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Computer-based expert system to optimize the water supply for modern irrigation systems in selected regions in Egypt

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1. Introduction

With growing population, urbanization and irrigated agriculture in arid and semiarid regions, water shortages are increasing. As a result of increasing demand for water resources, competition for existing water supplies becomes more critical each year and requires wise use of available water.

Egypt is located in an arid zone. Its present population of 70 mill. is “expected to reach over 90 mill. in the year 2015” (Bishay, 1993). “The 70 mill. Egyptians are living on the production of 5 % (5 mill. ha) of the total area of Egypt” (El-Shaer et al., 1999).

The location is practically rainless; its agriculture depends mainly on irrigation. The mean annual rainfall of 18 mm ranges from 0 in the desert to 200 mm $year^{-1}$ in the north coastal region. During summer, temperatures are extremely high, reaching 38°C to 43°C with extremes of 49°C in the southern and western deserts (mean daily maxima). The Mediterranean coast has cooler conditions with 32°C as mean daily maximum (FAO, 1995).

Egypt has been for a number of years dependent on basic food imports owing to population growth and an improving standard of living. Agriculture is still a mainstay of the Egyptian economy, but overall water supply available to the country is limited, while the demand for water for all sectors is increasing.

The Nile river is the main source of water for Egypt. Under the 1959 Nile Waters Agreement, Egypt’s share is 55.5 mrd. m^3 $year^{-1}$. The total renewable groundwater resources amount to 2.3 mrd. m^3 $year^{-1}$. The main source of internal recharge is percolation from irrigation water, and its quality depends mainly on the quality of the irrigation water. In the northern part of the Delta, groundwater becomes brackish due to sea water intrusion.

According to FAO (1997), the total water managed area is 3,246,000 ha, of which more than 90 % is in the Nile Valley and Delta. Another 920,000 ha are planned to be reclaimed before the year 2000. Irrigation potential has been estimated at 4,435,000 ha. Over 95 % of the area is irrigated with water from the Nile. In the provinces of Matrouh, Sinai and New Valley 146,000 ha are irrigated with ground water. In 1993, an area of 4,200 ha was irrigated with treated wastewater.

"Al-Salam-Canal is planned for the reuse of drainage water from two main drains in the Eastern Delta added to water extracted from the Damietta branch of the Nile. Salam-Canal water will be used for the irrigation of a new area of 252,000 ha in the Eastern Delta and North Sinai" (Abu-Zeid et al., 1997). The total area planned to be developed for irrigation by different projects in the Sinai is estimated at 630,000 ha.

"The amount of drainage water recycled in irrigation is about 4.7 mrd. m^3 $year^{-1}$ (about 2.6 mrd. m^3 $year^{-1}$ of drainage water is recycled in the Delta; 0.95 mrd. m^3 $year^{-1}$ is reused in Fayoum. The remaining part is the drainage water flow back to the Nile in Upper Egypt). It is likely to increase to 7 mrd. m^3 $year^{-1}$ by the year 2000" (Abu-Zeid, 1995). Therefore water is the most limiting factor for cultivation expansion.

Aziz et al. (1995), reported that improving the water efficiency of Egypt's irrigation system offers the best solution to its problem of how to increase food production. Water conservation and finding the best way of using water are the general practices of watershed managers in arid regions. As evapotranspiration is the most important component of the hydrologic cycle of dry land areas, the majority of researchers have been investigating plant water requirements so as to determine an optimal irrigation schedule which would secure an optimum soil moisture condition during the vegetation period and produce a maximum yield.

"The accurate knowledge of water demand in space and in time allows the irrigation engineers and managers to issue the criteria for ameliorating water distribution by matching: i) resources availability, ii) structural restrictions and iii) farmer needs. These three management levels can be linked to each other in a simulation tool which could be used to maximise the efficiency of water irrigation at both district and farm levels" (D'urso and Santini, 1996).

Finally, Vidal et al. (1999) reported that "around 500 mill. m^3 of water can be saved annually in the 600,000 ha Nile Middle Delta, and food production increased by almost 10 %, if spatially distributed crop requirements are applied instead of average values".

In the current investigation we endeavour to use the different spatially distribution of reference evapotranspiration as a tool for optimum irrigation water supply in the study area (Suez-Canal region).

2. Review of Literature

2.1. Water Resources in Egypt and Associated Problems

Egypt has a desert climate and is dependent on the waters of the Nile, which is Egypt's most imporant water source, at present supplying the country with almost all of its water requirements for human, municipal, and agricultural use, i.e. 97 % of water needs, and the development of additional water resources in the near future is not likely (Anonymous, 1995; Seckler and Altaf, 1997). Although the area under cultivation with wheat (which is a major food crop in all countries) was about 1,000,000 ha with production about 6,200,000 t, Egypt imports about 50 % of the total local consumption (Rayan et al., 1999).

It is estimated that already for the year 2000 the total water use approached 70 mrd. m^3 $year^{-1}$, which was more than the actual water availability (FAO, 1997; Attia et al., 1995). "The study of the Water Master Plan revealed requirement of 73 mrd. m^3 $year^{-1}$ in the year 2000 in Egypt" (Bishay, 1993).

The irrigated area (95 % irrigated from the Nile) is 3,246,000 ha (i. e. 100 % of the cultivated area, with 93.8 % surface irrigation; 3.6 % sprinkler irrigation; and 2.6 % micro-irrigation). The total actual surface water resources are 55.5 mrd. m^3 and represent Egypt's annual share from the Nile water. 47.4 mrd. m^3 $year^{-1}$ (i.e. 85.4 % of total water) is water withdrawal for agriculture therefrom 2 mrd. m^3 $year^{-1}$ are estimated loss due to evaporate from 31,000 km of canals (FAO, 1997). In additional, 0.2 mrd. m^3 $year^{-1}$ is reused treated wastewater and 4.7 mrd. m^3 $year^{-1}$ is reused agricultural drainage water. Abu-Zeid (1990) stated that "reused water will increase gradually to 7.0 mrd. by the year 2000 plus 2.3 mrd. m^3 $year^{-1}$ available ground water".

According to Dames and Moore (1983) an area of 5040 ha in Sinai was dependent on ground water and planted with olives, vegetables, groundnut, lucerne and sunflower. "Researches and studies carried out at the New Valley proved that about 1.042 mill. m^3 of ground water can be used annually for irrigation" (Abu-Zeid, 1995). The study of El-Baz (1979) and others indicate that this groundwater has been stored during earlier wet areas and accordingly should be considered as fossil water i.e. non-renewable. “The ground water in the deep aquifers in the Western Desert and Sinai are not renewable and available mostly at great depth. Furthermore, the occurring ground water resources in the El-Arish area are facing a state of quality deterioration in space and time” (Abu-Zeid, 1995).

2.1.1. Some Reasons Related to Water Scarcity in Egypt (Overview)

2.1.1.1. Socio-Economic Reasons

According to criteria of water scarcity , Egypt was classified by Seckler et al. (1998) in a group of countries which will have to divert water from irrigation to supply their domestic and industrial needs and will need to import more food, and have not sufficient water resources to satisfy their requirements in 2025. Yet according to results obtained by Salam and El-Shennawy (1999) who examined the awareness of rural women to the water resources problem “the women were generally unaware of the national limitation on water availability”. The study used 10 groups involving 240 women in four Egyptian governorates.

Although there are 17,200 ha of cultivable land (land that has potential for reclamation and cultivation) in the Kharga depression, only 3,880 ha are actually cultivated due to the low level of underground water which results in high pumping costs (Mansour and Zoghby, 1988).

2.1.1.2. Practical Reasons

On the other hand, Gad (1999) investigated the major problems facing agriculture in Egypt due to the degradation of soils of the Nile flood plain caused by human activities. He found that “under the present system of intensive perennial irrigation, ground water levels in many areas remain at high levels throughout the year”. According to El-Quosy et al. (1998) “soil salinization has accelerated due to the higher water table and waterlogging in some agricultural lands since construction of the High Aswan Dam in Egypt, and inadequate drainage systems and lack of leaching result in salt accumulation in the soil profile”. A similar conclusion was reported by Slavich (1992) and Abdel-Dayem et al. (1995).

“Seepage from open channels in Egypt is one of the major problems involved in the design of irrigation networks and mechanisms to stop this, thereby conserving water, become more important as water becomes a scare commodity” (Bakry and Awad, 1997). Seepage losses from the Nile and from main and branch canals form a considerable part of the total outflow downstream from the High Aswan Dam. Some of it goes to a shallow aquifer where it can be pumped, but most new development has taken place in sandy soils at the valley fringes, which slope upwards, so losses by seepage can occur (Beaumont, 1993; El-Shirbini et al., 1995).

According to Wilkinson (1986) “a canal having seepage less than 0.031 m^3 $year^{-1}$ m^{-2} of wetted area of canal is considered tight, while a canal exhibiting losses more than that limit is considered a good candidate for lining”.

“Many of the newly developed agricultural areas in Egypt (namely on sandy soils) where flood irrigation is used have problems with high water demand, high energy costs, intensive use of labour, spread of weeds under fruit trees, and stunted growth of fruit trees due to salinity” (El-Kadi et al., 1997). Most of the irrigation and drainage canals in the Western Delta of Egypt are affected and covered with floating weeds. These weeds greatly retard the velocity of flow and increase the seepage loss; subsequently they cause soil salinity and soil waterlogging.

“The Egyptian government spends mill. of pounds to control the growth of these weeds by chemical and mechanical means” (El-Noby et al., 1999). The aquatic weeds which are present on the canal bed have a significant effect on hydraulic efficiency, and “it cannot be removed completely from the infested irrigation networks, but they can be controlled to a minimum acceptable level” (El-Samman et al., 1997).

According to the results obtained by El-Noby et al. (1999) “the occurrence of floating weeds is strongly related to the seepage loss”. In the Western Nile Delta, the high amounts of floating weeds in drainage canals (62,775 kg fresh weight) and in irrigation canals (203,400 kg fresh weight) resulted in an increased seepage loss (563,147 m^3 $year^{-1}$ for drainage canals and 546,170 m^3 $year^{-1}$ for irrigation canals).

2.1.2. Egypt's Efforts Towards Overcoming Water Scarcity Problem

The water balance figures for Egypt as estimated in 2000 show that available water supply may in the near future not be sufficient to satisfy the demand. “To overcome this critical situation, the main options must be:

i) to develop new sources of water;

ii) to increase water use efficiency and reduce water losses;

iii) to reduce or suppress water uses of low priority” (Attia et al., 1995).

2.1.2.1. Horizontal Agricultural Expansion

The only way to reduce population density in the Nile Valley and Delta is to develop new areas in the surrounding widespread desert areas. Towards this objective “two giant horizontal expansion projects are under implementation: i) the New Wadi Canal in Upper Egypt, and ii) the Sinai Development Irrigation Project where mixed water supply (Nile-water mixed with agriculture drainage-water at 1:1 ratio) will be provided" (Abu-Zeid et al., 1997).

Blending saline water with fresh water for irrigation “enables improvement of the water quality, and has the potential to save significant quantities of good quality water to enlarge available water resources and increase the benefits of irrigation” (Leskys et al., 1999).

The Land Master Plan identified a gross area of about 113,200 ha in the Sinai peninsula for development. The area to be irrigated from El-Salam Canal (fresh water from Damietta branch of the Nile mixed with both drainage waters from Hadous Drain and El-Serw Drain), is situated in the Suez Canal region. Following the Land Master Plan, a project was prepared to develop agricultural land in an area of 20,000 ha covering the Tina Plain between Port Said and El-Arish (the study area in the following investigation includes this zone also). “It was proposed that this area would be reclaimed using surface water supplies delivered by the El-Salam Canal and a methodology was outlined for developing the mixture of saline clays, loamy alluvial clays and sandy soils in the project area." Therefore, the annual water requirements for the three soil types vary with the method of water application. In case of drip irrigation the annual water requirement for reclamation is about 14,000 m^3 ha^{-1} (Mahmoud, 1989).

El-Ganzouri et al. (1999) reported that the El-Salam Canal project was designed to irrigate 150,000 ha west of the Suez Canal and 275,000 ha in its east, using fresh water from the Nile and drainage water from both Hadus Drain and El-Serw Drain.

According to Willardson (1997) the government of Egypt had planned to increase the cultivated and irrigated area (approximately 3.0 mill. hectar) by 1.2 mill. ha. (already by the year 2000).

2.1.2.2. Water Saving: Reduction of Nile Outflow to the Sea and Drainage Water Reuse

The present Egyptian efforts are directed towards conservation of water through several re-use projects, and reducing freshwater losses to the northern lakes and the Mediterranean Sea (El-Kady and Hamdy, 1997).

There has been a clear reduction of Nile outflow to the sea in recent years. "The average annual Nile flow to the Mediterranean Sea was 6.2 mrd. m^3 from 1974 to 1980, and from 1981 to 1990 it was 3.9 mrd. m^3, while from 1991 to 1996 it was reduced to 1.7 mrd. m^3. For the 1995-1996 irrigation season, the Nile outflow to the sea was reduced to 0.26 mrd. m^3 " (Seckler and Altaf, 1997). Seckler and Altaf stated that managers have been devising ways for further reduction of outflow of water to the sea to save water for use in agriculture and other sectors, as future potential for further water savings of the Nile river is very limited.

"Drainage water .... in the Nile Delta is collected in the drainage canals and is partly diverted to coastal lakes and the Mediterranean Sea. At 21 locations, government pump stations lift water from the drainage canals into irrigation canals where it is mixed with fresh Nile water and is reused for irrigation" (Project Team, 1989).

"The total quantity of generated drainage water amounts to about 70 % of the total supply of irrigation water to the crops in the Eastern Nile Delta, while the quantity of drainage water used in irrigated land amounts to 30 % of the quantity of supplied water to the crops" (Willardson, 1997).There are some aquifers in the Nile Valley alluvial, which are recharged by percolation from the river Nile, the main sources of recharge for these aquifers being the Rosetta and Damietta branches of the Nile, the irrigation canals, and seepage from irrigated fields. Although during low flow conditions the aquifers feed water into the Nile branches, the major outlet of water from these Delta aquifers is seepage into the Mediterranean Sea.

According to Hammad (1986) estimates suggested that each year about 740 mill. cubic meters flow unused from the aquifers into the Mediterranean Sea. "Pumped wells scattered throughout the Nile Delta take water from these aquifers and reduce these losses effectively" (Beaumont, 1993).

2.1.3. Limitation of Saline Water Application in Egypt

Reuse of agricultural drainage water for irrigation in Egypt "is an important mechanism for increasing available fresh water resources to try to meet future needs" (Kotb et al., 2000). The common knowledge about drainage water quality and the environmental impacts of development of guidelines for the use of such water showed that the drainage water re-use is suitable for:

i) land reclamation at the fringes of the Nile Delta where the soil texture is light and soil salinity is higher than drainage water salinity;

ii) irrigation under certain criteria (for example, salt tolerant plants, salt leaching application etc.);

iii) if polluted, for use only in certain cases (mostly for wood production) after purification has been carried out.

The study of El-Bagoury et al. (1999) on Casurina equisetifolia seedlings irrigated with tap water for one month, then irrigated with 5,000, 10,000, 15,000 or 20,000 ppm saline water (NaCl and $CaCl_2$ at ratio 1:1) showed that irrigation with 5,000 ppm saline water significantly increased plant height, stem diameter, and fresh and dry weight of stems, branchlets, and roots, compared with controls treated with Nile water. The other all salinity treatments reduced branchlet contents of chlorophyll, compared with controls, but increased the contents of carbohydrates.

Afifi et al., (1996) in Egypt, investigated the influence of the application of diluted sea water (with 3,000 and 6,000 ppm salt content and fresh water) and soil conditioners (peat-moss and bituminous emulsion) on soil salinity in sandy soil and sandy clay loam soil. The results indicated that "frequent alternation of saline and fresh water at a 1:1 ratio caused considerable attenuation of salinity, especially in sandy soils in which peat-moss was more effective in reducing soil salinity". On the other hand in the sandy clay loam soil, they concluded that the use of diluted sea-water for irrigation appears to be limited. A similar result was obtained by Aldesuquy (1998) and Ashour et al., (1999).

Hassan (1999) studied the effect of brackish water at salinity levels of 1,750 and 4,300 ppm on maize grain yield and plant height in Siwa Oasis. The results showed that both parameters decreased significantly as salinity increased. Similar results were obtained by Abdel-Samad and El-Enany (1996), El-Karamity and Attaallah (1997), Soliman and Kostandi (1998) and El-Desoukki (1999). El-Dessouky and Atawia (1998) found that the germination percentage of Sour orange, Volkamer lemon, Rangpur lime and Cleopatra mandarin rootstocks decreased and the number of days required for germination increased as the level of salinity increased. The number of lateral roots and the dry weight of roots of the seedlings of the same 4 rootstocks were significantly reduced by irrigation with saline solution beyond the maximum tolerable level i. e. 4,000 ppm.

Plaut (1997) stated that "saline water can be used in sandy soils when the water table is deep, or in artificial substrates when the water is being recycled, therefore the potential for using such low quality water to improve fruit quality will depend on the possibility to minimize environmental hazard, mainly pollution of the subsurface water table. The magnitude of saline water depended on salt concentration, amount of water applied, climatic conditions and switches from low to high water qualities or vice versa". These different reactions of different plants must be considered when planning to use saline water for irrigation on specific soils and with specific irrigation methods, e. g. drip irrigation (see Section 2.3.4.3.).

However, there are concerns about environmental impacts of heavy metals resulting from drainwater reuse in irrigation (El-Hawary et al., 1998; Helal et al., 1998; Grieve et al., 1999). In Bahariya Oasis, Egypt “the ground water was contaminated with iron, manganese, lead, nickel and zinc which exceed the recommended critical limits of these elements in irrigation water where the data showed that use of such groundwater in irrigation increases the heavy metals content in the soil surface” (Shahin et al., 1996).

2.2. Water Use Efficiency (WUE)

A widely applicable expression of efficiency is the agronomic or crop water-use efficiency, which has been defined by Viets (1962) as “the amount of vegetative dry matter produced per unit volume of water taken up by the crop from the soil”, while the net amount of water added to the root zone divided by the amount of water taken from some source, was defined as “irrigation or technical efficiency” (Hillel, 1997).

The overall agronomic efficiency of water use, WUE_{ag}, can be expressed as (Hillel et al.,1998):

$$WUE_{ag} = P_c / W \qquad \text{Eq. 1}$$

where P_c is the crop production and W is the volume of water applied. Since only a fraction of the applied water is actually absorbed and utilized by the crop, the various components of the W must be defined as follows:

$$W = R + D_r + E_d + E_s + T_w + T_c \qquad \text{Eq. 2}$$

where R is the volume of water lost by runoff from the field, D_r the volume drained below the root zone (by deep percolation), E_d the volume lost by evaporation during delivery and application to the field, E_s the volume evaporated from the soil, T_w the volume transpired by weeds, T_c the volume transpired by the crop. All of these volumes pertain to the same unit area and the same time period, therefore,

$$WUE_{ag} = P_c / (R + D_r + E_d + E_s + T_w + T_c) \qquad \text{Eq. 3}$$

Clearly, WUE_{ag} can be maximized by decreasing the denominator and/or by increasing the numerator. “It requires both that growth be maximized by using high-yielding varieties well adapted to local soil and climate, and that water be conserved by avoidance of waste (runoff, seepage, evaporation and transpiration by weeds). But the one component of the field water balance that generally should not be reduced is transpiration by the crop” (Hillel et al., 1998).

Water use efficiency in crop production is important from both economic and environmental points of view, because over-irrigation accounts for water losses by deep percolation, potential fertilizer, underground water pollution and partial root anoxia (Clothier and Green ,1994; Al-Kaisi et al., 1999). On the other hand “under-irrigation causes a restricted wetted soil volume, which may fail to supply total plant evapotranspiration needs, and can create conditions for salt intrusion into the crop-rooting soil volume” (Curovich, 1999).

Aziz et al. (1995) reported that “ improving the water use efficiency of Egypt’s irrigation system offers the best solution to its problem of how to increase food production”. Therefore, enhancement of the water use efficiency is also the decisive objective of the following work (Chapter 3.).

“The results of Irrigation Management System (IMS) programme, in Egypt, indicate that it could lead to a 15 % increase in cropped area on currently cultivated lands and result in a 10 % increase in unit yield. Nevertheless, the potential benefit of the IMS programme is predicted on the assumption that the necessary volumes of water would be available when required” (Attia et al., 1995).

2.2.1. Management Practices and Water Use Efficiency

2.2.1.1. Regulated Deficit Irrigation (RDI)

Regulated deficit irrigation, RDI, “is an irrigation strategy based on limiting nonbeneficial water losses and applying water so that plant water deficits are controlled and occur during times of the season when adverse effects on productivity are minimized” (Chalmers et al., 1981).

According to Mitchell et al. (1986) RDI has been successfully used in pear and peach trees, and the results obtained showed that yield and fruit size were not affected by deficit irrigation. “Citrus response to irrigation water deficit has demonstrated that sensitivity of yield to water stress is dependent on the phenological phase in which water stress was applied” (Castel and Buj, 1990). The effect of two deficit irrigation treatments on plant water relations, growth, yield and fruit quality of Fino lemon was evaluated by Domingo et al. (1996). One RDI treatment was scheduled to save around 30 % of irrigation water, reducing the water supply during the whole season, except in the rapid period. The second was scheduled to save around 20 %, reducing irrigation only in the rapid period. The results showed that the second treatment did not induce significant reduction in the total yield. The first RDI treatment saved around 30 % of water without affecting total yield and only caused a reduction of lemon yield in the first harvest in one year. The investigators reported that the first treatment appears to be a promising irrigation strategy in areas with scarce water resources.

While the study (in Egypt) of Abdel-Monem et al. (1997) showed that there was no significant effect between 5 irrigations and 4 irrigations on barley and wheat grain yield (a similar result was obtained by Ibrahim, 1999, in North Delta, Egypt), the results obtained by Mohamed and Tammam (1998) showed that drought stress for wheat depressed plant height, spike length, number of spikes per m^2, 1,000-kernel weight, total yield and grain yield. Plant exposure to drought at stem elongation, milk and stem elongation and milk stages decreased grain yield by 13.6, 16.6 and 21.7 % respectively. Accordingly, the RDI strategy should be handled with care.

2.2.1.2. Canal lining

It is important that water losses due to percolation or evaporation from the distribution net are restricted. “The use of pipe-lines instead of open canals to deliver water to irrigation systems was investigated as a means of ensuring more efficient use of water resources” (Hussien et al., 1997). Egypt is lining canals and local water courses (mesqas) to improve water delivery efficiency. Several kinds of canal linings have successfully been used. “The channels lining is extensively used in the new developments area, but has been limited in the established irrigation area” (Aziz et al., 1995).

Moghazi and Ismail (1997) evaluated the water losses for three different types of canals. They were: earthern-uncompacted canals, compacted canal bed and canal lined by jute mats coated with bitumen emulsion on both faces. Their results showed that the process of compacting the canal bed reduced the rate of seepage by a considerable value and that lining of field channels by prefabricated bitumen jute mats caused a significant reduction in the seepage rate.

2.2.1.3. Land Preparation

The effect of land levelling precision on irrigation advance, application efficiency, and distribution uniformity in level basin was studied using statistical and computer models by Fangmeier et al. (1999): “The results indicated that the application efficiency and distribution uniformity (for a typical Egyptian field) decreased substantially when the standard deviations of the soil surface elevations were greater than 20 mm.”

The results obtained by Karaman et al. (1998) showed that the amount of water required for irrigation was reduced by 28.8, 24.2 and 10.4 % following laser treatment resulting in slopes of 3 cm per 100 m, laser treatment to zero slope, and manual levelling, respectively, compared with untreated controls. Cane and sugar yields were also significantly increased in the treated plots.

In North Delta, Egypt, El-Mowelhi et al. (1998) studied the effect of three land levelling practices and two levels of tillage on seed cotton production. The results showed that land levelling with 0.1 % slope resulted in the highest seed cotton yield and recorded the highest values of water utilization efficiency compared to other treatments (i. e. flat and traditional land levelling).

Barros and Hanks (1993) found that mulch on the surface reduced soil water evaporation by 45 mm and increased transpiration of beans (Phaseolus vulgaris L.) by the same amount. The effect of mulching the soil on soil moisture status in Egypt was investigated by Ghali and Nakhlla (1996). They found an improved root development and yield production and a high water use efficiency using the mulch of 75 % cover as the best treatment. “For onion crop, covering the soil reduced the amount of irrigation water required by about 70 % for all irrigation treatments compared with the amount of irrigation water added in the open soil surface treatments because wet soil surface evaporation was eliminated” (Abu-Awwad et al., 1999). Water use efficiency in the covered soil was the highest, where onion yield was significantly higher than in open surface treatments at low water level; a similar result was obtained by Gajera et al. (1998). In India, the fruit yield of tomato increased with mulch treatment from 16.63 ton ha^{-1} to 23.25 ton ha^{-1}, both under drip irrigation compared to 11.95 ton ha^{-1} under surface irrigation without mulching (Raine et al., 1999).

2.3. Reference-Evapotranspiration, Crop Evapotranspiration and Irrigation Requirements

2.3.1. Reference-Evapotranspiration (ET_o)

One way to improve water use efficiency and optimize plant production is to provide crops only with the water they need based on the climate-plant-soil relationship. Therefore the concept of evapotranspiration (ET) is the base for the right amount of irrigation water that should be applied.

“Evaporation and Transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. The evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface” (Withers and Vipond, 1978). This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominantly lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process.

"At sowing nearly 100 % of ET comes from evaporation, while at full crop cover more than 90 % of ET comes from transpiration" (Hillel, 1987). The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as Crop Water Requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be applied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. "The Irrigation Water Requirement basically represents the difference between the crop water requirement and effective precipitation" (Doorenbos and Pruitt, 1975). The irrigation water requirement also includes additional water for leaching of salts and for compensating for non-uniformity of water application.

According to Al-Ghobari (2000), the potential evapotranspiration is defined as the rate at which water would be removed from wet soil or plant surfaces (expressed as the rate of latent heat transfer per unit area, or as a depth of water per unit time), while the reference evapotranspiration is defined as the rate at which water would be removed from the soil and plant surfaces (expressed as the rate of latent heat transfer per unit area, or as a depth of water per unit time) and transpired from a reference crop. So, the use of reference evapotranspiration (= evapotranspiration from the reference crop) for a specified crop surface has largely replaced the use of the more general potential evapotranspiration.

The potential evapotranspiration depends only on climatic driving forces and the potential rate of evaporation from the fraction of the soil surface and is presumed to equal the potential energy available (Pereira et al., 1996; Allen et al., 1996).

"The use of a reference evapotranspiration permits a physically realistic characterization of the effect of the microclimate of a field on the evaporative transfer of water from the soil-plant system to the atmospheric air layers overlying the field" (Wright, 1996). When selecting a reference (standard) method to estimate crop evapotranspiration it is necessary to consider a reference crop with standard height, albedo, an aerodynamic resistance (from the wind speed) and an average surface resistance (results from the stomatal regulation and canopy structure as influenced by the climate). Adequate data are already available for clipped grass and alfalfa, allowing the definition of a general reference evapotranspiration, ET_o (Pereira et al., 1996). In the current investigation we will use the concept of reference evapotranspiration (ET_o) which has been defined as the rate of evapotranspiration from a hypothetical reference crop.

For calculation of (actual) crop evapotranspiration (ET_c), the crop coefficient (K_c) that acts as an aggregation of the physical and physiological difference between crops must be available in addition to the reference evapotranspiration (ET_o). Actual crop evapotranspiration can be calculated by multiplication K_c by ET_o ($ET_c = ET_o * K_c$).

2.3.2. Crop Coefficient, (K_c)

"The crop coefficient, K_c, is basically the ratio of the crop evapotranspiration to the reference evapotranspiration, and it represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass" (Achtnich, 1980). These characteristics are:

- Albedo (reflectance) of the crop-soil surface influences the net radiation of the surface. The albedo is affected by the fraction of ground covered by vegetation and by the soil surface wetness and colour.

- Crop height influences the aerodynamic resistance, r_a, and the turbulence of vapor from the crop into the atmosphere.

- "Canopy resistance, is the resistance of the crop to vapor transfer and it is affected by leaf area (number of stomata), leaf age and condition. The canopy resistance influences the surface resistance, r_s" (Alves, 1995).

- Crops such as pineapples, that close their stomata during the day, have a very small crop coefficient.

For many crops K_c increases as wind speed increases and as relative humidity decreases, herewith more arid climates and conditions of greater wind speed will have higher values for K_c, and vice versa. Three stages are recommended for the calculation of the crop evapotranspiration ET_c: The first is the effect of climate on crop water requirements, the second is the effect of the crop characteristics on crop water requirements, and the third is the effect of local condition and agricultural practices on crop water requirements. The first is given by the reference evapotranspiration ET_o and the second is given by the crop coefficient K_c, which represents the relationship between ET_o and ET_c, (Doorenbos and Pruitt, 1977);

$$ET_c = ET_o \cdot K_c \qquad \text{Eq. 4}$$

Palacios and Quevedo (1996) integrated the so-called Stress Coefficient K_s, (which is defined by Hanks and Ashcroft, 1980, as Soil Water Coefficient) to obtain the actual crop evapotranspiration as:

$$ET_c = ET_o \cdot K_c \cdot K_s \qquad \text{Eq. 5}$$

For the calculaction of the Stress Factor, a function obtained by Palacios (1980) is used, as follows:

$$K_s = \frac{1}{1 + \frac{ET_o}{S_u}\left[\frac{1 - AW}{AW}\right]} \qquad \text{Eq. 6}$$

where ET_o is the reference evapotranspiration (cm day^{-1}), S_u the soil factor, approxmately 1/5 of soil hydraulic conductivity (cm day^{-1}), and AW is the available soil water content, cm^3/cm^3. Therefore, the effects of soil water stress on Crop-ET are described by reducing the value for the crop coefficient.

Morton et al. (1998) used a water stress coefficient (K_s) to estimate the actual evaptranspiration ET_a, where ET_a becomes a smaller fraction of the reference evapotranspiration ET_o, as the magnitude of soil moisture deficit increases in the root zone:

$$ET_a = K_s \cdot K_{cb} \cdot ET_o \qquad \text{Eq. 7}$$

where K_{cb} is the basal crop coefficient (crop-type and time dependent), and K_s is a water stress coefficient, which varies from 0.0 (complete stress and no crop growth) to 1.0 (no stress). Morton et al. (1998) described K_c mathematically as follows:

$$K_s = \frac{\log\left[1 + 100\left[1 - \frac{\Theta_{fc} - \Theta}{\Theta_{fc} - \Theta_{wp}}\right]\right]}{\log(101)} \qquad \text{Eq. 8}$$

where Θ_{fc} is the soil moisture content at -33 KPa matric potential, Θ_{wp} is the soil moisture content at –1,500 KPa matric potential, and Θ is the actual soil moisture content.

Allen et al. (1998) classified the crop coefficients into two types as follows:
1) one Single Crop Coefficient (K_c), where the effects of crop evapotranspiration and soil evaporation are combined; its time step is daily, every 10 days or monthly;
2) or a Dual Crop Coefficient, which can be split into two factors (K_{cb} + K_e), where K_{cb} is the Basal Crop Coefficient to describe plant transpiration and defined as the ratio of ET_c to ET_o when the soil surface is dry but transpiration is occurring at a potential rate. It represents the baseline potential K_c in the absence of the additional effects of soil wetting by irrigation or precipitation. "The basal crop coefficient provides improved estimates of K_c on a daily basis where the effects of a wet soil surface are explicitly considered" (Allen et al., 1998). A similar conclusion was reported by Hunsaker (1999). K_e is the Soil Water Evaporation Coefficient, to describe evaporation from the soil surface. If the soil is wet following rain or irrigation, K_e may be large, and becomes smaller as the soil surface becomes drier. The estimation of K_e requires a daily calculation of the soil water content remaining in the upper topsoil. The Dual Coefficient requires more numerical calculations, and the time step for it is daily.

Changes in vegetation and ground cover mean that the crop coefficient varies during the growing period. The trends in K_c during the growing period are represented in the Crop Coefficient Curve. Only three values for K_c are required to describe and construct the crop coefficient curve: Those during the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$), and at the end of the late season stage ($K_{c\ end}$). The constructing of the crop coefficient curve allows one to determine K_c values for any period during the growing period.

2.3.2.1. Adjusted Crop Coefficient, $K_{c\ adj}$

According to the recommendation of Allen et al. (1996), Neale (1996) and ASCE (1996), the values of $K_{c\ mid}$ and $K_{c\ end}$ of Doorenbos and Pruitt (1977) should be modified, as they are for a subhumid climate (RH_{min} ~ 45%) with moderate wind speed (averaging 2 m s^{-1}). For more humid or arid conditions or for more or less windy conditions, they should be modified as follows:

$$K_{c\ mid\ adj} = K_{c\ mid\ (table)} + [\,0.04(U_2 - 2) - 0.004\,(RH_{\min} - 45)\,]\,(h_p\ /\ 3)^{0.3} \qquad \text{Eq. 9}$$

$$K_{c\ end\ adj} = K_{c\ end\ (table)} + [\,0.04\,(U_2 - 2) - 0.004\,(RH_{\min} - 45)\,]\,(h_p\ /\ 3)^{0.3} \qquad \text{Eq. 10}$$

where h_p is the maximum plant height (m). When $k_{c\ end\ (table)} < 0.45$, no adjustment is made

When crops are allowed to ripen and dry in the field (as evidenced by $K_{c\ end} < 0.45$), U_2 and RH_{min} have less effect on $K_{c\ end}$ and no adjustment is necessary. When $K_{c\ end}$ < 0.4, ASCE (1996) produced an adjustment as:

$$K_{c\ end} = K_{c\ end\ (table)} + 0.001\,(RH_{\min} - 45.0)\,.$$

Accordingly, as the research area is under arid condition, adjustments are made for $K_{c\ mid}$ and $K_{c\ end}$ in the following.

2.3.2.2. Crop Coefficient Calculation using Remote Sensing Tool

The crop coefficients (K_c) can be solved from remote sensing by:

a) directly determining ET_c and taking ET_o from standard synoptic stations;

b) interpreting tabulated K_c values throughout the season using a spectral vegetation index as the independent variable, as investigated by Choudhury et al. (1994); also the soil "adjusted vegetation index, SAVI, was a suitable index to extrapolate Kc for corn crop" (Bausch, 1995);
c) using airborne digital multispectral video imagery over the cropped field throughout the growing season (Neale et al., 1996).

Michael and Bastiaanssen (2000) introduced a simple technique improving the planning of irrigation water resources because the spatial crop coefficients K_c estimation based on satellite images (Landsat-TM) reveal the real agricultural practices. Their method is based on the simplified Priestley-Taylor equation (1972) for reference evapotranspiration calculations, "because its radiation and temperature parameters can be assessed from remotely sensed data. The input parameters for more complex and physically better Penman-Monteith equation cannot be obtained from remote sensing data" (Michael and Bastiaanssen, 2000). The approximation is based on remotely measured radiative properties of the surface which eliminates the need to identify crops and to know their development stages. The actual evapotranspiration is determined as the energy balance residual (ER), thus after having quantified net radiation (R_n), soil heat flux (G) and sensible heat flux (H):

$$LE_f = R_n - G - H \qquad \text{Eq. 11}$$

where LE_f is the latent heat flux (W m^{-2}), associated to actual evapotranspiration. The ER method for actual evapotranspiration is used to validate the Priestley-Taylor equation for reference crop evapotranspiration:

$$ET_o = a \frac{\Delta}{\Delta + g} (R_n - G) \qquad \text{Eq. 12}$$

with a = 1.26 being a constant $(W\, m^{-2})$, Δ = slope of the saturation vapor pressure curve at a given temperature and g = psychrometric constant.

2.3.3. Some Evapotranspiration-Calculation Methods

Estimation of evapotranspiration can be based on the hydrologic cycle or on climatological data. The first type requires measurements of soil water and thus it is subject to sampling error, or use of a lysimeter which also incurs problems, a long period of time and cost. Hence, other methods of estimating evapotranspiration have been sought that are simpler and faster. There is considerable interest in methods based on climatic measurements (Hanks and Ashcroft, 1980; Milivojevic et al., 1996):

1- The climatic variables apply to a wider scale than spot soil sampling.
2- Where average climatological data are available, these methods can be used for prediction.

There are four evapotranspiration methods adopted in the FAO-Paper No 24 (1984) to be used according to the availability of climatic data:

I) The FAO-modified Penman is an adaption of the original Penman method and includes a revised wind function, derived from lysimeter data of various locations worldwide. However, this modified equation tends to overestimate ET_o at many locations. It should be multiplied by 1.15 for converting the grass ET_o to the alfalfa ET_o for arid climates, as alfalfa has higher ET_o rates in arid areas (Al-Ghobari, 2000).

II) The FAO-radiation method was developed originally for the humid conditions (where the aerodynamic term is relative small) in the Netherlands. By introducing a correction coefficient for various wind and humidity conditions, its validity was extended to a wider range of climatic conditions.

III) The Blaney-Criddle method, introduced in the early 1950's in the arid western United States, found broad application in irrigation studies and, as the FAO Blaney-Criddle method was adapted by Doorenbos and Pruit (1975) to suit a wide range of climatic conditions by introducing a correction factor, which can be determined from estimates of humidity, wind and sunshine conditions.

IV) The Evaporation Pan method has been widly used in many agrometeorological stations. The evaporation pan data (E_p) collected in poorly maintained locations will not produce estimates as accurate as those based on good meteorological data. The measured evaporation of water in a standardized container has been extensively used as an ET_o parameter ($ET_o = E_p \cdot K_p$, where K_p = pan coefficient) and is applied in many irrigation studies and in real-time irrigation scheduling (Milivojevic et al., 1996; Smith et al., 1996; Al-Ghobari, 2000).

"Penman (1948) introduced an equation combining energy balance and aerodynamic transfer terms to represent the amount of water evaporated. Penman´s equation was developed for a short, green grass surface that completely shaded the ground of uniform height and no shortage of water. Much experience has shown that the original Penman equation was developed for a humid climate, and is not universally applicable without a local calibration" (Wright, 1996).

2.3.3.1. Modified Penman Equation

A modified Pruitt-Doorenbos equation, where Pruitt and Doorenbos (1977) calibrated the wind function of the Penman 1948 equation using micrometeorological and lysimeter data to obtain an hourly estimate of ET_o, was used by Ventura et al. (1999), where a comparison is made between the following equation (Eq. 13) and Penman-Monteith equation (Eq. 30) and an independent ET_o measured from lysimeter data:

$$PD_i = \frac{\Delta_i}{\Delta_i + g_i}(R_{ni}) + l_i \frac{g_i}{\Delta_i + g_i}(e_{si} - e_{ai}) F(U_i) \qquad \text{Eq. 13}$$

where $PD_i = ET_o$ (for the ith hour); R_{ni} = net radiation; Δ_i = slope of the saturation vapor pressure curve at T_i (air temperature at day i); g_i = psychrometric constant; e_{si} = saturated vapor pressure at air temperature; e_{ai} = measured vapor pressure; $F(U_i)$ = wind function:

$F(U_i) = 0.030 + 0.0576\, U_i$ if $R_{ni} > 0$

$F(U_i) = 0.125 + 0.0439\, U_i$ if $R_{ni} \leq 0$;

U_i = wind speed at 2.0 m; l_i = the latent heat of vaporization (694.5 [1 – 0.000946 T_i] W m^{-2} mm^{-1} h). The daily reference evapotranspiration PD_i' (mm day^{-1}) is calculated as the sum of PD_i over 24 hours devided by l_i as:

$$PD_i' = \sum_{i=1}^{24} PD_i \;/\; l_i \qquad \text{Eq. 14}$$

The comparison (between Eq. 13, 30 and lysimeter-ET_o) showed acceptable results, but the Pruitt-Doorenbos equation, Eq. 13, may over-estimate ET_o. In this connection, Jensen et al. (1990) found that this modified equation tends to overestimate ET_o at many locations. Abo-Ghobar and Mohammed (1995) reported that the FAO-modified Penman equation should be corrected since it is not expected to give the same values as obtained experimentally at all locations.

2.3.3.2. Priestley-Taylor Equation 1972

It is argued that this equation "is justified and has a good performance under humid conditions because the vapor pressure deficit increases linearly with radiation" (Mc Aneny and Itier, 1996). Simulation with numerical boundary layer models have shown that the Priestley-Taylor (PT) equation can be used safely to estimate evapotranspiration from wet and saturated surfaces over large areas (De Bruin, 1983; Mc Naughton and Spriggs, 1989). The field study by Sarwar et al. (2000) showed that numerical modeling using Priestley-Taylor equation gave satisfactory results and it can be expressed as:

$$ET_o = a\left[\frac{\Delta}{\Delta + g}\right](R_n - G) \qquad \text{Eq. 15}$$

where ET_o is the reference crop evapotranspiration ($MJm^{-2}d^{-1}$), Δ is the slope of the saturation vapour pressure vs air temperature relationship, a is a multiplier which essentially compensates for the lack of an aerodynamic term typically of combination aerodynamic energy balance equations, g is the Psychrometric Constant (Kpa / C°), R_n is the net radiation ($MJm^{-2}d^{-1}$), and G is the soil heat flux ($MJm^{-2}d^{-1}$). Priestley and Taylor (1972) found that a value for a of 1.26 provided estimates of ET for the land-studies in good agreement with measured ET.

2.3.3.3. Hargreaves Equation

The monthly ET_o can be calculated using Hargreaves et al. (1985) as follows:

$$ET_o = 0.0023\ Ra\ (T + 17.8)\ d^{0.5} \qquad \text{Eq. 16}$$

where Ra = daily extraterrestrial radiation in the same units (usually) as ET_o; $T = (T_M + T_m)/2$ (C°); T_M and T_m are the mean maximum and minimum temperature (C°), respectively; and $d = T_M - T_m$ (C°). Hargreaves (1995) recommended the Hargreaves equation for general use for computing values of ET_o. Due to its simplicity and reliability, the equation requires only measured values of maximum and minimum temperatures, and correlates well with results from the Penman combination equations.

Arellano and Gomez (1996) computed the potential evapotranspiration using Hargreaves's equation, and using the ratio $ET_{o\ Hargreaves} / ET_{o\ Class\ A\ Pan}$ the results did not fit and varied around an average 1.25. "When solar radiation data, relative humidity data and/or wind speed are missing, as an alternative, ET_o can be estimated using the Hargreaves's equation. Hargreaves equation has a tendency to underpredict under high wind conditions ($U_2 > 3\ m\ s^{-1}$) and to overpredict under conditions of high relative humidity" (Allen et al., 1998).

2.3.3.4. Penman-Monteith Equation

Attempting to better characterize water loss by plants, Monteith (1965) introduced some modifications, resulting in the now well-known Penman-Monteith equation. The Penman-Monteith formula is the most suitable method for estimating crop evapotranspiration and for the reference evapotranspiration (Allen et al., 1989 & 1996; Jensen et al., 1990; Hargreaves, 1994). The PM equation for ET_c is (see Eq. 19):

$$ET_c = \frac{\Delta (R_n - G) + r_a\ c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + g\left[1 + \dfrac{r_s}{r_a}\right]}$$

The Penman-Monteith equation has gained a renewed interest, especially to predict crop evapotranspiration in an one-step approach, without the use of a crop coefficient as it has been currently used for the last 20 years. But to do so and for the Penman-Monteith equation to be used predictively, methodologies for determining aerodynamic resistance and canopy surface resistance must be available (Alves et al., 1996; Smith et al., 1996).

"Also one important advantage in using the PM equation with an abstract reference crop is that it offers the opportunity to have a model that applies everywhere and does not need any local calibration" (Steduto et al., 1996). Relationships were often subject to rigorous local calibrations and proved to have limited global validity. Special attention was focused on the PM equation as a potential standard for ET_o estimate throughout the Mediterranean region and has been generally the most stable form of the Penman combination ET equation used around the world (Howell, 1996; Steduto et al., 1996; Simon et al., 1998; Vidal et al., 1999; Ventura et al., 1999; Michael and Bastiaanssen, 2000).

The American Society of Civil Engineers (ASCE) study reported by Jensen et al., 1990 (quoted by Smith et al. 1993) analyzed the performance of 20 different methods, using very detailed procedures to assess the validity of the methods compared to a set of carefully screened lysimeter data from 11 locations with variable climatic conditions. The study proved very revealing and showed the widely varying performance of the methods under different climatic conditions for humid and arid regions (see: Table 1).

"In a study commissioned by the European Community, a Consortium of European Research Institutes evaluated the performance of various evapotranspiration methods using data from different lysimeter studies in Europe" (Choisnel et al., 1992). The studies confirm the overestimation of the modified Penman introduced in FAO-No. 24 (Doorenbos and Pruitt, 1984), and the variable performance of the different methods depending on their adaption to local conditions. The comparative studies may be summarized as follows (Smith et al., 1996):

Table 1: Performance of various ET_o methods (after Jensen et al., 1990)

Locations	HUMID			ARID		
Performance Indicator	**Rank No.**	**Over-/ underes-timation ***	**Standard error ****	**Rank No.**	**Over-/ underes-timation ***	**Standard error ****
Combination Methods						
Penman-Monteith	1	+4%	0.32	1	-1%	0.49
FAO-24 Penman (c=1)	14	+29%	0.93	6	+12%	0.69
FAO-24 Pen-man(corrected)	19	+35%	1.14	10	+18%	1.1
FAO-PPP-17 Penman	4	+16%	0.67	5	+6%	0.68
Penman (1963)	3	+14%	0.6	7	-2%	0.7
Penman 1963 , VPD #3	6	+20%	0.69	4	+6%	0.67
1972 Kimberley Penman	8	+18%	0.71	8	+6%	0.73
1982 Kimberley penman	7	+10%	0.69	2	+3%	0.54
Businger-van Bavel	16	+32%	1.03	11	+11%	1.12
Radiation Methods						
Priestley Taylor	5	-3%	0.68	19	-27%	1.89
FAO – Radiation	11	+22%	0.79	3	+6%	0.62
Temperature Methods						
Jensen-Haise	12	-18%	0.84	12	-12%	1.13
Hargreaves	10	+25%	0.79	13	-9%	1.17
Turc	2	+5%	0.56	18	-26%	1.88
SCS Blaney-Criddle	15	+17%	1.01	15	-16%	1.29
FAO Blaney-Criddle	9	+16%	0.79	9	0%	0.76
Thornwaite	13	-4%	0.86	20	-37%	2.4
Pan Evapotranspiration Methods						
Class A Pan	20	+14%	1.29	17	+21%	1.54
Christiansen	18	-10%	1.12	16	-6%	1.41
FAO Class A	17	-5%	1.09	14	+5%	1.25

*** Over- or underestimation as percentage from 11 lysimeter data locations, corrected for reference type.**
**** Weighted standard error of estimates, mm day^{-1}.**

- The Penman methods require local calibration of the wind function to achieve satisfactory results.
- The radiation methods show good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions is erratic and underestimates evapotranspiration.

- Temperature methods remain empirical and require local calibration in order to achieve satisfactory results. A possible exception is the Hargreaves method (Hargreaves and Samani, 1985) which has shown reasonable ET_o results with a global validity.
- Pan evapotranspiration methods clearly reflect the shortcomings of predicting crop evapotranspiration from open water evaporation. The methods are susceptible to the microclimatic conditions under which the pans are operating and their performance proves erratic.
- The excellent performance of the Penman-Monteith approach both in humid and arid climates (only very slight over- and underestimates +4 % and –1 %, and negligible standard error 0.32 and 0.49 resp.) is convincingly shown both in the ASCE study and European study.

The main reason to recommend the use of different ET_o methods has been the limiting availability of the full range of climatic data as, in particular, sunshine, humidity or wind data are often lacking.

"The consultation of experts organized by FAO in May 1990 in Rome recommended the adoption of the Penman-Monteith combination method as a consistent and a new globally-valid standard for reference evapotranspiration and advised procedures for calculation of the various parameters (Hargreaves, 1994).

(PM-Equation's Components)

By introducing the aerodynamic resistance (which describes the resistance from the vegetation upward and involves friction from air flowing over the vegetation surface) and canopy resistance (which describes the resistance of vapor flow through stomata openings, total leaf area and soil surface) in the combination method, a better simulation of wind and turbulence effects and of the stomatal behavior of the crop canopy was achieved (Monteith, 1965). Aerodynamic resistance (r_a) can be determined by using the values of roughness and zero plane displacement height, which depend mainly on soil cover, leaf area and structure of canopy (Shaw and Pereira, 1982; Hatfield, 1988).

The average daily aerodynamic resistance to vapor and heat diffusion r_a (s/m), can be calculated as (Pereira et al., 1996):

$$r_a = \frac{\left[\ln\left(\frac{z_m - d}{z_{om}}\right)\right]\left[\ln\left(\frac{z_h - d}{z_{oh}}\right)\right]}{K^2 \; U_z} \qquad \text{Eq. 17}$$

where, Z_m is height of the wind measurement (2 m), Z_h is height of the temperature and relative humidity measurements (1.5 m), Z_{om} is the roughness length for momentum transfer = 0.13 h_c (m), where h_c is the crop height, Z_{oh} is roughness length for heat and vapor transfer =0.2 Z_{om} (m), d is zero plane displacement = 0.7 h_c (m), U_z is wind speed at height Z_m (m/s), K is the van Karman constant (0.41).

According to Smith (1992) and McGlinchey and Inman-Bamber (1996), it was suggested that surface resistance to vapor transfer r_s = 70 s/m for grass, and Allen et al. (1989) reported a value of 44 s/m for alfalfa. Grantz and Meinzer (1991) reported r_s = 34 s/m estimated from measurements taken over sugarcane. Russel (1980) calculated a value of 30 s/m for barley, and it is assumed to be 33 s/m to calculate ET_c of wheat crop according to de Jager and van Zyl (1989).

Surface resistance to vapor transfer (r_s) was detailed, described and calculated according to Allen et al. (1989) and Fisher and Elliot (1996) as:

$$r_s = \frac{r_i}{0.5 \; LAI} \qquad \text{Eq. 18}$$

where, r_i is single leaf resistance to vapor transfer (s/m), LAI is the leaf area index. Surface resistance to vapor transfer (r_s) has been a limiting factor for using the PM model to directly estimate crop evapotranspiration and it is particularly difficult to estimate due to the combined influence of plant, soil and climatic factors that affect its value. According to Baselga and Allen (1996), the crop evapotranspiration can be calculated from climatic data and by integrating directly the crop resistance and air resistance factors in the PM approach as follows:

$$ET_c = \frac{\Delta (R_n - G) + r_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + g\left[1 + \dfrac{r_s}{r_a}\right]} \qquad \text{Eq. 19}$$

where ET_c is the crop evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}) (it is the difference between the incoming net shortwave radiation R_{ns} and the outgoing net longwave radiation R_{nl}). It can be calculated according to Doorenbos and Pruitt (1977) as follows:

$$R_n = 0.75\ R_s - 2.0\ (10)^{-9}\ (T_a + 273.16)^4 \left(0.34 - 0.044\sqrt{e_s}\right)\left[-0.35 + 1.8\frac{R_s}{R_a}\right] \qquad \text{Eq. 20}$$

This equation had been modified by Pair et al. (1983) as:

$$R_n = 0.75\,R_s - 2.0\,(10)^{-9}\ (T_a + 273.16)^4 \left(0.31 - 0.044\sqrt{e_{sd}}\right)\left[-0.35 + 1.35\frac{R_s}{R_{so}}\right] \qquad \text{Eq. 21}$$

where R_s is observed solar radiation (mm day^{-1}), R_a is extraterrestrial solar radiation (mm day^{-1}), R_{so} is solar radiation on a clear day (mm day^{-1}), e_s is the saturated vapor pressure (mbar) at average air temperature T_a (C°) and e_{sd} is saturated vapor pressure at dew point temperature of air (mbar).

The relative shortwave radiation is the ratio of the actual solar radiation (R_s) to the clear day solar radiation (R_{so}). This ratio is a way to express the cloudiness of the atmosphere; the cloudier the sky, the smaller the ratio. In the absence of a direct measurement of the net radiation R_n, the relative shortwave radiation is used in the computation of the net radiation as showed in equation 21. The actual (observed) short wave radiation R_s can be estimated as (Doorenbos and Pruit, 1977):

$$R_s = (0.25 + 0.5\ n / N)\ R_a \qquad \text{Eq. 22}$$

where n is the mean daily sunshine hours and N is the mean daily maximum sunshine hours.

G is the Soil Heat Flux, it is the energy that is utilized in heating the soil. G is positive when the soil is warming and negative when the soil is cooling. Although the soil heat flux is small compared to R_n and may often be ignored, the amount of energy gained or lost by the soil in this process should theoretically be subtracted or added to R_n when estimating evapotranspiration. G is small compared to R_n, particulary when the surface is covered by vegetation and calculation time steps are 24 hours or longer. For day and ten-day periods, soil heat flux is relatively small, it may be ignored ($G_{day} \sim 0$), but for monthly periods, assuming a constant soil heat capacity of 2.1 MJ m^{-3} °C^{-1} and an appropriate soil depth, G (MJ m^{-2} d^{-1}) can be calculated as follows (Smith, 1993):

$$G_{month,i} = 0.07\,(T_{month,i+1} - T_{month,i-1}) \qquad \text{Eq. 23}$$

where $T_{month,i-1}$ is the mean air temperature (C°) of the previous month and $T_{month,i+1}$ is the mean air temperature of the next month. As stated by Nakamura (1996), the day-time soil heat flux can be estimated using the following equation which includes day-time net radiation (R_n) and vegetation coverage (VC, %):

$$G = (0.174 - 0.00086\,VC)\,R_n \qquad \text{Eq. 24}$$

The standard error of estimation in this equation is 0.46 MJ m^{-2} d^{-1}. Soil heat flux and net radiation can be measured directly with net radiometers and soil heat flux disks.

Δ is the slope of the relationship between saturation vapor pressure and temperature, Kp_a/°C, it had been calculated in (mbar °C^{-1}) according to Bosen's equation as follows:

$$\Delta = 2.00\,(0.00738\,T + 0.8072)^7 - 0.00116 \qquad \text{Eq. 25}$$

It can be also computed as (Allen, 1991):

$$\Delta = 4098\,\frac{e_s}{(T_a + 273.3)^2} \qquad \text{Eq. 26}$$

where e_s is the saturation vapor pressure in KPa and T_a is the air temperature, g is the Psychrometric Constant (KPa/C°), and can be calculated according to James (1988) as:

$$g = \frac{1615\,p_a}{2.49\,(10)^6 - 2.13\,(10)^3\,T_a} \qquad \text{Eq. 27}$$

where p_a is air pressure (mbar), Ta average air temperature (C°). P_a can be calculated as:

$$p_a = 1013 - 0.1152 \left(h\right) + 5.44 \left(10\right)^{-6} h^2 \qquad \text{Eq. 28}$$

g Eq. 29

$$g = \frac{p_a C_p}{e \; LE}$$

where p_a is the air pressure; C_p is the specific heat capacity of air; e is the ratio of the molecular weight of air to water, 0.622 (= 18 g/28.9 g), and LE is the latent heat of vaporization.

In the PM equation (Eq. 19), (e_s - e_a) is the vapor pressure deficit of the air (KP_a), r_a is the mean air density at constant pressure, C_p is the specific heat of the air, r_s and r_a are the surface and aerodynamic resistance.

As there is still a considerable lack of information for different crops, the PM method is used for the estimation of the standard reference crop to determine its evapotranspiration rate. According to Smith et al. (1996) the adaption of fixed values for crop surface resistance and crop height required an adjustment of the concept of reference evapotranspiration which was redefined as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height (12 cm), a fixed crop surface resistance (70 s/m) and albedo (0.23) closely resembling the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and with adequate water”. Thus, the PM equation used for 24-hour calculations of reference evapotranspiration using daily or monthly mean data can be defined as:

$$ET_o = \frac{0.408 \; \Delta \left(R_n - G\right) + g \dfrac{900}{T + 273} U_2 \left(e_s - e_a\right)}{\Delta + g \left(1 + 0.34 \; U_2\right)} \qquad \text{Eq. 30}$$

where, U_2 is wind speed at 2 m height (m/s).

A key element in the development of the PM equation is the assumption of the reference crop as a hypothetical crop with a fixed crop surface resistance value. Many studies on various crops have shown, however, that the crop resistance factor, which represents the stomatal behavior of the crop, is affected by climatic conditions. “The study commissioned by the European Community showed increasing crop resistance values for more southern latitudes and recommended a variable crop surface resistance factor” (Shoisnel et al., 1992). The original recommendation of the FAO expert panel for a universal crop are surface resistance of 70 s/m for a hypothetical grass crop is therefore maintained as a valid and standardized approximation.

FAO-PM equation can be adapted to hourly ET_o calculations, of relevance in detailed research studies and for automatic weather stations, by replacing the conversion factor 900 in the equation by 37 equal to 900/24 (Smith et al., 1996).

2.3.3.5. Evapotranspiration Calculation Using Remote Sensing Tool

“When spatial distribution of evapotranspiration is however difficult to calculate due to low density of meteorological equipments, the knowledge about crop water requirements may be constrained” (Vidal et al., 1999).

The planning of new irrigation schemes and the management of existing projects can benefit from the application of satellite remote sensing (Thiruvengadachari and Conley, 1993; Urso et al., 1996). The study of Caselles (1995) and Vidal and Baqri (1995) was to produce maps of evapotranspiration in real time using NOAA images (National Oceanic and Atmospheric Administration by Advanced Very High Resolution Radiometer, AVHRR), where daily thermal infrared data of NOAA satellite provide an estimation of the actual crop evapotranspiration with a resolution of 1 * 1 km. They could also detect the excess water in the middle infrared band, and thus achieve the better use of the available water.

Caselles (1995) proposed a simplified method for estimating evapotranspiration from maize and barley. The method used surface temperature obtained from thermal responses of satellite sensors. The maximum air temperature and daily net radiation were measured in a meteorological station. The method is based on the relationship suggested by Jackson et al. (1977):

$$ET = R_n + D\,(T_a - T_s) \qquad \text{Eq. 31}$$

where Rn is the daily value of the net radiation expressed in mm of water per day, (T_a – T_s) is the temperature difference between air and crop surface obtained near midday, and D is a semiempirical constant which depends on the climatology and the crop structure through the expression:

$$D = \frac{R_{nd}}{R_{ni}} \quad \frac{r_a\ C_p}{LE\left(r_a + r_c\right)} \qquad \text{Eq. 32}$$

where Rnd/Rni is the mean daily value within a year of the ratio between the daily and midday values of R_n, r_a is the air density, C_p is the specific heat of air at constant pressure, r_a and r_c are the aerodynamic and crop resistance, and LE is the latent heat of vaporization. For operative application the determination of the crop surface temperature from thermal NOAA-AVHRR data is required where an atmospheric correlation method can be used:

$$T_s = T_4 + E\,(T_4 - T_5) + F \qquad \text{Eq. 33}$$

where T_s is the crop surface temperature, T_4 and T_5 are the brightness temperature in the channels 4 and 5 of AVHRR instruments, and E and F can be expressed as:

$$E = 1 + 0.58\,(T_4 - T_5) \qquad \text{Eq. 34}$$

$$F = d + 45\,(1 - \in_4) - b\,\Delta\in \qquad \text{Eq. 35}$$

where $\in_4$ is the emissivity in channel 4, $\Delta\in$ is the emissivity difference between channels 4 and 5, d and b are parameters which decrease with atmospheric water vapor, but can be estimated for each climatic situation. The procedures for measuring $\in_4$ and evaluating $\Delta\in$ are described in Sobrino and Caselles (1993) and Coll et al. (1993), respectively.

"Daily potential evapotranspiration was estimated using daily maximum air temperature derived from the NOAA-AVHRR surface temperature measurements. As solar radiation can be considered uniform on a clear day, it needs only to be measured at one station located in the centre of the area. The resulting hourly evapotranspiration values obtained from PM-FAO equation were then used to calibrate information from 12 NOAA-AVHRR images taken at maximum temperature on clear days" (Vidal et al., 1999). The obtained results showed that the 7 * 7 km resolution is the optimal, where the correlation between local air temperature and average surface temperature is high.

2.3.4. Crop Evapotranspiration under Saline Conditions

As mentioned above, use of saline water is inevitable in the irrigation practice of Egypt. However, this has wide influence on a lot of important parameters.

Crop evapotranspiration can be affected by soil salinity since the soil water uptake by the plant can be drastically reduced due to the higher osmotic potential of the saline groundwater. Reduced water uptake under saline conditions is shown by symptoms similar to those caused by drought (Doorenbos et al., 1984; Katerji et al., 2000).

"The total effect of soil salinization on crop production is determined by the duration of physiological drought conditions (including osmotic pressure), which reduce evapotranspiration" (Willardson, 1997). Wayne et al. (1996) reported that the presence of a saline water table (EC = 16 dS m^{-1}) within the root zone seems to cause about an 18 % decrease in the evapotranspiration (lucerne). The results indicate the need to consider the effect of salinity especially to modify irrigation scheduling. A similar result was obtained by Grattan et al. (1997) and Nassar and Horton (1999). Roest et al. (1993) quantified the effect of soil salinity on evapotranspiration as follows:

$$ET = \frac{\Psi_l - \Psi_s - \Psi_{os}}{r_{pl} + \frac{b}{k_p}} \qquad \text{Eq. 36}$$

where ET = evapotranspiration (mm day^{-1}), Ψ_l = leaf water potential (bar), Ψ_s = mean matrix water potential in root zone (bar), Ψ_{os} = mean osmotic potential in root zone (bar), r_{pl} = crop resistance for water flow (bar*day/mm); b = geometry and activity factor of the root system (bar), k_p = unsaturated permeability of root zone (mm day^{-1}). The osmotic potential in the root zone is a function of the osmotic potential in the soil solution at field capacity and is given by (Roest et al., 1993):

$$\Psi_{os} = \frac{\Theta_{fc}}{\Theta} \Psi_o \qquad \text{Eq. 37}$$

where Ψ_o = osmotic potential at field capacity (bar), Θ_{fc} = water content at field capacity (m^3/m^3), Θ = actual water content in root zone (m^3/m^3).

For drainage water in the Eastern Nile Delta of Egypt, Abdel-Khalek et al. (1984) derived the following relationship:

$$\Psi_o = 0.1409 \left[Cl^- \right]^{0.7903} \qquad \text{Eq. 38}$$

where $\left[Cl^- \right] = Cl^-$ concentration (mol m^{-3}).

2.3.4.1. Crop Production under Saline Water

The principles of salinity control for irrigation with saline water, one of the main aims of the following work, has been described by Sheng and Xiuling (1997) as follows:

1- The salt accumulated in the soil should not exceed the crops salt tolerance limits;

2- The salt added to the soil by irrigation with saline water should be leached by rain or irrigation water so that the long term balance of soil salinity is maintained.

Research results indicate that soil salinity does not reduce crop yield measurably until a threshold level is exceeded. “Beyond the threshold, yield decreases approximately linearly as salinity increases” (Hoffman et al., 1990).

The equation of the crops salt tolerance index can be expressed according to Hoffman et al. (1990) as follows:

$$Y_r = 100 \qquad \text{for} \quad 0 < C < C_t \qquad \text{Eq. 39}$$

$$Y_r = 100 - S \, (C - C_t) \qquad \text{for} \quad C_t < C < C_o \qquad \text{Eq. 40}$$

$Y_r = 0$ for $C > C_o$ Eq. 41

where Y_r = relative yield, C = the average root zone salinity, C_o the level of soil salinity above which the yield is zero, C_t = threshold - the maximum soil salinity without yield reduction, S = slope i.e. the percent yield decrease per unit of salinity above the threshold. According to the results obtained by Franco et al. (1997) for muskmelon the reduction in seedling leaf area can be a good selection criterion to facilitate rapid screening for salt tolerance.

"Groundwater with a salt content of 3.0 to 11.0 dS m^{-1} could be used for a long time in some regions with a dry and warm climate where cotton planted areas were irrigated at germination with fresh water and after that irrigated with so-called saline water" (Dutt et al., 1984). "In the Nile Valley and Delta in Egypt a large area was irrigated successfully for decades using groundwater of 2.0 to 4.0 dS m^{-1}" (Rhoades et al., 1992). The effect of three levels of saline irrigation water (3,000; 6,000 and 9,000 ppm NaCl) on sugarbeet cultivated in Egypt was studied. The results showed that increasing salinity beyond 3,000 ppm decreased the root and sugar yield, but increased the percentage of sugar (El-Hawary et al., 1998).

According to Ayers and Westcot (1985) 90 % of the optimum crop could be obtained (for sugarbeet, sorghum, soybean and bean) using saline irrigation water with somewhat more than 3.0 dS m^{-1}, or somewhat more than 6.0 dS m^{-1} for cotton and barley. "Barley, for example, will not suffer decreases in yield if the electrical conductivity (salt content) of the saturation extract of the soil does not rise above 8.0 dS m^{-1}, or if the maximum salinity of the water leaving the root zone is less than 56 dS m^{-1}" (Willardson et al., 1997).

2.3.4.2. Soil Salinity Control in the Root zone

To prevent salt residues from accumulating during repeated irrigation-evapotranspiration cycles, the obvious remedy is to apply water in an amount greater than evapotranspiration, so as to deliberately cause a significant fraction of applied water to flow through and past the root zone and wash away the excess salt. It is a startling fact that a 1 m depth of even reasonably good-quality irrigation water (a possible amount applied in a single irrigation season) contains sufficient salt to salinate an initially salt-free soil (i.e. about 3 tons salt per hectar). The rule for the salt conditions should be expressed as follows (Xiuling et al., 1988):

$S_o + S_i - S_d \leq C_t$

where S_o = original salt content in the soil before irrigation, S_i = addition of salt to the soil due to irrigation with saline water, S_d = salt leached from soil by rain water or irrigation, and C_t = threshold value of crops salt tolerance.

Much attention has been devoted to the assessment of the optimal quantity of water that must be applied to cause leaching. Clearly, the application of too much water can be as harmfull as the application of too little. Exaggerated leaching not only wastes water but also tends to remove essential nutrients and to impede aeration by waterlogging the soil (Yaron and Thomas, 1968; Frenkel et al., 1978).

The Leaching Requirement concept was developed by the U.S. Salinity Laboratory (Richards, 1954). It has been defined as “the fraction of the irrigation water that must be leached out of the bottom of the root zone in order to prevent average soil salinity from rising above some specifiable limit”. The leaching requirement depends on the salt concentration of the irrigation water, on the amount of water extracted from the soil by the crop (evapotranspiration), and on the salt tolerance of the crop, which determines the maximum allowable concentration of the soil solution in the root zone.

“In particular, the spatial and temporal variation of root zone salinity is affected by the degree to which soil moisture is depleted between irrigation. The less frequent the irrigation regime, the greater the buildup of salt concentration between successive irrigations” (Hillel et al., 1998).

With modern methods of high-frequency irrigation (Rawlins and Raats, 1975; Hillel, 1987, 1996) it is possible to maintain the soil solution in the surface zone at a concentration essentially equal to that of the irrigation water. This zone can be deepened by increasing the volume of water applied. Beyond this zone the salt concentration of the soil solution increases with depth to a salinity level depending on the leaching fraction. Because the effects of matric and osmotic potentials on crop growth are approximately additive, it is doubly important to maintain a higher soil moisture condition (and hence higher levels of both matric and osmotic potentials, i.e. lower suction level) by frequent and sufficient irrigation whenever low-quality or brackish water is used for irrigation. Modern techniques of drip irrigation can help in this regard (Hillel et al., 1998; Aziz et al., 1998).

Irrigation requirements for salinity control can be calculated as (Hillel, 1998, after Richard, 1954):

$$W_{ras} = \left[\frac{D_s}{D_s - I_s} \right] W_{ra} \qquad \text{Eq. 42}$$

where I_s and D_s are the salinity of irrigation and drainage water, respectively.

The next equation was used by Beltrao and Asher (1997) to estimate irrigation water requirement for salinity control (Q_i) in m^3 day^{-1}:

$$Q_i = \frac{C_d}{C_d - C_i} \; A \; ET_a \qquad \text{Eq. 43}$$

where C_i and C_d are respectively, the concentration of irrigation water and drainage water (kg m^{-3}); A is the evaporating surface area (m^2) and ET_a the actual evapotranspiration (mm day^{-1}), therefore the daily volume of drainage water (Q_d, in m^3 day^{-1}) could be calculated as:

$$Q_d = Q_i - (A * ET_a) \qquad \text{Eq. 44}$$

2.3.4.3. Irrigation Methods under Saline Conditions

Sprinkler and drip irrigation are not suited to all qualities of water and all soil conditions, climate or crop. Several important factors should be considered before attempting to improve salinity control by changing the method of irrigation.

"The choice of irrigation method for brackish water irrigation may be guided by three considerations: 1) the distribution of salt and water in the soil under the different irrigation method; 2) crop sensitivity to foliar wetting and the extent of the damage to yield and 3) the ease with which high solute and matric potentials can be maintained in the soil" (Shainberg and Shalhevet, 1984).

Although sprinklers are sometimes used to aid germination and early seedling growth, at which time the crops may be particularly sensitive to salinity, sprinkler-irrigated crops are potentially subject to additional damage caused by foliar salt uptake and desiccation (burn) from spray contact of the foliage (Mass et al., 1982; Hillel, 1987; Beltrao et al., 1993). For example, Bernstein and Francois (1973) found that the yields of bell pepper were reduced by 59 % more when 4.4 dS m^{-1} water was applied by sprinklers compared to a drip system; a similar result for potatoes was found by Meiri (1984). Due to the above mentioned salt contact of the foliage "the threshold salinity is slightly lower with sprinklers, but the rate of yield decline is much steeper (8 % per 1 dS m^{-1}) than with drip (4 % per 1 dS m^{-1})" (Meiri et al., 1982) because of the above-mentioned salt contact of the foliage.

Chhabarra (1996) reported that "with poor quality water, yields may be better with drip irrigation because of the continuous high moisture contents and daily replenishment of water lost by evapotranspiration. With the drip method, salt accumulates both at the soil surface and within the soil at the outside edges of the area wetted by the emitters. With time the salt accumulation at soil surface and in wetted fringe areas between emitters can become appreciable and is a hazard if it is moved by rain into the root zone of the crop. If rainfall is sufficient each season to leach the accumulating salts, no problems are anticipated. Leaching by sprinklers or surface flooding prior to planting has been effective in removing acumulated salts".

Various irrigation systems for producing a range of irrigation water salinity for screening purposes and crop tolerance studies have been developed and they may be classified into three groups as follows (Aragües et al., 1999): a) systems in which fresh and saline waters are mixed in the irrigation line (Pasternak et al., 1986; Aragües et al., 1999); b) systems where fresh and saline waters are mixed in the air using sprinklers: double-line source systems (Frenkel et al., 1990); and c) systems where fresh and saline waters are mixed in the soil: double-emitter source (De Malach et al., 1996).

A new Drip-Injection Irrigation System, DIS, was developed, "which based on the combination of two pumps in parallel: a centrifugel pump for fresh water and an injection pump for saline water. The result showed that I) 0 to 50 cm soil profiles were very uniform both for salinity and water content; and II) the irrigation water salinity (EC_{iw}) and the soil salinity were significantly correlated indicating that the EC_{iw} gradient imposed by the DIS produced a satisfactory EC gradient in the soil" (Aragües et al., 1999).

2.4. Irrigation Scheduling

The irrigation performance can be improved either by means of developing new application systems (drip, sprinkler, etc.) or by a more accurate irrigation scheduling. "For any crop, schedule implies the determination of time and volume of water application to meet a specified management objective. So an irrigation schedule handles two key elements in irrigation: The limiting of irrigation (when to irrigate?) and the amount of irrigation (how much water should be applied?)" (Howel, 1996). These two elements are not independent of each other and are consequently dealt with jointly, by means of a method for scheduling irrigation on the basis of plant water requirement and weather and soil conditions.

Because scheduling is an important element in improving water use efficiency, several new plant and water sensor technologies have direct implications for improving irrigation management. "Methods based on direct measurements of plant water status have always attracted the attention of irrigation research as a tool for irrigation timing, but getting accurate and representative data for these parameters has always been very difficult" (Cremona et al., 2000).

2.4.1. Irrigation Scheduling Using Remote Sensing Tool

Remote sensing data and modelling were implemented by Bootsma et al. (1996) for early drought detection. Also Mogensen et al. (1997) reported that "the relative reflectance index, RRI, as a ratio of the reflectance index of the droughted crop to that of the fully irrigated crop is a sensitive index for determination of early water stress by frequent measurements of reflectance index". Due to the handling simplicity of the infrared thermometers a lot of research was focussed on the use of this sensor for irrigation scheduling.

Crop Water Stress Index (CWSI)

Several indices have been proposed as an aid to irrigation, for example: Stress degree day, SDD (Idso et al., 1977); critical temperature variability, CTV (Blad et al., 1981); or crop water stress index, CWSI, in which the surface temperature is measured with the infrared thermometer (Jackson et al., 1981). The latter technique which allows an estimate of the whole canopy temperature, and can measure the thermal radiation emitted by the crops, integrating the different parts of the plant, is an important tool for irrigation scheduling.

"As transpiring water cools the leaves below the temperature of the surrounding air, when water becomes limiting, stomata close and transpiration is reduced, and the absorbed radiation makes leaf temperature increase" (Jackson, 1982). These facts led to the idea of using leaf temperature as an indicator of plant water stress. Due to accuracy of the infrared thermometer, indices that can express plant water stress were developed (Jackson et al., 1981; Idso et al., 1981).

To make the interpretation using this index easier, Jackson et al. (1981) proposed the following expression:

$$CWSI = 1 - {ET_a}/{ET_o} = \frac{g \left(1 + r_c / r_a\right) - g^*}{\Delta + g \left(1 + r_c / r_a\right)} \qquad \text{Eq. 45}$$

where ET_a/ET_o is the ratio of actual (ET_a) to potential (ET_o) evapotranspiration and g^* can be calculated as:

$$g^{*} = g \quad \left(1 + r_{cp} / r_{a}\right) \qquad \text{Eq. 46}$$

where r_{cp} can be called the canopy resistance at ET_o. Although Yazar et al. (1999) found that the CWSI was useful for evaluating crop water stress in corn and should be a valuable tool to assist irrigation decision making together with soil water measurements. Cremona et al. (2000) stated that "the values of the CWSI during the early stages of the crop growth are relatively uncertain, as temperature measurements are done in conditions of partially soil cover". A similar conclusion was obtained by Moran (1995).

2.4.2. Irrigation Scheduling Options

Irrigation scheduling research priorities are recommended to focus on the evapotranspiration (ET) estimation method, on improved understanding of the spatial variation of ET and irrigation application, on identifying the water balance components in typical irrigated agriculture, and on integrating various sensing technologies into irrigation scheduling models and controls. Irrigation scheduling was defined by Jensen (1981) as: "A planning and decision-making activity that the farm manager or operator of an irrigation farm is involved in before and during most of the growing season for each crop that is grown". He further indicated four types of data needed for irrigation decision making:

1- Current level and expected change in available soil water for each field over the next 5 to 10 days.
2- Current estimates of the probable latest date of the next irrigation on each field to avoid adverse effects of plant water stress.
3- The amount of water that should be applied to each field, which will achieve high irrigation efficiency.
4- Some indication of the adverse effects of irrigation a few days early or late.

For an optimal irrigation the irrigation depth will bring soil moisture content back to field capacity, thus equal to the depleted soil moisture in the root zone. As the depletion in the root zone will normally vary over the growing season with changing root depth and allowable depletion levels, the application doses may vary substantially over the season.

The irrigation scheduling schemes should take into account the soil properties that affect soil moisture-holding capacity. James et al. (1982) reported that "the irrigation scheduling with a soil of low water-holding capacity would have to be more frequent with smaller amounts applied each time for best efficiency".

The crop water requirements, defined as the daily water needs of crops, have been calculated previously from climatic data (ET_o) and crop data (K_c, length of growth stages). They represent the daily uptake of soil moisture from the root zone due to ET of the crop. Smith (1992) classified the scheduling options into two different categories as follows:

a) Timing options - related to WHEN irrigation is to be applied:

1- Each irrigation defined by user; this type is used to evaluate irrigation practices and to simulate any alternative irrigation schedule.
2- Irrigation at critical depletion (100 % depletion of readily available soil moisture). Resulting in minimum irrigations, but irregular and therefore unpractical irrigation intervals.
3- Irrigation below or above critical depletion (% depletion of readily available soil moisture). Useful to set a safety level above critical soil moisture or allow a critical stress level.
4- Irrigation at fixed intervals per stage, suitable in particular in a gravity system with rotational water distribution, may result in some over-irrigation in the initial stages and under-irrigation in the peak season.
5- Irrigation at given ET_c reduction (%).
6- Irrigation at given yield reduction (%).
7- No irrigation, only rainfall.

b) Application options - HOW MUCH water is to be given per irrigation turn:

1- Each irrigation depth defined by user, as determined from field or simulated data.
2- Refill soil to field capacity, to bring soil moisture content back to field capacity, thus equal to the depleted soil moisture in the root zone, as the depletion in the root

zone will normally vary over the growing season with changing root depth and allowable depletion levels.

3- Refill below or above field capacity. Useful to allow for leaching for salinity control (above field capacity) or to accommodate possible rainfall (below field capacity).

The scheduling method that will be suggested in this work is mixed from a/2 (but with other critical depletion values, see Section 5.2.), b/2 and b/3. Generally the parameters described in the following chapters must be considered.

2.4.2.1. Net Crop Water Requirement: Effective Precipitation

To calculate the actual crop water requirement W_{ra}, the effective precipitation (p_{ef}) must be considered. “The effective precipitation depends on a number of variables: Amount, intensity and frequency of rainfall; evaporative demand; terrain characteristics; soil and crop; groundwater location; management practices; etc.” (Kopec et al., 1984). Due to the difficulty of measuring all these variables, some authors recommend the use of empirical equations or to estimate the effective precipitation as a percentage of total precipitation (p_{tot}). In the last case, a value of 80 % is recommended when rainfall depth is below 100 mm/month (Rojas and Rolda'n, 1996). Thus the actual water requirement (W_{ra}) becomes:

$$W_{ra} = ET_c - p_{ef} \qquad \text{Eq. 47}$$

Moon and Van der Gulik (1996) stated that “the effective precipitation is ignored if it is under 5 mm day^{-1} , where this amount is not likely penetrate the soil surface and will be evaporated”, in that case (as in arid region) is $W_{ra} = ET_c$. “The effective rainfall, defined as that part of the precipitation which is effectively used for evapotranspiration by the crop, can be calculated as produced by the USDA Soil Conservation Service” (Smith, 1993):

$$p_{ef} = p_{tot} \frac{(125 - 0.2\ p_{tot})}{125} \qquad for \quad p_{tot} \langle 250\ mm \qquad \text{Eq. 48}$$

$$p_{ef} = 125 + 0.1\ p_{tot} \qquad for \quad p_{tot} \geq 250\ mm \qquad \text{Eq. 49}$$

2.4.2.2. Water Supply Requirements

The supply requirements methods at the field level that are commonly used by many investigators are determined by the depth and interval of irrigation. According to Doorenbos et al. (1986) the required data are primarily determined by

I) the total available soil water ($S_a = S_{fc} - S_{wp}$), where S_{fc} is the soil water content at field capacity and S_{wp} is the soil water content at wilting point,

II) the fraction of the available soil water (p) permitting unrestricted evapotranspiration and/or optimal crop growth, and

III) the rooting depth, Z_r.

The depth of irrigation application (d_i) including application losses is:

$$d_i = \frac{(p \; S_a) \; Z_r}{E_i} \qquad \text{Eq. 50}$$

where E_i is the application efficiency (%). The frequency of irrigation expressed as irrigation intervals of the individual field, i (days), is:

$$i = \frac{(p \; S_a) \; Z_r}{ET_c} \qquad \text{Eq. 51}$$

Since p, Z_r and ET_c will vary over the growing season, the depth in mm and interval of irrigation in days will vary.

Rojas and Rolda'n (1996) in their study on Olive trees, produced the following equation to calculate the daily amount of water to be applied (D_{wd}, liter day^{-1} plant^{-1}):

$$D_{wd} = \frac{D_{cd} \; 10,000}{N_o} \qquad \text{Eq. 52}$$

where D_{cd} is the constant daily depth of irrigation water to be applied (mm day^{-1}) and N_o is the number of trees per hectar.

Particularly for drip systems is to be considered: As the drip system applies water only to the plant's rooting area, the crop factor C_f (see Figure 10) can be used, thereby reducing the area irrigated for some crops: 0.9 for vegetable and 0.7 for berries (Moon and Van der Gulik, 1996).

2.4.2.3. Total Available Soil Moisture Content (TAW) & Effective Root Depth

The total Available Soil Water content (TAW) is defined as the difference in soil moisture content between soil field capacity (f_c) and wilting point (w_p). It represents the ultimate amount of water available to the crop and depends on the texture, structure and organic matter content of the soil. As the water content above field capacity cannot be held against the forces of gravity and will drain and as the water content below wilting point cannot be extracted by plant roots, the total available water in the root zone can be calculated as follows (Hanks and Ashcroft, 1980):

$$TAW = 1000 \left(q_{fc} - q_{wp} \right) Z_r \qquad \text{Eq. 53}$$

where TAW is the total available soil water in the root zone (mm), q_{fc} is the water content at field capacity (m^3/m^3), q_{wp} is the water content at wilting point (m^3/m^3), and Z_r is the root depth (m). TAW is the amount of water that a crop can extract from its root zone, and its magnitude depends on the type of soil and the root depth.

Root depth growth with time can be calculated using the procedure described by Borg and Grimes (1986) and it reads as follows:

$$Z_r = Z_{rm} \left(0.511 + 0.511 \; Sin_{(rad)} \left(3.03 \; \frac{DAP}{DTM} - 1.47 \right) \right) \qquad \text{Eq. 54}$$

where the angle is in radiant, Z_r is the root depth in cm, Z_{rm} is the maximum root depth of the crop in cm, DAP is number of days after planting, and DTM is the number of days to maximum root depth. “The root depth growth rate is 1.2 mm day^{-1}, for grass and 1.5 mm day^{-1} for other crops until maximum effective root depth has been reached” (Plauborg et al., 1996). The maximum effective root depth is determined by both crop and soil type.

2.4.2.4. Readily Available Water (RAW) and Depletion Fraction

As the soil water content decreases, water becomes more strongly bound to the soil matrix and it is more difficult to extract. When the soil water content drops below a threshold value, soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the crop begins to experience stress. The fraction of total available water TAW that a crop can extract from the rootzone without suffering water stress is the Readily Available Water (RAW):

$$RAW = P * TAW \qquad \text{Eq. 55}$$

where P is an average fraction of the total available soil water (TAW) that can be depleted from the root zone before moisture stress (reduction in ET) occurs (p ranges from 0 to 1). The allowable depletion is a function of the evaporation power of the atmosphere where first drought stress occurs affecting evapotranspiration and crop production. At low rates of ET_c , the p values are higher than at higher rates of ET_c. The P values are expressed as a fraction of TAW with lower values taken for sensitive crops with limited root systems under high evaporative conditions, and higher values for deep and densely rooting crops and low evaporation rate (Doorenbos et al., 1986 and George et al., 2000).

2.4.2.5. Soil Water Depletion Fraction and Crop Production

The efficiency of current irrigation design and techniques requires assessment to identify an irrigation system that will minimise deep percolation. “To prevent the development of a shallow water table and subsequent soil salinity and waterlogging, many researchers aimed at developing systems also to minimise the deep percolation” (Tracy et al., 1997).

Curtius and Bohne (1997) found that to prevent the leaching of nitrate excessive irrigation must be avoided and an irrigation adapted to soil properties and plant requirements is necessary.

The results of Zea mays L. showed that the higher water applications that lead to reduced yields were associated with higher N leaching for a given N application amount (Pang et al., 1997).

In Egypt, a study of the water use efficiency for onion, cropped in Mallawi, found that bulb weight produced per unit of water consumed increased from 278.3 kg/cm ET (Evapotranspiration) in the wet treatment (irrigation at 25 % available soil moisture depletion, ASMD) to 316.9 kg/cm ET in the dry treatment, 75 % ASMD (Koriem et al., 1994). Mohamed (1994) studied the effect of soil moisture depletion of 35 %, 60 % or 85 % on water use efficiency for wheat under different soil salinity. He found that the water use efficiency was highest with irrigation at 85 % ASMD under low and medium soil salinity and with irrigation at 60 % ASMD at high soil salinity. Khedr et al. (1996) found that the irrigation at 25 % and 50 % water depletion gave similar yields, which were significantly higher than irrigation at 75 % depletion. WUE water use efficiency was highest with irrigation at 50 % water depletion; similar results were obtained by Gaafar et al. (1993) and El-Koliey et al. (1999).

3. Objectives and Locations Investigated

3.1. Objectives

In most of the arid and semi-arid areas of the world, as also in Egypt, the rainfall is insufficient for the development of crops and a satisfactory yield can not be achieved. Egyptian agriculture is almost entirely dependent on irrigation. The whole population lives of the produce of 5 % of the total land area. The demand for water is generally rising in all fields, whereas the available water resources of the country are limited. Even though Egypt has tried out several measures in order to solve the problem of lack of water (see Sections 2.1.2., 2.1.3. and 2.2.1.), there are still no scientifically tested guidelines for calculating the amount of irrigation water required or for the planning the best irrigation times.

Gowing and Ejieji (2000) have shown that higher earnings and greater efficiency in the use of irrigation water could be achieved by avoiding unnecessary use of irrigation water through precise planning. Vidal et al. (1999) have found that if the exact local water requirements were considered instead of average values, one would be able to save approximately 500 mill. m^3 of water a year on the 600,000 ha area of the middle Nile Delta, which could be used for an increase of 10 % in plant production.

The aim of the present study is to gain a clear picture of how to achieve higher water use efficiency with limited water resources but with no loss in crop yields. In order to achieve this, the application of irrigation water must be regulated and optimized. Research thus deals with the following three points:

1. Selection of areas in the newly developed irrigation regions for the use of mixed water (saline and sweet) from the El-Salam canal (for further information on these regions, see Chapter 4).

2. Evapotranspiration is the most important factor in the water regim of arid regions, and requires proper knowledge of the water demand of plants for optimal irrigation; precise calculation of evapotranspiration with due regard to temporal and locational factors is therefore necessary. The most important target of current research remains

the selection of the most suitable model for the calculation of the reference evapotranspiration, thus enabling successful irrigation planning.

3. Optimization of the irrigation water supply as a means of achieving greater efficiency of water use. There are three ways of effecting this:

a) As evapotranspiration influences the amount of irrigation water, it is necessary to calculate the geographically differentiation in reference evapotranspiration resulting from different climatic conditions (in this case, those of the three research locations). The consideration of these differences permits optimization of the supply of irrigation water. Our concept is based on the idea that plants with low water requirements are to be cultivated in areas with higher reference evapotranspiration (better geographical distribution of areas under specific crops). This enables considerable amounts of water to be saved, which could then be used in other areas. In order to obtain the above-mentioned differentiated determination of reference evapotranspiration, a mathematical model must be selected from literature and validated for the given locations.

b) A own new mathematical operation is developed in order to determine the amount of water required daily; this calculation needs to consider not seasonal fluctuations but daily changes in climatic conditions, soil-water regim (available water range), and plant parameters. Such a model is important for saving water and achieving higher water use efficiency. The model must also be able to maintain the balance between water requirement of plants and the amount of irrigation water supplied. It also has to be able to cope with saline water (Salam canal water) and shallow ground water levels (as at Port Said and El-Arish), in order to protect the soil from degradation (Chhabra, 1996; Willardson, 1997; Aziz et al., 1998). The model is also important for sandy soils (El-Ismailia), where it helps prevent water loss through percolation and the leaching of nutrients (James et al., 1982; Hillel 1987; Curtius and Bohne, 1997; Ayars et al., 1999).

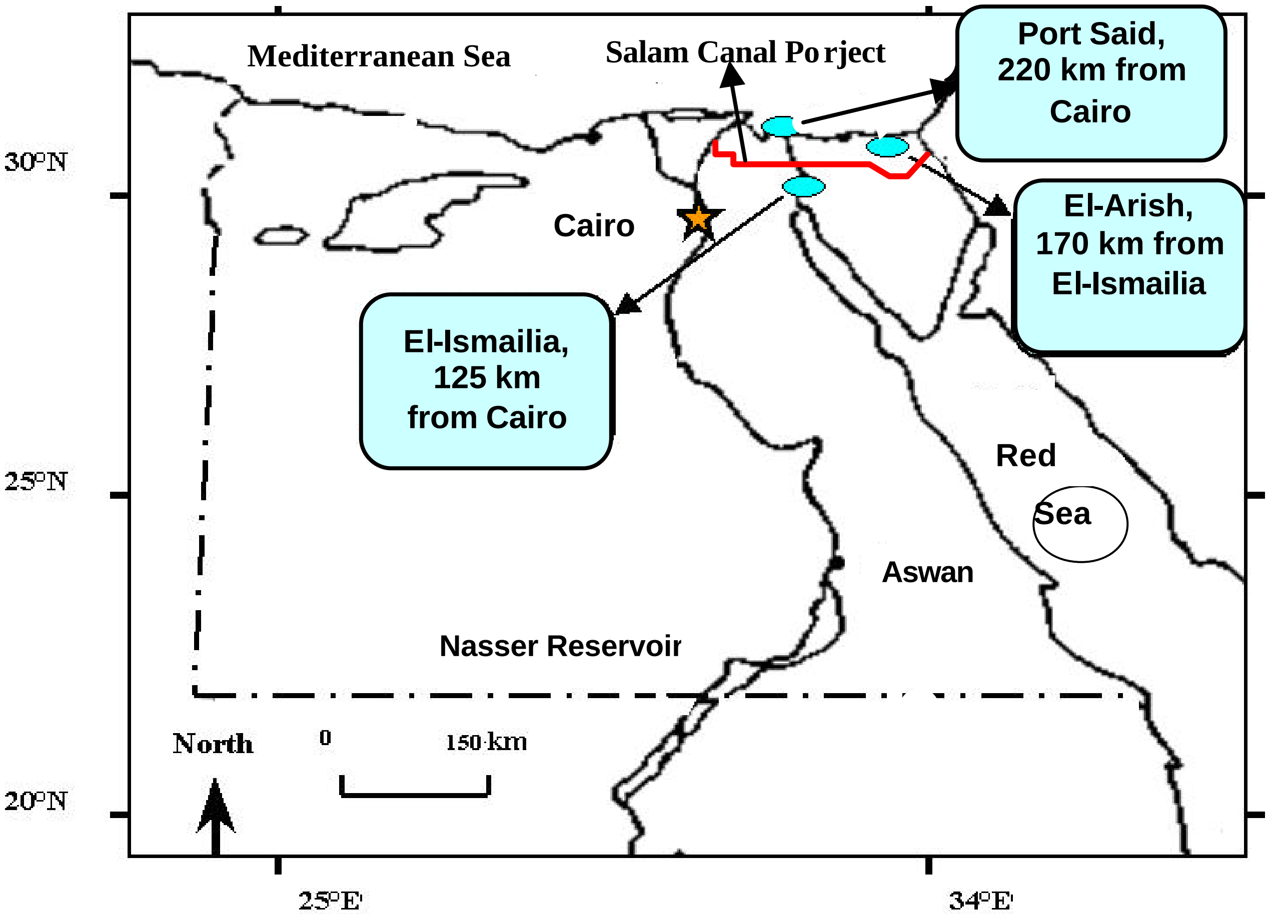
An irrigation method using relatively small amounts of water administered daily leads to a lower loss through evaporation. Such a model, however, can only be realised by means of modern irrigation systems, in particular drip irrigation.

c) The more saline the irrigation water is, the more irrigation water is needed for desalinisation, in order to achieve maximum yield especially with regard to sensitive crops. For this reason, one must check whether the amount of water then required remains an economic proposition in terms of obtained yield. As it is not possible to improve the quality of the water used, we suggest to use the water of given quality optimally at a threshold value for salt content in the root zone, with which one can achieve the highest possible yield with the lowest amount of water. The water saved by means of this procedure can then be used for further areas.

3.2. Locations investigated

Two areas near the Suez Canal (Port Said and Ismailia) and a further one in the north of the Sinai peninsula (El-Arish) were selected for research purposes (see Figure 1). This choice was made above all for the following reasons: All three areas are designated as areas of agricultural expansion, e.g. 150,000 ha in the Port Said area and 275,000 ha east of the Suez canal in the northern Sinai. These areas of expansion are important for Egypt, as previously only 4 % of the country (Abu-Zeid et al., 1997) consisting of only a narrow strip of land near sources of water is available for irrigational agriculture.

The irrigation water for the expansion sites at Port Said and El-Arish comes from the Salam Canal, which carries saline water from drainage systems (Hadus and El-Serw) and Nile water. The electronic conductivity (EC) of the Salam Canal water is between 1.5 dS m^{-1} and 2 dS m^{-1}. This requires careful water use in order to prevent soil degradation. The Port Said region already has some large salt-encrusted areas, partly natural in origin and partly induced by irrigation, and high groundwater levels (HDSSP, 1963). The same applies to El-Arish, where considerable sub-surface areas have groundwater levels of 30 to 70 cm and soil conductivity of over 15 dS m^{-1} (Hammad, 1986). The soils in the El-Ismailia area are mainly sandy with high percolation characteristics, but there are also some hard-pan areas affected by problems of perched water table and salinisation; in some cases problems also occur due to lack of drainage (Ministry of Agriculture, 1985; Goossens et al., 1999).



		Light-texture soils	Medium-texture soils	Heavy-texture soils	Calcareous soils	Saline soils > 4.0 dSm^{-1}
El-Ismailia	common	X				
	medium		X			
	few				X	X
Port Said	common		X			X
	medium			X		
	few	X			X	
Nord-Sinai	common				X	X
	medium	X	X			
	few			X		

Figure 1: Map of the Arab Republic of Egypt showing the research regions, Soils of research sites

Due to all of these factors, the primary targets for the irrigated agriculture in the areas mentioned are the protection of soils from degradation due to salinisation and the raising of crop-yields with a saving in water.

4. Methods of calculating reference evapotranspiration (ET_o)

In order to improve irrigation water management and achieve greater efficiency in water use through improved irrigation planning, improved regional calculations of the evapotranspiration of agricultural crops are required. For the planning of irrigation systems in irrigated agriculture, the decisive factors are the water consumption of plants (plant water requirements) and the amount of water required according to these calculations. The water requirement of crops comprises the water resulting from plant transpiration, the water stored in plant tissue, and the water released from plant surfaces due to interception and soil by evaporation.

The water consumption thus defined is termed evapotranspiration. The processes of evaporation and transpiration occur simultaneously and there is no simple method for distinguishing these processes. Transpiration and evaporation depend on the amount of heat energy available, the vapour-pressure gradient, the influence of wind, and the amount of soil water available to plants in the root zone. When the evapotranspiration of a reference area does not take place under water shortage conditions, one speaks of “reference evapotranspiration” – ET_o. The reference area is defined as a grassy area possessing certain characteristics. The concept of reference evapotranspiration was introduced in order to define the effects of atmospheric evaporation regardless of the type of plant, its developmental stage, or managements of cultivation. The factors influencing reference evapotranspiration are thus purely climatic. In comparison with the reference evapotranspiration, the actual evapotranspiration is dependent on the matric tension of the soil water, leaf mass, and the developmental stage of the plants. The effect of the climate on the amount of water required by plants is thereby defined by the reference evapotranspiration (ET_o), the effect of the plants by the crop coefficent (K_c). This crop coefficent is the quotient resulting from the reference evapotranspiration (a reference area planted with alfalfa or grass) divided by the actual evapotranspiration.

4.1. Calculation of ET_o for the locations investigated

According to the evaluation of the different ET_o-equations (Section 2.3.3.4.) the PM-equation was chosen for the further treatment of the questions stated, in order to calculate the effect of the climate on the water demand of plants (Eq. 30):

$$ET_o = \frac{0{,}408\ \Delta\ (R_n - G) + g\ \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + g\ (1 + 0{,}34\ U_2)}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n the net radiation (MJ m^{-2} day^{-1}), G the soil heat flux (MJ m^{-2} day^{-1}), T the daily average temperature at 2 m height (°C), e_s the saturated vapour pressure (KPa), e_a the actual vapour pressure (KPa $°C^{-1}$), ? the slope of the vapour pressure curve (KPa), U the wind velocity at a height of 2 m, and γ the psychrometer constant (KPa $°C^{-1}$). This equation derives from the original Penman-Monteith equation (Eq. 19) and equations for aerodynamic resistance and surface resistance (Eq. 17 and 18) for a grass-covered reference area. The Penman-Monteith equation was developed for a hypothetical reference crop with an assumed height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0,23, which simulates evaporation from an extensive surface of grass cover of uniform height, active growth, and an adequate supply of water.

The FAO-Penman-Monteith method uses standard climatic data that can be easily collected or derived from conventional sources. The method of calculating individual components on the basis of available weather-data is shown in Section 2.3.3.4.

The climatic data for the research area of El-Ismailia (20 m above sea level, 30,35°N, 30,26°E), Port Said (6 m above sea level, 31,17°N, 32,18°E) and El-Arish (10 m above sea level, 31,07°N, 33,45° E) were obtained from several different sources (see Table 2a-c). The data in Table 2a-c is a monthly average from January to December of air temperature (calculated from the minima and maxima), relative humidity, wind velocity, global radiation and hours of sunshine. Sections 4.1.1 to 4.1.6 below deal separately with the parameters involved in the Penman-Monteith equation.

Table 2a: Climate data for three research locations

Station: El-Ismailia, Altitude: 20 meters above M.S.L,
Latitude: 30, 35 °North, Longitude: 30 , 26 °East

Month	Average temperature, °C [1]	Average relative humidity,% [1]	Wind Speed, m/s [1]	Mean daily max. sunshine, Hours [2]	Mean daily actual sunshine, Hours, [1]	Extraterrestrial radiation, mm day^{-1} [3]
Jan.	13.4	63.0	1.60	10.40	7.10	8.72
Feb.	14.3	66.0	1.81	11.10	7.80	10.62
March	16.8	48.0	2.09	12.00	8.40	13.05
Apr.	20.8	42.0	1.90	12.90	9.50	15.16
May	23.6	44.0	1.70	13.60	10.50	16.50
June	27.25	47.0	1.40	14.00	11.90	17.00
July	27.9	56.0	1.70	13.90	11.60	16.80
Aug.	28.05	58.0	1.60	13.20	11.10	15.68
Sept.	25.9	55.0	1.40	12.40	10.30	13.85
Oct.	23.3	61.0	1.40	11.50	9.20	11.53
Nov.	19.2	64.0	1.20	10.60	8.00	9.42
Dec.	15.2	64.0	1.40	10.20	6.80	8.22

1 Smith, 1993
2 Table 3
3 Doorenbos et al., 1986

Table 2b:

Station: Port Said, Altitude: 6 meters above M.S.L.,
Latitude: 31, 17 °North, Longitude: 32, 18 °East

Month	Average temperature, °C [1]	Average relative humidity,% [1]	Wind Speed, m/s [1]	Mean daily max. sunshine, Hours [2]	Mean daily actual sunshine, Hours, [1]	Extraterrestrial radiation, mm day^{-1} [3]
Jan.	14.70	73.00	3.19	10.34	7.20	8.50
Feb.	15.30	69.00	3.60	11.10	7.50	10.40
March	16.80	67.00	3.80	12.00	8.20	12.92
Apr.	19.60	68.00	3.30	12.90	9.20	15.08
May	22.50	70.00	2.80	13.67	10.10	16.50
June	25.40	71.00	2.60	14.10	11.60	17.00
July	27.20	72.00	2.40	13.97	11.30	16.80
Aug.	27.80	72.00	1.90	13.26	11.10	15.64
Sept.	26.40	69.00	2.20	12.40	10.20	13.72
Oct.	24.50	68.00	3.60	11.50	9.30	11.36
Nov.	21.30	71.00	3.00	10.54	7.90	9.20
Dec.	16.60	74.00	3.30	10.12	6.40	8.00

1 Smith, 1993
2 Table 3
3 Doorenbos et al., 1986

Table 2c:
Station: El-Arish, Altitude: 10 meters above M.S.L,
Latitude: 31, 07 °North, Longitude: 33, 45 °East

Month	Average temperature, °C [1]	Average relative humidity,% [1]	Wind Speed, m/s [3]	Mean daily max. sunshine, Hours [4]	Mean daily actual sunshine, Hours [5]	Extraterrestrial radiation, mm day^{-1} [6]
Jan.	13.00	70.00	4.18 *	10.34	7.00	8.55
Feb.	13.40	69.00	5.30	11.10	7.70	10.45
March	15.30	67.00	4.18 *	12.00	8.60	12.95
Apr.	18.90	67.00	4.18 *	12.90	9.60	15.10
May	21.10	68.00	4.18 *	13.67	10.60	16.50
June	24.10	74.00	4.18 *	14.10	11.90	17.00
July	26.00	74.00	4.18 *	13.97	11.60	16.80
Aug.	26.20	75.00	4.18 *	13.26	11.30	15.65
Sept.	24.80	71.00	4.18 *	12.40	10.30	13.75
Oct.	22.60	73.00	4.18 *	11.50	9.30	11.40
Nov.	18.40	71.00	3.06	10.54	8.00	9.25
Dec.	14.40	66.00	4.18 *	10.12	6.60	8.05

1 El-Ismailia-Wetter-Station
2 Mostafa , 1992
3 Max. and Min. value, Shawky and Sallam, 1996
* Estimated mean of maxi. and mini. values
4 Table 3
5 Smith, 1993
6 Doorenbos et al., 1986

4.1.1. Radiation

The process of evapotranspiration is controlled by the amount of energy available to evaporate water. The potential amount of radiation that can reach the evaporating surface is defined by its location and the time of year. Not all the available radiation energy is used for the evaporation of water. Part of the solar energy is used to warm the atmosphere and the soil.

Extraterrestrial radiation (R_a) is the solar radiation that reaches the earth's atmosphere. It is a function of geographical latitude, time of year and time of day. As it enters the atmosphere, part of the radiation is spread, reflected or absorbed by gasses, clouds or dust. The amount of radiation that reaches the surface, calculated in horizontal projection, is termed solar radiation (R_s). On a cloudless day, R_s is approx. 75 % of R_a. On a very cloudy day R_s is approx. 25 % of Ra. The solar radiation Rs is also known as short-wave radiation, because the sun emits energy in the form of electromagnetic waves of short wave-length. R_s can be calculated with the aid of an equation which relates solar radiation to extraterrestrial radiation (R_a) and to the relative duration of sunshine (Doorenbos and Pruitt, 1977) (Eq. 22, Section 2.3.3.4.):

$$R_s = (0.25 + 0.5\ n/N)\ R_a$$

where n/N is the relative duration of sunshine as against the amount of cloud-cover and the relationship between the current duration of sunshine (n) and the maximum possible duration of sunshine (N). For the calculation showed in Figure 2 the maximum possible duration of sunshine (N) is extracted from Table 3 (Doorenbos and Pruitt, 1975) for the corresponding geographical latitude.

Table 3: Maximam daily Sunshine hours along the year (Doorenbos und Pruitt, 1975)

Northern latitudes	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Southern latitudes	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dez.**	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48°	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46°	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44°	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42°	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.9	11.1	9.8	9.1
40°	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35°	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30°	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25°	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20°	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15°	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10°	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5°	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Net radiation (R_n) is the difference between incoming short-wave radiation and reflected long-wave radiation. R_n is positive in the daytime and negative at night. The total diurnal value is mostly positive. Daily net radiation (expressed as MJ m^{-2} day^{-1} or in mm day^{-1}, because 2.45 MJ m^{-2} day^{-1} represents evaporation of 1 liter m^{-2} day^{-1}) is necessary to calculate evapotranspiration. R_n-data are not generally available, but can be derived from R_s and R_a following Doorenbos and Pruitt (1977) (see Eq. 20, Section 2.3.3.4.) as follows:

$$R_n = 0.75\ R_s - 2.0\ (10^{-9})\ (T_a + 273.16)^4\ (0.34 - 0.044 \sqrt{e_s})\ (-\ 0.35 + 1.8\ R_s/R_a)$$

4.1.2. Soil heat flux (G)

Soil heat flux (G) is the energy needed to warm the soil. If one assumes a constant soil heat capacity of 2,1 MJ m^{-3} °C, the monthly value of G can be calculated (Eq. 23, Section 2.3.3.4.) as:

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

where $T_{month\ i-1}$ equals the average air temperature of the previous month and $T_{month\ i+1}$ the average air temperature of the month that follows. When the soil warms, G is positive. The amount of energy needed for this is deducted from R_n when calculating evapotranspiration.

4.1.3. Temperature (T)

The warmth of the surrounding air transports energy to the plants and thus exerts some degree of control over the evapotranspiration rate. In order to calculate this loss, one needs the daily maximum and minimum temperatures (°C), or – as available for the present study – as monthly averages. Where only mean daily temperatures are used, a lower difference between the saturated and the actual vapour pressure will probably be evident; because the saturated vapour pressure calculated (e_s) is then lower. It is thus likely that ET_o will be underestimated owing to the non-linearity of the saturation vapour pressure/temperature relationship (Allen et al., 1998). The mean of T (T_{mean}) for a given month is defined as the mean of the average monthly temperature maxima (T_{max}) and the average monthly temperature minima (T_{min}). T_{mean} is calculated in the present study according to the following formula:

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \qquad \text{Eq. 56}$$

The rise in the saturation vapour pressure curve (Δ) can be calculated according to Allen et al. (1991) (Eq. 26, Section 2.3.3.4.):

$$? = 4098 [e_s / (T_a + 237.3)^2]$$

The values for (Δ) are listed in Table 4 and are transferred directly into the calculation program. The saturation vapour pressure e_s (KPa) was calculated as:

$$e_s = 0.6108 \exp [17.27 T_a / (T_a + 237.3)] \qquad \text{Eq. 57}$$

where T_a is the air temperature (°C). The values for the saturation vapour pressure as a function of the air temperature were calculated (see Table 5) and inserted as a numerical value into the calculation. The actual vapour pressure e_a can be derived from the relative humidity (RH) and the saturated vapour pressure:

$$e_a = e_s * RH /100 \qquad \text{Eq. 58}$$

4.1.4. Air Humidity (RH)

Whereas the energy supplied by the sun and the atmosphere is the main driving force behind the evaporation of water, it is the difference between vapour pressure at the evapotranspirating surface and in surrounding air that determines the release of the vapour. Higher humidity thus reduces the rate of evapotranspiration, which can therefore be lower in humid areas than in arid areas. The air humidity can be expressed in vapor pressure; in temperature at the dewpoint; or in relative humidity. Relative humidity (RH) expresses the level of vapour saturation in the air as the relationship between actual and saturated vapour pressure and that obtaining at a given temperature:

$$RH = 100\, e_a/e_s$$

The average RH values used during calculation in the present study are listed in Table 2a-c.

4.1.5. Air pressure (P_a)

Atmospheric air pressure (P_a) corresponds to the weight of the earth's atmosphere. The evaporation rate rises with increased altitude and lower atmospheric pressure.

Table 4: Slope of vapour pressure curve, D, for different temperatures, Ta

Ta, °C	D, KPa/°C	Ta, °C	D, KPa/°C	Ta, °C	D, KPa/°C	Ta, °C	D, KPa/°C
1.0	0.047	10.0	0.082	19.0	0.137	28.0	0.220
1.5	0.049	10.5	0.085	19.5	0.141	28.5	0.226
2.0	0.050	11.0	0.087	20.0	0.145	29.0	0.231
2.5	0.052	11.5	0.090	20.5	0.149	29.5	0.237
3.0	0.054	12.0	0.092	21.0	0.153	30.0	0.243
3.5	0.055	12.5	0.095	21.5	0.157	30.5	0.249
4.0	0.057	13.0	0.098	22.0	0.161	31.0	0.256
4.5	0.059	13.5	0.101	22.5	0.165	31.5	0.262
5.0	0.061	14.0	0.104	23.0	0.170	32.0	0.269
5.5	0.063	14.5	0.107	23.5	0.174	32.5	0.275
6.0	0.065	15.0	0.110	24.0	0.179	33.0	0.282
6.5	0.067	15.5	0.113	24.5	0.184	33.5	0.289
7.0	0.069	16.0	0.116	25.0	0.189	34.0	0.296
7.5	0.071	16.5	0.119	25.5	0.194	34.5	0.303
8.0	0.073	17.0	0.123	26.0	0.199	35.0	0.311
8.5	0.075	17.5	0.126	26.5	0.204	35.5	0.318
9.0	0.078	18.0	0.130	27.0	0.209	36.0	0.326
9.5	0.080	18.5	0.133	27.5	0.215	36.5	0.334

Table 5: Saturation vapour pressure, KPa, at different Temperatures, °C

Temperature C°	Saturation VapourPressure, KPa	Temperature C°	Saturation Vapour Pressure KPa
0	0.61	20	2.34
1	0.66	21	2.49
2	0.71	22	2.64
3	0.76	23	2.81
4	0.81	24	2.98
5	0.87	25	3.17
6	0.94	26	3.36
7	1.00	27	3.57
8	1.07	28	3.78
9	1.15	29	4.01
10	1.23	30	4.24
11	1.31	31	4.49
12	1.40	32	4.76
13	1.50	33	5.03
14	1.61	34	5.32
15	1.70	35	5.62
16	1.82	36	5.94
17	1.94	37	6.28
18	2.06	38	6.63
19	2.20	39	6.99

This is shown in the psychrometer constant γ (James et al., 1988) (Eq. 27, Section 2.3.3.4.):

$$\gamma = [\, 1615\, p_a / (\, 2.49\, (10)^6 - 2.13\, (10)^3\, T_a\,)$$

Here T_a is the mean air temperature in °C and p_a the air pressure (mbar). p_a can be derived as (Eq. 28, Section 2.3.3.4.):

$$p_a = 1013 - 0.1152\, (\, h\,) + 5.44\, (10^{-6})\, h^2$$

with h the height above sea level (m). The psychrometer constant γ is a function of altitude above sea level and air temperature.

4.1.6. Wind velocity (U)

The transportation of vapour relies to a great extent on wind velocity and turbulence, which can cause excessive amounts of air to be brought to the evaporating surface. If this air (saturated above the evaporation surface) is not continuously replaced with drier air, the driving gradient for vapour transportation decreases along with the rate of evapotranspiration.

Surface friction at ground level slows down wind velocity. The movement of air is slowest at the surface, and increases with height above ground level. This is why a-nemometers are placed at standardised heights – e.g. at 10 m above the ground in meteorology or 2-3 m in agricultural meteorology. For calculating the evapotranspirati-on in the present study, data of anemometers placed at 2 m above ground level are necessary. The corresponding values from the research locations are listed in Table 2a-c.

4.2. Description of the Calculation Process for Reference Evapotranspiration and Irrigation Water Requirement

The Penman-Monteith equation determines evapotranspiration for the reference plant and produces a standard against which evapotranspiration can be compared in different seasons and regions and to which the evapotranspiration of other crops can be correlated. ET_o can be calculated according to the method in Figure 2, on the basis of the following components: net radiation, wind velocity, psychrometer constant, soil heat flux, actual vapour pressure, slope of vapour pressure curve.

a) Net radiation. This was calculated from the solar radiation, Eq. 20 (which in turn was deduced from the mean daily hours of sunshine, Table 2a-c, the mean maximum hours of sunshine daily, Table 3, and the extraterrestrial radiation, Table 2a-c), from the average monthly temperature (Table 2a-c), and from the square root of the vapour saturation pressure. The net radiation was converted with the help of factors 0.408 from mm day^{-1} to MJ m^{-2}, this being the unit normally used in the Penman-Monteith equation.

b) Wind velocity, measured at a height of 2 metres (Table 2a-c).

c) The psychrometer constant was calculated from the air pressure, altitude and mean monthly temperature (Eq. 27, Eq. 28).

d) The soil heat flux was calculated from the mean monthly temperature in the previous month and the following month respectively (Eq. 23). In the Penman-Monteith equation the soil heat flux energy is to be subtracted from the net radiation.

e) The actual vapour pressure was calculated from the relative humidity and the saturated vapour pressure (RH = 100 e_a/e_s).

f) The slope of the vapour pressure curve was calculated on the basis of the saturated vapour pressure and the mean monthly temperature (Table 4).

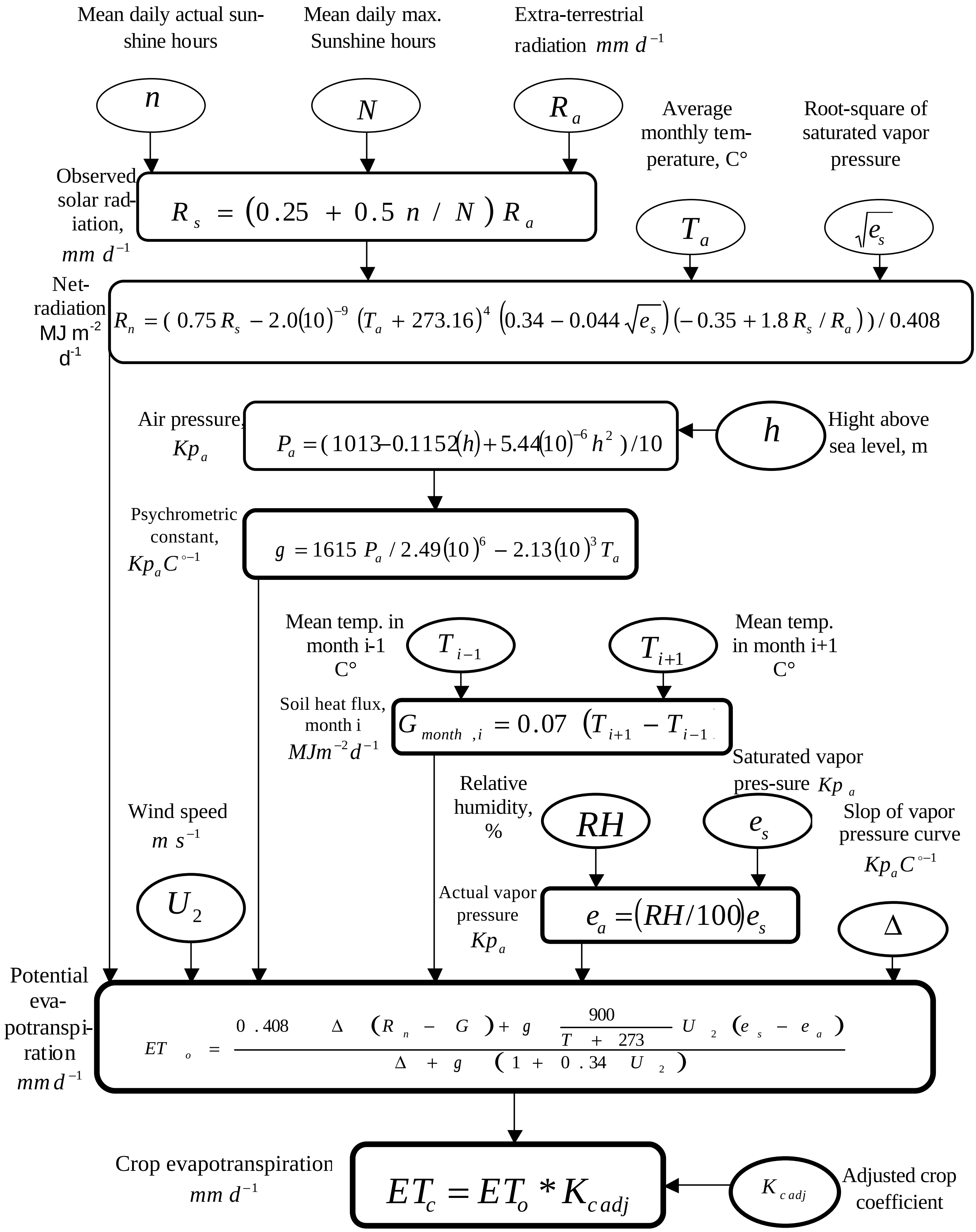


Figure 2: Calculation of reference evapotranspiration ET_o and plant water consumption ET_c, in mm day^{-1}

The calculation of ET_o was undertaken using Equation 30 (Section 2.3.3.4.), with the above components (a – f). This process can be carried out by hand with the help of the calculation sequence shown in Figure 2 or with a computer program. Therefore in the present study, a program using the programming language C++ was developed, into which all the climatic data needed for the Penman-Montieth equation can be fed. The result was a „plate form model" for the ET_o computation. This model is available as a software package and can be installed on a PC.

4.2.1. Comparison of evapotranspiration models

The reference evaporotranspiration over the year was determined for the three research sites using the model for calculating reference evapotranspiration. The model itself was compared to the results obtained by Shawky and Sallam (1996) from calculations using various other evaporation models. These contain results from 15 different calculation methods for reference evapotranspiration (excluding the Penman-Monteith equation) and for eight different Egyptian locations, including El-Ismailia and El-Arish. Shawky and Sallam were able to show, on the basis of field measurements of actual evapotranspiration, that no single method, in their view, was able to establish correctly the reference evapotranspiration over the course of the whole vegetation cycle. Conversely, the annual ET_o lines determined solely by the present model showed only a slight deviation from the mean values established by Shawky and Sallam on the basis of the fifteen calculation methods employed (see Table 6 and Figures 3 and 4).

The agreement between the minimum and maximum ET_o values of El-Ismailia and El-Arish on one side and Shawky and Salam on the other side was high. Moreover, there was also a high degree of correspondence with the values of CLIMWAT (FAO-climate data, Smith, 1993) (Figures 3 and 5). This shows that the present model is suitable for calculating the ET_o over the year, perhaps most of all near the coast (Port Said). This means that this model is well suited to irrigation planning, especially for irrigation in the El-Arish district, where such planning is still lacking.

Table 6: ET_o-Model-values in comparsion to CLIMWAT-values and Shawky and Sallam values

Month	El-Ismailia			Port Said		El-Arish	
	Model-values	CLIMWAT-values	Shawky & Sallam	Model-values	CLIMWAT-values	Model-values	Shawky & Sallam
Jan.	3.68	2.19		2.37	2.26	2.5	2.34 min.
Feb.	4.12	2.79		3.0	2.93	3.04	
Mrch	4.17	4.22		3.8	3.76	3.69	
April	5.48	5.44		4.55	4.49	4.72	
May	6.2	6.03		5.23	5.14	5.42	
June	6.97	6.57	7.73 max.	6.04	5.88	5.84	6.58 max.
July	6.89	6.63		6.17	5.96	6.15	6.58 max.
Aug.	6.49	6.14		5.94	5.59	5.9	
Sep.	5.54	5.04		5.34	4.89	5.42	
Oct.	4.24	3.81		4.82	4.4	4.31	
Nov.	2.96	2.49		3.43	2.98	3.15	
Dec.	2.25	2.03	2.06 min.	2.44	2.24	2.82	

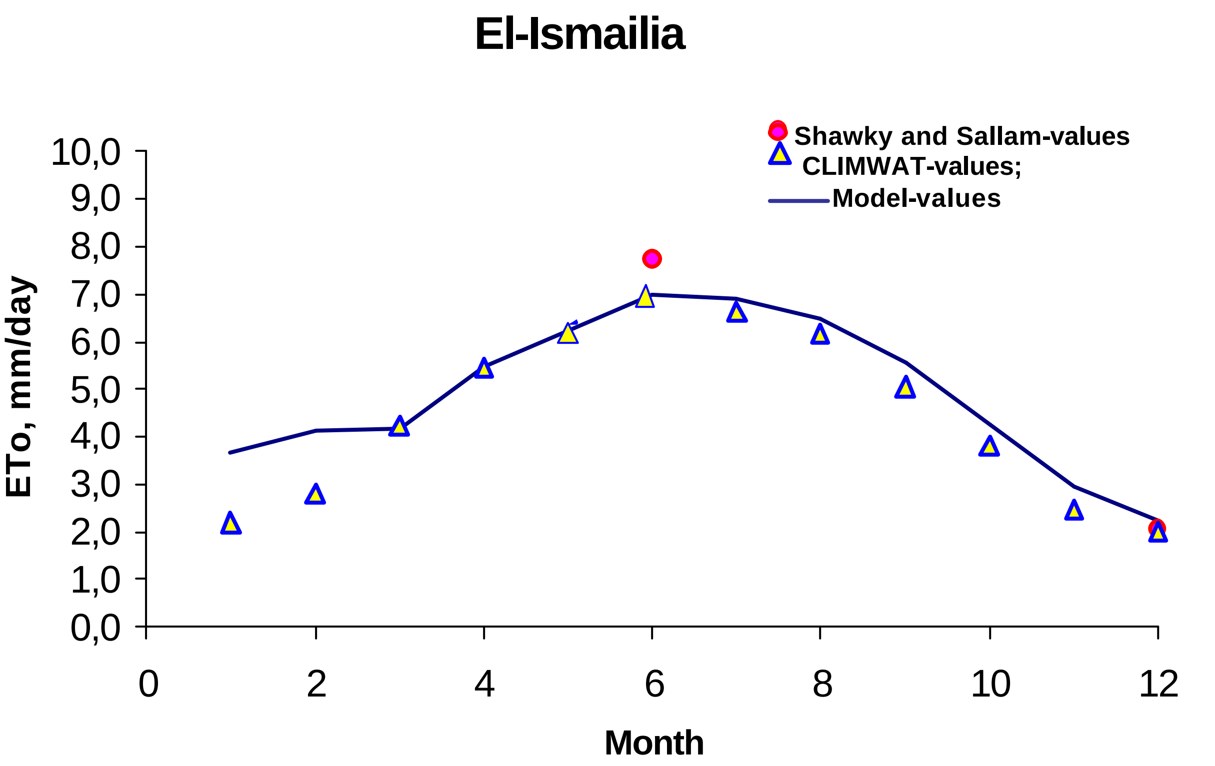


Figure 3: Comparsion between ET_o-modell-values and the values of CLIMWAT and Shawky and Sallam (1996) for El-Ismailia. The correlation coefficient (r) between the model-values and CLIMWAT-values was: r = 0.966

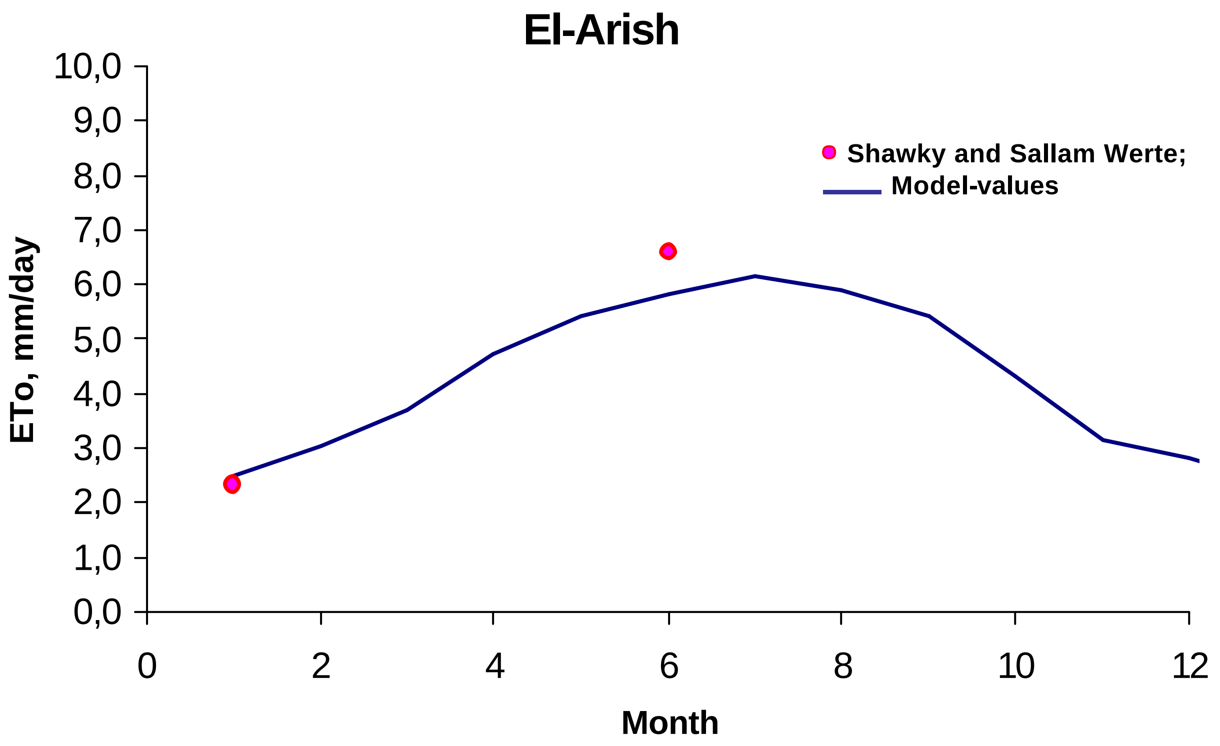


Figure 4: Comparsion between ET_o-modell-values and the values of Shawky and Sallam (1996) for El-Arish

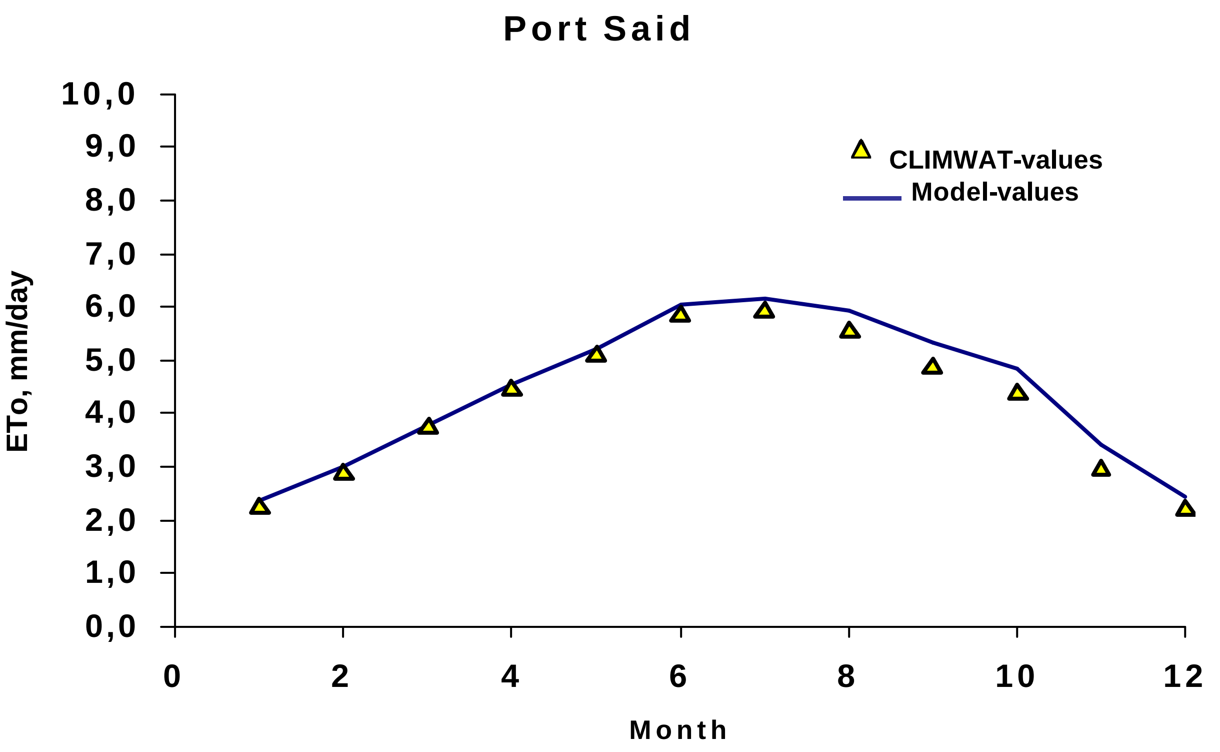


Figure. 5: Comparsion between ET_o-modell-values and the values of CLIMWAT for Port Said. The correlation coefficient (r) between the model-values and CLIMWAT-values was: r = 0.995

4.2.2. Calculation of irrigation water requirements (calculation and results)

Calculation of the irrigation water requirement for the research locations followed the procedure described in Figure 6.

1. First of all, the climatic data for the three stations – Port Said, El-Ismailia and El-Arish – were compiled (Table 2a-c): mean monthly value for temperature, relative humidity, wind velocity, actual hours of sunshine, maximum possible hours of sunshine, radiation.

2. For each research location, the reference evapotranspiration was calculated by the method shown in Figure 2 using equations 4, 20, 22, 26, 27 and 30 (Sections 2.3.2. and 2.3.3.4.), and climatic data in Table 2a-c. These calculations were carried out with a model (see Figure 7a-b) developed using the programming language Visual C++ (Jens and Jörg; 1996, Willms, 1998). In this model the data can be entered in a comparatively simple way. The resulting ET_o values are listed by district in Table 7 in mm $year^{-1}$ or m^3 ha^{-1} $year^{-1}$. The Table and the relevant Figure 8 show the considerable differences of more that 1,700 m^3 ha^{-1} $year^{-1}$ between El-Ismailia and the other two locations.

3. Calculation of the irrigation water requirements was carried out for five commercially important crops, namely maize, peanut, sunflower, soybean and cotton. Only summer crops were selected, as for other crops no precipitation data were available from the research locations. On the average over many years, there is no precipitation during the summer months in question. Restriction to summer crops meant that the natural precipitation in the model could be set at zero.

4. The plant water consumption (crop evapotranspiration ET_c) was calculated for each crop according to Equation 4 (Section 2.3.2.). As the standardised crop coefficients (K_c values) of the FAO (Table 8) are valid only for semi-humid conditions (RH_{min} ~ 45 % and wind velocity 2 m/s), the crop coefficient must be adjusted as recommended by ASCE (1996); Neale et al. (1996) and Allen et al. (1998). Equations 9 and 10 were used for this purpose. Here the minimum relative humidity was calculated with the equation $RH_{min.} = e_s(T_{min.}) / e_s(T_{max.})*100$, in which $e_s(T_{min.})$ and $e_s(T_{max.})$ represent the saturated vapour pressure at minimum and maximum air temperature.

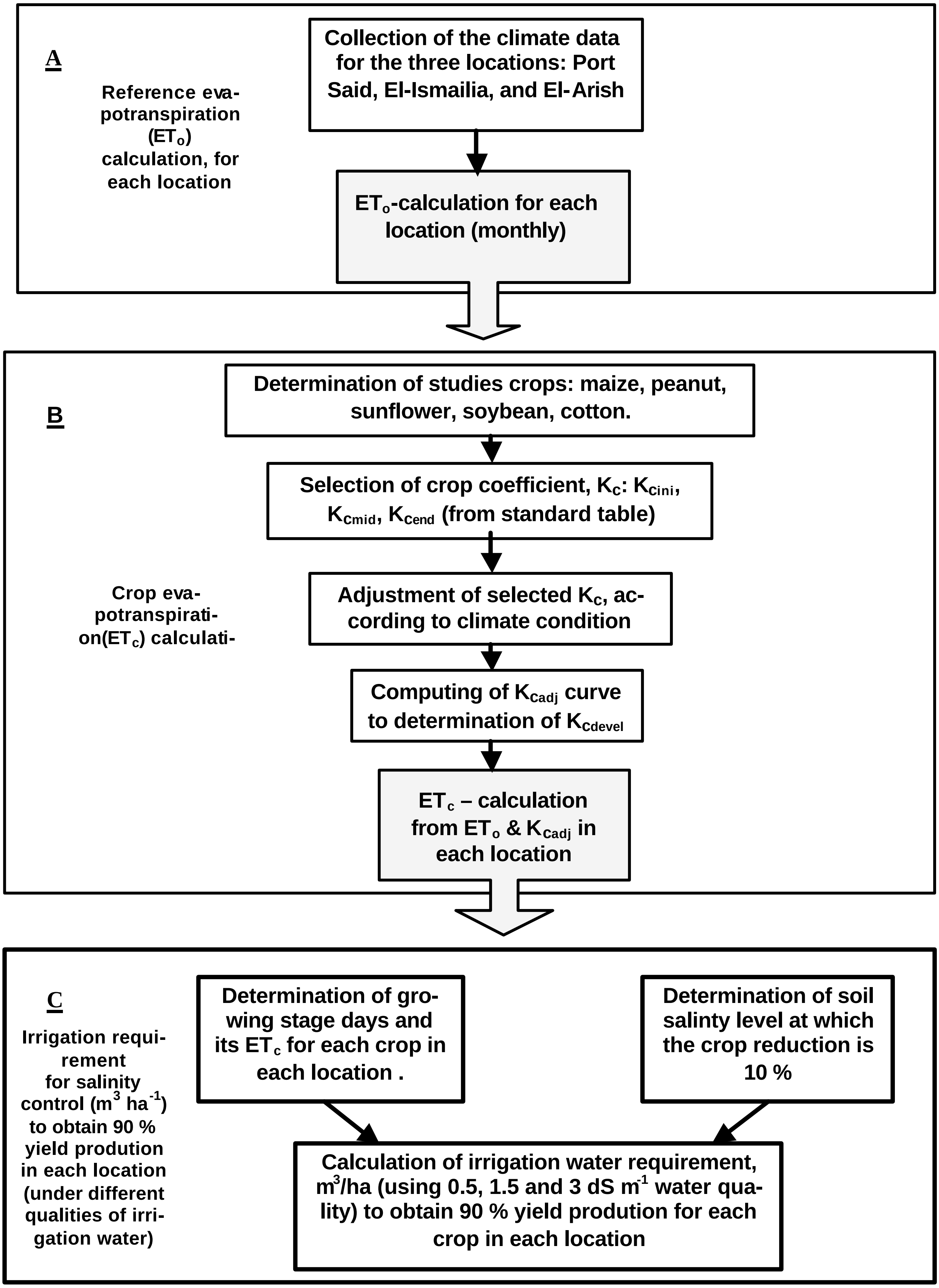


Figure 6: Process schema of the method of calculating the irrigation water demand

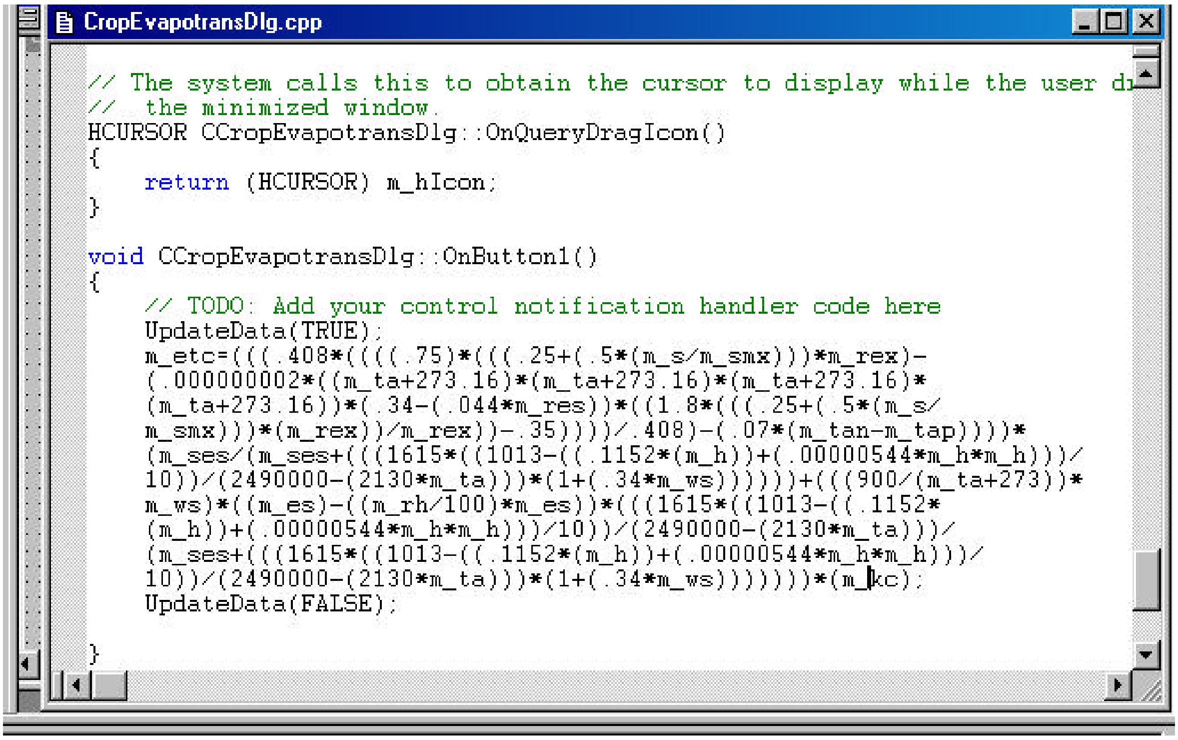


Figure 7a: Program-Code for calculating crop evapotranspiration (in mm/d) according to the process in Figure 2, by Visual C++ programm language

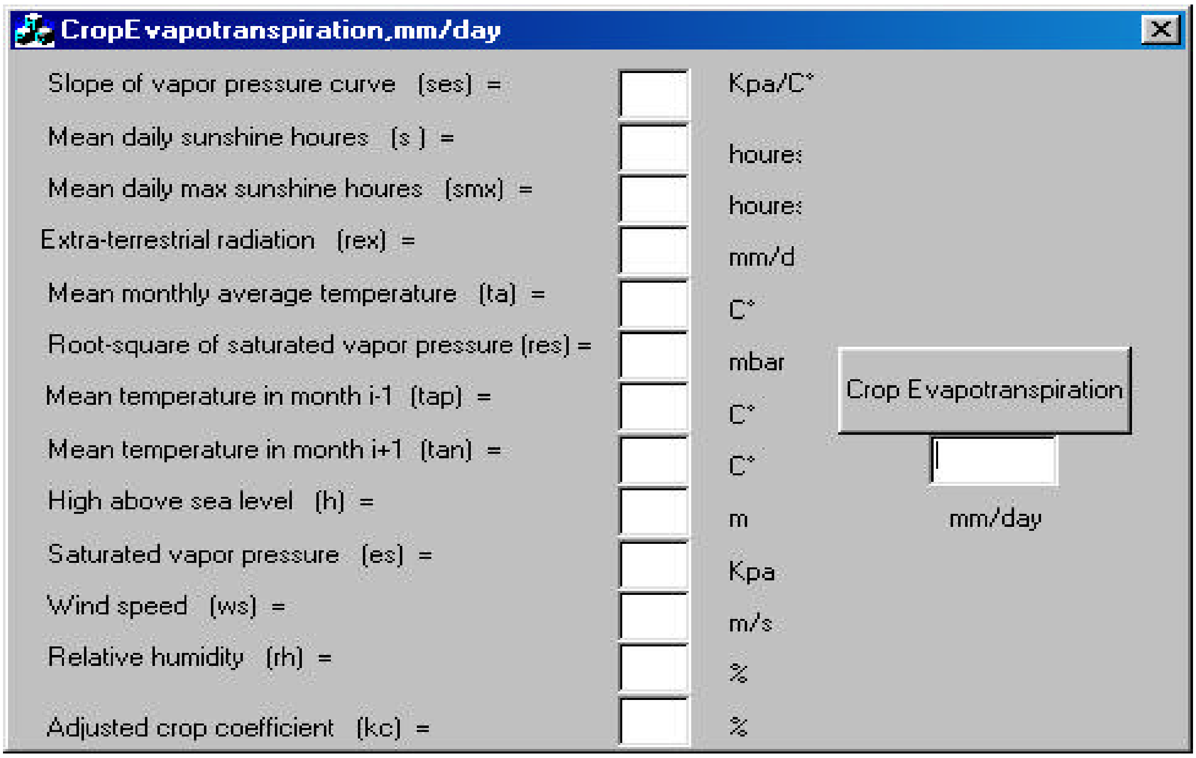


Figure7b: Program-Execute for calculating plant water requirement in mm day^{-1}. When K_c equal 1, reference evapotranspiration will be calculated instead of crop-evapotranspiration

Table 7: Reference evapotranspiration (ET_o) for the three study areas

Months	Reference-Evapotranspiration (ET_o), mm day^{-1}		
	El-Ismailia	**Port Said**	**El-Arish**
Jan	3.68	2.37	2.50
Feb	4.12	3.00	3.04
March	4.17	3.80	3.69
Apr	5.48	4.55	4.72
May	6.20	5.23	5.42
June	6.97	6.04	5.84
July	6.89	6.17	6.15
Aug	6.49	5.94	5.90
Sep	5.54	5.34	5.42
Oct	4.24	4.82	4.31
Nov	2.96	3.43	3.15
Dec	2.25	2.44	2.82
Total-ET_o, mm $year^{-1}$	1,795.38	1,618.67	1,613.51
Total-ET_o, m^3 ha^{-1} $year^{-1}$	17,954	16,187	16,135

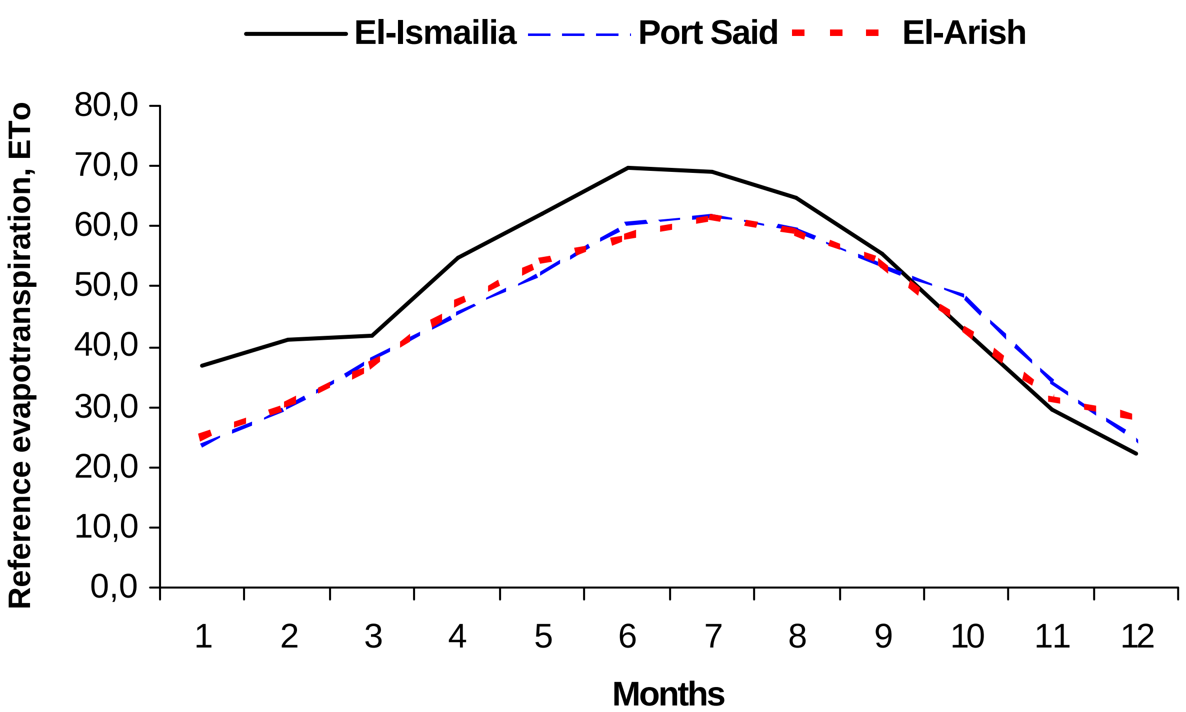


Figure 8: Reference evapotranspiration (ET_o, m^3 ha^{-1}) along the year for the three research locations

Table 8: Single (time average) crop coefficients (K_c), and mean maximum plant heights for non stressed, well-managed crops in subhumid climate (RH_{min} ~ 45%, U_2 ~ 2 m s^{-1}) for use with the FAO-PM ET_o (from Allen et al., 1998; modified)

Crop	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h_p), m
a. Legumes	**0.4**	**1.15**	**0.55**	
Beans, green	**0.5**	**1.05**	**0.90**	**0.4**
Beans, dry and Pulses	**0.4**	**1.15**	**0.35**	**0.4**
Chick Pea		**1.00**	**0.35**	**0.4**
Fababean (broad bean) - fresh -dry/Seed	**0.5** **0.5**	**1.15** **1.15**	**1.10** **0.30**	**0.8** **0.8**
Grabanzo	**0.4**	**1.15**	**0.35**	**0.8**
Green Gram and Cowpeas		**1.05**	**0.60-0.35** [1]	**0.4**
Groundnut (Peanut)		**1.15**	**0.60**	**0.4**
Lentil		**1.10**	**0.30**	**0.5**
Peas - fresh - dry / Seed	**0.5**	**1.15** **1.15**	**1.10** **0.30**	**0.5** **0.5**
Soybeans		**1.15**	**0.50**	**0.5 - 1.0**
b. Fibre Crops	**0.35**			
Cotton		**1.15 - 1.20**	**0.70 - 0.50**	**1.2 - 1.5**
Flax		**1.10**	**0.25**	**1.2**
Sisal [6]		**0.4 - 0.7**	**0.40 - 0.70**	**1.5**
c. Oil Crops	**0.35**	**1.15**	**0.35**	
Castorbean (Ricinus)		**1.15**	**0.55**	**0.3**
Sesame		**1.10**	**0.25**	**1.0**
Sunflower		**1.0 - 1.15** [2]	**0.35**	**2.0**
d. Cereals	**0.3**	**1.15**	**0.40**	
Barley		**1.15**	**0.25**	**1.0**
Oats		**1.15**	**0.25**	**1.0**
Spring Wheat		**1.15**	**0.25 - 0.4** [3]	**1.0**
Winter Wheat – with non-frozen soil	**0.7**	**1.15**	**0.25 -0.4** [3]	**1.0**
Maize - field (grain) (field corn) - Sweet (sweet corn)		**1.20** **1.15**	**0.6 - 0.35** [4] **1.05** [5]	**2.0** **1.5**
Millet		**1.00**	**0.30**	**1.5**
Sorghum - grain - sweet		**1.00 - 1.10** **1.20**	**0.55** **1.05**	**1 - 2** **2 - 4**
Rice	**1.05**	**1.20**	**0.90 - 0.60**	**1.0**

1 The first K_c is for harvested fresh, the second is for harvested dry
2 The lower values are for rainfed crops
3 The higher value is for hand-harvested crops
4 The first $K_{c\ end}$ is for harvested at high grain moisture, the second is for harvested after complete field drying of the grain (to about 18 % moisture, wet mass basis)
5 If harvested fresh for human consumption. Use $K_{c\ end}$ for field Maize if the sweet Maize is allowed to mature and dry in the field
6 K_c for Sisal depends on the planting density and water management

The RH_{min}- values of the three regions are shown in Table 9, and the accordingly adjusted crop coefficients $K_{c\ adj}$ in Table 10. When a mean $K_{c\ adj}$ value had to be calculated for a two- or three-month period and possibly with parts of calendar months (hence with different RH_{min} values and wind velocity values), the calendar months resp. part months were weighted accordingly.

If Figure 8 shows that the reference evapotranspiration at El-Ismailia is noticeably higher from January to September than in the other two locations, that will also be true for the crop water requirements. An example: A peanut crop at Port Said used 6,299.7 m^3 water per ha in a season whereas at El-Ismailia 7,300.4 m^3 per ha was required. This means that with the same amount of water approx. 16 % greater area of peanuts could be irrigated at Port Said. Table 11 shows the ET_c values of the treated crops calculated on the basis of the ET_o values and the corrected K_c values.

5. As already mentioned, most of the fields in the Port Said and El-Arish research locations are to be irrigated with saline water from the Salam canal. For the purpose of salinity control, the possible salt content must be taken into account when calculating the irrigation water requirement. This was done in the following by assuming three different levels of salt content: 0.5 dS m^{-1} (Nile water quality), 1.5 dS m^{-1} (winter conditions for irrigation water from the Salam canal; 2.0 dS m^{-1}in summer), 3.0 dS m^{-1} (occuring in exceptional cases). Table 12 shows what the plant water requirement will be in view of salinity control to achieve a particular level of yield with a given salt content in the root zone. These calculations were made according to Equation 42 (Section 2.3.4.2.). It is clear from Table 12 that if the irrigation water has an EC value of 0.5 dS m^{-1}, the crop water requirement according to Eq. 42 (ET_c + LR) for a yield level of 90-100 % is only slightly higher than for a yield level of 75-90 %. Consequently, in this case the slightly higher amount of irrigation is worthwhile. If the irrigation water has a conductivity of EC = 1.5 dS m^{-1}, then (in the case of peanut, soybean and cotton) the corresponding difference in crop water requirement for the two yield levels according to Eq. 42 will be similarly minimal, so that the extra irrigation for a 90-100 % yield level is prudent. In the case of maize, the crop water requirement for a yield level of 90-100 % would be about three times (Table 12) that needed for a yield level of 75-90 %.

Table 9: Minimum relative humidity for the three locations, $RH_{min.}$ %

El-Ismailia	Temperature, °C		Vapour Pressure Sat.		Minimum Relative
Month	Max.	Min.	e_s ($T_{max.}$)	e_s ($T_{min.}$)	Humidity, $RH_{min.}$, %
Jan.	19.8	7.0	2.31	1.00	43.30
Feb.	21.0	7.6	2.49	1.04	41.77
March	23.8	9.8	2.95	1.21	41.02
Apr.	28.6	13.0	3.92	1.50	38.27
May	31.1	16.0	4.52	1.82	40.27
June	35.0	19.5	5.62	2.27	40.40
July	35.0	20.8	5.62	2.46	43.77
Aug.	35.0	21.1	5.62	2.51	44.66
Sep.	32.7	19.1	4.95	2.21	44.65
Oct.	30.2	16.3	4.29	1.86	43.37
Nov.	25.6	12.7	3.28	1.47	44.82
Dec.	21.5	8.8	2.57	1.13	43.97
Port Said	Temperature, °C		Vapour Pressure Sat.		Minimum Relative
Month	Max.	Min.	e_s ($T_{max.}$)	e_s ($T_{min.}$)	Humidity, $RH_{min.}$, %
Jan.	18.0	11.3	2.06	1.33	64.60
Feb.	18.5	12.0	2.13	1.40	65.70
March	20.1	13.5	2.36	1.56	66.10
Apr.	22.5	16.7	2.73	1.90	69.60
May	25.5	19.5	3.27	2.27	69.42
June	28.5	22.3	3.90	2.69	69.00
July	30.3	24.0	4.32	2.98	69.00
Aug.	30.7	24.8	4.42	3.13	70.81
Sep.	29.1	23.7	4.03	2.83	70.22
Oct.	27.2	21.7	3.61	2.60	72.02
Nov.	24.0	18.5	2.98	2.13	71.50
Dec.	19.7	13.5	2.30	1.56	67.83
El-Arish	Temperature, °C		Vapour Pressure Sat.		Minimum Relative
Month	Max.	Min.	e_s ($T_{max.}$)	e_s ($T_{min.}$)	Humidity, $RH_{min.}$, %
Jan.	16.3	9.6	1.86	1.20	64.52
Feb.	16.6	10.1	1.89	1.24	65.61
March	18.6	12.0	2.14	1.40	65.42
Apr.	21.8	16.0	2.61	1.82	69.73
May	24.1	18.1	3.00	2.07	69.00
June	27.2	21.0	3.61	2.49	68.98
July	29.1	22.8	4.03	2.78	68.98
Aug.	29.1	23.2	4.03	2.84	70.47
Sep.	27.5	22.1	3.66	2.66	72.68
Oct.	25.3	19.8	3.23	2.31	71.52
Nov.	21.1	15.6	2.51	1.77	70.52
Dec.	17.5	11.3	2.00	1.33	66.50

Table 10: Adjusted Crop Coefficients ($K_{c\ adj}$) (according to relative humidity and wind conditions) and mean maximum plant height, h_p (m), in the research locations for the research crops

Crop Coefficients	El- Ismailia				
	Maize $h_p = 2.0$	Peanut $h_p = 0.4$	Sunflower $h_p = 2.0$	Soybean $h_p = 0.8$	Cotton $h_p = 1.3$
$K_{c\ init.}$	0.70	0.40	0.35	0.50	0.35
$K_{c\ mid\ adj.}$ [1]	1.19	1.14	1.14	1.14	1.20
$K_{c\ mid\ original}$	1.20	1.15	1.15	1.15	1.20
$K_{c\ end\ adj.}$ [1]	0.35	0.59	0.35	0.49	0.59
$K_{c\ end\ original}$	0.35 [2]	0.60	0.35	0.50	0.60
Crop Coefficients	**Port Said**				
	Maize $h_p = 2.0$	Peanut $h_p = 0.4$	Sunflower $h_p = 2.0$	Soybean $h_p = 0.8$	Cotton $h_p = 1.3$
$K_{c\ init.}$	0.70	0.40	0.35	0.50	0.35
$K_{c\ mid\ adj.}$ [1]	1.12	1.10	1.07	1.09	1.14
$K_{c\ mid\ original}$	1.20	1.15	1.15	1.15	1.20
$K_{c\ end\ adj.}$ [1]	0.35	0.54	0.35	0.43	0.52
$K_{c\ end\ original}$	0.35 [2]	0.60	0.35	0.50	0.60
Crop Coefficients	**El Arish**				
	Maize $h_p = 2.0$	Peanut $h_p = 0.4$	Sunflower $h_p = 2.0$	Soybean $h_p = 0.8$	Cotton $h_p = 1.3$
$K_{c\ init.}$	0.70	0.40	0.35	0.50	0.35
$K_{c\ mid\ adj.}$ [1]	1.19	1.14	1.13	1.14	1.20
$K_{c\ mid\ original}$	1.20	1.15	1.15	1.15	1.20
$K_{c\ end\ adj.}$ [1]	0.35	0.58	0.35	0.47	0.58
$K_{c\ end\ original}$	0.35 [2]	0.60	0.35	0.50	0.60

1 The original values of $K_{c\ mid}$ and $K_{c\ end}$ are determined for subhumid climates (RH_{min} » 45%) for moderate wind speed (averaging 2 m s^{-1}). For more humid or arid conditions or for more or less windy conditions, $K_{cmid.}$ and $K_{c\ end}$ should be modified (ASCE 1996, Allen et al. 1998) as follows:

$$K_{c\ mid\ adj.} = K_{c\ mid}\ (\text{table}) + [\,0.04(U2 - 2) - 0.004\,(HR_{min.} - 45)\,]\,(h/3)^{0.3}.$$
$$K_{c\ end\ adj.} = K_{c\ end}\ (\text{table}) + [\,0.04(U2 - 2) - 0.004\,(HR_{min.} - 45)\,]\,(h/3)^{0.3}$$

No adjustment is made when $K_{c\ end}$ (table) < 0.45 ($K_{c\ end} = K_{c\ end}$ (table)). When crops are allowed to senesce and dry in the field (as evidenced by $K_{c\ end}$ < 0.45), U_2 and RH_{min}. have less effect on $K_{c\ end}$ and no adjustment is necessary (ASCE 1996 preduced an adjustment when $K_{c\ end}$ < 0.4, as $K_{c\ end} = K_{c\ end}$ (table) + 0.001 ($RH_{min.}$ ~ 45 %)

2 For harvest after complete field drying of the grain (to about 18 % moisture, wet mass basis)

In the case of an irrigation water conductivity of EC = 3 dS m^{-1}, one would need to use a quantity of water that is some 15 times the ET_c value in order to gain a yield level of 90-100 % for peanuts, and for a 75-90 % yield level, six times the ET_c value. The high water expenditure for maize (irrigation water with EC = 1.5 dS m^{-1}) and for peanuts (irrigation water with EC = 3 dS m^{-1}) is unacceptable. The extra water needed to reach a higher yield level would be better used for other crops. See further Section 5.3.

Table 11: Calculated ET_c-values (plant water requirement) for research crops

Maize

Region	Growing Stages(days)				Total	Total
	1 (30)	2 (50)	3 (60)	4 (40)	mm $season^{-1}$	m^3 ha^{-1} $season^{-1}$
El-Ismailia	115.1	308.7	484.4	182.6	1,090.8	10,908
Port Said	95.6	255.4	408.4	164.7	924.0	9,240
El-Arish	99.1	264.9	429.7	171.4	965.1	9,651

Peanut

Region	Growing Stages(days)				Total	Total
	1 (25)	2 (35)	3 (45)	4 (25)	mm $season^{-1}$	m^3 ha^{-1} $season^{-1}$
El-Ismailia	62.0	183.6	347.5	137.0	730.0	7,300
Port Said	52.3	156.9	302.1	118.7	630.0	6,300
El-Arish	54.2	154.5	311.8	126.0	646.4	6,464

Sunflower

Region	Growing Stages(days)				Total	Total
	1 (25)	2 (35)	3 (45)	4 (25)	mm $season^{-1}$	m^3 ha^{-1} $season^{-1}$
El-Ismailia	54.3	179.5	347.5	120.3	701.6	7,016
Port Said	45.8	146.5	293.9	103.1	589.2	5,892
El-Arish	47.4	149.3	309.1	107.0	612.8	6,128

Soybean

Region	Growing Stages(days)				Total	Total
	1 (20)	2 (35)	3 (60)	4 (25)	mm $season^{-1}$	m^3 ha^{-1} $season^{-1}$
El-Ismailia	62.0	153.6	461.3	127.8	804.7	8,047
Port Said	52.3	163.0	396.9	105.9	718.1	7,181
El-Arish	54.2	164.4	412.0	112.0	742.6	7,426

Cotton

Region	Growing Stages(days)				Total	Total
	1 (30)	2 (50)	3 (60)	4 (55)	mm $season^{-1}$	m^3 ha^{-1} $season^{-1}$
El-Ismailia	43.8	228.9	489.0	317.4	1,079.0	10,790
Port Said	39.9	179.8	404.7	268.8	893.2	8,932
El-Arish	38.8	197.0	421.1	271.5	928.4	9,284

Table 12: Plant water requirements when using saline water (m^3 ha^{-1} $Saison^{-1}$), for yield level of von 90 to 100 % and of 75 to 90 %; allowable salt content in root zone see Table 16

Yield level of 90 to 100 %				
Location	Crop	EC of irrigation water, dS m^{-1}		
		0.5	**1.5**	**3**
El-Ismailia	**Maize**	15,453	92,717	
	Peanut	8,652	13,742	116,806
	Soybean	8,941	11,496	20,118
	Cotton	11,540	13,401	17,678
Port Said	**Maize**	13,090	78,542	
	Peanut	7,466	11,858	100,795
	Soybean	7,979	10,259	17,954
	Cotton	9,552	11,093	14,633
El-Arish	**Maize**	13,672	82,034	
	Peanut	7,661	12,167	103,422
	Soybean	8,251	10,608	18,564
	Cotton	9,929	11,530	15,210
Yield level of 75 to 90 %				
Location	Crop	EC of irrigation water, dS m^{-1}		
		0.5	**1.5**	**3**
El-Ismailia	**Maize**	13,635	27,270	
	Peanut	8,517	12,776	51,103
	Sunflower	7,928	10,523	21,047
	Soybean	8,852	11,065	17,704
	Cotton	11,383	12,789	15,695
Port Said	**Maize**	11,550	23,101	
	Peanut	7,350	11,025	44,098
	Sunflower	6,658	8,838	17,677
	Soybean	7,900	9,874	15,799
	Cotton	9,423	10,586	12,992
El-Arish	**Maize**	12,064	24,128	
	Peanut	7,541	11,312	45,247
	Sunflower	6,925	9,192	18,384
	Soybean	8,168	10,210	16,336
	Cotton	9,794	11,003	13,504

5. Optimizing irrigation water requirements

5.1. Improved (ET_o-oriented) geographical distribution of crop types (IGDC)

Ainer et al. (1999) have made two general proposals for solving the problems of water shortage and conserving irrigation water in Egypt. First, using modern irrigation techniques (sprinkler and drip irrigation), through which some 15 to 25 % of irrigation water could be saved in comparison with gravity irrigation. Secondly, refraining from extending rice cultivation beyond a total extent of 420,000 ha, and reducing the area under sugar cane cultivation. According to El-Marsafawy and Eid (1998), however, current rice cultivation already covers 582,000 ha. The above-mentioned reduction advocated would appear to be unacceptable anyway, as Egypt's population is increasing by 2.2 % annually. A better geographical distribution of crop types would seem much more sensible: crops with lower water requirements should be grown in areas with higher reference evapotranspiration, and vice versa. The irrigation water saved as a result of improved geographical distribution could then be used for the necessary extension of rice and sugarcane cultivation.

As shown in Table 7 (Section 4.2.2.), there are clear differences between the research locations. At El-Ismailia, 17,953.8 m^3 of water can evaporate annually per hectare (calculated as ET_o); at both Port Said and El-Arish, by contrast, about 1,700 m^3 less per hectare per annum. Thus crops with a high water consumption should be grown in the Port Said area and at El-Arish, those with a low water requirement at El-Ismailia.

The following two examples A and B should make clear the result to be achieved. In both instances, five crops differently distributed over the research locations - maize, soybean, peanut, sunflower and cotton - were planted, each in an area of 60 ha in all. It was accepted that the resulting total area of 300 ha would be distributed as 100 ha per location (in both cases, only the crop water consumption ET_c was calculated without consideration of the salinity of the irrigation water or the salt tolerance of the crop in question. Nor were any crop rotation factors taken into consideration.).

<u>Case A.</u>

300 hectare area (60 ha for each crop) could be distributed as follows:

El-Ismailia (100 ha)		Port Said (100 ha)		El-Arish (100 ha)	
Maize	60%	Sunflower	60%	Soybean	40%
Cotton	30%	Peanut	30%	Cotton	30%
Soybean	10%	Soybean	10%	Peanut	30%

On the basis of Table 11 (Section 4.2.2.) the following crop water consumption results (m^3/100 ha):

El-Ismailia	Port Said	El-Arish
1,058,656	614,343	769,460

Total water consumption (ET_c) = 2,442,459 m^3 / 300 ha .

<u>Case B.</u>

300 hectare area (60 ha for each crop) could be distributed as follows:

El-Ismailia (100 ha)		Port Said (100 ha)		El-Arish (100 ha)	
Sunflower	60%	Maize	60%	Soybean	40%
Peanut	30%	Cotton	30%	Cotton	30%
Soybean	10%	Soybean	10%	Peanut	30%

On the basis of Table 11 (Section 4.2.2.) the following crop water consumption results (m^3/100 ha):

El-Ismailia	Port Said	El-Arish
720,421	894,180	769,460

Total water consumption (ET_c) = 2,384,061 m^3 / 300 ha.

The two cases A and B show that in accordance with the distribution of the crop types the water consumption can be differentiated considerably resp. reduced. Exchanging maize / cotton on the one hand and sunflower / peanut on the other between El-Ismailia and Port Said reduced the total crop water consumption of case A (2,442,459 m^3/300 ha) in case B (2,384,061 m^3/300 ha) to about 60,000 m^3. In other words, the new organization of only 100 ha between only two of the three areas can bring a total saving of 60,000 m^3 water, which can be used to open up new irrigation tracts.

5.2. Scheduling of irrigation using Daily Data Based Model (DDBM)

Limited water resources necessitate a precise scheduling of water dosage in irrigated agriculture. Although seasonal changes, e.g. the parameter crop coefficient (K_c), root development (Z_r), or maximum allowable soil moisture depletion (P) have a considerable influence on the crop water requirement and as a result also on the amount of water to be applied and the consequent yield, these seasonal changes have not been taken into account in many existing studies. It could thus happen that two different research groups arrived at contrary findings for the same locations investigated. Abada et al. (1998) report that for determining the reference evapotranspiration the Blaney-Criddle method is less suited with regard to the actual water requirement than the modified Penman method; for Abdel-Hafez et al. (1999), on the other hand, the Blaney-Criddle method was the best. In their experiment, for example, only one maximum allowable soil moisture depletion value for the whole vegetation period was employed. A too high water dosage was calculated because of this, consequently reducing the water use efficiency (unit of yield per unit of water). In this connection, Gallardo et al. (1995) have found that an increase in water use efficiency requires detailed information about the seasonal changes involved in plant growth. El-Sabagh (1993) and Simon et al. (1998) have likewise noted a considerable change in K_c values and plant water requirement ET_c in the course of the growing season, as do Doorenbos et al. (1986) (see Table 13). However, Rashad et al. (1999) only made use of the maximum allowable soil moisture depletion for calculating the maximum water use efficiency for lentils in the El-Ismailia area, but he used only one value for the overall vegetation period. Ghali et al. (1997), Eid et al. (1998) and numerous other researchers have employed only a K_c value for the overall vegetation period in their investigations.

Table 13: Max. allowable soil moisture depletion, P, in dependence on max. crop evapotranspiration, ET_c (Doorenbos et al., 1986)

Crop group		ET_c mm day^{-1}								
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	**Onion, Pepper, Potato**	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20	0.175
2	**Banana, Cabbage, Grape, Pea, Tomato**	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25	0.225
3	**Alfalfa, Bean, Peanut, Citrus, Pineapple, Sunflower, Wheat, Watermelon**	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35	0.30
4	**Cotton, Maize, Olive, Tobacco, Safflower, Sorghum, Soybean, Sugarbeet, Sugarcane**	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425	0.40

Method for irrigation scheduling on the basis of daily data

In contrast to those authors, who carry out irrigation scheduling by means of average values, in the following – according to the process scheme of Figure 9 and Figure 10 (with Eq. 42, 47, 52, 53 and 55; see Sections 2.3.4.2. and 2.4.2.) - a simple decision model for irrigation scheduling based on daily data (DDBM) will be derived.

The model is based on the functions represented in Figures 11a-e and 12a-d for daily fluctuations in plant water consumption ET_c, maximum allowable soil moisture depletion P, and root development Z_r. These values can be derived from the curves of the Figures mentioned. Root development was calculated from the equation of Borg and Grimes (1986) (see Eq. 54).

In calculating irrigation water requirements, location data (e.g. effective precipitation, moisture content at field capacity and at permanent wilting point, quality of irrigation water) have been taken into consideration in this model along with daily changes in plant parameters (see Figure 9).

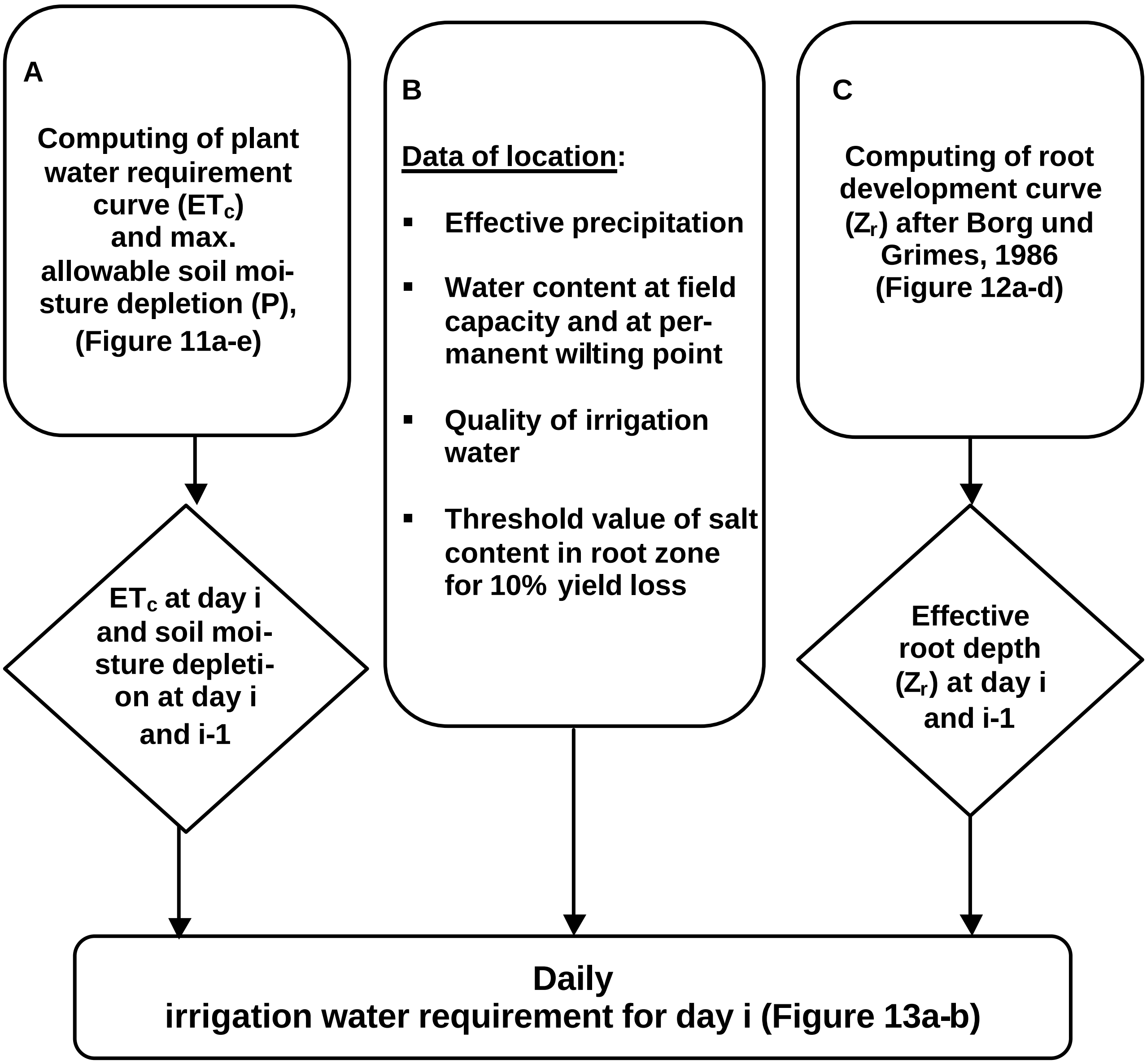


Figure 9: Structure of daily data based model for irrigation scheduling, (DDBM)

Determination of the amount of water to be applied on a specific day i involved a reading of the daily data of the plant parameters mentioned along characteristic curves established for this purpose (on days i and i-1) and entered directly in a dialog box (program developed with Visual C++), see Figure 13a-b. The program then calculates the daily irrigation water requirement in litres per day and plant (or hectares: when the number of plants, N_o., is 1, litre day^{-1} hectare^{-1} will appear instead of litre day^{-1} plant^{-1}), on the basis of the daily climate-plant-soil-water balance with due consideration of measures to prevent salinisation.

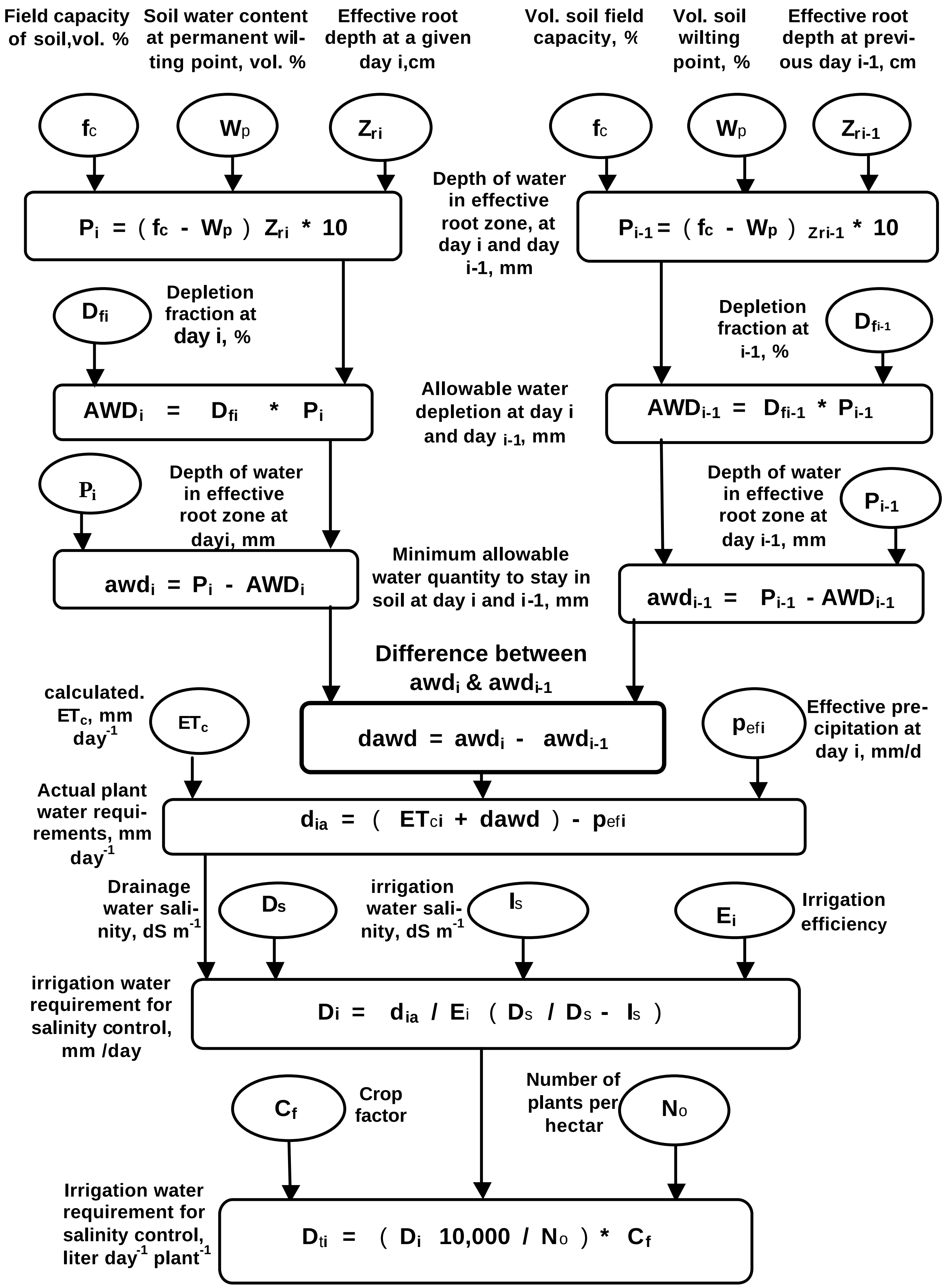


Figure 10: Calculation process for determination of daily irrigation water requirement, Liter day^{-1} plant^{-1}

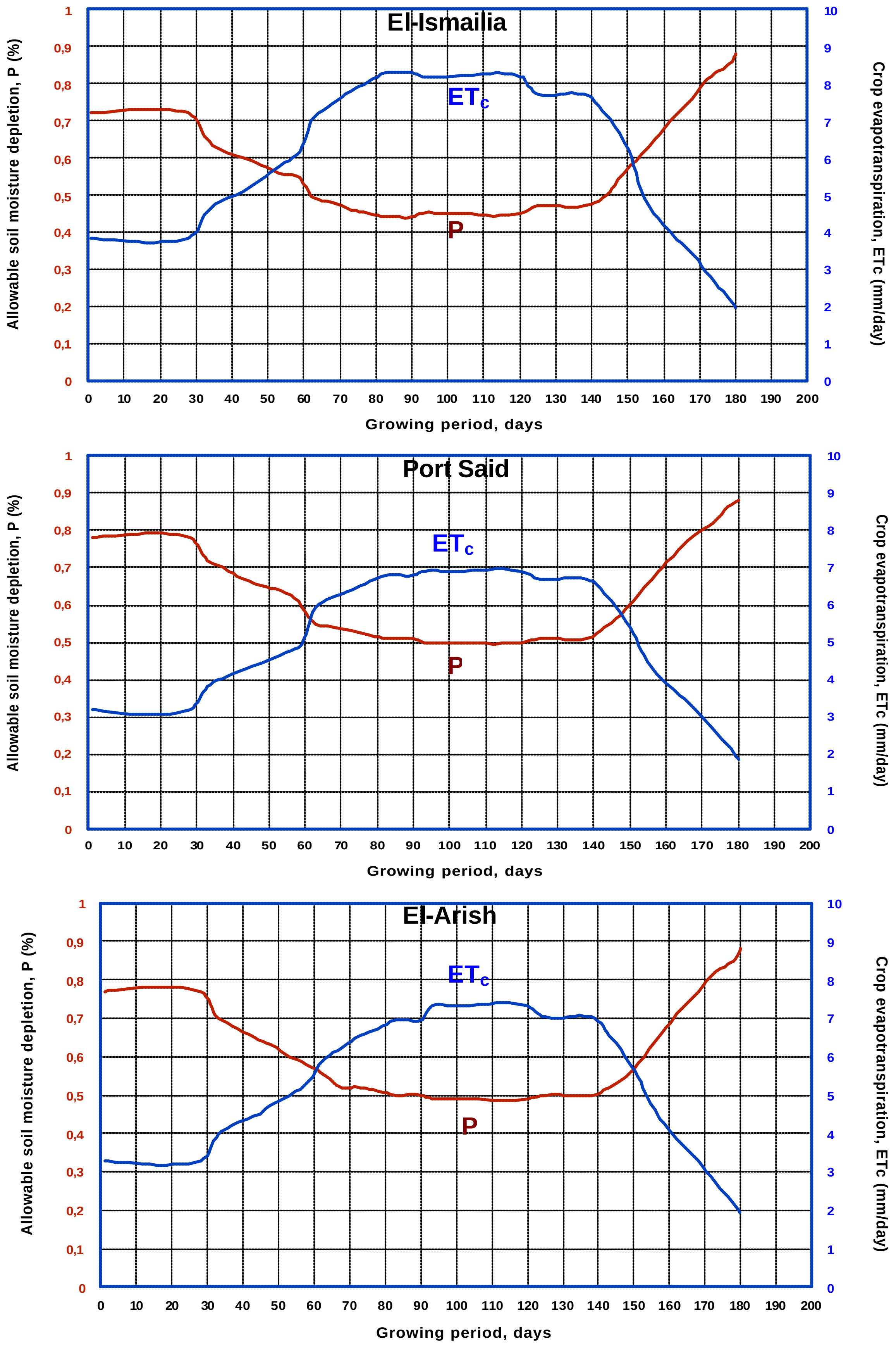


Figure 11a: Daily changes of plant water requirement, ET_c, and of max. allowable soil moisture depletion, P, for maize

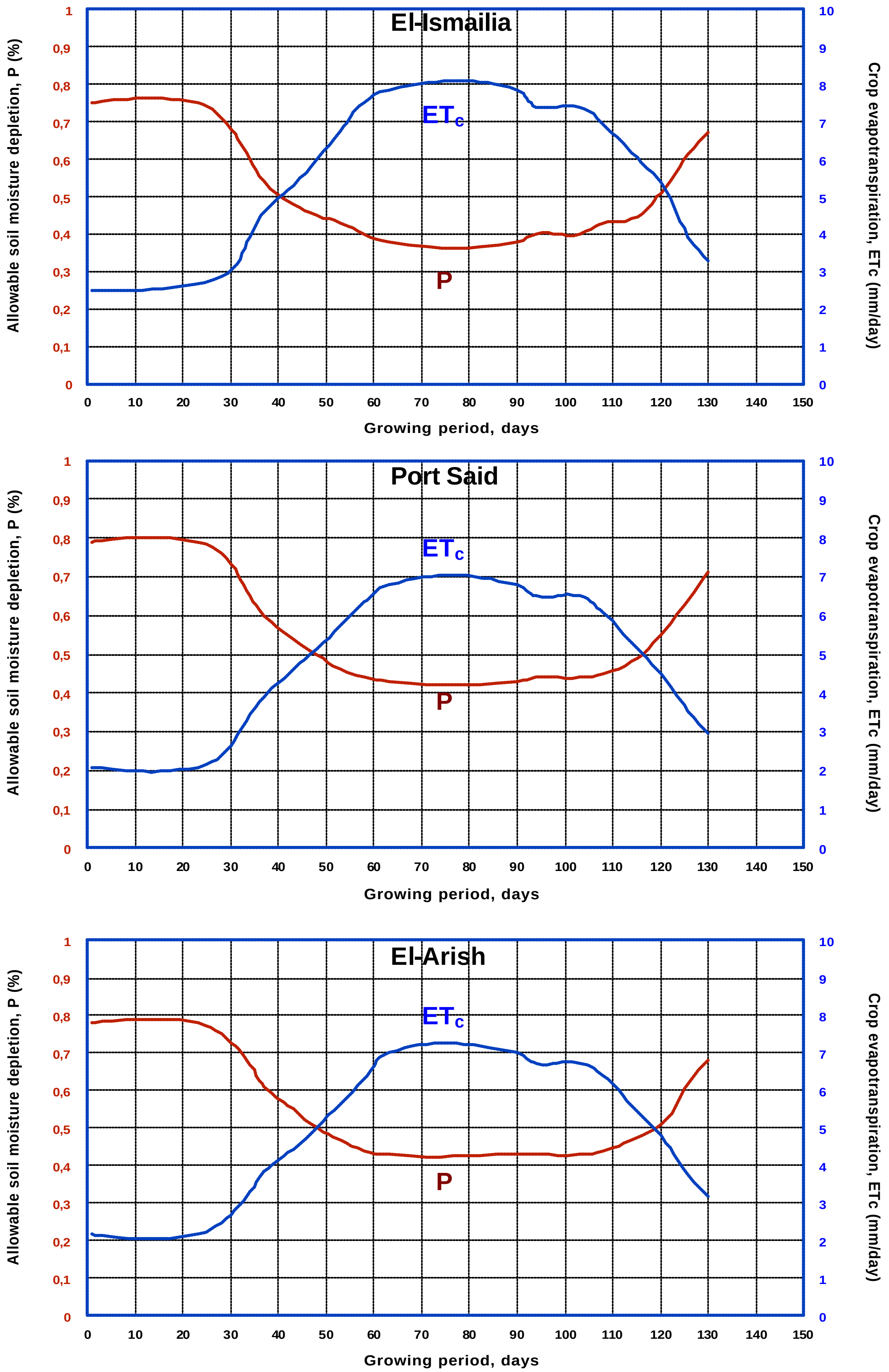


Figure 11b: Daily changes of plant water requirement, ET_c, and of max. allowable soil moisture depletion, P, for peanut

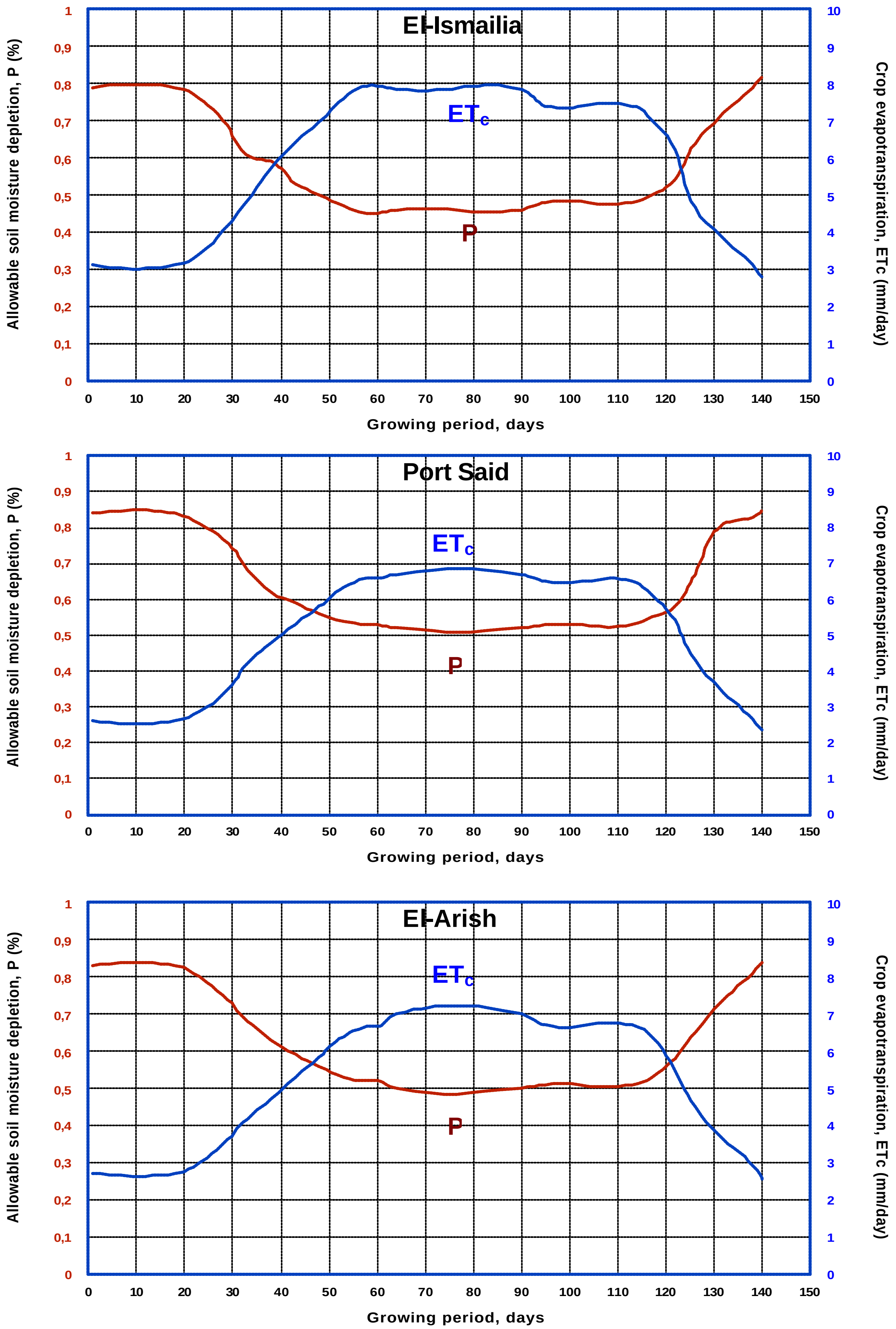


Figure 11c: Daily changes of plant water requirement, ET_c, and of max. allowable soil moisture depletion, P, for soybean

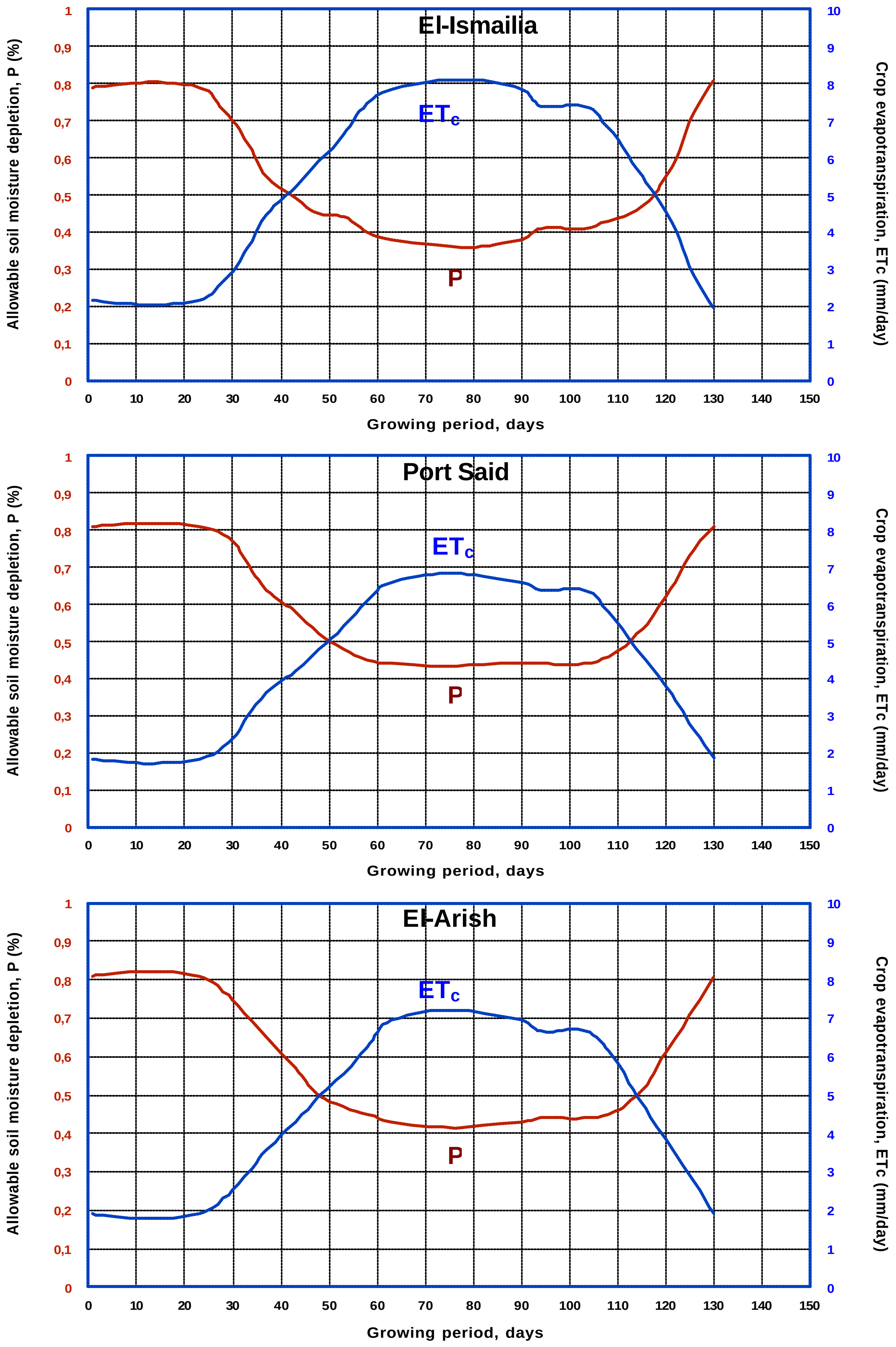


Figure 11d: Daily changes of plant water requirement, ET_c, and of max. allowable soil moisture depletion, P, for sunflower

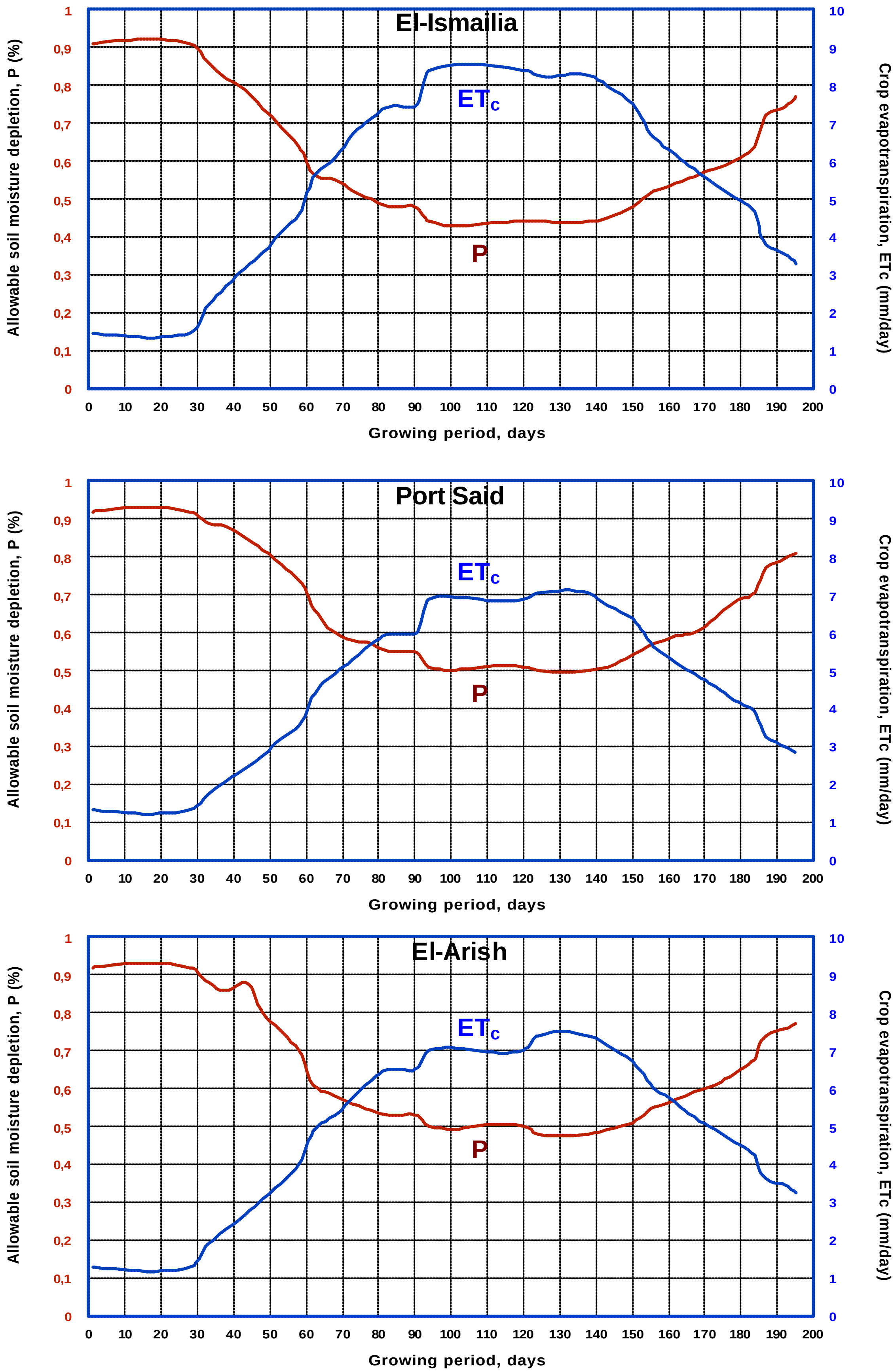


Figure 11e: Daily changes of plant water requirement, ET_c, and of max. allowable soil moisture depletion, P, for cotton

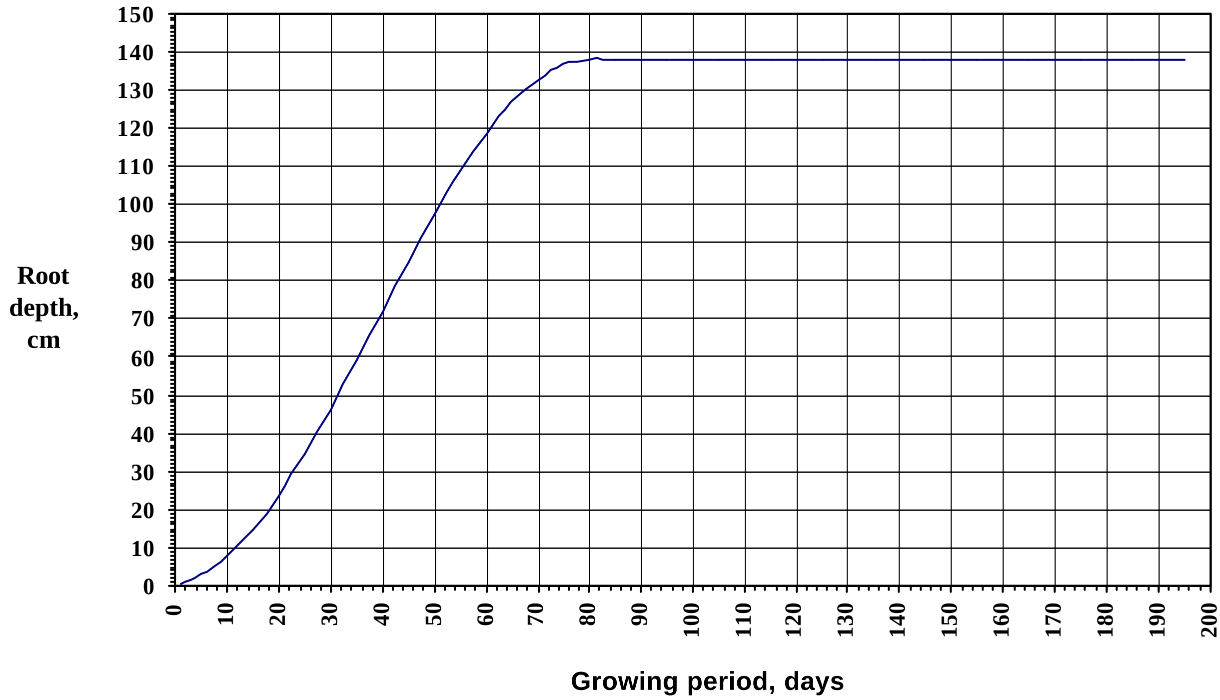


Figure 12a: Root development curve (Z_r) for maize and cotton, after Borg and Grimes, 1986 (Eq. 54, Section 2.4.2.3.)

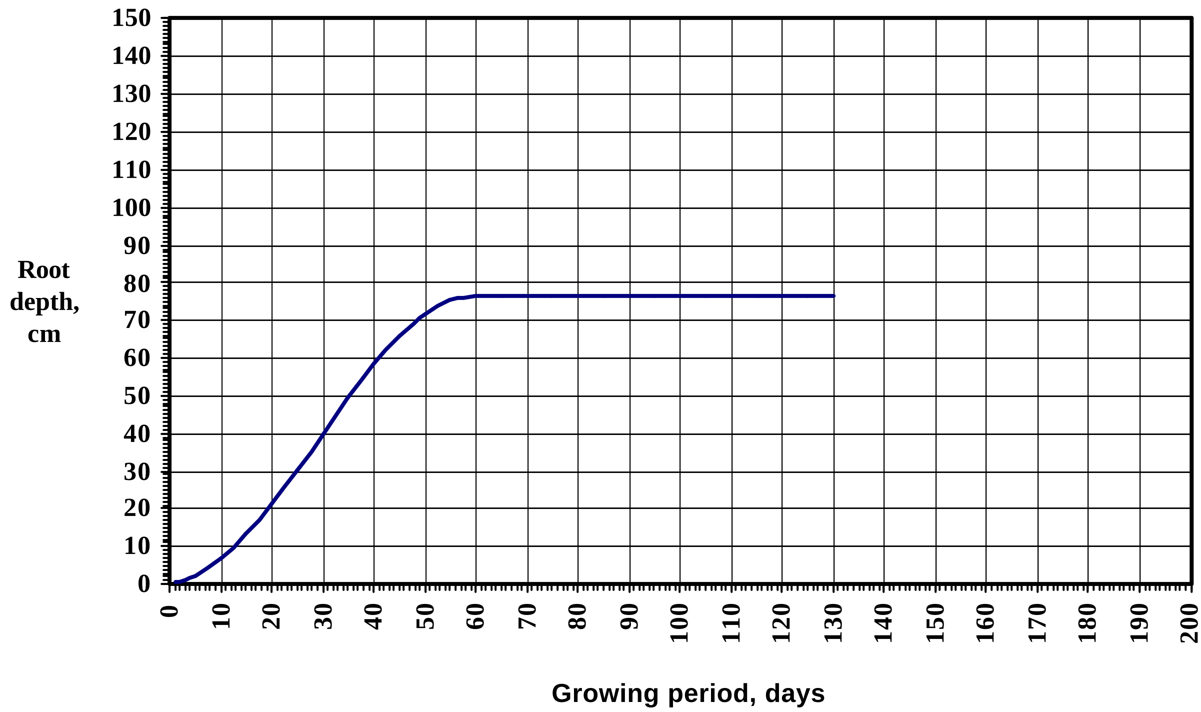


Figure 12b: Root development curve (Z_r) for peanut, after Borg and Grimes, 1986 (Eq. 54, Section 2.4.2.3.)

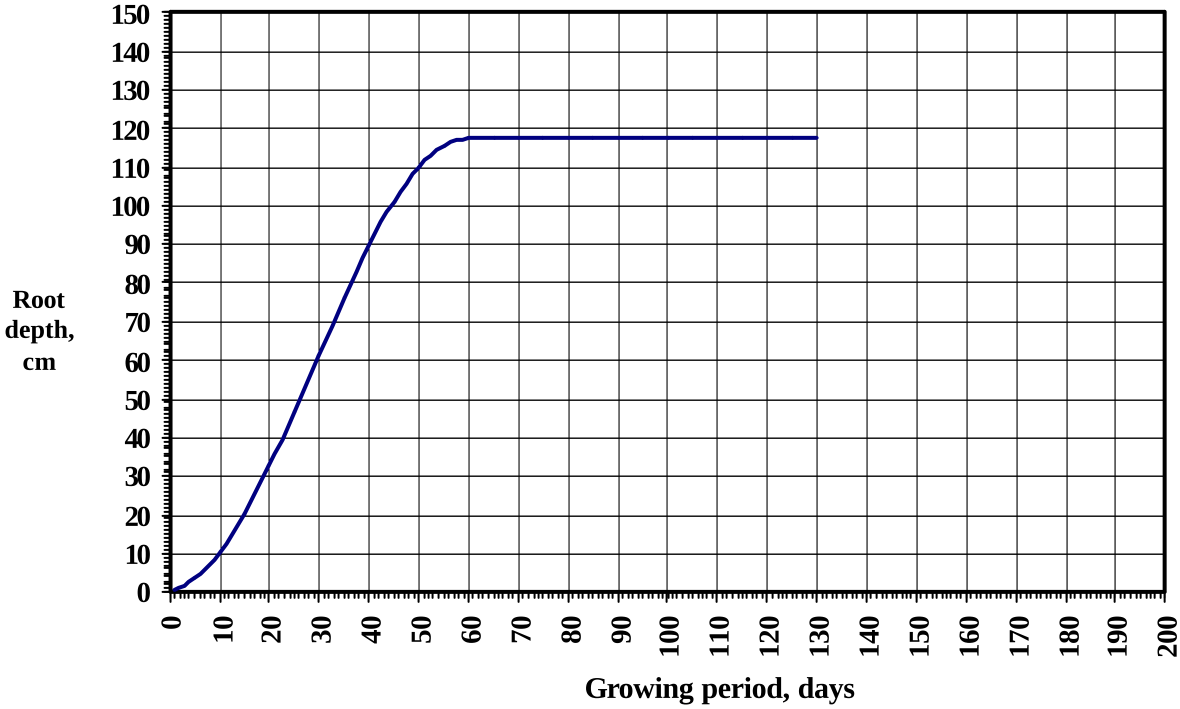


Figure 12c: Root development curve (Z_r) for sunflower, after Borg and Grimes, 1986 (Eq. 54, Section 2.4.2.3.)

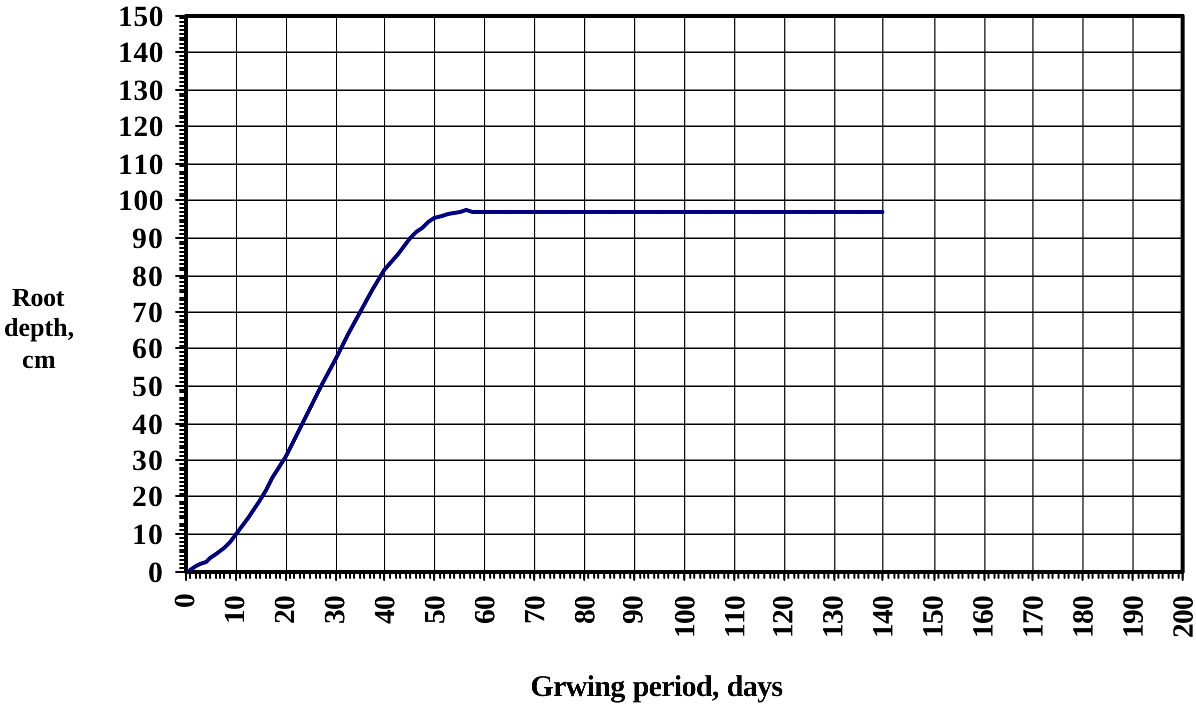


Figure 12d: Root development curve (Z_r) for soybean, after Borg and Grimes, 1986 (Eq. 54, Section 2.4.2.3.)

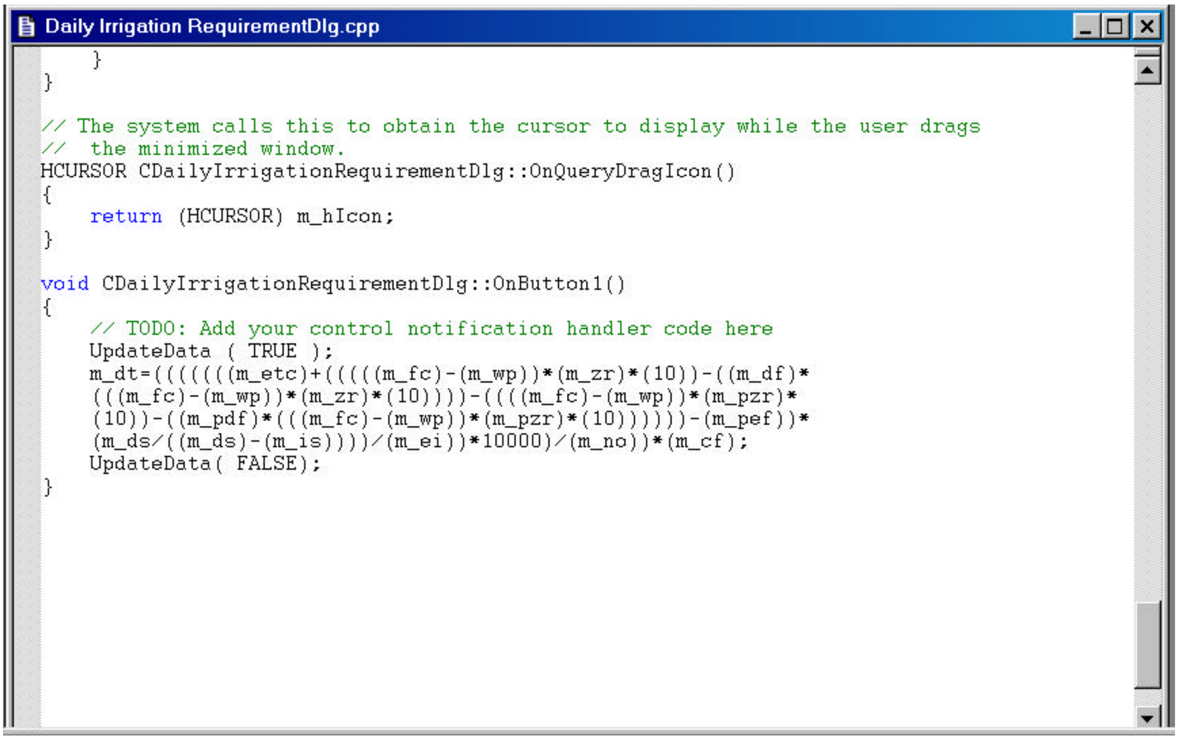


Figure 13a: Program-Code for calculation of irrigation water requirement in Liter day^{-1} plant^{-1}

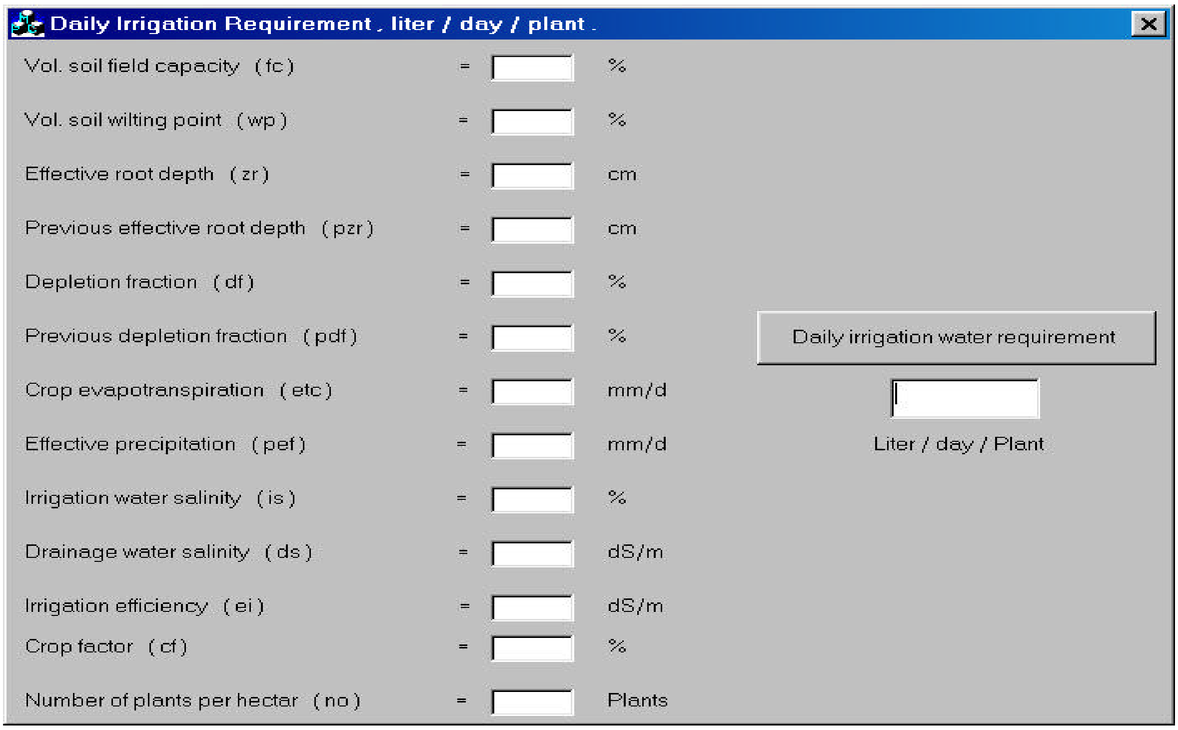


Figure 13b: Input mask for calculation of irrigation water requirement in Liter day^{-1} plant^{-1}

Description of the mathematical derivation of DDBM model

Derivation (Figure 10) of the calculation of the daily irrigation water requirement (in litres per day and hectare) consists of seven equations. The first six relate to data input, the seventh to data output (in litres per day and plant). The horizontal root spread was included by means of the crop factor C_f. As C_f factors could not be obtained from the existing literature for the crops investigated in the present study, a C_f factor of 0.8 was assumed, in line with the C_f factors in Table 14.

Under practical aspects a value of 80 % was assumed for irrigation efficiency of drip irrigation, considering that 90 % (Table 15) are hard to be reached in the field. N_o being the number of plants per hectar. In certain cases (e.g. grain crops in contrast to row crops such as cotton), N_o does not appear or is replaced by the number 1. The seven equations concerned have the following specific functions:

First equation (Eq. 53, Section 2.4.2.3.). This estimates the maximal amount of water in the effective root zone on a given day i and on the previous day i-1.

Second equation (Eq. 55, Section 2.4.2.4.). This is used to convert the proportion of maximum allowable soil moisture depletion beyond which the plant undergoes water stress) into mm of water for both the given day and the previous day.

Third equation (derived from the first two). This estimates the soil moisture content that needs to be present at a given day and the previous day in the root zone under non-waterstress conditions.

Fourth equation (developed here). This calculates the positive or negative change in soil moisture content necessary to avoid water stress in the root zone.

Fifth equation (developed here). This is used to calculate the actual plant water requirement (mm day^{-1}) from ET_c and with due consideration of effective precipitation and the positive or negative changes registered by the fourth equation.

Sixth equation (derived from Eq. 42). This is used to calculate the irrigation water requirement in terms of the desired irrigation efficiency and the quality of irrigation and drainage water.

Seventh equation (derived from Eq. 52, Section 2.4.2.2.). This yields a result in litres per day and plant or litres per day and hectare.

After integration of all the components of the soil-water balance model (Figure 10), the soil-water status (dawd) of the root zone can be simulated in order to forecast the irrigation water requirement.

Table 14: Crop factor, C_f, (for horizontal root extension) for Drip / Microjet Systems, Moon and Van der Gulik, 1996

Crop		Crop Factor, C_f
Apples	**High density**	0.90
	Medium den.	0.85
	Low den.	0.80
Cherries		0.90
Pears		0.80
Grapes		0.70
Berries		0.70
Vegetables		0.90
Nursery		0.75

Table 15: Irrigation efficiency for different irrigation systems, Moon and Van der Gulik, 1996

Irrigation System	Application Efficiency, Ea
Handmove	0.70
Over head solid set sprinkler	0.70
Unter tree solid set sprinkler	0.72
Unter tree micro sprinkler	0.75
Stationary gun systems	0.55
Travelling gun systems	0.65
Drip irrigation	0.90
Microjet irrigation	0.85

Consideration of soil texture, soil water depletion (P), crop evapotranspiration (plant water consumption) (ET_c) and salinity of the irrigation water in DDBM

To demonstrate the significance of soil texture and salinity of the irrigation water, trial calculations are made in accordance with the following assumptions:

Soil A:

sandy-clayey loam (clay 31.9 %; silt 18.1 %; sand 50 %)
field capacity 20.35 vol %
permanent wilting point 8.6 vol %
water available for plants 11.75 vol %

Soil B:

loamy sand (clay 9.5 %; silt 20 %; sand 70.5 %)
field capacity 12.9 vol %
permanent wilting point 7.42 vol %
water available for plants 5.48 vol %

Water quality:

water a: Nile water, EC = 0.5 dS m^{-1}
water b: Salam canal water, EC = 1.5 dS m^{-1}

Research crops:

maize: salt tolerance 1.7 dS m^{-1} estimated yield 95 % (see Table 16)
cotton: salt tolerance 7.7 dS m^{-1} estimated yield 95 % (see Table 16)
(Soil data from Ministry of Agriculture, 1985)

5.2.1 Effect of considering soil texture on irrigation water quantity

The irrigation water requirement per day (in each case on a given day for maize in El-Ismailia) was calculated using the model DDBM (see Table 17 and Figure 14). The

Table 16: Salt tolerance of crops in dependence of electronic conductivity in the root zone (soil extraction, dS m^{-1}) after Doorenbos et al., 1986

Crop	Sensitivity to salinity	Yield decrease (%) under increasing soil salinity
Maize	moderately sensitive	0-10% at 1.7 dS / m 10-25 % at 2.5 dS / m 25-50 % at 3.8 dS / m 50-100 % at 5.9 dS / m 100 % at 10.0 d S/ m
Pepper	moderately sensitive except in the seedling stage when it is more sensitive	0-10% at 1.5 dS / m 10-25 % at 2.2 dS / m 25-50 % at 3.3 dS / m 50-100 % at 5.1 dS / m 100 % at 8.5 dS / m
Sugarbeet	tolerant except during the early stage; during early growth EC should not exceed 3 dS m^{-1} .	0-10% at 7.0 dS / m 10-25 % at 8.7 dS / m 25-50 % at 11.0 dS / m 50-100 % at 15.0 dS / m 100 % at 24.0 dS / m
Wheat	moderately tolerant soil salinity should not exceed 4.0 dS / m in the upper soil layer during germination	0-10 % at 6.0 dS / m 10-25 % at 7.4 ds / m 25-50 % at 9.5 dS / m 50-100 % at 13.0 dS / m 100 % at 20.0 dS / m
Cotton	tolerant	0-10% at 7.7 dS / m 10-25% at 9.6 dS / m 25-50% at 13.0 dS / m 50-100% at 17.0 dS / m 100% at 27.0 dS / m
Peanut	moderately sensitive	0-10% at 3.2 dS % m 10-25% at 3.5 dS / m 25-50% at 4.1 dS / m 50-100% at 4.9 dS / m 100% at 6.5 dS / m
Soybean	moderately tolerant	0-10% at 5 dS / m 10-25 at 5.5 dS / m 25-50% at 6.2 dS / m 50-100% at 7.5 dS / m 100% at 10 dS / m
Sunflower	moderately tolerant in the later growth periods The emergence percentage of seedling is an indication of tolerance	80-100 % emergence at 0.0 dS / m 70 - 75 % " at 4.5 dS / m 30 - 60 % " at 9.5 dS / m 15 - 55 % " at 10.0 dS / m 0 - 25 % " at 13.0 dS / m

Table 17: Irrigation water requirement for maize in El-Ismailia on soil A (sandy-clayey loam) & B (loamy sand), water a (Nile-water, EC= 0.5 dS m^{-1})

Day	daily irrigation water requirement, m^3 ha^{-1}	
	Soil A	**Soil B**
15.	63.1	57.8
30.	66.9	60.7
45.	88.6	80.7
60.	108.7	99.8
75.	120.2	115.8
90.	117.6	117.6
105.	116.2	116.2
120.	116.2	116.2
135.	109.1	109.1
150.	88.5	88.5
165.	52.4	52.4

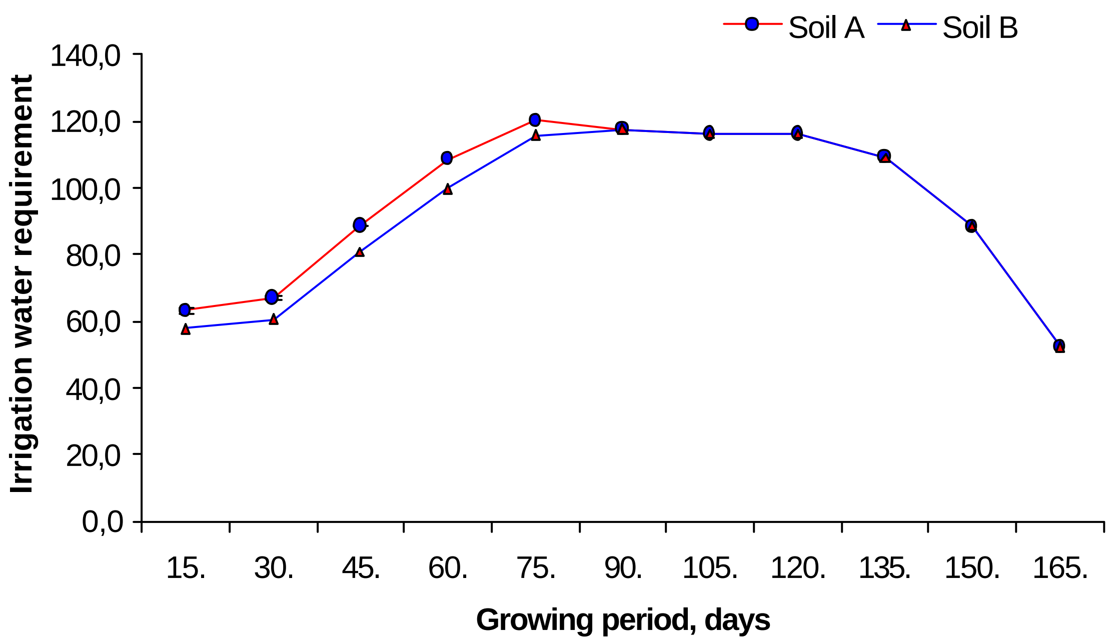


Figure 14: Effect of plant available water ratio of differently textured soils (soil A, sandy-clayey Loam & soil B, loamy Sand, under water a, Nile water, EC = 0.5 dS m^{-1}) on irrigation water requirement (m^3 ha^{-1}) in DDBM for maize in El-Ismailia

same water quality was always assumed (water a). It is shown that from about the 75th day the soil differences no longer play a role. This can be explained by the fact that the root-filled area does not change any further, as the roots hardly grow any more. In the period before the 75th day, by contrast, the difference in the irrigation water requirement is about 5 to 10 m^3 per hectare.

The difference in water available to the crop is between 11.8 % (soil A) and 5.5 % (soil B); this led in the first 75 days of the growth period of maize to a difference in irrigation water requirement of about 560 m^3 per hectare in total.

5.2.2. Effect of using the allowable soil moisture depletion as seasonal average value on the irrigation water quantity (55 % of field capacity)

Differences during the first 90 days are also obtained (in case of cotton), when calculating the irrigation water requirement by means of the DDBM model using daily values for all parameters or – in comparsion – identically but for one of them (allowable soil moisture depletion, P) using that value, which is given in literature mostly as a constant value (see Table 18 and Figure 15). When using daily values only, 558 m^3 ha^{-1} less are calculated for the whole vegetation period. Figures 11a-e show that the more the plant evapotranspiration increases the more the allowable soil moisture depletion decreases. In other words, at the first times of the vegetation period the plants are more tolerant for water deficit (up to a soil moisture depletion amounts to 90 % of the soil field capacity). Therefore, using an average value of allowable soil moisture depletion of 55 % throughout the vegetation period as common at irrigation planning, results in a lot of irrigation water losses in the early stages of the vegetation period.

5.2.3. Effect of crop water consumption as phase average value on irrigation water quantity

From the example of cotton in the Port Said region (variants water b, Soil A) it can be seen how strongly estimates of irrigation water requirements can vary according to whether the calculations were based on daily data or phase average values in DDBM (Figure 16). For case A the parameters ET_c, P and Z_r were processed as daily data, for case C, P and Z_r as daily data, but ET_c as phase average value (1.4 mm day^{-1} for initial-phase, 3.25 mm day^{-1} for development-phase, 6.8 mm day^{-1} for mid-phase, and

5 mm day^{-1} for end-phase). There is a considerable divergence between the two cases, especially between the 50th and 90th day and between the 135th and 170th day. The reason is: In the development phase (in case C between the 30th and 80th day) ET_c value was taken as phase mean value, 3.28 mm day^{-1}. According to Figure 11e, however, in case A, for example, on the 45th day 2.5 mm day^{-1} and on the 75th day 5.5 mm day^{-1} were entered as daily values. Result of this comparison (Figure 16): The case C led to a considerable impairment of the balance between the actual crop water requirement and the amount of irrigation water supplied.

Table 18: Irrigation water requirement for Cotton in Port Said under: Soil A; water b (Salam canal water, EC = 1.5 dS m^{-1})

day	Irrigation requirement using DDBM (m^3 ha^{-1})	
	Allowable depletion - daily value	Allowable depletion - average value, P = 0.55
15.	20.3	31.7
30.	21.0	32.3
45.	36.1	45.2
60.	58.7	63.7
75.	73.3	74.3
90.	74.5	76.9
105.	87.0	86.2
120.	86.3	85.5
135.	87.6	86.8
150	79.5	78.8
165.	62.1	61.5
180.	51.0	51.7

Again, if one used for ET_c a constant value for each crop stage and for the maximal allowable soil moisture depletion P a value for the whole vegetation period so too here a very discontinuous irrigation requirement would result, case D (Table 19 and Figure 17 which does not correspond to the real crop requirement (case A). h the case of case D the balance between irrigation water quantity and plant requirement is not maintained. If one also takes into account the root depth, though also only with an average value for each crop stage, the result (irrigation requirement) is only slightly improved (Table 20, Figure 18). However, if - in the case of soil A - only the quality of the irrigation water (water a or water b) is varied (calculated in both cases according to DDBM), then there is a very considerably different result for the irrigation requirement

(Table 21, Figure 19). The differences in salt content (EC = 0.5 or 1.5 dS m^{-1}) thus cause a difference in the irrigation requirement for the whole growth period of maize (180 days) of more than 60,000 m^3 altogether.

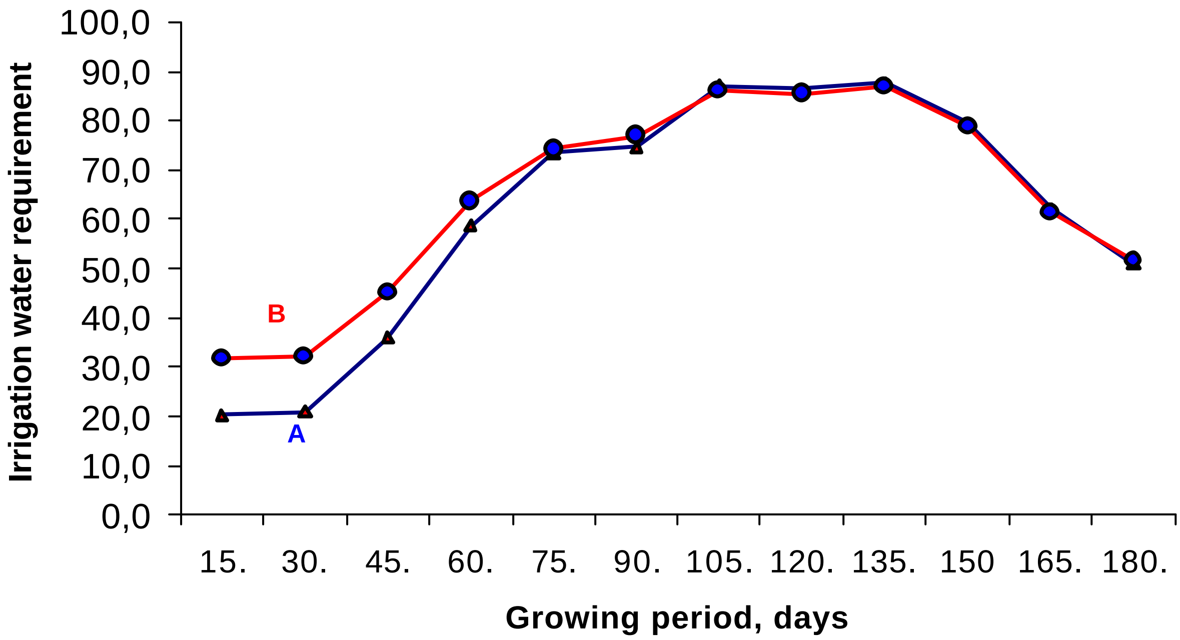


Figure 15: Effect of allowable soil moisture depletion on irrigation water requirement (m^3 ha^{-1}) in DDBM for Cotton in Port Said (soil A; water b);
Case A: ET_c P and Z_r as daily values from curves 11e and 12a;
Case B: ET_c and Z_r as daily values, P as season average value (55 % from soil field capacity)

Conclusion: a spatial redistribution of the cultivated crop according to ET_o of the location is of no use if the water quality is so different between the locations that the necessary irrigation water is determined chiefly by the water quality. In other words, salt-tolerant crops should be cultivated in regions with lower water quality, salt-sensitive plants in those of higher water quality, regardless of the ET_o of the location.

Table 22 shows a further comparison between the DDBM result and the usual advice for optimising the irrigation water requirement for cotton in north Egypt. The Egyptian Agricultural Research Centre in Cairo (ARC) which advises the irrigation agriculturalists calculates the irrigation water requirement according to a method based on the methodic CROPWAT of the FAO (El-Marsafawy and Eid 1998). The water requirement

Figures thus calculated (Table 22) are distinctly higher than those of the DDBM model. It appears that DDBM would save 1,500 m^3 per ha and season compared to variant 1 of the ARC method; compared to variant 2, the water savings of the DDBM method would be 1,200 m^3 per ha and season.

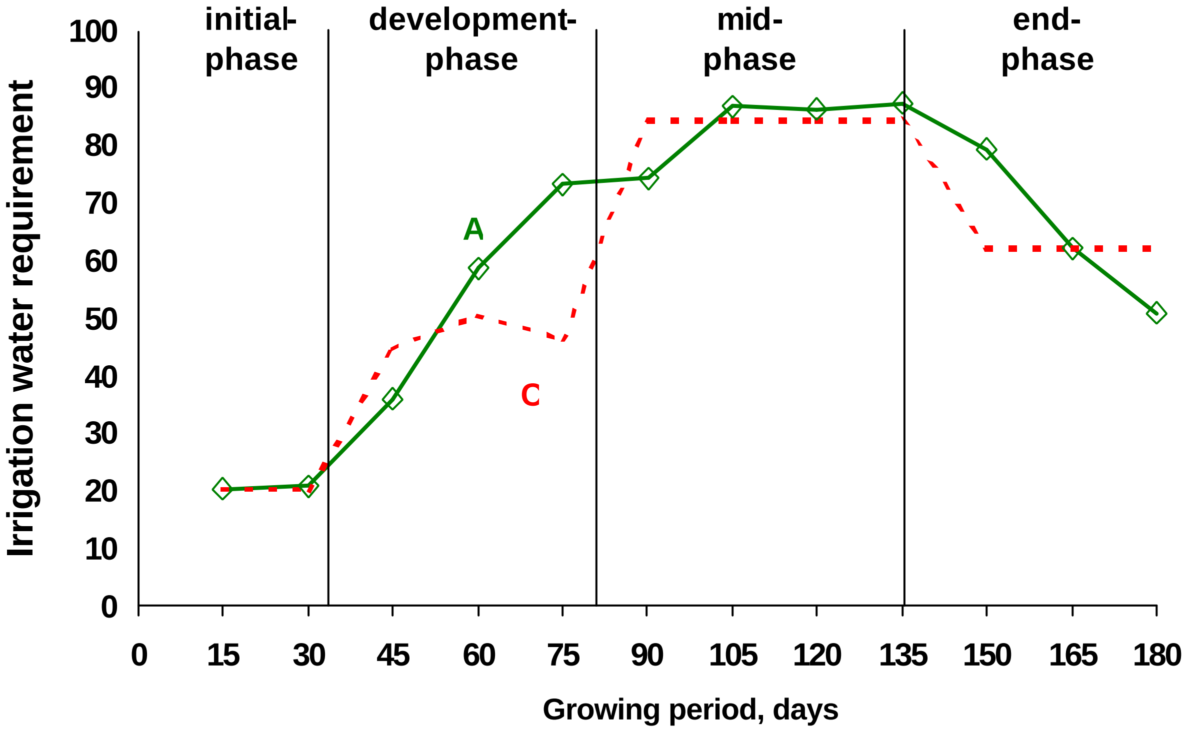


Figure 16: Effect of plant water requirement as phase average value on irrigation water requirement in DDBM (m^3 ha^{-1}), for Cotton in Port Said (soil A; water b): Case A: ET_c P and Z_r as daily values from curves 11a-e and 12a-d; Case C: P und Z_r as daily values and ET_c as phase average values:1.4 mm day^{-1} for initial-phase; 3.25 mm day^{-1} for development-phase; 6.8 mm day^{-1} for mid-phase and 5 mm day^{-1} for end-phase

The use of conventional calculation methods for the irrigation water requirement, which are based purely on averages, leads to faulty estimates compared to those based on daily values. In the case of cotton, there was an overestimate of the irrigation water requirements in the first 50 days of the growth period, as well as between the 80th and 90th and after the 165th day. Such overestimates result in a waste of irrigation water which could have been used for other crops at the same time. Between the 50th and 80th day and between the 100th and the 165th day considerable underestimates of the actual requirement arose in some cases. Such underestimates lead to an undersupply of the plant with water, which can seriously affect the success of irrigation.

Table 19: Irrigation water requirement (ET_c) for cotton in Port Said under: soil A; water b; max. allowable soil moisture depletion, 0.55; ET_c as phase value: 1.4 for (initial-phase); 3.25 (development-phase); 6.8 (mid-phase) and 5 mm day^{-1} (end-phase)

Day	Irrigation water requirement using DDBM, m^3 ha^{-1}	
	using ET_c and P as daily values	using ET_c and P as average values
15.	20.3	31.7
30.	21.0	31.7
45.	36.1	54.5
60.	58.7	54.5
75.	73.3	47.2
90.	74.5	83.7
105.	87.0	83.7
120.	86.3	83.7
135.	87.6	83.7
150.	79.5	61.5
165.	62.1	61.5
180.	51.0	61.5

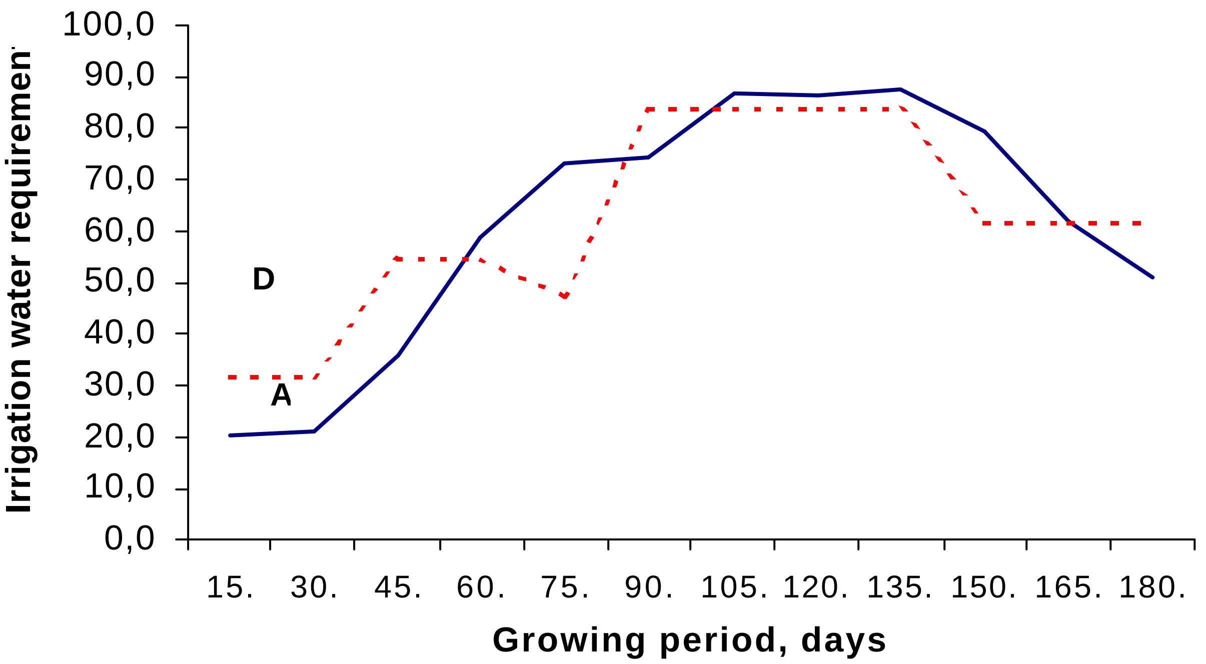


Figure 17: Importance of DDBM to correspond the applied irrigation water requirement (m^3/ha) with the real plant requirement, for Cotton in Port Said (soil A; water b):
Case A: ET_c P and Z_r as daily values from curves 11a-e and 12a-d;
Case D: Z_r as daily values, P as season average values and ET_c as phase average values:1.4 mm day^{-1} for initial-phase; 3.25 mm day^{-1} for development-phase; 6.8 mm day^{-1} for mid-phase and 5 mm day^{-1} for end-phase

Table 20. Irrigation water requirement for cotton in Port Said under following a-sumptions: soil A; water b; max allowable soil moisture depletion 0.55; ET_c = 1.4 for (initial-phase), 3.25 (development-phase), 6.8 (mid-phase) and 5 mm day^{-1} (end-phase) and root depth 30, 110, 138 and 138 cm for each phase resp.

Day	Irrigation water requirement, m^3 ha^{-1}	
	Parameters: daily values	Parameters: average values
10.	18.8	32.0
20.	20.3	32.0
30.	21.0	32.0
40.	31.7	55.0
50.	42.5	55.0
60.	58.7	55.0
70.	68.6	55.0
80.	72.7	55.0
90.	74.5	84.5
100.	87.0	84.5
110.	87.0	84.5
120.	86.3	84.5
130.	87.6	84.5
140.	87.0	84.5
150.	79.5	62.1
160.	67.1	62.1
170.	58.4	62.1
180.	51.0	62.1

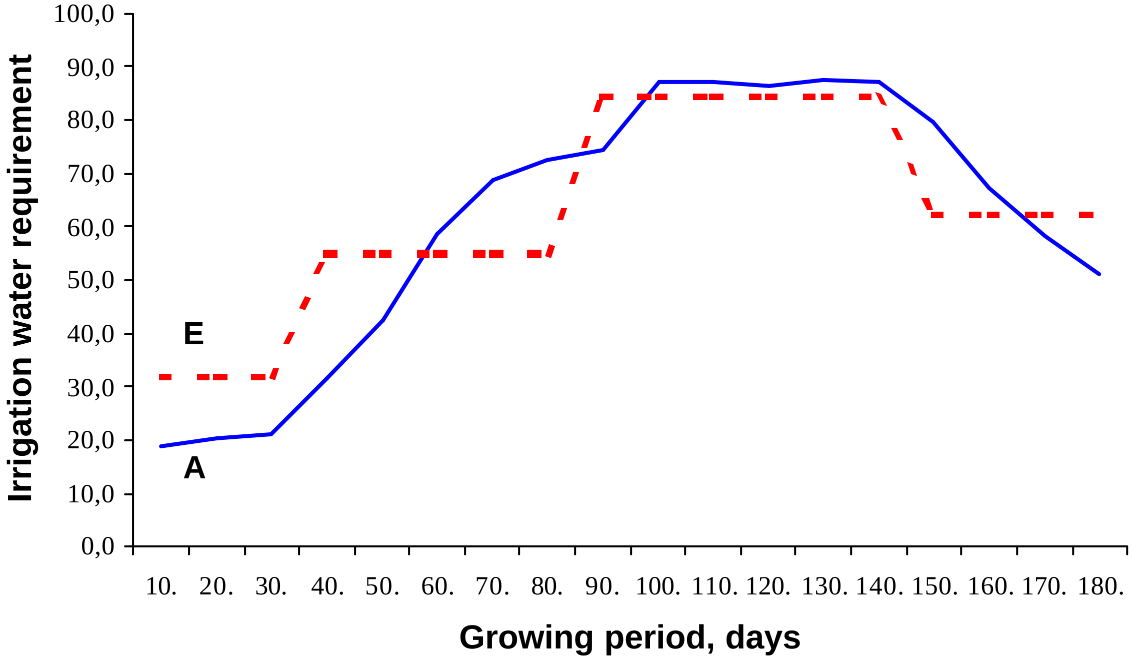


Figure 18: Irrigation water requirement for cotton in Port Said under following assumptions:
Case A: ET_c P and Z_r as daily values from curves 11a-e and 12a-d;
Case E: ET_c as phase average value, P as season average value and Z_r, depen-ding on phase, 30, 110, 138 and 138 cm resp.

Table 21. Irrigation water requirement for Maize in Port Said under: soil A; water a (Nile-water) & b (Salam canal water) using DDBM

Day	Irrigation water requirement, $m^3\ ha^{-1}$.	
	Nile-water	Salam canal water
15.	51.3	307.7
30.	55.8	334.7
45.	74.0	444.0
60.	89.1	534.7
75.	99.6	597.4
90.	96.3	578.0
105.	97.8	586.5
120.	97.8	586.5
135.	95.0	569.5
150.	77.2	463.3
165.	48.9	293.3

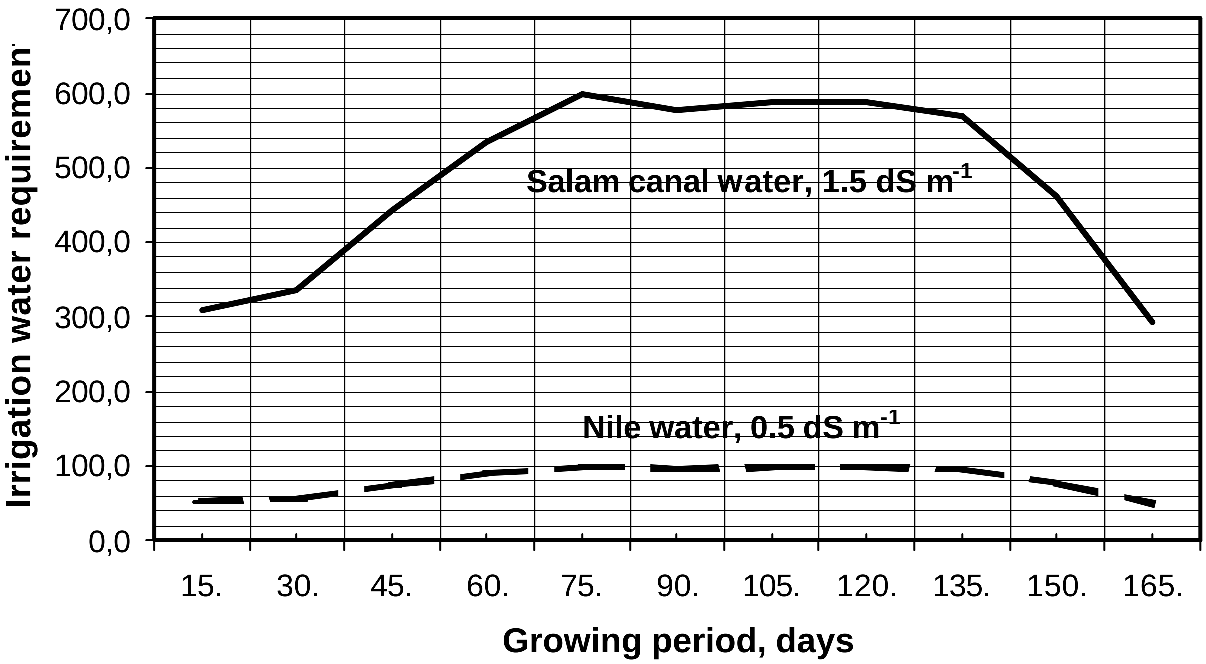


Figure 19: Effect of irrigation water quality on irrigation water requirement, $m^3\ ha^{-1}$, calculated with DDBM-model for Nile water and Salam canal water for maize in Port Said. This Figure can also be used as a nomogramm for assessment the irrigation water requirement

Table 22. Comparison of the irrigation water requirements for cotton (Egypt) calculated by the DDBM method and the usual ARC method.

Method	Irrigation water requirement (m^3 ha^{-1} $Season^{-1}$)
ARC – Variante 1, (ET_c season average based)	12,739
ARC – Variante 2, (ET_c phase average based)	12,401
DDBM (daily data based)	11,205

5.3. Raising water use efficiency by reducing the leaching requirement for salinity conditions

Maximising salt leaching efficiency or lowering the leaching requirement can reduce the amount of water needed. The salt leaching efficiency can be higher under unsaturated than saturated conditions. Soil characteristics or irrigation methods that lead chiefly to unsaturated water moving through the soil reduce not only water consumption and leaching requirement but also maximise leaching efficiency. There are various proposals for reducing the leaching requirement, some of which, however, are limited to specific situations or do not represent a lasting solution: Cultivation of crops in the cooler season instead of the warmer, as the leaching requirement depends on the evapotranspiration; cultivation of salt-tolerant crops; application of cultivation methods which restrict percolation in and through large pores (Chhabra, 1996).

Hoffmann et al. (1990) have proposed a model that describes the relationship between salt concentration in the root zone and yield (Eq. 40):

$$Y_r = 100 - S\,(C - C_t)$$

where Y_r is the relative yield, S the percentual yield loss per unit of salt concentration, C the mean salt content in the root zone, and C_t the highest value of salt concentration before yield loss would occur. The equation shows how the yield rises as the salt content falls. But therefore it can be necessary that the amount of irrigation water needed for the reduction of salt content by leaching is not limited, which is not the case in our study. An equation like this therefore has no practical significance for us, as we must strive for high yields while using as little irrigation water as possible.

The research presented here recommends a new concept: an “economic water quantity” aimed at higher efficiency in irrigated agriculture.

Normally, with a higher salt content in the soil a greater quantity of irrigation water is needed to regularly obtain the maximum yield. However, this can be uneconomical. It would be more economical to sacrifice the maximum yield: that is, to be satisfied with a lower yield in favour of using less irrigation water. Figure 19 (example: maize at Port Said location with two different qualities of irrigation water) clearly shows the influence of water quality on the partly unrealistically high irrigation water requirement. If the more saline Salam canal water is used, about six times more water is needed than would be required with the Nile water variant. One needs to ask whether the yield justifies this extra quantity of water. In other words, how high would yield-loss be with a specified reduction in irrigation water?

Table 23 has been calculated after Eq. 42 as follows:

$$W_{ras} = D_s / (D_s - I_s) * W_{ra}$$

where W_{ras} is the plant water requirement under saline conditions. It was calculated with the help of parameters: W_{ar} = plant water requirement under non-saline irrigation water (Table 11); I_s = salt content in the irrigation water (EC); and D_s = salt content in the drainage water (EC). Salt content in root zone is a limiting factor for yield level obtained under salinity conditions. For example, Table 16 shows that the yield levels of maize will be 95, 82.5, 62.5, 25 and 0 % at salt content in root zone equal to 1.7, 2.5, 3.8, 5.9 and 10.0 dS m^{-1} resp.

Figure 20 illustrates the relationship between plant water requirement and yield level (for maize in Port Said under two irrigation water qualities: Nile water, EC = 0.5 dS m^{-1}, and Salam Canal water, EC = 1.5 dSm^{-1}. The high plant water requirement value in case of Salam Canal water (in brackets, Table 23) is purely calculated, but unrealistic in practice. Such amounts of water are hardly available and technically not to be apply.

The results in Figure 20 which are based on Table 23 (in addition the plant water requirement for peanut under 3.0 dS m^{-1} irrigation water quality was also calculated) indicate that it is not reasonable to increasethe yield using high saline irrigation water. The obtained yield will only slightly increase with using of an unrealistic amount of water.

As the calculated irrigation water requirements for maize and peanut under 1.5 and 3.0 dS m^{-1} water quality resp. (Table 23) are unrealistic (i. e. aprox. 80.000 and 100.000 m^3 ha^{-1} $season^{-1}$ for maize and peanut resp.), it was recommended that Eq. 42 should be used only when the difference between the salt content in irrigation water and the salinity threshold in root zone is more than 0.5 dS m^{-1} (see Table 12).

Figure 20 makes it clear that if water b is used, a decline in the rate of yield increase results. With a water dosage (with maize) of more than 22,000 m^3 ha^{-1} $season^{-1}$, there is little appreciable increase in yield. For example, raising the amount of water from 22,000 m^3 ha^{-1} $season^{-1}$ to 30,000 m^3 ha^{-1} $season^{-1}$ (i.e. an increase of 8,000 m^3) would only produce a yield increase of 3 %. If one adds the same amount of water to hitherto inadequately irrigated fields there would be a yield increase of approx. 30 %.

To calculate the EC value in the root zone (D_s) there is an example in Figure 20 and Table 23: According to Eq. 42 the crop water requirement under saline conditions (W_{ras}) is calculated as follows:

$$W_{ras} = [\, D_s / D_s - I_s \,] \; W_{ra}$$

Accordingly, the salt content in the root zone (D_s) amounts to ....

$$D_s = [\, W_{ras} \;\; I_s \,] / [\, W_{ras} - W_{ra} \,]$$

It can now be shown which D_s value (EC) obtains in the root zone under specified irrigation methods with the following assumptions:

I_s Irrigation water salinity of the Salam canal water with EC=1.5 dS m^{-1}

W_{ra} Plant water requirement ET_c = 9240,2 m^3 ha^{-1} $season^{-1}$ (Table 11)

W_{ras} Plant water requirement under saline conditions = 20,000 m^3 ha^{-1} season^{-1}.

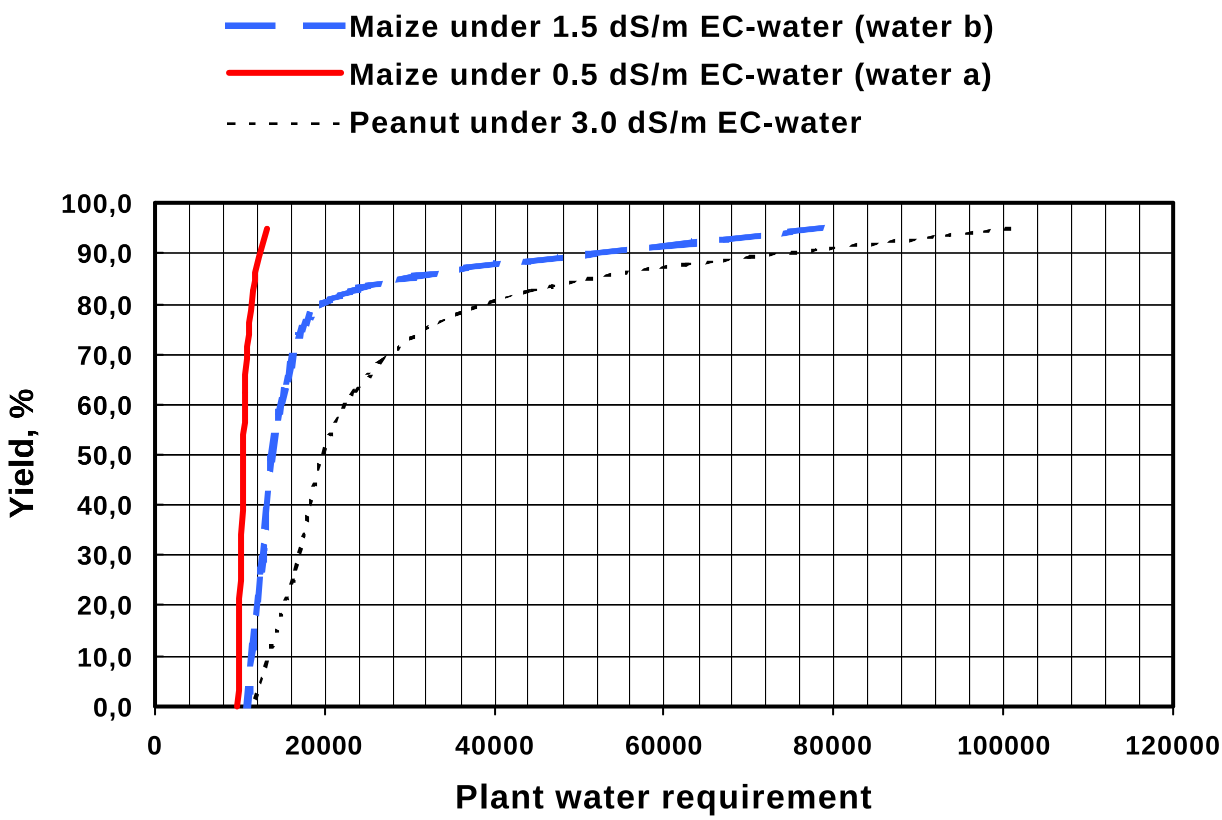


Figure 20: Relationship between plant water requirement (m^3 ha^{-1} Season^{-1}) and yield level under three irrigation water qualities for maize and peanut in Port Said (using Eq. 42)

Table 23: Plant water requirement for Maize in m^3 ha^{-1} season^{-1} under two water qualities and accordingly yield level (Port Said).

EC-Threshold values in root zone (dS m^{-1})	Yield level, %	Plant water requirement (W_{ras}), m^3 ha^{-1} Season^{-1}	
		Nile water	Salam canal water
1.7	95.0	13090	(78542)
2.5	82.5	11550	23101
3.8	62.5	10640	15266
5.9	25.0	10096	12390
10	0.0	9727	10871

Here a yield level (example of maize) of about 80 % is assumed. The application of 20,000 m^3 irrigation water to achieve this level of yield makes economic sense. A greater quantity of water would achieve too slight an increase in yield. The quantity of water thus reduced is called the “economic irrigation water quantity”. A soil EC value of approx. 2.8 dS m^{-1} is calculated here for D_s using Eq. 42. This is about the same value as is given in Table 16 for this case.

If better-quality (EC = 0.5 dS m^{-1}) Nile water were used instead of Salam canal water, sacrificing a yield level of 90-100 % would not be economic, because a full yield compared to an 80 % yield can be achieved with merely 2,000 m^3 of irrigation water.

Figure 21 demonstrates the relationship between the plant water requirement under saline conditions and the yield level for other crops (location Port Said) and exclusively in the case of using Salam canal water (EC = 1.5 dS m^{-1}). The curve in Figure 21 is again calculated using Eq. 42 on the basis of data in Tables 11 and 16. It can be seen that in the case of cotton it is good policy not to reduce the quantity of water used, as the last 1,000 m^3 of irrigation water still produces 35 % of the yield and that because of the higher salt tolerance of cotton not so much leaching water would be needed as with maize. The same is true, for example, for soybeans and in general for those cases where the salt tolerance of a crop plant clearly lies above the salt content of the irrigation water. This is shown in Table 12. From the salt tolerance in Table 16 it is to be expected that pepper will react like maize, whereas sugar beet would be like cotton. With peanuts the last 1,000 m^3 brings a rise in yield of 15 % (Figure 21) whereas with maize (Figure 20) the last 10,000 m^3 brings an increase of only 2 %. The conclusion is that while with a higher salt content in the soil one normally applies a higher quantity of irrigation water to achieve the maximal yield, this can be uneconomic for plants which are not salt tolerant. In other words: When calculating the leaching requirement attention must be paid to the following: If the calculation is made according to the usual equations or the normal local practice, then either a higher loss of water can occur (e.g. in the case of maize: 58,542 m^3 ha^{-1} $season^{-1}$) or by underestimation a considerably lower yield, for example, by an underestimate of 1,000 m^3 in the case of soybean a yield loss of 45 % (see Figure 21). This is why the concept of paying attention to an economic EC threshold level is so important.

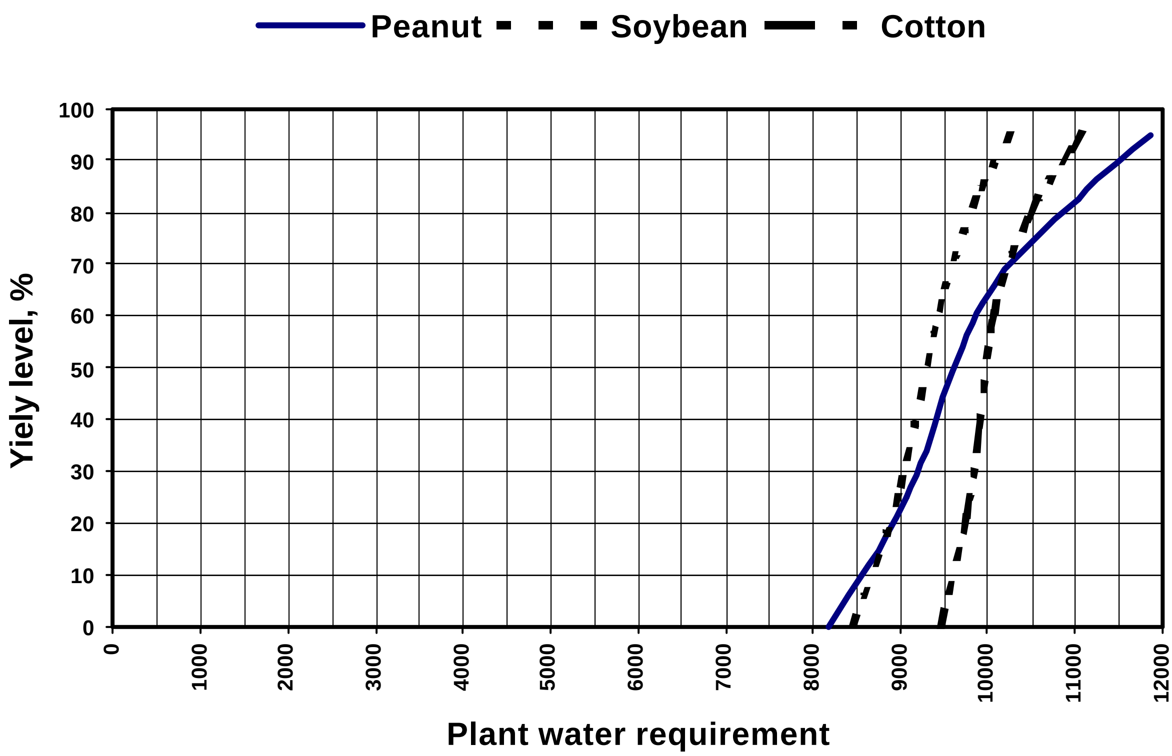


Figure 21: Relationship between plant water requirement, m^3 ha^{-1} Season^{-1} and yield level for peanut, soybean, and cotton under 1.5 dS m^{-1} saline water (location: Port Said)

Should the quality of the crop grown sink because of lack of water, then in calculating the quantity of irrigation water new values for salt content in the root zone must be derived instead of threshold values in Table 16. Figure 22 shows the relationship between crop water requirement and salt content in the root zone: If for maize a value of 1.8 dS m^{-1} is taken instead of 1.7 dS m^{-1}, then the water requirement would sink by 23,000 m^3 ha^{-1} season^{-1} with only a light drop in yield to 91 %. If for peanuts a value of 3.3 dS m^{-1} is taken instead of 3.2 dS m^{-1}, the water requirement would sink by 31,000 m^3 ha^{-1} season^{-1} with only a slight drop in yield level to 89 %.

However, Figure 21 also shows that according to calculations using Eq. 42 a comparatively slight undersupply of irrigation water can already lead to a considerable reduction in the yield level. If cotton were given about 1,000 m^3 water per hectare and season less than would be necessary for a yield level of 95 %, then this would lead to a yield level of only 60 %. For cotton, which has a growth period of 195 days, 1,000 m^3 is an average of 5 m^3 hectare^{-1} day^{-1} or barely 10 % of the daily irrigation water quantity. That means that a relatively little irrigation deficit of only 10 % daily in the average can lead to a great loss in yield. Of course, applied to individual phases, the percentage error can be considerably higher in some cases and lower in others. The conclusion is that undersupply is also to be avoided, and this is only possible through precise scheduling of irrigation.

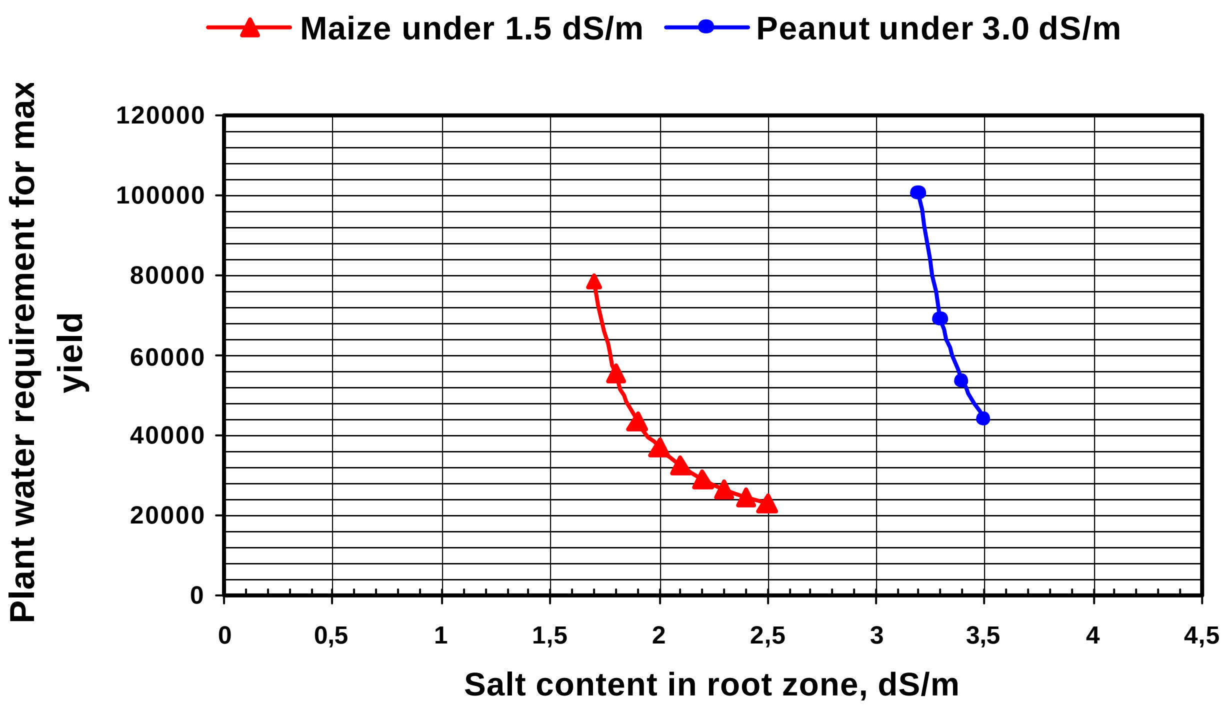


Figure 22: Correlation between plant water requirement m^3 ha^{-1} $Season^{-1}$ and salt content in root zone, dS m^{-1}

In practice, however, there is no guarantee that slight undersupply of this order can always be avoided. It is recommended, therefore, to raise the plant water requirement as calculated with Eq. 42 by a fixed safety margin. This addition should be about as large as the water quantity that would be required to produce the last 10 % of yield level: i.e. the difference between the 85 % and 95 % yield levels. According to Figure 21 (Salam canal water) these last 10 % of yield, i.e. the difference between the 85 % and 95 % yield levels, was produced by about 700 m^3 (5.9% of total requirement for peanuts), 400 m^3 (3.6 % of total requirement for cotton) and 350 m^3 (3.4 % of total requirement for soybeans) of water per ha per season. In Figure 20 (in the case of Nile water and maize) this last 10 % was produced by about 1,000 m^3 water per ha and season (7.6 % of the total requirement).

As the water requirement for the last 10 % of yield level varies from crop type to crop type, a simple method of calculation for the appropriate extra quantity of water $Z_{wm10\%}$ must be developed. As the extra quantity of water ($Z_{wm10\%}$) is a function of I_s (irrigation water salinity) and D_s (drainage water salinity), the following applies:

$$Z_{wm\ 10\%} = f\ (I_s, D_s)$$

where $Z_{wm10\%}$ to I_s is proportional, to D_s reverse proportional - thus

$Z_{wm\ 10\%} = f\ (I_s)$

$Z_{wm\ 10\%} = f\ (1 / D_s)$

For calibration and to determine the unknown factor F, this equation was adjusted to those percentages of irrigation water quantities (see Figures 20 and 21) which are necessary to obtain the last 10 % of yield increase from the individual crop types (Table 24) thus:

$$Z_{wm\ 10\%} = 0{,}1 * (I_s / D_{s1})^{\ 0{,}45\ Is} \qquad \text{Eq. 59}$$

(D_{s1}=drainage water salinity for yield level of 95 % according to Table 16). Table 24 shows that the extra quantities (%) determined by Eq. 59 each approximately correspond to the values obtained from Figures 21 and 20 (from Eq. 42) as mentioned above.

These minimal additional quantities will ensure that a high water use efficiency is achieved.

Table 24. Comparison between the water quantities that must be added as extra (relative) to ensure the last 10% of yield level. Calculated by means of Eq. 59 and after the curves (Figures 20 and 21)

Method	**Maize**	**Peanut**	**Soybean**	**Cotton**
	Irrigation water quality (I_s), dS m^{-1}			
	0.5	1.5	1.5	1.5
from the curves (Figures 20 and 21) after Eq. 42	7.6 %	5.9 %	3.4 %	3.6 %
after Eq. 59	7.6 %	6.0 %	4.4 %	3.3 %

6. Discussion

The entire water requirement of all consumers in Egypt totals 71-73 mrd. m³ per year. However, the combined water resources of the Nile, groundwater and drainage water recycling add up to only 63 mrd. m³ (Bishay,1993; Attia et al., 1995; FAO, 1997; Abdel-Hafiez et al., 1999). There is no possibility of accessing additional water resources (Anonymus, 1995; Seckler and Altaf, 1997). Therefore, Egypt has been trying to save water in order to be able to irrigate additional areas for agricultural production, for e-xample in the New Valley and Sinai Development Irrigation Project (Abu-Zeid, 1997). To this end, the outflow of the Nile to the Mediterranean Sea has been reduced: in the period from 1974 until 1996 the flow dropped from 6.2 mrd. m³ to 0.26 mrd. m³ per year (Seckler and Altaf, 1997). Furthermore, drainage water from irrigated areas is recycled, at this present date, more than 4.7 mrd. m³ a year. According to Rhoades et al. (1992) more than 6800 ha were irrigated with saline water (electronic conductivity: 0.5 – 6.0 dS m^{-1}). However irrigation with saline water has not always been successful (Afifi et al., 1996; El Karamity and Attaallah, 1997; El-Dessouky and Attawia, 1998; Helal et al., 1998; Ashour et al., 1999), see Section 2.1.3.

Egypt has a number of practical field methods, by which water loss can be reduced and water use efficiency increased, for example lining the irrigation-feeder-canals (re-duces the rate of seepage), using pipelines instead of open canals (reduces evaporati-on), and exact leveling of the irrigated areas, possibly with a slight slope (as recommen-ded in Section 2.2.1.3). Some suggest using the RDI-strategy (RDI = Regulated Deficit Irrigation) in irrigation management (Chalmers et al., 1981), though Mohamed and Tammam (1998) report that the application of this strategy led to a considerable reducti-on in the wheat-yield (see Section 2.2.11). What is still missing among these efforts to solve the water problem is an exact scientifically based regulation of the amount of irri-gation water, the application of regulating methods and the quantification of the effects of the regulation process with regard to the water use efficiency. Viddal et al. (1999) re-port that approximately 500 mil. m³ of water a year could be saved from 600.000 ha in the middle Nile Delta, and that food production could be raised by 10 %, if the local irri-gation water requirements were taken into account instead of regional or national requi-rement averages.

The present study attemps to find further ways of saving water and improving existing possibilties in order to achieve a greater water use efficiency with limited water resources and without losses in yield, or in other words, to reduce the waste of water. The task has been approached as follows:

The Suez Canal region was chosen as research area, because it mainly consists of land new to agricultural cultivation. Parts of this region are already irrigated and some parts still have to be ameliorated, e. g. the Tina Plains between Port Said and El-Arish. In total, the agricultural land in the research area amounts to 425,000 ha. The government decided that this region is to be irrigated with water from the Salam Canal Project (a mixture of drainage water and Nile water). The specific characteristics and problems of the research area have already been discussed in chapter 4: - Partially salinized soils, high levels of groundwater, saline irrigation water and a high sandy content in some soils. In order to protect the soil, plants and water supply, the irrigation process must be executed with great care.

The reference-evapotranspiration (ET_o) is the strongest factor influencing the water requirement of plants. The Penman-Monteith-Equation (Smith et al., 1996; see Eq. 30) was chosen as the most suitable method of calculation. This choice was made by a comparison of the accuracy of prediction of several methods (see Section 2.3.3.4.). The Penman-Monteith-Equation is also named by Howell (1996), Simon et al. (1998) and Michael & Bastiaansen (2000) as the standard method for the Mediterranean area. In order to calculate the crop water requirement the FAO-standard crop coefficient K_c was adjusted to the climatic-conditions of each location by means of equations 9 and 10 (see Table. 10). A dialog-box was designed to calculate the reference-evapotranspiration (ET_o) and the crop evapotranspiration ($ET_c = ET_o * K_c$) respectively and to facilitate the input and output of data (Figure 7). As the information on precipitation in the research area necessary for the calculation of the irrigation water requirements could not be obtained, only crops from the precipitation-free summer half year were used, namely the economically important crops maize, peanut, sunflower, soybean and cotton.

To ensure that the ET_o-values, calculated with aid of the dialog box (Figure 7) were correct (results of all three locations, see Table 7) they were compared with ET_o-values from the literature on the subject (see Section 4.2.1.). As shown in Figures 3, 4 and 5 there is a good correspondence between the values calculated and those obtained from the literature. The greatest correspondence was shown at the locations of Port Said and El-Arish (see Table 6). The model is therefore especially suitable for the planning of new irrigation in the area of El-Arish. After confirming the validity of the method the next point to be dealt with was the optimization of the water supply that is:

Improved ET_o oriented geographic distribution of crops (IGDC)

Figure 8 shows a considerable difference between the ET_o-values of the three locations, especially between Port Said and El-Arish on the one hand and El-Ismailia on the other hand in the time period between January and October. For that reason, the following concept was designed with the help of the values of the water requirements of plants of all crop types (Table 11) in order to achieve a better geographical distribution of the different crops: Crops with high water requirements are to be cultivated in regions with low reference evapotranspiration; Table 11 shows in a simple example, that maize is a culture with high water requirement whereas sunflower has a low water requirement. The Table 7 shows that El-Ismailia has the highest reference evapotranspiration and El-Arish has the lowest. With these figures in mind it should be suggested that maize should be cultivated in the El-Arish area and sunflower should be cultivated in the El-Ismailia area.

In Section 5.1., two cases (A and B) are compared. This comparison shows the significance of the concept for irrigation-planning. In case B approximately 60,000 m³ of water can be saved per season in comparison to case A. These 60,000 m³ result from a reorganisation of only 100 ha arable acreage in each of the three regions, in accordance with the IGDC-concept (Improved Geographic Distribution of Crops). The statement of Viddal et al. (1999), that approximately 500 mil. m³ of water could be saved from 600,000 ha if the local irrigation water requirements were taken into consideration, can be confirmed, as following the IGDC -concept (projected) 600,000 ha would bring a saving of 360 mil m³ of water per season. Another aspect: The amelioration (desalinisation) of 20,000 ha in the Tina plains (between Port Said and El-Arish) with the help of Salam-canal-water, as Mahmoud suggests (1989), would require approximately 14,000 m³ per hectar a year; with the 60,000 m³ of water saved per season following case B it would be possible to ameliorate 4 ha. Or the saving of 60,000 m³ could be used to irrigate 6 ha of a crop which requires 10,000 m³ per season.

Daily data based model for irrigation scheduling (DDBM)

It was pointed out that in the planning of irrigation scheduling management, many specialists calculate the necessary parameters (plant water requirement, ET_c, allowable soil-moisture depletion, P, and root-depth of plants, Z_r) using average monthly and seasonal values (see Section 5.2.). The present work, by contrast, attemps to examine the effect of the daily change in these parameters (in comparison with the use of average values) on water-use efficiency. In simulating daily irrigation-water requirements the model applied uses curves for the water-requirement of plants, allowable soil-moisture depletion levels and root development taking into account the following location-data: Effective precipitation, soil water content at field capacity and at permanent wilting point, quality of the irrigation water and threshold value of salinity at 10 % yield reduction (see Section 5.2.).

For the examination of the effect of using daily data (in comparison to the use of average values) on the irrigation water requirement, calculations were made for certain cultures according to DDBM under specific assumptions (see Section 5.2.). For that purpose the following variants were calculated on the example of cotton in the area of Port Said:

- Case A: All parameters (ET_c, Z_r and P) were put in as daily values. This variant is also the standard case (and can also serve as nomogramm for determining the irrigation water requirement on a specified day), with which the other cases are to be compared.

- Case B: ET_c and Z_r were used as daily values, P was put in seasonal average value (according to the literature, equal to 55 % field capacity) see Figure 15.

- Case C: P and Z_r were inserted as daily values, ET_c as phase value (see Figure 16).

- Case D: All Parameters were put in as average values (see Figure 18).

Cases A and B (Figure 15) differ as regards irrigation water requirements during the first 90 days; the calculations for case A resulted in 558 m³/ha less than for case B: The overestimation in case B would lead to a waste of irrigation water which could have been used for other crops at the same time.

Figure 16 shows that in the cases A and C, even though the allowable soil moisture depletion in the form of daily values was considered in the model, there was a considerable impairment of the balance between the actual crop water requirement (A) and the irrigation water dosage as calculated according to case C. This occurred especially between the 50th and 90th, and the 135th and 170th day. In Figure 18, variant D, for which all parameters were set as average values, shows both underestimates and overestimates compared with A.

A comparison with results of the ARC (Agricultural Research Center, Cairo), which has been dealing with the optimization of irrigation of cotton in Northern Egypt, shows that the DDBM- method achieves a saving of 1,500 m³ ha^{-1} per season (when using seasonal average values for ET_c) and 1,200 m³ ha^{-1} (when using phase average values for ET_c) in comparison with the ARC-method (see Table 22).

The effect on the quantity of irrigation water when soil texture was taken into consideration, was also analysed. For that purpose the irrigation water requirement for maize in the El-Ismailia area was examined on two different soils (a = sandy clay loam and b = loamy sand), with a water quality of EC = 0.5 dS m^{-1}. The results (Table 17 and Figure 14) show that in the time period up until the 75th day, the difference in soils causes a difference of 4 to 9 m³ per hectar per day in the amount of irrigation water needed (approximately 500 m³ per hectar and season). The fact that after about the 75th day of the growing period, the difference in soil type no longer has any effect on the amount of irrigation water needed, can be traced to the fact that the value of the root zone no longer changes. The difference between 11.8 % and 5.5 % of the water available for plants (see Section 5.2.) thus leads to a difference in the irrigation water required of aproximately 500 m³ per hectar per season.

To analyse the effect of water quality on the amount of irrigation water needed, a calculation was made for maize in the Port Said area. This was done with two variants for water, namely (a) with EC = 0.5 dS m^{-1} and (b) with EC = 1.5 dS m^{-1}. The results show great differences in the amount of irrigation water required (Table 21): A difference of 1.0 dS m^{-1} in the salt content causes a difference of more than 60,000 m^3 ha^{-1} in the amount of irrigation water required for the entire period of vegetation. This means that even a small difference in irrigation water quality between locations must be considered when planning irrigation in accordance with the IGDC concept.

Reduction of leaching requirements (Economic amount of irrigation water)

With saline irrigation water and salt concentration in the soil a certain amount of water is required in addition to the actual irrigation water for the purpose of desalinisation. The present research therefore calculates the amount of water required by plants in saline conditions (see Table 12). The desalinisation requirement was calculated with the help of Eq. 42 and Table 16. An examination of Figure 20, which shows the relation between the crop water requirement and yield level with three irrigation water qualities for maize and peanut crops in Port Said, reveals two extreme problems:

1. In the case of maize (irrigation water quality 1.5 dS m^{-1}) and peanut (3.0 dS m^{-1}) an unrealistically high amount of water (calculatively 78,542 and 100,795 m^3 ha^{-1} season^{-1}, respectively) would be required to achieve the maximum yield.

2. An inexact scheduling of the irrigation of maize (irrigation water quality 0.5 dS m^{-1}) resulting in a minus of only 1,000 m^3 ha^{-1} season^{-1} would already reduce the level of yield from 95 % to 85 %.

In order to solve the problem referred to under point 1, it is suggested that when calculating the quantity of irrigation water according to Eq. 42 and Table 16 a lower level of yield should be accepted, for example 82.5 %. This would mean that to achieve a yield of 82.5 % from maize in Port Said with the above-mentioned irrigation water quality, 23,101 m^3 ha^{-1} season^{-1}, (instead of 78,542 m^3 ha^{-1} season^{-1}) would be required; in the case of peanut 44,098 m^3 ha^{-1} season^{-1} would be needed instead of 100,795 m^3

ha^{-1} $season^{-1}$ (see Figure 20). This reduced water quantity should be called the economic irrigation water quantity. Water saved in this way could be used for other crops. In the case of cotton (salt tolerant) in the Port Said region, on the other hand, it is better not to reduce the amount of water used, as the last 1,000 m³ of water still achieve a growth in yield of 35 percentage points (see Figure 21). The same goes for soyabeans for example and generally in any of those cases where the salt toleration of the crop clearly lies above the salt concentration in the irrigation water. This can be deduced from Table 12. In cases like these, it is not necessary to apply the concept of "economic amount of irrigation water". Allthough with higher soil salinity, a higher quantity of irrigation water is normally used to achieve the maximum yield this could be uneconomical for crops with no salt tolerance. (see Section 5.3.).

Should the quality of the harvest sink due to lack of water, other values for the salt content in the root zone would have to be determined and used in the calculation of the amount of irrigation water required instead of the threshold values in Table 16. Figure 22 shows the correlation between crop water requirement and salt content in the root zone: Taking a threshold value of 1.8 dS m^{-1} for maize instead of 1.7 dS m^{-1}, would lower the water requirement by 23,000 m³ ha^{-1} * season with only a slight yield reduction to in 91 %. A shift in threshold value from 3.3 dS $m^{-1}$to 3.2 dS m^{-1}in the case of peanut would lower the water requirement by 31,000 m³ ha^{-1} $season^{-1}$ with only a minimal drop in yield to 89 %.

With regard to the problem raised in number 2: The final 10 % of yield, namely the difference between 85 % and 95 %, is seasonaly produced according to Figure 21 (using of Salam Canal water) in the case of peanuts with 700 m³ ha^{-1} $season^{-1}$, in the case of cotton with 400 m³ ha^{-1} $season^{-1}$ and in the case of Soya with 350 m³ ha^{-1} $season^{-1}$. This amounts to 5.9 %, 3.6 % and 3.4 % of their respective total irrigation requirements. In the case of maize (Figure 20, with water from the Nile), these last 10 % are produced with 1,000 m³ ha^{-1} seasonal irrigation water (7.6 % of the total requirement). In order to secure this last 10 % of yield, a safety margin reserve is recommended, for which purpose the Eq. 59 was developed in this work. Table 24 shows the additions calculated with the help of Eq. 59.

If the salinity of the irrigation water and the drainage water (the latter corresponds to the salt content of the root-zone) is known, the equation (Eq. 59), which was developed during this study, enables the expert to calculate a safety reserve to add to the quantity of irrigation water calculated according to Eq. 42.

7. Summary

This investigation is an attempt to find further ways to solve the water scarcity problem in Egypt, where the existing water resources (˜ 63 mrd. m^3 $year^{-1}$) are less than the water demand (˜ 71 – 73 mrd. m^3 $year^{-1}$). Although Egypt had made quite a number of efforts to overcome its water shortage, a quantification of the contribution of regulating the irrigation water supply under field condition for increasing the water use efficiency is still missing.

This study aims to increase the water use efficiency through optimizing the irrigation water supply of a certain area in Egypt (Suez Canal region), where the Sinai Irrigation Development Project is an Egyptian try to irrigate additional areas for agricultural production. In this project about 425,000 ha have been planned to be irrigated. The irrigation water used for this purpose is the Salam-Canal water (Nile water mixed with agricultural drainage water for saline irrigation with EC = 1.5 dS m^{-1}). Five economic crops, namely: maize, peanut, soybean, sunflower and cotton were selected in this investigation. To achive a greater water use efficiency and an irrigation water saving three ways were developed: Improved ET_o oriented geographic distribution of crops(IGDC), a daily data based model for irrigation scheduling (DDBM) and reduction of leaching requirements. The Penman-Monteith equation has been selected for calculation the main factor influencing the plant water requirement i. e. reference evapotranspiration, ET_o.

The first way: An improved ET_o oriented geographic distribution of crops (IGDC) means that crops with high water requirements are to be cultivated in regions with low reference evapotranspiration and vice versa. For example, because there are considerable differences between the ET_o-values of the three research locations, especially between Port Said and El-Arish on the one hand and El-Ismailia on the other hand, it was suggested that maize (that is a culture with high water requirement) should be cultivated in El-Arish while sunflower (that has a low water requirement) should be cultivated in El-Ismailia that has the highest reference evapotranspiration. In such case a quantity of approximate 60.000 m³ of water can be saved per season of only 100 ha. These 60.000 m³ resulting from a reorganisation could be used for amelioration (desalinisation) of 20.000 ha in the Tina plains (between Port Said and El-Arish) with the help of Salam-canal-water or could be used to irrigate 6 ha of a crop which requires 10.000 m³ per season.

The second way: It was pointed out that in the planning of irrigation management, many specialists calculate the necessary parameters (plant water requirement, ET_c, allowable soil-moisture depletion, P, and root-depth of plants, Z_r) using average values. The present work, by contrast, attemps to examine the effect of the daily change in these parameters (in comparison with the use of average values) on water-use efficiency. With the examination of the effect of using daily data (in comparison to the use of average values) on the irrigation water requirement, the results showed that considering the P-Value as daily value can only lead to irrigation water saving aproximate resulted in 558 m³ ha^{-1} in the first 90 days, which could have been used for other crops at the same time. The result indicated that the balance between the actual plant water requirement and applied irrigation water can agree when all parameters as daily values are considered as it is done by DDBM. The effect on the quantity of irrigation water when soil texture was taken into consideration was also analysed. The DDBM model is also very suitable for the conditions of the investigated locations where saline soils and/or soils with high water tables are to be irrigated with saline water.

The third way is the reduction of leaching requirements. With saline irrigation water and critical salt concentrations in the soil a certain amount of water is required in addition to the actual irrigation water for the purpose of desalinisation. The present research therefore calculates (using Richard´s equation) the amount of water required by plants under saline conditions. The results showed that a lower level of yield should be accepted, for example 82,5 % instead of 95%, where the latter would required an unrealistic amount of irrigation water. Thus, this reduced water quantity should be called the economic irrigation water quantity. This concept should be considered when the difference between the irrigation water salinity and the threshold salinity in the root zone is less than 0.5 dS m^{-1}. Water saved in this way could be used for other crops. With regard to the problem raised due to an inexact scheduling of the irrigation, the final 10 % of yield (namely the difference between the 85 % and the 95 % yield level) is seasonaly produced for example, in the case of peanuts with 5.9 %, in the case of cotton with 3.6 % of their respective total irrigation requirements. In order to secure this last 10 % of yield, a safety margin reserve is recommended, for which purpose an equation was developed in this work. This equation enables the expert to calculate a safety reserve to add to the quantity of irrigation water calculated according to Ri-chard´s equation.

8. Zusammenfassung

Ägypten ist ein arides Land im Nordosten Afrikas. Die gesamt Landesfläche beträgt 1.000.000 km^2. Davon eignen sich jedoch nur 4 % als Fläche für die Nahrungsproduktion der 70 mill. (im Jahre 2015 vermutlich mehr als 90 mill.) Ägypter. Das Land ist sehr niederschlagsarm; es hat ein Wüstenklima; im Mittel fallen pro Jahr 18 mm Niederschlag. Die Landwirtschaft hängt daher von der Bewässerung ab. Während des Sommers sind die Lufttemperaturen sehr hoch. Sie erreichen etwa 36 °C im Bereich der Mittelmeerküste und 49 °C im Süden.

Der Nil deckt als wichtigste Wasserressource etwa 97 % des Wasserbedarfs aller Nutzer. Gleichzeitig limitiert die Wasserzufuhr durch den Nil die Wasserversorgung. Der Anteil Ägyptens am Nilwasser beträgt 55,5 Milliarden m^3 pro Jahr. Die erneuerbaren Grundwasservorräte betragen 2,3 Milliarden m^3 pro Jahr. Wiederverwendet werden 0,2 mrd. m^3 pro Jahr behandeltes Abwasser. Zusätzlich werden 4,7 mrd. m^3 Dränagewasser aus Bewässerungsgebieten rezykliert: 2,6 mrd. m^3 im Nildelta, 0,95 mrd. m^3 in Fayum; der Rest fließt in Oberägypten in den Nil zurück. Die tiefen Grundwasservorkommen in der Westlichen Wüste und im Sinai sind nicht erneuerbar. Daraus ergibt sich eine Summe von 62,7 mrd. m^3 pro Jahr an verfügbarem Wasser. Für das Jahr 2001 schätzt man, daß der Gesamtbedarf aller Nutzer 70 (FAO, 1997) oder 73 (Bishay, 1993) mrd. m^3 erreicht. Die Erschließung zusätzlicher Wasserressourcen in naher Zukunft ist nicht wahrscheinlich (Anonymous, 1995; Attia et al., 1995; Seckler und Altaf, 1997).

Da die in Ägypten und in anderen ariden Ländern herrschende Wasserknappheit zu möglichst rationellen Bewässerungsmethoden zwingt, ist es erforderlich, den Wasserbedarf der Bewässerungskulturen möglichst exakt zu bestimmen. Ägypten hat einige praktische Feldmethoden, mit denen die Wasserverluste reduziert und die water use efficiency erhöht werden kann, z. B. Auskleidung der Zuleitungskanäle für Bewässerungswasser (Verminderung der Sickerungsverluste), der Einsatz von geschlossenen Rohren anstelle von offenen Kanälen (Verminderung von Verdunstungsverluste) und exaktes Einebnen der bewässerten Fläche, u. U. mit leichtem Gefälle, wie in Kap. 2.2.1.3. empfohlen. Außerdem hat Ägypten den Abfluss des Nils ins Mittelmeer reduziert; im Zeitraum von 1974 bis 1996 sank dieser von 6,2 mrd. m^3 auf 0,26 mrd. m^3 pro

Jahr (Seckler und Altaf, 1997). Auch, wie gesagt, wird Dränwasser aus Bewässerungsflächen rezykliert, zur Zeit mehr als 4,7 mrd. m^3 jährlich. Allerdings war die Bewässerung mit salzhaltigem Wasser nicht immer erfolgreich (Afifi et al., 1996; El-Karamity and Attaallah, 1997; El-Dessouky and Attawia, 1998; Helal et al., 1998; Ashour et al., 1999), siehe Kap. 2.1.3.). Von manchen wird auch vorgeschlagen, die RDI-Strategie (RDI = Regulated Deficit Irrigation) beim Bewässerungsmanagement anzuwenden (Chalmers et al., 1981), jedoch berichten Mohamed und Tammam (1998), daß bei Anwendung dieser Strategie eine starke Reduzierung des Weizenertrags eintrat (siehe Kap. 2.2.1.1.). Was jedoch neben diesen Bemühungen, das Wasserproblem zu lösen, fehlt, ist die genaue, wissenschaftlich fundierte Regulierung der Bewässerungswassermenge, die Anwendung von Regulierungsmethoden und die Quantifizierung der Effekte der Regulierung im Hinblick auf die water use efficiency. Viddal et al. (1999) berichten, dass etwa 500 Mill. m^3 Wasser jährlich von 600.000 ha im mittleren Nildelta eingespart werden könnten und die Nahrungsproduktion um 10 % erhöht werden könnte, wenn der standörtliche Bewässerungswasserbedarf anstelle von regionalen oder landesweiten Bedarfsmittelwerten berücksichtigt würde.

Die bewässerte Fläche beträgt 3.246.000 ha (= 100 % der kultivierten Fläche); davon werden 95 % mit Nilwasser bewässert (davon 90 mittels Schwerkraftbewässerung,10 % mittels Beregnung und Tropfbewässerung). Erweiterungsflächen für die Bewässerungslandwirtschaft sind sehr wichtig, da Ägypten seit einer Reihe von Jahren abhängig vom Import von Nahrungsrohstoffen ist; zum Beispiel wird der Verbrauch von Weizen zu 50 % durch Importe gedeckt (Rayan et al., 1999). Eine Erweiterung der Bewässerungsflächen ist aber nur möglich wenn:

- gering-salzhaltiges Wasser eingesetzt werden kann;
- der aktuelle Pflanzenwasserbedarf durch genauere Wasserbilanzierung im Komplex Klima-Boden-Pflanze besser berücksichtigt wird,

Im sogenannten El-Salam-Kanal des „Sinai Development Irrigation Projects“ wird Mischwasser zu Verfügung gestellt, das mit einer elektrischen Leitfähigkeit von 1,5 - 2,0 dS m^{-1} auch noch für Pflanzen mit geringer Salztoleranz geeignet ist. Mit diesem Mischwasser aus Nil-Süßwasser und Drainagewasser aus Bewässerungsflächen (Mischungsverhältnis 1:1) sollen Erweiterungsflächen von 150.000 ha im Raum Port Said und 275.000 ha östlich des Suezkanals im Nord-Sinai bewässert werden. Das Bewässerungsgebiet (Untersuchungsgebiet der hier vorgestellten Arbeit) verteilt sich auf drei Zonen: Nord-Sinai (El-Arish), Port Said und ein Teil von El-Ismailia. Jedes der drei Gebiete hat seine speziellen Eigenschaften und Probleme: El-Arish: hoher Grundwasserstand, salzhaltige Böden, kalkhaltige Böden, salzhaltiges örtliches Bewässerungswasser; allmähliche Verschlechterung der Qualität des vorhandenen Grundwassers (El-Baz, 1979; Abu-Zeid, 1995); Port Said: hoher Grundwasserstand, schlecht dränende Böden, salzhaltige Böden, salzhaltiges örtliches Bewässerungswasser; El-Ismailia: sandige Böden, salzhaltige Böden (Kapitel 4).

Möglich wird die Verwendung von Mischwasser nicht zuletzt durch den Einsatz der Tropfbewässerungstechnik aus folgenden Gründen:

- Anders als bei der Beregnung kommt das salzhaltige Wasser nicht mit den oberirdischen Pflanzenteilen in Berührung, so daß keine Salzschäden an Blättern zu erwarten sind.
- Der Boden des Wurzelraumes wird ständig durchfeuchtet, so daß kritische Salzkonzentrationen und zu hoher osmotischer Druck im Boden nicht entstehen können. Erst am Rand des durchfeuchteten Bereiches entstehen höhere Salzkonzentrationen; dieser Bereich wird jedoch nur noch schwach durchwurzelt.

In der vorliegenden Arbeit wurde versucht, weitere Wege zur Wasserersparnis zu finden und vorhandene Möglichkeiten zu verbessern, um bei begrenztem Wasservorrat ohne Ertragseinbußen eine höhere water use efficiency zu erreichen, mit anderen Worten, die Wasserverschwendung zu vermindern. Dazu wurde das Suez-Kanal-Gebiet (zwischen El-Ismailia und Port Said) als Untersuchungsgebiet ausgewählt, da es sich dort überwiegend um neu in landwirtschaftliche Nutzung genommene Flächen handelt. Die Flächen in diesem Gebiet sind teilweise schon Bewässerungsflächen, teilweise müssen sie zunächst melioriert werden, z. B. die Tina-Ebene zwischen Port Said und El-Arish. Insgesamt beträgt die landwirtschaftliche Fläche im Untersuchungsgebiet 425.000 ha. Es wurde seitens der Regierung entschieden, diese Fläche mit Wasser aus dem Salam-Kanal-Projekt (Gemisch aus Dränagewasser und Nilwasser) zu bewässern (siehe Abb. 1).

Zu Berechnung die Referenze-Evapotranspiration (ET_o), die der am stärksten den Pflanzenwasserbedarf beeinflussende Faktor ist, wurde die Penman-Monteith-

Gleichung (Smith et al., 1996; siehe Gl. 30) als das am besten geeignete Modell ausgewählt. Diese Auswahl wurde getroffen anhand eines Vergleichs der Schätzgenauigkeiten verschiedener Methoden. Die Penman-Monteith-Gleichung wird auch von Howell (1996). Simon et al. (1998) und Michael & Bastiaansen (2000) als Standardmethode für den Mittelmeerraum genannt. Zur Berechnung des Pflanzenwasserverbrauchs wurde der FAO-Standard-Pflanzenkoeffizient K_c an die Klimabedingungen eines jeden Standorts mit Hilfe der Gleichungen 9 und 10 angepasst (siehe Tab. 10). Zur Berechnung der Referenze-Evapotranspiration (ET_o) bzw. der Crop Evapotranspiration ($ET_c = ET_o * K_c$) wurde eine Dialog-Box entwickelt (Abb. 7). Fünf ökonomisch wichtige Kulturen, Mais, Erdnuss, Sonnenblume, Sojabohne und Baumwolle, wurden als Untersuchungsfrüchte ausgewählt. Nach Validierung der berechnten ET_o-Werte mit ET_o-Werten aus der Literatur wurde die Optimierung des Bewässerungswasserversorgung im Untersuchungsgebiet bearbeitet wie folgt:

Bessere, an der ETo orientierte geographische Kulturarten-Verteilung (IGDC):

Da eine erheblich Differenz zwischen den ET_o-Werten der drei Standorte gefunden wurde, besonders zwischen Port Said und El-Arish einerseits und El-Ismailia andererseits im Zeitraum Januar bis Oktober, wurde mit Hilfe der Werte des Pflanzenwasserverbrauchs aller Kulturarten (Tab. 11) folgendes Konzept für eine bessere geographische Kulturarten-Verteilung (IGDC) entwickelt: Kulturen mit hohem Pflanzenwasserbrauch sind in Regionen mit niedriger Reference-Evapotranspiration anzubauen; Ein einfaches Beispiel anhand von Fällen (Fall A und Fall B in Kapitel 5.1.) zeigt, dass nach dem IGDC -Konzept im Fall B etwa 60.000 m^3 Wasser gegenüber Fall A innerhalb einer Saison eingespart werden könnten. Diese 60.000 m^3 resultieren aus einer Neuorganisation nach dem IGDC -Konzept (Improved ET_o oriented Geographic Distribution of Crops) von nur 100 ha Anbaufläche in jeder der drei Regionen. Für die von Mahmoud (1989) vorgeschlagene Melioration (Salzauswaschung) von 20.000 ha in der Tina-Ebene (zwischen Port Said und El-Arish) mit Hilfe von Salam-Kanal-Wasser würde man für einen Hektar ca. 14.000 m^3 Wasser jährlich benötigen; mit den nach Fall B pro Saison eingesparten 60.000 m^3 Wasser könnte man daher 4 ha meliorieren. Oder man könnte mit den eingesparten 60.000 m^3 ca. 6 ha einer Kultur, die pro Saison 10.000 m^3 benötigt, bewässern.

Tagesdatenbasiertes Entscheidungsmodell (DDBM):

Es wurde darauf hingewiesen, daß in der Planungspraxis der Bewässerungssteuerung zahlreiche Fachleute für die Berechnung wesentliche Parameter (Pflanzenwasserverbrauch, ET_c, zulässiges Bodenfeuchtedefizit, P, und Durchwurzelungstiefe der Pflanzen,Z_r) in Form von Monats- und Saisonmittelwerten heranziehen (siehe Kap. 5.2.). Das Ziel unserer Untersuchung ist es, eine klare Vorstellung zu entwickeln, wie bei begrenztem Wasservorrat eine höhere Water use efficiency erreicht werden kann. Daher wurde ein einfaches tagesdatenbasiertes Entscheidungsmodell (DDBM) zu Steuerung der Bewässerung entwickelt (Abb. 9). Mit Hilfe dieses Modells wurde versucht, den Effekt der täglichen Veränderung der Pflanzenwasserbedarfs-Parameter (ET_c, P und Z_r) im Vergleich zur Verwendung von Mittelwerten (neben den üblichen Standortdaten) auf den Bewässerungswasserbedarf zu untersuchen.

Mit Hilfe von DDBM wurde der tägliche Bewässerungswasserbedarf auf der Basis einer täglichen Klima-Pflanzen-Boden-Wasser-Bilanz unter gleichzeitigem Schutz vor Versalzung geschätzt und der Vorteil der Verwendung von täglichen Klima-Boden-Pflanze-Daten anstelle von saisonalen oder monatlichen (wie in den meisten Untersuchungen üblich) für die Wasserersparnis bzw. für die Einhaltung des Gleichgewichts zwischen Wasserzufuhr und Pflanzenwasserbedarf ermittelt.

Zur Untersuchung des Effekts einer Verwendung von Tagesdaten (im Vergleich zur Verwendung von Mittelwerten) auf den Bewässerungswasserbedarf wurden für einige Kulturen Berechnungen nach DDBM unter bestimmten Annahmen (siehe Kap. 5.2.) durchgeführt. Dazu wurden am Beispiel von Baumwolle im Raum Port Said folgende Varianten berechnet:

- Fall A: Alle Parameter (ET_c, Z_r und P) wurden als Tageswerte eingesetzt. Diese Variante kann auch als Nomogramm für Ermittlung des Bewässerungswasserbedarfs bei einem bestimmten Tag dienen (siehe Abb. 14), mit dem die anderen Fälle zu vergleichen sind.

- Fall B: ET_c und Z_r wurden als Tageswerte, P als Saisonmittelwert (nach der Literatur gleich 55 % der Feldkapazität) eingesetzt (siehe Abb. 15).

* Fall C: P und Zr wurden als Tageswerte, ET_c als Phasenmittelwerte eingesetzt (siehe Abb.16).

* Fall D: Alle Parameter wurden als Mittelwerte eingesetzt (siehe Abb. 18).

Die Fälle A und B (Abb. 15) unterschieden sich hinsichtlich ihres Bewässerungswasserbedarfs während der ersten 90 Tage; die Berechnung ergab für Fall A 558 m^3 ha^{-1} weniger als für Fall B: Die Überschätzung bei Fall B würde zu einer Verschwendung von Bewässerungswasser führen, das zur gleichen Zeit für andere Kulturen eingesetzt werden könnte. Abb. 16 zeigt für die Fälle A und C, dass, obwohl das zulässige Bodenfeuchtedefizit in Form von Tageswerten im Modell berücksichtigt wurde, hier eine erhebliche Beeinträchtigung des Gleichgewichts zwischen dem tatsächlichen Pflanzenwasserbedarf (A) und den gemäß Fall C berechneten Bewässerungswassergaben besteht, vor allem zwischen dem 50. und 90. und zwischen dem 135. und 170. Tag. In Abb. 18 erkennt man gegenüber A sowohl Unterschätzungen wie Überschätzungen der Variante D, für die alle Parameter als Mittelwerte eingesetzt wurden.

Ein Vergleich mit Ergebnissen des ARC (Landwirtschaftsforschungszentrum, Kairo), das sich mit der Optimierung der Bewässerung bei Baumwolle in Nordägypten befasst, zeigt, dass das DDBM-Verfahren gegenüber der ARC-Methodik zu einer Wasserersparnis von 1.500 m^3 ha^{-1} $Saison^{-1}$ (bei Verwendung von Saisonmittelwerten für ET_c) bzw. von 1.200 m^3 ha^{-1} (bei Verwendung von Phasenmittelwerten für ET_c) kommt (siehe Tab. 22).

Der Effekt einer Berücksichtigung der Bodentextur auf die Bewässerungswassermenge wurde auch untersucht. Dazu wurde der Bewässerungswasserbedarf für Mais im Raum El-Ismailia auf zwei verschiedenen Böden (a = sandig- toniger Lehm und b = lehmiger Sand) bei einer Wasserqualität von EC = 0,5 dS m^{-1}geprüft. Die Ergebnisse (Tab. 17 und Abb. 14) zeigen, dass im Zeitraum bis zum 75. Tag die Bodenunterschiede eine Differenz in der Bewässerungswassermnege von 4 bis 9 m^3 pro ha und Tag (ca. 500 m^3 pro ha und Saison) bewirken. Der Unterschied zwischen 11,8 % und 5,5 % an pflanzenverfügbarem Wasser (siehe Kap. 5. 2. 1.) führt so zu einem Unterschied im Bewässerungswasserbedarf von ca. 500 m^3 pro ha und Saison.

Zur Untersuchung des Effektes der Wasserqualität auf den Bewässerungswasserbedarf wurde eine Berechnung für Mais im Raum Port Said durchgeführt, und zwar mit zwei Varianten für Wasser, nämlich (a) mit EC = 0,5 dS m^{-1} und (b) mit EC = 1,5 dS m^{-1}. Die Ergebnisse zeigen sehr erhebliche Unterschiede im Bewässerungswasserbedarf (Tab. 21): Der Unterschied im Salzgehalt von 1,0 dS m^{-1} bewirkt einen Unterschied in der Bewässerungswassermenge von insgesamt mehr als 60.000 m^3 ha^{-1} für die gesamte Vegetationszeit. Das bedeutet, dass auch ein geringer Unterschied zwischen den Standorten hinsichtlich der Bewässerungswasserqualität bei der Planung der Bewässerung nach dem IGDC-Konzept berücksichtigt werden muss.

Ökonomische Bewässerungswassermenge:

In diesem Teil der Untersuchung wurde der Pflanzenwasserbedarf unter salinen Bedingungen errechnet (siehe Tab. 12). Der Salzauswaschungsbedarf wurde mit Hilfe von Gl. 42 und Tab. 16 berechnet. Aus Abb. 20, die die Beziehung zwischen dem Pflanzenwasserbedarf und dem Ertragsniveau bei drei Bewässerungswasserqualitäten für Mais und Erdnuss in Port Said zeigt, erkennt man zwei extreme Probleme: Erstens würde man im Fall von Mais (Bewässerungswasserqualität 1,5 dS m^{-1}) und Erdnuss (Bewässerungswasserqualität 3,0 dS m^{-1}) unrealistisch hohe Wassermengen (78.542 bzw. 100.795 m^3 ha^{-1} $Saison^{-1}$) benötigen, um den Maximalertrag zu erzielen. Zweitens würde eine ungenaue Steuerung der Bewässerung zu Mais (Bewässerungswasserqualität 0,5 dS m^{-1}) durch ein Minus von nur 1,000 m^3 ha^{-1} $Saison^{-1}$ bereits zu einem Absinken des Ertragsniveaus von 95 % auf 85 % führen. Es wird daher vorgeschlagen, bei der Berechnung der Bewässerungswassermenge nach Gl. 42 und Tab. 16 sich mit einem niedrigeren Ertragsniveau zu begnügen, also mit z. B. mit 82,5 %. Das würde bedeuten, dass bei den o. g. Bewässerungwasserqualitäten zur Erzielung eines Ertragsniveaus von 82,5 % bei Mais in Port Said 23.101 m^3 ha^{-1} $Saison^{-1}$ (anstelle von 78.542 m^3 ha^{-1} $Saison^{-1}$) an Bewässerungswasser benötigt würden; im Fall von Erdnuss würden anstelle von 100.795 m^3 ha^{-1} $Saison^{-1}$ 44.098 m^3 ha^{-1} $Saison^{-1}$ benötigt. Die so reduzierte Wassermenge soll „ökonomische Bewässerungswassermenge“ genannt werden. Eingespartes Wasser könnte für anderen Kulturen eingesetzt werden. Dagegen ist es sinnvoll, bei Baumwolle (salztolerant) im Raum Port Said die eingesetzte Wassermenge nicht zu reduzieren, da die letzten 1.000 m^3 Wasser pro ha noch einen Ertragsanstieg von 35 Prozentpunkten hevorrufen (siehe Abb. 21).

Sollte die Qualität der ereugten Früchte wegen Wassermangels absinken, müssten bei der Berechnung der Bewässerungswassermenge neue Schwellenwerte für die Salzgehalte im Wurzelraum anstelle derjenigen in Tab. 16 ermittelt werden. Geht man nach Abb. 22 bei Mais von einem Schwellenwert von 1,8 dS m^{-1} anstelle von 1,7 dS m^{-1} aus, sinkt der Wasserbedarf um 23.000 m^3 ha^{-1} $Saison^{-1}$ bei einem nur geringfügigen Rückgang im Ertragsniveau auf 91 %. Geht man bei Erdnuss von einem Schwellenwert von 3,3 dS m^{-1}anstelle von 3,2 dS m^{-1} aus, sinkt der Wasserbedarf um 31.000 m^3 ha^{-1} $Saison^{-1}$ bei einem nur geringfügigen Rückgang im Ertragsniveau auf 89 %.

Zum zweiten Problem: Die letzten 10 % Ertragsniveau, also die Differenz zwischen dem $85_{prozentigen}$ und dem $95_{prozentigen}$ Ertragsniveau, werden nach Abb. 21 (bei der Verwendung von Salam-Kanal-Wasser) bei Erdnuss von 700 m^3 ha^{-1} $Saison^{-1}$, bei Baumwolle von 400 m^3 ha^{-1} $Saison^{-1}$ und bei Soja von 350 m^3 ha^{-1} $Saison^{-1}$ erzeugt. Das sind 5,9 % bzw. 3,6 % bzw. 3,4 % des jeweiligen Gesamtbedarfs an Bewässerungswasser. Bei Mais (Abb. 20, mit Nilwasser) werden diese letzten 10 % mit 1.000 m^3 ha^{-1} $Saison^{-1}$ Bewässerungswasser (7,6 % des Gesamtbedarfs) erzeugt. Zur Sicherung der letzten 10 % Ertragsniveau wird ein Sicherheitszuschlag empfohlen, für den in dieser Arbeit die Gl. 59 entwickelt wurde. Tab. 24 zeigt die mittels Gl. 59 errechneten Zuschläge. Mit der Gleichung (Gl. 59) kann der Praktiker, wenn er die Salinität von Bewässerungswasser und Drainagewasser (letztere entspricht dem Salzgehalt im Wurzelraum) kennt, relativ leicht den Zuschlag errechnen, um den er aus Sicherheitsgründen die nach Gl. 42 berechnete Bewässerungswassermenge erhöhen muss.

9. List of Symbols

A	Evaporating surface area, m^2
ASCE	American Society of Civil Enginers
ASMD	Alowable Soil Moisture Depletion, %
AVHRR	Advanced Very High Resolution Radiometer
AW	Available soil water content, %
AWD_i	Allowable Soil Water Depletion at Day i, mm
awd	Min Allowable Soil Water Depletion, mm
B	Convertion factor between $PWB_{ök}$ and PWB_{max}.
b	Geometry and Activity Factor of Root System, bar
IGDC	Improved ET_o Oriented Geographic Crop Distribution
C	Average Root Zone Salinity, dS m^{-1}
C_d	Salt Concentration of Drainage Water, kg m^{-3}
C_f	Crop Factor (for the horizontal root extension), %
C_i	Salt Concentration of Irrigation Water, kg m^{-3}
C_o	Level of Soil Salinity Above Which the Yield is Zero, dS m^{-1}
C_p	Specific Heat Capacity of Air, cal cm^{-3} °K^{-1}
C_t	Threshold of Soil Salinity, dS m^{-1}
CWSI	Crop Water Stress Index
D	Semiempirical Constant Depends of Climatology and the Crop Structure
d	Zero Plane Displacement (0.7 h_c. m. where h_c is the crop heigh)
DAP	Number of Days after Planting, days
dawd	Difference between awd at Day i and at Day i-1, mm
D_{cd}	Constant Daily Depth of Irrigation Water to be Applied, mm day^{-1}
DDBM	Daily Data Based Model for Irrigation Scheduling
D_{fi}	Depletion Fraction of Soil Water at day i, %
D_i	Irrigation Water Requirement,for Salinity Control, mm day^{-1}
d_i	Depth of Irrigation Application, mm
d_{ia}	Actual Plant Water Requirement, mm day^{-1}
D_r	Volme of Water Drained below the Root Zone, m^3
D_s	Drainage Water Salinity (soil salinita at the root zone), dS m^{-1}
D_{s1}	Drainage Water Salinity for Yield Level = 95 %
D_{ti}	Irrigation Water Requirement for Salinity Control, L day^{-1} $plant^{-1}$
DTM	Number of Days to Maximum Root Depth, days
D_{wd}	Daily Amount of Water to be Applied, liter day^{-1} $plant^{-1}$
E	Evaporation, mm day^{-1}
e_a	Measured Vapor Pressure, bar or KPa
EC	Electronic Conductivity, dS m^{-1}
EC_{ec}	Economic Electronic Conductivity in the Root Zone, dS m^{-1}
E_d	Volume of Water Lost by Evaporation, m^3
E_i	Irrigation Application Efficiency, %
ER	Energy Balance Residual, W m^{-2}
E_s	Volume of Water Evaporated from Soil, m^3
e_s	Saturated Vapor Pressure at Air Temperature, bar or KPa
e_{sd}	Saturated Vapor Pressure at Dew Point Temperature of Air, mbar
ET	Evapotranspiration, mm day^{-1} or MJ m^{-2} day^{-1}
ET_a	Actual Evapotranspiration, mm day^{-1}
ET_c	Crop Evapotranspiration, mm day^{-1}
ET_o or ET_r	Reference Evapotranspiration, mm day^{-1}

f_c	Soil Field Capacity, vol %
F (U_i)	Wind function, m s^{-1}
G	Soil Heat Flux, MJ m^{-2} day^{-1}
h	Hight above the Sea Level, m
H	Sensible Heat Flux, MJ m^{-2} day^{-1}
h_c	Crop Height, m
h_p	Maximum Crop Hight, m
i	Irrigation Intervals, days
I_s	Irrigation Water Salinity, dS m^{-1}
K	Van Karman Constant (0.41)
K_c	Crop Coefficient, %
K_{cadj}	Adjusted Crop Coefficient, %
K_{cb}	Basal Crop Coefficient, %
$K_{c\ dev}$	Crop Coefficient of Vegetation Development Stage, %
$K_{c\ end}$	Crop Coefficient of Vegetation End Stage, %
$K_{c\ mid}$	Crop Coefficient of Vegetation Mid-season Stage, %
K_e	Soil Water Evaporation Coefficient, %
K_p	Unsarurated Permeability of the Root Zone, mm day^{-1}
K_s	Water Stress Coeffiocient, %
LAI	Leaf Area Index
LE	Latent Heat, cal $gram^{-1}$
LE_f	Latent Heat Flux, W m^{-2}
LFZ	Agricultural Research Center in Cairo
ls	Loamy Sand Soil
n	Mean Daily Sunshine Hours, hour
N	Mean Daily Max Sunshine Hours, hour
N_o	Nummber of Trees (Plants) per Hectar, plants
NOAA	National Oceanic and Atmospheric Administration
P	Allowable Soil Moisture Depletion, %
P_c	Crop Production, kg
p_a	Air Pressure, bar
PDi	ET_o for the ith Hour, mm h^{-1}
PDi´	Daily Reference Evapotranspiration, mm day^{-1}
p_{ef}	Effective Precipitation, mm day^{-1}
P_i	Depth of Water in Effective Root Zone at Day i, mm
p_{tot}	Total Precipitation, mm day^{-1}
Q_d	Daily Volume of Drainage Water, m^3 day^{-1}
Q_i	Irrigation Water Requirement of Salinity Control, m^3 day^{-1}
R	Volume of Water Lost by Runoff, m^3
Ra	Daily Extraterrestrial Radiation, mm day^{-1} or MJ m^{-2} day^{-1}
r_a	Aerodynamic Resistance, s m^{-1}
RAW	Readily Available Soil Water, %
r_c	Canopy Resistance, s m^{-1}
r_{cp}	Canopy Resistance at ET_p, s m^{-1}
r_i	Single Leaf Resistance to Vapor Tarnsfer, s m^{-1}
RH	Relative Air Humidity, %
$RH_{min.}$	Minimum Relative Air Humidity, %
R_n	Net Radiation, mm day^{-1} or MJ m^{-2} day^{-1}
R_{nd}/ R_{ni}	Mean Annual of Ratio between Daily and Mid-day Value of R_n, MJ m^{-2} d^{-1}
r_{pl}	Crop Resistance for Water Flow, bar day mm^{-1}

r_s	Surface Resistance, s m^{-1}
R_s	Observed Solar Radiation, mm day^{-1} or MJ m^{-2} day^{-1}
R_{so}	Clear day Solar Radiation, mm day^{-1} or MJ m^{-2} day^{-1}
S	Percent Yield Decrease per Unit of Salinity above the Threshold, %.
S_a	Available Soil Water Content, %
S_d	Salt Leached from Soil by Rain or Irrigation, dS m^{-1}
S_{fc}	Soil Water Content at Field Capacity, %
S_i	Addition of Salt to the Soil due to Irrigation of Saline Water, dS m^{-1}
S_o	Original Salt Content in the Soil before Irrigation, dS m^{-1}
stl	Sandy Clay Loam Soil
S_u	Soil Factor ~1/5 of Soil Hydraulic Conductivity, cm day^{-1}
S_{wp}	Soil Water Content at Wilting Point, %
T_4	Brightness Temperature in Channel 4 of AVHRR Instrument, °C
T_5	Brightness Temperature in Channel 5 of AVHRR Instrument, °C
T_a or T	Air Surface Temperature, °C
TAW	Total Available Soil Water Content, %
T_c	Volume of Water Transpired by Crop, m^3
DDBM	Daily Data Based Model for Irrigation Scheduling
T_m	Mean Minimum Air Temperature, °C
T_M	Mean Maximum Air Temperature, °C
T_s	Crop Surface Temperature, °C
T_w	Volume of Water Transpired by Weeds, m^3
U_2	Wind Speed at 2 m Height, m s^{-1}
U_z	Wind Speed at Heigh Z_m, m s^{-1}
VC	Vegetation Cover, %
W	Volume of Applied Water, m^3
W_p	Soil Water Content at Permanent Wilting Point, vol %
W_{ra}	Actual Plant Water Requirement, mm day^{-1}
W_{ras}	Irrigation Requirement for Salinity Control, mm day^{-1}
WUE_{ag}	Agronomic Efficiency of Water Use, kg m^{-3}
Y_r	Relative Yield
Z_h	Heigh of the Temperature and Relative Humidtity Mesurements, 1.5 m
Z_m	Heigh of the Wind Measurement (2 m), m
Z_{oh}	Roughness Length for Heat and Vapor Transfer (0.2 Z_{om}), m
Z_{om}	Roughness Length for Momentum Transfer (0.13 h_c)
Z_r	Effective Root Depth, cm
Z_{ri}	Effective Root Depth at Day i, cm
Z_{rm}	Maximum Root Depth of the Crop, cm
$Z_{wm\ 10\%}$	Additional Water Amount to Secure the Last 10% Yield Production, %
$\sin_{(rad)}$	Angle in Radiant
Θ	Actual Soil Water Content in Root Zone, %
Θ_{fc}	Soil Moisture Content at –33 KP_a, %
Θ_{wp}	Soil Moisture Content at –1500 KP_a, %
g	Psychrometric Constant
Δ	Slope of the Saturation Vapor Pressue, KPa °C^{-1}
a	Multiplier for Aerodynamic Term (Constant = 1.26 Wm^{-2})
r_a	Mean Air Density at Constant Pressure, gram cm^{-3}
e	Ratio of the Molecular Weight of Air to Water (18 g / 28.9 g = 0.622)

$\in_4$	Emissivity in Channel 4 of AVHRR Instrument
$\Delta\in$	Emissivity Difference Between Channels 4 and 5 of AVHRR Instrument
b	Parameter which Decrease with Atmospheric Water Vapor
d	Parameter which Decrease with Atmospheric Water Vapor
Ψ_l	Leaf Water Potential, bar
Ψ_o	Osmotic Potential at Field Capacity, bar
Ψ_{os}	Mean Osmotic Potential at Root Zone, bar
Ψ_s	Mean Matrix Water Potential in Root Zone, bar

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