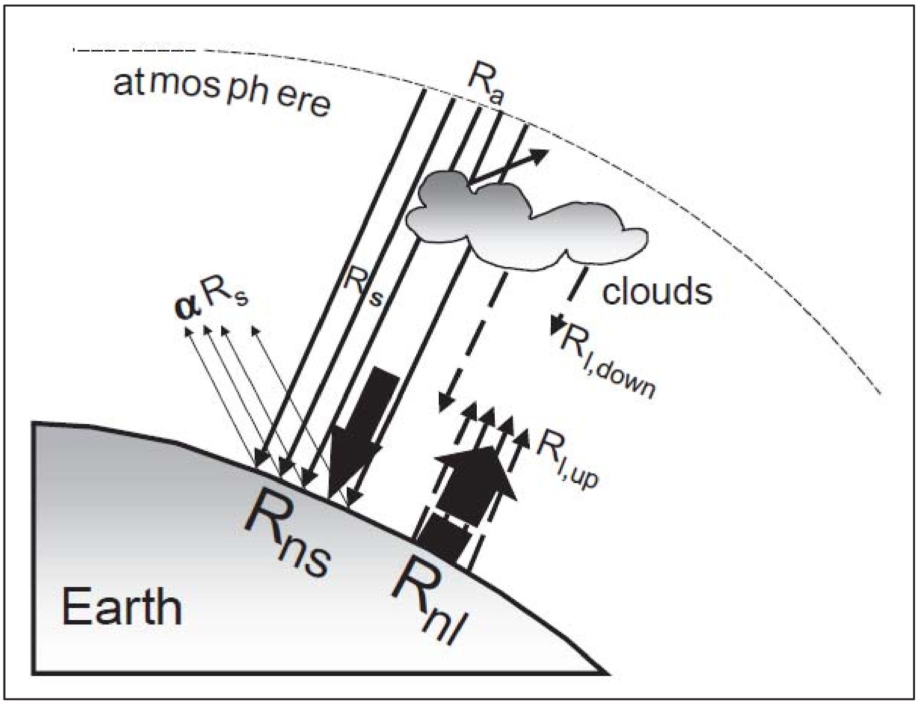


Figure 3-3 A diagrammatic representation of radiation, showing the sub-units that comprise it. (R_a = extra-terrestrial radiation; R_s = solar or shortwave radiation; R_{ns} net solar radiation; α = albedo; R_l = long wave radiation, with up and down components; R_{nl} = net long wave radiation) (Allen *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} day^{-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} day^{-1} (Allen *et al*., 1998; Wikipedia, 2014e).

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 (Rs/Rso). 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, 2014e).

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} day^{-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, 2014e).

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):

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \quad (18)$$

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 (21)),
- ω_s sunset hour angle (rad) (Equation (23) or Equation (24)),
- φ latitude (rad) (Equation (20)),
- δ solar declination (rad) (Equation (22)).

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

$$\text{equivalant evaporation} = 0.408 \times R_a \quad (19)$$

where:
- Equivalent evaporation: equivalent evaporation (mm day^{-1}),
- R_a: extra-terrestrial radiation (MJ m^{-2} d^{-2}) (Equation (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):

$$\text{Rad}=\frac{\pi}{180}\left[\text{decimal degrees}\right] \quad (20)$$

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):

$$d_r=1+\cos\left(\frac{2\pi}{365}J\right) \quad (21)$$

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):

$$\delta=0.409\sin\left(\frac{2\pi}{365}J\text{-}1.39\right) \quad (22)$$

where: δ solar declination (rad) (Equation (22)),

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

The sunset hour angle is given by:

$$\omega_s=\arccos\left[-\tan\left(\varphi\right)\tan\left(\delta\right)\right] \quad (23)$$

where: ω_s sunset hour angle (rad),

φ latitude (rad) (Equation (20)),

δ solar declination (rad) (Equation (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)

$$\omega_s = \frac{\pi}{2} - \left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}} \right] \quad (24)$$

where: ω_s sunset hour angle,

φ latitude (rad) (lookup Weatherstations.dbf, Equation (20)),

δ solar declination (rad) (Equation (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 are given by (Allen *et al.*, 1998):

$$N = \frac{24}{\pi}\omega_s \quad (25)$$

where: N maximum possible daylight hours,

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

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \quad (26)$$

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

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

N maximum possible duration of sunshine or daylight hours (h) (Equation (25)),

n/N relative sunshine duration,

R_a extra-terrestrial radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a \tag{27}$$

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

R_a extra-terrestrial radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$R_{so} = (a_s + b_s)R_s \tag{28}$$

where: R_{so} clear sky solar radiation (MJ m^{-2} day^{-1}),

R_s solar or short wave radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$R_{so} = (0.75 + 2\times10^{-5}z)R_a \tag{29}$$

where: R_{so} clear sky solar radiation (MJ m^{-2} day^{-1}),

R_a extra-terrestrial radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$R_{ns}=(1\text{-}\alpha)R_s \tag{30}$$

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

R_s solar or short wave radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$R_{nl}=\sigma\left[\frac{T_{max,K}{}^4+T_{min,K}{}^4}{2}\right]\left(0.34\text{-}0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}}\text{-}0.35\right) \tag{31}$$

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

σ Stefan Boltzmann constant (4.903*10^{-9} MJ K^{-4} m^{-2} day^{-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 (16)),

R_s measured or calculated solar radiation (MJ m^{-2} day^{-1}) (Equation (27)),

R_{so} calculated clear sky radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$R_n = R_{ns} - R_{nl} \qquad (32)$$

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

R_{ns} incoming net short wave radiation (MJ m^{-2} day^{-1}) (Equation (30)),

R_{nl} net long wave radiation (MJ m^{-2} day^{-1}) (Equation (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):

$$G = c_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z \qquad (33)$$

where: G soil heat flux (MJ m^{-2} day^{-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: SAPWAT4 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):

$$G_{day} \approx 0 \qquad (34)$$

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 (33) can be adapted to Equation (35) for monthly calculations (Allen *et al*., 1998):

$$G_{month,i} = 0.07\left(T_{month,i+1} - T_{month,i-1}\right) \qquad (35)$$

where: $G_{month,i}$ soil heat flux for month i (MJ m^{-2} day^{-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 (33) can be adapted to Equation (36) for monthly calculations (Allen *et al*., 1998):

$$G_{month,i} = 0.14\left(T_{month,i} - T_{month,i-1}\right) \quad (36)$$

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

3.4.2.4.8.1 Application in SAPWAT4

For the calculation of net radiation at the crop surface for inclusion in the reference evapotranspiration calculation (Equation (3)), SAPWAT4 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 (21)).
3. Calculate solar declination (Equation (22)).
4. Calculate sunset hour angle (Equation (23)).
5. Calculate daylight hours (Equation (25)).
6. Calculate extra-terrestrial radiation (Equation (18)).
7. Calculate solar radiation if not include in weather data table:
    a. If sunshine hours is given (Equation (26)).
    b. If sunshine hours is not given (Equation (27)).
8. Calculate clear sky radiation (Equation (28)).
9. Calculate net shortwave radiation (Equation (30)).
10. Calculate net long wave radiation (Equation (31)).
11. Calculate the net radiation (Equation (32)).
12. Soil heat flux is calculated as:
    a. If weather data interval is monthly (Equation (36));
    b. If weather data interval is daily, soil heat flux is assumed to be zero (Equation (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, from daily measurements giving 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 (37)) (Allen *et al*., 1998).

$$u_2 = u_z \frac{4.87}{\text{int}(67.8z - 5.42)} \tag{37}$$

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 SAPWAT4

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), except for South African weather stations where the default is 1.6 m s^{-1} (Schulz and Maharaj, 2006).

3.4.3 Crop coefficients

SAPWAT4 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 (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 let the crop grow, similar to crop growth simulation 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. The use of short grass reference evapotranspiration reduces the impact of climatic change 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 is 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 SAPWAT4. 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 SAPWAT4.

The crop coefficients included in the SAPWAT4 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 3-4 and Figure 3-5.

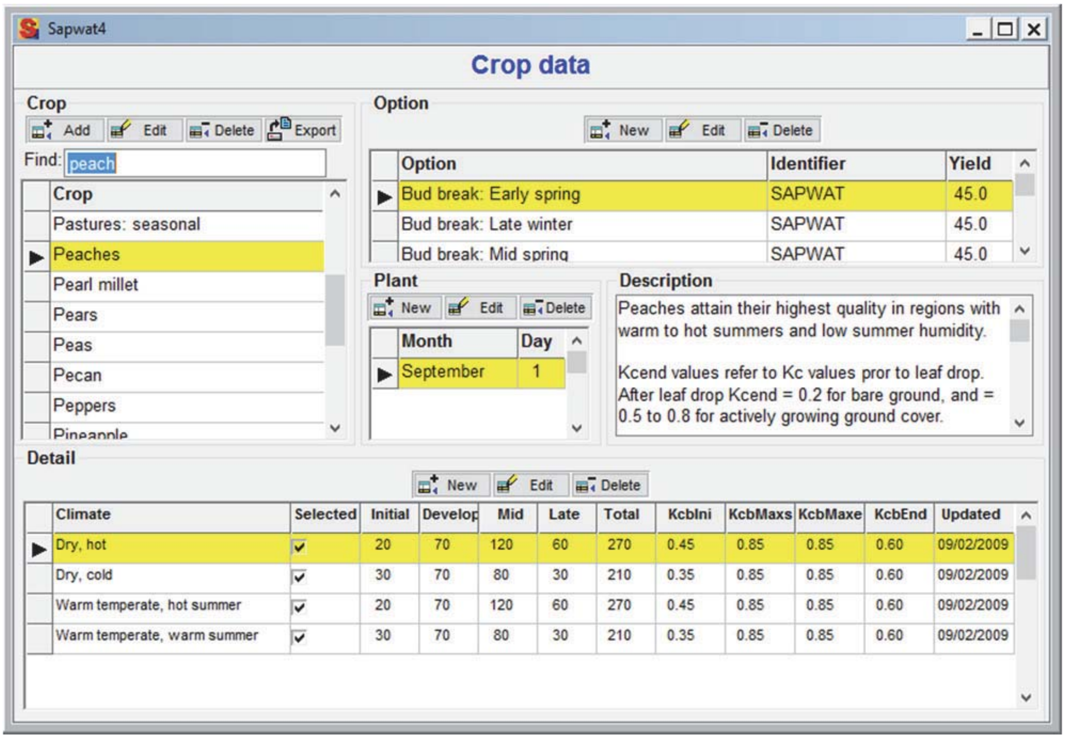


Figure 3-4 Crop data screen showing crop characteristics for peaches, early spring bud break, for different climates

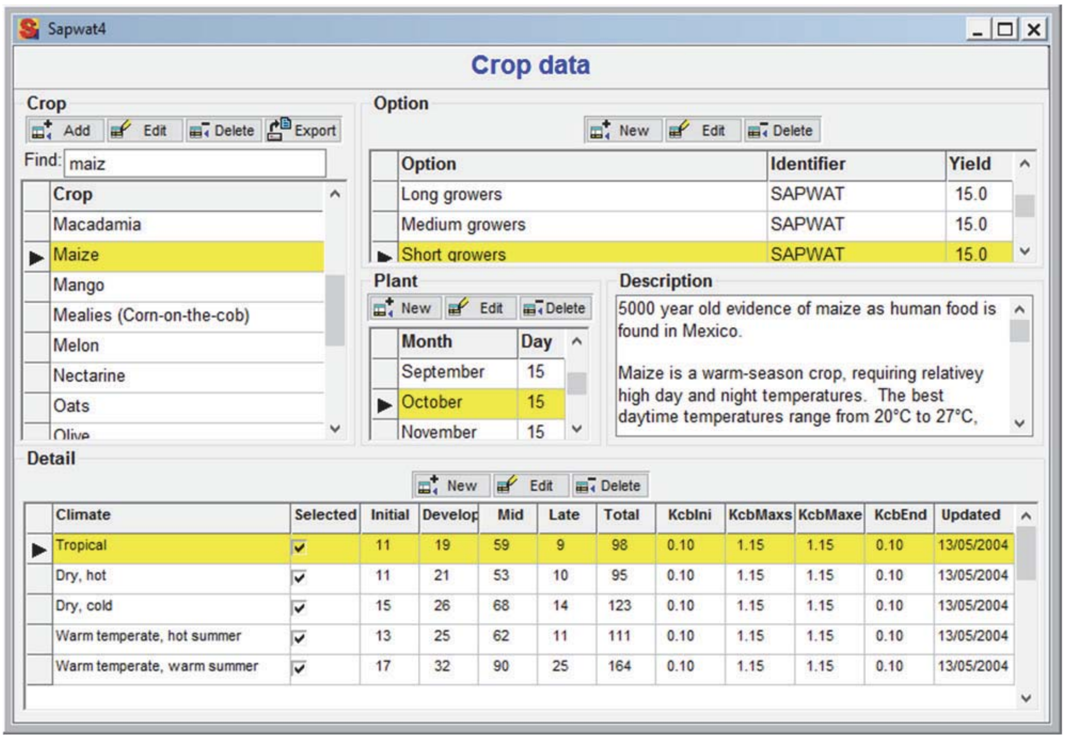


Figure 3-5 Crop data screen showing crop characteristics for maize, short grower, planted October 15, for different climates

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 is more fully discussed in Chapter 4. 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 SAPWAT4

While doing the crop set-up for calculating irrigation water requirements, the user selects a crop, a crop option and a planting date. SAPWAT4 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 $f_{ew}.K_{cmax}$, 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 ($\theta_{FC)}$, 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):

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \quad (38)$$

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). SAPWAT4 uses 0.1 m as default soil evaporation layer for Z_e. The relationship between REW (readily evaporable water) and TEW is shown in Figure 3-6 (Allen *et al*., 1988).

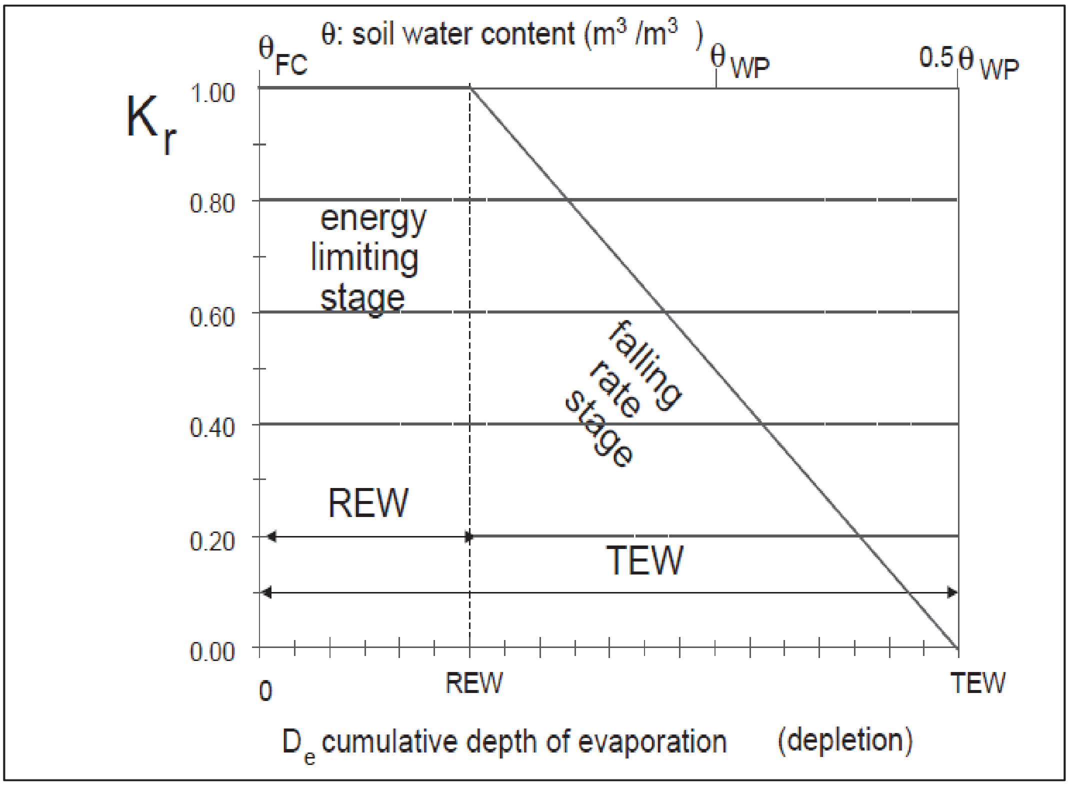


Figure 3-6 Soil evaporation reduction coefficient, K_r. The effect of the two stages, the energy limiting stage and the falling rate stage of soil surface evaporation (Allen *et al*., 1998) (REW = readily evaporable water; TEW = total evaporable water; K_r = dimensionless evaporation coefficient)

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

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \qquad (39)$$

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 (Allen *et al*., 1998).

Table 3-2 Typical soil evaporable water values for soils for readily evaporative water (REW) and total evaporative water (TEW) (Allen *et al*., 1998)

Soil type	**Amount of water that can be depleted by evaporation**	
	REW (mm)	**TEW (mm)**
Sand	2-7	6-12
Loamy sand	4-8	9-14
Sandy loam	6-10	15-20
Loam	8-10	16-22
Silt loam	8-11	18-25
Silt	8-11	22-26
Silt clay loam	8-11	22-27
Silt clay	8-12	22-28
Clay	8-12	22-29

The evaporation coefficient (K_e), which is linked to ET_0 to calculate soil surface evaporation, is calculated by SAPWAT4 with Equation (40) (Allen *et al*., 1998):

$$K_e = K_r (f_{ew} K_{c\,max} - K_{cb}) \leq f_{ew} K_{cmax} \tag{40}$$

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 (42)),

K_r dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depletion (evaporated) from the top soil (Equation (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 (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 (41)) (Allen *et al*., 1998).

$$\lambda ET = R_n - G - H \tag{41}$$

where: λET latent heat flux (MJ m^{-2} day^{-1}),

R_n net radiation (MJ m^{-2} day^{-1}),

G soil heat flux (MJ m^{-2} day^{-1}),

H sensible heat (MJ m^{-2} day^{-1}).

$K_{c\ max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_0 and is calculated with Equation (42) (Allen *et al*., 1998) by SAPWAT4 before calculating the evaporation coefficient with Equation (40) where its value is used as an input.

$$K_{c\ max}=\max\left(\left\{1.2+\left[0.04\left(u_2-2\right)-0.004\left(RH_{min}-45\right)\right]\left(\frac{h}{3}\right)^{0.3}\right\},\left\{K_{cb}+0.05\right\}\right) \tag{42}$$

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 (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):

$$f_{ew}=\min(1-f_c,f_w) \tag{43}$$

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 3-7 (Allen *et al*., 1998).

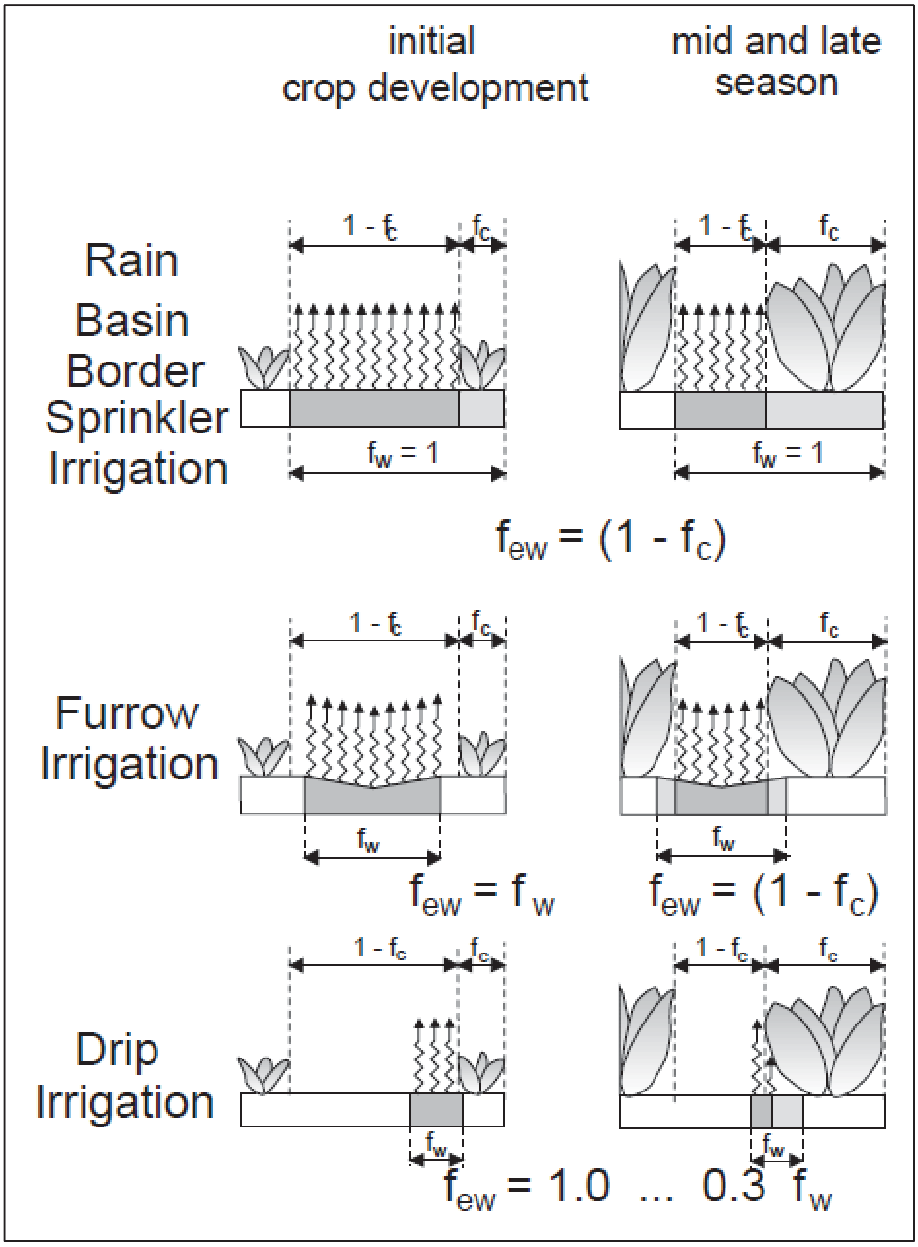


Figure 3-7 Determination of variable F_{ew} (cross hatched areas) as a function of the fraction of ground surface cover (f_c) and the fraction of the surface wetted (f_w) area (Allen *et al.*, 1998)

Where f_c is not measured, it can be estimated with Equation (44) (Allen *et al*., 1998)

$$f_c = \left(\frac{K_{cb} - K_{cmin}}{K_{cmax} - K_{cmin}} \right)^{(1+0.5h)} \quad (44)$$

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 (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 (45)) and is diagrammatically represented in Figure 3-8 (Allen *et al*., 1998; Bennie *et al.*, 1998):

$$\Delta D = I + (P - RO) - E - T + CR - DP \pm SF \quad (45)$$

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.

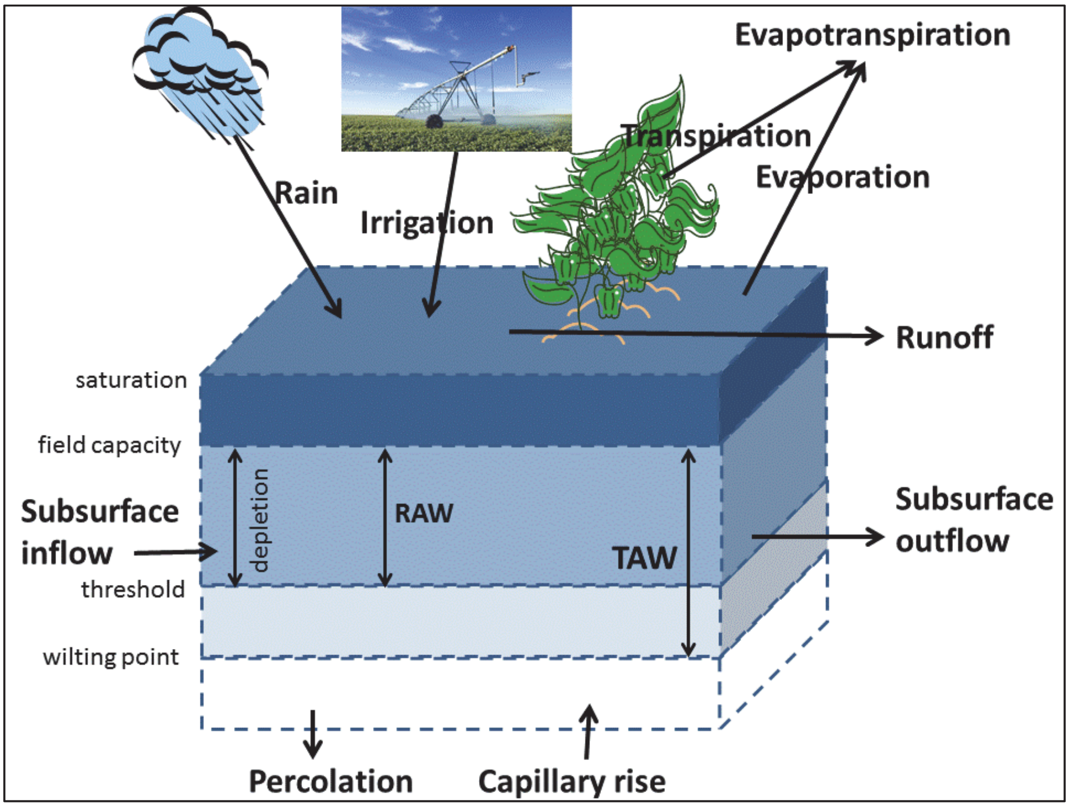


Figure 3-8 A diagrammatic representation of the soil water balance in the root zone of crop (Allen *et al*., 1998)

Figure 3-8 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 3-8 (mm);
TAW	Total available water – total amount of plant available water a soil can hold in root zone (mm)

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

Table 3-3: 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)	θ_{FC}-θ_{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 (45)) for the top soil layer (0.1-0.15 m) so that evaporation from this layer can also be taken into account (Figure 3-9; Equation (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 (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 (46), where in the case of SAPWAT4, a limit of 0.10 m has been set (Allen *et al*., 1998).

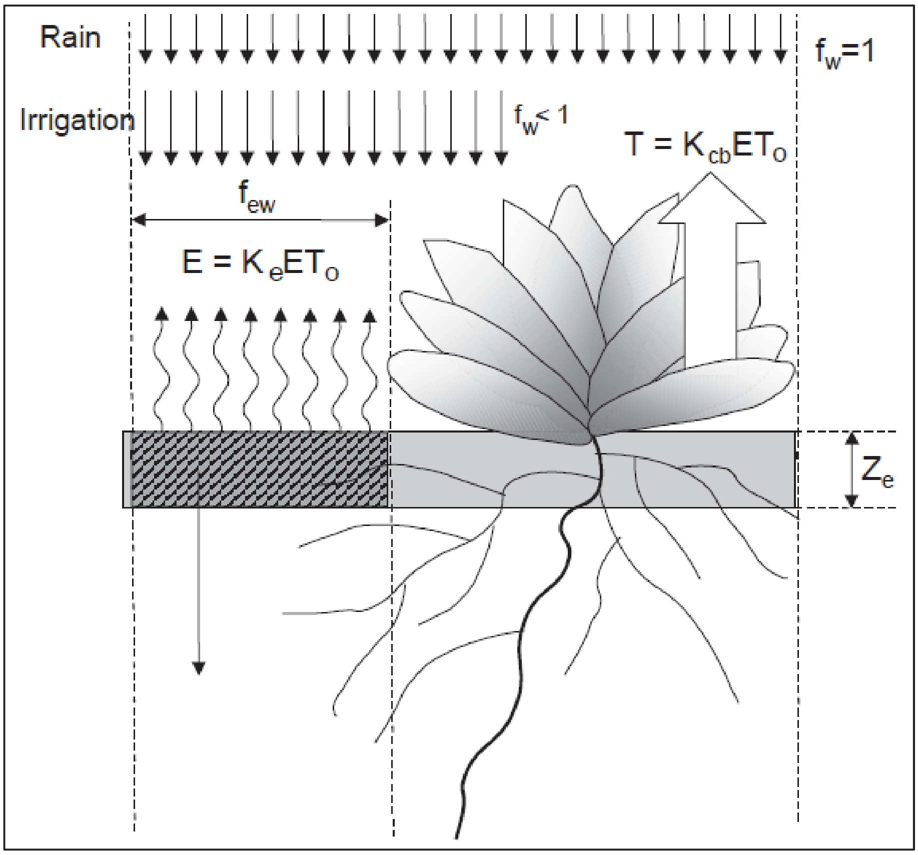


Figure 3-9 A graphic representation of the water balance of the topsoil layer, where Z_e = topsoil layer

$$D_{e,i}=D_{e,i-1}-(P_i-RO_i)-\frac{I_i}{f_w}+\frac{E_i}{f_{ew}}+T_{ew,i}+DP_{e,i} \tag{46}$$

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, 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 SAPWAT4 the allowed depletion level is calculated with Equation (47) with set outer boundaries of 0.1 and 0.8 (Equation (48)) (Allen et al., 1998).

$$p = p_{table} + 0.04(5 - ET_c) \tag{47}$$

With

$$0.1 \le p \le 0.8 \tag{48}$$

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 salts 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 (49)) (Allen *et al*., 1998):

$$LF = \frac{EC_{iw}}{5EC_e - EC_{iw}} \tag{49}$$

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 3-4) (dS m^{-1}),

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

3.4.5.2 Application in SAPWAT4

SAPWAT4 does a daily water balance calculation using the adapted soil water balance equation (Equation (46)). During each daily cycle soil surface evaporation and transpiration calculations are done as follows:

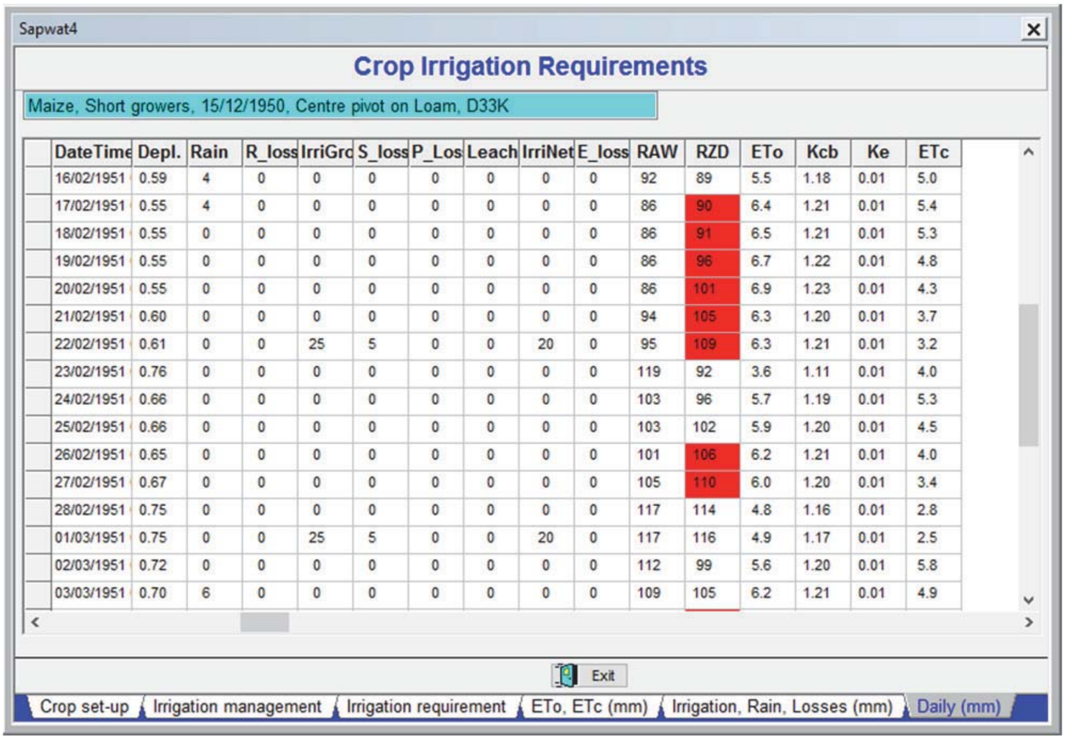
- Calculate leaching fraction at start for application during each round of calculation;

- 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 (43));
- Calculates 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 (39));
    - If a value for evaporable water is not available: $K_r = 0$.
- Calculates the evaporation coefficient (Equation (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 it tests for satisfaction of the irrigation strategy definition (Table 3-1) for the growth stage relevant at that time. The data that make up the soil water equation is noted and a new round is started.

If the irrigation strategy definition is satisfied, an irrigation is simulated, the values of all relevant variables are tabled (Irriricrop3.dbf) and a new irrigation cycle is started. Detail can be seen in Figure 3-10. 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 SAPWAT4 cycles through the daily soil water balance calculations, atmospheric demand for the specific day is used to determine depletion levels by using Equations (47) and (48) (Allen *et al.*, 1998). On completion of the seasonal irrigation water requirement calculation all relevant data is totalled and shown on screen.



DateTime	Depl.	Rain	R_loss	IrriGro	S_loss	P_Los	Leach	IrriNet	E_loss	RAW	RZD	ETo	Kcb	Ke	ETc
16/02/1951	0.59	4	0	0	0	0	0	0	0	92	89	5.5	1.18	0.01	5.0
17/02/1951	0.55	4	0	0	0	0	0	0	0	86	90	6.4	1.21	0.01	5.4
18/02/1951	0.55	0	0	0	0	0	0	0	0	86	91	6.5	1.21	0.01	5.3
19/02/1951	0.55	0	0	0	0	0	0	0	0	86	96	6.7	1.22	0.01	4.8
20/02/1951	0.55	0	0	0	0	0	0	0	0	86	101	6.9	1.23	0.01	4.3
21/02/1951	0.60	0	0	0	0	0	0	0	0	94	105	6.3	1.20	0.01	3.7
22/02/1951	0.61	0	0	25	5	0	0	20	0	95	109	6.3	1.21	0.01	3.2
23/02/1951	0.76	0	0	0	0	0	0	0	0	119	92	3.6	1.11	0.01	4.0
24/02/1951	0.66	0	0	0	0	0	0	0	0	103	96	5.7	1.19	0.01	5.3
25/02/1951	0.66	0	0	0	0	0	0	0	0	103	102	5.9	1.20	0.01	4.5
26/02/1951	0.65	0	0	0	0	0	0	0	0	101	106	6.2	1.21	0.01	4.0
27/02/1951	0.67	0	0	0	0	0	0	0	0	105	110	6.0	1.20	0.01	3.4
28/02/1951	0.75	0	0	0	0	0	0	0	0	117	114	4.8	1.16	0.01	2.8
01/03/1951	0.75	0	0	25	5	0	0	20	0	117	116	4.9	1.17	0.01	2.5
02/03/1951	0.72	0	0	0	0	0	0	0	0	112	99	5.6	1.20	0.01	5.8
03/03/1951	0.70	6	0	0	0	0	0	0	0	109	105	6.2	1.21	0.01	4.9

Figure 3-10 Daily water balance table as shown in SAPWAT4. Red cells indicate stress.

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 where it is safe for crop use, or a combination of water stress and salinity stress. Stress reduces crop yield in direct relationship to the severity of the stress situation (Equation (53)) – a relationship that varies from crop to crop and also between different growing periods of crops (Figure 3-11). A yield response factor of more than one (k_y>1) indicates a bigger sensitivity to yield loss than the relation to reduced evapotranspiration, or crop is sensitive to stress. 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).

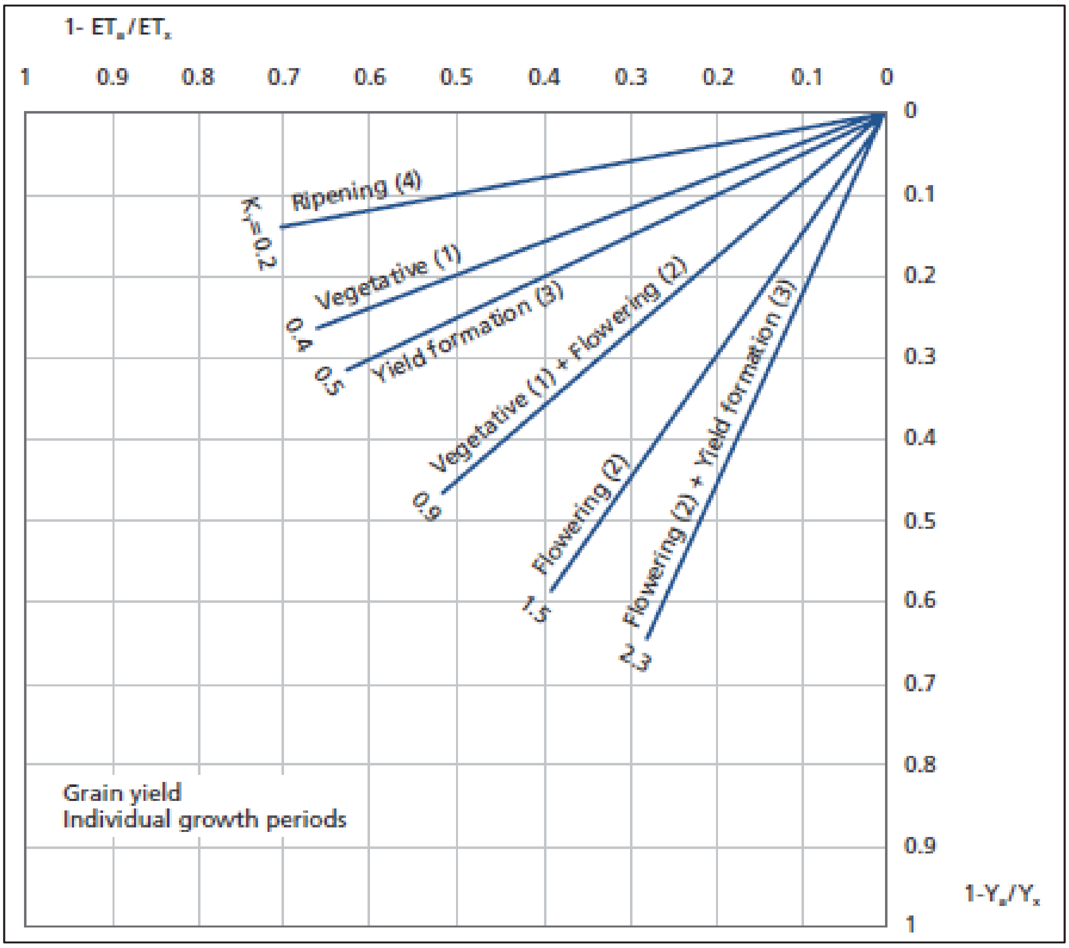


Figure 3-11 Yield response of maize to stress situations showing different sensitivities for different growth stages (k_y = yield response factor; ET_a = actual evapotranspiration; ET_x = maximum evapotranspiration; Y_a = actual yield and Y_x = maximum yield) (Smith and Steduto, 2012)

Under conditions of stress Equation (1) becomes (Allen *et al.*, 1998):

$$ET_c = K_s \times K_c \times ET_0 \quad (50)$$

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):

$$K_s = \frac{TAW\text{-}D_r}{(1\text{-}p)\,TAW} \qquad (51)$$

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):

$$\frac{Y_a}{Y_m} = 1\text{-}\left(EC_e\text{-}EC_{e\ threshold}\right)\frac{b}{100} \qquad (52)$$

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 3-4.

Table 3-4 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, 1984; Tanji and Kielen, 2002)

Crop	EC Threshold	EC Reduction rate	EC Rating
Almonds	150	19	Sensitive
Apples			Sensitive
Apricot	160	24	Sensitive
Artichokes			Moderately Tolerant
Asparagus	410	2	Tolerant

Crop	EC Threshold	EC Reduction rate	EC Rating
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
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

Crop	EC Threshold	EC Reduction rate	EC Rating
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
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

Crop	EC Threshold	EC Reduction rate	EC Rating
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 3-4 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 3-5 Default salinity sensitivity values used by SAPWAT4 in absence of data table values (Ayers and Westcot, 1994)

EC Rating	EC Threshold	EC Reduction rate
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):

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_{c\ adj}}{ET_c}\right) \quad (53)$$

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 day^{-1}),

ET_c crop evapotranspiration for standard conditions (no water stress) (mm day^{-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 SAPWAT4 come from Allen *et al*., 1998 (Table 3-6):

Table 3-6 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
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 do not necessarily occur as only water or only salinity; 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, SAPWAT4 gives it a default value of 1.

- Salinity stress with no water stress:

$$K_s = 1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\ threshold}\right) \quad (54)$$

- Salinity stress with water stress:

$$K_s = \left[1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\ threshold}\right)\right]\left(\frac{TAW - D_r}{TAW - RAW}\right) \quad (55)$$

where:

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 3-12 (Allen *et al*., 1998):

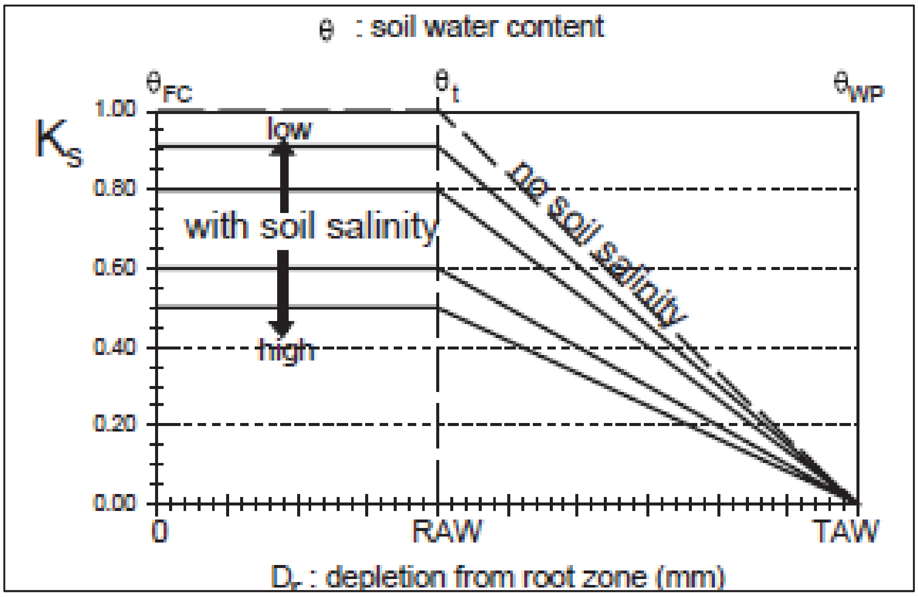


Figure 3-12 The effect of soil salinity on the water stress coefficient, K_s (Allen *et al.*, 1998)

3.4.6.4 Application in SAPWAT4

During irrigation requirement calculations, SAPWAT4 tests for salinity and water stress situations and applies:

- Water stress only: Equation (51)
- Salinity stress only: Equation (54)
- Combined water and salinity stress: Equation (55)

3.5 Enterprise budgets

The ability to calculate a basic enterprise budgets has been incorporated into SAPWAT4, 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 the production cost of the goods sold. 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 SAPWAT4 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 (56)) (DAEARD, 2011).

$$GM = GI - DAC \tag{56}$$

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 SAPWAT4 has three calculation levels which can be used in any combination to calculate gross margin. At its simplest it requires only the input of total expected income and total expected directly allocable variable costs as inputs into Equation (56).

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

$$GI = \text{product volume} \times \text{unit price} \tag{57}$$

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.

$$DAC = \text{area related cost} + \text{yield related cost} \tag{58}$$

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

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

$$\text{area related cost} = \text{fertiliser cost} + \text{pest and disease cost} + ... \tag{59}$$

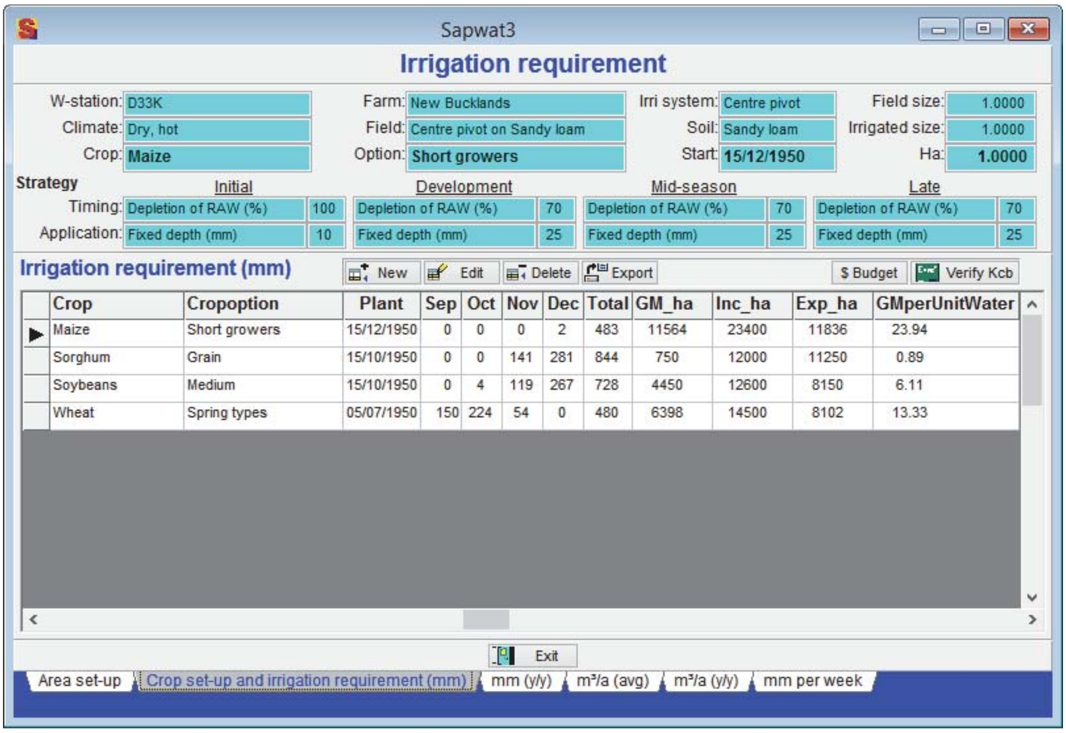
At the third level gross income is calculated with Equation (57) and cost breakdown is done in detail to show every cost item as a separate entry:

$$\text{fertiliser cost} = \text{nitrogen cost} + \text{phosphae cost} + \text{potasium cost} + ... \tag{60}$$

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 3-13. 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 lastly sorghum. However, it must be kept in mind that water use and relative profitability alone does 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 determinant factor when deciding which crops to grow.



Crop	Cropoption	Plant	Sep	Oct	Nov	Dec	Total	GM_ha	Inc_ha	Exp_ha	GMperUnitWater
Maize	Short growers	15/12/1950	0	0	0	2	483	11564	23400	11836	23.94
Sorghum	Grain	15/10/1950	0	0	141	281	844	750	12000	11250	0.89
Soybeans	Medium	15/10/1950	0	4	119	267	728	4450	12600	8150	6.11
Wheat	Spring types	05/07/1950	150	224	54	0	480	6398	14500	8102	13.33

Figure 3-13 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 3-14). The parent table is the controlling table, shifting from record to record in it, automatically moves to the right linked records in the child table.

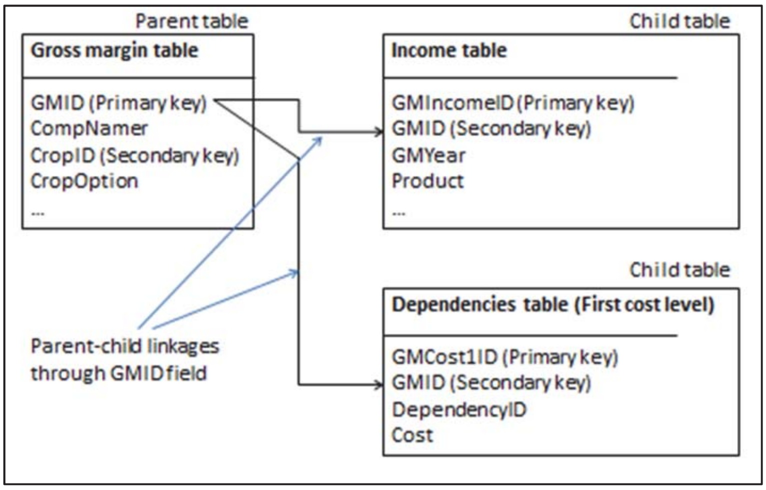


Figure 3-14 Linking hierarchical related data tables

3.5.2 Gross margin screen form

The gross margin screen form (Figure 3-15) 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 3-15);

(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 3-16);

(iii) detailed: where the cost of each and every cost component is known (Figure 3-17).

Enterprise budgets are calculated on an area basis, usually based on the previous financial year, but also 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.

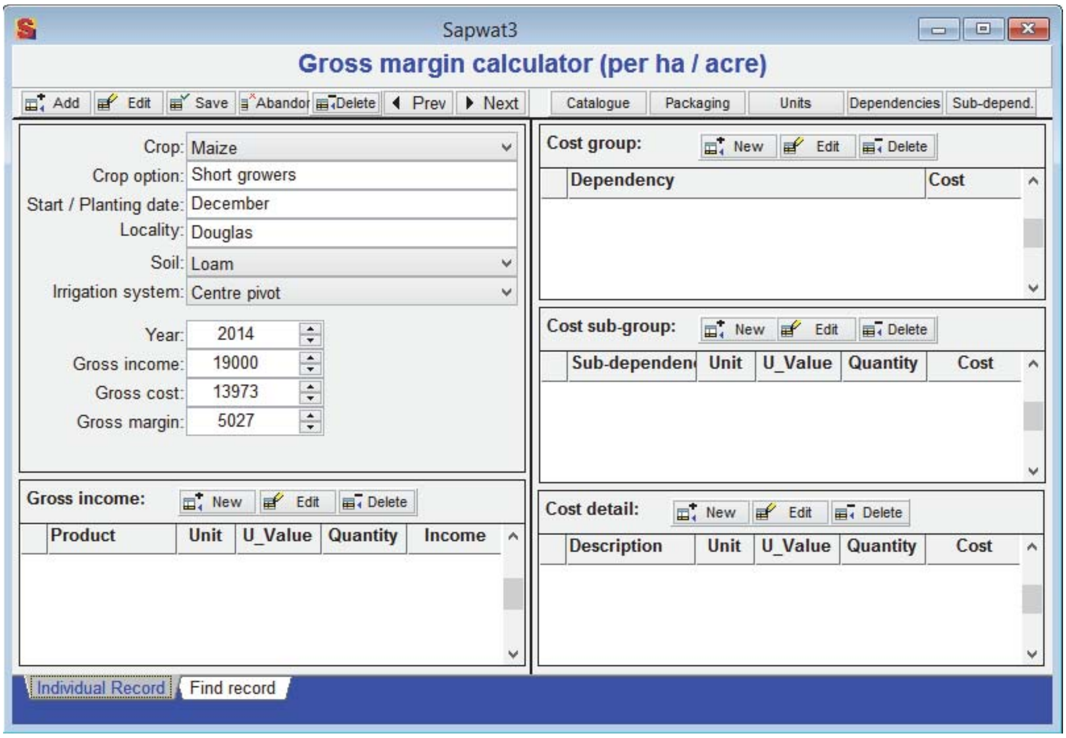


Figure 3-15 The gross margin screen form when inputting the minimum data required for doing an enterprise budget – data required has been filled in. In this case blank parts of the form do not contain or need to contain data.

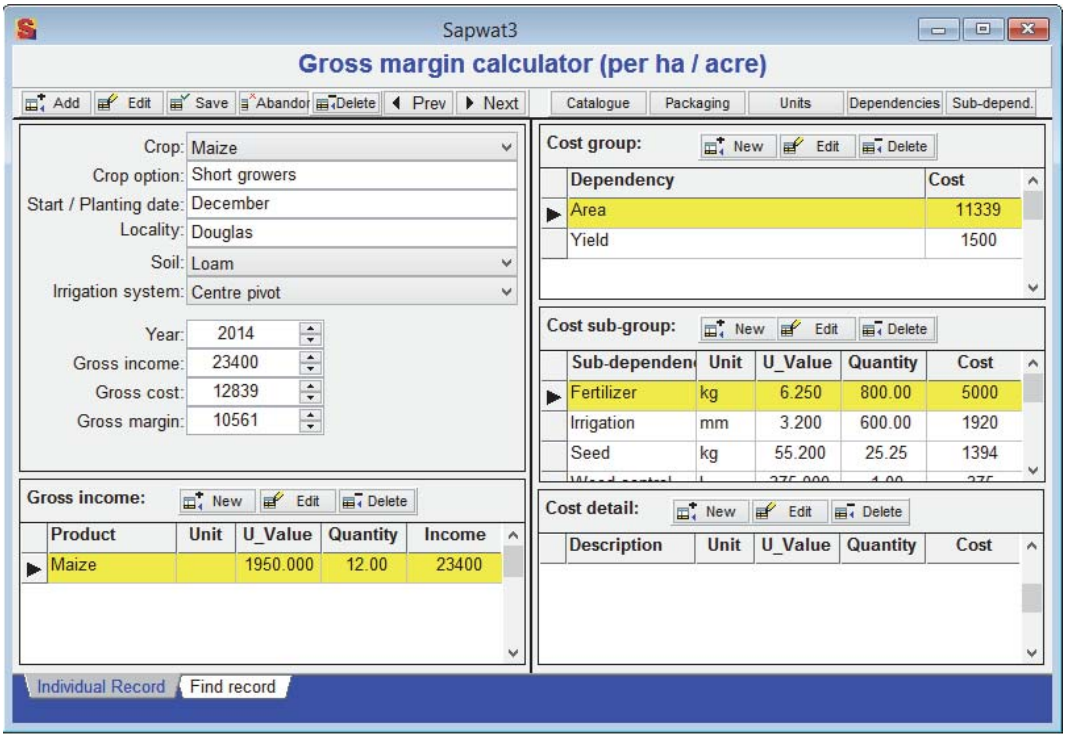


Figure 3-16 The gross margin screen form showing semi-detailed or cost sub-dependency data input for doing an enterprise budget – data has been entered.

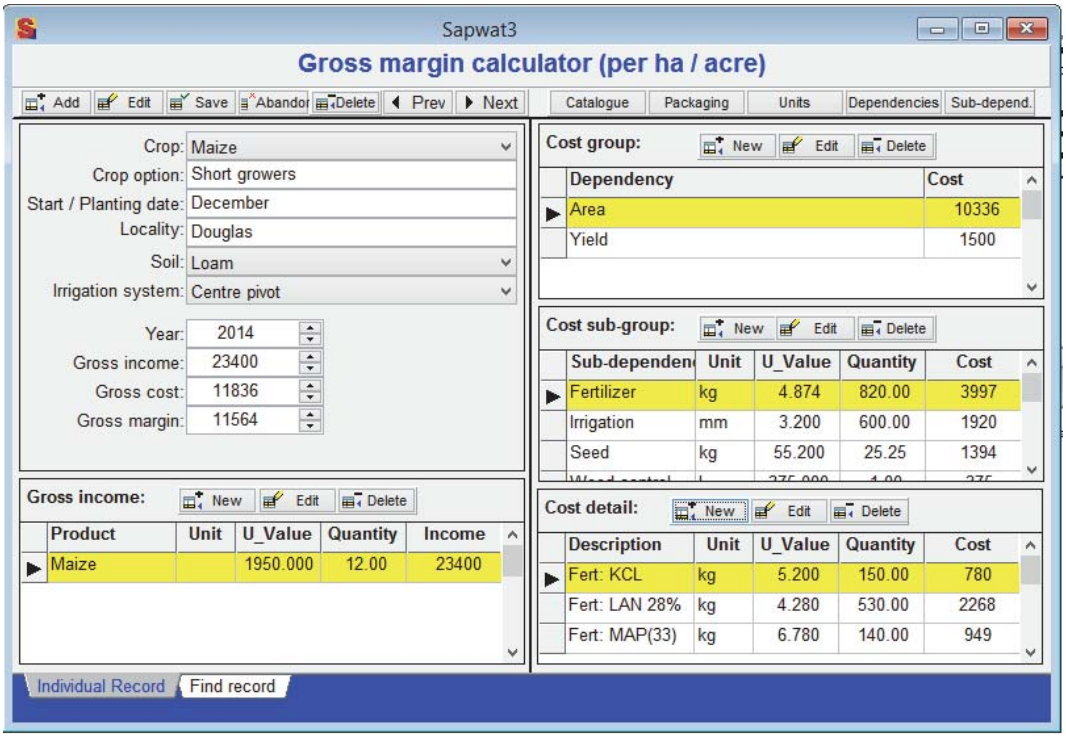


Figure 3-17 The gross margin screen form showing detailed data input for doing an enterprise budget – data already filled in. Detailed cost data is automatically summed to the relevant semi-dependency field, then summed from there to the relevant dependency field and finally summed from there to the gross cost field

3.6 Water harvesting.

SAPWAT4 includes a module on water harvesting and storage of water on a small scale meant for the back-yard garden or similar situations which does water balances for one season only. The opening screen is seen in Figure 3-18, with the volume of water required having been calculated in the normal SAPWAT4 way as described in 3.4. The opening screen provides for input in terms of greywater, 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 SAPWAT4 is based on an empty start – empty finish approach, except when a balance is requiem at the beginning of the season, in which case that will be carried over from the end of the period.

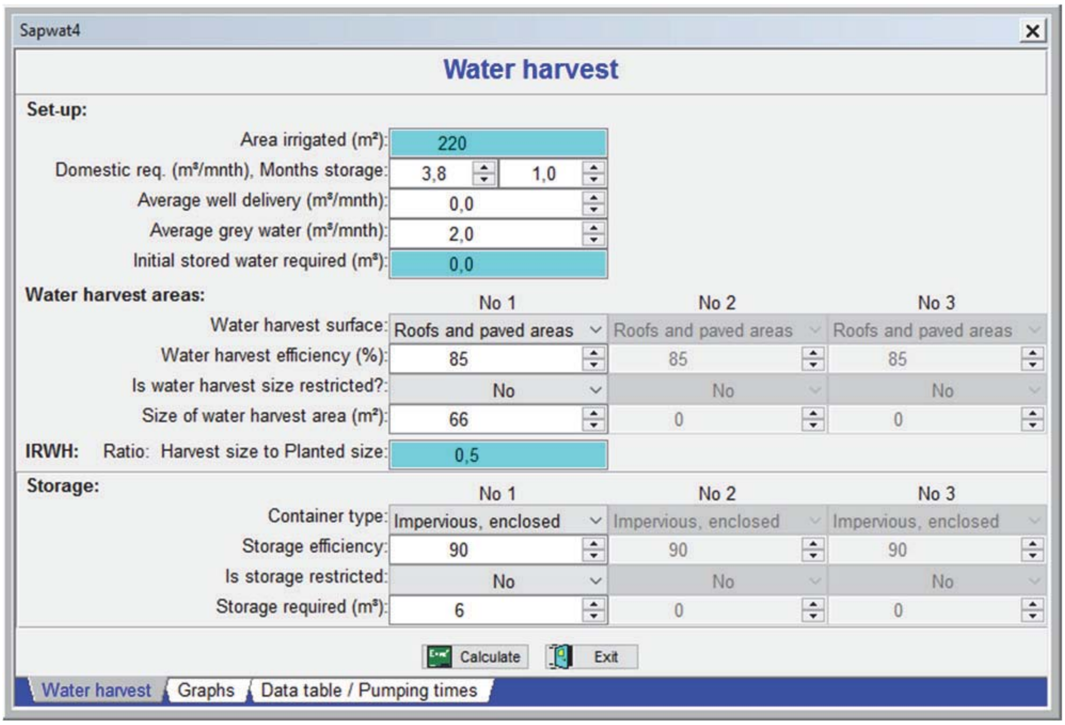


Figure 3-18 The water harvesting setup form.

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 3-18, 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 too small, an additional storage must be planned for, or a smaller garden or a different crop combination. The results show a harvesting area requirement of 143 m^2 and a storage requirement of 67 m^3 as. 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 vegetables 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 area indicated under the relevant options.

Figure 3-19 show the monthly and total water balances graphically. Figure 3-20 shows the tabulated results of the water harvest situation depicted in Figure 3-18. 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.

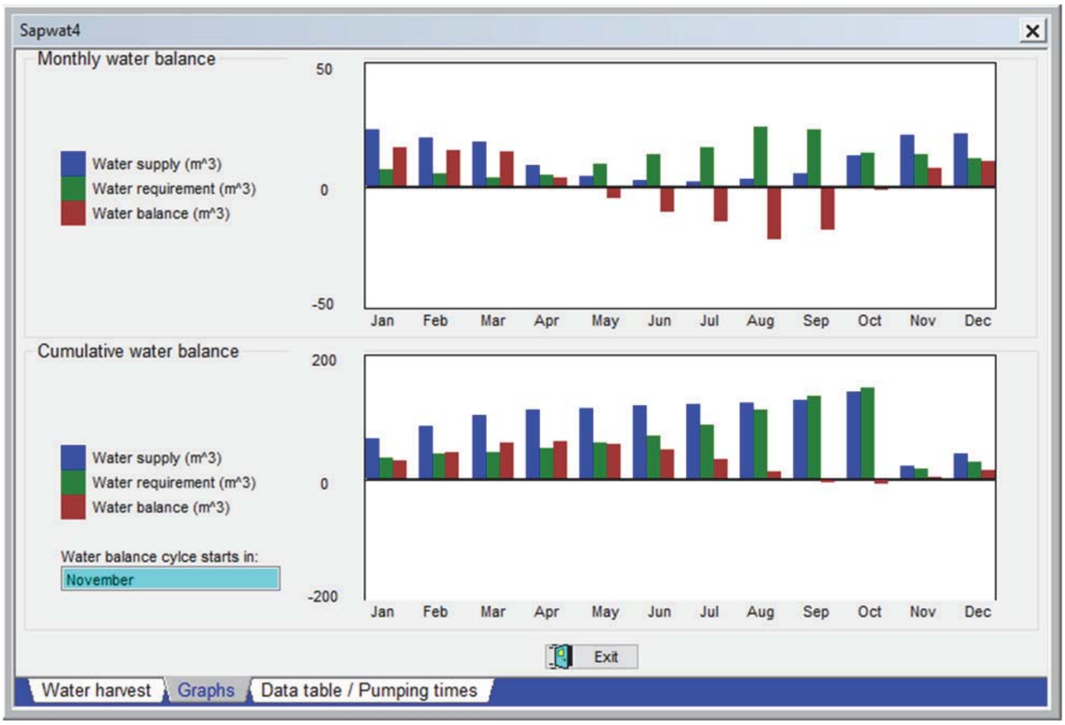
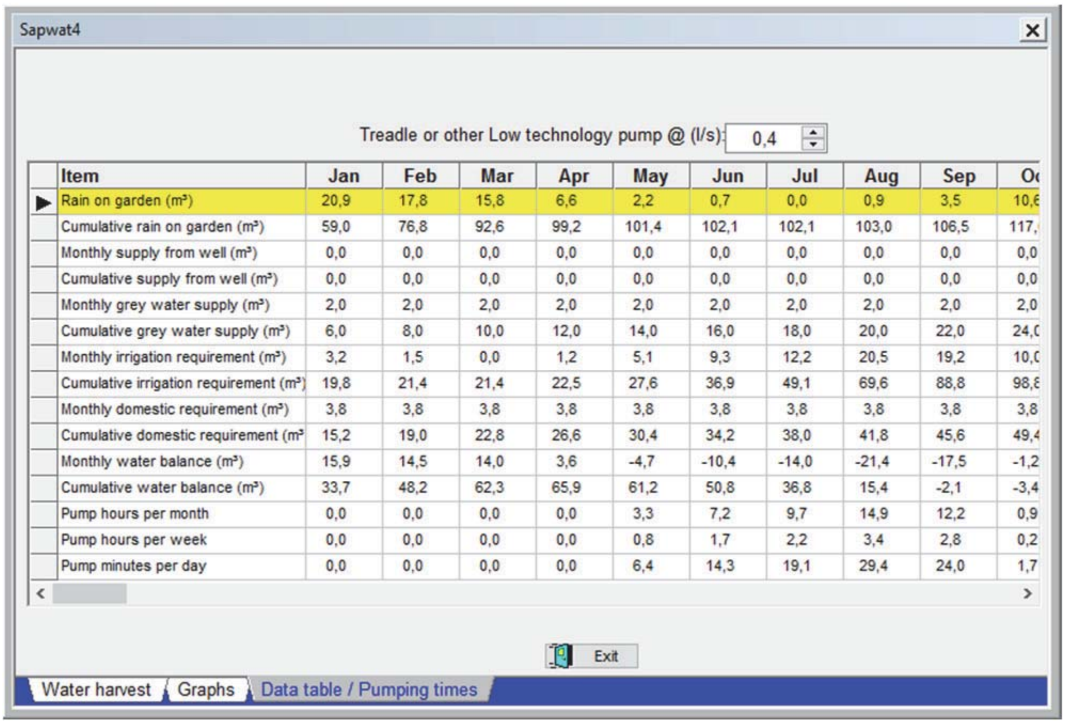


Figure 3-19 The water harvest monthly and total water balances.



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)	59,0	76,8	92,6	99,2	101,4	102,1	102,1	103,0	106,5	117,
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)	6,0	8,0	10,0	12,0	14,0	16,0	18,0	20,0	22,0	24,0
Monthly irrigation requirement (m³)	3,2	1,5	0,0	1,2	5,1	9,3	12,2	20,5	19,2	10,0
Cumulative irrigation requirement (m³)	19,8	21,4	21,4	22,5	27,6	36,9	49,1	69,6	88,8	98,8
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	15,2	19,0	22,8	26,6	30,4	34,2	38,0	41,8	45,6	49,4
Monthly water balance (m³)	15,9	14,5	14,0	3,6	-4,7	-10,4	-14,0	-21,4	-17,5	-1,2
Cumulative water balance (m³)	33,7	48,2	62,3	65,9	61,2	50,8	36,8	15,4	-2,1	-3,4
Pump hours per month	0,0	0,0	0,0	0,0	3,3	7,2	9,7	14,9	12,2	0,9
Pump hours per week	0,0	0,0	0,0	0,0	0,8	1,7	2,2	3,4	2,8	0,2
Pump minutes per day	0,0	0,0	0,0	0,0	6,4	14,3	19,1	29,4	24,0	1,7

Figure 3-20 The water harvest water balances table.

3.7 Data volume, management and storage

SAPWAT4, 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 SAPWAT4 (Mayer, 2005; Van Heerden *et al*., 2008).

All data required by SAPWAT4 is 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 SAPWAT4 to its fullest capabilities on site and irrespective of internet linkages, 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; the design is based on crop irrigation requirement and is done on 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 could implement desired changes by changing cropping patterns, or design specifications, and show the results to the farmer immediately on site. Thus they can provide an efficient and interactive client-friendly service. With a lack of internet access as it was then, this was not possible. The designer had to go back to his office, make the required changes and return to the farmer for further discussions. Having data on-board obviated this problem. The situation regarding internet access has improved substantially since then, but even so, SAPWAT3 (Crosby and Crosby, 1999; Van Heerden *et al*., 2008), and now SAPWAT4, retained the principle of having all required data on board. This aspect of the set-up could however be changed in future for high tech researchers where a server or internet access is readily available.

3.7.1 Safeguarding data

Data management in SAPWT4 is designed to prevent accidental change of content. In all cases where the user interacts with data, SAPWAT4 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 SAPWAT4 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

SAPWAT4 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 SAPWAT4 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 SAPWAT4 data tables. SAPWAT4 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 SAPWAT4 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 weather station data table includes monthly values of average air temperature, maximum temperature, minimum temperature, average humidity, minimum humidity, wind run, sunshine hours, solar radiation, reference evapotranspiration, rain and rainfall events. Averages are calculated from all data included in the weather data tables, irrespective of the time period included in the weather data tables.

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 3-21) is the look-up table for selection of a station from the complete list available in SAPWAT4. The world-wide placements of weather stations show the relative position of all station included in SAPWAT4. 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 becomes over-extended, leading to a program crash, if such a facility is included.

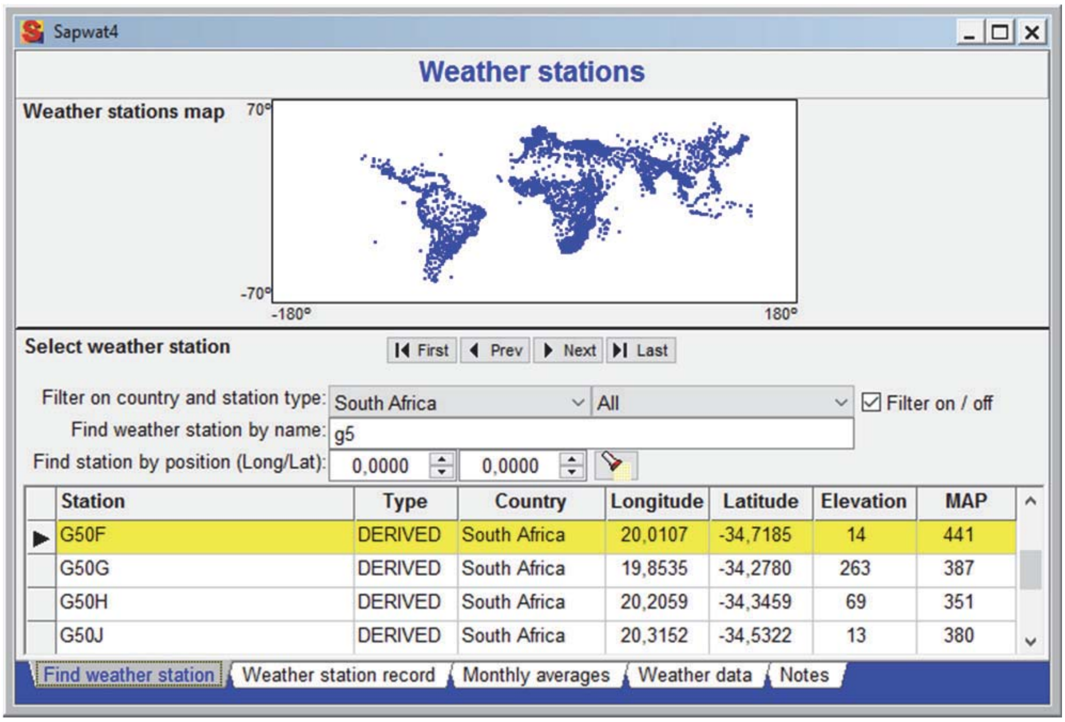


Figure 3-21 Page 1 of the weather stations screen form: a weather station is selected on this screen

Page two shows the summarised detail of the selected weather station (Figure 3-22). 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.

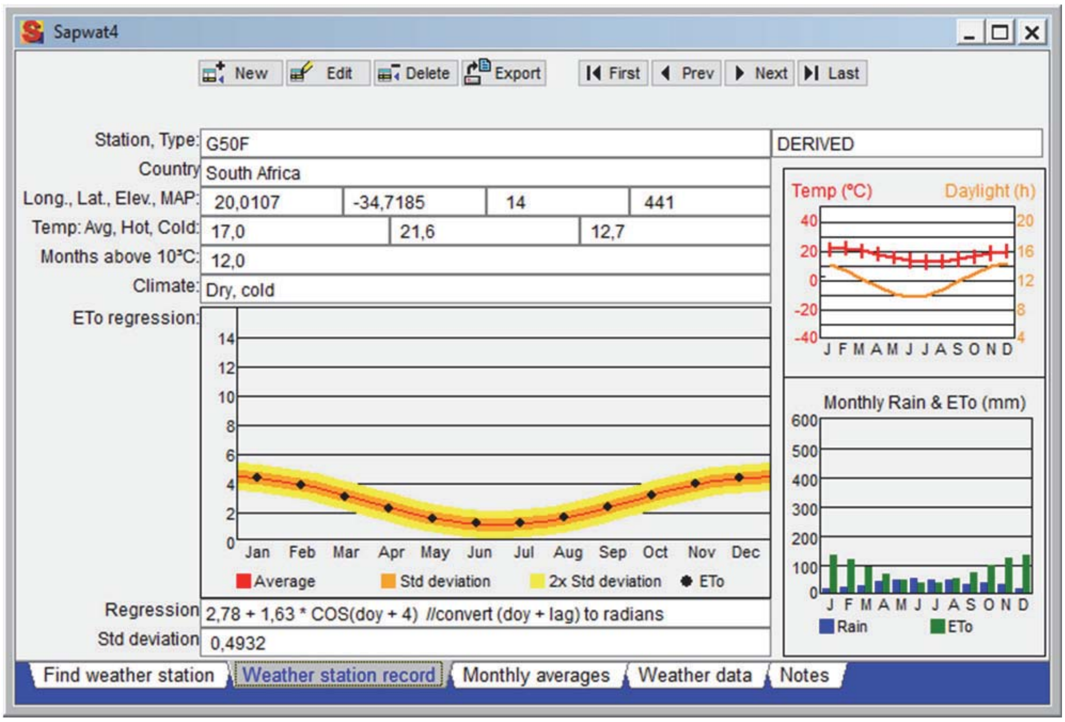
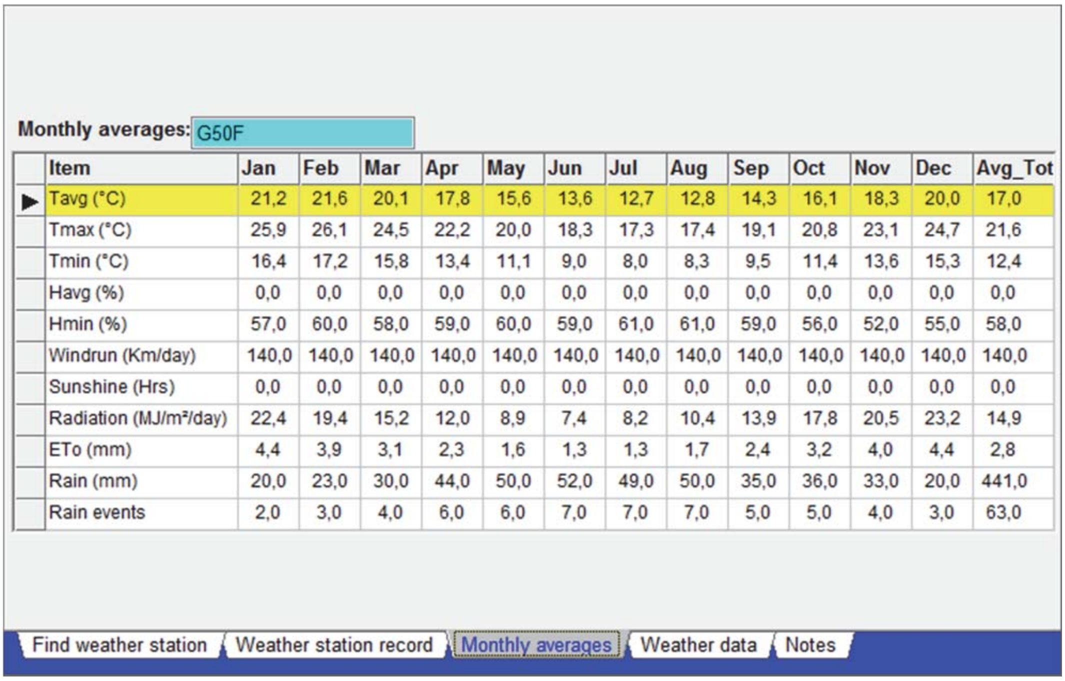


Figure 3-22 Page 2 of the weather stations screen showing screen detail

Average monthly weather data is shown on page 3 of the form (Figure 3-23). These average values are calculated by SAPWAT4 from weather data stored in the detail weather data table (Figure 3-24). Weather data of a station can be added manually or can be imported when a weather station is added to the SAPWAT4 weather data table or when weather station data is updated.

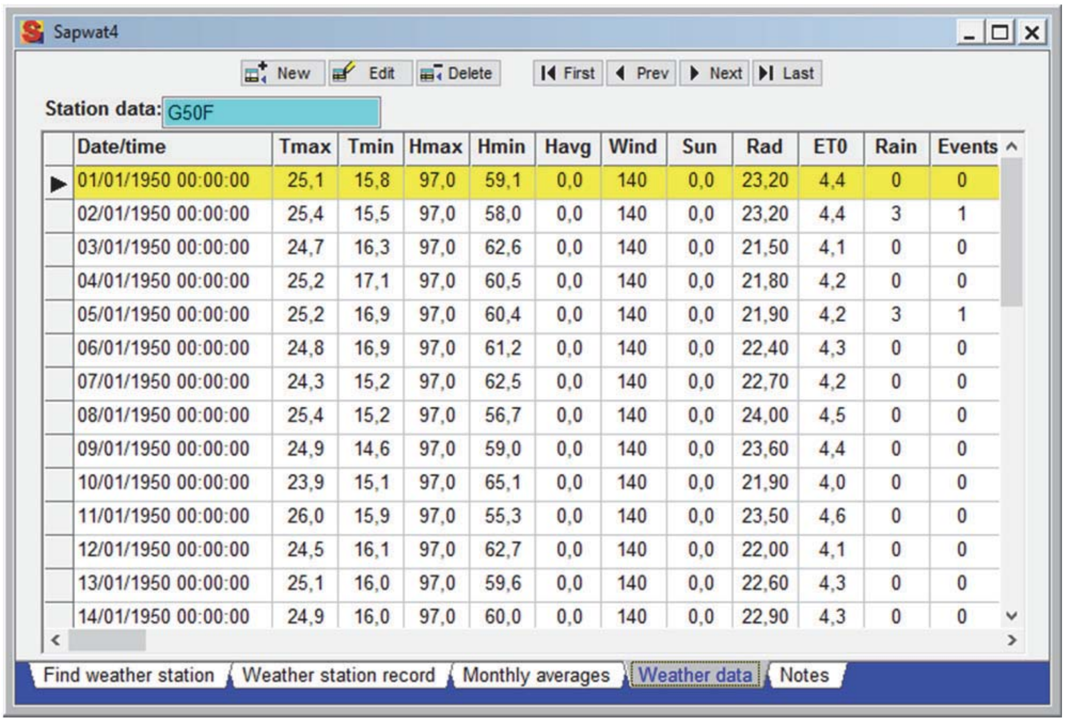


Monthly averages: G50F

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg_Tot
Tavg (°C)	21,2	21,6	20,1	17,8	15,6	13,6	12,7	12,8	14,3	16,1	18,3	20,0	17,0
Tmax (°C)	25,9	26,1	24,5	22,2	20,0	18,3	17,3	17,4	19,1	20,8	23,1	24,7	21,6
Tmin (°C)	16,4	17,2	15,8	13,4	11,1	9,0	8,0	8,3	9,5	11,4	13,6	15,3	12,4
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 (%)	57,0	60,0	58,0	59,0	60,0	59,0	61,0	61,0	59,0	56,0	52,0	55,0	58,0
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)	22,4	19,4	15,2	12,0	8,9	7,4	8,2	10,4	13,9	17,8	20,5	23,2	14,9
ETo (mm)	4,4	3,9	3,1	2,3	1,6	1,3	1,3	1,7	2,4	3,2	4,0	4,4	2,8
Rain (mm)	20,0	23,0	30,0	44,0	50,0	52,0	49,0	50,0	35,0	36,0	33,0	20,0	441,0
Rain events	2,0	3,0	4,0	6,0	6,0	7,0	7,0	7,0	5,0	5,0	4,0	3,0	63,0

Find weather station | Weather station record | Monthly averages | Weather data | Notes

Figure 3-23 Page 3 of the weather station screens showing monthly average values



	Date/time	Tmax	Tmin	Hmax	Hmin	Havg	Wind	Sun	Rad	ET0	Rain	Events
▶	01/01/1950 00:00:00	25,1	15,8	97,0	59,1	0,0	140	0,0	23,20	4,4	0	0
	02/01/1950 00:00:00	25,4	15,5	97,0	58,0	0,0	140	0,0	23,20	4,4	3	1
	03/01/1950 00:00:00	24,7	16,3	97,0	62,6	0,0	140	0,0	21,50	4,1	0	0
	04/01/1950 00:00:00	25,2	17,1	97,0	60,5	0,0	140	0,0	21,80	4,2	0	0
	05/01/1950 00:00:00	25,2	16,9	97,0	60,4	0,0	140	0,0	21,90	4,2	3	1
	06/01/1950 00:00:00	24,8	16,9	97,0	61,2	0,0	140	0,0	22,40	4,3	0	0
	07/01/1950 00:00:00	24,3	15,2	97,0	62,5	0,0	140	0,0	22,70	4,2	0	0
	08/01/1950 00:00:00	25,4	15,2	97,0	56,7	0,0	140	0,0	24,00	4,5	0	0
	09/01/1950 00:00:00	24,9	14,6	97,0	59,0	0,0	140	0,0	23,60	4,4	0	0
	10/01/1950 00:00:00	23,9	15,1	97,0	65,1	0,0	140	0,0	21,90	4,0	0	0
	11/01/1950 00:00:00	26,0	15,9	97,0	55,3	0,0	140	0,0	23,50	4,6	0	0
	12/01/1950 00:00:00	24,5	16,1	97,0	62,7	0,0	140	0,0	22,00	4,1	0	0
	13/01/1950 00:00:00	25,1	16,0	97,0	59,6	0,0	140	0,0	22,60	4,3	0	0
	14/01/1950 00:00:00	24,9	16,0	97,0	60,0	0,0	140	0,0	22,90	4,3	0	0

Figure 3-24 Page 4 of the weather stations screen showing daily weather data

3.7.2.3.1 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 3-25).

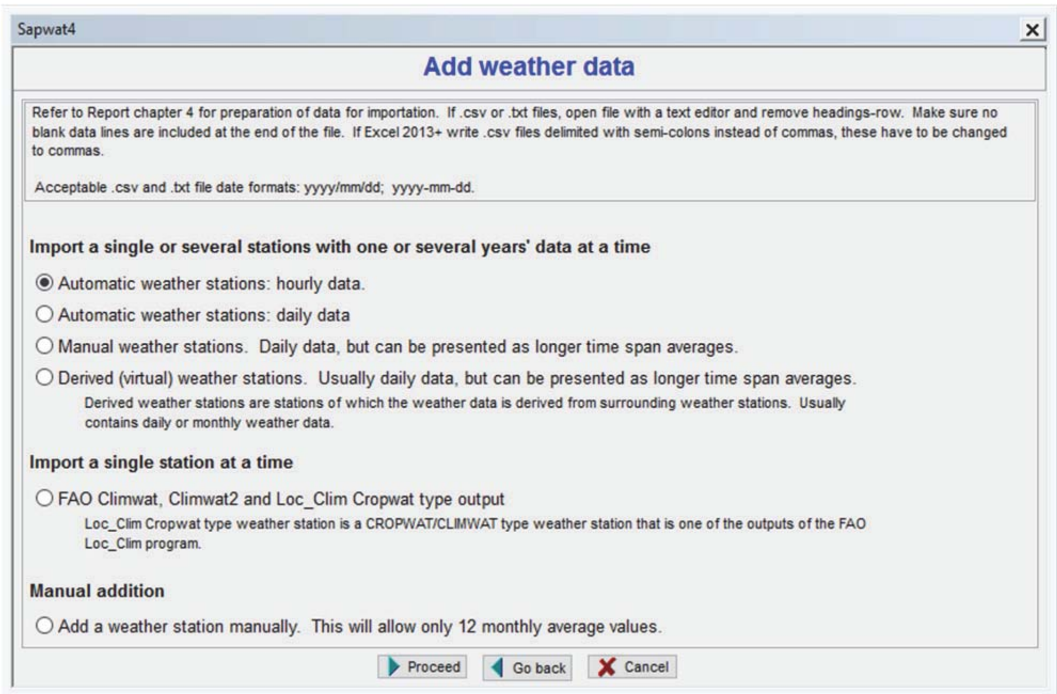


Figure 3-25 Adding a weather station, the screen form on which the users selects the type of input when adding a weather station

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 is added the volume of data makes manual addition impractical.

3.7.2.3.1.1 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 3-26 and Figure 3-27. The weather station data asked at input must be included for correct calculation ET_0 through Equation (3) and its sub-units. Of the weather data, maximum and minimum temperature and sunlight or radiation must be included. If humidity data is not provided saturated vapour pressure is calculated by assuming minimum temperature as equivalent to dew point temperature (Equation (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 has originally been added manually or imported electronically.

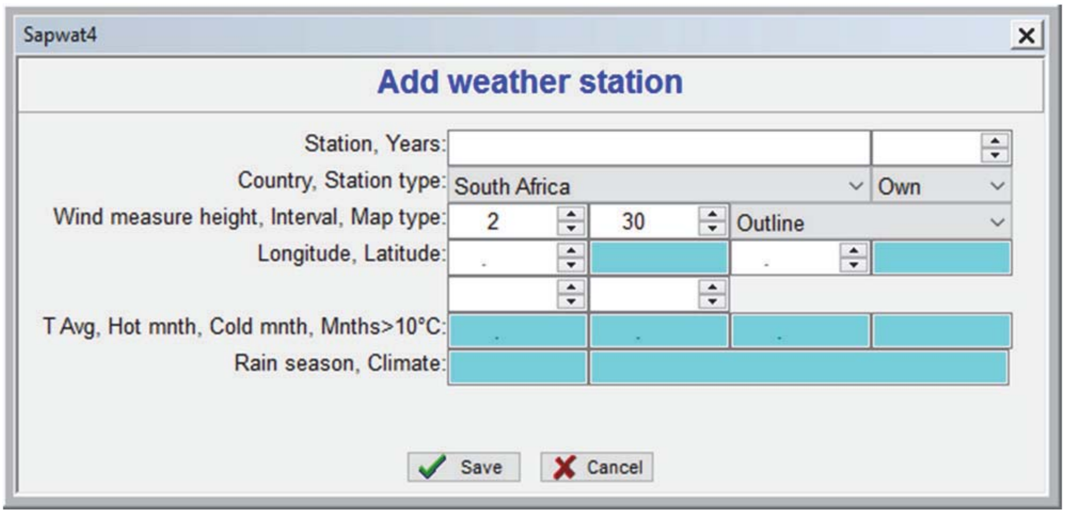


Figure 3-26 Screen form for adding or editing weather station data.

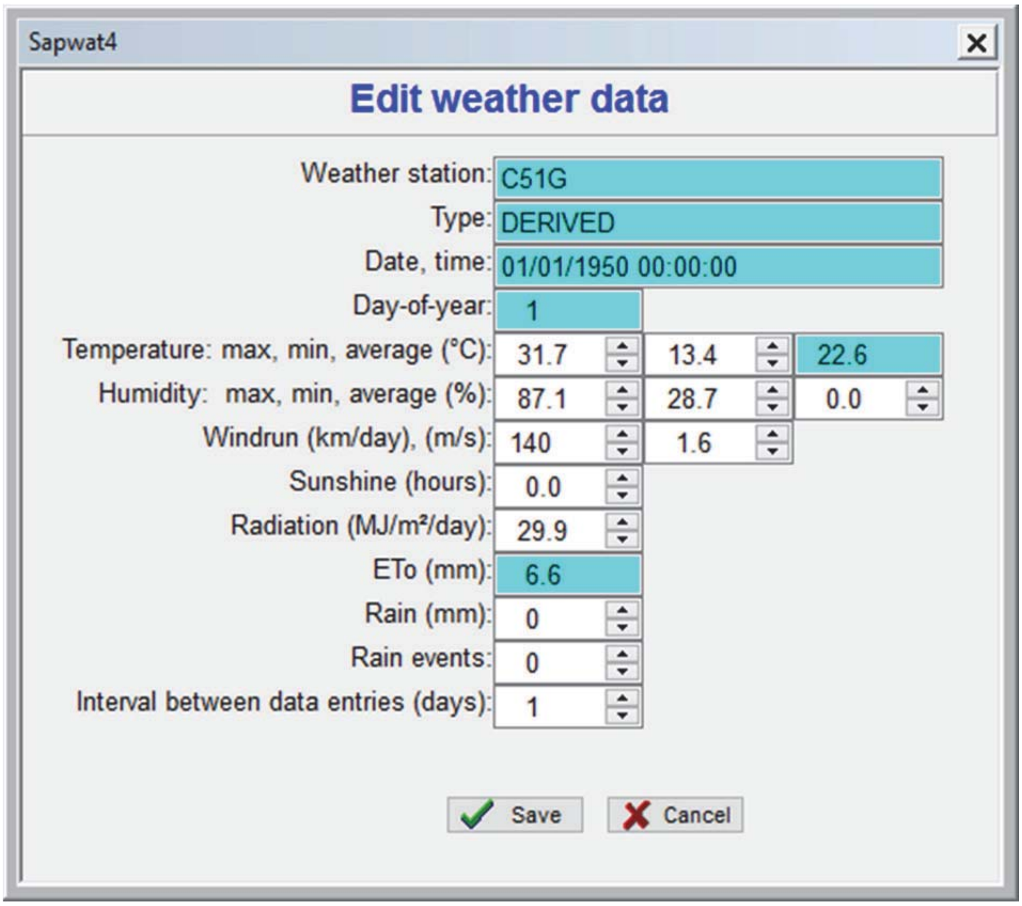


Figure 3-27 Screen form for adding or editing a specific date in the weather station weather data records.

3.7.2.3.1.2 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} day^{-1}). Longitude degrees west and latitude degrees south are indicated with a negative sign.

Similar to the manual addition of weather station data, SAPWAT4 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 (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 SAPWAT4 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.

3.7.2.3.1.2.1 Importing of daily or monthly weather station data

The required preparation for the importation of manual weather station data into the SAPWAT4 weather data tables is shown in Table 3-7. 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 3-7 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.
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

Field name	Data type	Field width	Decimals	Remarks
				RadWatt must be included.
Radiation	Numeric	5	1	Average radiation (MJ m^{-2} day^{-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.

3.7.2.3.1.2.2 Importing of hourly weather station data

Table 3-8 shows the required structure for the importation of automatic weather station data into SAPWAT4. The data is stored in a different format than that for manual weather stations. SAPWAT4 converts automatic weather station data to the same format as used for manual weather station. Automatic weather station data that has 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 3-8 Prepared data table structure for importation of automatic weather station data into SAPWAT4

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.

3.7.2.3.1.2.3 Screen form for electronic importation

The screen form for setting up electronic importation of weather station data is shown in Figure 3-28. Selection between automatic and manual station has been done in the selection form for importation action (Figure 3-25), therefore the setup screen form directs SAPWAT4 to the file for importation as 'Data source:'.

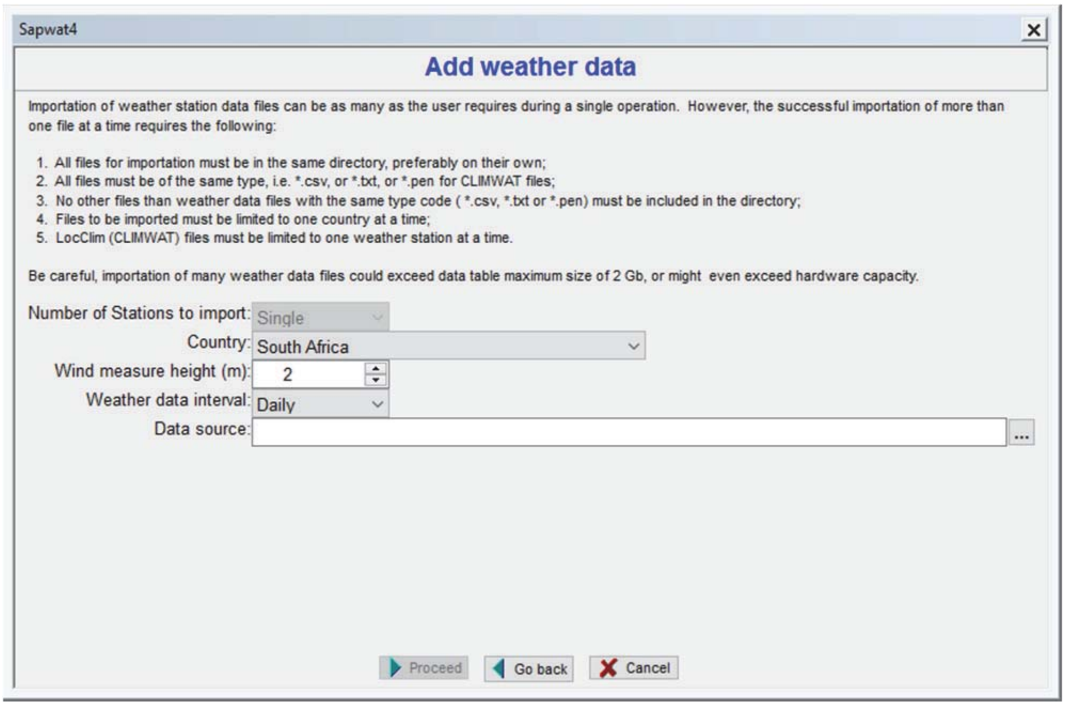


Figure 3-28 The set-up screen for electronic importation of weather station data

3.7.2.4 Climate

One of the strengths of CROPWAT and the associated climatic program CLIMWAT is that they are universally applicable. SAPWAT4 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. The significance of this is that SAPWAT4 will be universally applicable.

3.7.2.4.1 Climate screen forms

The three pages of the climate screen forms giving visual information are shown in Figure 3-29 (the world climate map), Figure 3-30 (the Southern African climate map) and Figure 3-31 (map legend). The Köppen-Geiger climate is important for SAPWAT4 because it is based on combinations of rainfall and temperature and crop growth and development is also linked to temperature. The stations' 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).

Note: The influence of climate om crop growth and development is discussed in Chapter 4.

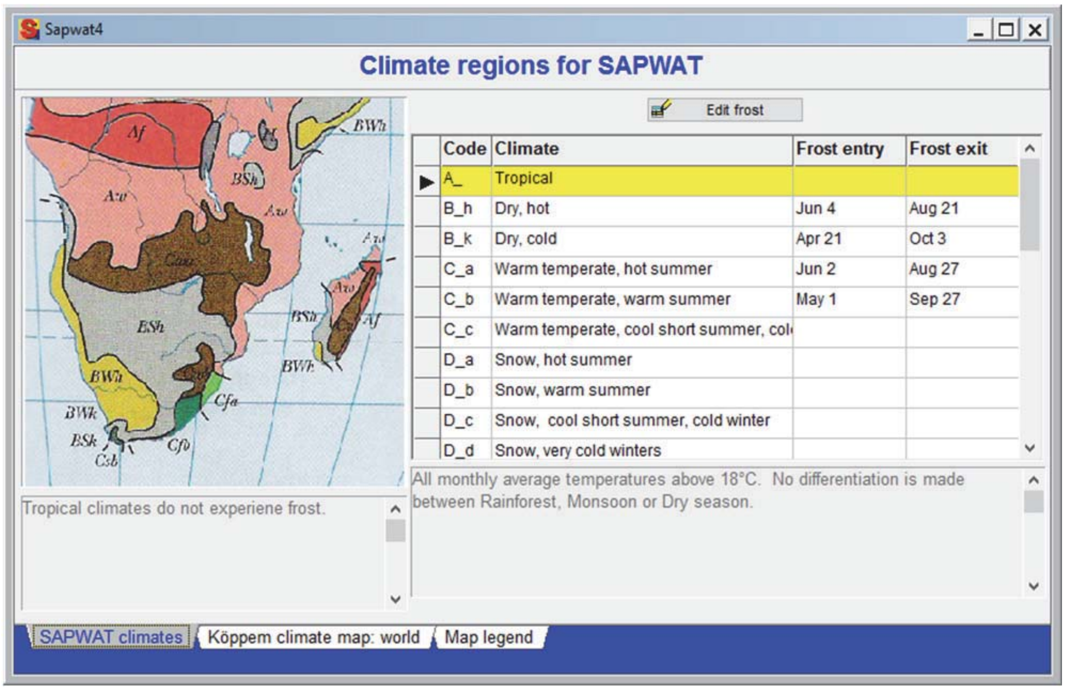


Figure 3-29 Screen form page 1: Köppen-Geiger climate map of Southern Africa and major climates

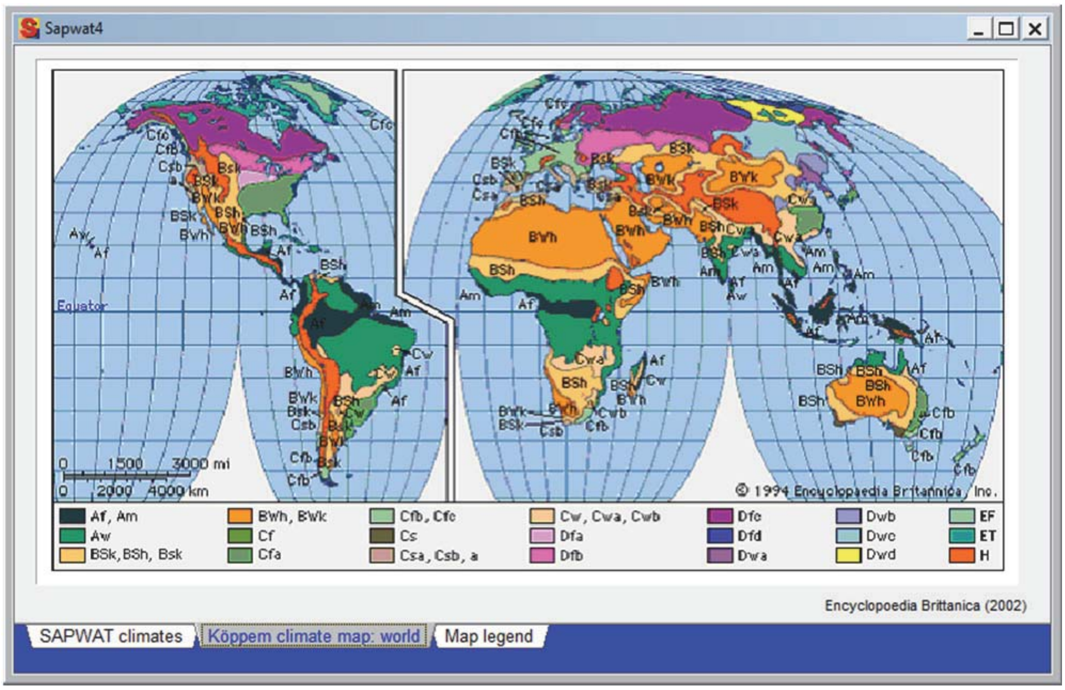
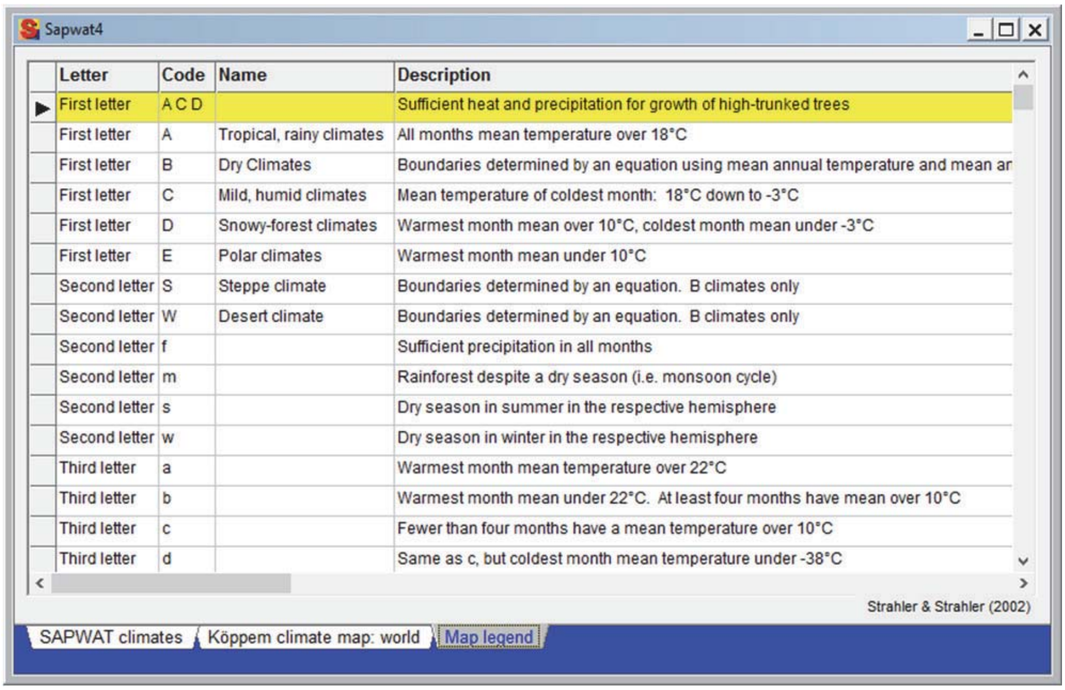


Figure 3-30 Screen form page 2: Köppen-Geiger climate map of the world



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 mean ar
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 3-31 Screen form page 3: Köppen-Geiger climate map legend

3.7.2.5 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 SAPWAT4 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, is 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 SAPWAT4 simulations. This is successful where there is 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, SAPWAT4 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 is 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 SAPWAT4 data files:

- Bananas: (Morse, Robinson and Ferreira, 1996).

- Chicory (Aucamp, 1978; Luckman, 2002[5]).
- 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[6];).
- Fodder crops and Pastures (Dickinson and Hyam (Ed), 1984; Marais, Rethman and Annandale, 2002; Meredith, 1959).
- Grapes (Myburgh, 2004a; Myburgh, 2004b; Myburgh and Howell, 2007).
- Groundnuts (Jansen, 2004[7]).
- 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[8]).
- 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; Mappledoram, 2004; Reader's Digest 1984; 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 unforeseen 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

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[5] Luckman, B. (2002) Field agriculturalist, Chicory SA. Alexandria, South Africa.

[6] Otto, W. (2004) Researcher, ARC – Small Gain Institute, Bethlehem, South Africa.

[7] Jansen, W. (2004) Research Technician, Vaalharts Experimental Farm, Jan Kempdorp, South Africa.

[8] Liebenberg A, 2002. Researcher, ARC – Grain Crops Institute, Potchefstroom, South Africa.

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 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.

3.7.2.5.1 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 SAPWAT4. 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.

3.7.2.5.2 Crops screen forms

Screen forms consist of a control screen (Figure 3-32) from which all editing related to the relational crop data tables are controlled through screen forms shown in Figure 3-33, Figure 3-34, Figure 3-35, Figure 3-36 and Figure 3-37. 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 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 vary across regions and therefore sources.

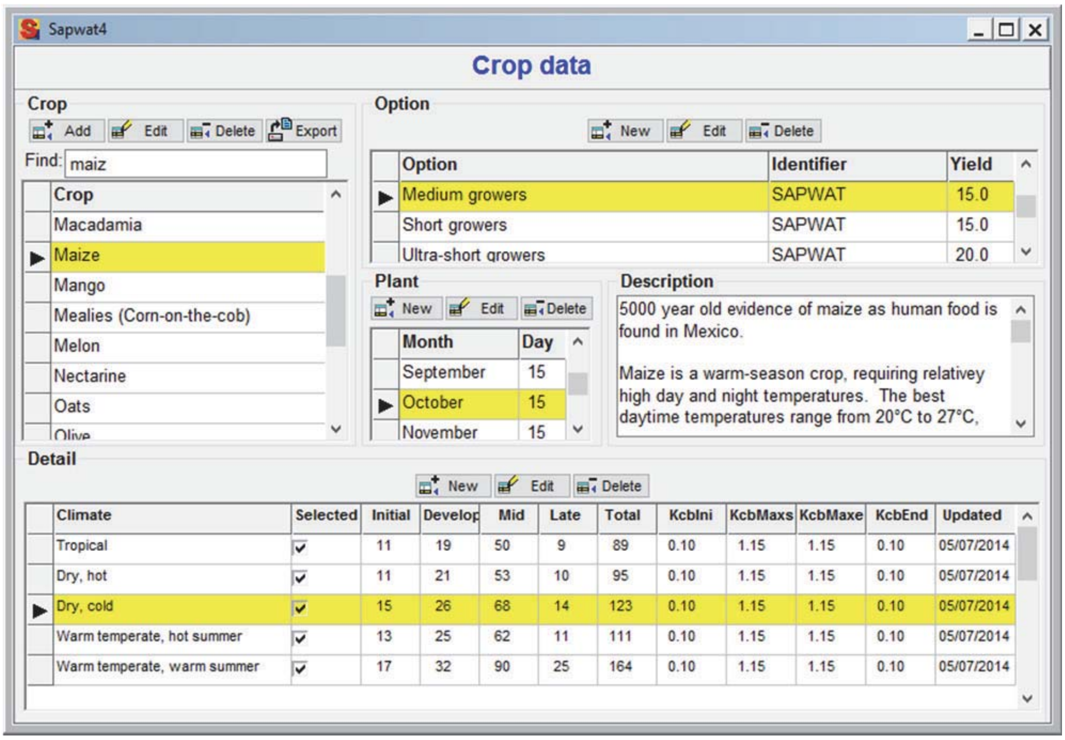


Figure 3-32 The crop data screen from which the different relational data tables are managed

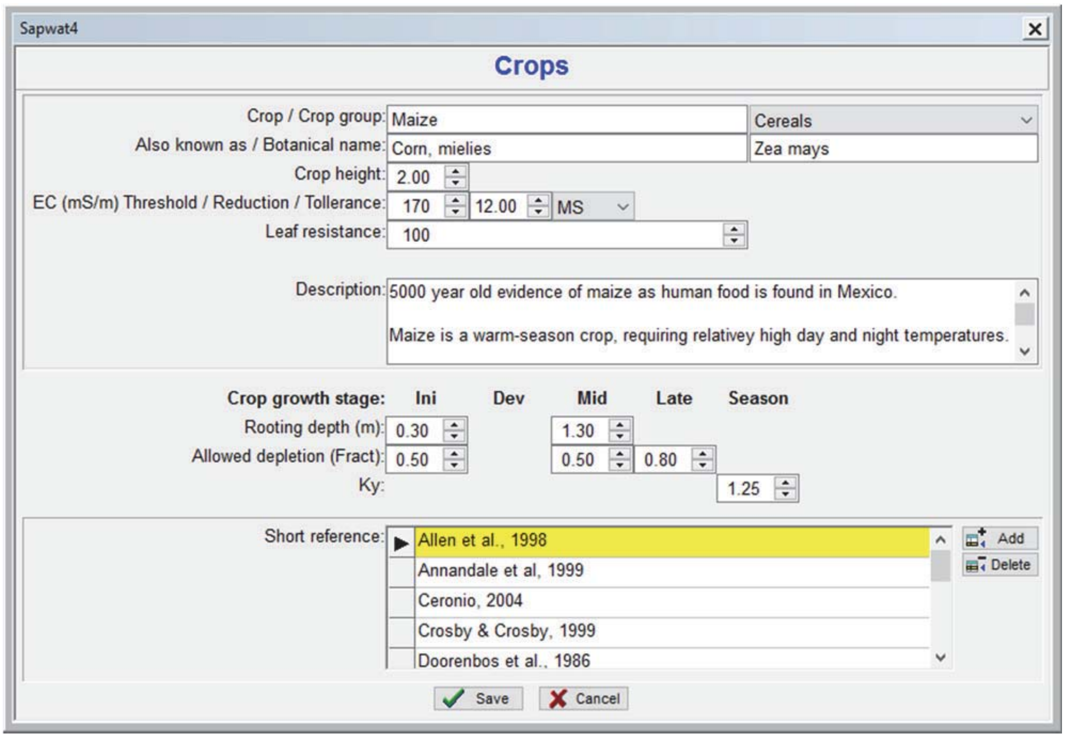


Figure 3-33 The crop edit screen

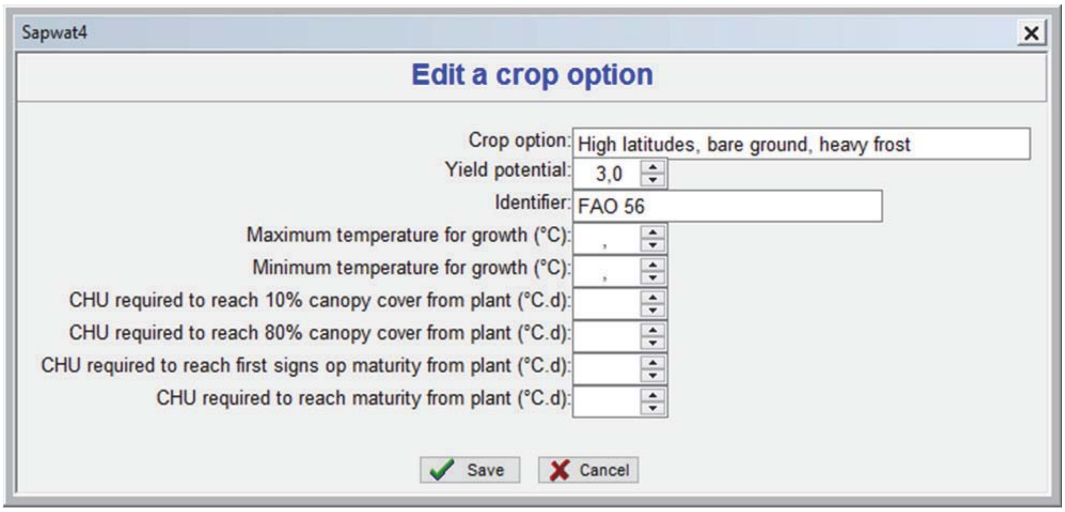


Figure 3-34 The crop option edit screen

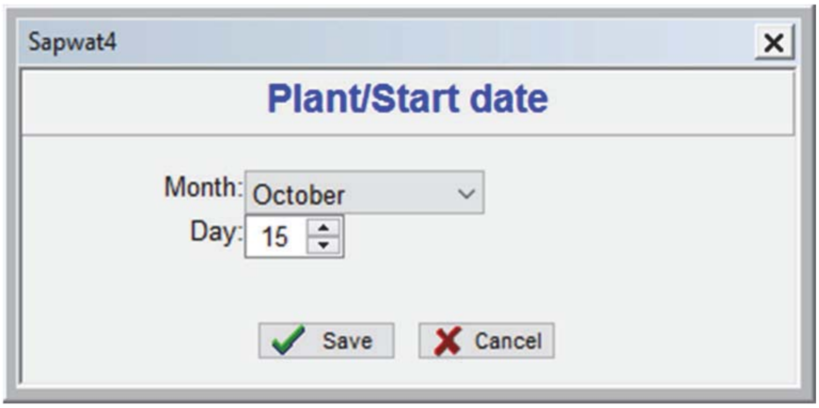


Figure 3-35 The crop plant edit screen.

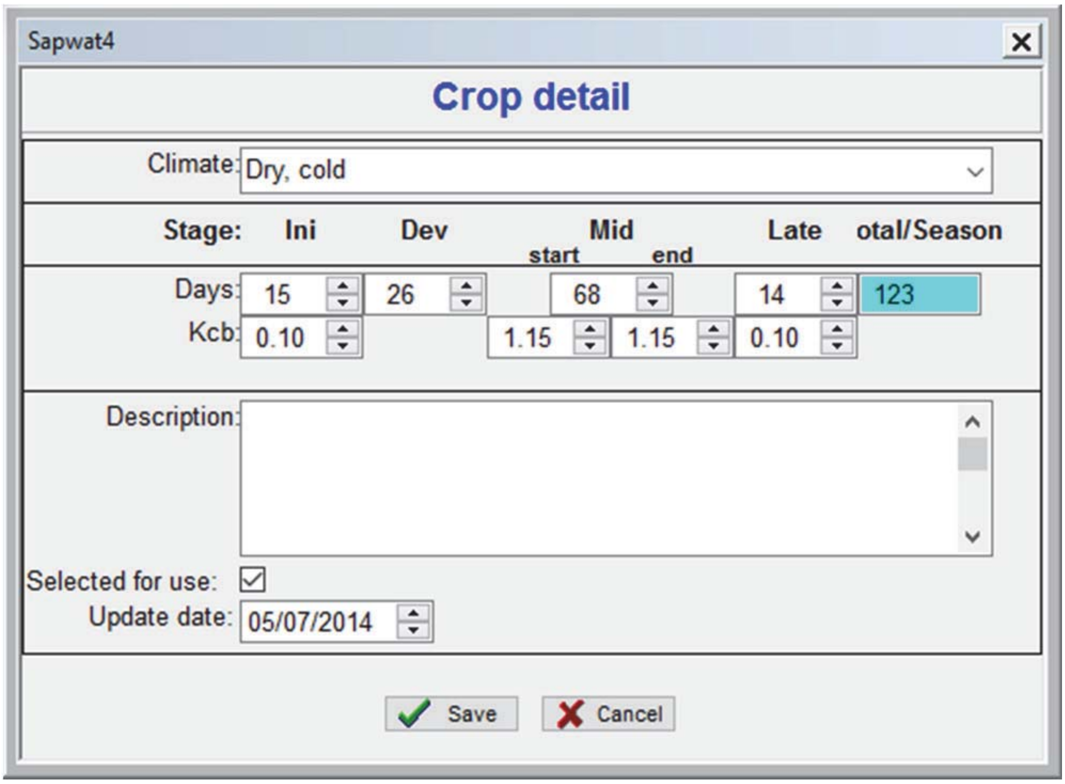


Figure 3-36 The crop detail edit screen

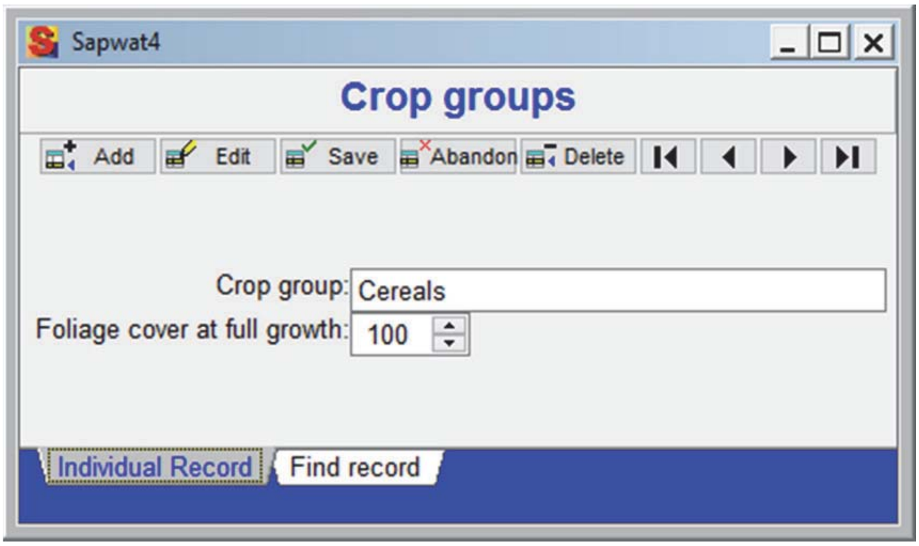


Figure 3-37 The crop group edit

3.7.2.6 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, 1967).

3.7.2.6.1 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, 1967). 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 influences 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.*, 1967). 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 restraint, such as physical or chemical manipulation, would, in broad terms, have the properties shown in Table 3-9 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 economic feasibility becomes impossible.

Table 3-9 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	1.2 m 0.9 m
Texture	6% < clay < 35%
Structure development	No structure, weak developed block (dry), Medium developed block (dry)
Stones (>75 mm) Gravel (2-75 mm)	< 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

3.7.2.6.2 Application in SAPWAT4

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 3-9). 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 m^3/m^3 and mm/m depth, because experience have shown that these forms of expressing it his published in both formats by different publishers. This is just to make things easier for the user, because automatic conversion takes place from the input data format to the other format. Evaporation depth has been discussed in 3.4.4.

Table 3-10 Soil water holding capacities included as default values in SAPWAT4 (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		

3.7.2.6.3 Soil screen forms

The soils screen form is shown in Figure 3-38 and the soil texture triangle, which is available in the soils screen form, as Figure 3-39.

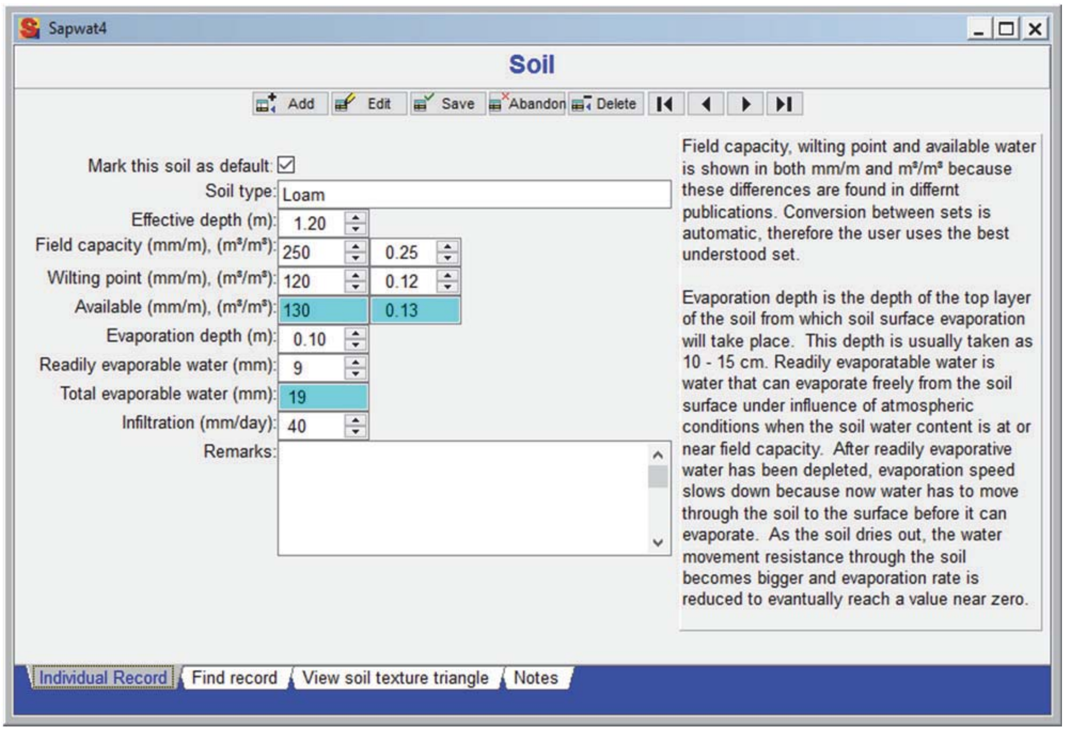


Figure 3-38 The soils screen form

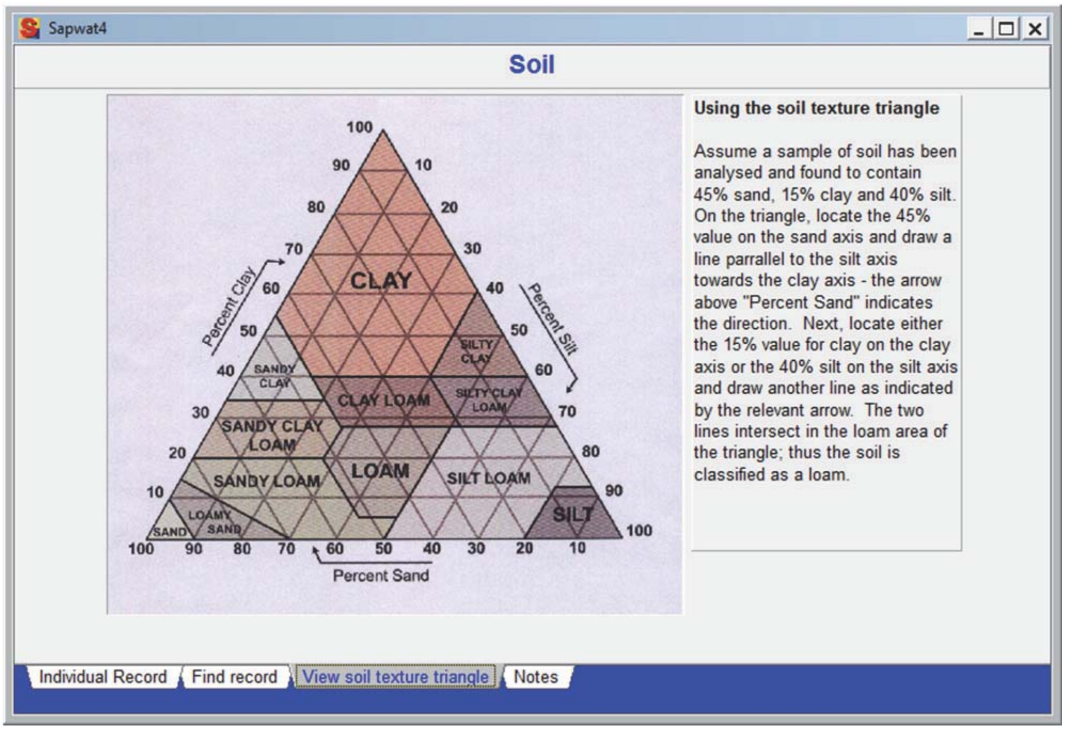


Figure 3-39 The soils texture triangle, page 3 of the soils screen form (Soilsensor.com, 2015)

3.7.2.7 Irrigation systems

Irrigation systems, consisting of surface, sprinkler and micro systems, are the means to distribute water over the field that need to be irrigated. Each system has its own inherent efficiency, expressed as a default percentage (Table 3-11), from the SABI[9] design manual and have been generally accepted by designers and planners (ARC-IAE, 1996). The Stam (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 *et al.* (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 in-field irrigation efficiency (Jensen *et al*., 1987; Reinders *et al.*, 2010).

Table 3-11 Irrigation systems and their traditional efficiencies as used by irrigation system designers and irrigation planners (Reinders *et al.*, 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 3-12) (Crosby and Crosby, 1999). These values were used to estimate irrigation requirement, which, when compared to Table 3-11, would result in a big increase in irrigation water requirement because of a lower efficiency.

[9] South African Irrigation Institute

Table 3-12 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 3-12 would result in over-design of irrigation systems, but arguments for this approach were found. An example is Li (1998), who argued that on small-scale water distribution in a field under irrigation is not uniform. This is because of micro-topography unevenness causes some water to move sideways on the soil surface, or small pockets of soil may have a different infiltration rate 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 3-40 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.

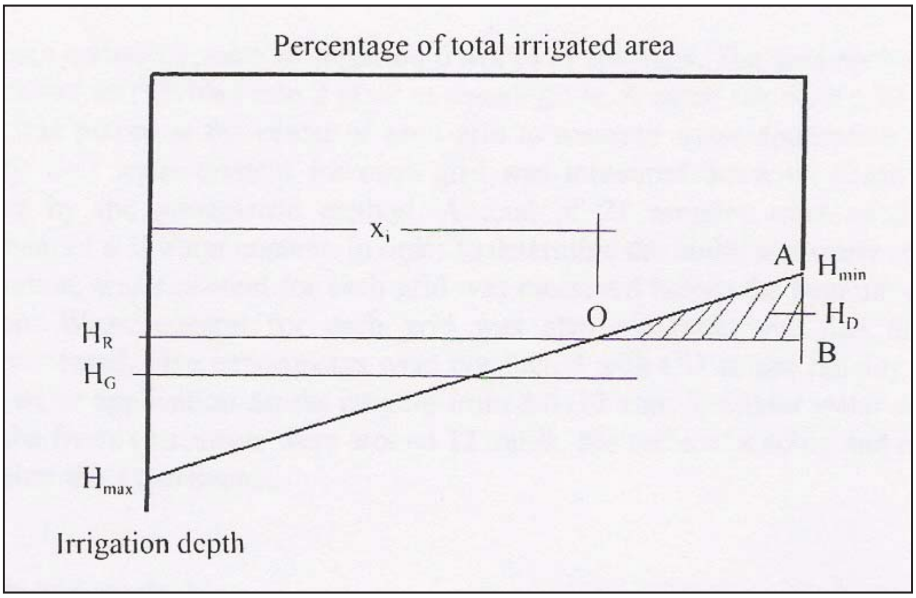


Figure 3-40: Frequency distribution of irrigation depths in the field assuming a uniform distribution (Li, 1998)

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."

Reinders *et al*. (2010) recommends that the single figure irrigation system efficiency be replaced by a 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 ICID[10] (Reinders *et al*., 2010) recommended approach which is aimed at reducing the confusion surrounding the terms "irrigation efficiency", especially where irrigation systems are concerned. Recommended system efficiencies that are mostly higher than the presently accepted default values for most irrigation systems (Table 3-13). These are based on analyses done for the publication of the Reinders *et al.* (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 *et al*. (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 SAPWAT4 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 *et al*. (2010).

In SAPWAT4 irrigation system and their efficiencies is placed 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 research results. Irrigation systems included in the look-up table as well as their default system efficiencies (Table 3-13).

[10] International Commission on Irrigation and Drainage

Table 3-13 Irrigation systems and efficiencies included as default values in SAPWAT4

System	Distribution uniformity (%)	System efficiency used in SAPWAT4 (based on ARC-IAE, 1996) (%)	System efficiency recommended by Reinders *et al.* (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.

3.7.2.7.1 Screen forms

The irrigation system screen form is shown in Figure 3-41.

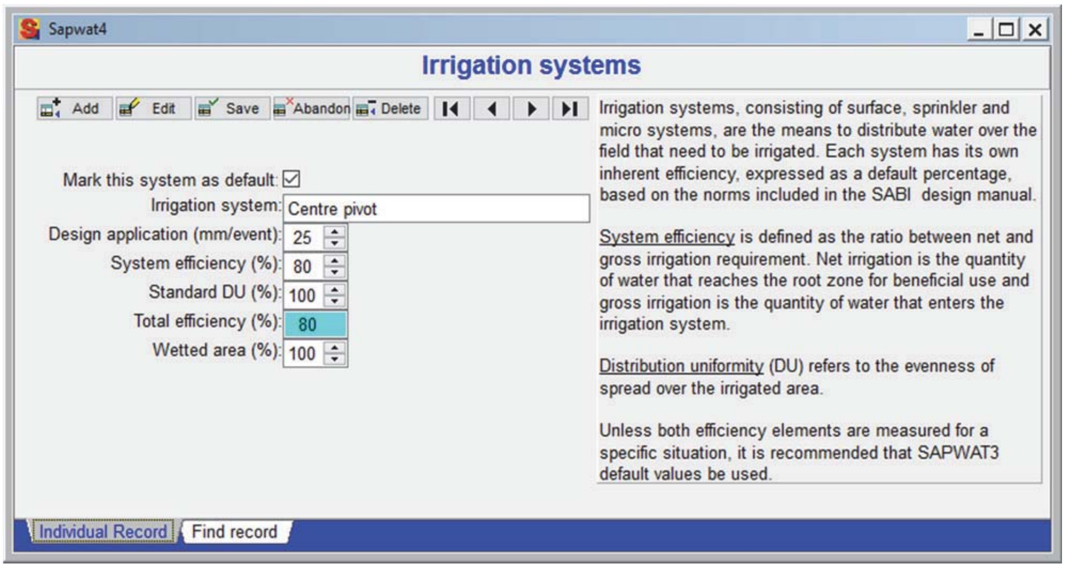


Figure 3-41 Irrigation system screen form

3.7.2.8 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[11] made up of specialists, most of who were eventually also involved in the Reinders *et al.* (2010) project, were asked for advice. They reached consensus that the values shown in Table 3-14 should be used as default values.

Table 3-14 Conveyance system efficiencies included as default values in SAPWAT4 where WMA = water management area; WUA = water user's 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
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

3.7.2.9 Screen forms

The water conveyance system screen form is shown in Figure 3-42.

[11] PS van Heerden of PICWAT; FB Reinders and F H Koegelenberg of the ARC – Institute of Agricultural Engineering; Ms I 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.

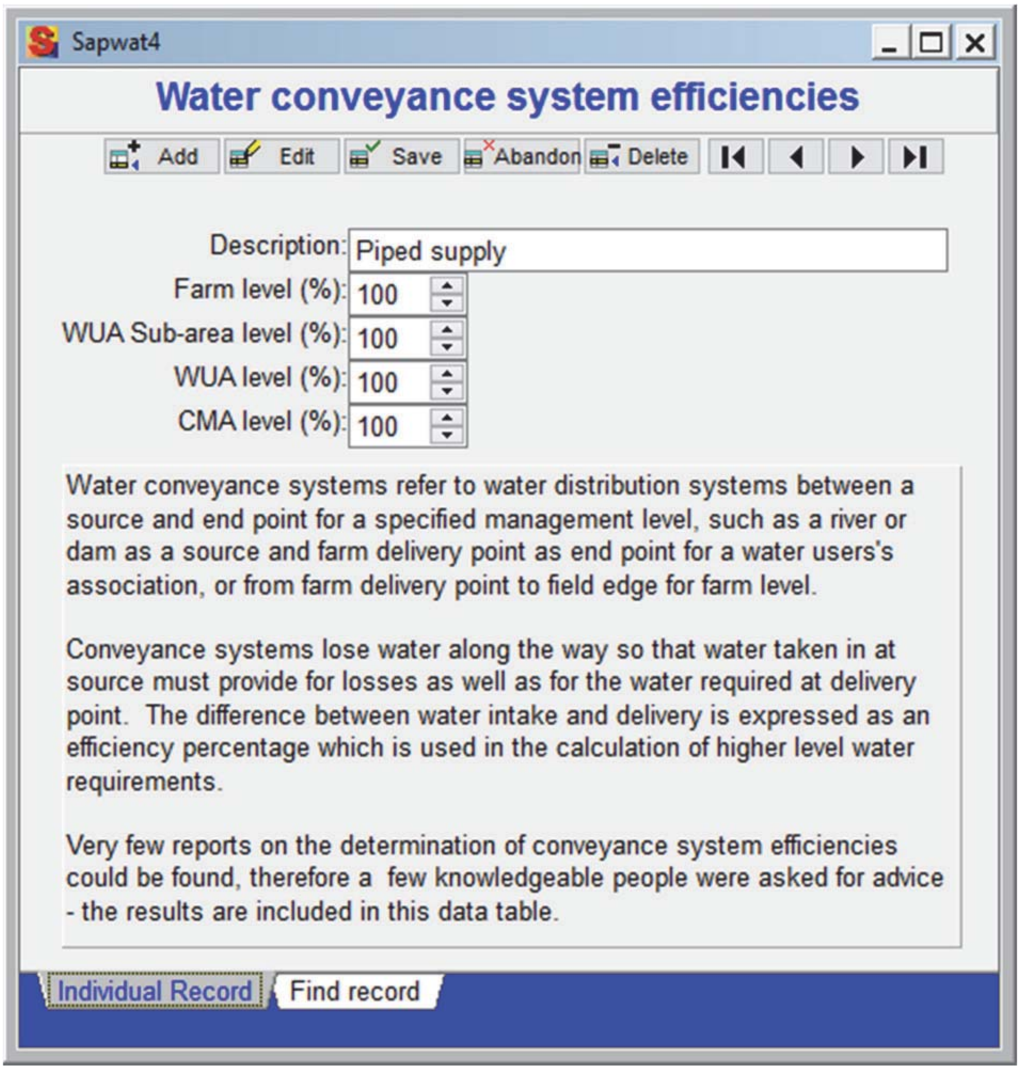


Figure 3-42 Water conveyance system efficiencies screen form

3.7.2.10 Countries

Countries are included to enable the user to select a country to work with 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[12]. These country maps are used for selecting weather stations for use in SAPWAT4. As many map types or subdivision maps of a country as required can be linked to the country data table.

[12] ISO 3166, 1993

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.

3.7.2.10.1 Countries screen forms

The countries screen form is shown in Figure 3-43 and the detail country form in Figure 3-44. Placing the pointer onto a weather station, shows its name and double clicking on it will open the weather station screen for that station.

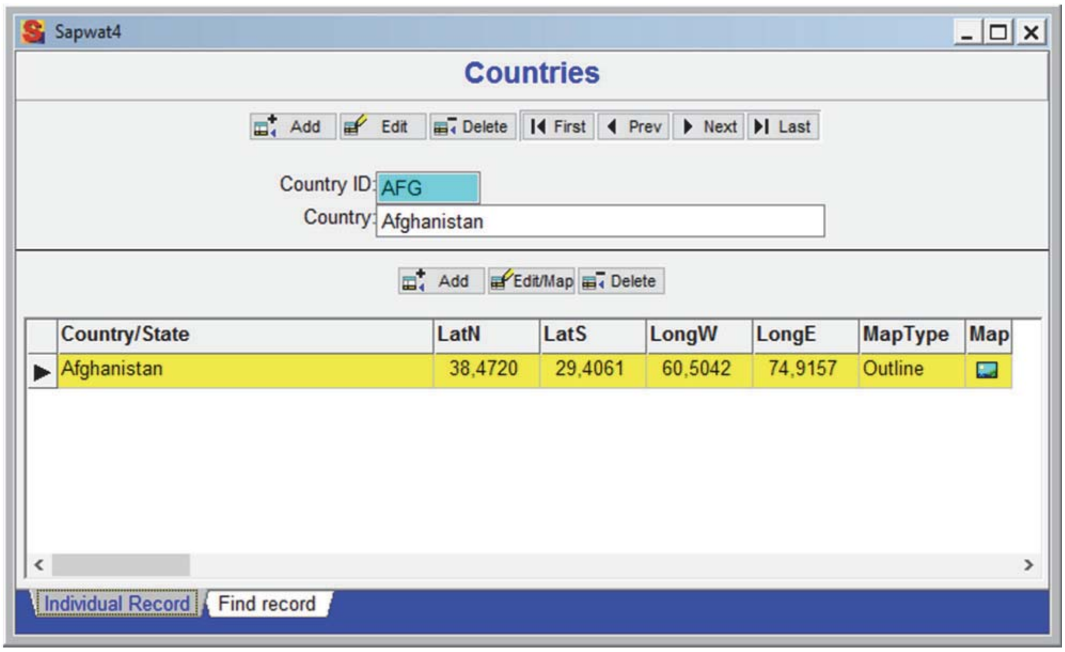


Figure 3-43 Screen form for countries, showing South Africa with choice of topographic and outline maps

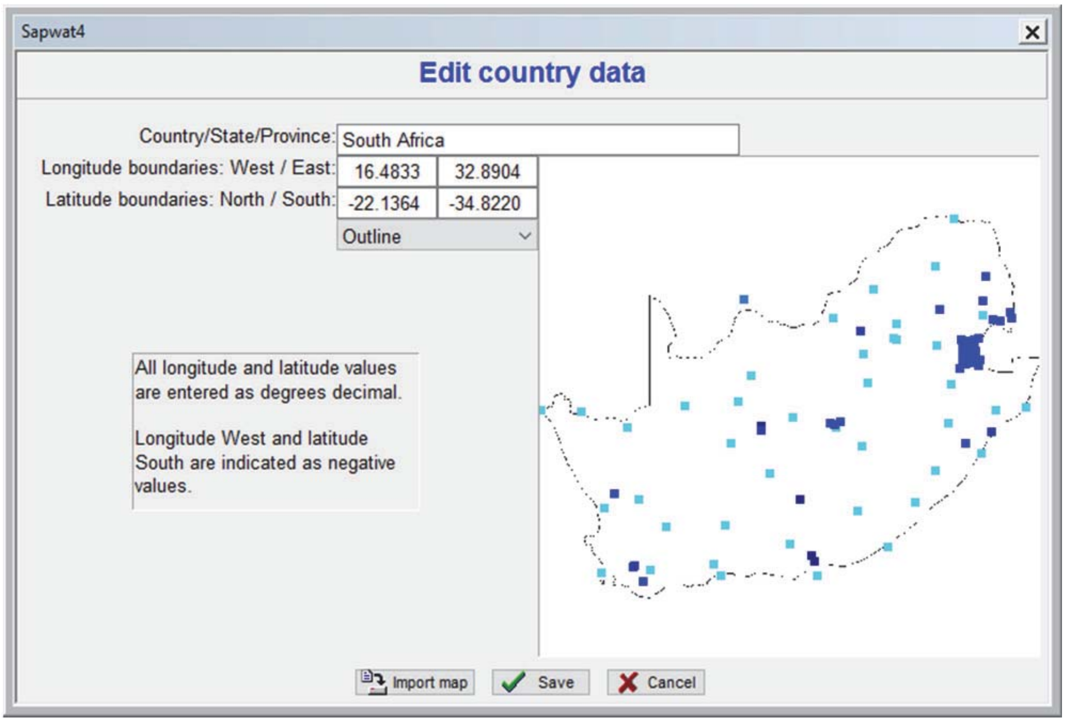


Figure 3-44 Detail map of South Africa showing CLIMWAT weather stations (light blue) and own weather stations (dark blue)

3.7.2.11 Address list

An address list is included to enable the user to keep track of people that are linked to projects.

The addresses on the list cannot be used for anything but keeping track of people; there is no linkage to address lists of other programs.

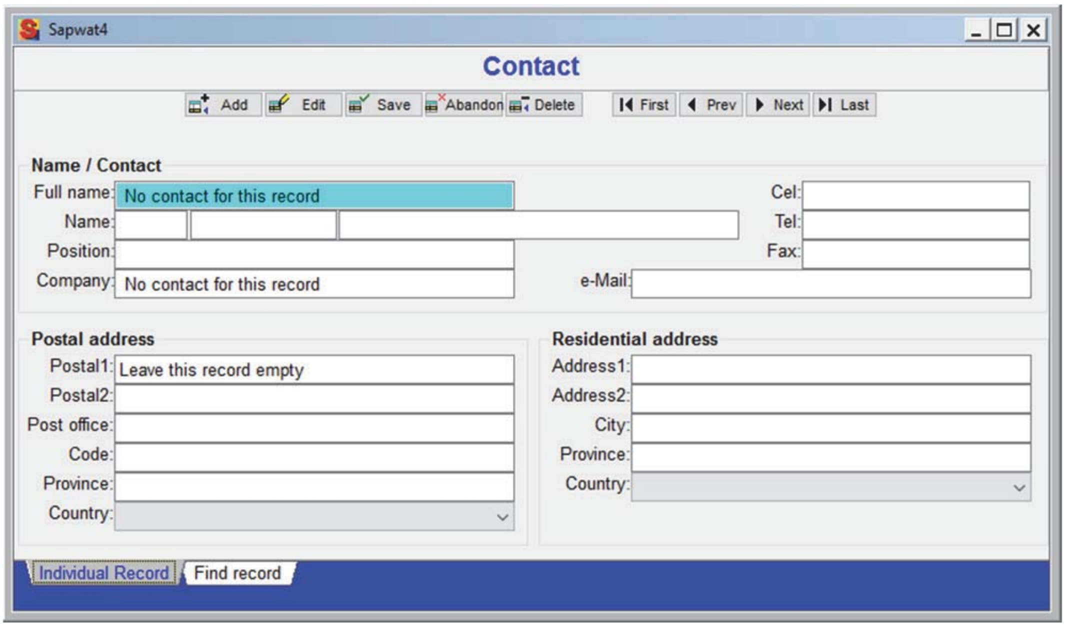


Figure 3-45 The screen form of the address list

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 SAPWAT4 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 this 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 is 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 time. 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 now to SAPWAT4 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 infield rainwater harvesting; provision of comprehensive built-in datasets; importation of weather data; and, exporting data to other file formats

SAPWAT and PLANWAT was 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 could also sum results backwards so that not only the estimated irrigation requirements of a crop would be shown, but results of a field on which several crops are grown could be shown. Similarly, the estimated requirements of a farm or a group of farms in a water users association (WUA) or on a larger scale, that of a water management area

(WMA), could also be shown. The extra functionality of adding data backwards to higher than farm level was asked for by irrigation scheme managers to make their job of managing water at that level easier. 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 SAWPAT4, this does not seem to be a problem anymore.

An enterprise budget functionality was included in SAPWAT4 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 in order to calculate both water harvest area needed and water storage capacity required to supply water to the garden. 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. It is designed to work from empty start to empty end situations, in other words, start the season on an empty tank and have an empty tank again at the end of the season. 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), each with its own efficiency of harvesting and of storage. For in-field rainwater harvesting it also shows the ration between harvest area and production area.

Data include a full range of crops and their characteristics, a full set soil texture classes, complete set of Köppen climate and a comprehensive set of weather data that can be managed, stored and adapted as the user requires. Weather data is included for most of the third-world countries and more than 100 crops are included. All data is on-board, and even though present day broadband connectivity makes it possible to all 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 SAPWAT4 results as tables and graphs in reports.

SAPWAT4 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 was found to enable this improvement. Methods to solve this problem are being sought and is included in SAPWAT4.

CHAPTER 4.
Linking crop growth to climate

4.1 Introduction

The 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 4-1) 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 4-1) 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 4-1) 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.

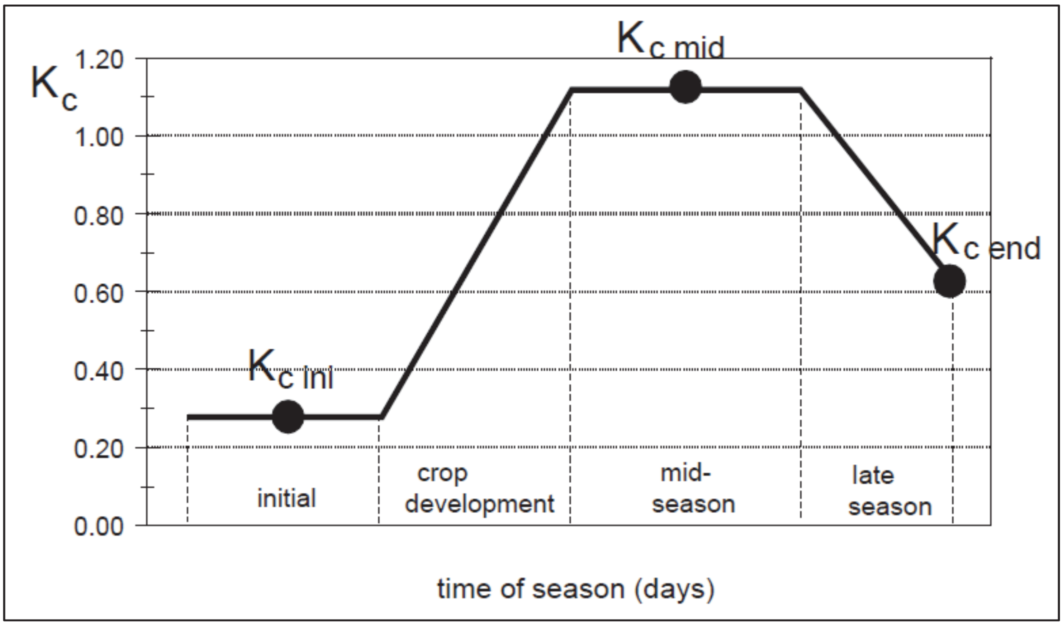


Figure 4-1 Construction of the Kc four-stage growth curve (Allen *et al.*, 1998)

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 4-1) 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 4-2) (Crosby and Crosby, 1999). The differences in growing periods shown in Figure 4-2 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.

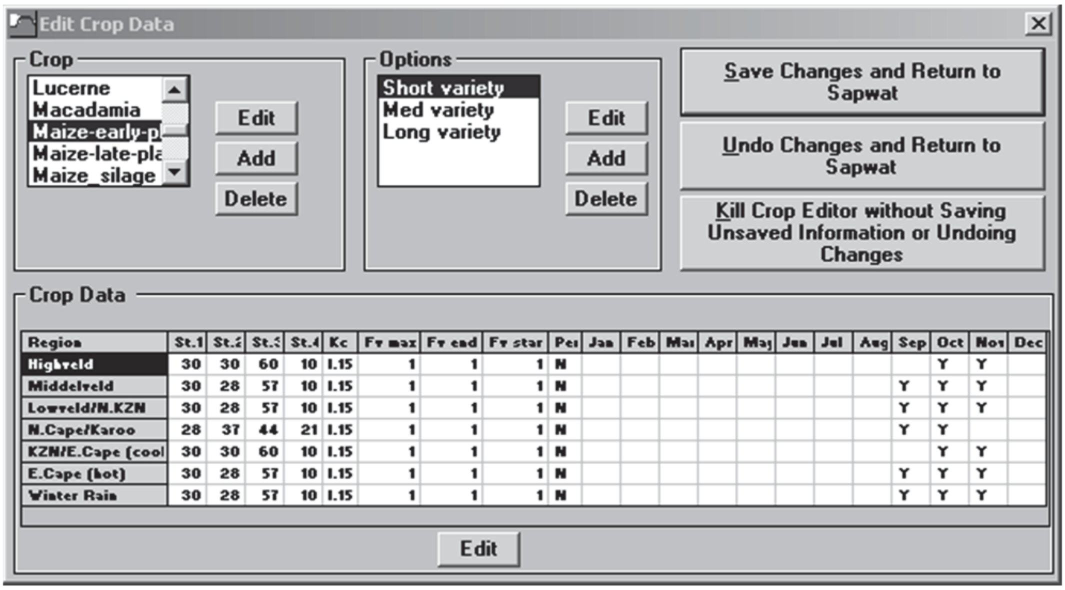


Figure 4-2 A screen shot of the SAPWAT crop editor screen form. SAPWAT growth stages for different geographic (by implication: climatic areas) regions in South Africa (shown in left-hand-side list) for short variety of maize planted in spring (Crosby and Crosby, 1999)

4.2 Objectives

The objective of this chapter is:

1. To find a suitable climate definition approach to be used in the upgraded SAPWAT4;
2. To describe the process of building the SAPWAT4 crop data tables;
3. To show the soundness of distinguishing between climate regions by comparing SAPWAT4 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 SAPWAT4 crop data.

4.3 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 SAPWAT4; and
- To link crop growth and development to climate.

4.3.1 Selection of a climate system suitable for SAPWAT4

SAPWAT3 and SAPWAT4 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 SAPWAT4.

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 4-3). 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 SAPWAT4. The world map of the Köppen-Geiger climate system is shown in Figure 4-3, while the South African map is shown in Figure 4-4. A description of the major climate regions and their sub-regions as used in the Köppen-Geiger climate system are defined in Table 4-1.

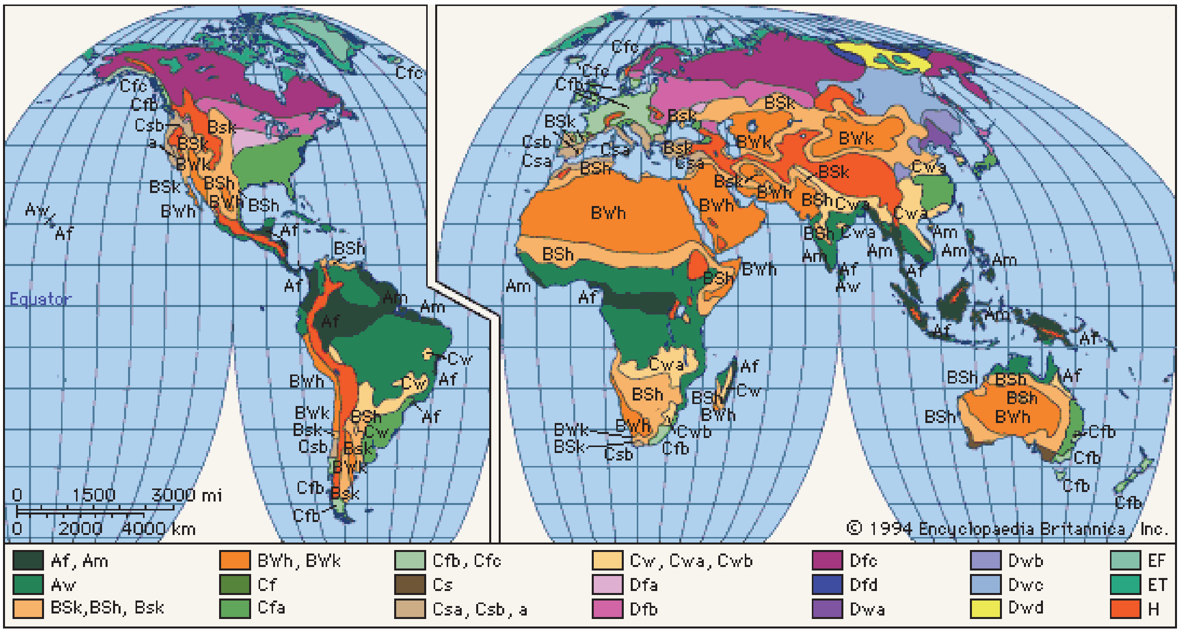


Figure 4-3 Köppen-Geiger climate map of the world (Encyclopaedia Britannica, 2010)

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

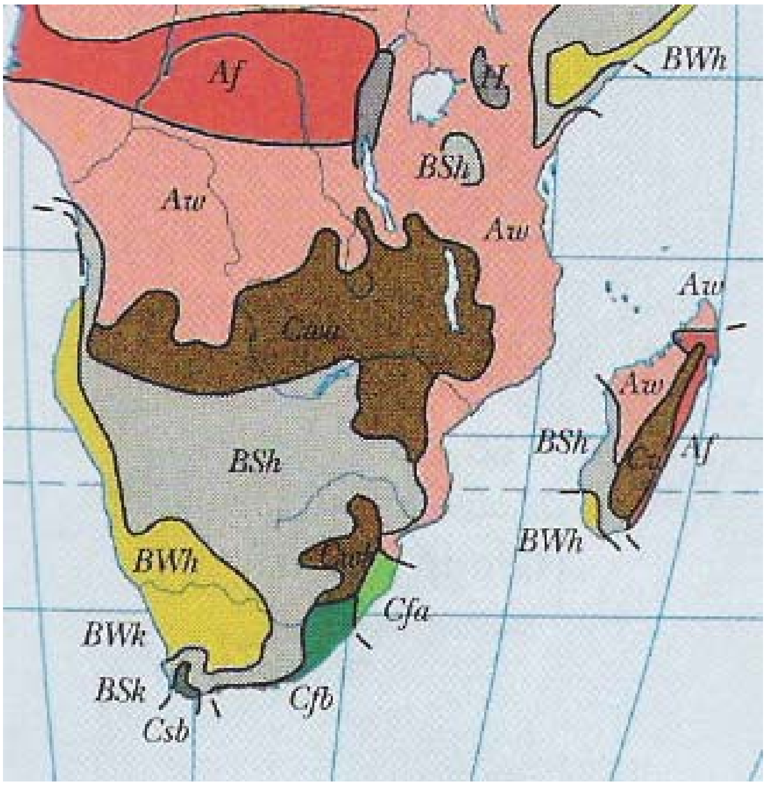


Figure 4-4 Köppen-Geiger climate map of Southern Africa (Strahler and Strahler, 2002)

The determination of boundaries between wetter and drier areas in Table 4-1 is based on equations that have the general format of (Strahler and Strahler, 2002):

$$P_{benchmark} = k_1(C + k_2) \tag{61}$$

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 4-2 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 4-2:

Table 4-2 Values to be used for the constants k_1 and k_2 in Equation (61) (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.

4.3.2 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 4-3).

Table 4-3 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 4-4). The optimum temperature is the temperature at which the highest percentage of germination takes place in the shortest time (Pessarakli, 2001).

Table 4-4 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 (62)) (Parthasarathi *et al*., 2013).

$$CHU=\sum_{n=1}^{365}\left[\left(\frac{(T_{max}+T_{min})}{2}-T_b\right)\Delta t\right] \qquad (62)$$

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 4-5, 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 4-5 Phenology and related heat units for some crops (Miller *et al*., 2001; Parthasarathi *et al*., 2013)

Stage	Description	Growth stage	CHU
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

Stage	Description	Growth stage	CHU
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
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

Stage	Description	Growth stage	CHU
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

4.4 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 SAPWAT4 needs to be linked to these. Crop data has not been included in SAPWAT4 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 SAPWAT4, seems to refer to the warmer climates. Therefore, the applicability and correctness of the crop growth data included in SAPWAT4 need to be verified for the colder climates.

4.4.1 Adapting crop growth characteristics to climate regions in SAPWAT4

A comparison of the Köppen-Geiger climate system and the South African geographic regions that imply climate (Table 4-6), shows why it was necessary to change the climate reference approach for use in SAPWAT4. 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 4-6 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 SAPWAT4**
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 SAPWAT4 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 SAPWAT4 climate data table is shown in Table 4-7 (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-climate data points (Schulze and Maharaj, 2006) included in SAPWAT4 (Table 4-7, Figure 4-5).

Table 4-7 Table showing the adaptation of the Köppen-Geiger climate system for SAPWAT4 (Van Heerden *et al*., 2008)

Köppen-Geiger climate codes	SAPWAT4 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 SAPWAT4
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

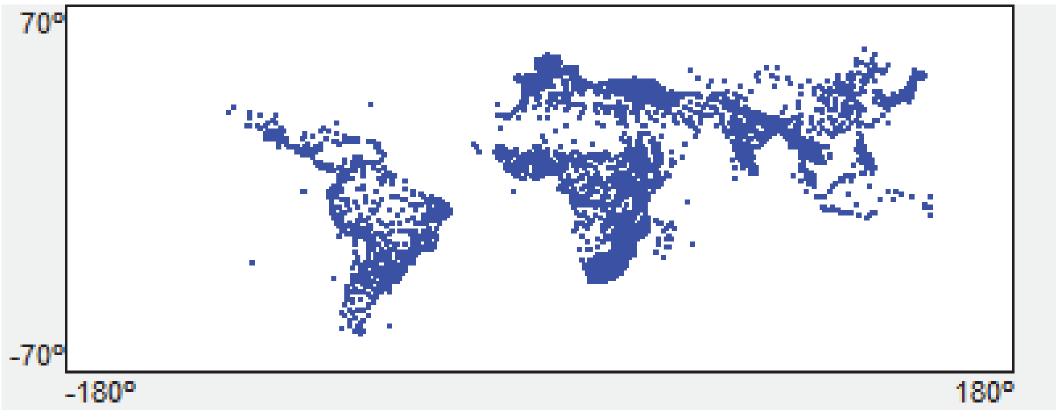


Figure 4-5 Distribution of weather stations included in SAPWAT4 (Smith, 1993; Schulze and Maharaj, 2006)

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 SAPWAT4" in Table 4-7. The definitions of the different climates can be seen in Table 4-1 and are available in the Climate data table that is included in SAPWAT4 (Van Heerden *et al*., 2008).

Figure 4-6 shows the application of the Köppen-Geiger climate system (Strahler and Strahler, 2002) in the crop data table of SAPWAT4. 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 SAPWAT4 (Figure 4-6) and SAPWAT (Figure 4-2) 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).

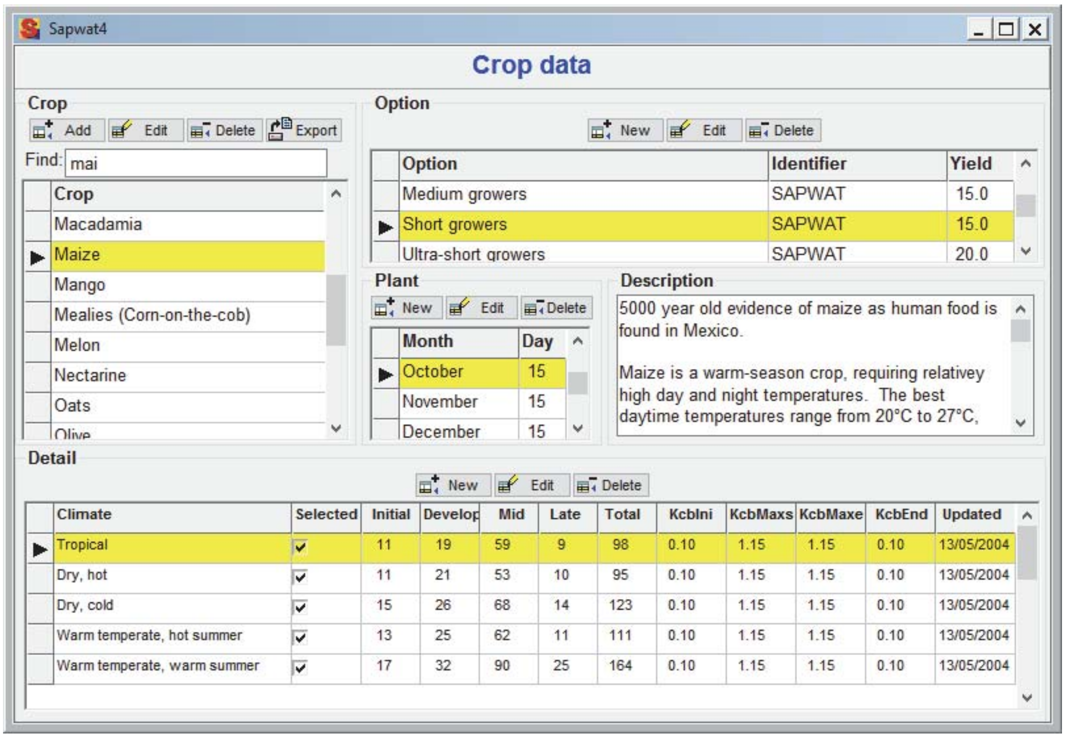


Figure 4-6 Crop characteristics of maize, short grower, planted middle of October showing the different stage lengths for warmer and colder areas (Van Heerden *et al*., 2008)

4.4.2 Fitting an ET_0 curve to weather station data

SAPWAT4 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):

$$ET_c = ET_0 \times K_c \tag{63}$$

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 4-7 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 4-8) (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 4-9 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 4-10). 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 4-10).

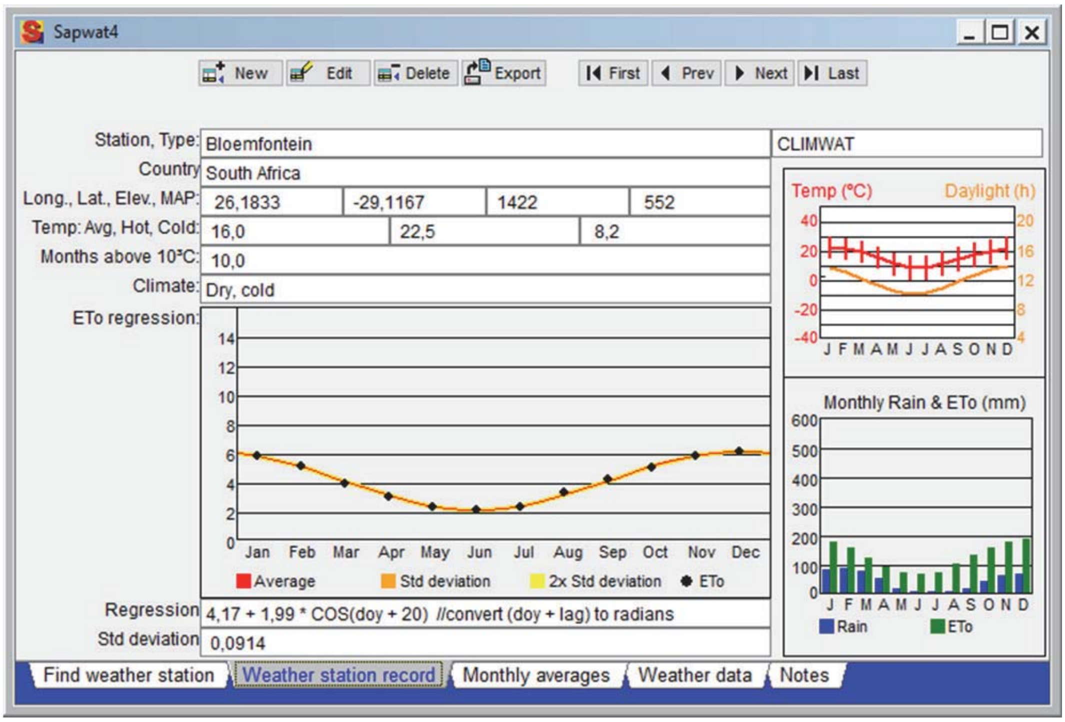
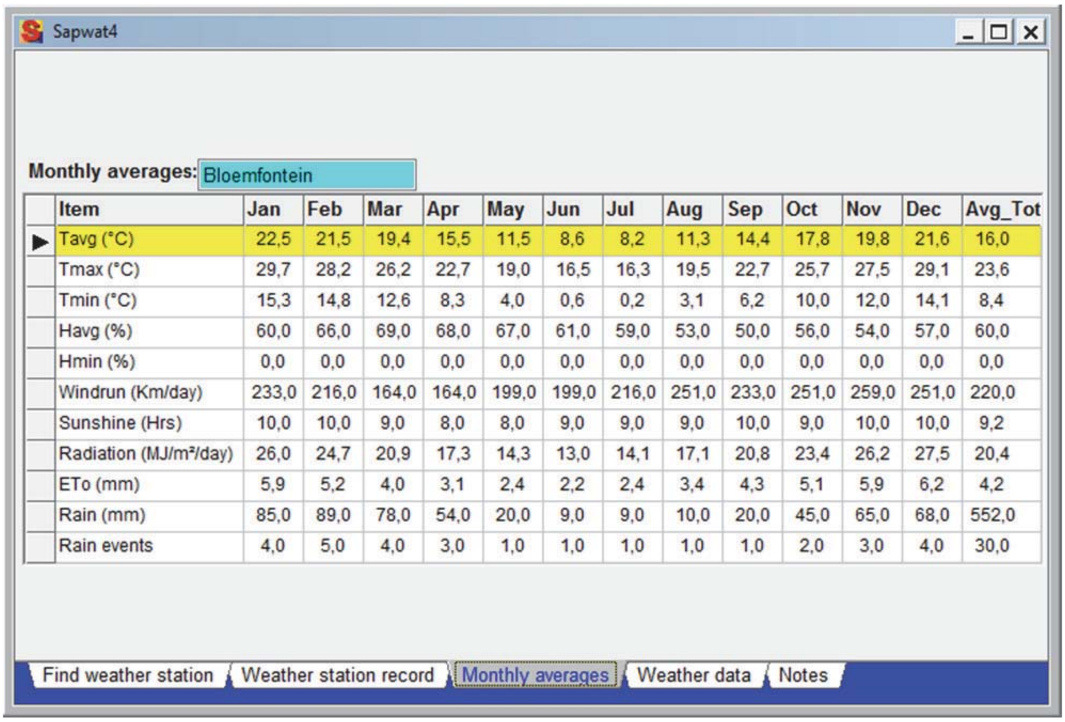


Figure 4-7 SAPWAT4 representation of the climate of the Bloemfontein CLIMWAT weather station (Smith, 1993) showing the cosine regression curve and its equation through monthly average ET_0 data – standard deviation values does not show when a single set of monthly average values are used (Van Heerden *et al*., 2008)



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	17,8	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)	5,9	5,2	4,0	3,1	2,4	2,2	2,4	3,4	4,3	5,1	5,9	6,2	4,2
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

Figure 4-8 Monthly climate data of the Bloemfontein CLIMWAT weather station (Smith, 1993; Van Heerden *et al*., 2008)

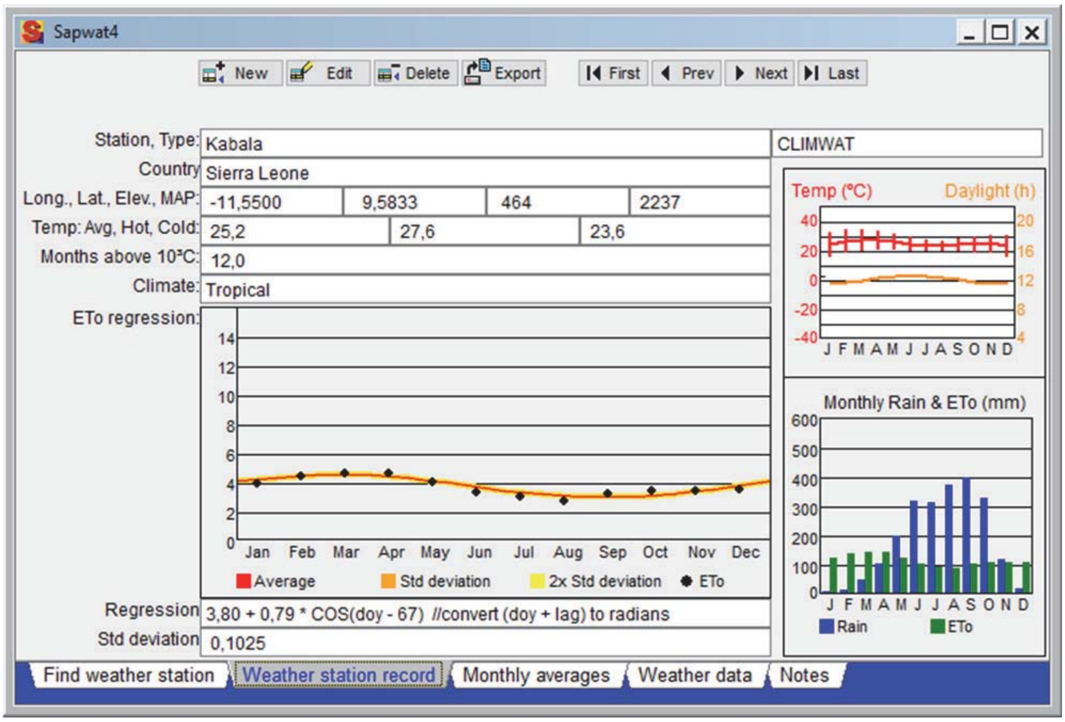
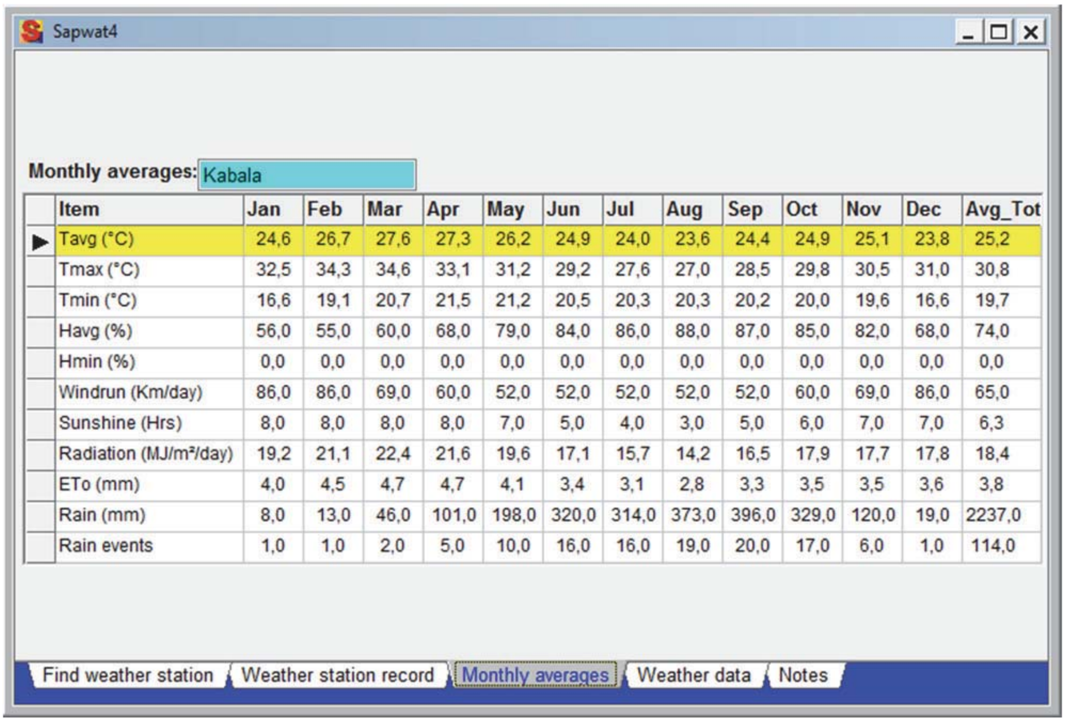


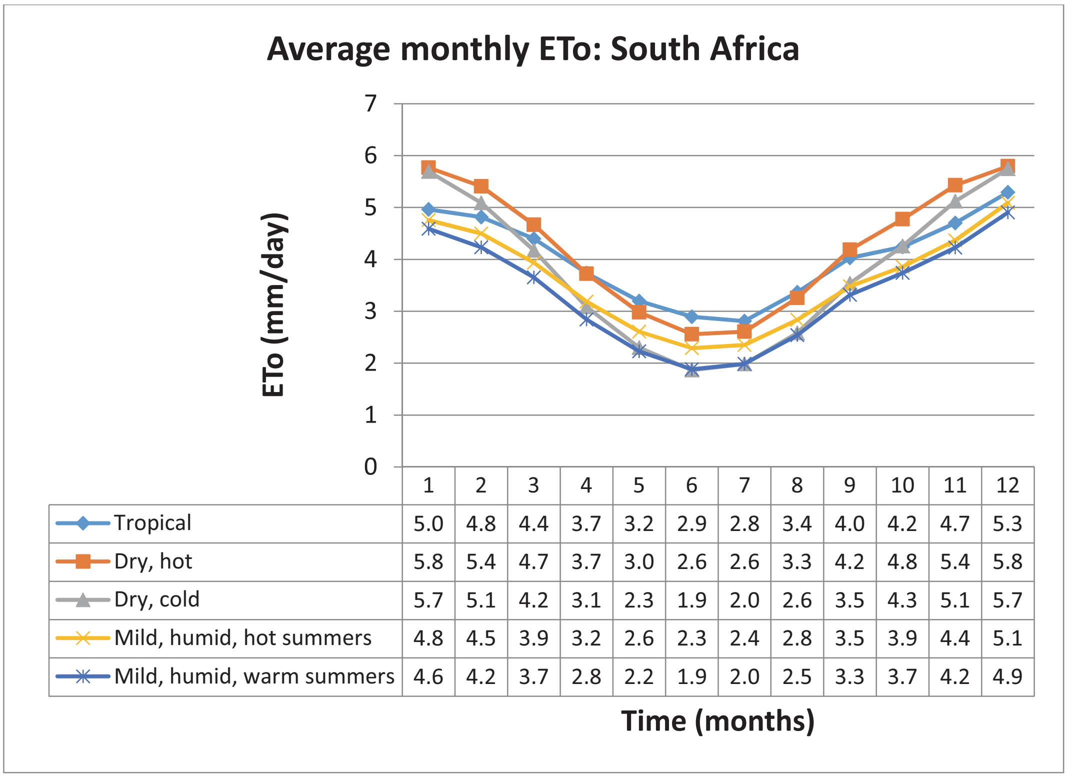
Figure 4-9 SAPWAT4 representation of the climate of the Kabala CLIMWAT weather station (Smith, 1993), situated in a rainy area, showing a significantly shifted cosine regression curve through monthly average ET_0 data relative to the solar time cosine curve (Van Heerden *et al*., 2008)



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

Figure 4-10 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 4-11. 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 4-11 Mean monthly ET_0 values (mm/day) for Köppen-Geiger climates found in South Africa weather stations included in the SAPWAT4 weather data table (Van Heerden *et al*., 2008)

4.4.3 Temperatures of South African Köppen-Geiger climates

Temperature is an important determinant of crop growth and development that is used in SAPWAT4, 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 SAPWAT4 weather data table (Figure 4-12) (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 4-12 can be used to calculate CHU by using Equation (62). 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 SAPWAT4 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 (64). 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[13]. The results are shown in Figure 4-12 to Figure 4-17.

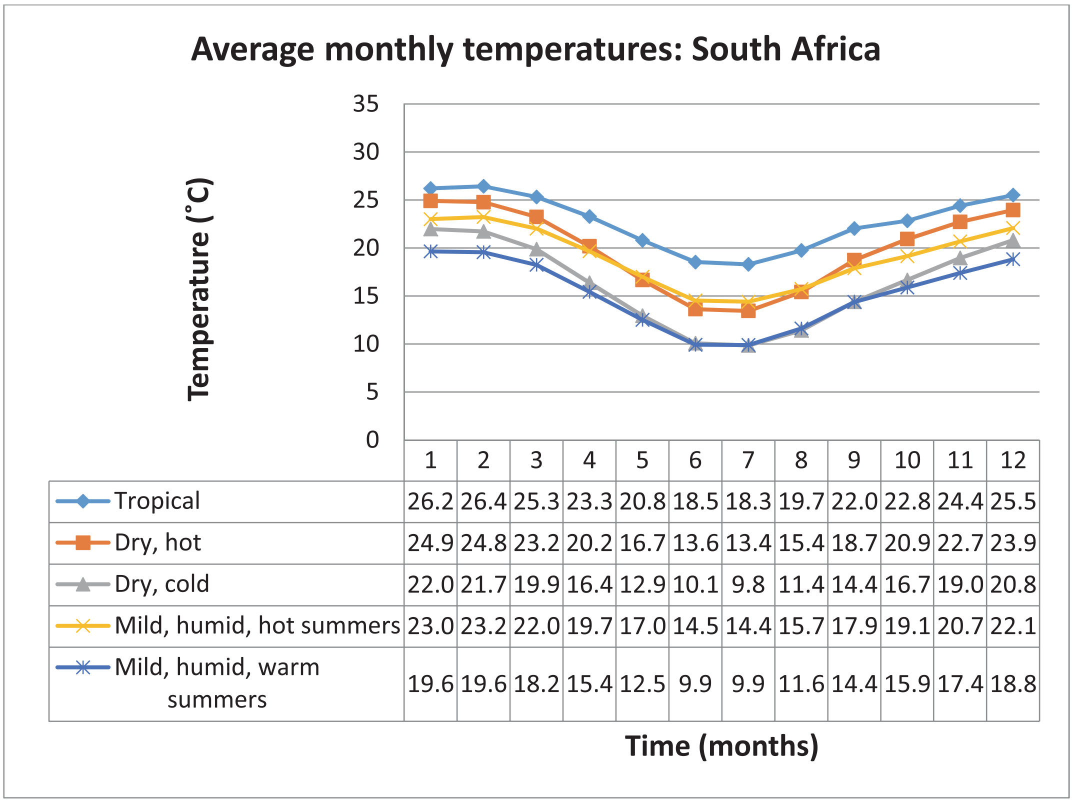
$$\overline{Y} = A + B.\cos\left\{\text{radians}\left[0.9863(DOY + lag)\right]\right\} \tag{64}$$

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

[13] 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 SAPWAT4 as an integral part of the program need further research.

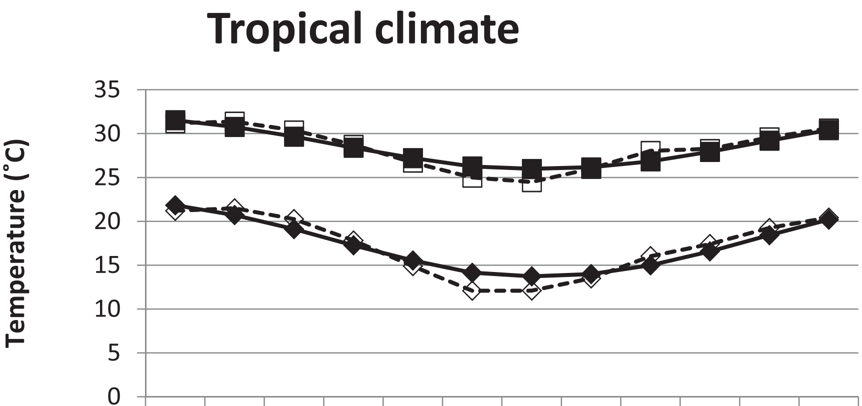
Table 4-8 Regression equations for average monthly maximum and minimum temperatures for all weather stations of Köppen-Geiger climates found in South Africa. Climate codes refer to SAPWAT4 climate codes described in Table 4-7. n = number of weather stations per climate

Climate	n	Parameter	Regression equation	r^2	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

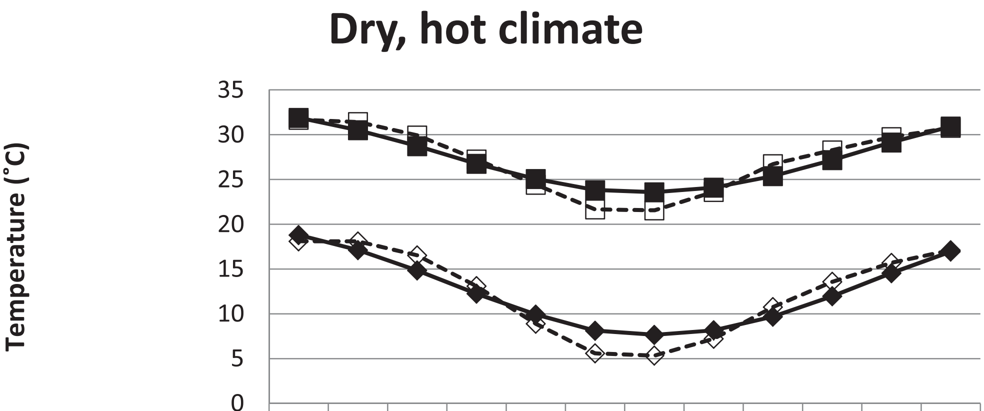
Figure 4-12 Average monthly temperatures for Köppen-Geiger climates for all South African weather stations included in the SAPWAT4 weather data table (Van Heerden *et al.*, 2008)



	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)

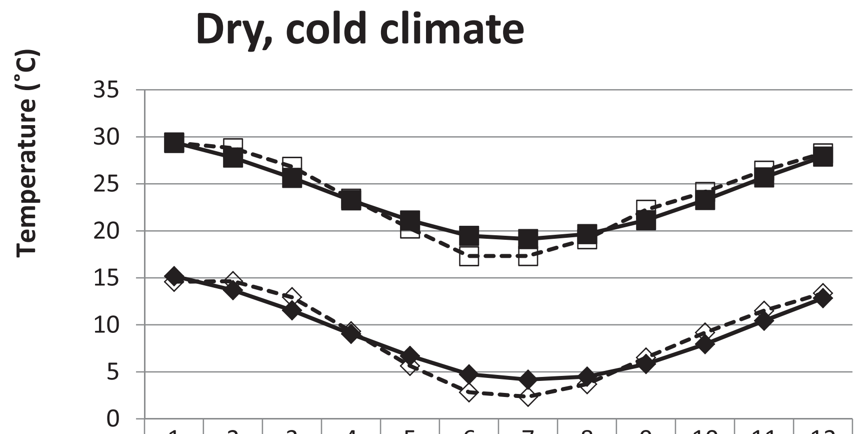
Figure 4-13 Comparison of actual and cosine regression predicted monthly temperatures for the tropical climate of South Africa based on weather data included in the SAPWAT4 program



	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)

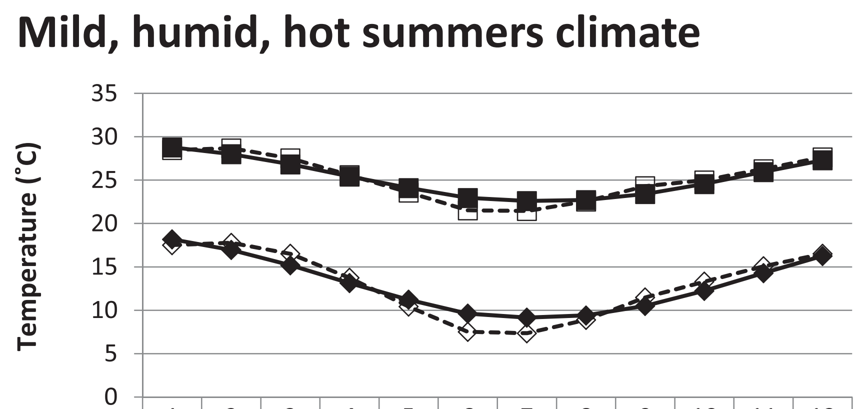
Figure 4-14 Comparison of actual and cosine regression predicted monthly temperatures for the dry, hot climate of South Africa based on weather data included in the SAPWAT4 program



	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

Time (months)

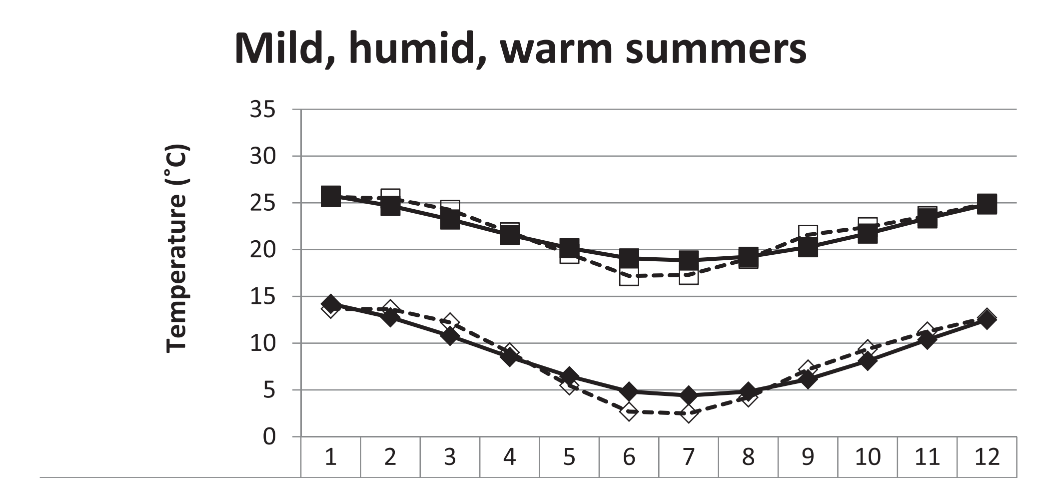
Figure 4-15 Comparison of actual and cosine regression predicted monthly temperatures for the dry, cold climate of South Africa based on weather data included in the SAPWAT4 program



	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

Time (months)

Figure 4-16 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 SAPWAT4 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

Time (months)

Figure 4-17 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 SAPWAT4

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 4-8). 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 SAPWAT4.

4.5 Linking crop growth and development to the climate regions of SAPWAT4

Equation (62) was adapted to Equation (65) for computerised calculation of crop heat units in SAPWAT4. 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.

$$CHU=\sum_{n=1}^{365} max\left[0,\left(\frac{min\left(T_{cardinalmax},T_{max}\right)+T_{min}}{2}-T_{base}\right)\Delta t\right] \qquad (65)$$

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)

4.5.1 Maize

The cosine regressions (Figure 4-13 to Figure 4-17) were used to calculate the growth period for maize as a summer grain crop planted on 15 October by using data shown in Table 4-5 from Miller *et al*. (2001). Canopy cover is not shown in Table 4-5; 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 SAPWAT4 (Van Heerden *et al*., 2008) as well as data included in FAO 56 (Allen *et al*., 1998). From Table 4-9 it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT4 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT4 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT4 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 SAPWAT4 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 SAPWAT4 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 4-9 An example of a comparison of heat unit calculated growing periods for five climate regions found in South Africa, SAPWAT4 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 4-5. 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
SAPWAT4	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

From Table 4-9 it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT4 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT4 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT4 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 SAPWAT4 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 SAPWAT4 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.

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 SAPWAT4, 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 SAPWAT4.

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 4-10) 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 SAPWAT4. However, SAPWAT4 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 Table 4-9 it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT4 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT4 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT4 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 SAPWAT4 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 SAPWAT4 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.

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 4-10) 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 Table 4-9 it can be seen that:

- The total heat unit calculated growing days show a much larger variation between climates than that indicated by the SAPWAT4 or FAO 56 data. The range of heat unit calculated data covers the complete spectrum of growing days included in SAPWAT4 for the ultra-short, short and medium growing types – long growing types, although included in the SAPWAT4 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 SAPWAT4 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 SAPWAT4 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.

to estimate irrigation requirements are shown in Figure 4-18 to Figure 4-21 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 give 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 4-10 Chi-squared tests for homogeneity on maize groups (DF = degrees of freedom = (rows-1) x (columns-1) in Table 4-9 used for the Chi-squared test)

Group	DF	Required at P=0.95	Observed	Homogenous at P=0.95	Homogenous at P=?
Maize, Medium, SAPWAT4	12	5.226	0.300	Yes	0.99
Maize, Short, SAPWAT4	12	5.226	0.373	Yes	0.99
Maize, Ultra-short, SAPWAT4	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, SAPWAT4/ Maize, Medium, SAPWAT4	27	16.151	2.003	Yes	0.99
Maize, Ultra-short, SAPWAT4 / Maize, Short, SAPWAT4	27	16.151	3.206	Yes	0.99
Maize, HU / Maize, Ultra-short	27	16.151	8.294	Yes	0.99
Maize, Ultra-short, SAPWAT4 / Maize, Medium, SAPWAT4	27	16.151	8.810	Yes	0.99
Maize, HU / Maize, Medium, SAPWAT4	27	16.151	16.800	No	0.90
Maize, HU/ Maize, Short, SAPWAT4	27	16.151	18.355	No	0.80
Maize, HU / Maize, Ultra-short, SAPWAT4	27	16.151	28.649	No	0.30
Maize, Ultra-short / Maize, FAO 56	28	16.151	33.928	No	0.20
Maize, Short, SAPWAT4 / Maize, FAO 56	28	16.151	44.569	No	0.01
Maize, Medium, SAPWAT4 / 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

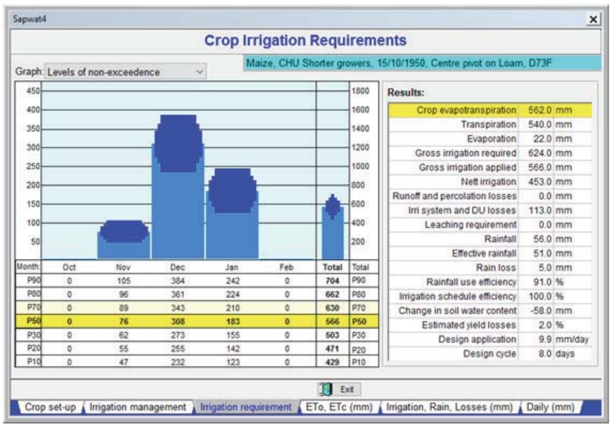


Figure 4-18 Maize planted 15 October in a dry, hot climate. Expected to reach maturity in the second week of January

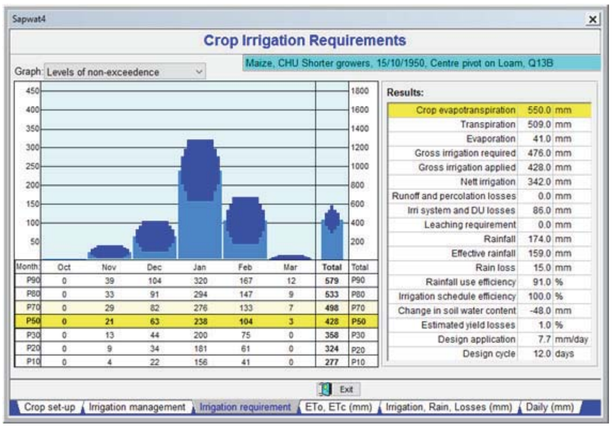


Figure 4-19 Maize planted 15 October in a dry, cold climate. Expected to reach maturity in the second week of February

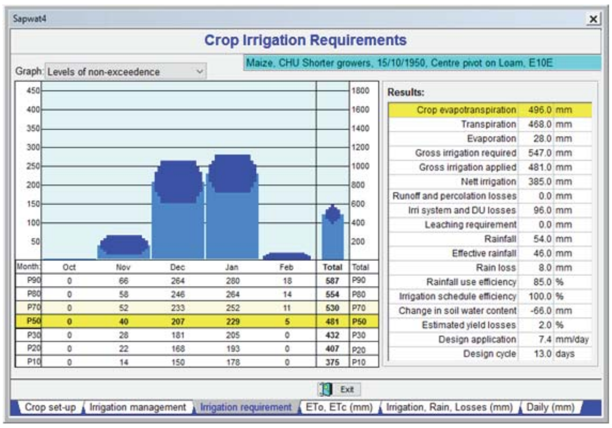


Figure 4-20 Maize planted 15 October in a mild, humid with hot summers climate. Expected to reach maturity in the last week of January

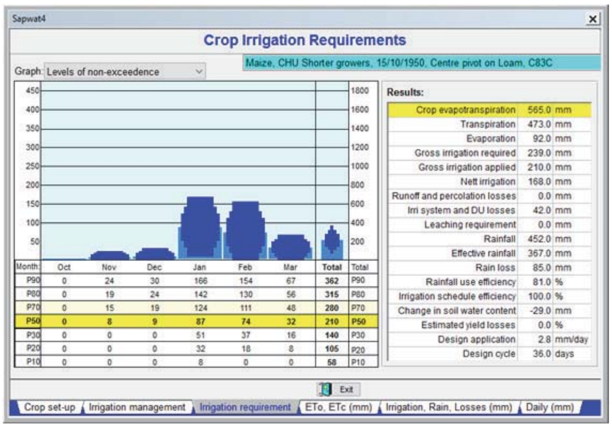


Figure 4-21 Maize planted 15 October in a mild, humid with warm summers climate. Expected to reach maturity in the second week of March

4.5.2 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[14] 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).

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

The growth period for wheat planted on 25 June was calculated by using data shown in Table 4-5. 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 growing stages are not provided in Table 4-5, 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 SAPWAT4 (Van Heerden *et al*., 2008) as well as data included in FAO 56 (Allen *et al*., 1998) and are shown in Table 4-11.

Table 4-11 An example of a comparison of heat unit calculated growing periods, SAPWAT4 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 4-5. 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
SAPWAT4	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 SAPWAT4 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 SAPWAT4 for wheat are longer than that of the calculated data based on heat units. Because SAPWAT4 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 SAPWAT4 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 4-12).

Table 4-12 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 SAPWAT4	9	3.325	0.276	Yes	0.99
Wheat FAO 56	9	3.325	42.519	No	0.01
Wheat, HU / Wheat SAPWAT4	21	11.591	15.696	No	0.70
Wheat, HU / Wheat FAO 56	22	12.338	60.494	No	<0.01
Wheat SAPWAT4 / 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 SAPWAT4 and in the thermal time calculated growth periods, but that there is virtually no homogeneity in the FAO 56 data. Linkage of the SAPWAT4 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 progems, could play havoc with thermal time calculations if these factors are not part of the consideration of wheat growth and development.

4.5.3 Sunflower

The cosine regressions shown in Figure 4-13 to Figure 4-17 were used to calculate the growing period for sunflower as an oil-seed crop planted on 15 October by using data shown in Table 4-5. 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 SAPWAT4 (Van Heerden *et al*., 2008) as well as from FAO 56 (Allen *et al*., 1998) (Table 4-13).

Table 4-13 An example of a comparison of calculated heat unit growing periods for sunflower for climate regions found in South Africa, SAPWAT4 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 4-5. 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
SAPWAT4	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 4-13) show:

- Heat unit calculations show adaptation: warmer climate zones have a shorter growing period than colder climate zones.
- The growth data included in SAPWAT4 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 SAPWAT4 crop tables for sunflower were drawn up.

The consistency of growth periods was investigated by applying the Chi-squared analyses for homogeneity within and on paired groups to investigate consistency of crop growth periods (Table 4-14).

Table 4-14 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, SAPWAT4	4	0.711	0.000	Yes	1.00
Sunflower, HU / Sunflower, SAPWAT4	27	16.151	1.659	Yes	0.99
Sunflower, HU / Sunflower, FAO 56	15	7.261	0.893	Yes	0.99
Sunflower, SAPWAT4 / 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 4-14) on the growth periods for sunflowers grown in different climate zones (Table 4-13) show:

- The growing period analysis for SAPWAT4 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 SAPWAT4 growing periods the mild, humid, warm summer climate zones show homogeneity.

Applying the heat unit calculations shown in Table 4-13 in the calculation of irrigation requirement estimates by SAPWAT4 for the four most common climate regions in South Africa, yields the results shown in Figure 4-22 to Figure 4-25. 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.

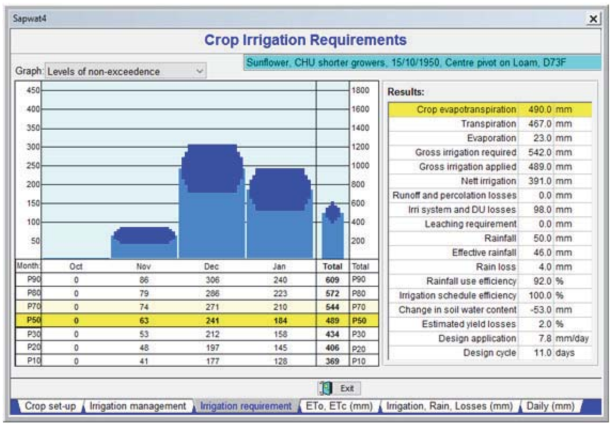

Figure 4-22 Sunflower planted 15 October in a dry, hot climate. Expected to reach maturity in the third week of January

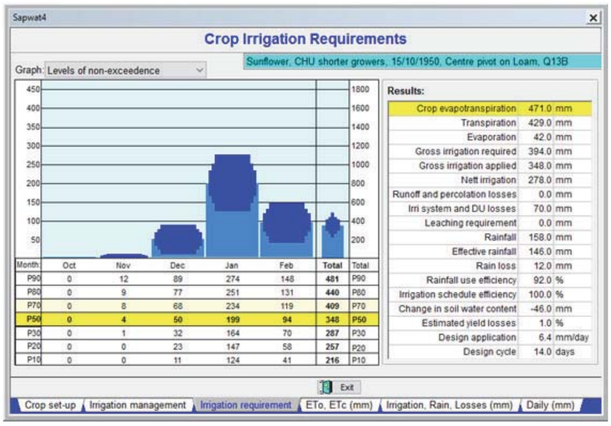

Figure 4-23 Sunflower planted 15 October in a dry, cold climate. Expected to reach maturity in the third week of February

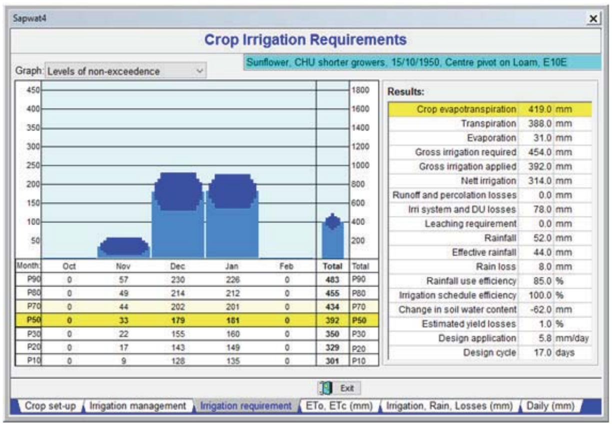

Figure 4-24 Sunflower planted 15 October in a mild, humid with hot summers climate. Expected to reach maturity in the first week of February

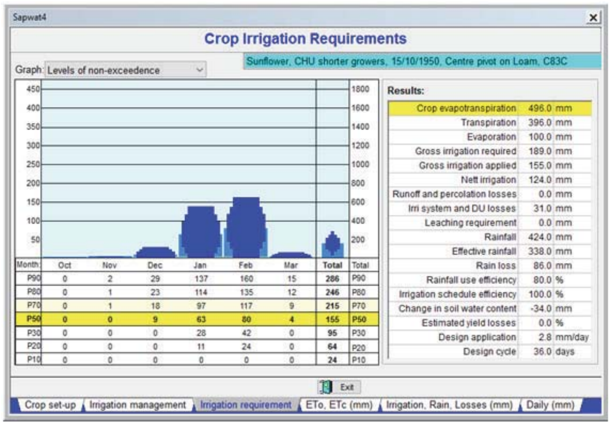

Figure 4-25 Sunflower planted 15 October in a mild, humid with warm summers climate. Expected to reach maturity in the third week of March

4.6 Conclusions

The weakest point in the SAPWAT4 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 SAPWAT4 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 SAPWAT4 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 SAPWAT4 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 SAPWAT4 because its climates are defined by temperature and rainfall combinations, data which are contained in the SAPWAT4 climate data tables. It was therefore possible to link each weather station location included in SAPWAT4 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 SAPWAT4, 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 SAPWAT4 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 SAPWAT4 irrigation requirement calculations. A thermal time calculator has been designed for use in SAPWAT4, in order to verify, and correct if necessary, crop growth stage times. However, this calculator is still under development and therefore not available for SAPWAT4 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 SAPWAT4 was tested on published thermal time data for maize, wheat and sunflower. After upgrading the SAPWAT4 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. SAPWAT4 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 SAPWAT4 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[15]). 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 SAPWAT4 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 SAPWAT4 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 SAPWAT4 and then activated in the program.

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

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.

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

The incorporation of a fully-fledged heat unit calculator into SAPWAT4 to enable the user to improve crop growth stage periods, could improve the accuracy of SAPWAT4 results which will increase its usefulness and credibility.

CHAPTER 5.
Verification of SAPWAT4 K_{cb} values

5.1 Introduction

Plants 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 A-pan based crop factors. Irrigation estimates were reasonable as long as the pan evaporation was calibrated for the area and the crop. However, these practices were not necessarily possible, often resulting in incorrect estimates, which in turn lead 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); SAPWAT4 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 determined for non-stressed, well-managed crops grown in sub-humid climates (Allen *et al*., 1998). This problem is relevant to SAPWAT4, because it is based on the FAO 56 approach. 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 SAPWAT4. The users of FAO 56 K_c and K_{cb} values and of SAPWAT4 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 SAPWAT4 need to be adapted if so required, however the adaptation means that research results need to be collected so that the relevant values could be changed. 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.

SAPWAT4 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 SAPWAT4, 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 SAPWAT4 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 is available.

5.2 Objectives

The objectives of this chapter concerning the verification of K_{cb} values included in SAPWAT4 and the resultant correctness of calculated ET_c are:

1. to describe the theoretical background underlining 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.

5.3 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 SAPWAT4, CROPWAT (Smith, 1992), AquaCrop (Raes *et al*., 2009) or similar models are to be used. These are unfortunately not possible and not even the desired *modus operando* as it would defeat one of the purposes of using a model. Thus, it should be possible for extrapolation of results from research sites to application sites. Therefore, K_c values are given as generalised values and the area and/or climate that the values refer to are also included as part of the assumptions and definition, e.g. 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" (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 SAPWAT4 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 predict values and indicate bias could be too elusive to be adequately encapsulated 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).

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. Instead of statistical tests of significance, he recommends that the predictive worth of models should rather be done 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.

5.4 Materials and methods

The verification of SAPWAT4 K_{cb} and growth period data entails the comparison of the SAPWAT4 table data with field measured data. The SAPWAT4 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.

5.4.1 Data used

The development of this 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} evaluation module of SAPWAT4 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 verification of crop characteristics used in SAPWAT4 to draw the four-stage FAO crop K_{cb} curve (Allen *et al*., 1998) for maize, wheat and peas.

5.4.2 Soil water balance

Irrigation requirement and related calculations by SAPWAT4 are based on the soil water balance equation. In the verification module Equation (66) (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 parameters 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 parameters in the equation are determined *in situ* (Bennie *et al*., 1998).

$$ET=I+P-RO-DP+CR\pm\Delta SF\pm\Delta SW \tag{66}$$

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

5.4.3 The SAPWAT4 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 SAPWAT4 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} coefficient by subtracting the value of the soil surface evaporation coefficient (K_e) (Equation (40)) from the Kc value.

The K_c equation $K_c=K_{cb}+K_e$ is therefore changed to:

$$K_{cb}=K_c-K_e \tag{67}$$

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 SAPWAT4 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 grow day 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 SAPWAT4 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 SAPWAT4 calculate the estimated irrigation requirement on the existing K_{cb} table values contained in SAPWAT4.

2. The verification module is then called, the source of the observed data is given and the following procedure is followed by SAPWAT4:

   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 (section 0) 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 SAPWAT4 recalculate the estimated irrigation requirement on the updated K_{cb} table values contained in SAPWAT4.

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 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.

5.4.3.1 Applying the verification module

Out of the SAPWAT4 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 SAPWAT4 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.

5.4.4 Statistical analyses

Model evaluation consists of two components. These are an operational component where the output of the model is evaluated visually through graphic representation. There 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 (68), is the average of the percentage of 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).

$$MPE=\frac{100\%}{n}\sum_{i=1}^{n}\frac{y_i-x_i}{x_i} \tag{68}$$

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 (69)), 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 SAPWAT4, 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).

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(y_i-x_i\right)^2}{n}} \tag{69}$$

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 (70)) is a measure of the model's linear or systematic bias. A low value indicates that a model, such as SAPWAT4, is predicting at its maximum possible accuracy (Willmott, 1981).

$$RMSEs=\sqrt{\frac{\sum_{i=1}^{n}\left(\bar{y}_i-x_i\right)}{n}} \tag{70}$$

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 (71)) is a measure of the model's predictive bias (Willmott, 1981).

$$\mathrm{RMSEu}=\sqrt{\frac{\sum_{i=1}^{n}\left(y_i-\bar{y}_i\right)}{n}} \tag{71}$$

Where: $RMSE_u$ root mean square error – unsystematic

$\bar{y}_i$ y values (expected predicted values)

y_i y values (predicted values)

N number of data pairs

d: Index of agreement. Equation (72) 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).

$$d=1-\frac{\sum_{i=1}^{n}\left(y_i-x_i\right)^2}{\sum_{i=1}^{n}\left(\left|y_i-\bar{x}\right|+\left|x_i-\bar{x}\right|\right)^2} \tag{72}$$

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

5.5 Results and discussion

The aim of verifying crop coefficients is to get the coefficients of the FAO four-stage crop growth curve to imitate 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.

5.5.1 Selecting adapted crop coefficients

A problem linked to RMSE analyses and the eventual selection of the right recommended set of crop characteristics for use in SAPWAT4 is that several repeats of testing could satisfy statistical analysis acceptance norms, such as table versus observed data regression slope that falls within an accepted range of 0.7 to 1.3 (Willmott, 1981) or RMSE expressed as a percentage of observed data mean that is less than 30% (Willmott, 1981). One possibility is to accept the analysis with lowest RMSE value as the correct, but experience in testing such analyses for SAPWAT4 purposes did not necessarily give the best observed fit of K_{cb} table values when compared to observed values. This duplicates and 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 SAPWAT4: 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.

5.5.2 Crop evapotranspiration data

The wheat planted 3 July 2003 data was initially used to develop the basal crop coefficient verification module of SAPWAT4 Data is 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 have 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 $\mathrm{R}_n - \mathrm{G} - \mathrm{H}$: 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 range 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 values are found for humid, calm climates and higher than the tabulated value are found in arid and windy climates (Figure 5-1) (Allen *et al*., 1998). The $K_{c\ max}$ shown in Table 5-1 have been calculated (Equation (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.

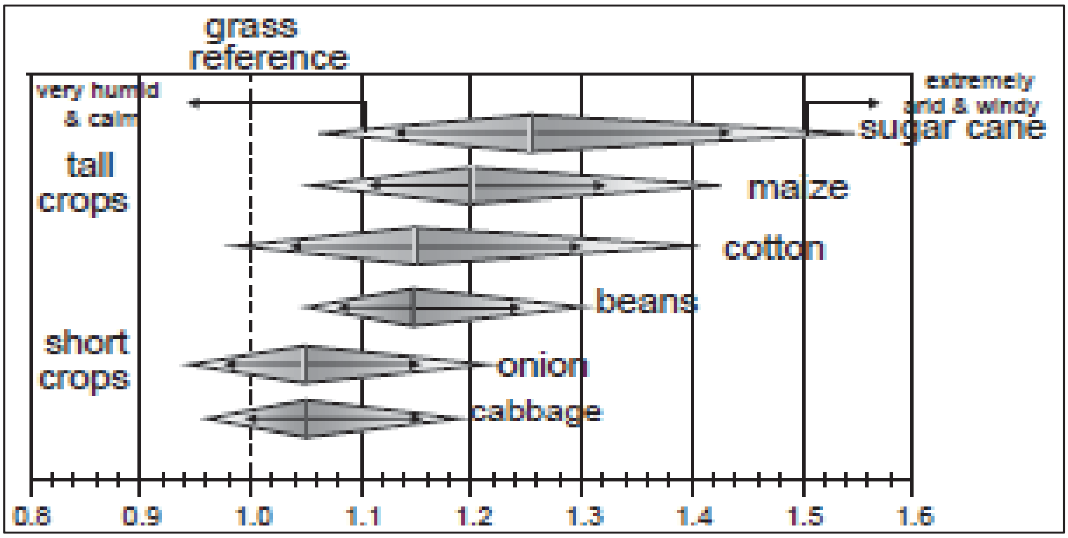

Figure 5-1 K_c ranges of some crops as influenced by climate (Allen *et al.*, 1998)

Table 5-1 Data used for the verification of SAPWAT4 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[16], 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

[16] K_e: evaporation coefficient; ET_c: crop evapotranspiration; K_{cb}: basal crop coefficient; K_c: crop coefficient

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}
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 1.32) (Table 5-1). This is higher than the 1.10 for small grain cereals found in the FAO 56 $K_{cb\ mid}$ tables of Allen *et al*. (1998). However, values higher than FAO 56 and SAPWAT4 $K_{c\ mid}$ table values were found in a number of other sited 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.

5.5.3 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 SAPWAT4.

5.5.3.1 Spring wheat: salinity

The wheat cultivar SST 806 was planted on 3 July 2003 for the salinity experiment (Ehlers *et al*., 2007).

5.5.3.1.1 K_{cb} predicted and observed

The initial run with original K_{cb} data from the SAPWAT4 table and the comparative result of the observed data is shown in Figure 5-2 (repetition 1). The SAPWAT4 table data used as recommended values for a next repetition of analysis calculations is shown in the bottom right side of the screen. Figure 5-3 show the related RMSE analysis for repetition 1 of the SAPWAT4 evaluation module. The crop data was 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 5-4 and Figure 5-5 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 5-4, Table 5-2 and Table 5-3).

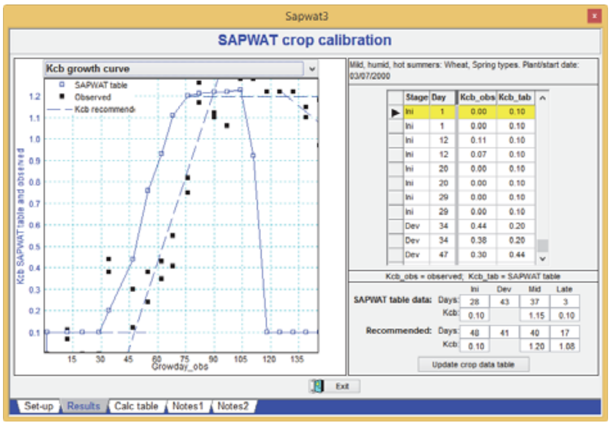

Figure 5-2 The SAPWAT4 table K_{cb} data curve, the observed data and the first repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

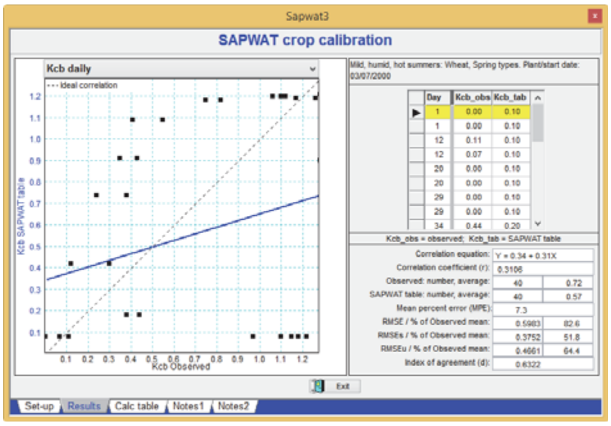

Figure 5-3 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

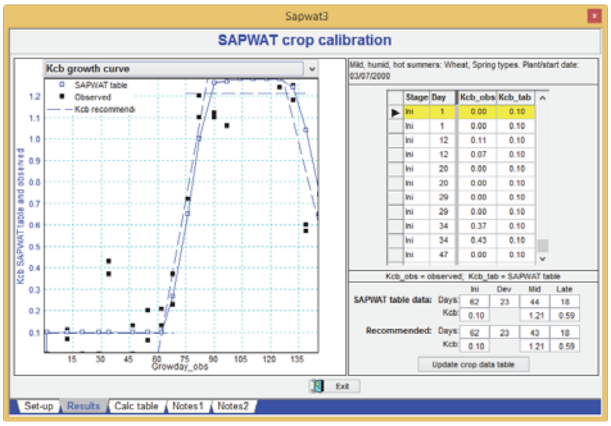

Figure 5-4 The SAPWAT4 table K_{cb} data curve, the observed data and the fourth repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

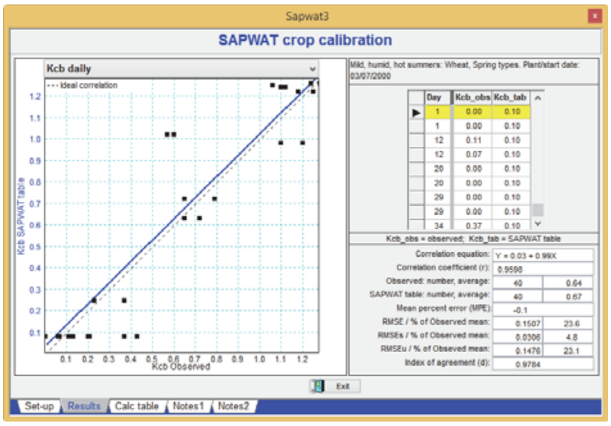

Figure 5-5 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the fourth repeat for wheat planted on 3 July 2003 at Kenilworth near Bloemfontein

Table 5-2 Changes in successive repeats of verifying 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 5-3 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 5-3 and Figure 5-5 show the improvement in the comparison of $K_{cb\ tab}$ to $K_{cb\ obs}$ between the first and the last verification repeats while Figure 5-2 and Figure 5-4 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. The RMSE expressed as a percentage of the average of observed data improved from 82.6% to 23.6% (Table 5-3). 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.

5.5.3.1.2 Irrigation requirement

The SAPWAT4 estimated gross irrigation requirements are shown in Table 5-4. 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 5-4 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.

5.5.3.2 Spring wheat: water table

The wheat cultivar SST 825 was planted on 6 June 2000 for the water table experiment (Ehlers *et al.*, 2003).

5.5.3.2.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT4 table and the comparative result of the observed data is shown in Figure 5-6. Figure 5-7 show the related RMSE analyses for repetition 1. The crop data was 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 5-8 and Figure 5-9 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 5-8, Table 5-5 and Table 5-6).

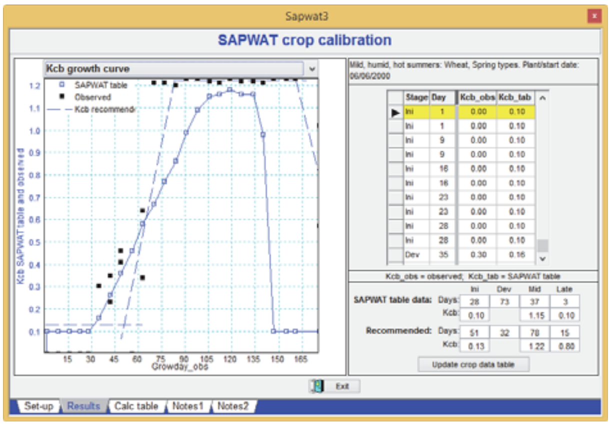

Figure 5-6 The SAPWAT4 table K_{cb} data curve, the observed data and the first repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

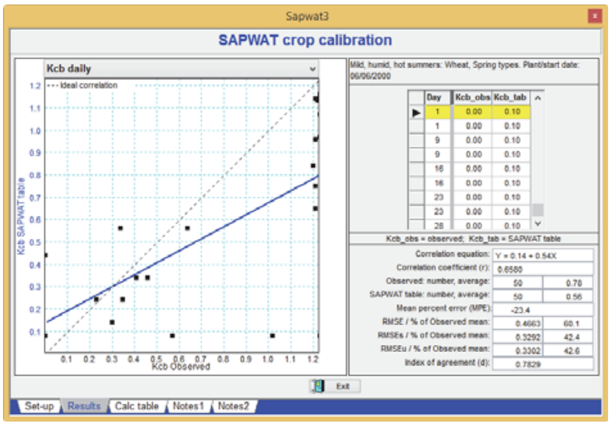

Figure 5-7 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

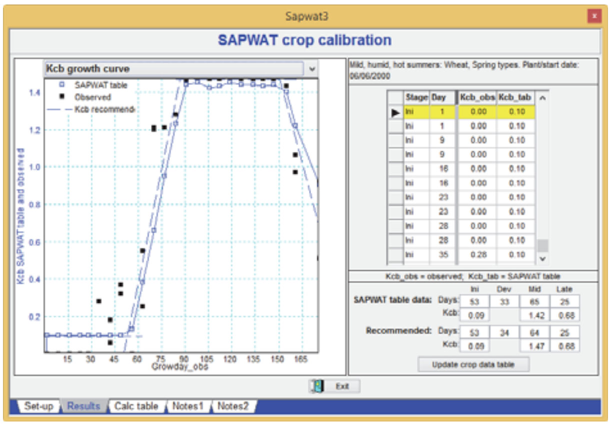

Figure 5-8 The SAPWAT4 table K_{cb} data curve, the observed data and the sixth repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

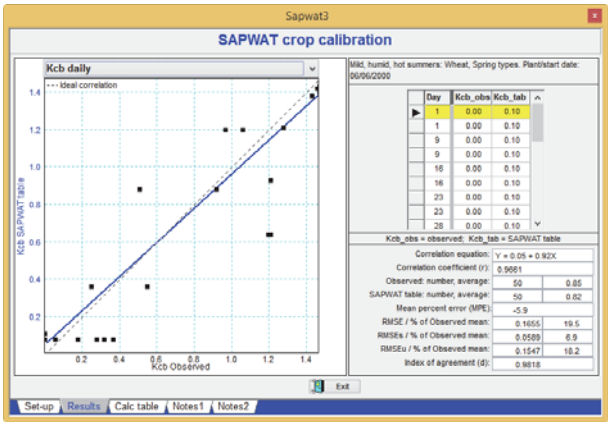

Figure 5-9 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the sixth repeat for wheat planted on 6 June 2000 at Kenilworth near Bloemfontein

Table 5-5 Changes in successive repeats of verificating 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 5-6 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 5-7 and Figure 5-9 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 5-6), 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.

5.5.3.2.2 Irrigation requirement

The SAPWAT4 estimated gross irrigation requirements are shown in Table 5-7. 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. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 5-7 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 is 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.

5.5.3.3 Spring wheat: Comparison of crop growth stages and crop coefficients

The crop growth periods estimated for spring wheat by SAPWAT4 and published in FAO 56 (Allen *et al*., 1998) are compared in Table 5-8. Differences between all the rows are significant (Chi-squared $p < 0.01$), as are the differences between the SAPWAT4 estimated values ($p=0.15$). The big differences between the SAPWAT4 estimates could possibly be because two different cultivars were used. A further possible reason could be too few repeats – only two different years with only two repeats per year.

Table 5-8 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)
SAPWAT4 (salinity)	62	23	43	18	146
SAPWAT4 (water table)	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 SAPWAT4 is compared to FAO 56 crop coefficients in Table 5-9 – 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 SAPWAT4 estimates ($p=0.96$).

Table 5-9 Comparison of crop coefficients for spring wheat between SAPWAT4 estimates and FAO 56 data

Source	K_{cb}		
	Initial	Mid-season	Late season
SAPWAT4 (salinity)	0.10	1.21	0.59
SAPWAT4 (water table)	0.09	1.42	0.68
FAO 56 (Allen *et al*., 1998)	15	30	65

The SAPWAT4 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 SAPWAT4. 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.

5.5.3.4 Peas: salinity

The pea cultivar Solara was planted on 20 July 2004 for the salinity experiment (Ehlers *et al*., 2007).

5.5.3.4.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT4 table and the comparative result of the observed data is shown in Figure 5-10. Figure 5-11 show the related RMSE analyses for repetition 1. The crop data was 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 5-12 and Figure 5-13 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 5-12, Table 5-10 and Table 5-11).

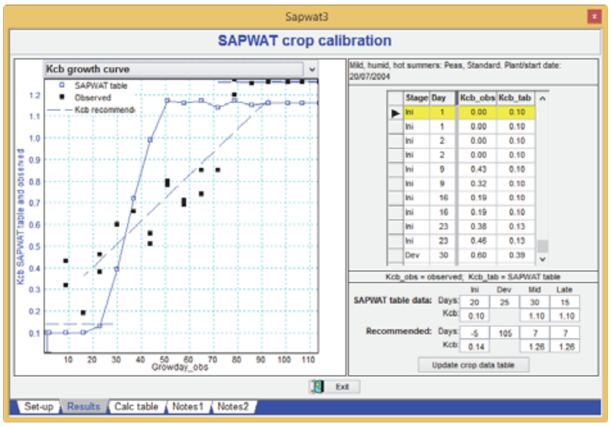

Figure 5-10 The SAPWAT4 table K_{cb} data curve, the observed data and the first repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

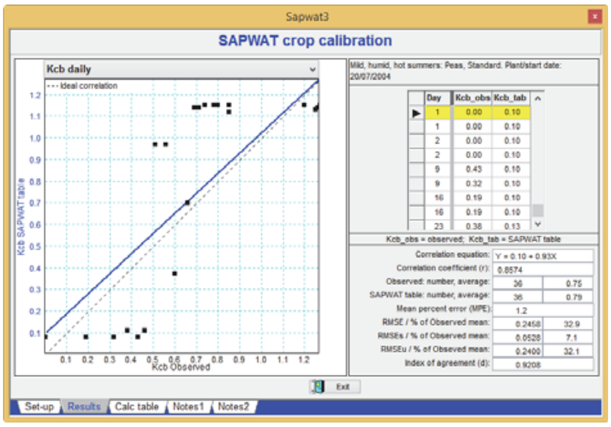

Figure 5-11 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

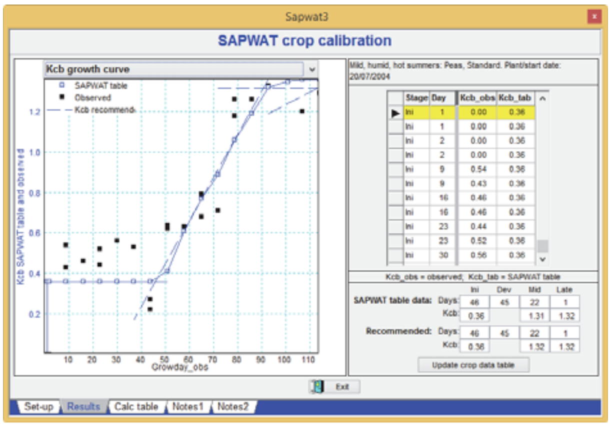

Figure 5-12 The SAPWAT4 table K_{cb} data curve, the observed data and the sixth repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

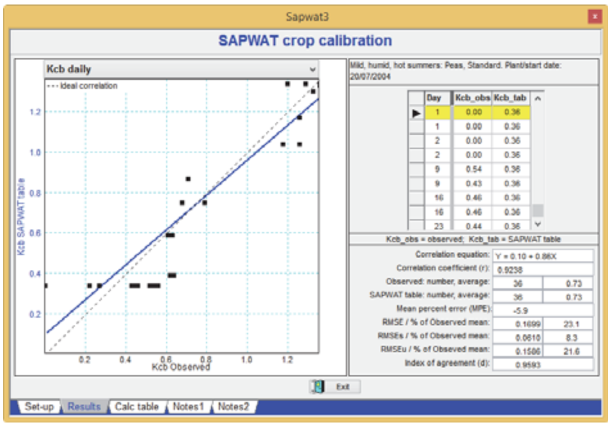

Figure 5-13 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the sixth repeat for peas planted on 20 July 2004 at Kenilworth near Bloemfontein

Table 5-10 Changes in successive repeats of verificating 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 5-11 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 5-11 and Figure 5-13 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 5-11). 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 5-10 and Figure 5-12 that the application of the SAPWAT4 verification module did improve the $K_{c\ tab}$ values to a closer imitation of the $K_{cb\ obs}$ values.

5.5.3.4.2 Irrigation requirement

The SAPWAT4 estimated gross irrigation requirements are shown in Table 5-12. 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. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 5-12 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 is significant (Chi-squared test $p<0.01$) while there is no significant difference between repeats 2, to 6 ($p=0.98$) , therefore the tabulated values differ significantly from all updates.

5.5.3.5 Peas: water table

The pea cultivar Solara was planted on 27 June 2001 for the water table experiment (Ehlers *et al*., 2003).

5.5.3.5.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT4 table and the comparative result of the observed data is shown in Figure 5-14. Figure 5-15 show the related RMSE analyses for repetition 1. The crop data was 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 5-16 and Figure 5-17 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 5-16, Table 5-13 and Table 5-14).

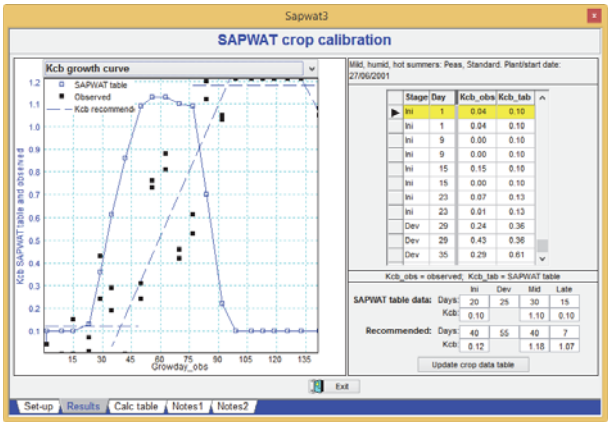

Figure 5-14 The SAPWAT4 table K_{cb} data curve, the observed data and the first repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

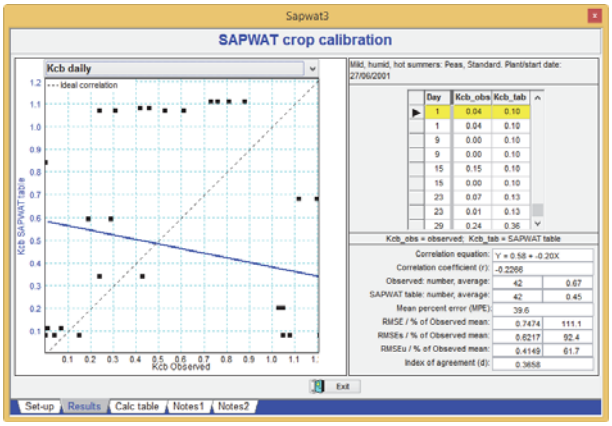

Figure 5-15 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

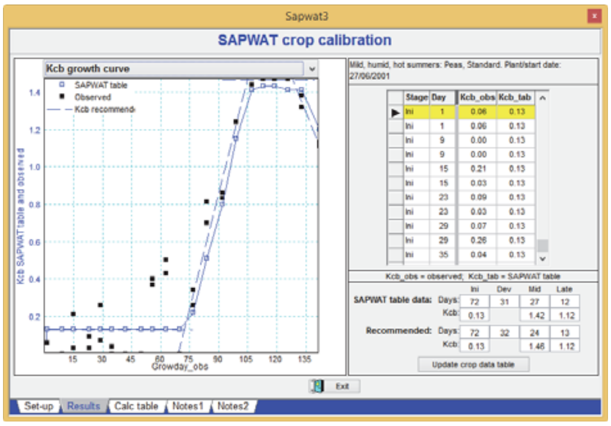

Figure 5-16 The SAPWAT4 table K_{cb} data curve, the observed data and the seventh repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

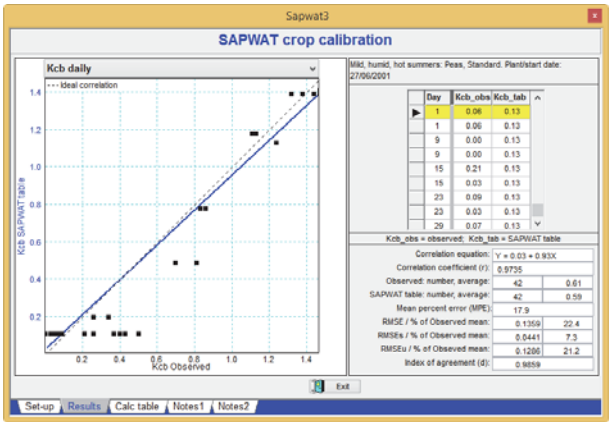

Figure 5-17 The comparison of adapted K_{cb} tab with lysimeter $K_{cb\ obs}$ data for the seventh repeat for peas planted on 27 June 2001 at Kenilworth near Bloemfontein

Table 5-13 Changes in successive repeats of verificating 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 5-14 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 5-15 and Figure 5-17 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 5-14). 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.

5.5.3.5.2 Irrigation requirement

The SAPWAT4 estimated gross irrigation requirements are shown in Table 5-15. 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. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 5-15 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 is 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.

5.5.3.6 Peas: Comparison of crop growth stages and crop coefficients

The crop growth periods estimated for peas by SAPWAT4 and published in FAO 56 (Allen *et al*., 1998) are compared in Table 5-16. 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 SAPWAT4 estimated values for (p<0.01). The big differences between the SAPWAT4 estimates are unexpected and no specific reason for that could be identified. A possible reason could be too few repeats – only two different years with only two repeats per year.

Table 5-16 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)
SAPWAT4 (salinity)	46	45	22	1	114
SAPWAT4 (water table)	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 SAPWAT4 is compared to FAO 56 crop coefficients in Table 5-17. 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 SAPWAT4 estimates (p=0.95), this in spite of an obviously higher values for mid-season K_{cb} for the SAPWAT4 calculated values.

Table 5-17 Comparison of crop coefficients for peas between SAPWAT4 estimates and FAO 56 data

Source	K_{cb}		
	Initial	Mid-season	Late season
SAPWAT4 (salinity)	0.36	1.32	1.32
SAPWAT4 (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

5.5.3.7 Maize: salinity

The maize cultivar PAN 6335 was planted on 17 December 2004 for the salinity experiment (Ehlers *et al*., 2007)

5.5.3.7.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT4 table and the comparative result of the observed data is shown in Figure 5-18. Figure 5-19 show the related RMSE analyses for repetition 1. The crop data was updated with recommended changes and crop irrigation water requirement reruns were done until the situation shown in Figure 5-20 and Figure 5-21was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 5-21, Table 5-18 and Table 5-19).

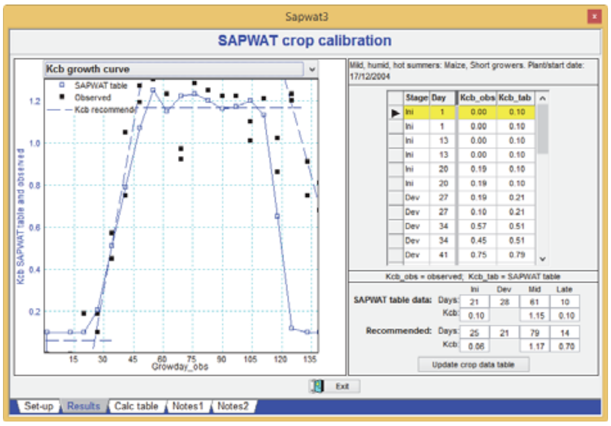

Figure 5-18 The SAPWAT4 table Kcb data curve, the observed data and the first repeat proposed Kcb growth curve based on observed data of lysimeter measured ETc data for maize planted on 17 December 2004 at Kenilworth near Bloemfontein

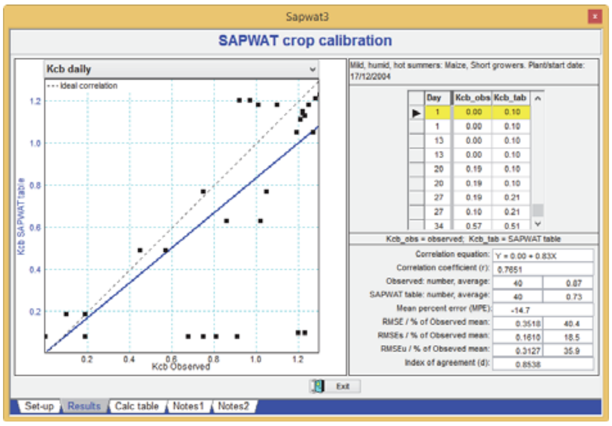

Figure 5-19 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for maize planted on 17 December 2004 at Kenilworth near Bloemfontein

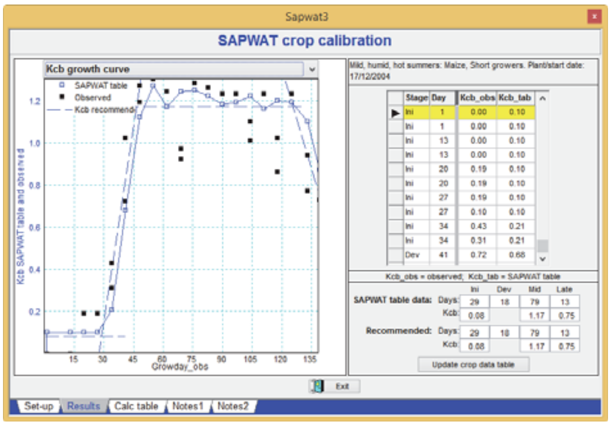

Figure 5-20 The SAPWAT4 table K_{cb} data curve, the observed data and the fifth repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for maize planted 17 on December 2004 at Kenilworth near Bloemfontein

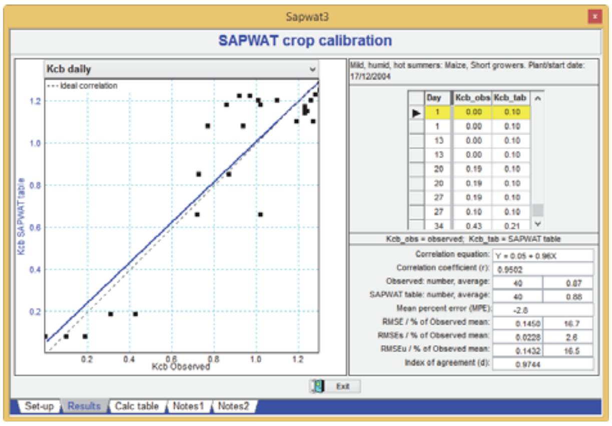

Figure 5-21 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the fifth repeat for maize planted on 17 December 2004 at Kenilworth near Bloemfontein

Table 5-18 Changes in successive repeats of verification 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 5-19 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 5-19 and Figure 5-21 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 5-19). 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.

5.5.3.7.2 Irrigation requirement

The SAPWAT4 estimated gross irrigation requirements are shown in Table 5-20. 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. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 5-20 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.

5.5.3.8 Maize: water table

The maize cultivar PAN 6335 was planted on 6 December 2000 for the water table experiment (Ehlers *et al*., 2003)

5.5.3.8.1 K_{cb} predicted and observed

The first repeat with original K_{cb} data from the SAPWAT4 table and the comparative result of the observed data is shown in Figure 5-22. Figure 5-23 show the related RMSE analyses for repetition 1. The crop data was 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 5-24 and Figure 5-25 was reached. Both evaluation of the graphic representation and the statistical analysis indicate this as a good point to stop further repeats (Figure 5-24, Table 5-21 and Table 5-22).

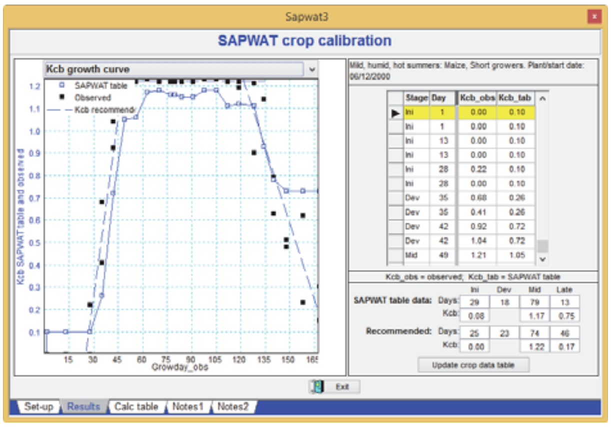

Figure 5-22 The SAPWAT4 table K_{cb} data curve, the observed data and the first repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

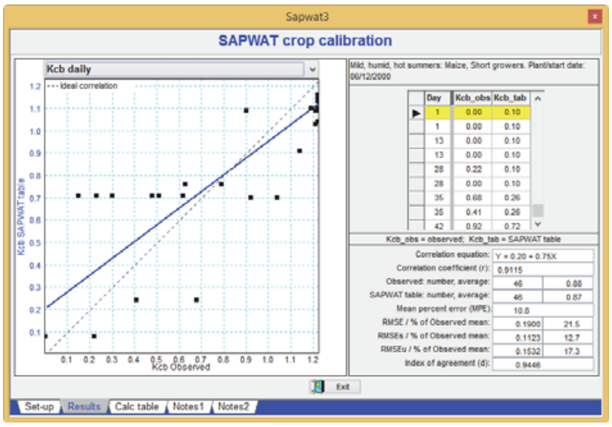

Figure 5-23 The comparison of $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the first repeat for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

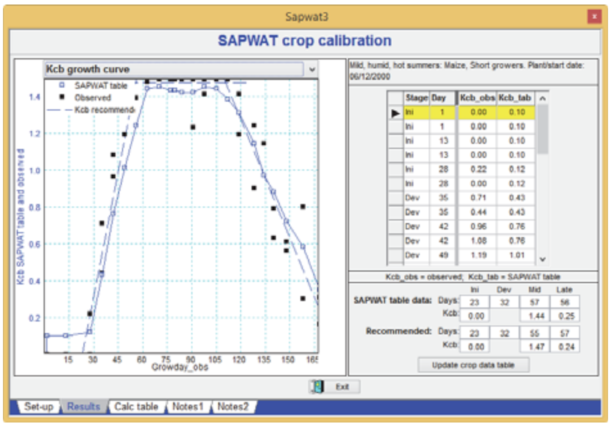

Figure 5-24 The SAPWAT4 table K_{cb} data curve, the observed data and the fourth repeat proposed K_{cb} growth curve based on observed data of lysimeter measured ET_c data for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

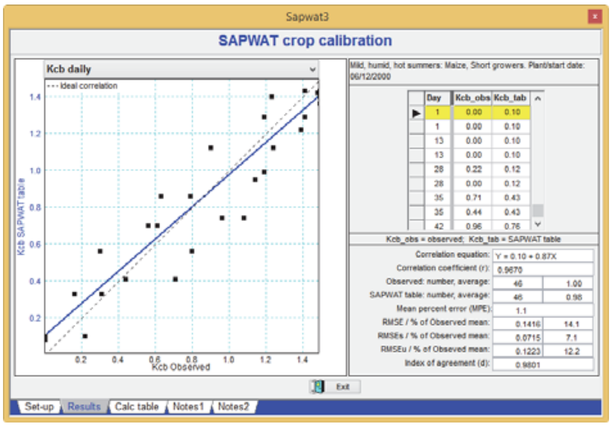

Figure 5-25 The comparison of adapted $K_{cb\ tab}$ with lysimeter $K_{cb\ obs}$ data for the fourth repeat for maize planted on 6 December 2000 at Kenilworth near Bloemfontein

Table 5-21 Changes in successive repeats of verificating 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 5-22 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 5-23 and Figure 5-25 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 5-22), 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.

5.5.3.8.2 Irrigation requirement

The SAPWAT4 estimated gross irrigation requirements are shown in Table 5-23. 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. Good irrigation water management is the ability to make the best use of rainfall as part of the soil water budget.

Table 5-23 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 is 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.

5.5.3.9 Maize: Comparison of crop growth stages and crop coefficients

The crop growth periods estimated for maize by SAPWAT4 and published in FAO 56 (Allen *et al.*, 1998) are compared in Table 5-24. 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 SAPWAT4 rows are significant (p<0.01). A possible reason for the difference found in the SAPWAT4 estimates could be too few data sets – only two different years with only two repeats per year.

Table 5-24 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)
SAPWAT4 (salinity)	25	18	79	13	135
SAPWAT4 (water table)	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 SAPWAT4 is compared to FAO 56 crop coefficients in Table 5-25. Chi-squared tests indicate no significant differences between all row in the table, (p=0.98). Differences between rows are significant for the SAPWAT4 estimates (p=0.81).

Table 5-25 Comparison of crop coefficients for maize between SAPWAT4 estimates and FAO 56 data

Source	K_{cb}		
	Initial	**Mid-season**	**Late season**
SAPWAT4 (salinity)	0.18	1.17	0.75
SAPWAT4 (water table)	0	1.44	0.24
Field FAO (Allen *et al*., 1998)	0.15	1.15	0.5

5.6 Conclusions

A problem encountered with models such as SAPWAT4 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); SAPWAT4 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). Applying the Penman-Monteith equation in areas in different climates does not necessarily give the right answers. Allen *et al*., (1998) has described a methodology for constructing the FAO four-stage crop growth curve and it was decided to include a module in SAPWAT4 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 was 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 SAPWAT4 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 of the change 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 is described by Allen *et al*. (1998). Furthermore, higher than expected mid-season 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 the effect that an enclosed rooting area in the lysimeter pot could have on crop water use. 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.

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 seen (Figure 5-4, Figure 5-8, Figure 5-12, Figure 5-16, Figure 5-20, Figure 5-25)

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 is not necessary. 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.

SAPWAT4 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 SAPWAT4’s responsibility to make sure that the estimation of irrigation water requirements be as correct as is possible. The methodology described here, if applied, will ensure that a more correct irrigation water quantity is estimated, and will result in that a higher level of credibility will be ascribed to the results of SAPWAT4. It should also decrease the potential conflict between farmers and the Department of Water and Sanitation on the matter of the correctness of the allocate water use right.

Acknowledgement:

The use of experimental results and climate data from the Water Research Commission project reports (WRC Report Nos. 1089/03 and 1359/07) and the cooperation of the authors (Ehlers, L., Bennie, A.T.P., Du Preez, C.C., Barnard, J.H., Dikgwatlhe, S.B., Van Rensburg, L.D. and Ceronio, G.M) is acknowledged.

CHAPTER 6.
Using SAPWAT4 to estimate small irrigation dam water balance

6.1 Introduction

Some users of SAPWAT4, mainly from the Western Cape, have asked for the inclusion of an irrigation dam water balance module. Their problem stems mainly form the fact that a farmer or group of farmers who use small irrigation dams to store runoff water during the rainy winter season for use during dry summer, need to do a good planning of water use in order to let the stored irrigation water last for -+the summer season. This becomes crucial if the winter rainfall has been lower than normal and the dams are not quit full at the beginning of the growing season.

Dam water balances requires hydrological calculations, which is not the approach used in SAPWAT4; SAPWAT4 makes use of the soil water balance approach with rainfall and irrigation as major additives and evapotranspiration as a major extractor of water to the equation. SAPWAT4 assumes a stable and ample water source, but does provide the user with the facility to plan for situations where the source does not supply enough water for a full growing season.

Two possible approaches for the inclusion of a dam water balance module in SAPWAT4 is possible. These are:

i. Build a module that can do the water balances from scratch as an integral part of the SAPWAT4 program;
ii. Look for existing small dam water balance models available and, with due permission and cooperation, build an export function into SAPWAT4 that could export the required data set for use in such a program.

The second option is the preferred option because option (i) would require a substantial amount of programming in SAPWAT4 in order to create a usable tool. This is of course, provided that such a model could be found and that it would be made available to SAPWAT4 users by the author of the model.

6.2 Methodology

Feelers were put out to consulting engineering firms explaining the need of a small irrigation dam water balance model and requesting information about such possible development. It transpired that the engineering consultancy Schoeman and Partners of Brits had developed an Irrigation Models suite in Excel[17] which includes a small dam water balance module (Dambalance). The author was visited and he agreed to participate. An export module for SAPWAT4 farm level irrigation requirement data that could be used as an import by the Dambalance module was designed, tested and found to be successful for the purpose.

During the discussions Hennie Schoeman[18], the author, indicated that his Irrigation Models suite will be made available free of charge to SAPWAT4 users who require it, provided that they either do a short course on its use or that he is satisfied that they will be able to use it.

6.2.1 Preparing and exporting data to the small farm dam module

The user need to estimate the irrigation requirement of all area/farm-field-crop combinations for the relevant farm or area by using SAPWAT4. The following is essential when doing the calculations:

i. Crop growing areas (ha) need to be specified because the module uses volume of irrigation water required for calculating small dam water balances;
ii. Rainfall, as part of the field water supply, must be included in the irrigation estimates.

Once the crop irrigation requirement estimates have been completed, the farm-export-pushbutton of SAPWAT4 is clicked and the export form (Figure 6-1) will be shown. Select "Export irrigation requirement for use in the Dambalance modulel. …." Click the proceed button and export the data as an Excel file for importing into the Dam balance module.

Subsequent to the export, the Dambalance module is opened. A submodule, contained in the Dambalance model suite, will then be used to import and convert the exported SAPWAT4 Excel file into the format that can be used by the Dambalance model.

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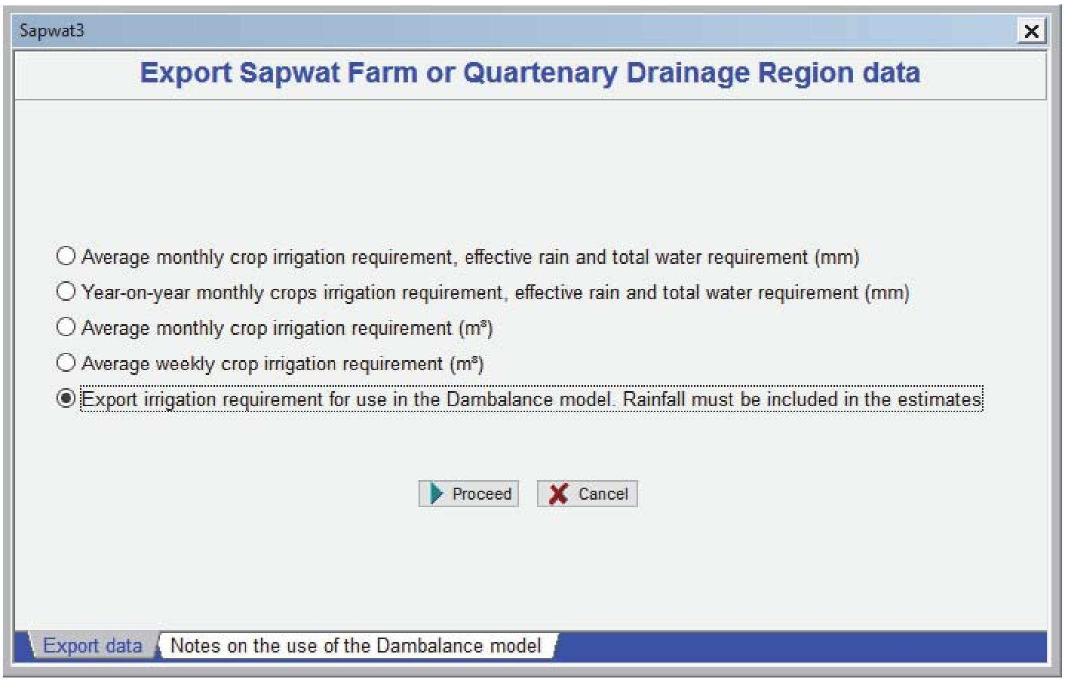

Figure 6-1 The farm export form of SAPWAT4.

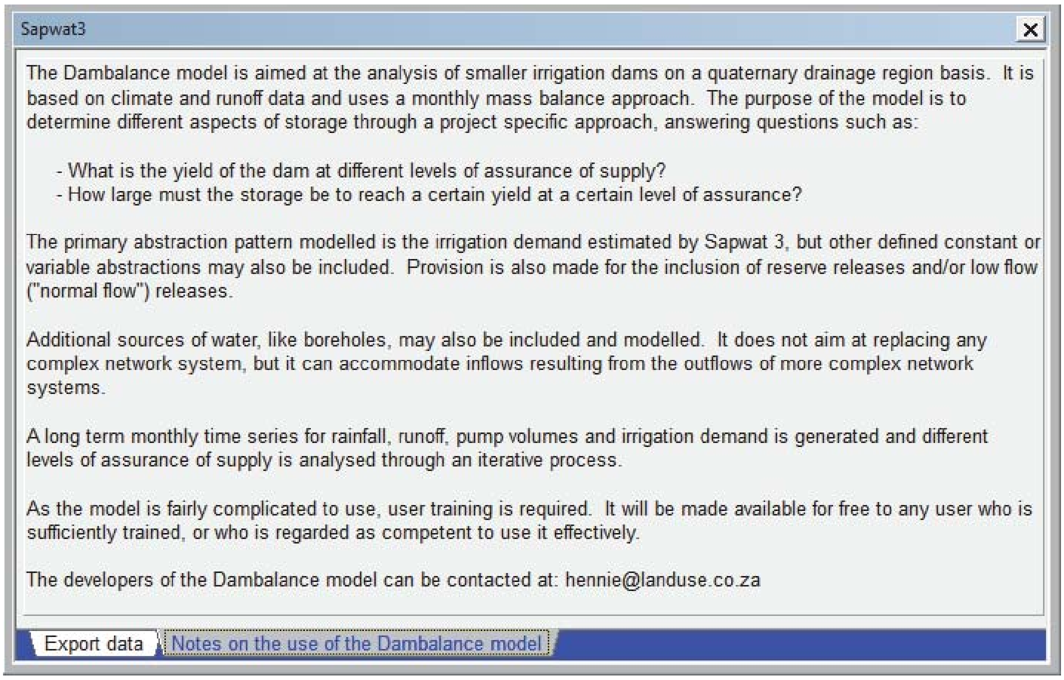

Figure 6-2 The information page of the farm export form showing guidelines for exporting data for use by the Dambalance module

6.3 Results

Some output of the Dambalance module is shown in Figure 6-3 to Figure 6-7.

YIELD

Assurance	Yield m³	Pump
50%	1 081 384	146 100
55%	1 054 606	139 769
60%	995 574	119 802
65%	939 763	103 731
70%	909 043	95 452
75%	876 884	85 225
80%	835 953	76 946
85%	801 508	70 615
90%	767 562	63 310
95%	664 332	42 369
98%	598 372	29 707

Figure 6-3: Image of output table showing dam yield at different levels of assurance

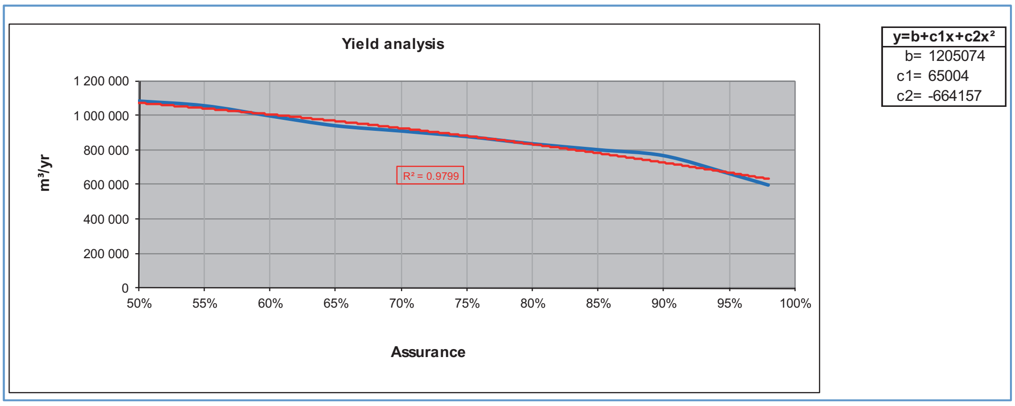

Figure 6-4: Dam yield-assurance curve with regression analysis

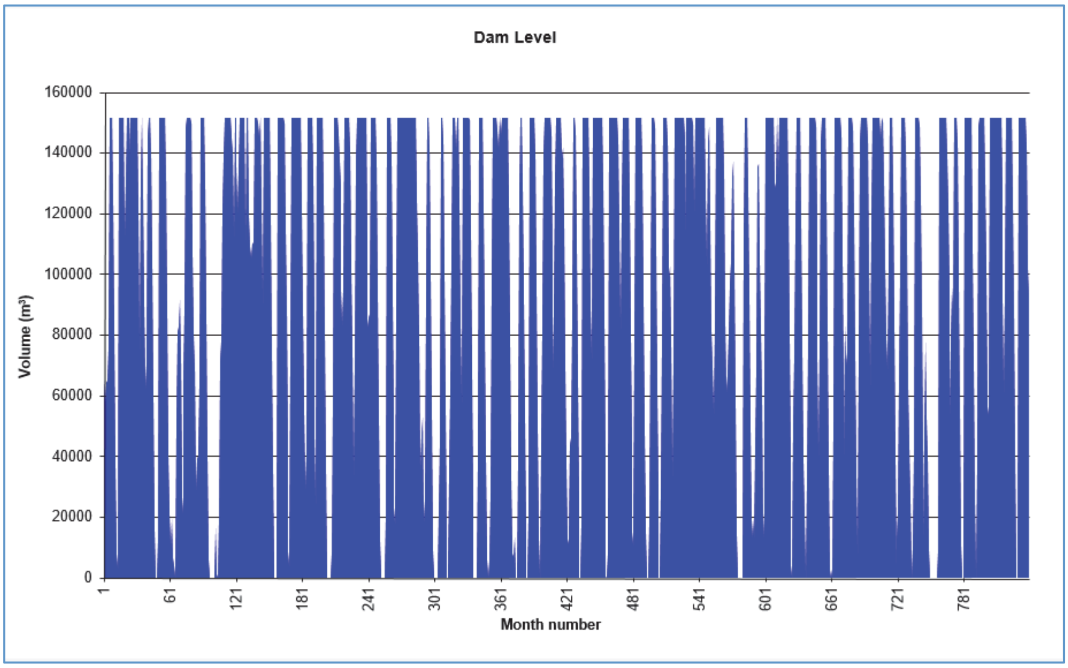

Figure 6-5 Graphic representation of dam water volume over time

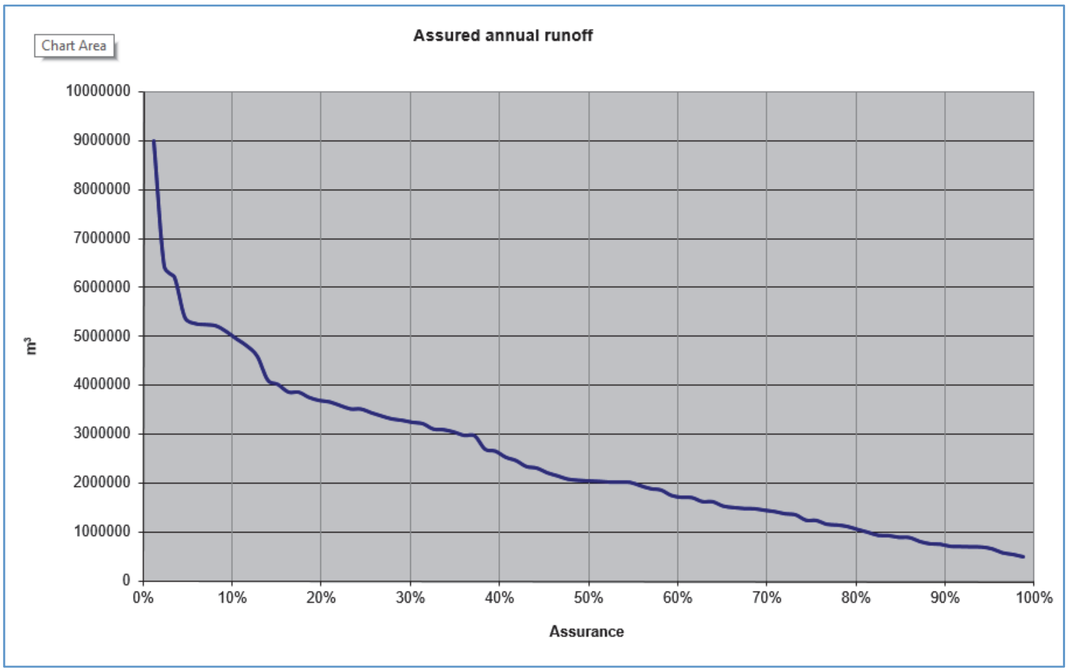

Figure 6-6 Levels of assurance for different runoff volumes

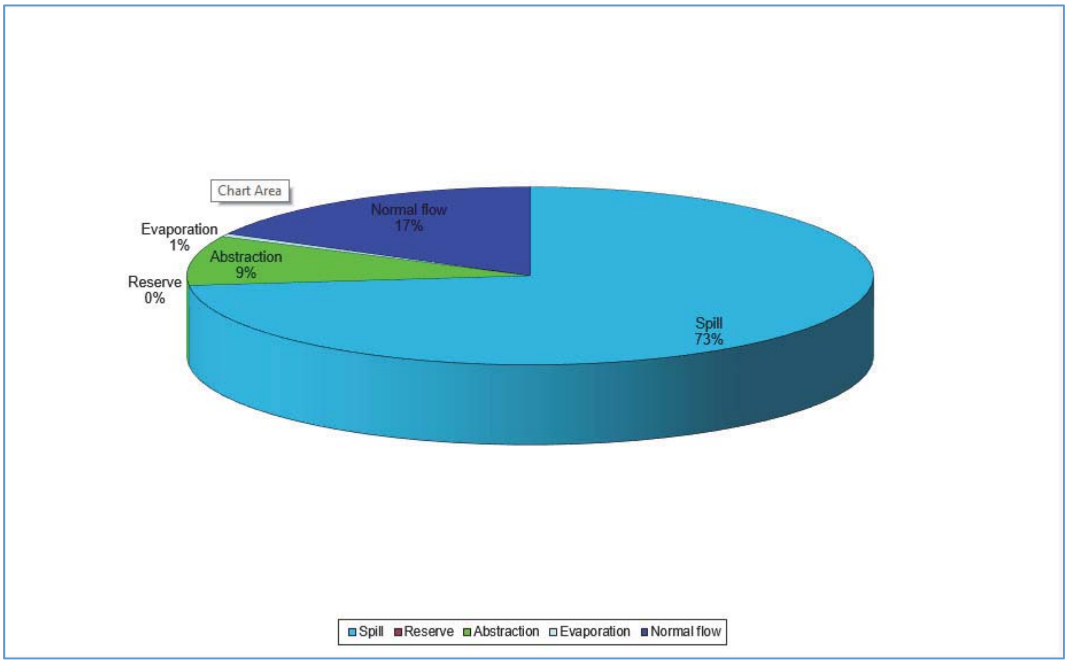

Figure 6-7 Graphic representation of dam water volumes as calculated by the Dambalance module

Acknowledgement:

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