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SUDAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF AGRICULTURAL STUDIES

A COMPUTER MODEL FOR IRRIGATION WATER INDENTING AND OPTIMIZATION OF MINOR CANAL OPERATION

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A THESIS SUBMITTED IN FULFILLMENT FOR THE REQUIREMENTS OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN AGRICULTURAL ENGINEERING.

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April 2005

DEDICATION …

To the souls of my parents,

To my, wife, daughter and sons

To my sisters and brother.

ACKNOWLEDGMENT

I would like to express my gratitude and sincere appreciation to my main supervisor Dr. Abdel Moniem Elamin Mohamed, Department of Agricultural Engineering, Faculty of Agriculture, University of Khartoum, for his full guidance and sincere encouragement. My deep thanks and gratitude and full appreciation to my co-supervisor Dr. Hassan Ibrahim Mohammed, Department of Agricultural Engineering ,College of Agricultural Studies, Sudan University of Science and Technology for his close and continuous guidance and utmost care.

I am forever indebted to Ustaz Abdelghani Ahmed Hussein for his appreciated help throughout the course of this study.

Thanks to the colleagues in Sudan Gezira Scheme for supplying the agricultural data .

Thanks are due to Engineer Salah Elnour for his valuable help.

Thanks are also due to Ustaz Sami Atta Elmoula for his cooperation and help. I would like to thank Mrs. AlMugam Ali and Miss Sulafa Abdelsalam for typing this thesis.

Thanks are extended to every helping hand throughout the time of this study.

Last but not least my sincere appreciation to my family, wife, daughter and sons for their patience and encouragement every one in his own way.

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ABSTRACT

This study was carried out with objectives of developing a proper decision aid for irrigation indenting of multiple crop rotation based on Penman- Montieth equation(1994) and amenable for the format of meteorological data of the Sudan. Consequently the study developed a mathematical simulation of canal operation for the purpose of optimization of water allocation within such a canal.

Linear programming algorithm was made to optimize irrigation water allocation between different outlets in the irrigation canal under the constraints of fixed canal capacity and irrigation interval.

The model was coded in a personal computer using Excel – visual basic application language (VBA).

These models were verified statistically in comparison with published models. Both water indent and allocation modules were applied to the real cases of wet and dry regions of Gezira Scheme – Sudan. The modules were applied to estimate water indent and for sequencing canal outlets for the cases of early and peak season at Sunni Minor canal and Ugud Minor canal. The model sensitivity to changes in outlet - inflow rate (working time per outlet) was made for the said two cases to

conclude the developed model capabilities to optimize water scheduling and allocation process which can be used to save irrigation water during early stages and to upgrade the operation of minor canals in the irrigated schemes in the Sudan.

ملخص الأطروحة

اجريت هذه الدراسه بهدف تصميم نظام طلبيات مياه رى حديث لدوره مركبه ذات محصولات متعدده وعلى اساس المناوبه وذلك وفق معادله بنمان مونتيث (1994)

لتيسير استخدام البرنامج روعى فيه امكانية است قبلال المعلومات المناخيه كما تصدرها مصلحة الارصاد الجوى السودانيه. ثم صممت الدراسه نموزج رياضى بهدف تحـ قيق نظام تشغيل امثل للا قنوات الحـ قليه .استخدمت البرمجه الخطيه فى سبيل الوصول الى امثل الخيارات فى تتابع تشغيل الـ قنوات الحـ قليه، ملتزمين بسعات تصرف الـ قنوات المعروفه سلفا مع المحافظه على الفترات بين الريات المعلومه لمحصولات مشروع الجزيره .

كتبت النماذج على الحساب الشخصى(PC) فى اطار برنامج الشرائح الجدوليه(spread sheet) مستخدمين لغه البيسك المصوره(VBA) فى محيط (Excel) .

استخدم البرنامج فى حالتين دراسيتين بمشروع الجزيره وهما ترعة السنى(Sunni Minor) وهى تمثل وسط الجزيره الاكثر رطوبه وترعة الأ قد(Ugud) وهى تمثل شمال الجزيره الاكثر جفافا واستخدمت وحدات البرنامج فى حساب الاحتياجات المائيه لمحصولات الدورة منفرده ومركبه . كما استخدم بنامج التشغيل فى تحديد تتابع فتح ابوعشرينات مستخدمين تصرف التصميم والتصرف العملى السائد فى الظروف الحاليه وبغرض اختبار الحساسيه . و قد تمت مـ قارنة النتائج احصائيا مع البيانات المنشوره عالميا.

ونخلص من هذه الدراسه الى انه يمكن استخدام البرنامج لتقدير الاحتياجات المائيه للمحاصيل المرويه فى السودان بكفاءه عاليه اضافة الى ان البرنامج يعطى نظام تشغيل لل قنوات الحقليه تحقق وفورات فى المياه يمكن الاستفاده منها فى استخدامات اخرى.

CHAPTER ONE

INTRODUCTION

1.1 Background and justification

Development strategies of most of the Third World Countries are mainly constrained by the serious food-population imbalance. Developing countries need an average annual increase in food supply of about 3-4 percent together with a proportionate increase in net imports of grains. The growth of population at an alarming rate in this region is further aggravating the problem through limiting the land and water resources available for cultivation. It seems that the intensification of food production remains the only way out. Effective irrigation together with adequate fertilizer and pesticide application and the use of high yielding varieties represent the possible avenue for sharp production increase. World wide fresh water resources are limited, often polluted and face growing multiple uses in domestic, industrial and agricultural applications. More than two thirds of the fresh water withdrawn from earth’s rivers is used in irrigated agriculture. In developing countries the portion is even higher amounting to more than 80 percent (FAO, 1996). In recent years water issues have been the focus of increasing international concern and debate. The source of urgency is the need for food production to combat the present and future threats to food security, the increase in the cost of water delivery to farmers and the stochastic nature of water resources.

The Sudan is the largest country in Africa, with an area of more than two million square km. This large area covers a diverged range of agro-ecological zones. The northern part of the country has large land areas that are arid or semi-arid, 51% of the country lies in the semi-arid zone. These areas have limited supplies of renewable water resources, and limited potential for rain fed agriculture. In the last two decades of last century the country experienced rapid urbanization due to chronic civil war, recurrent droughts and population growth. This together with the expansion of irrigation has resulted in great increase in use and need for water resources. The present trends in availability, allocation and use of water resources point to unsustainable water resource exploitation and demand. The new trend is for adopting water management solutions rather than structural improvements due to the high cost incurred by the latter. Efficient water management strategy is meant to increase productivity in existing irrigation schemes (rather than developing new ones) via better planning and operation of the scarce resources.

Irrigation management is an essential component of water use in irrigated agriculture. Sound irrigation management requires dependable information on crop water requirement, areas under crops, planting dates, available water supplies and efficient operating rates.

The water supplies in terms of river flow or rainfall are stochastic resources. Likewise is the dynamic demand of different crop types throughout their time span. Proper irrigation management ensures optimal allocation of water for crops to produce maximum possible output per unit water.

Sudan being one of the sub-Sahara African countries, encounters irrigation water limitation (McDonald, 1992). This is mainly due to poor performance of water resource utilization. The reason is attributed to surface irrigation systems deterioration, change in project goals and the economic and social pressures. Certainly, the critical issue in improving performance of the canal system is the relative priority assigned to structural and non-structural measures. Structural improvements (such as canal lining, new flow control structures, land leveling) are generally the most popular options particularly to government agencies, These improvements are considered as the most expensive ones. Nevertheless, increased emphasis on operation and maintenance (operation optimization) and turnover management are often more efficient than modification of infrastructure. Even in areas with adequate water supply any success depends on high level of management of the distribution of the available supplies. The managing bodies whether public agencies, users or private sector are continually faced with questions on:-

What is the optimum canal operation plan to be followed to cultivate maximum total cropped areas? And the other question of how to operate the delivery system in accordance with the seasonal plan and irrigation schedule in order to justify project objectives.

1.2 Problem identification

Many surface irrigation projects in most developing countries perform at levels much below their potential in terms of dependability, equity and efficiency. Thus frustrating the efforts to attain food supply for self-sufficiency and often threatening the economic justification on which the projects rest. The 1974 World Food Conference gave the improvement via rehabilitation programme of irrigation systems top priority in the joint development of land and water resources.

Thereafter improvement efforts were focused on infrastructure and canal modeling projects (hardware) which did not solve all the problems, although increased capacity. Continuation on this line, will obviously yield diminishing returns. To achieve appreciable progress it worth to supplement rehabilitation programmes with better management programmes (software) which is expected to maximize returns against lower costs. Better management can be achieved via appropriate capacity building programmes, better scheduling procedures, and sound canal operating rules. Building capacity is a matter of daily on job training. Irrigation scheduling involves the answer to the questions of how much and when to irrigate (indenting). Indenting or water order in Gezira Scheme is simply an advance request by Block Inspectors to Assistant Divisional Engineer for expected daily requirement for the next period of days, to be delivered at the heads of the various Minors with which they are concerned. The traditional mode for calculating the indent is to indent for 5000 m^3/day for each field outlet pipe (FOP) irrespective of crop type or its growth stage. The validity of this indent is certainly questionable particularly for the changing circumstances of today.

Sound canal operation rules particularly under multi-crop diversified cropping pattern is a difficult task. It requires establishment of procedure adaptable to the physical, socio-economic environment so as to accomplish canal system up grade.However methods of operating irrigation canal system include on demand, continuous and rotational method.

In general, for project level operations, variable irrigation flows with constant irrigation intervals has many advantages over alternative constant flow and variable interval (Sagardoy *et al.,* 1982). The project level operation of delivery systems must be matched to such a desired farm level application methodology that results in minimum losses in the process of water delivery from the source.

Rotational water distribution in irrigation projects is a common practice throughout the world. The supply is rotated among individual farmers in an outlet command, among outlets on a distributary channel, and among different distributaries on a main canal. Until recently, a constant frequency, constant depth policy of water distribution has been followed. With this policy the operation schedule of the distribution system is calculated by knowing the irrigated area of each outlet. Once the area to be irrigated is known, the operation schedule for the distribution system is prepared and implemented throughout the season. During the last decade, however, in several places, the constant frequency constant depth policy has been replaced by the constant frequency variable depth policy. Frequency of irrigation in a command area is based on the soil-crop-climate conditions. With constant frequency variable depth, the depth of irrigation in each rotation is varied according to the crop needs, thus, a rotation system that closely matches demand has been introduced.

In Sudan major schemes were designed following the Gezira design. The Minor canals of the Gezira were designed on rotational basis for a mono-cropping pattern, cotton being the main crop. Half the number of outlet pipes per Minor was operated at the same time for seven days on, and seven days off with constant irrigation interval of fourteen days.

Due to the intensification and diversification the classical operation model is no longer valid. Some of the impacts of intensification and diversification can be summarized in low water course inflow (Abu xx),Longer irrigation intervals, longer operating time, unattended irrigation, lower canal maintenance levels, and hence lower canal carrying capacity.

The indenting method (water demand system) practiced by Block Inspectors (BI) relied on demanding the maximum carrying capacity of the canal depending on their personal experience,an indication of improper indenting and canal operation system.

1.3 Study objectives

The improvement of irrigation management has become a priority to deal with food shortage and the increasing world population. It can be done through proper estimation of crop water demand and canal operation under conditions of limited water resources, equipment and manpower. It depends on generating reliable input data to estimate water demand of multiple crops, on the procedure to estimate such a demand and on the sequential operation of the canal outlets under rotation delivery system to serve different fields of different crops.

Hence guided by this background the specific objectives of this study are three folds.

1-To develop a proper decision aid system for irrigation indenting based on the (1994). Penman-Montieth equation

2-To develop a mathematical model for simulation of canal operation.

3-To verify and apply the model under field conditions of the Sudan Gezira Scheme. .

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Estimation of crop water demand

Irrigation systems are designed, constructed and operated to meet the deficit in crop water requirements due to shortages in precipitation or soil-moisture storage capacities. Nevertheless, little efforts are sometimes exerted in estimating crop water requirements for the purpose of design and management of irrigation system. The portion of system capital costs allocated for improved water requirement estimates is very minor, compared to that spent on equipment specifications and other hydraulic aspects.

The crops water requirement is the driving force of the entire system. Improper crop water estimates may offset the economic profitability of the system and lead to complete economic failure. The reasons why crop water requirement estimates was given secondary priority are lack of personnel training and the complexity of the methods used in crop water requirement estimation. This confusion is gradually being rectified by the leading work performed by specialized committees or consultants for the American Society of Agricultural Engineers (Jensen, 1980) and the Food and Agriculture Organization of the United Nations (Doorenbos and Pruitt, 1977; FAO, 1998).

Proper estimation of crop water requirements (crop water demand) is a pre-requisite for proper irrigation water management. Irrigation management is concerned mainly with the optimization of water supply and demand. The end goal is to sustain an optimum water supply avoiding both excess and deficit conditions. This is achieved by fair compensation of the depleted portion of soil moisture, predetermined depletion, after the excess soil water has been drained. Crop water requirements and soil storage characteristic have to be known as priority to achieve proper water management. Effective precipitation is a very important factor in determining the crop water needs. Crop water demand is a function of climatic factors, crop type, its growth stage, soil characteristics and their interaction. The climatic factors are the essential inputs in estimating reference Evapotranspiration (ETo) (Pereira and Smith, 1989; Jensen *et al.,* 1990; Smith *et al.,* 1991; Burman and Pochop, 1994; Pereira *et al.,* 1996; Allen *et al.,* 1997;;), while crop type and its growth stages are considered by determining crop factor (Kc) (Wright, 1988;Allen *et al.,* 1997; Grattan *et al.,* 1998;). Soil factors and management parameters are usually related to soil water management, allowable deficit, water delivery regime, irrigation method and system efficiency, scheduling and operation (Allen *et al.,* 1998).

2.1.1 Determination of reference evapotranspiration (ETo)

Reference evapotranspiration can either by measured through actual measurement methods or calculation methods.

Actual measurement methods: include soil water depletion, lysimeters and soil-water balance (Allen *et al.,* 1991; Grebet and Cuenica, 1991; Waiter *et al.,* 1991; Carrijo and Cuenca, 1992). Actual measurement method are more accurate but more expensive and require well trained personnel.

Calculation methods: early approaches were laborious and site specific but newly developed methods are of general and wider use. Their level of accuracy depends on the accuracy of climatic data involved. The calculation methods are extensively used for irrigation planning, scheduling and system operation (Bailey and Spackman, 1996; Carazza *et al.,* 1996; De Jager an Kennedy, 1996; Hess, 1996; Hill and Allen, 1996). These methods can be classified into:

Temperature methods (Blaney-Criddle equation 1950).

Radiation method: (Jensen-Haise equation, 1963).

Pan evaporation (Christiansen, 1968; and Allen *et al.,* 1998). They include class A pan, sunken pan, Piche tube and evaporometers.

Combination method (Penman equation, 1948 and FAO,1998)Penman-Montieth equation

Calculation methods are based on the concept of reference crop (Doorenbos and Pruitt, 1977). A number of theoretical and practical attempts have been made to improve the estimation performance of these methods for different locations and data availability (Coleman and De Coursey, 1976; Doorenbos and Pruitt, 1977; Beven, 1979; Batchelor, 1984; Jensen *et al.,* 1990). Still, many of these attempts have manifested some weaknesses under global application, due to:-

a- grass variety and its morphological characteristics have not been standardized for different climatic conditions, causing a great difficulty in relating calculated (ETo) to a reference crop.

b- grass management such as (alfalfa) varies with location (Allen *et al.,* 1994a).

c- problems associated with lysimeters and microclimatological measurement as they affect (ETo) values (Abu Khalid *et al.,* 1982 and Allen *et al.,* 1991).

The FAO adopted Penman combination equation (Doorenbos and Pruitt, 1977), although considered as the most comprehensive equation, it is still found to overestimate (ETo) for many reasons pertaining to the conceptual procedures used to compute the parameters within the equation and party for data reliability and processing.

Other equations such as the FAO-Radiation, FAO Blaney-Criddle and FAO-Pan evaporation equations have exhibited variable adherence to a reference ETo. Nevertheless the deviation of these equations from the grass reference is not as wide as that of the FAO –Penman.

Methodologies used to improve the estimation of crop water requirement were revised by FAO, in collaboration with the International Commission on Irrigation and Drainage (ICID). Consequently, a decision was taken to change the concept of reference evapotranspiration and revise the calculation procedures, in an expert consultation held in Rome (1990). A hypothetical reference canopy, as described by Penman-Montieth equation has been substituted for a living reference crop (Smith *et al.,* 1991). Grass reference evapotranspiration (ETo) is defined as: The rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m of a fixed surface resistance of 70s/m and an albido of 0.23 m. It closely resembles the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, with adequate water supply and free from diseases.

The FAO Penman-Montieth equation (1994) of estimating ETo is as follows:-

$$ETo = \frac{0.408\,\Delta\,(Rn - G) + \gamma \left[\frac{900}{T+273}\right] U_2\,(e_s - e_a)}{\Delta + [\gamma\,(1 + 0.34\,U_2)]} \qquad (2.1)$$

Where:

ET_o = Reference evapotranspiration (mm day^{-1}),

R_n = Net radiation at the crop surface (MJ m^{-2} day^{-1}),

G = Ground heat flux density (MJ m^{-2} day^{-1}),

U_2 = Wind speed at 2 m height (ms^{-1}),

e_s = Saturation vapour pressure (kPa),

e_a = Actual vapour pressure (kPa),

$e_s - e_a$ = Saturation vapour pressure deficit (kPa),

Δ = Slope of vapour pressure curve (kPa $^oC^{-1}$),

γ = psychometric constant (kPa $^oC^{-1}$)

Calculation steps are detailed in appendix (I-Table.1and2)

2.1.2 Determination of crop water requirements (ETc)

Reference evapotranspiration is estimated for a standard crop grown in vast fields under standard field conditions, securing optimum agronomic and soil water conditions. These conditions can rarely be maintained for field crops. This is why crop evapotranspiration (ETc) is distinctly different from ETo, as ground cover, canopy properties and aerodynamic resistances of field crops are different from those of the standard reference crop. The effects of the characteristics that distinguish field crops from standard (reference) crop are integrated into the crop coefficient (Kc). Consequently, crop evapotranspiration is calculated using crop coefficient approach as follows: -

$$ETc = ETo * Kc \qquad (2.2)$$

Where:

ETc: Crop evapotranspiration (mm day^{-1})

ETo: Reference crop evapotranspiration (mm day^{-1})

Kc : Crop coefficient

The crop coefficient (Kc) is basically the ratio of the (ETc) to the (ETo) (Elliott *et al.*, 1988). Factors for determining the crop coefficient include crop type, climate, soil evaporation and crop growth stages (Elliott *et al.*, 1988; Grattan *et al.*, 1998; Martin and Gilley, 1993). The procedure suggested by Doorenbos and Pruitt (1977) for the determination of crop coefficient (Kc) for various crop stages is based on selecting (Kc) for mid and late stages from established tables. For initial crop growth stage it uses a curve relating the evapotranspiration of the initial growth stage and average recurrent interval of irrigation or significant rainfall. This procedure for estimating initial (Kc) was considered by many researchers as laborious, cumbersome and tedious (Elkayal, 1983 and Rayan and Cuenca, 1984). Regression equations have been developed to allow for convenient computation and calculation of initial (Kc) (Elkayel, 1983 and Rayan and Cuenica, 1984) as follows:-

a- Kcin = (1.286 – 0.27 LnIf) exp [(- 0.01 – 042 LnIf) ETri]

(for If < 4 days) (2.3 a)

b- Kcin = 2 (If) – 0.49 exp [(-0.02 – 0.04 LnIf) ETri]

(for If ≥ 4 days) (2.3 b)

Where:

If = Normal interval between irrigations or significant rainfall (days)

Kcin = Initial stage crop coefficient

ETri = Average initial period reference evapotranspiration (mm day^{-1})

Such regression equations are limited by an irrigation interval of four days only. However, for drip and sprinkler irrigation systems four days interval is considered very large while in surface irrigation a wide range of intervals is used such as seven or even fourteen days. Unfortunately, the developed regression equations treat the seven, ten and fourteen day's interval as the same. This case needs to be corrected if proper irrigation scheduling is targeted.

2.1.3 FAO Method for Determination of Crop Coefficient (Kc)

The growing period of the crop is divided into four general growth stages namely the initial, development, mid-season and late season stage. Kc values are determined for each of these stages referred to as Kcin, Kc dev., Kcmid and Kc end respectively.

The values for (Kcin) provided in FAO paper (1998) are only approximations to be used in planning studies. Only one value for Kcin is given for several crop group types and is considered to be representative of the whole group. For a typical irrigation water management more accurate estimates of Kcin can be obtained by considering: -

- Time interval between wetting events:

Evapotranspiration during the initial stage for annual crops is predominately in the form of evaporation. Therefore, accurate estimates for Kcin should consider the frequency with which the soil surface is wetted during the initial period. When the evaporation from soil surface is considerable Kcin will be large. Where the soil surface is dry, evaporation is restricted and the Kcin will be small.

- Evaporative power of the atmosphere:

The value of (Kcin) is affected by the evaporating power of the atmosphere (i.e ET_o). The higher the evaporative power of the atmosphere; the quicker the soil will dry between water applications and the smaller the time averaged Kc will be for any particular period.

- Magnitude of the wetting event:-

As the amount of water available in the topsoil for evaporation ,and hence the time for the soil surface to dry, is a function of the magnitude of the wetting event, Kcin will be smaller for light wetting events than for heavy wettings.

Depending on the time interval between wetting events, the magnitude of the wetting event itself, and the evaporative power of the atmosphere (Kcin) can be between 0.1 and 1.15. Crop coefficients for initial stages can be derived from (Fig. 4.6 and 4.7a and b) which provide estimates for Kcin as a function of the average interval between wetting events, the evaporative power of the atmosphere ET_o, and the intensity of the wetting event. Fig. 4.6 is used for all soil types when wetting events are light or when wetting during the initial period is only by precipitation. The graph can also be used when irrigation is by high frequency systems such as micro irrigation and centre pivot and light application of about 10 mm or less per wetting event are applied.

Figure 4.7 is used for heavy wetting events, when the infiltration depths are greater than 40 mm (i.e when wetting is primarily by periodic irrigation, e.g. by sprinkler or surface irrigation). Following a wetting event, the amount of water available in the topsoil for evaporation is considerable, and the time for the soil surface to dry might be significantly increased. Consequently, the average Kc factor is larger than for light wetting events. As the time for the soil surface to dry, a part from the evaporation power and the frequently of wetting, is determined by the water storage capacity of the top soil, a distinction is made between soil types.

Figure 4.7a is used for coarse textured soils and Fig. 4.7b is used for fine and medium textured soils.

Where average infiltration depths are between 10 and 40 mm, the value for the Kcin can be estimated from Figs. (4.6 and 4.7).

$$Kcin = Kcin\ Fig. + \frac{1 - 10}{40 - 10}\ [Kcin\ (Fig) - Kcin\ (Fig)] \qquad (2.4)$$

Adjustment for partial wetting in irrigation can be achieved by the following(FAO ,1998) equation:-

$$Kcin = f_w\ Kcin\ (Table,\ Fig.) \qquad (2.5)$$

Where: f_w is the fraction of surface wetted by irrigation or rain (0 – 1).

Table = FAO Kcin tables. Fig. = Fig 4.6, 4.7a and 4.7b

2.1.3.1 FAO method for determination of Kcmid:-

Values for Kcmid are listed in tabular forms in FAO paper (1998). The values for Kcmid as well as Kc end in these tables represent a sub-humid climate with an average day light, minimum relative humidity (RH min) of 45% and with calm to moderate wind speeds averaging 2 m/s. For more humid or arid conditions, or for more or less windy conditions, the Kc coefficient for the mid-season and end of late season stages should be modified. The values in these tables are values for non-stressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield (standard conditions). When stand density, height or leaf area are less than attained under such conditions the values for Kcmid, and for most crops, for Kc end need to be modified.

Kcmid from these tables is adjusted as follows:-

$$Kcmid = Kcmid\ (Tab) + [0.04\ (u_2 - 2) - 0.004\ (RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \qquad (2.6)$$

2.1.3.2 Crop coefficient for the end or the late season stage (Kc end):-

Typical values for the crop coefficient at the end of the late season growth stage (Kc end) are given in Kc tables for various agricultural crops. The value given in these tables reflect both crop and water management practices adopted for those crops.

The Kc end values provided in FAO tables are typical values expected for average Kc end under the standard climatic conditions. More arid climates and conditions of greater wind speed will have higher values of Kc end. More humid climates and conditions of lower wind speed will have lower values of Kc end. Specific adjustments for climate changes are made as follows: -

$$Kc\ end = Kc\ end\ (tab) + [0.04(u_2 - 2) - 0.004\ (RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (2.7)$$

2.1.4 Construction of the Kc curve:-

For the construction of Kc curves for annual crops FAO paper (1998) suggests only three point values which are required to describe and construct the Kc curve. The curve can be constructed using the following three steps:-

a- The crop growing period is divided into four general growth stages that describe crop phenology or development (initial, development, mid-season and late season stage).

b - The length of the growing stage are determined, the three values of Kc that correspond to Kcin, Kcmid and Kc end are identified from FAO tables.

c - Adjust the Kc values to the frequency of wetting and/or climatic conditions of the growth stages as outlined earlier.

d- Construct a curve by connecting the straight line segments through each of the four growth stages. Horizontal lines are drawn through Kcin in the initial stage and through Kcmid in the mid-season stage. Diagonal lines are drawn from Kcin to Kcmid within the course of the crop development stage and from Kcmid to Kc end within the course of the late season stage.

Concerning maximum Kc Hess (1996) reported values of 1.1 or 1.2 depending on crop type. However values higher than 1.2 are sometimes used. It should be pointed out that these values were probably obtained from field experiments performed under advective conditions (very small plots) and that they are not valid for fields larger than one hectare.

The crop coefficient (Kc) being a ratio of the crop ET_c to the reference ET_o, represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass. These characteristics are as follows :-

a -Crop height: The crop height influences the aerodynamic resistance term, (Ra), of the FAO Penman-Montieth equation and the turbulent transfer of vapour from the crop into the atmosphere. The (Ra) term appears twice in the full form of the FAO Penman-Montieth equation.

b-Albedo (reflectance) of the crop-soil surface: The albedo is affected by the fraction of the ground covered by vegetation and by the soil surface wetness. The albedo of the crop-soil surface influences the net radiation of the surface, Rn, which is the primary source of the energy exchange for the evaporation process (FAO paper ,1998).

c-Canopy resistance: The resistance of the crop to vapour transfer is affected by leaf area (number of stomata), leaf age and condition and the degree of stomatal control. The canopy resistance influences the surface resistance (rs).

d-Evaporation from especially exposed soil: The soil surface wetness and the fraction of ground covered by vegetation influence the surface resistance (rs). Following soil wetting, the vapour transfer rate from the soil is high, especially for crops having incomplete ground cover. The combined surface resistance of the canopy and of the soil determines the (bulk) surface resistance (rs). The surface resistance term in the Penman-Montieth equation represents the resistance to vapour flow from within plant leaves and from beneath the soil surface.

The (Kc) in the equation $ET_c = Kc * ET_o$ predicts ET_c under standard conditions. This represents the upper envelope of the crop evapotranspiration and represents the conditions where no limitations are placed on the crop growth or evapotranspiration due to water shortage, crop density, disease, weed, insect and salinity pressures.

The calculation procedure for crop evapotranspiration, (ET_c) involves the following steps:-

a-Identifying the crop growth stages, determining their lengths and selecting the corresponding Kc coefficients.

b-Adjusting the selected Kc coefficients for frequency of wetting or climatic condition during the stage.

c-Constructing the crop coefficient curve (allowing one to determine ETc as the product of ET_o and Kc).

2.2 Length of growing stages

Since ground cover, crop height and leaf area change as crop develops, then the Kc for a given crop will also vary over the growing period.FAO paper (1998). This is due to the difference in evapotranspiration during the various growth stages. The growing period can be divided into four distinct growth stages, which are initial, development, mid-season and late season stages. The general lengths of the four distinct growth stages for most important crops and their total growing periods for various types of climates and locations are compiled from different sources and given in the FAO papers 24 and 56, and detailed as follows: -

a- Initial stage: The initial stage extends from planting date to approximately 10% ground cover. The length of the initial period is highly dependent on the crop, the crop variety, the planting date and the climate. For the perennial crops the green-up date is taken instead of the planting date. The green-up time is when the initiation of the new leaves occurs.

The leaf area is small in the initial stage and hence evapotranspiration is mainly in the form of soil evaporation. Therefore, the Kc during the initial stage (Kcin) is large when the soil is wet from irrigation and rainfall and low when the soil surface is dry. The time for the soil surface to dry is determined by the time interval between wetting events, the evaporative power of the atmosphere (ET_o) and the intensity of the wetting event.

b- Crop development stage: The crop development stage extends from 10% ground cover to effective cover (70%). Effective full cover for many crops occurs at the initiation of flowering. For row crops where rows interlock leaves such as beans, sugar beets, potatoes and corn, effective cover can be defined as the time when some leaves of plants in adjacent rows begin to intermingle so that the soil shading becomes nearly complete or when plants reach nearly full size if no intermingling occurs. For some crops especially those taller than 0.5 m, the average fraction of the ground surface covered by the vegetation (fc) at the start of effective full cover is about 0.7 – 0.8 for densely sown vegetation such as cereals and grasses. The heading or flowering stage, which is easily detected, is generally used.

Another way of determining effective full cover is when the leaf area index (LAI) reaches three. LAI is defined as the average total area of leaves (one side) per unit area of ground surface

As the crop develops and shades more and more of the ground surface, evaporation becomes more restricted and transpiration becomes gradually the major process. During the crop development stage, the Kc value corresponds to amount of ground cover and plant development (FAO paper ,1998).

c- Mid-season stage: The mid-season stage extends from effective full cover to the start of maturity. The start of maturity is often indicated by the beginning of the aging, yellowing or senescence of leaves, leaf drop, or the browning of fruits to the degree that the crop evaportranspiration is reduced relative to the reference ET_o. The mid-season stage is the longest for perennials and for many annuals. It may be relatively short for vegetable crops that are harvested fresh for their green vegetation.

At mid-season stage the Kc reaches its maximum. The value for (Kcmid) is relatively constant for most growing and cultural conditions. Deviation of the Kc_{mid} from the reference value "1" is primarily due to the differences in crop height and resistance between the grass reference surface and the agricultural crop and weather conditions.

d- Late season stage:- The late season stage extends from the start of maturity to harvest or full senescence. The calculation of Kc and ET_c is assumed to end when the crop is harvested, dries out naturally, reaches full senescence or experiences leaf drop.

For some perennial vegetation in frost free climates, crops may grow year round that the date of termination may be taken as the same as the date of planting.

The Kc value at the end of the late season stage K_c end value is high if the crop is frequently irrigated until harvested fresh. If the crop is allowed to senesce and dry out in the field before harvest, the Kc end value will be small.

2.3 Determination of irrigation efficiency and losses

While conveying water to the field some losses due to evaporation, leakage, seepage and deep percolation are encountered.The conveyance efficiency is expressed by (Boss and Nugteren (1974) as follows:-

$$E_c = \frac{\text{Water received at the block inlet}}{\text{Water received at the head works}} \quad (2.8)$$

The conveyance efficiency (E_c) depends on canal length, seepage, leakage and evaporation. Estimates of (E_c) are shown in Table (2.1) as reported by Bos and Nugteren (1974); and FAO (1998).

The canal efficiency E_b is the efficiency of water conveyance in the canal within a sector, block or sub-unit. The canals at this level are usually unlined and seepage losses along them are usually high. Table (2.1) gives the values of E_b at different kinds of canals and block areas.It can be defined, as reported by Boss and Nugteren (1974), as follows:-

$$E_b = \frac{\text{Water received at field inlet}}{\text{Water received at block inlet}} \quad (2.9)$$

At the field level losses occur mainly as deep percolation and surface runoff. Field application efficiency is defined as:-

$$E_a = \frac{\text{Water stored at the root zone}}{\text{Water received at field inlet}} \quad (2.10)$$

Recommended (E_a) values suggested by Boss and Nugteren (1974) are given in Table (2.1).

The overall scheme or project efficiency (E_p) can be defined as:

$$E_p = \frac{\text{Water stored in the root zone}}{\text{Water received at head works}} \quad (2.11)$$

The scheme efficiency can also be calculated as follows:

$$E_p = E_a \, . \, E_b \, . \, E_c \quad (2.12)$$

Gross irrigation water need (1Ng) is usually determined as follows:-

$$1Ng = 1N\ net/E_p \quad (2.13)$$

Where:

1Ng = Gross irrigation needs

1N net = Net irrigation needs

E_p = The overall scheme or project efficiency

E_a = Field application efficiency

E_b = Canal efficiency

E_c = Conveyance efficiency

*** sourse: Boss and Nugteren (1974)**

Table (2.1): Conveyance, Field Canal, Distribution and Field Application Efficiencies*

1- Conveyance efficiency (E_a) :			**ICID/ILRI**
. Continuous supply with no substantial change in flow			0.90
. Rotational supply in projects of 3 000 to 7 000 ha and Rotational areas of 70 – 300 ha with effective Management			0.80
Rotational supply in large schemes (>10 000 ha) and Small schemes (< 10 000 ha) with respective problematic Communication and less effective management:			
. Based on predetermined schedule			0.70
. Based on advance request			0.65
2- Field canal efficiency(E_b) :			
. Blocks large than 20 ha			
Unlined			0.80
Lined or piped			0.90
. Block below or up to 20 ha			
Unlined			0.70
lined or piped			0.80
3- Distribution efficiency ($E_d = E_a – E_b$) :			
. Average of rotational supply with management and communication :			
. Adequate			0.65
. sufficient			0.55
. insufficient			0.40
. poor			0.30
4- Field application efficiency (E_d) :			
	USDA	**US(SCS)**	**ICID/ILRI**
i. Surface methods :			
Soil type			
. light soils	0.55		
. medium soils	0.70		
. heavy soils	0.60		
Irrigation method			
. graded border		0.60-0.75	0.53
. basin and level border		0.60- 0.80	0.58
. contour ditch		0.50-0.55	
. furrow		0.55-0.70	0.57
. corrugation			
ii. Subsurface		Up to 0.80	
iii. Sprinkler			
. hot, dry climate		0.60	
. moderate climate		0.70	
. humid, cool climate		0.80	0.67
iv. Rice			0.32

2.4 Determination of effective rainfall:-

According to CROPWAT the FAO Irrigation and Drainage Paper (46) (1992) and El-Ramlawi (1999) four different methods are used to determine the effective rainfall. The different options are:-

a-Fixed percentage of rainfall: effective rainfall is calculated according to:

$$P_{eff} = a . P_{tot} \qquad (2.14)$$

Where (a) is a fixed percentage to be given by the user to account for losses from runoff and deep percolation. Normally the losses are around 10 to 30%, thus a = 0.7 – 0.9. A value of 0.75 was given by Adam (1996) for conditions of central clay plains of the Sudan.

b-Dependable rain: based on an analysis carried out for different arid and sub-humid climates an empirical formula was developed in FAO/AGLW to estimate dependable rainfall, the combined effect of dependable rainfall (80% probability exceedance) and estimated losses due to runoff and percolation this formula may be used for design purposes where 80% probability of exceedance require calculation according to:-

$$P_{eff} = 0.6\, P_{tot} - 10 \qquad \text{for } P_{tot} \leq 70 \text{ mm} \qquad (2.15\ a)$$

$$P_{eff} = 0.8\, P_{tot} - 24 \qquad \text{for } P_{tot} > 70 \text{ mm} \qquad (2.15\ b)$$

c-Empirical formula:- The parameters may be determined from an analysis of local climate records, which may allow an estimate of effective rainfall. The relationship,in most cases, can be simplified by the following equations:-

$$P_{eff} = a\, P_{tot} + b \qquad \text{for } P_{tot} < Z \text{ mm} \qquad (2.15\ c)$$

$$P_{eff} = c\, P_{tot} + d \qquad \text{for } P_{tot} > Z \text{ mm} \qquad (2.15\ d)$$

a, b, c and d are correlation coefficients.

d-USDA Soil Conservation Service Method:

Where effective rainfall can be calculated according to:

$$P_{eff} = P_{tot}\,(125 - 0.2\, P_{tot})/\,125 \qquad \text{for } P_{tot} < 250 \text{ mm} \qquad (2.16\ a)$$

$$P_{eff} = 125 + 0.1\, P_{tot} \qquad \text{for } P_{tot} > 250 \text{ mm} \qquad (2.16\ b)$$

2.5 Estimation of water indent (water order) in the Sudan

In the context of irrigation in the Sudan an indent is simply an advanced and timely written request by the Block Inspector demanding a certain discharge expressed in cubic meters to be let by the assistant Division Engineer (ADE), into a certain Minor canal for certain number of coming days unless unforeseen conditions prevail. In practice the orthodox water order (indenting) begins from the Block Inspector who simply calculates the indent by counting the number of field outlet pipes (FOP) to be open along a Minor Canal and multiplies that number by (5000 m^3). He then sums up the indents of all Minors in his Block. Requests should reach the canal authorities (ADEs), in time to enable them to meet the demands at the earliest convenient time.

The (ADE) in his turn usually adjusts the indent to suit the crop factor, command area and limits of Minor maximum carrying capacity (Mohamed 1992).

Since the early start of the Gezira Project till recently it became an established tradition to quote the following figures (Adam, 1993):-

- Average irrigation 400 m^3/fed/irrigation
- 14 days irrigation interval and
- 5000 m^3/12 hrs per field outlet pipe (FOP)

The 5000 m^3/12 hrs crop water requirement as expressed by the term indent for irrigated agriculture of the Central Sudan was based on peak demand of cotton in August (30 m^3/fed/day). An average irrigation of 400 m^3/fed is found to be sufficient to sustain the crop for 14 days. To irrigate a field of 90 feddans about 36000 m^3 (400 x 90) is required. The Minor canal was designed to operate on the basis of 50% cropping intensity (half FOPs to be operated at the same time). Hence, each field of 90 feddans needs to be irrigated in seven days so that the discharge of FOP had to be 5000 m^3/day of 12 hour (36000/7 days).

In the late Seventies Farbrother (1975; 1976a; 1977; 1978; 1979a and 1979b) made a series of soil moisture monitoring and Pan evaporation (E_{pan}) measurements to develop water requirement tables for the major irrigated crops in Sudan. These tables were used as a planning tool to operate Sinnar Dam (Tajel Din *et al.,* 1984) and for optimized operation for the Blue Nile System (HLLCOOBNS, 1999).

With intensification and diversification, the Gezira tenant has developed new field methods of unattended night continuous-flow watering and the number of (FOPs) that must be opened simultaneously during peak demand periods has risen. It is therefore logical to agree that the assumption of 5000 m^3 per day per FOP is no longer valid.

According to Farbrother (1974) there is a necessity for research on alternative methods to assist the judgment of the inspector when he is in doubt. The auther suggested that the research can be directed toward two main objectives:-

1- To provide the Block Inspector and the Assistant Divisional Engineer with basic forecast of the Minors daily requirements for successive periods of 10 or 11 days for the coming season.

2- The official recognition of the operation of the Minors as continuous-flow canals.

Farbrother,(1974) commented that: “Clearly a great deal of applied research and field extension are required to establish a sound basis for indenting in the future.”

Since the rapid intensification and diversification of the rotations, the management of the Sudan Gezira Board has come to recognize the increasingly urgent need to improve the standard of “indenting” for water supplies in the Gezira and Managil.

Under the terms of FAO Technical Cooperation Project 6/SUD/01M the new “Crop-Water-Requirements” (CWR) method of indenting has been introduced to the commercial areas, after the initial field trials proved satisfactory. CWR indenting requires two basic inputs:

a) The total feddans actually planted (or expected to be planted) by the tenants on any individual Minor canal, covering each cropping component of the rotation by successive 10/11 day periods.

b) The mean water requirements in cubic meters per feddan per day, for each crop over its normal length of season, in a year of average climatic conditions.

The water requirements, from planting to harvest of a number of irrigated crops, when grown to good standards of husbandry in Gezira area, in cubic meters per feddan per day were published in tables under the permission of the Agricultural Research corporation. Examples of these tables for main Gezira crops are given in the Appendix (I-Tables,3to8)

It is worth to note that Farbrother indenting tables were based on actual pan evaporation (E_o) instead of evapotranspiration (ET_o). In addition conveyance and application losses were assumed fixed as 15% while world wide losses in surface irrigation are estimated to be of higher values (Boss and Nugerten, 1974). The table values when subjected to practical application at Moharam Minor in Gezira scheme manifested over prediction of crop water demand (Hussein and El-Daw 1989).

In an attempt to utilize crop water requirement for planning purposes Adam (1996) used Penman-Montieth equation for estimation of crop evapotranspiration (ET_o). This can be considered as an improvement to Farbrother indent estimation method. For driving crop water demand Adam (1996) used the FAO (1977) method for estimation of Kcin. This method was claimed to consider only two elements i.e. irrigation interval and ET_o and it neglects soil type and infiltration depth. These two elements were considered latter by Allen *et a*l (1998). Adam’s (1996) method uses the same value of Kcin irrespective of sowing date of the crop in question.

2.6 Systems of canal water delivery and allocation

There are wide variations in the design and management practices adopted on irrigation enterprises in different parts of the world. There may also be significant differences between regions in a single country and between schemes of different sizes.

The way by which water is delivered, whether by continuous-flow, rotational, on demand or limited demand, evolves different management practices. The choice of crop will affect the pattern of operation, as will social factors and traditions.

At lower level, the degree of control which can be exercised by managers over their systems is constrained by economic cost, engineering design and conditions of the system. With increasing competition for water the returns for irrigated agriculture appear low by comparison with other uses. The governments are increasingly concerned by the costs and levels of staffing which are associated with irrigation. The returns from large, centrally managed schemes are almost always insufficient to cover staff costs without subsidy. On Minor schemes the situation is proportionally worse, shortage of trained operators and management (O & M) staff exerts a constraint on many schemes. The limitations imposed by the original design may also affect the degree of control which can be imposed on a system.

Management of water, though fundamental to the irrigation enterprise is only one of many tasks with which they must deal. The items in Table (2.2) divides up managerial responsibilities and problems into a number of categories. They are not necessarily listed in priority order. Nonetheless, Bottral (1986) identified poor management of water in the main system as an important component of the under performance and suggested that computer-based Decision Support Systems (DSS) could assist managerial decision making.

The objectives of irrigation are to maximize quantity and quality of crop production and the returns from investment in agriculture. For this purpose water needs to be distributed and delivered to fields and crops at the right timing and in the right volume. From water users point of view, in addition to timely and adequate delivery of water, equity of water distribution among water users will be of importance to avoid water disputes and to encourage the cooperation among water users which in turn will improve the smooth operation and management of the system. When the water delivery is unpredictable or unreliable, upstream users will often take as much water as possible when water is available and the tail-enders will suffer. It is important to establish clearly defined guidelines on how the water will be distributed among water users belonging to the same operation unit such as tertiary canal.

Table (2.2). Types of problems faced by irrigation managers.

FINANCE AND BUDGETING

- inadequate funds for O & M, need to prioritize

- difficulty in recovering water charge fees

- acquiring and presenting data needed to support estimates for central funding

HUMAN RESOURCES

- poor salary, promotion prospects affect staff motivation

- shortage of trained and skilled staff

- corruption

MANAGERIAL-SOCIAL

- lack of authority to distribute water

- lack of cooperative working amongst farmers

- disputes between farmers and irrigation staff

- lack of irrigation experience amongst farmers

- lack of transport, poor communications

- unplanned extension to the scheme area

- fragmented landholdings

- farmers no longer wish to irrigate at unsocial hours

WATER SUPPLY/DEMAND

- competition for resources and social changes reduce security of supply

- extreme weather conditions cause large fluctuations in basic demand

- microclimatic variations over project affect areal unit demands

- other water sources/unofficial abstractions from system affect demand/supply

- farmers change to more water-demanding crops

TECHNICAL

- lack of system capacity at peak demand/command/tertiary canal development
- insufficient control due to lack, or poor condition, of structures
- unrealistic design assumptions (irrigating hours); changes in cropping patterns
- unreliable power supply (pumps)

ENVIRONMENTAL

- water logging/high water tables/salinity
- aquatic weeds
- water-borne sediment

INFORMATION/POLICY

- conflicting objectives
- failure to set realistic targets
- lack of parameters by which to assess performance realistically
- lack of information and limited analytical capacity
- lack of formalized operational rules

Sourse: Proceedings of the FAO Expert Consultation (1993)

When the management of the main system and the tertiary unit is separate, the management of the main system considers distributing water itself is the objective and sometimes pays little attention to the ultimate objective of irrigation as mentioned above.

Water delivery and distribution can be supply-oriented or demand based. In a supply-based irrigation system, water is often distributed proportionally to the area of irrigation regardless of the actual demand of crops. Under a diversified cropping system the chances of over and under-irrigation are high because crops require different amounts of water at different growth stages when the supply to the main system is not sufficient, the flow in successive canals such as secondary and tertiary will be reduced proportionately. It often happens that water is monopolized by upstream users at the time of shortage and no water will be provided to tail-enders. It is rather the location of farm plots and power balance among water users which determine the priority and the amount of irrigation.

Under demand-based system, the amount of irrigation for each crop (plot) is defined by the water requirements and thus there could be little chance of over – and under – irrigation so far as the rule of water delivery is observed as determined. The constraints to introducing a demand-based are the requirements of data processing and the flexibility of the infrastructure to accommodate the fluctuating water demand. Demand-based water distribution has better prospects of satisfying timely, adequate and equal distribution and hence, achieving the objectives of irrigation.

The function of the main irrigation system is to supply irrigation water to the tertiary units according to the operational objectives.The general objective of main irrigation systems is to deliver water to the tertiary units with:-

- sufficient head above the terrain (command).

- a reliable supply of water (water arrives when it is supposed to and in proper quantities and flow rates).

- in an assured way (i.e. chance of failure of 20%).

flexible supply of water (i.e meeting the changing water needs for irrigation).

2.7 Operational objectives in irrigation delivery system

As cited by Ankum (1995) water delivery practices between farms are historically grouped into:-

a-Continuous-flow: Furnishing a continuous-flow throughout the season.

b-Delivery on-demand: Based on the request of the neighbouring farmers to have all the water during a short period of time.

c-Rotation: Each farmer may receive his share, to be worked out in advance.

The presently used classification as summarized by Sagardoy (1982) is:-

a-On-demand: Water is available to the farmers at any time.

bSemi-demand: Water is made available to the farmer within a few days of his request.

c-Canal rotation and free demand: Secondary canals receive water by turns and once the canal has water farmers can take the amount they need.

d-Rotational system: Secondary canals receive water by turns, and the individual farmer receives water at a pre-set time.

e-Continuous-flow: Throughout the irrigation season the farmers receive a small but continuous-flow that compensates the daily crop evaporation.

As another version the World Bank (1986) shows four options of water scheduling: (i) continuous (ii) demand (iii) fixed rotational with constant flow and (iv) variable rotational at variable flow and/or at variable periods.

The operational objectives of a main irrigation system are specified by three fundamental factors:-

a) Decision making procedure: This includes imposed allocation, semidemand allocation and on-demand allocation.

b) Method of water allocation: Includes splitted flow, intermittent flow and adjustable flow.

c) Method of water distribution: Which envolves splitted flow, intermittent flow, rotational flow and adjustable flow.

The overall objective can be aimed at maximizing the returns of the water. Maximizing the returns can be based on two concepts.

- Protective irrigation: to maximize the returns per meter cube of water.
- Productive irrigation: to maximize the returns per meter square area.

2.8 The system of water delivery and allocation in Sudan:-

The system of water delivery and allocation for all irrigation schemes in Sudan is based on the model of the Gezira Scheme. The function of which is to carry properly controlled supplies of water to within reasonable access of all parts of the irrigable area. The distributive system of the Gezira comprises the Main Canal, Branches and the Majors. The Minor in spite of the name, should not be thought of simply as the next stage down in canal size. It is quite different in its agricultural purpose. It is designed to irrigate land rather than to convey water.

As reported by Shafique (1993) in Sudan, the design of the Gezira scheme was made to meet the following conditions:-

a- No field irrigation at night is possible.

b-Disposal of water in excess of actual requirements is not possible after it has left the main canal.

c-Under the terms of agreement, actual requirements of the cultivating syndicate have to be satisfied.

d-Measurements of water under varying conditions and levels are necessary.

In the same context Tajel Din *et al.* (1984) stated that the design of the operating system is to deliver the required quantities of water at the proper time at the farm level. In order to achieve such design objectives, it was necessary for the Ministries of Agriculture and Irrigation to ensure that water delivered in the main canal is adequate for crop water requirements and effective control of the water ensures that sufficient water is delivered at the correct time to the cultivators.

Following the previous discussion, four design objectives can be stated:- a) adequate water supply b) dependable, reliable water supply irrespective of time and location in the scheme, c) equity and d) efficiency. Also addition emphasis is given to the operational performance of the managing agency to ensure that the design objectives are being achieved.

The scheme was originally designed for night storage irrigation. It is operated under a continuous-flow system. Hence the Block Inspector (BI) and his staff have to operate the regulators between the successive reaches in such a way that the distribution to the tenants from head to tail in the Minor is as equitable as possible irrespective of their location on the Minor. The equitable distribution can be obtained by relative opening of the gate in the night storage weirs and the partial opening or closing of the FOPs. It is also quite clear that in order to have equitable water distribution at Minor level, Main and Major canals have to supply equitable water supplies to it.

Consequently, the most relevant variables for water control and planning are:-

a-indents prepared by the agricultural staff.

b-crop water requirements.

c-actual deliveries which are functions of actually available supply.

d-crop type, mix and cultivated area.

It is important to note that none of the supply canals (Majors and above) are drawn on directly for application of water to the field, under normal practice, and all down to the smallest Major, are controlled, operated and gauged entirely by the Ministry of Irrigation. In contrast, the Minors, as canals directly associated with field watering are operated by the officials of the Sudan Gezira Board, although the maintenance and servicing of the regulators and the canal was the responsibility of the Ministry of Irrigation. In recent days this responsibility was shifted to the Sudan Gezira Board.

Minor canals as described as basic repetitive irrigation units of the Gezira, and although they vary greatly in size (up to 2 km long, and commanding gross areas ranging between 300 and 12,000 feddans) they follow a formal layout, in contrast with the supply network.

Minors are constructed in parallel layout, in which each Minor is 1.42 km from its neighbour. In general, their alignment tends to cross the contours, following the slope of the land, but there can be no hard fast rule.The sole purpose of the Minor is to command land for direct application of irrigation water to the fields. The minimum limit for command is taken to be 20 cm over the highest parts of the field to be irrigated, while for safety reasons, a command up to a limit of 50 cm is permitted above the ground level adjacent to the Minor canals. The water level to which these commands refer is designated as the Full Supply Level (FSL). The highest of the banks above the water level at (FSL) should be 60 cm after settling. The banks themselves should be not less than one meter broad at the top, with side slopes of 2:1 both inside and outside (Table 2.3).To keep the command between the upper and lower limits, a regulator is installed when command exceeds 50 cm to drop the water level to the minimum of 20 cm command over the highest part of the next area served down stream.

The Minor consists of successive reaches, varying between 8 and 10 meters wide at FSL, separated by regulators at distances determined by the general slope of the land in the direction of flow. The overall average slope of land is about 15 cm per km, so that if the FSL is to drop 30 cm at each regulator, the average length of a reach is 2 km, but it varies from 1 to 5 km.

Table 2.3 Data for Design

Field canals

	DA.XX	A.XX	A.VI
Canals section:			
a) Command, Minimum F.S.L. Flalt	15 cm	10 cm	8 cm
" Maximum " "	25 cm	20 cm	12 cm
b) Water slope, Minimum	5 cm/k	5 cm/k	5 cm/k
c) Manning's 1/n	50	50	50
d) Discharge per 12 hours	10.000 m^3	5000 m^3	2000 m^3
e) Side Slope (Hand excavation)	2 to 1	2 to 1	2 to 1
f) Bed width (" ")	1.5 m	1.0 m	0.6 m
g) Depth to dig	0.5 m	0.4 m	0.3 m
Bank section:			
a) Bank cover (F.S.L. to top)	0.25 m	0.20 m	0.10 m
b) Hydraulic gradient from F.S.L.	7 to 1	7 to 1	7 to 1
c) Bank height, minimum	0.55 m	0.50 m	0.20 m
d) Top width	0.50 m	0.50 m	0.25 m
e) Side slopes	3 to 2	3 to 2	3 to 2
f) Berm – Minimum	0.30 m	0.20 m	0.20 m
g) Excavation			
Net bank area	0.92	0.92	0.92

For for hand dug field channels.

Key:
DA.XX = Double Abu XX
A.XX. = Abu XX
A.VI = Abu VI

Source: Gezira Design Sheet Book (undated)

(Table 2.3) continued

Explanation Note:

Abu xx:

A number of 90 feddans is usually watered in about 7 days = approximately 13 feddans per day. With a duty of 400 m^3/fed, 5200 m^3 has to be supplied in 12 hours (assuming 12 hours night storage) which is equivalent to a discharge of approximately 10,000 m^3 per 24 hour per day.

Watercourses on continuous watering system usually water a number of 180 feddans in 7 days, about 26 feddans per day. The cross section is unchanged as these channels are in flow continuously at a rate of 10,000 m^3 per 24 hour day.

Double Abu xx:

There may be two Numbers watering simultaneously from a double Abu xx. The discharge capacity therefore should be 20,000 m^3/24 hour day.

Abu vi:

A discharge capacity of 2000 m^3/day allow for the watering of 5 feddan.

Canal section

a) <u>Command</u> – Minimum – from higher G.L. on the reach to flat F.S.L.	20 cm
(Not: The 1st number waters from upstream the regulator)	
<u>Command</u> – Maximum – from adjacent G.L. to flat F.S.L.	50 cm
b) <u>Water slopes</u>	
Original design operative slopes after silting to design water section design water section for required discharge as follows:	Flat
Low supply slope from point of minimum command	2 cm
Full supply slope from downstream regulator	5 cm
Night storage slope from downstream regulator	1 cm
c) <u>Manning's 1/n</u> Excavation in dry	45
Excavation in wet	40
f) Bed width – grader excavation	

Table 2.3 continued

Bed width – hand and draggling excavation	1 to 4 m
g) <u>Water depth</u> – from chart of manning's formula:	See ref. Chart No.
Check proportions of water depth to bed width by laoey's chart.	Ref. chart No.
h) Night storage depth	
Minimum at downstream regulator	20 cm
i) Night storage width	

The mean width and the mean depth on a reach between N.S.L. and F.S.L. should be sufficient to give 5.1 m^3 storage volume per gross feddan. This will give 12 hours storage at factor 10 equivalent to 7 hours storage at factor 17.

Bank Section

a) Bank cover above flat N.S.L.	40 cm
b) Hydraulic gradient from flat N.S.L.	7 to 1
c) Bank height – maximum	1.10 m
– minimum	0.80 m
d) Bank top width – minimum	1.0 m
e) Inner side slope	2 to 1
f) Outer side slope	2 to 1
	or to 1.0 m top width
g) Volume of excavation	0.92

As a consequence of the design to command, the size and carrying capacity of a Minor canal is always far in excess of that necessary to convey water from the head to points downstream.

The pipes and regulators between reaches are designed to gradually decreasing capacities down the length of the Minor, decreasing proportionately with area served below them. A typical series of regulating pipes would have diameters in the standard range:- 1.24 m, 1.01 m, 0.91 m, 0.76 m, 0.50 m and 0.35 m for gross areas from 6,000 down to 270 feddans (Farbrother, 1974).

The Field Outlet Pipe (FOP) is a steel pipe 35 cm in diameter and 12 m long, which takes the supply from the Minor, under the roadway to an Abu XX. The standard spacing between FOPs down the length of the Minor is 292 m and each FOP is designed to irrigate one standard number of 90 feddans. Design discharge of water (Abu XX) is 116 lit/sec to irrigate one Number of 90 feddan (Table 2.2).

According to Farbrother (1974), in standard layout, the field channel (Abu VI) runs at right angle to the Abu XX. When hand-dug, the bed width was 0.6 m and the depth was 0.3 m, providing a design command between 8 and 12 cm over the land of each Hawasha. The design capacity of an Abu VI was originally 2000 m^3 per 12 hour day. The Abu VI is supplied through the bank of Abu XX by a short length of pipe 7.5, 8 or 8.5 inches in diameter. These pipes are seldom used today. The Abu VI normally waters a 10-feddans Hawasha. Furrows (275 m length) are usually at right angle to Abu XX. They run down the slope to compensate for any deficiency in land leveling. The field unit (Hawasha) is divided traditionally into a system of 14 basins (Angayas) by seven field channels (Gadwals) and seven bunds (Tagnats).

2.9 Operation of the Minor canal

The system of irrigation in the canal network higher than the Minor is known to be continuous flow system.The Night Storage System (NSS) is supposed to be practiced at the Minor canals and the field water courses. The main idea behind (NSS) is to use the Minor canals as conveyors during the day time and as reservoirs by night. All intermediate regulator gates along the Minors and all FOPs are supposed to be closed at night. Water would thus be stored in the Minor canal to the night storage level. The intermediate regulators should be opened at 6 a.m. next morning together with the FOPs scheduled for irrigation that day. The main features of this system are to overcome difficulties of irrigation by night and keep the high head, and so high discharges to Abu XXs during the day time. Each Abu XX should irrigate for one week and be kept closed for the next week. Average design flow through the field outlet pipe is about 5000 m^3 per day (about 116 L/S) and that through Abu VI is expected to be around 60 L/S and 30 L/S depending on whether the plots are nine or eighteen in number. In practice the flow rate and time of operation of a water course and irrigation interval are different (Ahmed *et al*, 1986).

As given by Farbrother (1974) and Ahmed *et al.* (1989). The Sudan Gezira Board shoulders the responsibility of the day-to-day operation of the Minor canals.

The block inspector has a staff of one to three Khaffirs per Minor. After receiving the continuous 24-hr supply at the head of each Minor from the major in response to their indent, the inspector and his staff have to operate the regulators between successive reaches in such a way that the distribution from head to tail of the Minor is as fair and equitable as possible to all tenants, irrespective of their location on the Minor.

The water Khaffirs have only two variables with which to ensure fair distribution between reaches:

a) control of the number of FOP, open simultaneously

b) the relative openings of the regulator gates.

The number of FOPs required to be open has changed completely since intensification and diversification in recent years. Although the number of FOPs open has been given above as one of the variables traditionally under the control of water Khaffirs, this is now not effective in practice. Moreover, the timing of the opening of FOPs on which recommended interval depended, is not now imposed by schedule from above, but originates, instead, from below, depending on the tenants judgment of the requirements of their crops. Since intensification, the situation is entirely different from the traditional management, under which the number of open FOPs was arranged by the inspector and Khaffirs solely to achieve the recommended timing of the "Angaya" system and giving priority to cotton numbers.

The increased number of FOPs now open has imposed the change of the method of operation of the gates of the successive regulators so that the distribution to down stream reaches still remains fair.The Khaffirs judge the opening and closing of the Minor regulators on a scale of screws (the number of turns of thread above the frame nut).

The traditional system of complete shutting of regulators at night is no longer valid, because operation of Minor has moved almost entirely to continuous-flow system. Instead the regulators are left as long as possible at the openings that are found in practice to give comparable supply heads in the immediate reaches above and below, irrespective of where they might be relative to the FSL.

The shifting of the system from night-storage to continuous-flow lead to the rise of many complaints.The irrigation engineers complain that they are no longer able to maintain the traditional supply levels expected. The Block Inspector complains that Khaffirs readily agree to tenants request for supply and the tenant may complain that water is not always available when he needs it.

The present understanding between Khaffirs and tenants and their present method although appreciated, does not mean that the present operation of the Minor as continuous flow canal can not be further improved. While the old concepts of full supply level (FSL) and night storage level continue to be urged as objectives for water Khaffirs, the highly irregular pattern of levels at about FSL, however, are quite unobtainable under present conditions.

A new concept, Optimum Supply Level (OSL) would be introduced to define the stable level in the Minor that would be best suited to continuous-flow watering.

Under present field method of unattended night watering, heads unexpectedly higher than optimum can disrupt the smooth progress of irrigation with far more serious agricultural consequences than sub-optimal level heads. Flooding of low areas, and waste of water to roads or drains through breaks along ‘the tagnet’ boundaries of numbers affect yield and efficiency of water use.

The working level and the stable head that constitutes it are not yet defined, but the Gezira Research Station (G.R.S) field survey findings given by Farbrother (1974) suggested 20 cm below design FSL as a first approximation. The average of 3,550 m^3 per 24 hour day per FOP can be suggested as a suitable norm which would be convenient for unattended night watering.

It could be concluded that a great deal of applied research supported by mathematical modeling and field extension is required to establish a sound basis for indenting and sequence of opening of FOPs in the future.

2.10 Linear programming technique for water allocation

The development of software for the specific utilization of computers in irrigation system is is rather slow when compared to other sectors. One reason for this may be that the problems of irrigation systems are very site-specific and diverse. Whatever the reasons may be the fact remains that only large irrigation systems have moved in the direction of developing their own software to solve their specific problems.

World wide computer simulation of irrigation systems has been attempted by several workers for determining crop water allocation. In accordance with this Anderson and Maass (1971) developed a simulation procedure to study the effect of water supply and operation rules on the production and income of irrigated farms. The irrigation model proposed by Jensen *et al.* (1970) uses the climatic, crop and soil data for the purpose of scheduling irrigation using a computer-based approach. A soil balance approach was adopted by Rajput and Michael (1989) for development of an integrated canal scheduling model. The U.S Department of Interior Bureau of Reclamation (USBR) has developed programmes to assist in irrigation management (Brower and Buchheimn, 1982). Rao *et al.* (1992) considered the problem of real-time irrigation under limited water supply. Many researcher (Bellostass ,1994); Lakshminarayana and Rajagopalan 1977; Matanga and Marino, 1979a, 1979b and Zhenmin 1994, developed models for water allocation between different crops based on linear programming for maximization of economic benefit. Many of these models were developed for specific conditions and can not be used directly in all irrigation systems. In addition, those models employ the economic evaluation as the only decision criteria. The economic decision are based on single prices. Estimate for future status from the current values and price profile through season is unknown.

A linear objective function with variable constraints is usually defined .The LP models emphasize one or more particularities concerning the spatial scale, time horizon, the specificity of the decision variables and the constraint or any element entering in the equations. Solving the problem requires very careful preparation of the equations, while the complex programming and debugging (tracking down and fixing program bugs to spot problems and make the programming more rewarding) were time consuming.

Many optimization techniques available in literature which are made for allocation of scarce water, employed linear programming techniques (Bellostass,1994;Upcraft et al.1989 and Yoo and Busch,1985).This is because linear programming (LP) is an excellent tool for solving optimization problems.

Suryavanshi and Reddy (1986) published a paper on the operation schedule of an irrigation distribution system in which the constant- frequency variable-depth method of water delivery is discussed. The problem of clustering and sequencing outlets on a distributary channel to determine required quantity of water is described and formulated as a zero-one linear programming problem. The optimal operation schedule of the outlets are shown in (Table 5.10a and b).

In Sudan manual calculation procedure for indenting and Minor canal operation were employed during early days of construction of Gezira scheme. In the 1960's intensification and diversification program was introduced into the Gezira. The introduction of this program made the classical manual calculation procedure of indenting and Minor canal operation not operable. In order to rectify the situation a series of studies were made by different researchers (Hamid,1985; Shafique et al.,1993; Fadul,1993; Lado,1994 and Warrag,1995).The focus of the evaluating and monitoring studies adopted was restricted to the physical sub system component of the irrigation water delivery system and to the operating status of the conveyance and distribution system.

The previous studies quantified the inequity in water distribution system, lack of proper indenting system and inefficient structural components. However, no definite solution scheme was recommended.

Recently ElRamlawi (1999) claimed that it is better to make the solution to these problems on basis of management and system operation rather than to rehabilitate the hardware part of the system. The claim was based on the rising cost and ineffectiveness of the rehabilitation programms adopted in the past, consequently, he developed a model for the simulation and optimization of irrigation water demand and supply (HEWASP) as a preseasonal planning tool. This arises the question of how to implement such a plan and how to operate the system in order to achieve the goals of equity and dependability in water distribution. Such a gap needs to be filled.

Due to the intensification and diversification the discharges through the outlets and the areas irrigated under the outlets often differ, but the discharge capacity of each outlet is assumed constant. Crops grown on individual farms are also different as are their irrigation requirements in each rotation. Hence it is necessary to vary the running time of each outlet during each rotation.

Once the running time of each outlet is estimated, the operation schedule of the outlets, which determines the inflow hydrograph into the distributaries, must be specified. At this stage it must be decided whether to operate all the outlets simultaneously or in sequence. Irrigating with all the outlets simultaneously open would necessitate a larger canal capacity ,which is economically undesirable. Running the outlets in sequence would allow the use of a smaller canal ,which is economically desirable, but the total running time might exceed the time available for that part of the rotation (economically undesirable). The optimal operation schedule is the one that would supply water to all outlets within the time available for the rotation using the most economic canal capacity. In an existing irrigation project, the capacity of the distributary channel is already fixed. Hence, optimal operation scheduling only deals with sequencing the outlets so that within the given system capacity, the total running time of the outlets is less than the available rotation time. The inflow hydrograph into the distributary channel (Minor) must match the opening and closing sequence of the outlets or vice versa. Otherwise, significant amounts of water may be wasted. The optimal operation schedule of the outlets and the inflow hydrograph into the distributary channel can be prepared manually, but in a large irrigation project with many outlets and distribution channels the procedure is time-consuming. With the aid of a computer, a plan can be prepared quickly and well before the start of any rotation.

CHATER THREE

MATERIALS AND METHODS

3.1 The study area

The Gezira scheme is one of the largest irrigation schemes in the world (Fig. 3.1). It is still the largest and most important agricultural scheme in Sudan. Its management is shared by the Sudan Gezira Board (SGB) and the Ministry of Irrigation (MI). SGB is responsible for the agricultural operations while MI looks after the irrigation network. The scheme covers more than two millions of feddans (880,000 ha) of the plains between the Blue and White Niles south of Khartoum. Irrigation water is fed by gravity from Sennar Dam through two main canals. Their combined design capacity is of about 30 millions cubic meters per day. These lead to 860 kilometers of Branch and Major canals and 7500 kilometers of Minor canals. Water is fed from the Minor canals through field outlet pipes (FOPs) to the field water courses (Abu Ishreens, Abu XXs). Each Abu XX used to feed nine lateral water courses (Abu Sittas, Abu VIs). Now it generally feeds 19 (Abu VIs) each of which commands about half the area commanded by the old Abu VI (Ahmed *et al*, 1996;.Fig 3.2)

The main crops currently grown in the scheme are extra long and medium staple cotton, wheat and dura or groundnuts. Vegetables are sometimes grown on the first fields of the groundnut/dura area. Forests and permanent gardens are also grown in some locations, but comprise a small area compared to the total cropped area. The main crops are grown in four course rotations.

Managil area which is a part of the Gezira scheme, used to follow a three years course rotation. It worth noting that Managil area was introduced in the Gezira scheme during the late 1950’s, more than thirty years after the start of the Gezira scheme. Roseires Dam was then constructed to help Sennar Dam in securing water to the extended scheme and other new schemes.

3.2 The study sites:

3.2.1-Sunni Minor: The field data was collected from Tayba Block at Massalamia Group which is located at the centre of the Sudan Gezira Scheme (Fig. 3.3). Sunni Minor was selected to represent the central Gezira which is much wet than the Northern Gezira.

Figure 3.1 Gezira Scheme map

Source:Mohamed ,H.I.(1992)

Fig. (3.2): Typical schematic representation of Gezira Canalization Layout

Sourse: Farbrother (1971)

Figure 3.3 Sunni agricultural area map

Sourse: Mohamed, H.I. (1992)

El Sunni Minor (four kilometers long) was selected for data monitoring to represent Tayba Major. El Sunni Minor consists of fourteen water courses (FOPs) with a total area of 842 feddans. A well head regulator with intermediate night storage weir (at kilo 2) divides the Minor into two reaches. The site was chosen because it is the site of the Gezira rehabilitation program pilot farm, also because it is the site at which the study of the crop water requirement was initiated.

3.2.2-Ugud Minor:

The agricultural data was collected for Ugud Right Genn., Laota Office .Ugud is chosen to represent the northern part of the Gezira Scheme. The canal extends to a length of 8.4 Kms It is constituted of 30 outlets (numbers) distributed over three reaches and in the order of;(1 to 10) , (11 to 16) and (17 to 30).The outlets involve permanent gates the first of which serves about 30 feddans and the next serves about 60 feddans The areas grown at the time of the study were as follows :

Cotton	480 feddans	(6) Numbers.
Dura	548 feddans	(7) Numbers
Ground nuts	526 feddans	(8) Numbers
Gardens	120 feddans	

3.3 Data collection

3.3.1 Meteorological data

Data of maximum and minimum temperature, rainfall, wind speed, bright sunshine hours and relative humidity were taken for the period of 30 years (1961 – 1990) as reported by Wad Medani Meteorological Station and given in Table (3.1).

3.3.2 Agricultural data:

Sunni Minor was selected to represent the central Gezira area which tends to be much wet than northern Gezira. agricultural data was obtained from the corresponding Block Inspectors.

Data concerning Sunni Minor is given in table (3.2), while data concerning Ugud Minor is given in table (3.3). These data include type and areas of crop grown, for each FOP, dates of planting and water indents. The data given here are for season 2003/2004.

Five main crops were grown in each Minor, namely; cotton, groundnuts, sorghum wheat and sunflower with small areas of vegetables.General crop data concerning sowing dates, the length of the growing stages, total crop growing periods and rooting depth are given in Table (3.4) as reported by (Mahmoud, 1999).

Table 3.1 Sudan Meteorological Department Climatological Normals 1961-1990.

Station: Wad Medani LAT. 14º 23\ N LONG. 33º 29\ E ALT. 405 m

ELEM.	Stat. Level press.	Air temperature ºC						Mean dry tem. max + min / 2	Rad. 2 MJM	Bright sun shine	
		Daily maximum			Daily minimum						
Month	HPA	MEAN	HST	DATE	MEAN	LST	DATE	ºC		HRS	%
Jan.	964.4	32.9	39.6	26-1961	14.3	5.5	17-1968	23.6	21.39	10.4	92
Feb.	963.3	34.8	43.3	25-1974	15.9	6.9	3-1968	25.3	23.46	10.5	90
Mar.	961.5	38.2	45.1	7-1988	19.1	10.5	1-1990	28.7	24.94	10.3	85
Apr.	959.9	40.9	46.0	21-1973 14-1990	21.6	13.0	6-1983	31.3	26.03	10.6	85
May	960.4	41.6	46.2	2-1982	24.5	15.7	18-1972	33.1	26.44	9.8	77
June	961.5	39.8	45.2	10-1970	24.9	18.4	4-1971	32.3	24.05	9.0	70
July	962.5	36.3	42.6	10-1966	23.3	18.5	22-1965	29.8	22.67	7.6	58
Aug.	962.7	34.7	42.4	25-1990	22.5	18.5	7-1965	28.6	22.98	7.8	62
Sep.	962.2	35.9	41.7	1-1990	22.2	17.0	5-1981	29.1	23.48	8.9	75
Oct.	961.7	38.0	41.5	12-1979 17-1986	22.0	11.2	31-1977	30.0	22.67	9.9	84
Nov.	961.3	36.2	41.5	1-1980	18.4	9.1	20-1967	27.3	21.63	10.6	92
Dec.	964.3	33.4	40.0	26-1980	15.3	4.1	25-1971	24.3	20.72	10.4	93
Year	962.3	36.9	46.2	2/5/1982	20.3	4.1	25/12/1971	28.6	23.37	9.7	80

Table 3.1 continued

STATION: WAD MEDAN

ELEM.	R.H. %	Cloud amount (OKTAS)				RAINFALL (MM)						Evp. Piche (mm)	Wind	
						TOTAL MMS	NO. OF DAYS			MAXIMUM IN ONE DAY			Prv. DIR.	MEAN SPEED M.P.H
Month	Mean	0.0	06	12	18		0.1	1.0	10.0	Total	Date			
Jan.	32	1.9	2.8	2.9	2.6	TR	0	0	0	0.3	31-83	12.4	N	7
Feb.	25	2.0	3.0	2.8	2.5	TR	0	0	0	TR	SEV	14.9	N	8
Mar.	20	2.6	3.2	3.3	3.1	TR	0	0	0	TR	SEV	18.3	N	7
Apr.	18	2.1	2.8	3.0	2.7	1.2	0.3	0.3	0	9.4	30-75	20.0	N	7
May	27	3.9	4.2	4.3	4.0	13.5	2.4	1.5	0.3	47.8	8-63	19.0	N	8
June	41	5.2	5.2	5.4	5.5	28.2	4.6	3.7	0.9	48.3	28-76	17.9	SW	11
July	58	6.5	6.2	6.2	6.4	88.0	8.6	3.9	2.7	117.7	29-67	12.3	SW	11
Aug.	67	7.1	6.2	6.1	6.4	112.1	10.3	4.8	3.5	93.4	21-85	8.7	SW	8
Sep.	62	6.3	6.0	5.5	6.1	45.9	5.8	4.5	1.5	63.4	3-73	8.4	SW	7
Oct.	47	2.3	4.1	4.3	4.8	16.0	3.4	2.2	0.4	40.4	17-64	11.2	NW	5
Nov.	35	1.5	2.0	2.5	1.9	1.5	0.1	0.1	0	32.3	2-89	13.4	NW	7
Dec.	35	1.0	2.3	2.4	2.0	TR	0	0	0	TR	10-76	11.9	N	7
Year	39	3.5	4.0	4.1	4.0	306.4	35.3	21.0	9.3	117.7	29/7/ 1967	14.0	-	-

Note: All times are G.M.T. (Sudan time + 2)

SEV. = Severals

TR = Trace

Sourse: Sudan Meteorological Department.

Table 3.2 Tayba Office - Sunni Minor Agricultural Data

	Number of Abu XX															
Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Crop	**Sowing Dates**															
Groundnuts	Fallow	Fallow				Fallow		01-10/06/2003		Fallow		Fallow				
Dura				01-10/07/2003	01-10/07/2003									01-10/07/2003		
Cotton									11-20/07/2003		11-20/07/2003 "40 Fed"					
Wheat			01-10/11/2003					01-10/11/2003					01-10/11/2003		01-10/11/2003	
Gardens																01-10/11/2003 "20 Fed"

Table 3.3 Laouta Office - Ugud Canal Agricultural Data

Number of Abu XX

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Crop	Sowing Dates																													
Groundnuts			01-10/06/2003							01-10/06/2003		11-20/06/2003				11-20/06/2003							21-30/06/2003							
Dura	Fallow	Fallow		Fallow	Fallow	Fallow	Fallow	21-30/06/2003			Fallow		21-30/06/2003		Fallow			01-10/07/2003	Fallow	01-10/07/2003	Fallow				11-20/07/2003	Fallow	11-20/07/2003		Fallow	Fallow
Cotton									11-					11-			21-					21-		01-				01-		
Gardens																														

Sourse: Sudan Gezira Scheme

Table 3.4 General Crops data

Growth stage		Crop data				
		Cotton MS				
		Init.	Devel.	Mid.	Lat.	Total
Length	(days)	30	40	60	50	180
Crop coefficient	(coeff.)	0.60		1.30	0.80	
Rooting depth	(meter)	0.30		0.70	0.70	
Deplecion level	(fract.)	0.65		0.65	0.90	
Yield response f.	(coeff.)	0.20	0.20	0.50	0.25	0.85
Growth stage		Crop data				
		Sorghum				
		Init.	Devel.	Mid.	Lat.	Total
Length	(days)	15	25	30	20	90
Crop coefficient	(coeff.)	0.55		1.20	0.80	
Rooting depth	(meter)	0.30		0.70	0.70	
Deplecion level	(fract.)	0.65		0.65	0.65	
Yield response f.	(coeff.)	0.20	0.55	0.45	0.20	0.90
Growth stage		Crop data				
		Groundnut				
		Init.	Devel.	Mid.	Lat.	Total
Length	(days)	25	40	45	30	140
Crop coefficient	(coeff.)	0.55		1.20	0.75	
Rooting depth	(meter)	0.25		0.50	0.50	
Deplecion level	(fract.)	0.55		0.55	0.55	
Yield response f.	(coeff.)	0.20	0.80	0.60	0.20	0.70
Growth stage		Crop data				
		Wheat				
		Init.	Devel.	Mid.	Lat.	Total
Length	(days)	25	30	40	0.25	120
Crop coefficient	(coeff.)	0.70		1.20	0.66	
Rooting depth	(meter)	0.25		0.50	0.50	
Deplecion level	(fract.)	0.60		0.60	0.60	
Yield response f.	(coeff.)	0.20	0.65	0.55	0.55	1.15

Source: Mahmoud (1999).

CHAPTER FOUR

MODEL DEVELOPMENT

4.1 General

The model functions comprise the follows:-

a- The prediction of reference Evapotranspiration (ET_o) on decade basis (10 days period) from data supplied by Sudan Meteorological Department based on Penman-Montieth equation (Allen *et al.* 1998).

b- Calculation of crop factor (Kc) for the four crop growth stages: Kcin for the initial growth stage is calculated through equations embedded in the model based on the graphical methods suggested by FAO Irrigation and Drainage Paper -56.(1998). Kcdev is calculated by linear interpolation between the values of Kcin and Kcmid. Kcmid is taken from FAO tables(1998) and subjected to the necessary adjustment.

c- Calculation of crop evapotranspiration (ETc) is made on decade basis through the estimation of the crop factor and reference evapotranspiration.

d- Estimation of irrigation water requirements (IWR) is obtained from crop evapotranspiration (ETc) and effective rainfall (Pe). Effective rainfall can be calculated using one of four options namely, the fixed percent, the FAO method, the USDA method and the empirical method as well as an option for not considering any rainfall.

e- Losses in application and conveyance are considered as user defined values and used to calculate the gross irrigation water requirements. Allowance is made to apply pre-seasonal first watering as user defined values.

f- The crop water requirements in units of mm/day are converted in m^3/feddan and the total volume needed can be obtained by considering the areas planted at each planting date. The programme can handle five crops per each FOP or Abu XX and each crop can accommodate five sowing dates.

g- Calculation of indent per minor is made through estimating irrigation water needs (IWN) for multi-crops per each FOP through out the growing season. Thereafter the water volumes and Minor inflows are estimated for all outlets in the Minor in question throughout the growing season.

As a prerequisite for sequencing of FOPs operation water volumes per each outlet are converted into irrigation working days by considering a user defined inflow rate per each FOP. Development of the Minor canal operation model is obtained by employing integer linear programming optimization technique.

4.2 The Model limitations:

1. The total open water surface losses are estimated as percentages of irrigation water needs, they are inserted as user defined values, and not calculated directly as functions of open water surface area losses.
2. The programme requires the installation of the optimization unit (What's Best) which works within the excel medium.
3. The maximum number of integers is 200 which limits the maximum capacity of the programme to twenty eight working outlets.
4. The programme offers only four scenarios viz; eight, ten, twelve and fourteen working outlets. However with a simple modification the programme can accept up to twenty eight working outlets.
5. Wind speed is normally given by Sudan Metrological Department in miles/hr as round figures .A difference of 0.5 miles/hr can make a considerable difference in ET_o calculation.
6. The decade calculation of crop growth stages enforces the rounding up of figures greater than five and rounding down of figures less than five.

4.3 The programme structure

4.3.1 Programme technique and style

The programme is interactive and composed of sub modules, where the user is prompt to enter relevant data for the sub modules via a sequence of button driven menus. The user has the option to execute each sub-module separately or the whole model as one unit.

In this study built in data were made available for crop type, growth stages and crop factor for mid and late stages from FAO tables (1998) alternatively the user has the option of using his own crop stages figures when available. Data is entered in special cells or text boxes which are linked to other cells through data processing equations. Data entry is a step by step process in specifically designed interfaces for each sub-module.

Relevant guiding notes are given where necessary to help the user in programme use. For data correction excel engine facilities are used. The user is always given the freedom to use site specific data or use built in data when available with the necessary adjustments. Programme style of links between cells and work sheets is designed in order to build the modular form of programme and reach efficient solution.

4.3.2 Programme technical specification:

The programme technical specifications are as given in Table (4.1).

4.3.3 Programme logic and flow chart

The programme is composed of an introductory interface and a main menu form (Fig. 4.1 and 4.2). It derives through sub-modules distributed over the spread sheets. The main menu controls the sequence of all programme operations. Spread sheets are either visible input interfaces or hidden processing sheets. Visible input interfaces receive input data subjected to them to the necessary conversions and direct them to hidden processing sheets where all the necessary processes are done. Data will then appear as output data in an appropriate visible form. (Vide programme flow chart: Fig. 4.3)

4.3.4 Data entry:

The user needs to enter input data in tabular format directly from the screen. Alternatively built in FAO published data can be used for estimating the suitable values if no local data is available. The format of the needed data is explained and described in the following sections with their respective modules.

4.4 Programme algorithm

4.4.1 Reference evapotranspiration (ETo) module

Reference evapotranspiration was estimated using Penman – Monteith as suggested by Allen,*et al* (1998) with slight modifications for the purpose of direct use of Sudan Meteorological data. Details of calculation steps are given in Appendix Data entry and output form of Fig. (4.4).

Table 4.1 Programme technical specifications.

Item	Description
Programme language	Visual basic and What's Best in excel environment ,excel 2000
Programme type	Button Menu driven
Programme flexibility	Inherited from excel 2000, What's Best and visual basic.
Programme adaptability	Works under windows, specifically developed under windows XP.
Programme interface	Multi menus with automated control tools including one main menu and multi sub- menus.
Units used	SI-system + (feddan for areas)
Minimum required operating system	Windows 98
Memory (RAM) needed	256 MB
Space required for hard disc	4.MB
Output available (displayed)	Available on screen option Monitor display.
Output printed	Available option for each interface.
Minimum speed required	500 MHZ
Mouse activated menus	Available

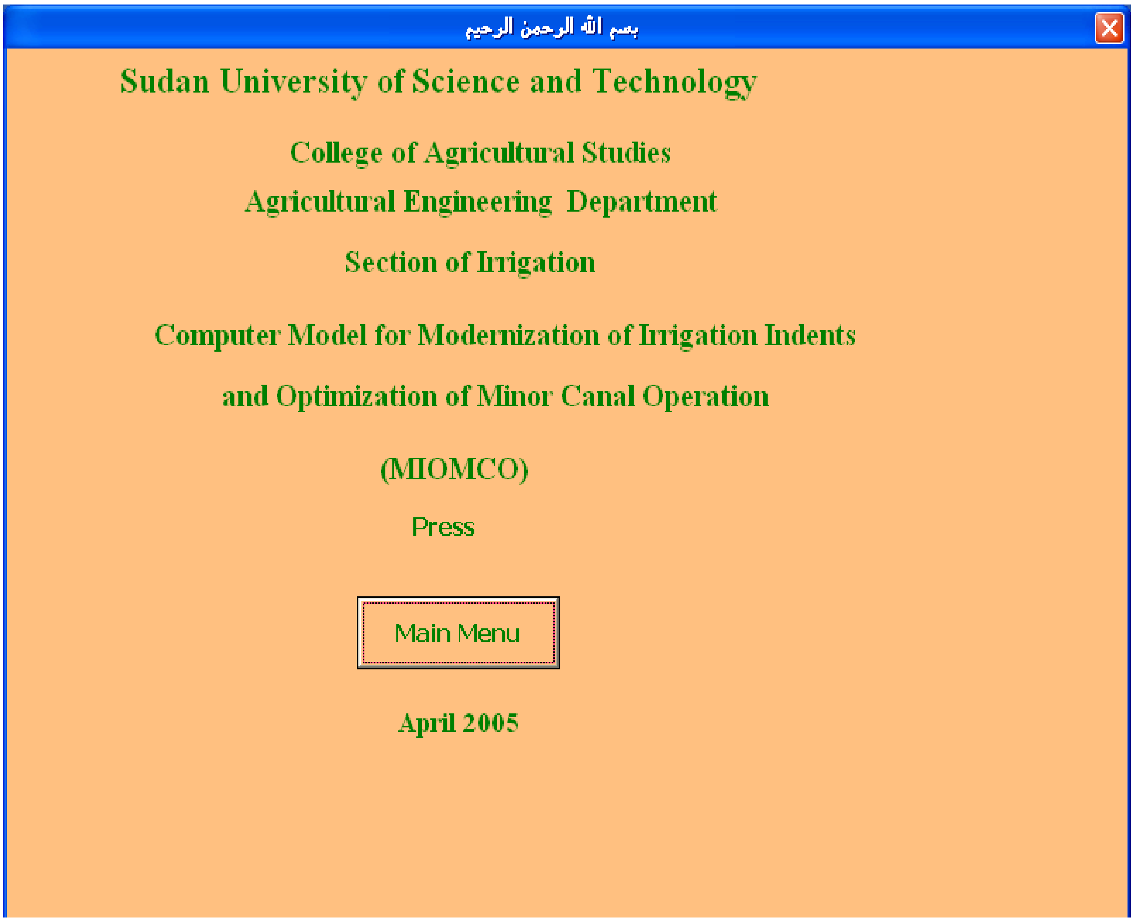

Figure 4.1 Programme main interface.

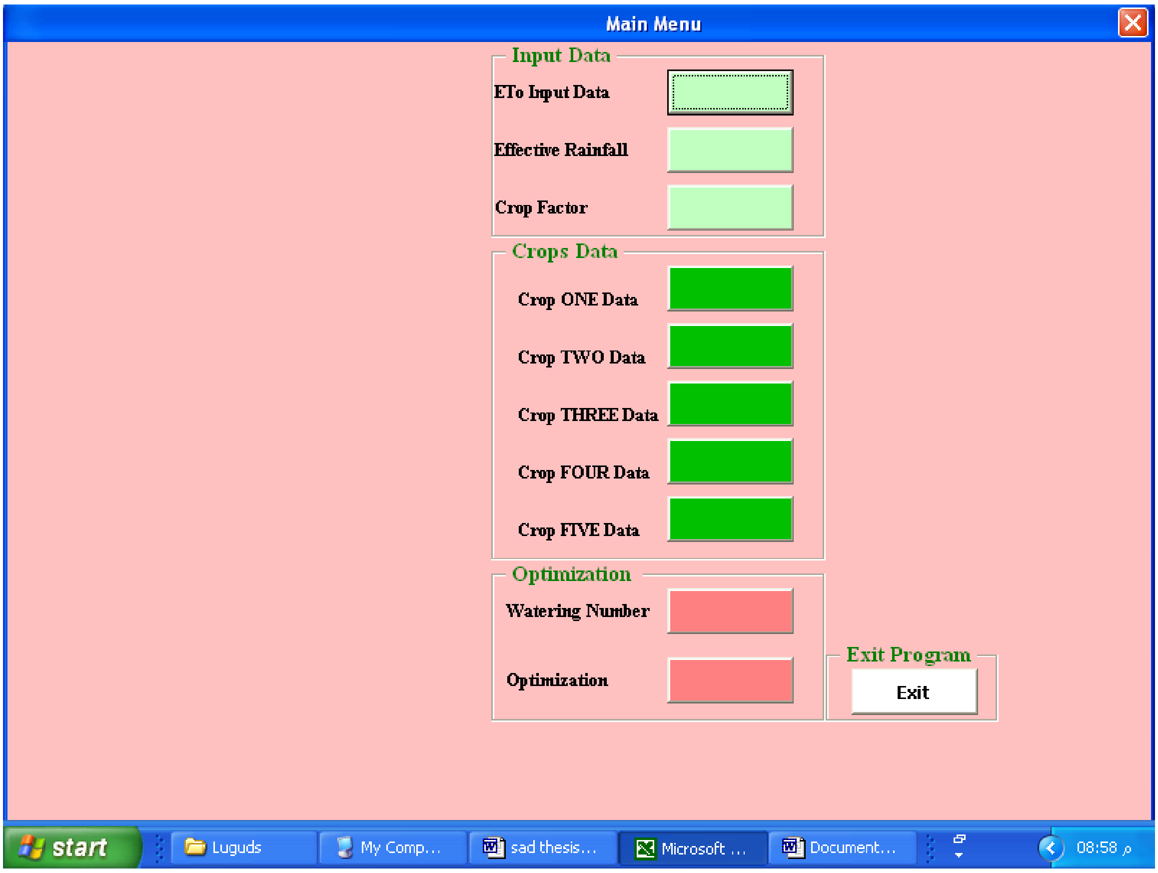
Main Menu
Input Data
ETo Input Data
Effective Rainfall
Crop Factor
Crops Data
Crop ONE Data
Crop TWO Data
Crop THREE Data
Crop FOUR Data
Crop FIVE Data
Optimization
Watering Number
Optimization
Exit Program
Exit
start
Luguds
My Comp...
sad thesis...
Microsoft ...
Document...
08:58

Figure 4.2 Programme main menu.

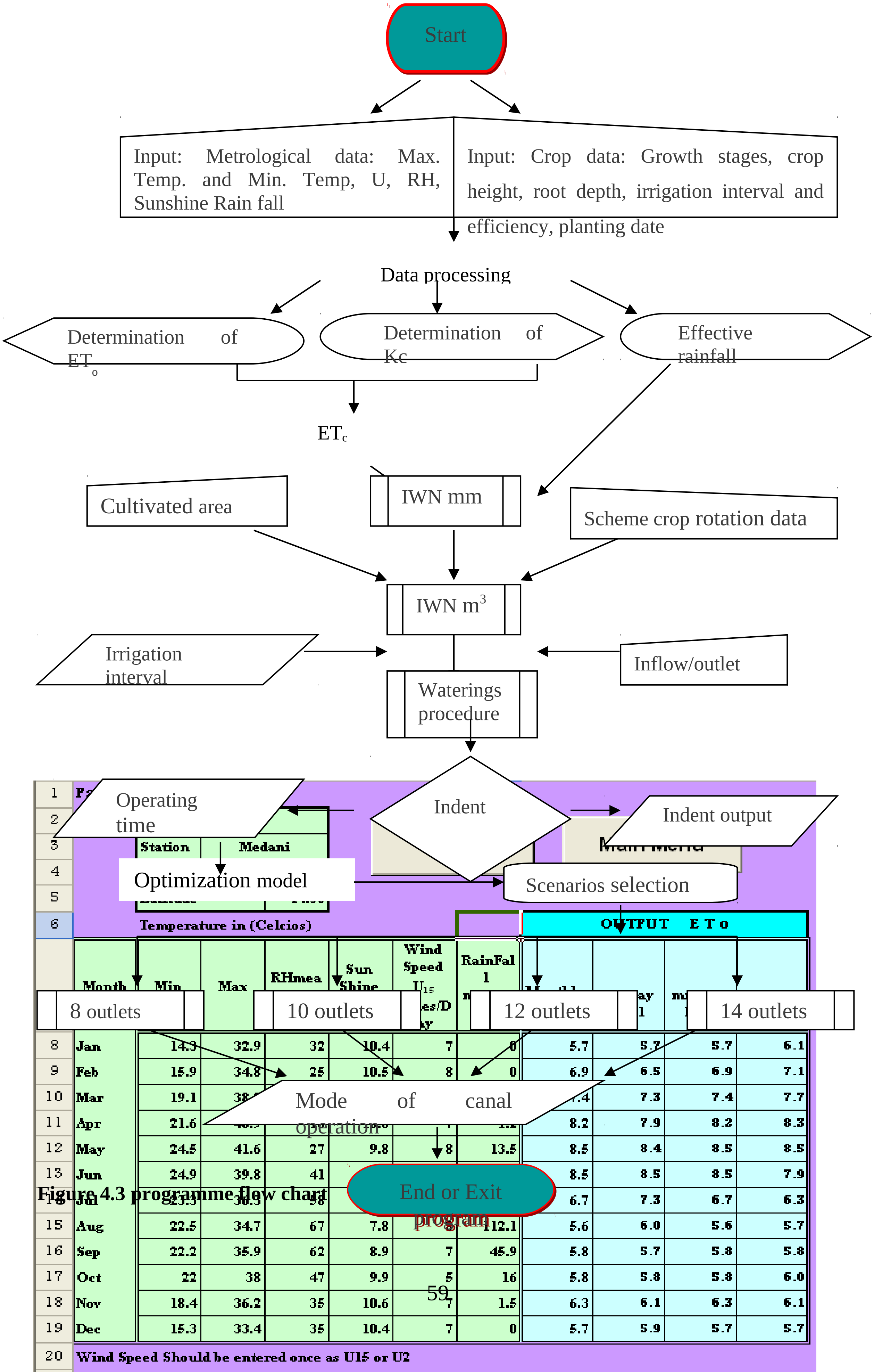

Figure 4.3 programme flow chart

Figure 4.4 ET_o module.

4.4.2 Crop Coefficient (Kc) Module

a- Determination of (Kc) per growth stages: (Fig. 4.5)

Length of growth stages are either user defined values or can be selected from FAO Tables (1998) Appendix (II-table.1)

Crop coefficients for initial stage (Kcin), for mid stage (Kcmid) and and final stage Kcend are calculated from input data.

Kcin is normally calculated as given in FAO paper 24 (1977) by using a graph in which only two factors are taken in consideration i.e ETo and irrigation interval. However, other important factors such as infiltration depth, and soil type are ignored. More over, the graphical solution of Doorenbos and Pruitt (1977) uses wide irrigation intervals and the determination of mid values are left to the user's eye judgment and his accuracy in using the ruler.

In accordance with Cuenca (1984) and El Khayal (1983), working separately, have realized the problem of inaccuracy of the estimation and developed a simplified two stage equation. Equations are pivoted around only a four day irrigation interval (2.3a and2.3b) .

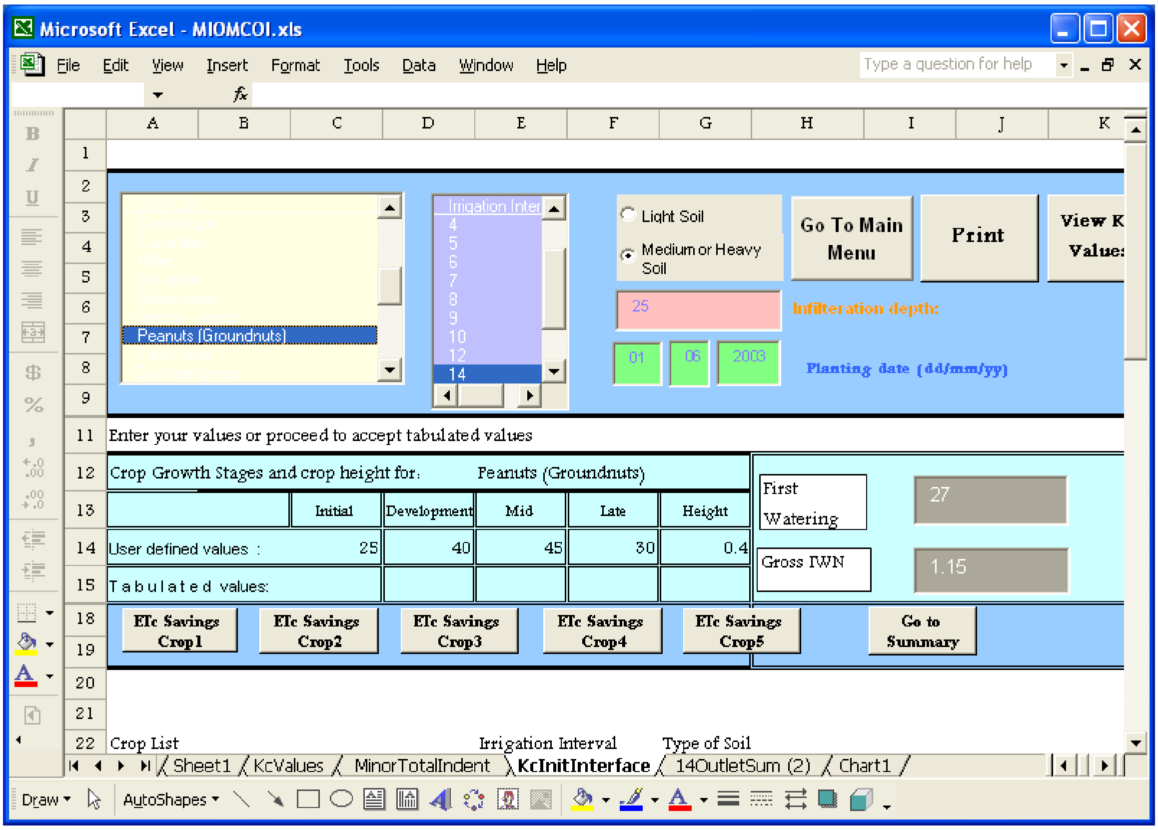

Figure 4.5 Crop coefficient module.

As an improvement of the method of estimating Kcin ,Allen *et al.* (1998) considered the importance of the infilteration depth and soil type factors which were normally neglected. Hence he developed three graphs to estimate Kcin by involving these two factors. His method kept an irrigation interval pace of 1, 2, 4, 7, 10 and 20 days interval.

As suggested by FAO paper 56 (1998) Fig. (4.6) the first graph was assigned to be used for infiltration depths between 3 to 10 mm for all soil types. The second graph (Fig. 4.7a) and the third graph (Fig.4.7b) were assigned to be used for infiltration depths over 40 mm. and they were for light ,medium and heavy textured soils respectively.

For infiltration depths between 10 mm and 40mm Kcin is interpolated from Figs. (4.6) and (4.7a) for light soils and from Figs (4.6) and (4.7b) for medium and heavy textured soils. It is important to note that all these readings are ruler measurements.

The module algorithm follows the same principles given by Allen *et al.* (1998). To improve the accuracy of estimating Kcin when using any irrigation method, other than surface irrigation this module has taken an irrigation interval of 24 hours from day one to day ten and an irrigation interval of 48 hours from day ten to day twenty. Targeting further accuracy the model shifted from the less accurate ruler measurement method to numerical values for irrigation intervals, soil type root depth to be fed in a mathematical relation. The use of narrow irrigation intervals has necessitated the development of fifteen equations for each figure and hence the development of fifteen curves per each figure instead of the original six curves used by Allen (1998). Trend lines, namely linear, logarithmic, power, exponential and polynomial for original curves Figs (4.8a to 4.10e) and trend lines for intermediate curves were tested to select the best fitting equation for each of the fifteen irrigation interval curves Figs (4.11a to 4.11c). The equations of the lines with coefficients of determination (R^2) closest to unity were selected. A summary of the best fitting formulae is shown in Tables (4.2a to 4.2c).

Once the required input data are fed into the algorithm the model automatically calculates (Kcin) starting from sowing date. Hence the Kcin value is estimated with respect to sowing date of the specified crop and not a fixed value as estimated in previous attempts (Adam, 1993).

Estimation of Kcmid and Kcend values is done by selecting tabulated values from FAO Tables (1998) and adjusting them for variation in relative humidity, wind speed and

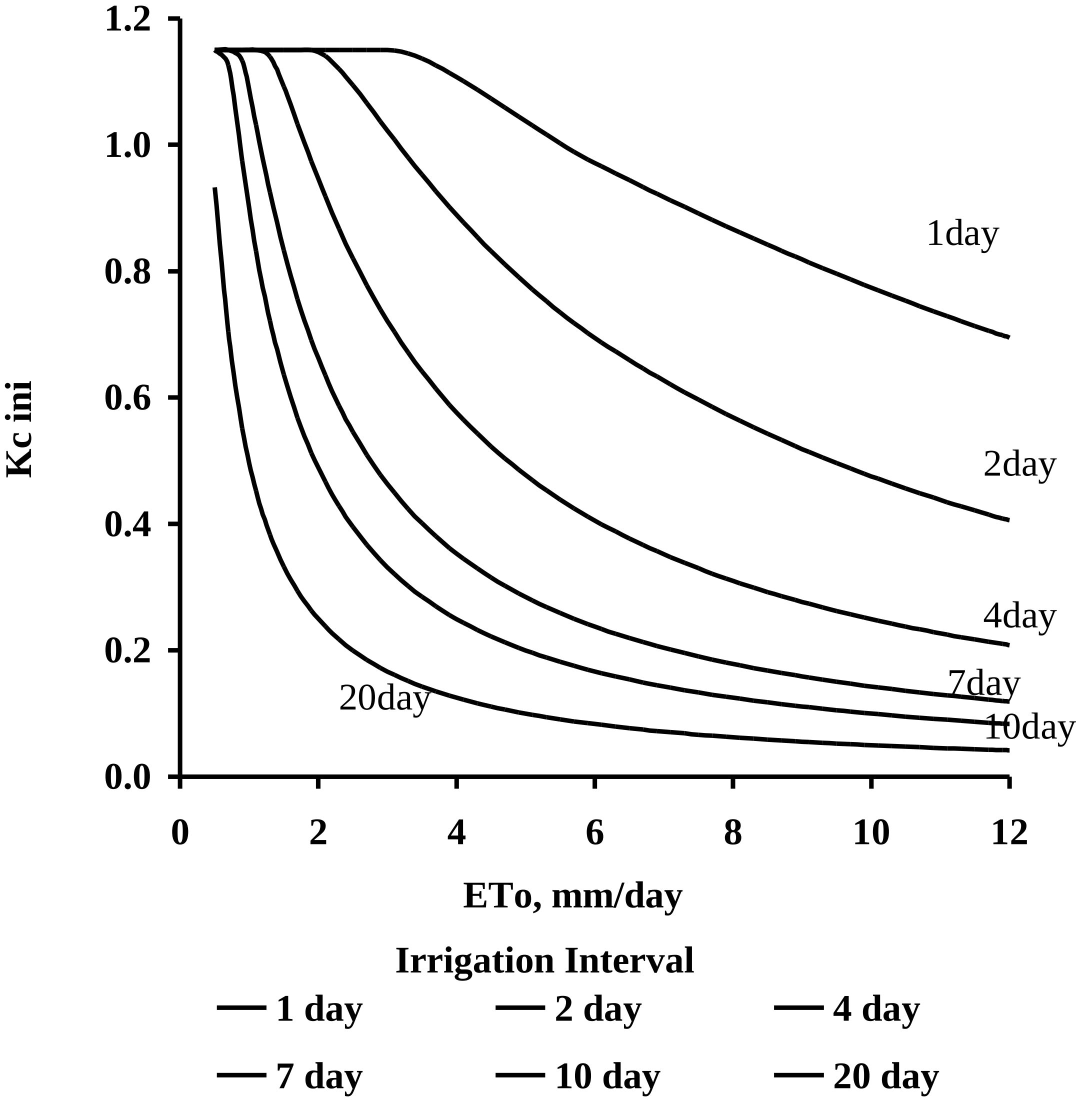

Fig. 4.6. Small Infiltration Depths
Source: FAO Irrigation and drainage paper No. 56.(1998)

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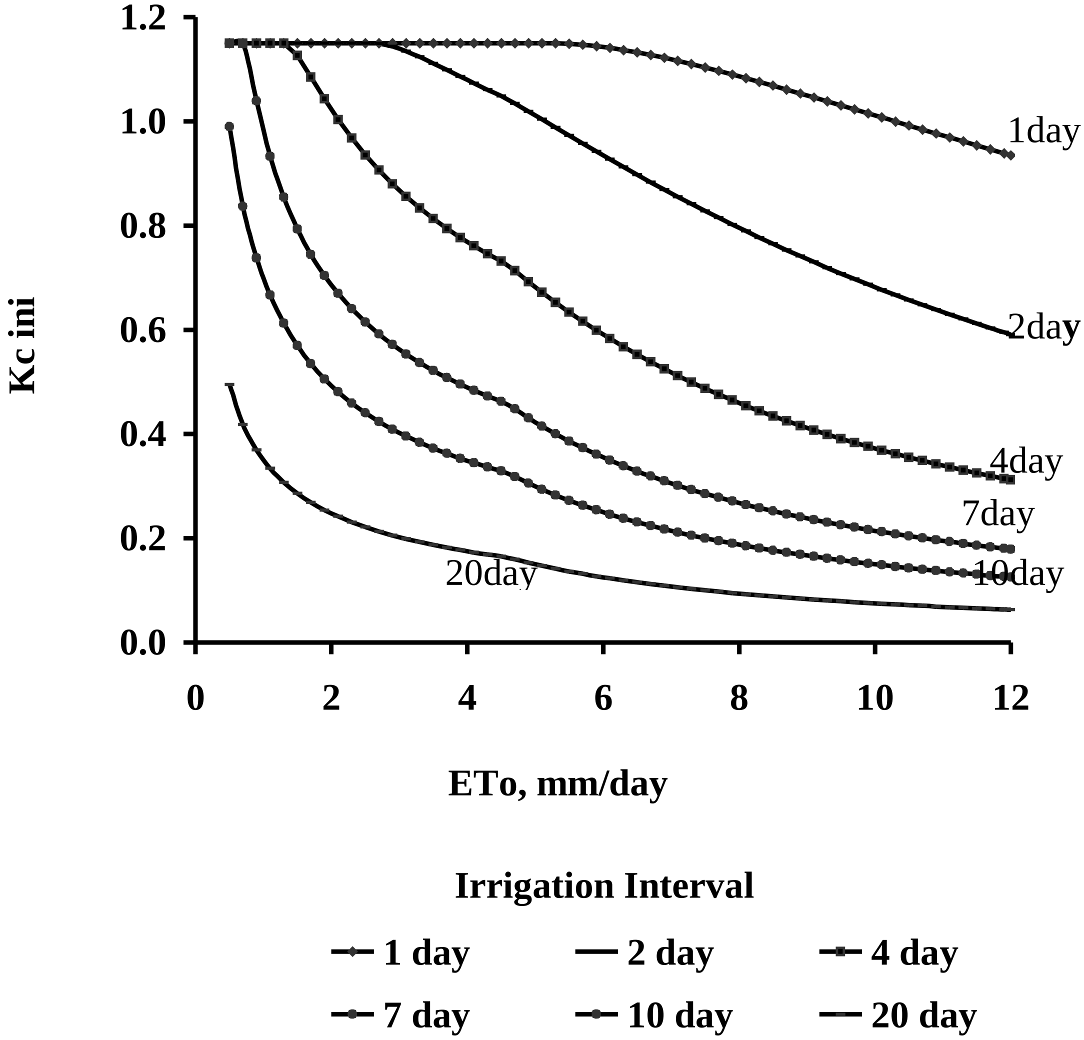


Fig. 4.7a. Coarse Soil, Infil. > 40 mm

Source: FAO Irrigation and drainage paper No. 56,(1998)

64

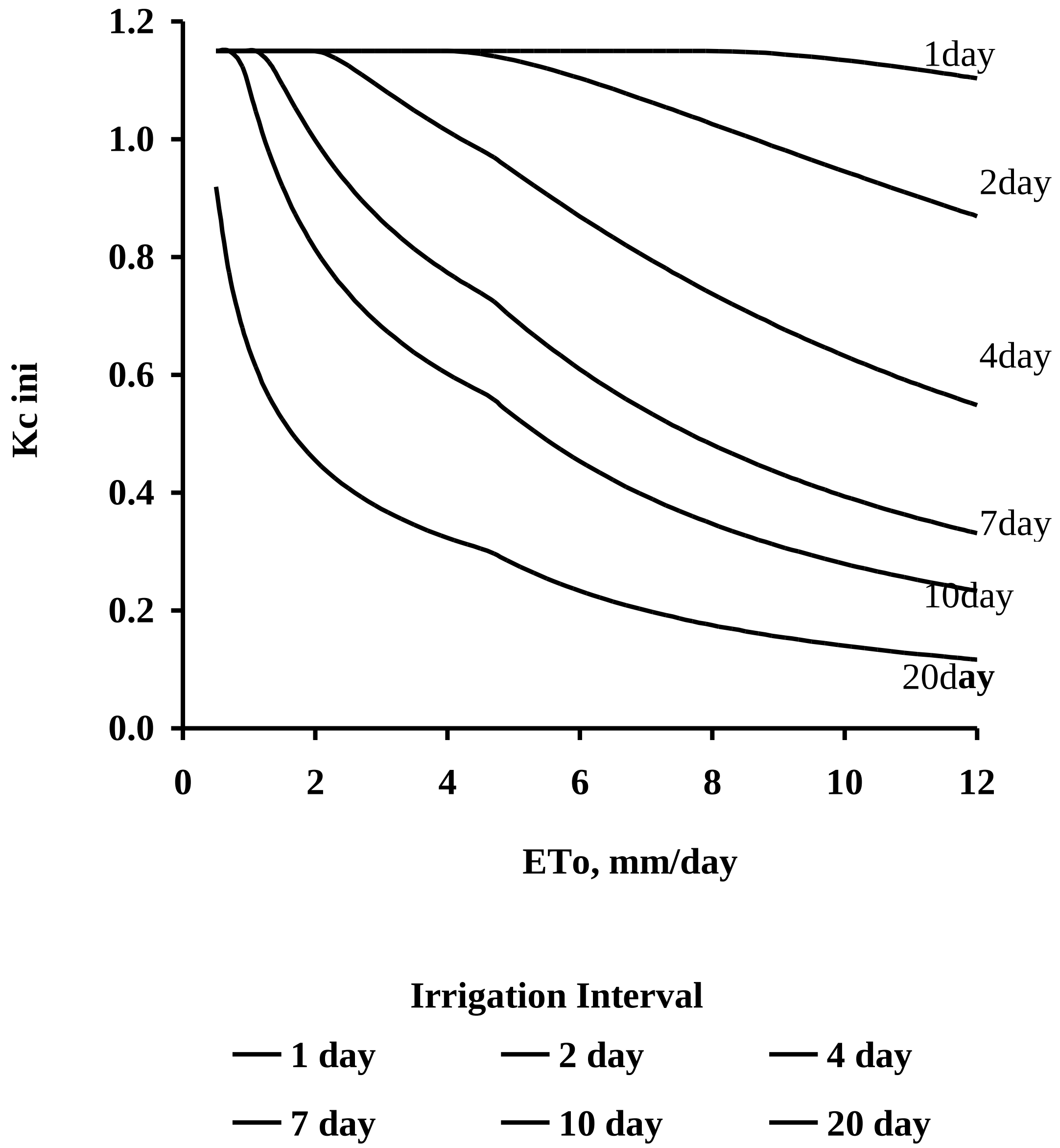
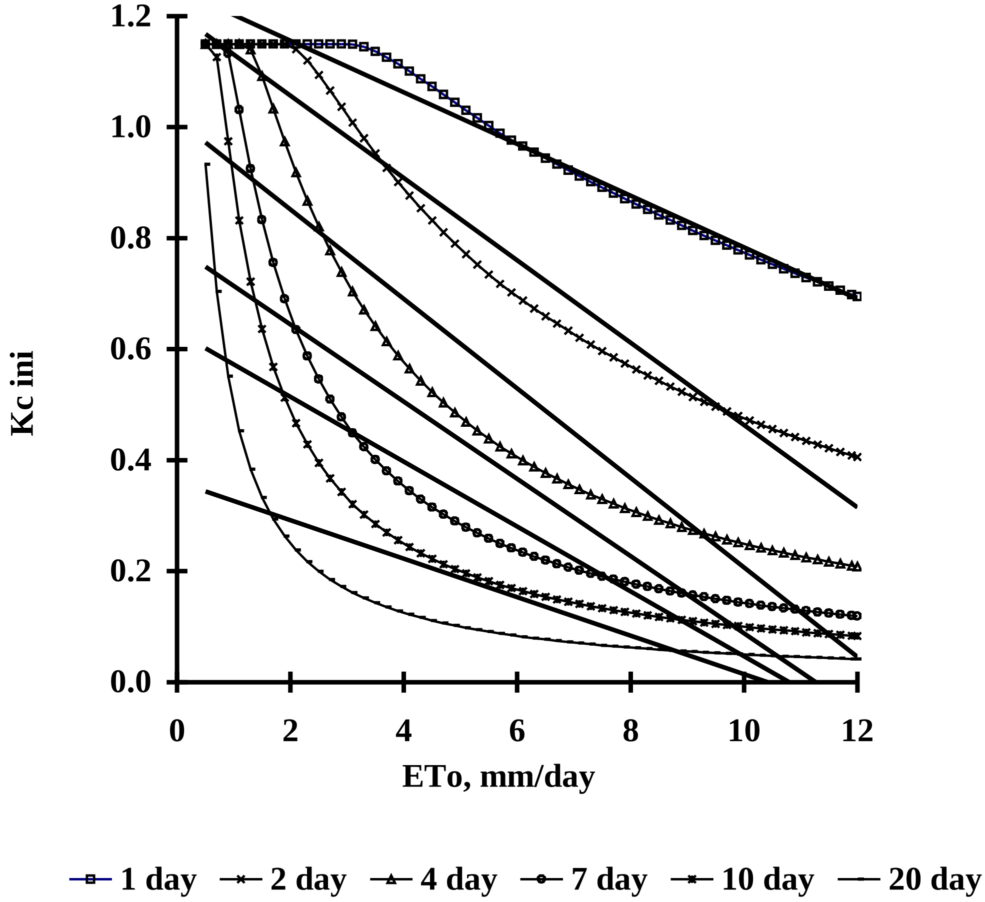


Figure 4.7b. Fine/Med., Infil. > 40 mm
Source: FAO Irrigation and Drainage paper No. 56,(1998)

65



Linear Equations

y1day = -0.0465x + 1.2489
R2 = 0.9731

y2dy = -0.0741x + 1.2051
R2 = 0.9612

y4day = -0.0806x + 1.0128
R2 = 0.8551

y7day = -0.0696x + 0.7838
R2 = 0.7186

y1oday = -0.0584x + 0.6312
R2 = 0.6267

y20day = -0.0346x + 0.3612
R2 = 0.511

Fig. 4.8a. Small Infiltration Depths

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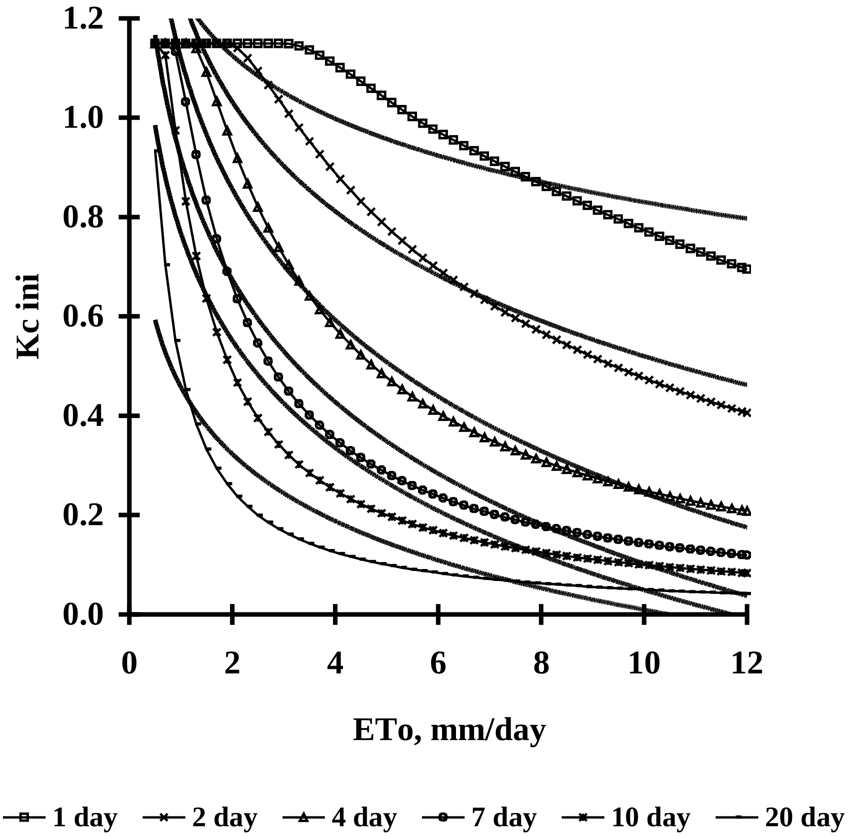


Logarithmic Equations

y1day = -0.1833Ln(x) + 1.2524
R2 = 0.7682

y2day = -0.3184Ln(x) + 1.2532
R2 = 0.901

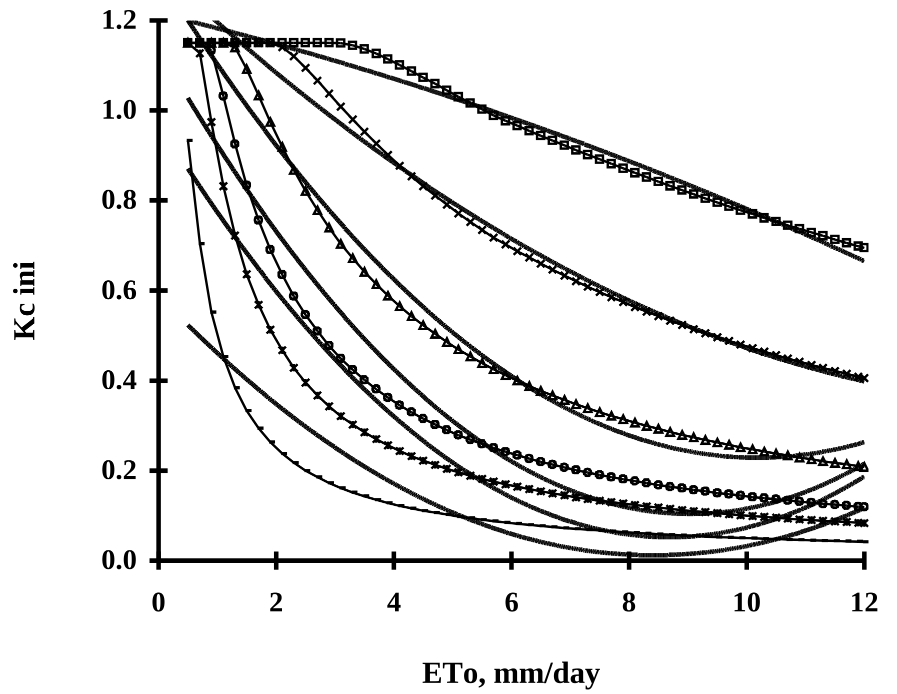
y4day = -0.3806Ln(x) + 1.1207
R2 = 0.9689

y7day = -0.3555Ln(x) + 0.9206
R2 = 0.9536

y10day = -0.3125Ln(x) + 0.7687
R2 = 0.9114

y20day = -0.195Ln(x) + 0.4584
R2 = 0.8231

Fig. 4.8b. Small Infiltration Depths



Polynomial Equations

y1dya = -0.0012x^2 - 0.0313x + 1.2151
R2 = 0.9791

y2day = 0.0039x2 - 0.1238x + 1.3157
R2 = 0.9863

y4day = 0.0104x2 - 0.2111x + 1.3034
R2 = 0.9854

y7day = 0.0127x2 - 0.2292x + 1.1393
R2 = 0.9387

y1oday = 0.0122x2 - 0.2123x + 0.9739
R2 = 0.8797

y20day = 0.0082x2 - 0.1375x + 0.5903
R2 = 0.7732

Fig. 4.8c. Small Infiltration Depths

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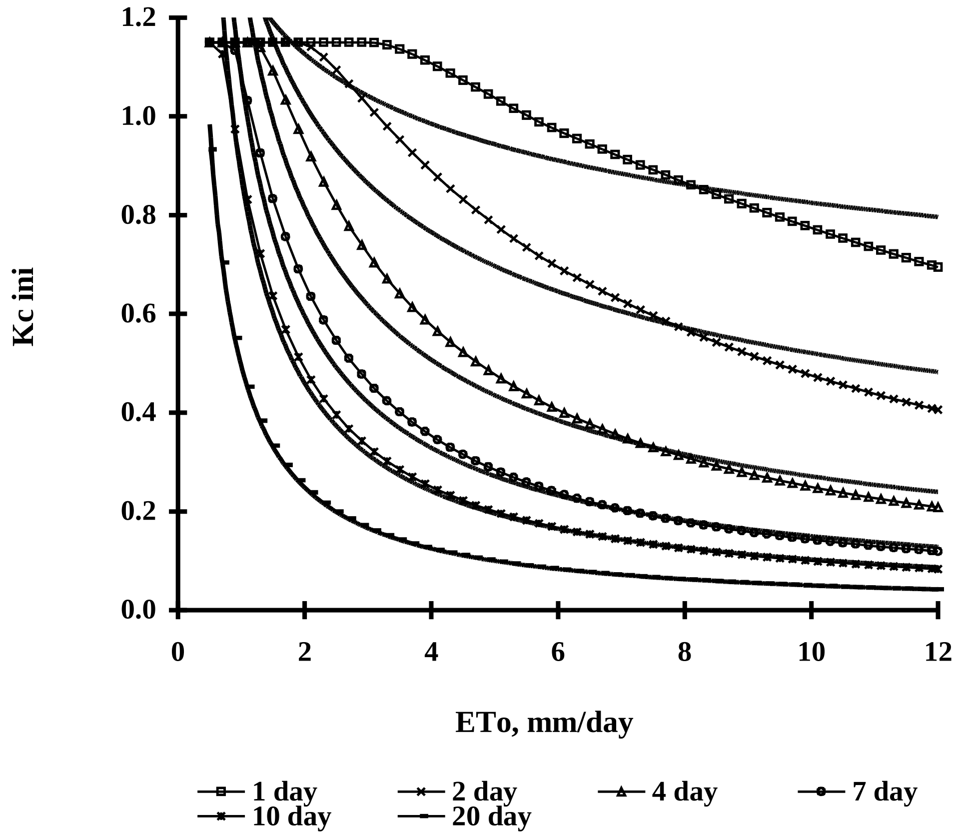


Power Equations

$y_{1day} = 1.288x^{-0.1934}$
$R^2 = 0.7401$

$y_{2day} = 1.3718x^{-0.4207}$
$R^2 = 0.8545$

$y_{4day} = 1.3089x^{-0.684}$
$R^2 = 0.9368$

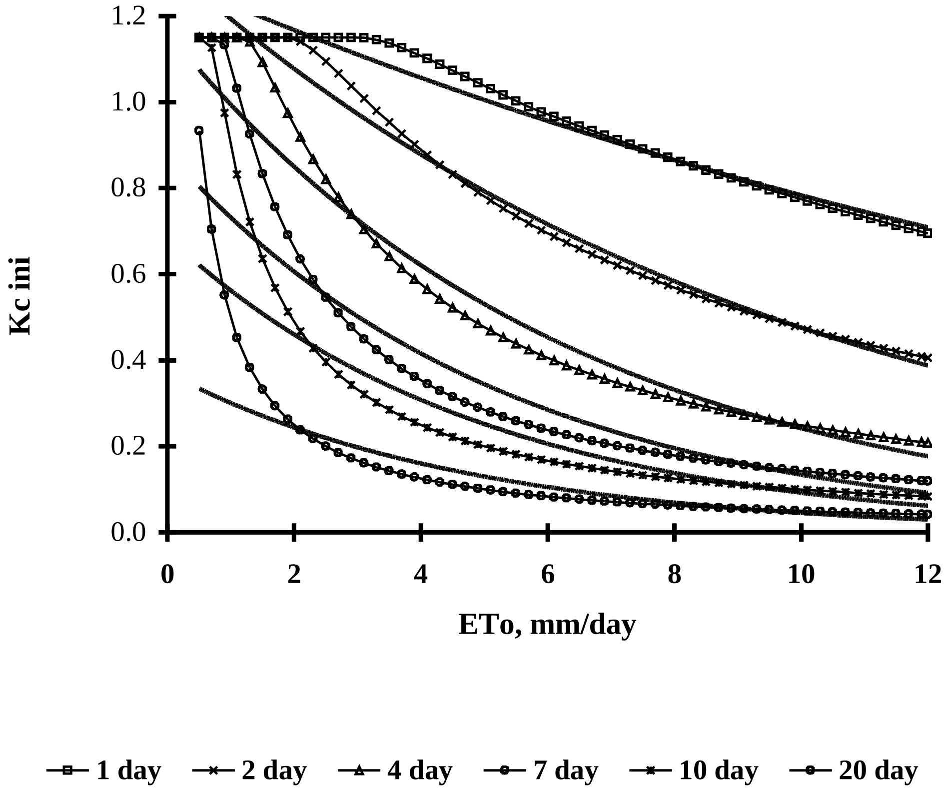
$y_{7day} = 1.0783x^{-0.8568}$
$R^2 = 0.979$

$y_{10day} = 0.8767x^{-0.9319}$
$R^2 = 0.9931$

$y_{20day} = 0.4941x^{-0.9938}$
$R^2 = 0.9999$

Fig. 4.8d. Small Infiltration Depths

69



Exponemtial Equations

$y_{1day} = 1.2897e^{-0.0499x}$
$R^2 = 0.9682$

$y_{2day} = 1.3215e^{-0.1021x}$
$R^2 = 0.9905$

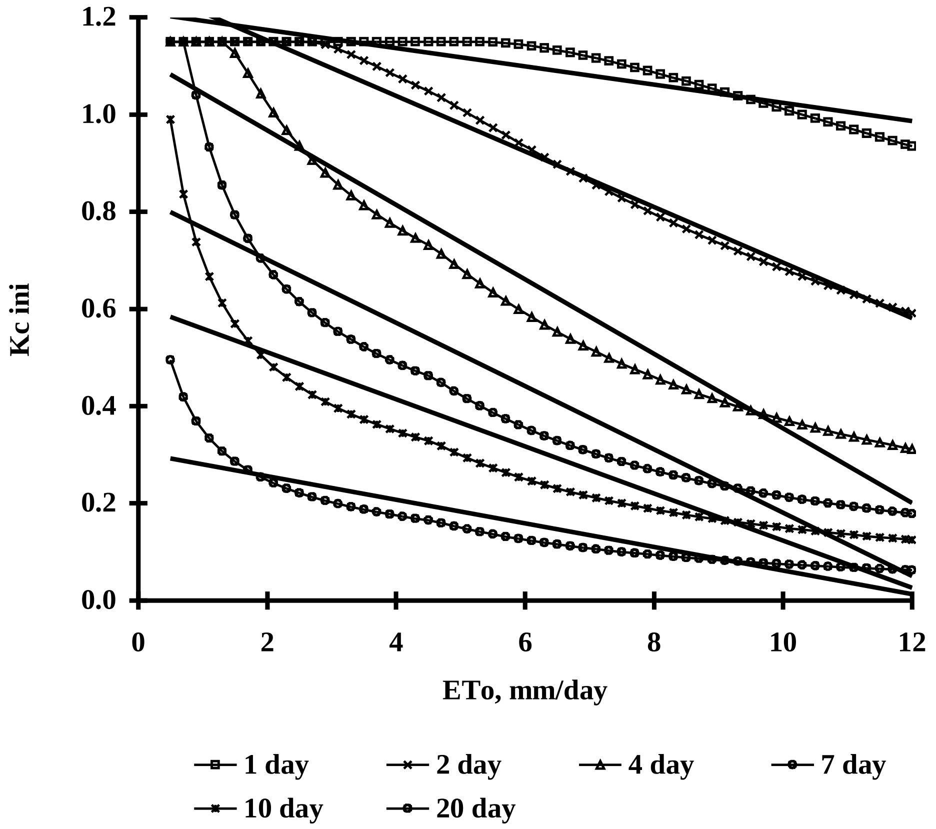
$y_{4day} = 1.1631e^{-0.1569x}$
$R^2 = 0.9699$

$y_{7day} = 0.8836e^{-0.1884x}$
$R^2 = 0.9315$

$y_{10day} = 0.687e^{-0.2006x}$
$R^2 = 0.9054$

$y_{20day} = 0.371e^{-0.2097x}$
$R^2 = 0.8761$

Fig. 4.8e. Small Infiltration Depths



Linear Equations

$y_{1day} = -0.0188x + 1.212$
$R^2 = 0.8135$

$y_{2day} = -0.0571x + 1.2673$
$R^2 = 0.9776$

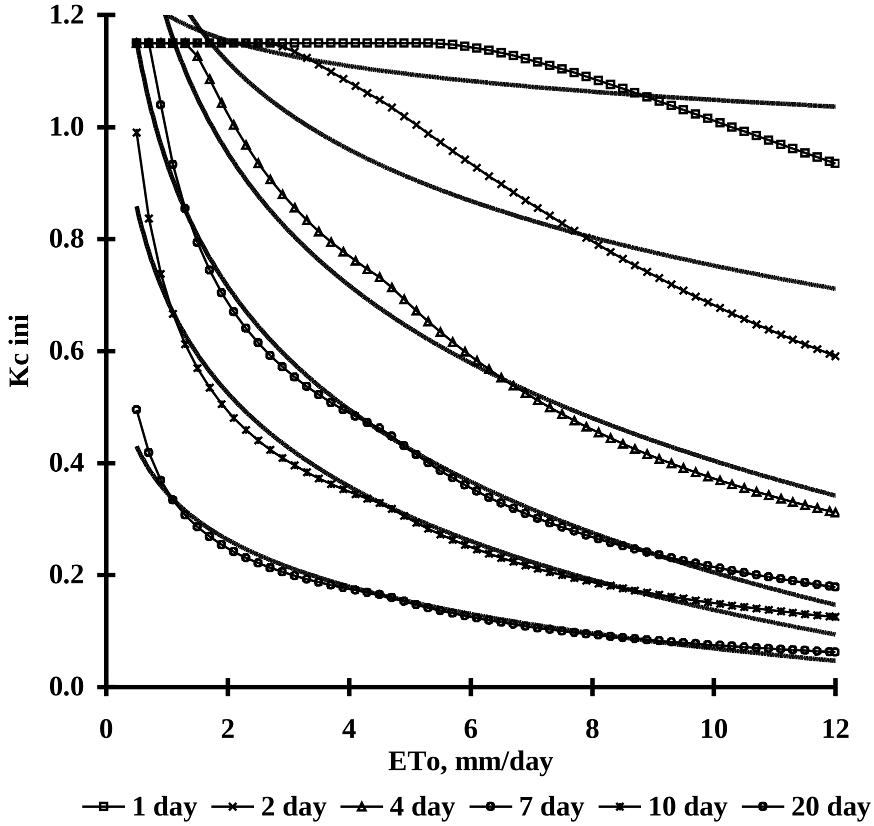
$y_{4day} = -0.0767x + 1.1208$
$R^2 = 0.9464$

$y_{7day} = -0.0651x + 0.8322$
$R^2 = 0.8216$

$y_{10day} = -0.0485x + 0.608$
$R^2 = 0.7843$

$y_{2oday} = -0.0243x + 0.3049$
$R^2 = 0.7864$

Fig. 4.9a. Coarse Soil, Infil. > 40 mm



Logarithmic equations

y_{1day} = -0.066Ln(x) + 1.2004

y_{2day} = -0.2259Ln(x) + 1.2728

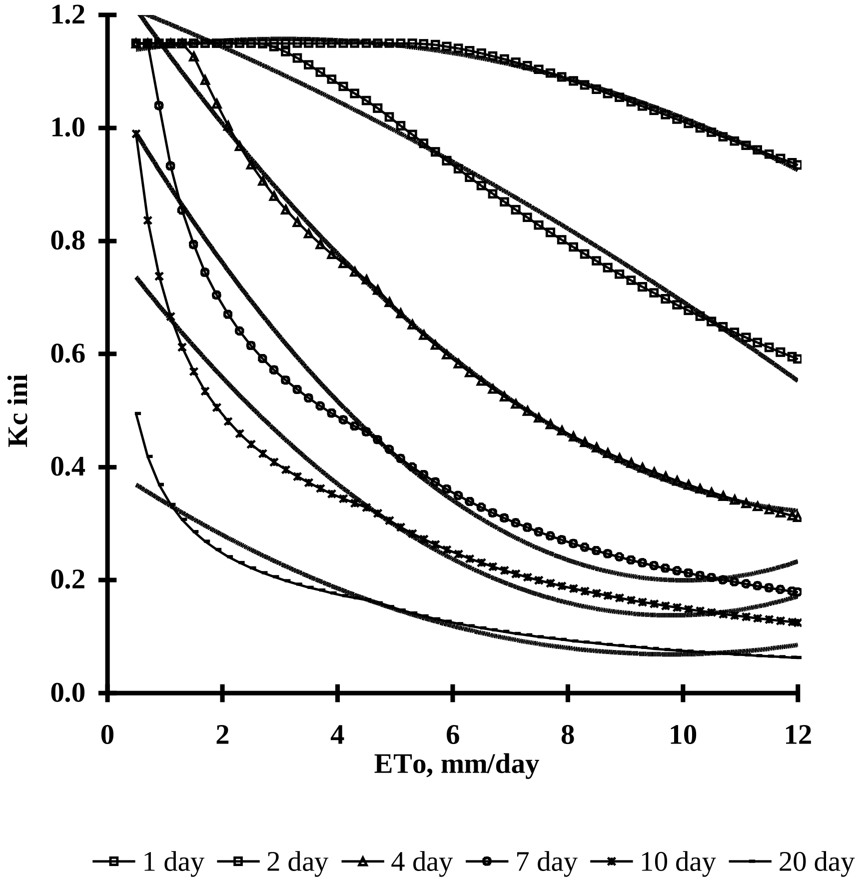
y_{4day} = -0.3414Ln(x) + 1.1902

y_{7day} = -0.3173Ln(x) + 0.9352

y_{10day} = -0.2406Ln(x) + 0.6918

y_{20day} = -0.1206Ln(x) + 0.3467

Fig. 4.9b. Coarse Soil, Infil. > 40 mm



Polynomial equations

$y_{1day} = -0.0029x^2 + 0.0178x + 1.1305$
$R^2 = 0.9929$

$y_{2day} = -0.0014x^2 - 0.0398x + 1.2286$
$R^2 = 0.9829$

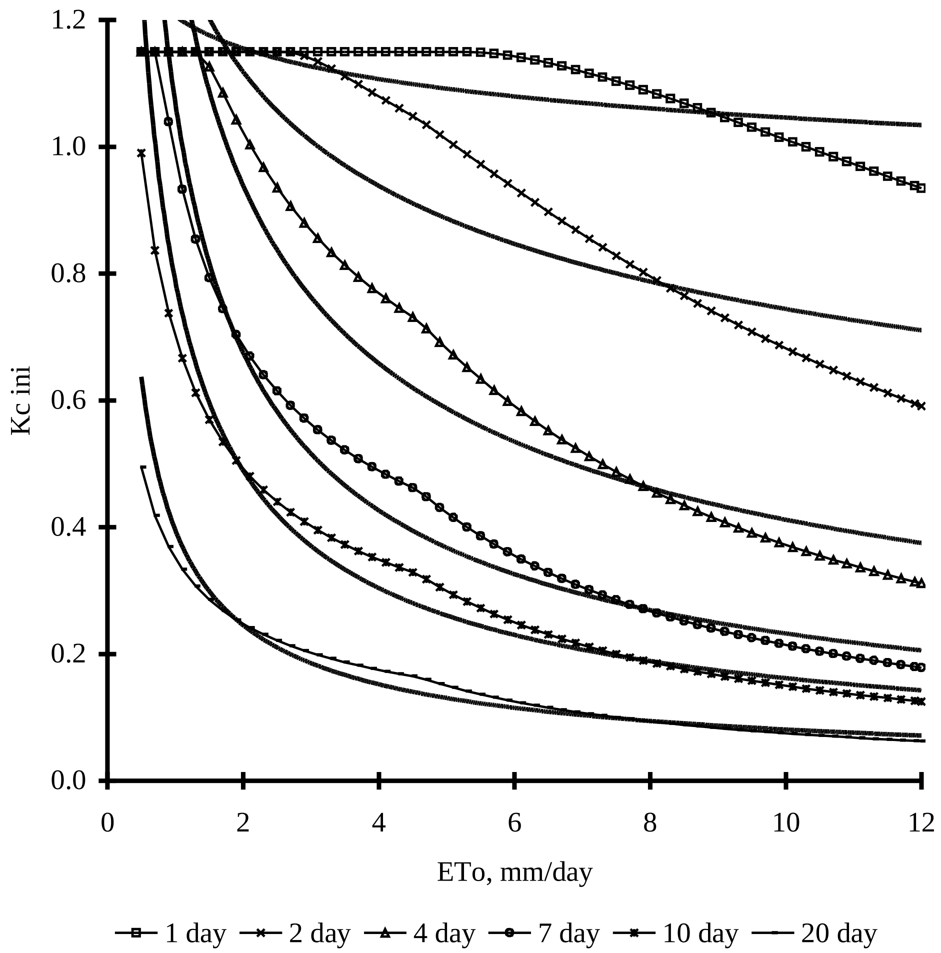
$y_{4day} = 0.0058x^2 - 0.1496x + 1.2833$
$R^2 = 0.9963$

$y_{7day} = 0.0087x^2 - 0.1745x + 1.0758$
$R^2 = 0.9564$

$y_{10day} = 0.0069x^2 - 0.1357x + 0.8021$
$R^2 = 0.9317$

$y_{20day} = 0.0035x^2 - 0.068x + 0.402$
$R^2 = 0.9335$

Fig.4.9c. Coarse Soil, Infil. > 40 mm



Power equations

$y_{1day} = 1.2059x^{-0.0617}$
$R^2 = 0.4999$

$y_{2day} = 1.3326x^{-0.253}$
$R^2 = 0.7367$

$y_{7day} = 1.0689x^{-0.6628}$
$R^2 = 0.9592$

$y_{4day} = 1.3387x^{-0.5119}$
$R^2 = 0.8904$

$y_{20day} = 0.3954x^{-0.6884}$
$R^2 = 0.9664$

$y_{10day} = 0.788x^{-0.6871}$
$R^2 = 0.967$

Fig. 4.9d. Coarse Soil, Infil. > 40 mm

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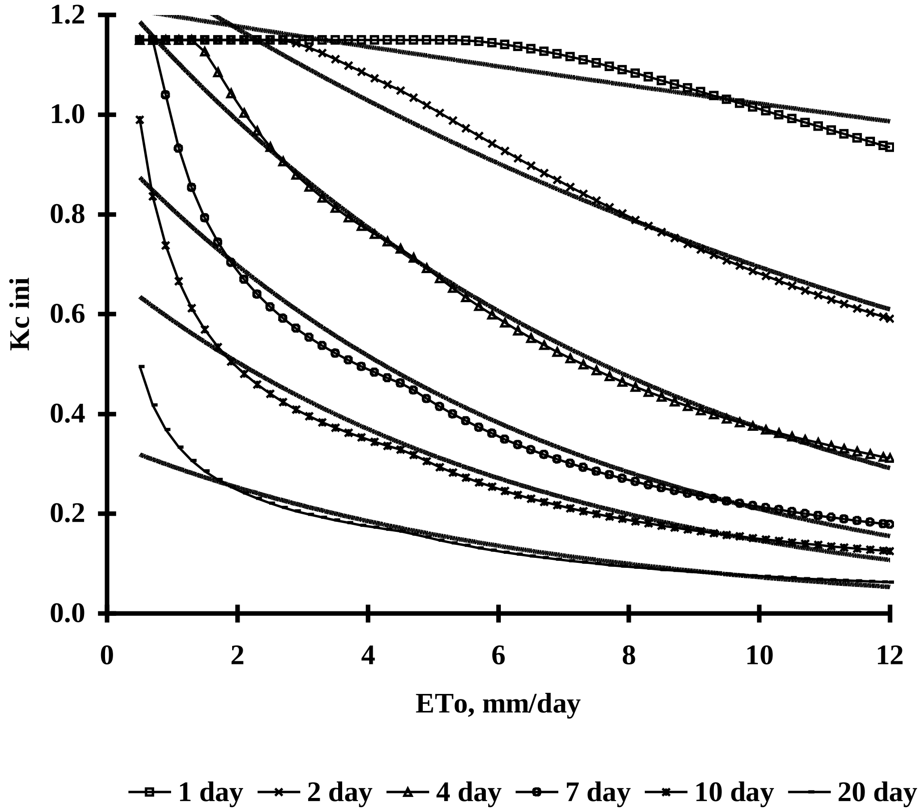


Exponential Equations

$y_{1day} = 1.2196e^{-0.0176x}$
$R^2 = 0.8033$

$y_{2day} = 1.3362e^{-0.0654x}$
$R^2 = 0.9684$

$y_{4day} = 1.261e^{-0.122x}$
$R^2 = 0.9947$

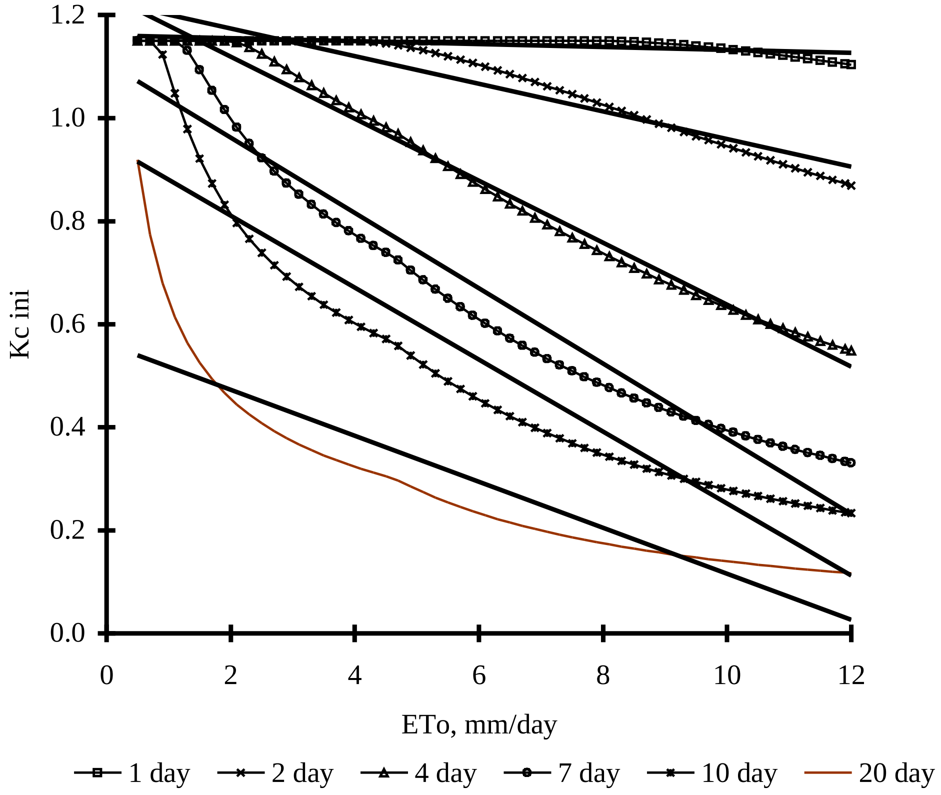
$y_{7day} = 0.9428e^{-0.1503x}$
$R^2 = 0.9701$

$y_{10day} = 0.6866e^{-0.1546x}$
$R^2 = 0.9631$

$y_{20day} = 0.3447e^{-0.155x}$
$R^2 = 0.9637$

Fig.4.9e. Coarse Soil, Infil. > 40 mm

75



Linear equations:

$y_{1day} = -0.0028x + 1.1609$
$R^2 = 0.5538$

$y_{2day} = -0.0268x + 1.2275$
$R^2 = 0.9057$

$y_{4day} = -0.0602x + 1.2396$
$R^2 = 0.9895$

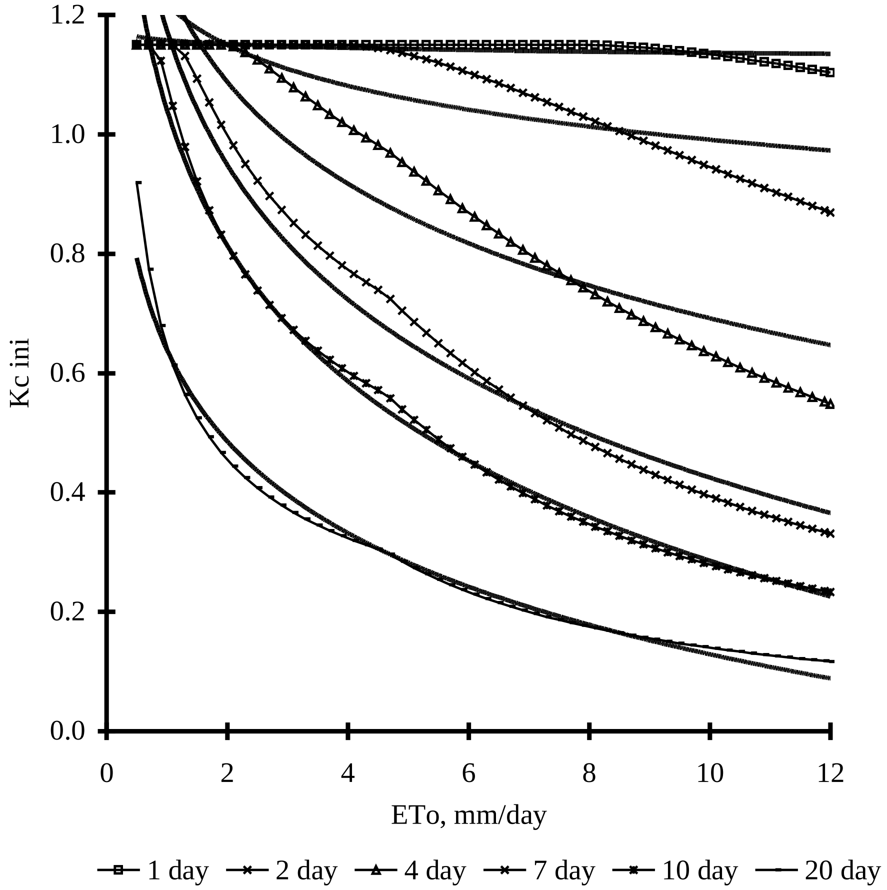
$y_{7day} = -0.0731x + 1.1083$
$R^2 = 0.951$

$y_{10day} = -0.0698x + 0.9505$
$R^2 = 0.8857$

$y_{20day} = -0.0447x + 0.5623$
$R^2 = 0.7841$

Fig. 4.10a. Fine/Med., Infil. > 40 mm

76



Logarithmic equations

y_{1day} = -0.0092Ln(x) + 1.1579
R^2 = 0.2974

y_{2day} = -0.0985Ln(x) + 1.2181
R^2 = 0.6225

y_{4day} = -0.2461Ln(x) + 1.2587
R^2 = 0.8412

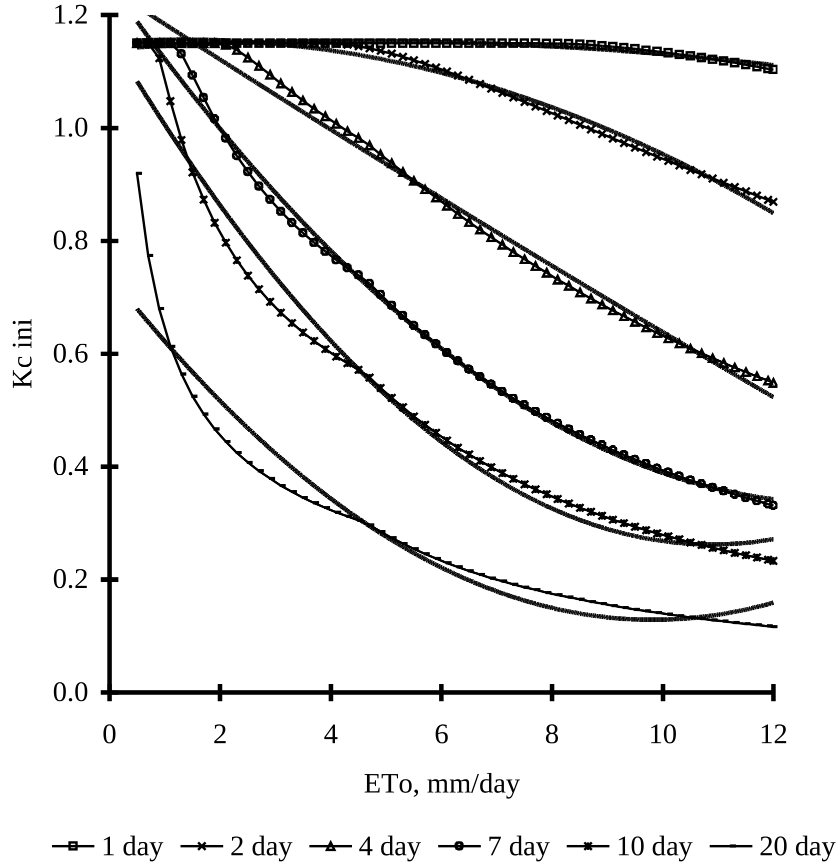
y_{7day} = -0.3255Ln(x) + 1.1746
R^2 = 0.9593

y_{10day} = -0.3282Ln(x) + 1.0414
R^2 = 0.9937

y_{20day} = -0.2217Ln(x) + 0.6395
R^2 = 0.9808

Fig. 4.10b. Fine/Med., Infil. > 40 mm

77



Polynomial equations

$y_{1day} = -0.0007x^2 + 0.0065x + 1.1401$
$R^2 = 0.9041$

$y_{2day} = -0.0027x^2 + 0.0072x + 1.1517$
$R^2 = 0.9906$

$y_{4day} = 0.0003x^2 - 0.0636x + 1.2473$
$R^2 = 0.9897$

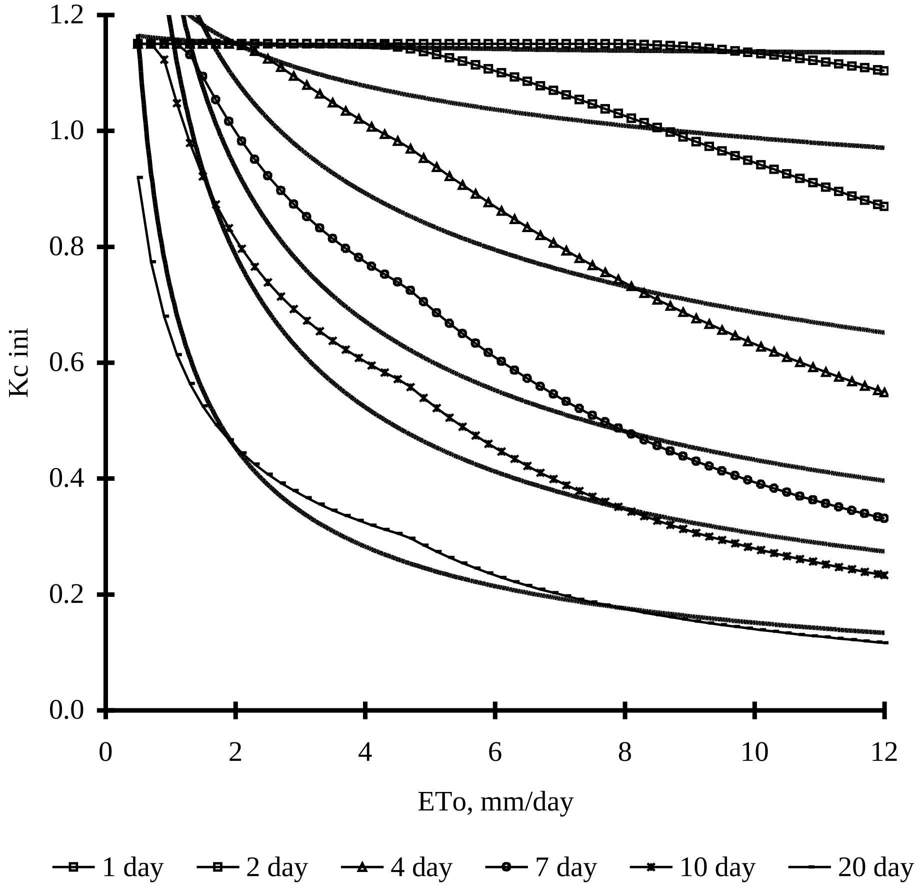
$y_{7day} = 0.0053x^2 - 0.1397x + 1.2567$
$R^2 = 0.9971$

$y_{10day} = 0.0076x^2 - 0.1655x + 1.1634$
$R^2 = 0.9823$

$y_{20day} = 0.0063x^2 - 0.1245x + 0.7402$
$R^2 = 0.9298$

Fig. 4.10c. Fine/Med., Infil. > 40 mm

78



Power equations

$y_{1day} = 1.1581x^{-0.0081}$
$R^2 = 0.2961$

$y_{2day} = 1.2291x^{-0.0949}$
$R^2 = 0.6061$

$y_{4day} = 1.327x^{-0.2861}$
$R^2 = 0.7942$

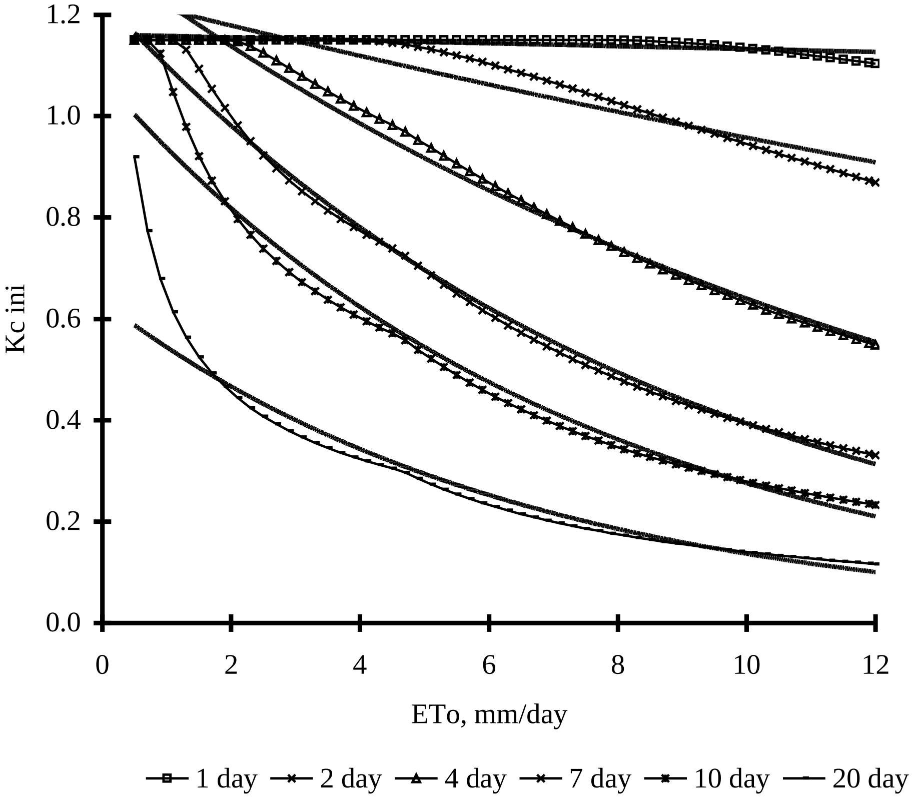
$y_{7day} = 1.3051x^{-0.4797}$
$R^2 = 0.8945$

$y_{10day} = 1.1815x^{-0.5878}$
$R^2 = 0.9377$

$y_{20day} = 0.7272x^{-0.682}$
$R^2 = 0.9666$

Fig. 4.10d. Fine/Med., Infil. > 40 mm

79



Exponential Equations

$y_{1day} = 1.1611e^{-0.0025x}$
$R^2 = 0.5517$

$y_{2day} = 1.2417e^{-0.026x}$
$R^2 = 0.8944$

$y_{4day} = 1.3141e^{-0.0719x}$
$R^2 = 0.9878$

$y_{7day} = 1.2326e^{-0.1141x}$
$R^2 = 0.9958$

$y_{10day} = 1.0736e^{-0.1358x}$
$R^2 = 0.9841$

$y_{20day} = 0.6344e^{-0.1535x}$
$R^2 = 0.9632$

Fig.4.10e. Fine/Med., Infil. > 40 mm

80

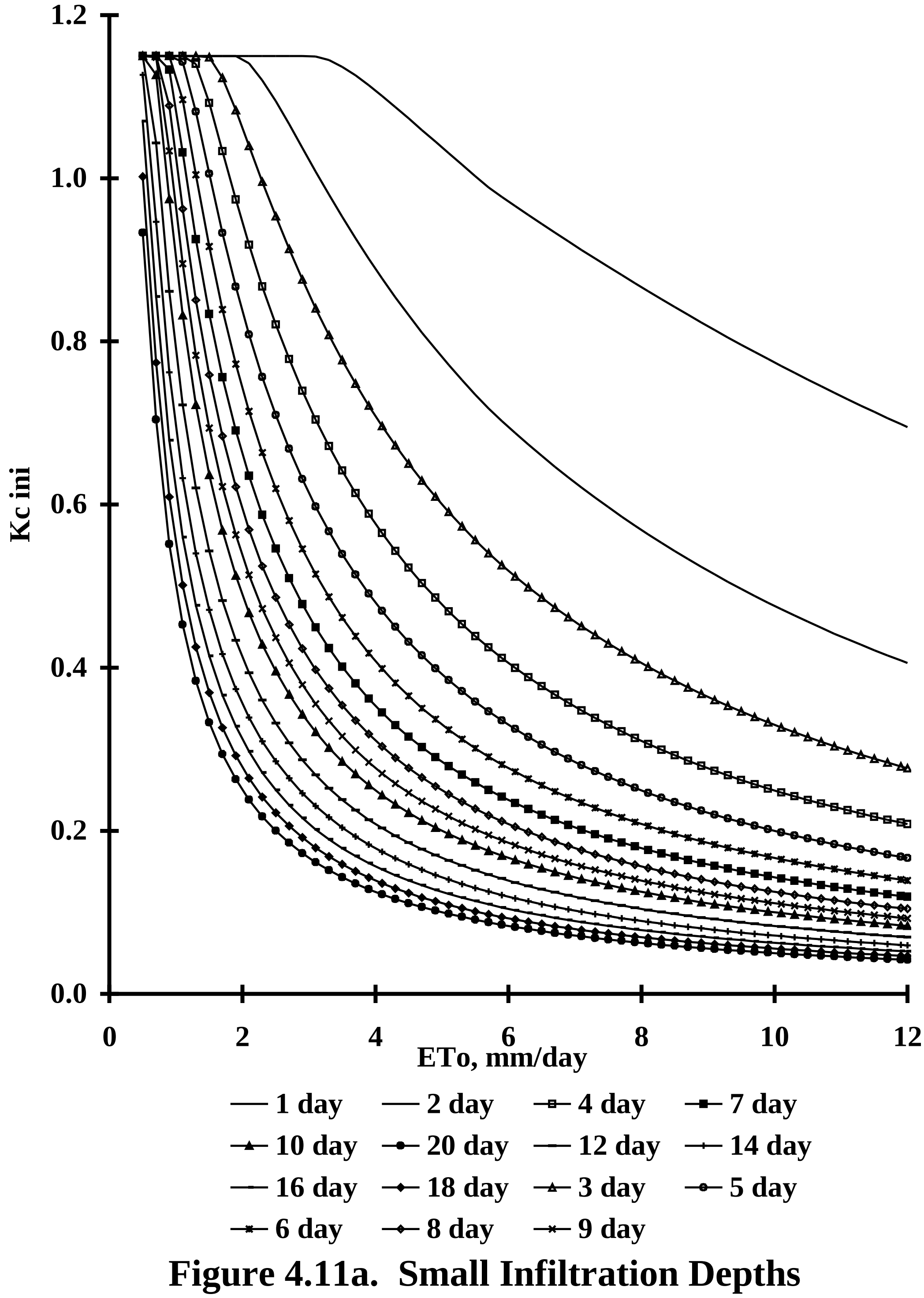


Figure 4.11a. Small Infiltration Depths
15 equations.

81

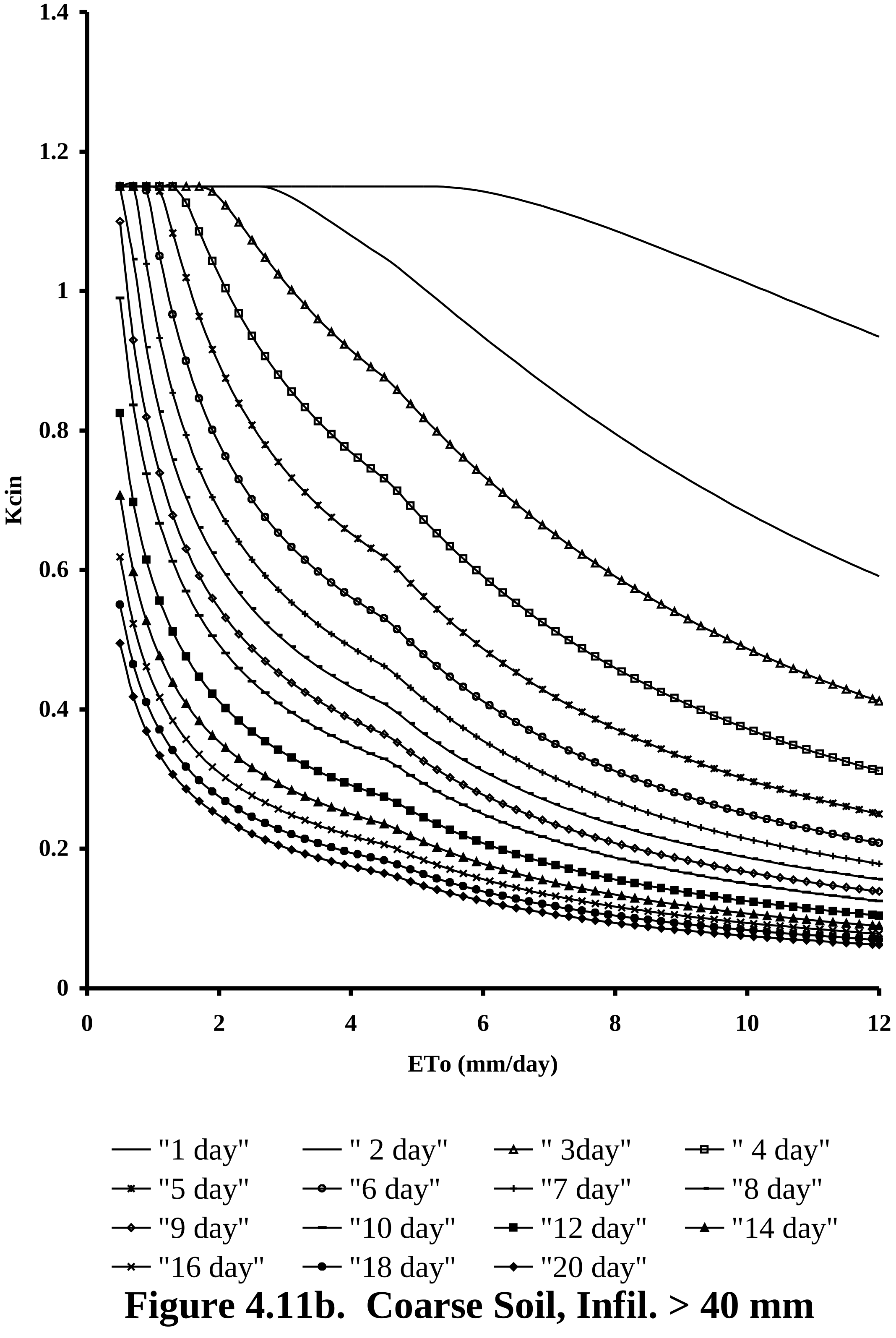


Figure 4.11b. Coarse Soil, Infil. > 40 mm
15 equations

82

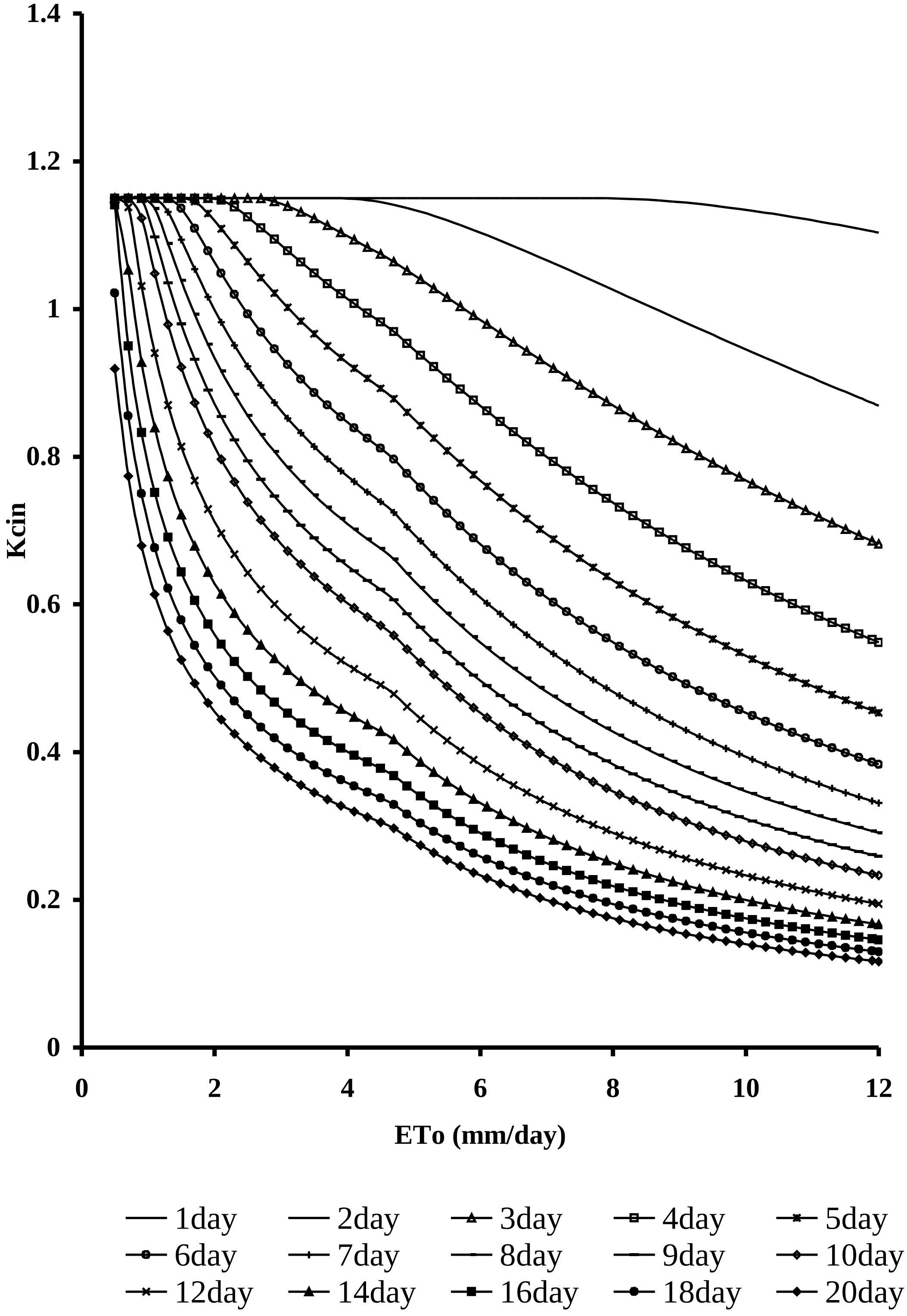


Figure 4.11c Fine/Med., Infil. > 40 mm
15 Equations

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Table 4.2a Best fit equations for irrigation intervals 1,2,3,4,5,6,7,8,9,10,12,14,16,18 &20 days forFig.4.11a

$y_{1day} = -0.0012x^2 - 0.0313x + 1.2151$
$R^2 = 0.9791$

$y_{2day} = 0.0039x^2 - 0.1238x + 1.3157$
$R^2 = 0.9863$

$y_{3day} = 0.0079x^2 - 0.1809x + 1.3319$
$R^2 = 0.9903$

$y_{4day} = 0.0104x^2 - 0.2111x + 1.3034$
$R^2 = 0.9854$

$y_{5day} = 0.0117x^2 - 0.2253x + 1.2547$
$R^2 = 0.9736$

$y_{6day} = 1.1558x^{-0.8154}$
$R^2 = 0.9699$

$y_{7day} = 1.0783x^{-0.8568}$
$R^2 = 0.979$

$y_{8day} = 1.0052x^{-0.8883}$
$R^2 = 0.9854$

$y_{9day} = 0.9384x^{-0.9129}$
$R^2 = 0.99$

$y_{10day} = 0.8767x^{-0.9319}$
$R^2 = 0.9931$

$y_{12day} = 0.7696x^{-0.9586}$
$R^2 = 0.997$

$y_{14day} = 0.681x^{-0.975}$
R2 = 0.9988

$y_{16day} = 0.6069x^{-0.9846}$
$R^2 = 0.9995$

$y_{18day} = 0.5454x^{-0.9903}$
$R^2 = 0.9998$

$y_{20day} = 0.4941x^{-0.9938}$
$R^2 = 0.9999$

Table 4.2b Best fit equations for irrigation intervals 1,2,3,4,5,6,7,8,9,10,12,14,16,18 &20 days For Fig 4.11b.

$y_{1day} = -0.0029x^2 + 0.0178x + 1.1305$
$R^2 = 0.9929$
$y_{2day} = -0.0014x^2 - 0.0398x + 1.2286$
$R^2 = 0.9829$
$y_{3day} = 0.0027x^2 - 0.1069x + 1.2893$
$R^2 = 0.9918$
$y_{4day} = 0.0058x^2 - 0.1496x + 1.2833$
$R^2 = 0.9963$
$y_{5day} = 0.0076x^2 - 0.171x + 1.234$
$R^2 = 0.9902$
$y_{6day} = -0.3359Ln(x) + 1.022$
$R^2 = 0.9926$
$y_{7day} = -0.3173Ln(x) + 0.9352$
$R^2 = 0.9913$
$y_{8day} = -0.2927Ln(x) + 0.8483$
$R^2 = 0.9864$
$y_{9day} = -0.2667Ln(x) + 0.767$
$R^2 = 0.9808$
$y_{10day} = -0.2406Ln(x) + 0.6918$
$R^2 = 0.9815$
$y_{12day} = -0.2009Ln(x) + 0.5775$
$R^2 = 0.9821$
$y_{14day} = -0.1723Ln(x) + 0.4952$
$R^2 = 0.9823$
$y_{16day} = -0.1508Ln(x) + 0.4334$
$R^2 = 0.9823$
$y_{18day} = -0.134Ln(x) + 0.3853$
$R^2 = 0.9823$
$y_{20day} = -0.1206Ln(x) + 0.3467$
$R^2 = 0.9823$

Table 4.2c Best fit equations for irrigation intervals 1,2,3,4,5,6,7,8,9,10,12,14,16,18 &20 days For Fig.4.11c

$y_{1day} = -0.0007x^2 + 0.0065x + 1.1401$
$R^2 = 0.9041$
$y_{2day} = -0.0027x^2 + 0.0072x + 1.1517$
$R^2 = 0.9906$
$y_{3day} = -0.0017x^2 - 0.0262x + 1.2054$
$R^2 = 0.9859$
$y_{4day} = 0.0003x^2 - 0.0636x + 1.2473$
$R^2 = 0.9897$
$y_{5day} = 0.0022x^2 - 0.0959x + 1.2681$
$R^2 = 0.9944$
$y_{6day} = 0.0039x^2 - 0.1211x + 1.2699$
$R^2 = 0.9971$
$y_{7day} = 0.0053x^2 - 0.1397x + 1.2567$
$R^2 = 0.9971$
$y^{8day} = 0.0063x^2 - 0.1526x + 1.2326$
$R^2 = 0.9943$
$y_{9day} = 0.0071x^2 - 0.161x + 1.201$
$R^2 = 0.9891$
$y_{10day} = -0.3282Ln(x) + 1.0414$
$R^2 = 0.9937$
$y_{12day} = -0.3137Ln(x) + 0.9515$
$R^2 = 0.9954$
$y_{14day} = -0.2929Ln(x) + 0.8647$
$R^2 = 0.99$
$y_{16day} = -0.2713Ln(x) + 0.7868$
$R^2 = 0.9795$
$y_{18day} = -0.2447Ln(x) + 0.7069$
$R^2 = 0.9799$
$y_{20day} = -0.2217Ln(x) + 0.6395$
$R^2 = 0.9808$

Estimation of Kcmid and Kcend values is done by selecting tabulated values from FAO Tables (1998) and adjusting them for variation in relative humidity, wind speed and

crop height using equations (2.6) and (2.7) (Allen, 1998). Depending on values of Kcin and Kcmid already calculated by the model for the development stage crop factor (Kc dev.) are calculated by assuming a linear function throughout the plant development growth stage. An option of a hard copy print is given (Fig 4.12).

b- Construction of the Kc curves on decade basis:-

The model estimates the Kc values for initial, mid and late stages starting from effective planting dates. The model segments the total crop growing period into four segments each representing the growing stage that describes the crop phenology. The values of Kcin and Kcmid are fixed for each decade in its respective growth stage. The algorithm estimates the values of Kc dev. and Kc end for its respective decade by using the slope of the inclined curve.

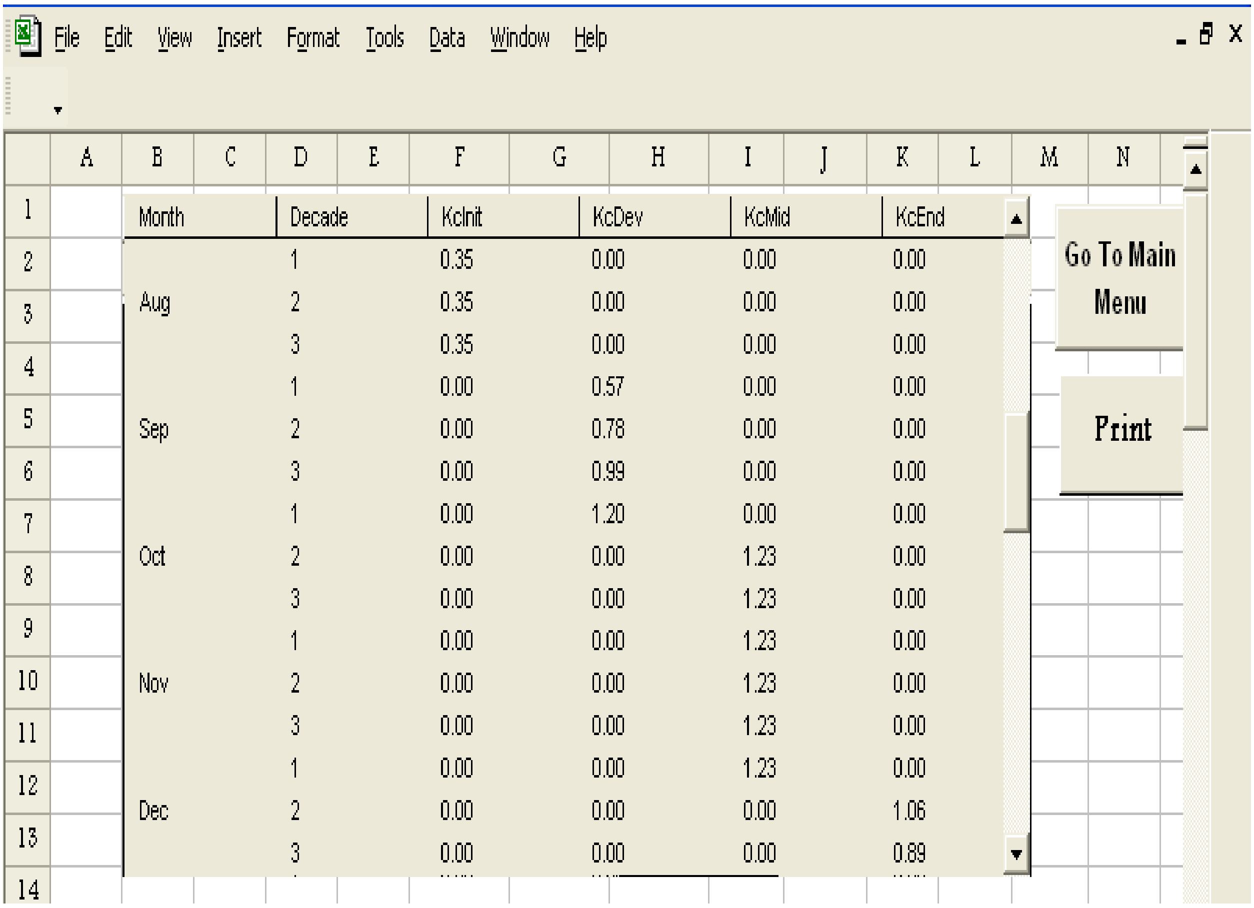
4.4.3 Effective precipitation (Pe) module

The mean monthly values of the effective rainfall are estimated by the model following one of alternative options to calculate rainfall as given in chapter two and additional alternative of not considering rain is also given (Fig 4.13).

The mean monthly value are assumed to correspond to the middle of its respective month. A linear rotation is assumed between each two successive mean values consequently the model calculates the decadal values of rainfall from the slope of the line connecting each two adjacent monthly mean values. However a positive slope is taken for rising limb and a negative value is taken for a falling limb.

4.4.4 Crop water requirements module

From the values of ETo and Pe and project irrigation efficiency defined by model user, crop water requirement is calculated in mm/day throughout the plant growing period on decadal basis (Fig. 4.14a).



Month	Decade	KcInit	KcDev	KcMid	KcEnd
Aug	1	0.35	0.00	0.00	0.00
	2	0.35	0.00	0.00	0.00
	3	0.35	0.00	0.00	0.00
Sep	1	0.00	0.57	0.00	0.00
	2	0.00	0.78	0.00	0.00
	3	0.00	0.99	0.00	0.00
Oct	1	0.00	1.20	0.00	0.00
	2	0.00	0.00	1.23	0.00
	3	0.00	0.00	1.23	0.00
Nov	1	0.00	0.00	1.23	0.00
	2	0.00	0.00	1.23	0.00
	3	0.00	0.00	1.23	0.00
Dec	1	0.00	0.00	1.23	0.00
	2	0.00	0.00	0.00	1.06
	3	0.00	0.00	0.00	0.89

Figure 4.12 Kc values at different phonological stages (in decades)

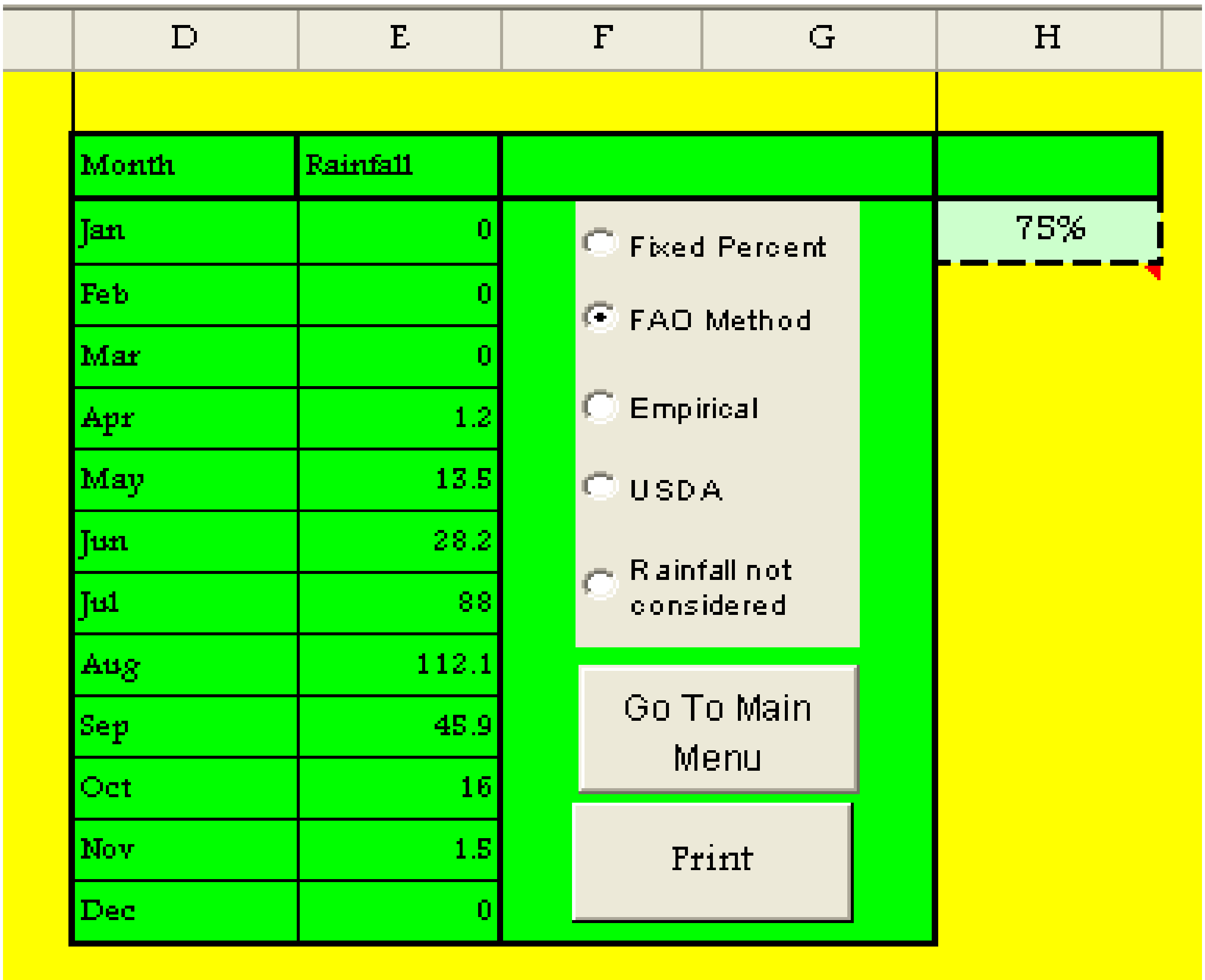
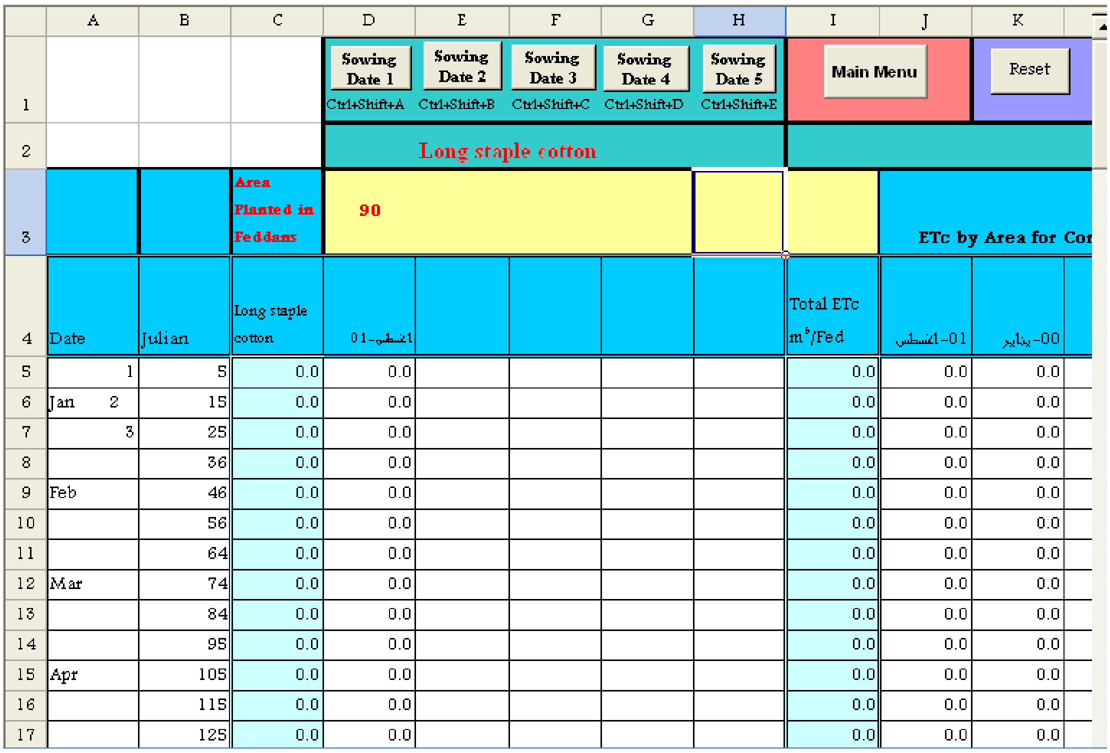


Figure 4.13 Effective precipitation (Pe).



	A	B	C	D	E	F	G	H	I	J	K
1				Sowing Date 1 Ctrl+Shift+A	Sowing Date 2 Ctrl+Shift+B	Sowing Date 3 Ctrl+Shift+C	Sowing Date 4 Ctrl+Shift+D	Sowing Date 5 Ctrl+Shift+E	Main Menu		Reset
2				Long staple cotton							
3			Area Planted in Feddans	90						ETc by Area for Cor	
4	Date	Julian	Long staple cotton	01-اغسطس					Total ETc m^3/Fed	01-اغسطس	00-يناير
5	1	5	0.0	0.0					0.0	0.0	0.0
6	Jan 2	15	0.0	0.0					0.0	0.0	0.0
7	3	25	0.0	0.0					0.0	0.0	0.0
8		36	0.0	0.0					0.0	0.0	0.0
9	Feb	46	0.0	0.0					0.0	0.0	0.0
10		56	0.0	0.0					0.0	0.0	0.0
11		64	0.0	0.0					0.0	0.0	0.0
12	Mar	74	0.0	0.0					0.0	0.0	0.0
13		84	0.0	0.0					0.0	0.0	0.0
14		95	0.0	0.0					0.0	0.0	0.0
15	Apr	105	0.0	0.0					0.0	0.0	0.0
16		115	0.0	0.0					0.0	0.0	0.0
17		125	0.0	0.0					0.0	0.0	0.0

Figure 4.14 a. Crop water requirements module

4.4.5 Irrigation water need module

From crop cultivated area per each outlet (Abu XX) and crop water requirements the irrigation water needs (IWN) of the crop on decadal basis and in m^3/feddan is calculated for each sowing decade by using the relevant conversion factor. However, the model offers the facility to consider five sowing decades. This was made so as to cater for the late sowing decades usually expected due to low level of management associated with large scale irrigation projects (Fig 4.14b).

4.4.6 Indenting module

Indent (water order) for each minor canal is calculated by the model for each irrigation interval from the irrigation demand for each outlet and for a number of operating outlets in that minor canal (Fig. 4.15)

As a pre-requisite for optimization module the indent module calculates each outlet operation time on basis of user defined outlet inflow rate (m^3/day) for the respective irrigation intervals (Fig 4.16).

4.4.7 The optimization model

The optimization model for minor canal operation is an integer linear programming model. The minor is assumed to be operated on rotational flow basis between distributor outlets (Abu XXs). In formulating the water distribution problem in a mathematical form, the canal capacity is assumed to be fixed and it is assumed to serve a number of live outlets. The maximum number of live outlets in the model is 14 outlets but with some simple modification the model can accept up to 28 live outlets. The minor is thus supposed to contain a number of sub-routes each with a design discharge equivalent to that of the supplied outlet. Therefore, the total capacity of the minor is equal to the sum of the capacities of the sub-routes contained. Each outlet is assumed to run with a user defined fixed discharge (Fig. 4.17).

The operating cost of each live outlet and hence the operating cost per minor is assumed to be a function of the operating time and expressed as penalty factor. During the operation each live outlet once open remains functioning until it satisfies the demand of its cultivated area. The numbers of outlets working simultaneously are determined by the canal capacity and the average discharge of the outlets.

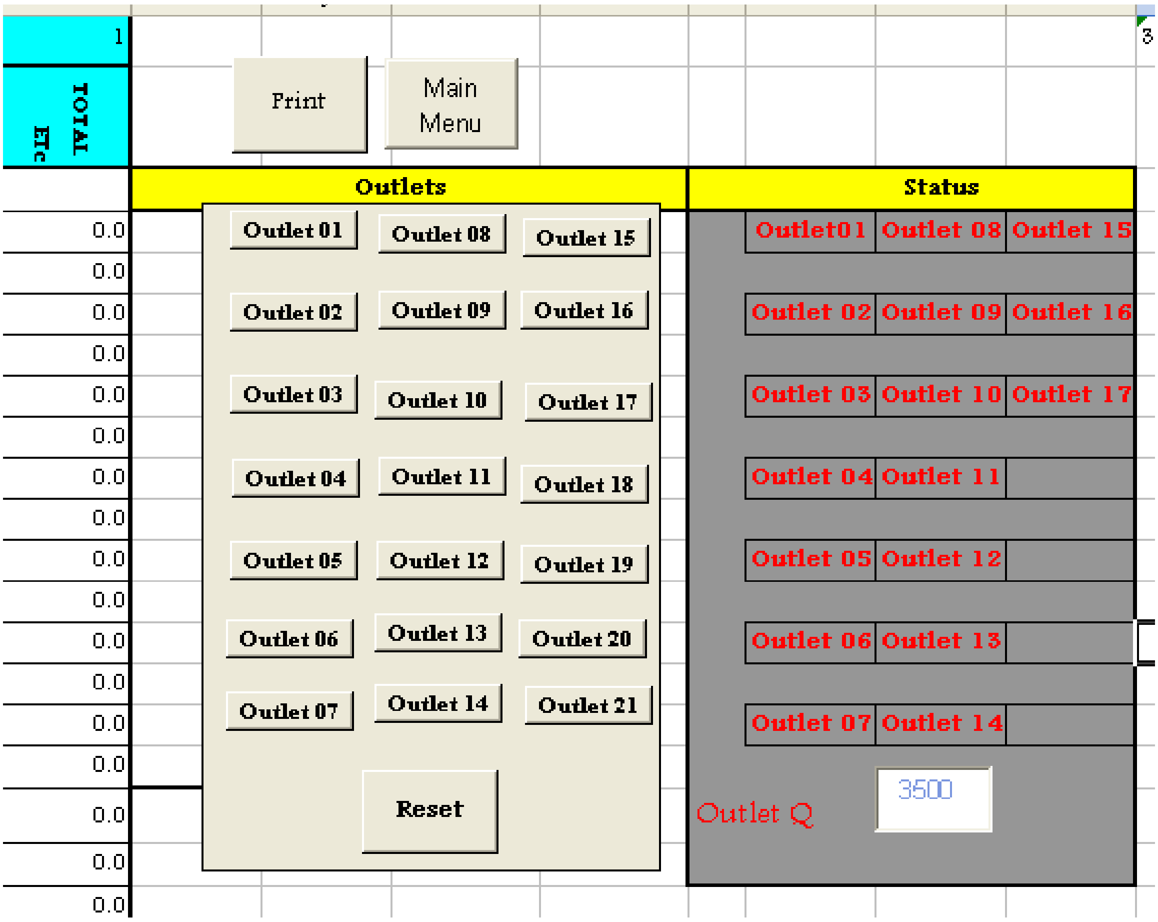


Figure 4.14b. Irrigation water need module

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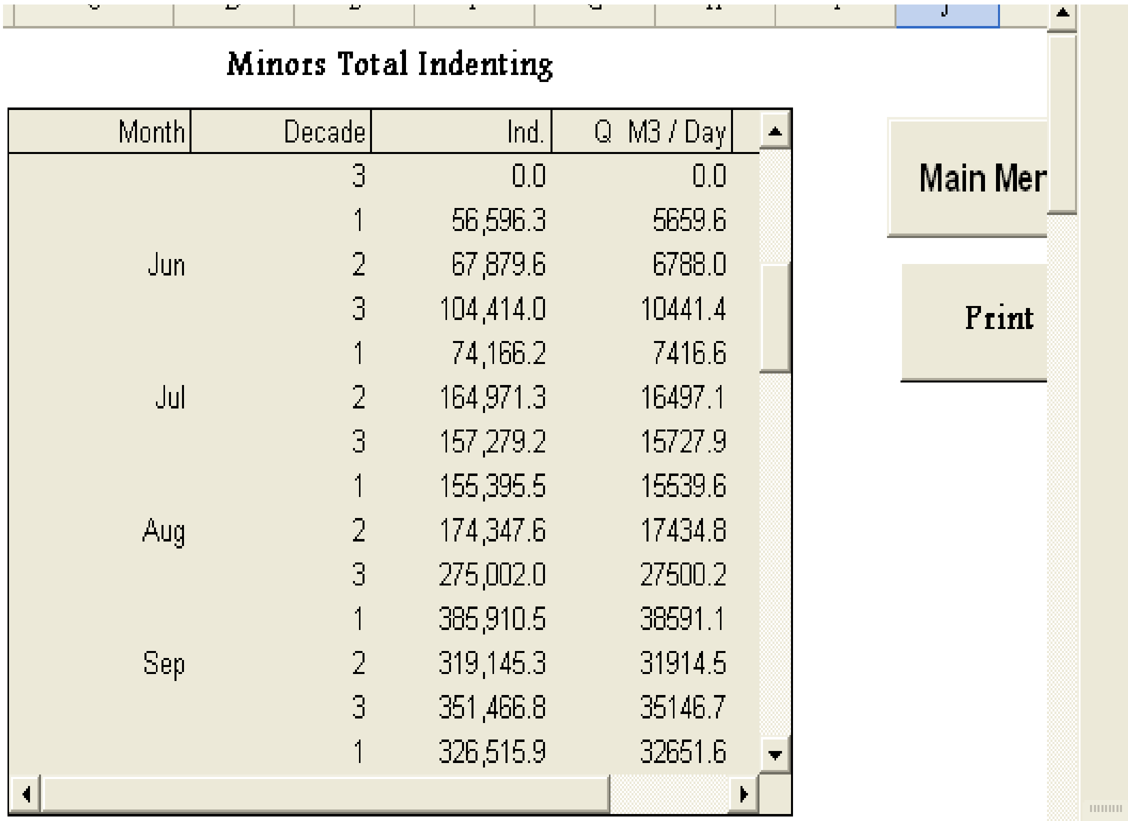
Minors Total Indenting

Month	Decade	Ind.	Q M3 / Day
	3	0.0	0.0
	1	56,596.3	5659.6
Jun	2	67,879.6	6788.0
	3	104,414.0	10441.4
	1	74,166.2	7416.6
Jul	2	164,971.3	16497.1
	3	157,279.2	15727.9
	1	155,395.5	15539.6
Aug	2	174,347.6	17434.8
	3	275,002.0	27500.2
	1	385,910.5	38591.1
Sep	2	319,145.3	31914.5
	3	351,466.8	35146.7
	1	326,515.9	32651.6

Figure 4.15 Minor indenting module

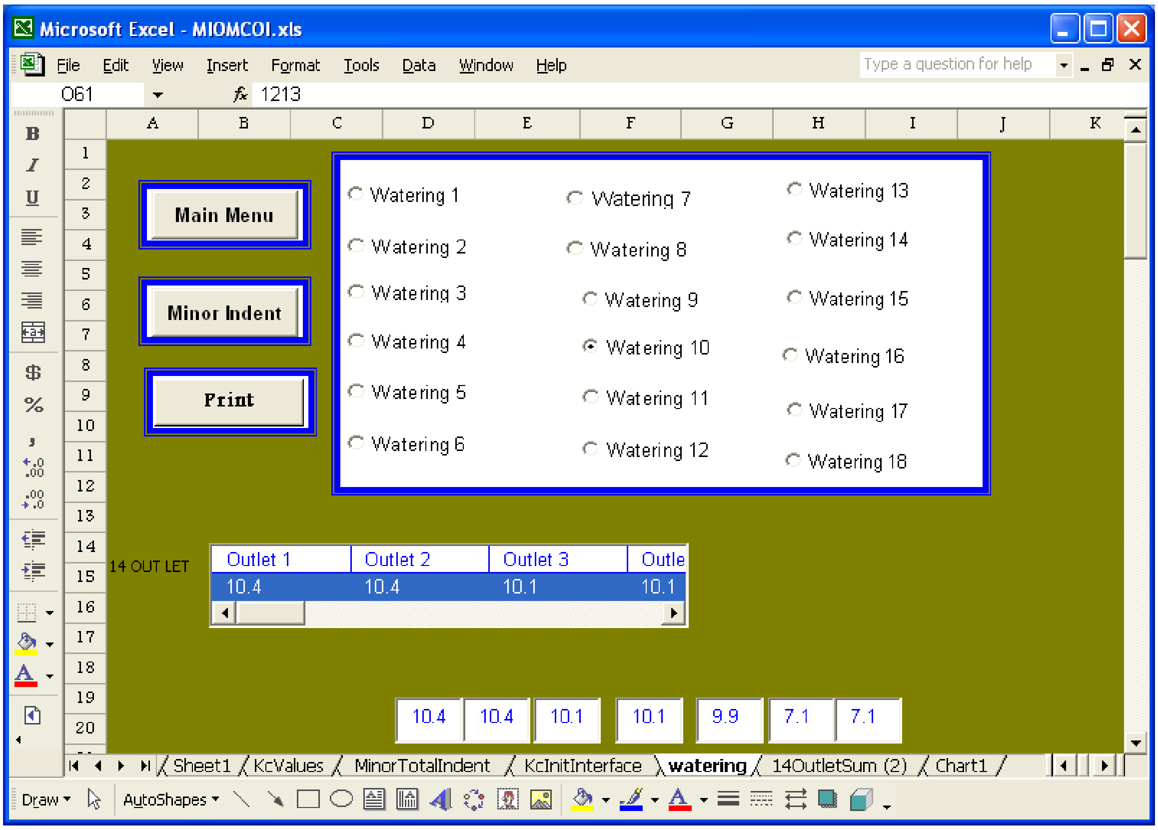

Figure 4.16 Waterings module.

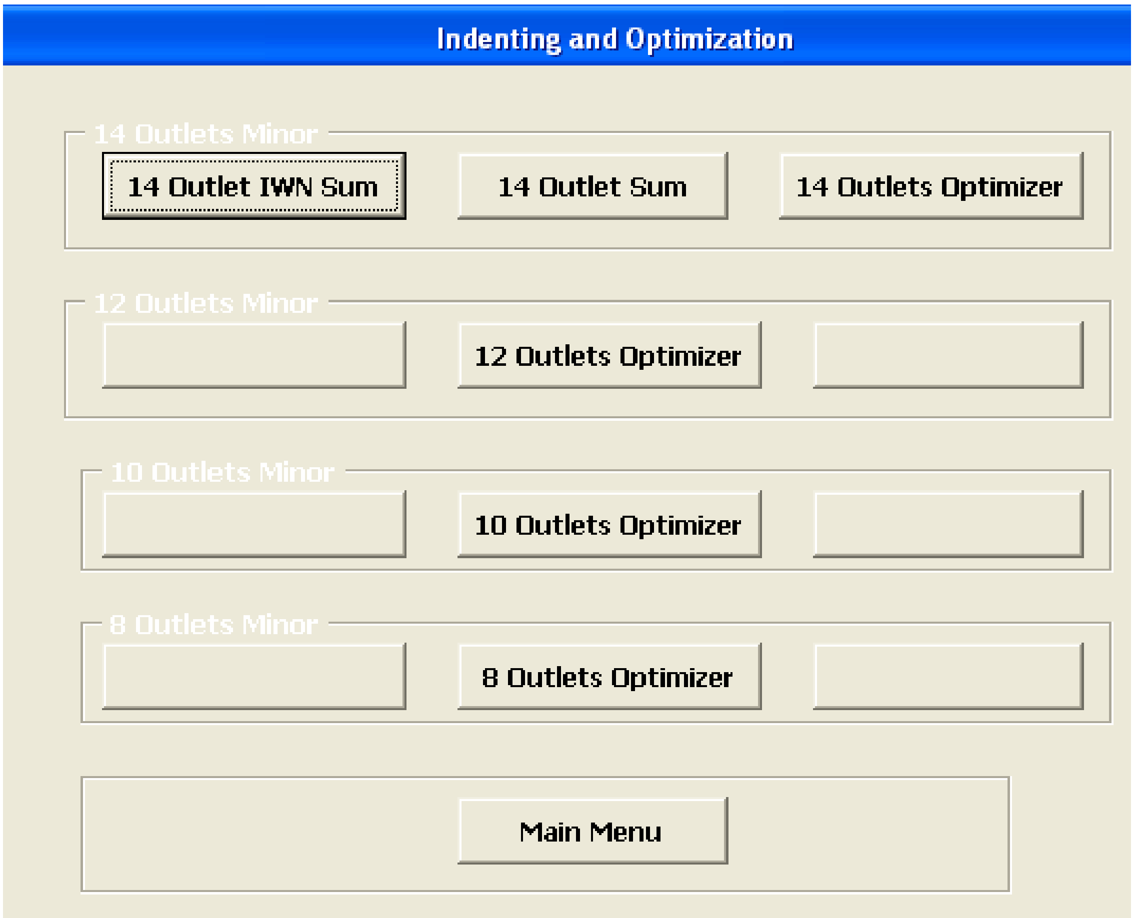

Figure 4.17 Optimization model

The objective function is expressed in terms of the decision variables Xij. Assuming that it is an existing minor canal the objective is the operational schedule that minimizes the cost of operation of the distributary (Abu XX) and consequently the minor canal. The objective function is expressed as:-

$$\text{Min} \sum_{ij}^{nm} C_i \; X_{ij} \quad (n = m) \tag{4.1}$$

Where n is number of routes (groups); and m is the number of outlets on the minor and Ci is the operation cost penalty factor of the outlet via its respective route. Initially n is assumed to be equal to m. The operating cost penalty factor is introduced so as to minimize the total operation cost and to assure that once the outlet is open it remains on for the coming working days. By virtue of the penalty each outlet seeks to start operation as early as possible and tries to avoid opening twice because the second opening will incur a penalty. Hence the theoretically economic condition is to open all outlets at one time but the canal capacity is not sufficient to supply all outlet at one time. To schedule the operation of the outlets, the system is subject to some constraints and preferences that need to be satisfied these constraints are specified as follows:-

1. The total running time of the outlets in any group running sequentially should not exceed the irrigation interval (running time). If aj represent the running time of outlet j the n constraints are stated as:-

$$\sum_{ij}^{nm} a_j \, X_{ij} \leq D \tag{4.2}$$

Where aj is the running time of outlet j (days) and D is the total time available for irrigation during a given rotation of each distributary channel (Abu XX) in days.

2. The binary constraint states that a value of one is assigned to an outlet when it is open while a value of zero is assigned to it when it is closed. Hence:-

$$X_{ij} = I \text{ when outlet } j \text{ is open} \quad (4.3\text{ a})$$

$$X_{ij} = 0 \text{ when outlet } j \text{ is closed} \quad (4.3\text{ b})$$

In order to schedule the sequence of operating the outlet within the limits of the existing canal capacity the number of open outlets at any one time should not exceed the maximum number of outlets (via their respective routes) the canal can satisfy.

This is stated mathematically as follows:-

$$\sum_{ij}^{nm} X_{ij} \leq \text{canal capacity} \quad (4.4)$$

Where canal capacity represents the maximum number of outlets (routes) that can work at any one time in the minor canal. i.e. Minor discharge divided by average outlet discharge.

Or

$$\sum_{i}^{m} q_i \leq Q_t$$

Where:

m =the number of open outlets (i) at one time .

q_i = inflow rate for outlet (i)

Q_t = Canal capacity

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Verification of the model.

5.1.1 Determination of ET_O

Allen (1998) used meteorological data of April month for Bankok city in Thailand to determine ETo by applying Penman- Montieth Equation. Table (5.1) shows the results obtained. The result is split into two parts, the first part resembles the energy component (3.9647 mm/day) and second part resembles the aerodynamic component (1.751mm/day) with a total of 5.716 mm/day.

The same data of Bankok is used by the model (MIOMCO) to determine ETo. The actual water vapour pressure (e_a) has been calculated indirectly by the model from data of relative humidity and air temperature .Wind speed is fed directly in miles per hour.

As given in Figure (5.1) the result obtained by the model (ETo = 5.719) is almost identical with that obtained by Allen (1998) (ETo = 5.716) in addition the model generates ETo per decade.

ETo calculated by the model for Central Gezira using Wad Medani meteorological data is compared to ETo computed by FAO Cropwat computer programme.

The scatter diagram given in Figure (5.2) indicates the close correlation (standard deviation = 0.0213 and R^2 = 0.99) between mean ETo of the two procedures (Table 5.2).

5.1.2 Crop coefficient (K_C)

Crop coefficients for groundnuts and Cotton are estimated by the model for the four crop growth stages, initial, development, middle and end stage and given in Tables (5.3 and 5.4) and Figures (5.3a and 5.3b). The crop coefficient for the initial stage computed by the model and that extracted from reference curves of FAO paper (56) (Allen *et al* 1998) had similar values of (0.26) as shown in Fig. (5.4a and 5.4b).

Table 5.1 Estimation of ETo for Bankok City-Thailand by Allen et al. (1998) Using Penman Montieth equation.

Monthly	**Bangkok**			
April				
DoY	105		omega s	1.61171
lat	13.7333		Ra	38.0577
elev	2	m	N	12.3126
Tmax	34.8		n/N	0.69035
Tmin	25.6		Rs	22.651
ea	2.85		Rso	28.5448
U2	2		Rs/Rso	0.79353
n	8.5		Rns	17.4413
April Tm	30.2		sigmTmax^4	44.1001
March Tm	29.2		sigmTmin^4	39.0618
Tmean	30.2		ave(sigmT^4's)	41.5809
delta	0.2458		.34-.14Sqrt(ea)	0.10365
P	101.276		1.35Rs/Rso-.35	0.72126
gamma	0.06738		Rnl	3.10861
(1+.34U)	1.68		Rn	14.3327
del/()	0.68468		G	0.14
gam/()	0.18769		Rn-G	14.1927
900/(Tm+273)U2	5.93668		.408(Rn-G)	5.79061

e(Tmax)	5.5608 2	**first part PM**	**3.96**	mm
e(Tmin)	3.2827 7	**sec part PM**	**1.75**	mm
es	4.4218	**ETo**	**5.72**	mm
es-ea	1.5718			
dr	0.9922 6			
delta	0.1658 4			
lat	0.2396 9			

Figure 5.1 ETo For Bankok City as Computed by Model

Country		
Station		**Bankok**
Altitude (elevation)		**2**
Latitude		**13.36**

	Temperature in (Celcios)						OUTPUT E T o			
Month	**Min**	**Max**	**RHmean**	**Sun Shine Hours**	**Wind Speed U_{15} Miles/Day**	**RainFall mm/Mon**	**Monthly mm/day**	**mm/day Dec1**	**mm/day Dec2**	**mm/day Dec3**
Jan										
Feb										
Mar										
Apr	**34.8**	**25.6**	**64.36**	**8.5**	**6.5**	**0**	5.719	**4.139**	**5.719**	**4.390**
May										
Jun										
Jul										
Aug										
Sep										
Oct										
Nov										
Dec										

Wind Speed Should be entered once as U15 or U2

Note: Provide Button for Save and Print

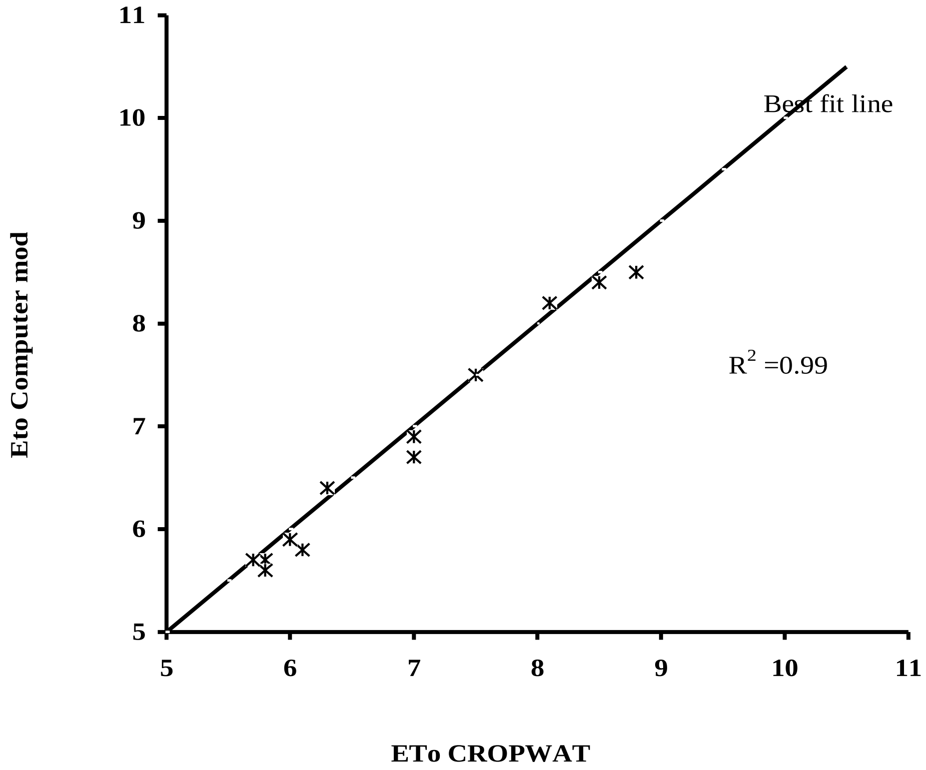

Figure 5.2 ETo computer model Versus CROPWAT.

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Table 5.2 ETo CROPWAT Versus Computer Model in mm/day

Month	Cropwat	Computer model	C.model /Cropwat	R^2	Std.dev.
Jan	5.8	5.7	0.98	0.9983	0.021366
Feb	7	6.9	0.99		
Mar	7.5	7.5	1.00		
Apr	8.1	8.2	1.01		
May	8.5	8.4	0.99		
Jun	8.8	8.5	0.97		
Jul	7	6.7	0.96		
Aug	5.8	5.6	0.97		
Sep	6.1	5.8	0.95		
Oct	6	5.9	0.98		
Nov	6.3	6.4	1.02		
Dec	5.7	5.7	1		

Table 5.3 Crop Kc For Cotton determined by the model.

As it appears in the screen in the tabular form

Month	Decade	KcInit	KcDev	KcMid	KcEnd
	1	**0.35**	0.00	0.00	0.00
Aug	2	**0.35**	0.00	0.00	0.00
	3	**0.35**	0.00	0.00	0.00
	1	0.00	**0.55**	0.00	0.00
Sep	2	0.00	**0.75**	0.00	0.00
	3	0.00	**0.95**	0.00	0.00
	1	0.00	**1.15**	0.00	0.00
Oct	2	0.00	0.00	**1.18**	0.00
	3	0.00	0.00	**1.18**	0.00
	1	0.00	0.00	**1.18**	0.00
Nov	2	0.00	0.00	**1.18**	0.00
	3	0.00	0.00	**1.18**	0.00
	1	0.00	0.00	**1.18**	0.00
Dec	2	0.00	0.00	0.00	**1.07**
	3	0.00	0.00	0.00	**0.96**
	1	0.00	0.00	0.00	**0.85**
Jan	2	0.00	0.00	0.00	**0.74**

Table 5.4 Crop Kc For Groundnut determined by the model.

As it appears in the screen in the tabular form

Month	Decade	KcInit	KcDev	KcMid	KcEnd
	1	0.00	0.00	0.00	0.00
May	2	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00
	1	0.26	0.00	0.00	0.00
Jun	2	0.26	0.00	0.00	0.00
	3	0.26	0.00	0.00	0.00
	1	0.00	0.47	0.00	0.00
Jul	2	0.00	0.70	0.00	0.00
	3	0.00	0.92	0.00	0.00
	1	0.00	1.15	0.00	0.00
Aug	2	0.00	0.00	1.15	0.00
	3	0.00	0.00	1.15	0.00
	1	0.00	0.00	1.15	0.00
Sep	2	0.00	0.00	1.15	0.00
	3	0.00	0.00	1.15	0.00
	1	0.00	0.00	0.00	0.97
Oct	2	0.00	0.00	0.00	0.79
	3	0.00	0.00	0.00	0.61
	1	0.00	0.00	0.00	0.00
Nov	2	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00

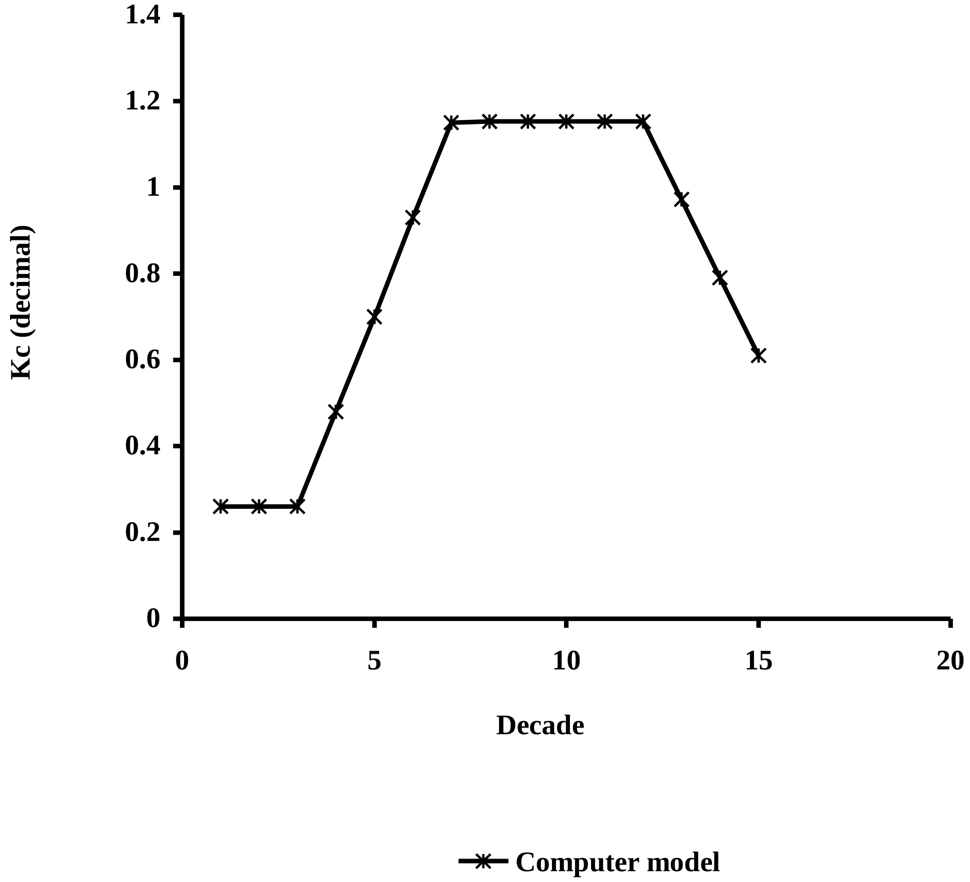

Figure 5.3a Groundnuts Kc computer model

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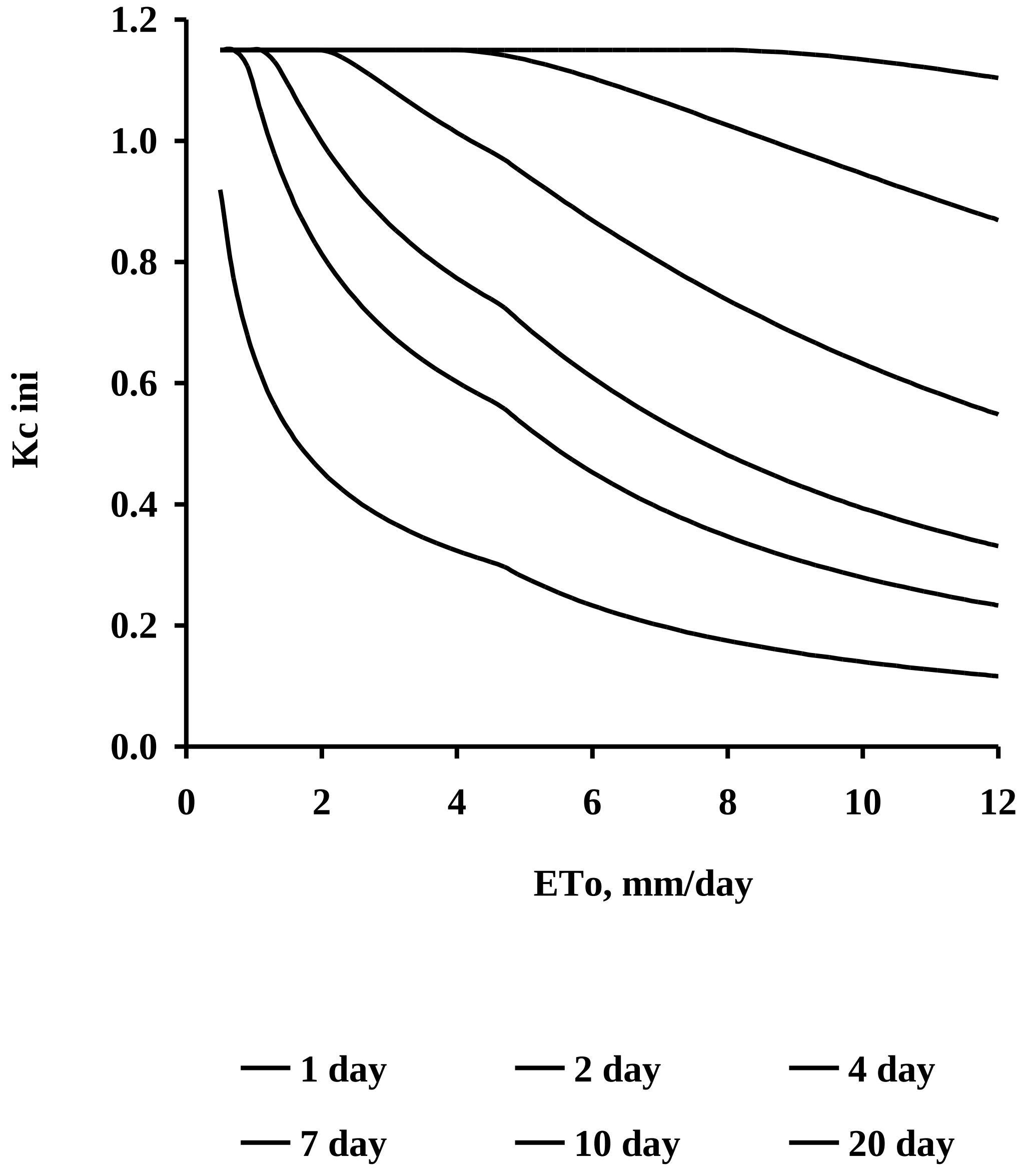

Figure 5.3b Groundnuts Kc as suggested by FAO paper 56,(1998)

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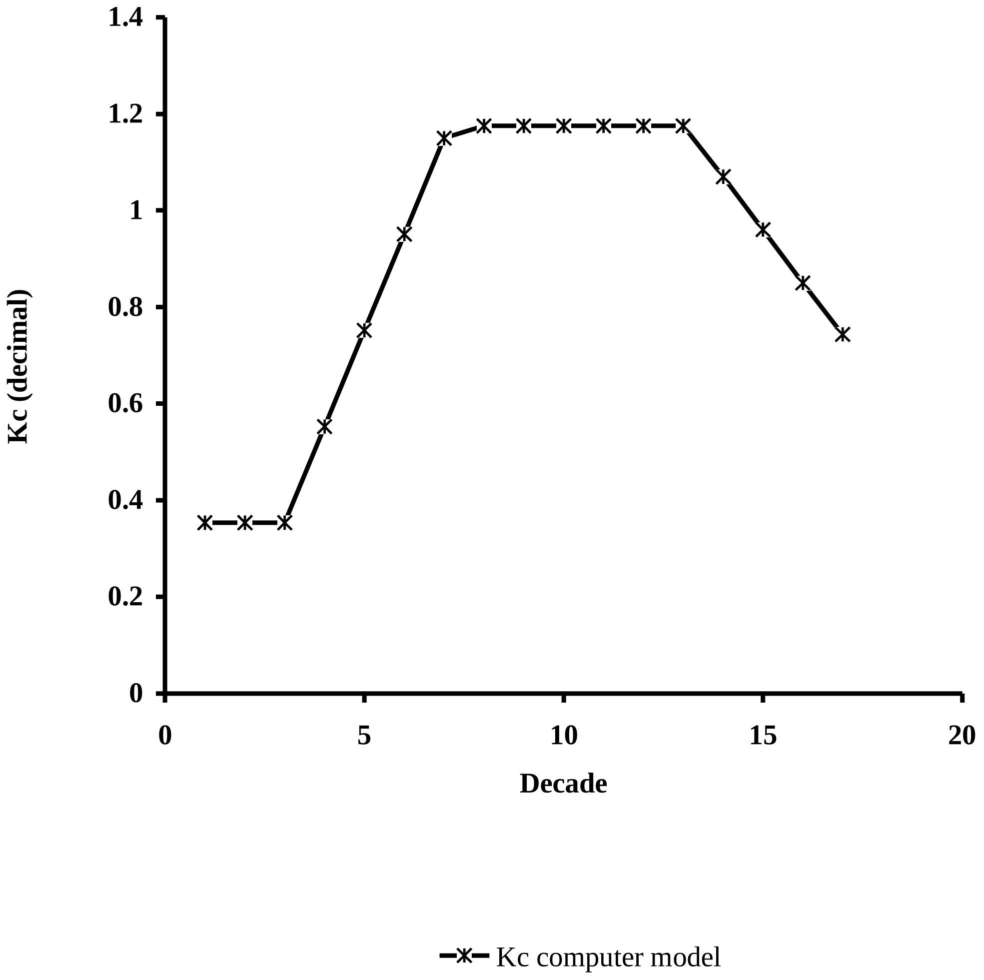

Figure 5.4a cotton Kc Computed by the model

Kc values for middle and end stages given by the FAO tables (Appendix II-table.2) are 1.15 and 0.6 respectively. The same results were reached by the model Table (5.3). Likewise cotton Kc values obtained by the two procedures are identical (Fig. 5.4b). Kc values for cotton and groundnuts at the different growth stages were calculated by both model and followed by Adam (1993) and are given in Figure (5.5 and 5.6).

It is evident from both figures that Adam procedure resulted in higher values at the initial, development and middle stages than those estimated by the model this result avails a high probability to save irrigation water for the critical demand times, September, October and November in the Gezira Scheme, if the model is adopted as a tool for indenting.

5.2 Verification of the Indenting Model

Using Ugud Input Data the model was used to estimate irrigation water need (m3/interval /feddan) and water indent (m3/decade/feddan) for cotton and ground nut crops (Tables 5.5, 5.6, 5.7 and 5.8).It is evident that there is a variation in irrigation water need through the crop growth cycle. The traditionally used estimate of 400 m^3/ interval/ feddan is not valid for ground nut and cotton. During the initial and development growth stages 400 m^3/ interval/ feddan is greater than the actual irrigation need. While during the middle stage which is the peak demand , the actual crop irrigation water need exceeds the 400 m3/interval/ feddan for cotton crop.

The water indenting for multi- crop rotation (m^3/decade) calculated by the model in comparison with the estimates calculated using the conventional methods of Gezira is depicted in Table (5.9). It is clear that considerable amounts of irrigation water are wasted specially during the initial and development stages of crop growth period. The calculated over estimation may amount to 80% .This Of course does not mean that the actual applied irrigation water is equivalent to the booked indents. The results show that at least 34% is wasted irrigation water. This considerable amount a of irrigation water can be saved for peak season demand and other industrial uses.

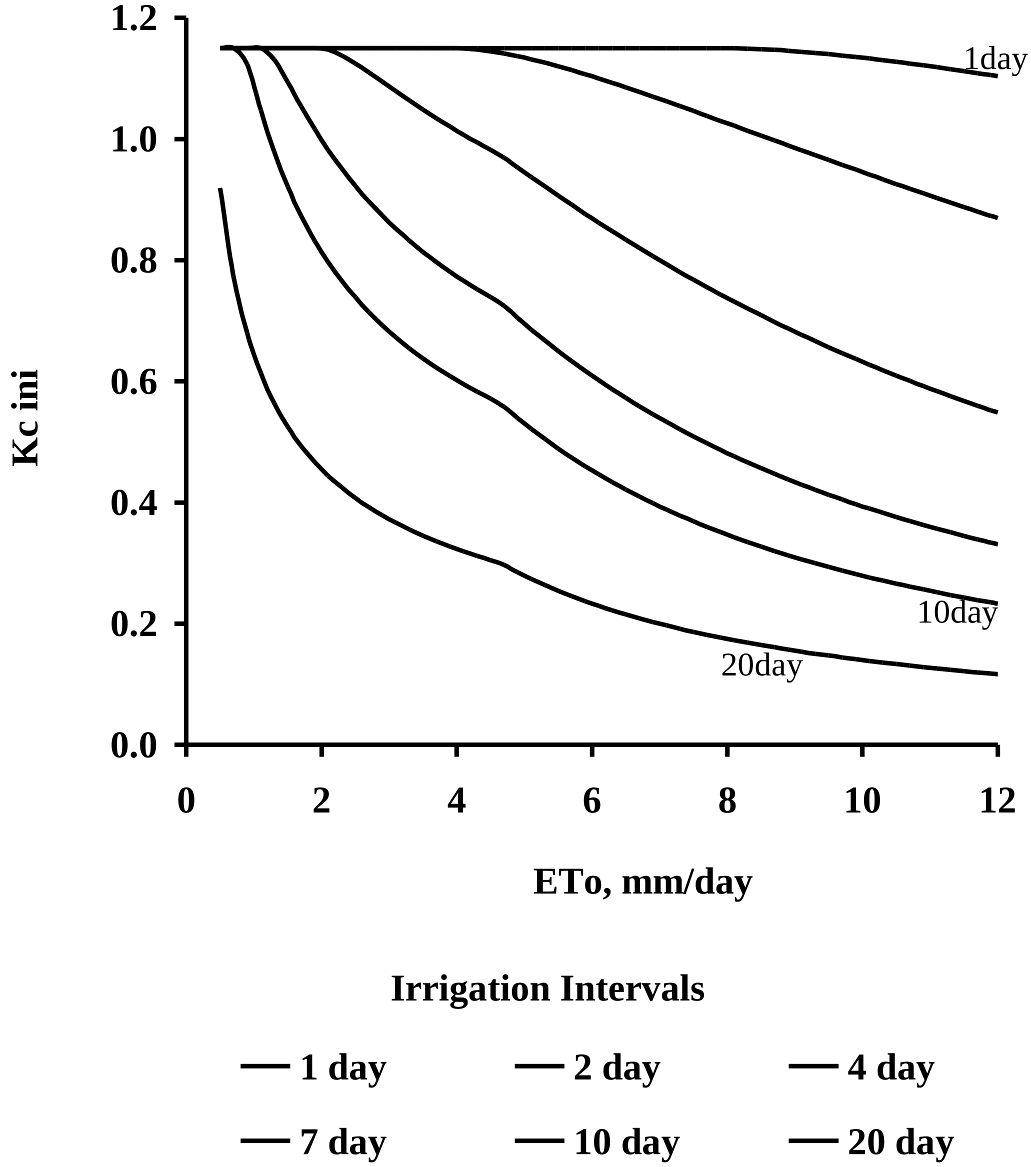

Figure 5.4b Determination of Cotton Kc as suggested by FAO (1998)

109

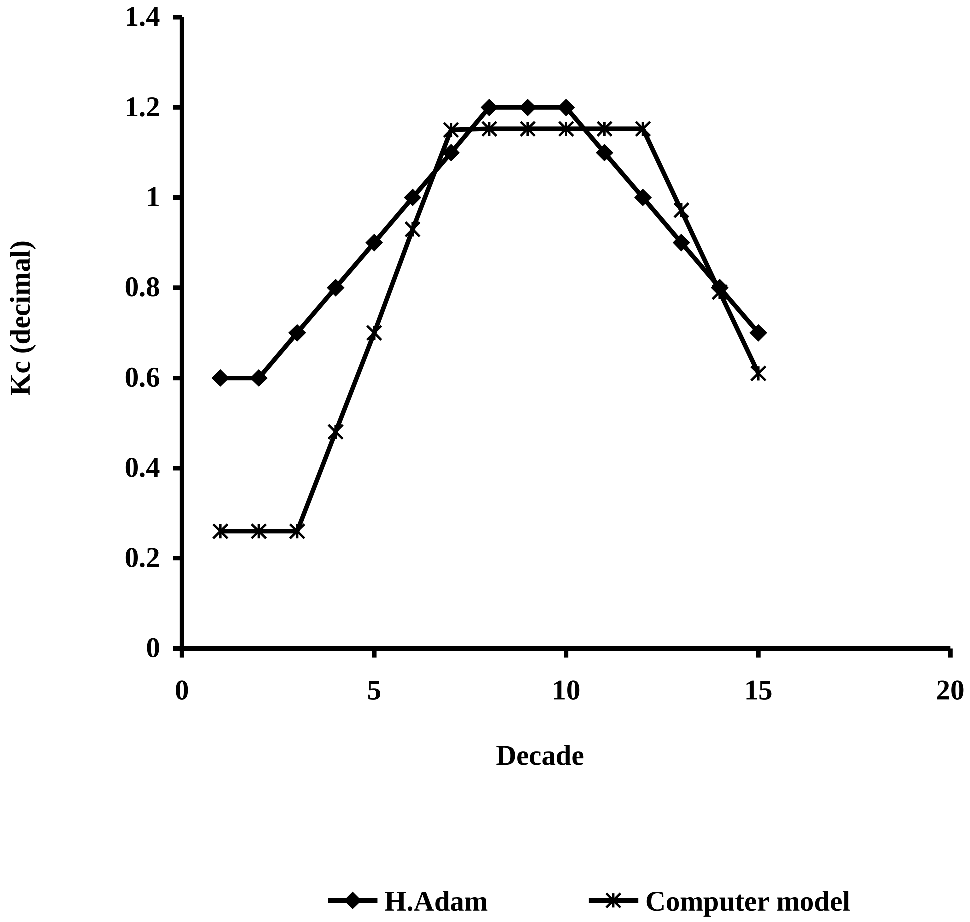

Figure 5. 5 Groundnuts Kc computer model versus Adam's procedure (1993)_

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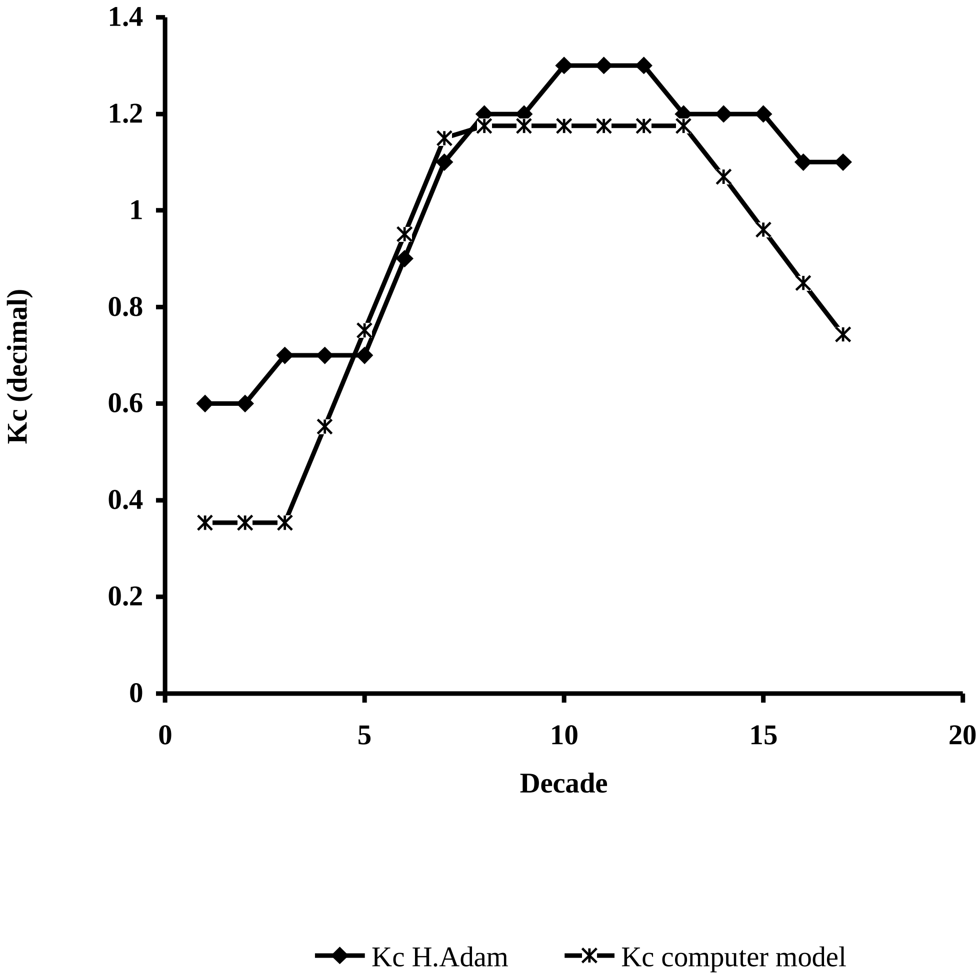

Figure 5. 6 Cotton Kc by Computer model versus Adam's procedure(1998)

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Table 5.5 Model Estimation of Irrigation Water Need per
(14 days) Interval for Cotton in Ugud Canal

	Etcm3/interval	pem^3/interval	iwnm^3/interval
01-Aug	268.1	156.4	111.7
15-Aug	134.4	146.3	0
29-Aug	214.7	99.9	114.8
13-Sep	329.4	61.2	268.2
28-Sep	430.3	42.4	387.9
11-Oct	466.2	21.5	444.8
25-Oct	482.3	12.4	470
09-Nov	496	3.1	492.9
23-Nov	476.1	1.2	474.9
07-Dec	424.6	0.2	424.4
21-Dec	358.6	0	358.6
05-Jan	304	0	304

Table 5.6 Model Estimation of Irrigation Water Need per (10 days) Decade for Cotton in Ugud Canal

	ETcm3/dec	Pem^3/decl	IWNm^3/dec
Aug	230	109.3	120.7
Aug	95.2	117.7	0
Aug	96.6	94.5	2
Sep	153.1	71.4	81.8
Sep	211.3	48.2	163.1
Sep	276.3	37.7	229.6
Oct	323.3	27.3	296.1
Oct	330.5	16.8	313.7
Oct	339.4	11.7	327.7
Nov	348.4	6.7	341.7

Nov	357.3	1.6	355.7
Nov	345.2	1.1	344.2
Dec	333.2	0.5	332.6
Dec	291.4	0	291.4
Dec	265.1	0	265.1
Jan	233.6	0	233.6
Jan	204.8	0	204.8
Jan	0	0	0

Table 5.7 Model Estimation of Irrigation Water Need per a (14 days) Interval for Groundnut in Ugud Canal

	Etcm3/interval	Pem3/interval	Iwnm3/interval
01-Jun	350.7	36.3	314.4
15-Jun	135.1	58.2	76.9
29-Jun	230.1	100.1	130.1
13-Jul	350.1	134.4	215.7
27-Jul	443.7	149.6	294.1
11-Aug	436.8	155.5	281
25-Aug	444.6	113.8	330.8
09-Sep	452.5	70	382.7
23-Sep	422.7	46.5	376.2
07-Oct	329.9	27.7	302.1

Table 5.8 Model Estimation of Irrigation Water Need per
(10 days Decade) for Groundnut in Ugud Canal

	Etcm3/dec	Pem3/dec	Iwnm3/dec
JUN	310.5	24.5	286
JUN	100.6	29.6	71
JUN	93.5	50.5	42.9
JULY	166	71.5	94.8
JULY	225.8	92.4	133.4
JULY	282.4	100.8	181.6
AUG	330.8	109.3	221.5
AUG	310.5	117.7	192.8
AUG	315	94.5	220.5
SEP	319.5	71.4	248.1
SEP	324	48.2	275.8
SEP	324	37.7	286.3
OCT	272.5	27.3	245.3
OCT	220.8	16.8	204
OCT	176.1	11.7	164.4

Table 5.9 : Determintion of the water indeting for multi-crop rotation in Ugud canal (m^3/ interval). Model estimation versus Gezira conventional method

Watering number	*Computer Model indent*	*Number of working out lets*	*Traditional Gezira indent*	*Difference percent*
1	56596.3	2	140000	59.57
2	67879.6	4	280000	75.76
3	104414.0	7	490000	78.69
4	74166.2	7	490000	84.86
5	164971.3	11	770000	78.58
6	157279.2	10	700000	77.53
7	155395.5	11	770000	79.82
8	174347.6	9	630000	72.33
9	275002.00	12	840000	67.26
10	385910.5	13	910000	57.59
11	319145.3	11	770000	58.55
12	351466.8	11	770000	54.35
13	326515.9	10	700000	53.35
14	347623.3	9	630000	44.82
15	208252.0	5	350000	40.50
16	183279.1	4	280000	34.54
17	173439.4	4	280000	38.06
18	168532.3	4	280000	39.81
Total	3694216.4		10080000	
T - test	-8.02 **			

** Highly significant at p= 0.01

5.3 Verification of the Canal Operation Model

The data of watering days for operating a distributor canal in India is given by Suryavanshi and Reddy Muhan (1985) and were used as input in MIOMCO model. Table (5.10a and b) and Figure (5.7) show the operating schedule of outlets given by Suryavanshi and Reddy Muhan (1985). Their numerical solution indicates that there are four groups of outlets watering simultaneously. This requires a canal capacity of 120 l/s Figure (5.7). The data of Suryavanshi and Reddy Muhan (1985) was formulated as an 8*8 scenario and depicted in Fig (5.8).As given in Fig (5.9),MIOMCO model solution succeeded in reducing the number of groups working simultaneously to only three groups. which results in a reduced canal capacity of 90 l/s fig (5.9). and consequently cuts down construction and operating cost of the canal by about 25%.

5.*4* Application of Canal Operation Model

5.4.1 The Case of Sunni Canal:-

As shown in table (5.11) the number of outlets working together in the same watering in the early season (watering 6) is very small and can be manually solved, thus no need to run the operation model for such a case. That is due to the limited number of grown crops namely, groundnuts and sorghum, which are at there initial and development stages that have relatively low water requirements In the peak season (watering 12) Sunni canal working days were calculated in table (5.11) and were formulated in a matrix form in (Fig 5.10and 5.11)The results show that the model gave a feasible operating schedule while the design and operating rules of canal management are maintained.

In actual operating conditions in the Gezira the inflow of outlet drops to 3500m^3/day (Farbrother, 1974). When operating the canal under the reduced outlet inflow still the model can generate a feasible solution (Fig. 5.12 and 5.13),

Table 5..10 a Data of Meena Branch Canal in. The Kukadi Irrigation Project In Maharashtra, India

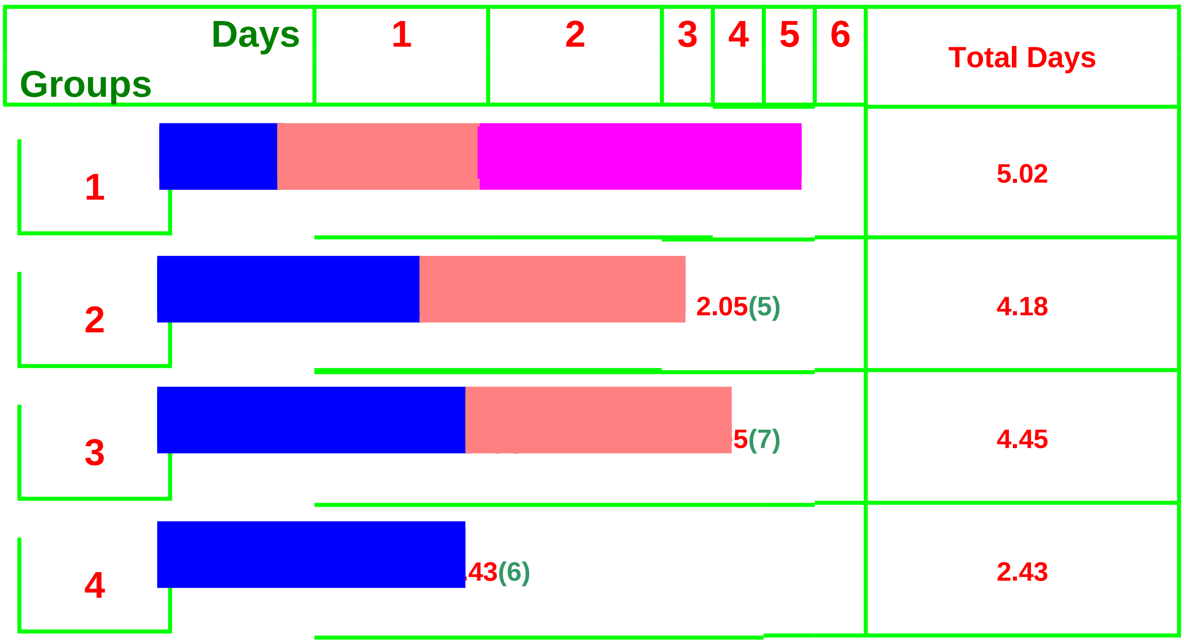
Outlet	Work day	Outlet discharge
1	0.8 days	30 L / s
2	2.13	30 L / s
3	2.40	30 L / s
4	1.72	30 L / s
5	2.05	30 L / s
6	2.05	30 L / s
7	2.43	30 L / s
8	2.05	30 L / s
9	2.5	30 L / s

Table 5.10 b Operating schedule as determined by Suryavanshi A.B and Reddy J.M

Group	Outlets opening successively one after the other
1	1 , 4 and 8
2	2 and5
3	3 and 7
4	6

Fig 5.7 Canal Outlet Operating Shedule 8 X 8

A. R. Suryavanchi and J. Muhan Reddy



Red figures represent working days

Green figures represent outlet number

Fig 5.8

Fig 5.9

Table 5.11 Sunni Early Season Working Days

Sunni Ẃ6 inflow 5000 m^3/day

Out lets	Working Days
Outlet 1	0
Outlet 2	0
Outlet 3	0
Outlet 4	1.9
Outlet 5	1.9
Outlet 6	0
Outlet 7	0
Outlet 8	5.3
Outlet 9	0
Outlet 10	0
Outlet11	0
Outlet 12	0
Outlet13	0
Outlet 14	0.9
Outlet15	0
Outlet 16	0

Fig 5.10

Fig 5.11

Fig 5.12

Fig 5.13

5-4-2 The Case of Ugud

1- Early Season

At early season (watering 6) data is formulated in a matrix form (14X14) as shown in (Fig 5.14) to be amenable for solution by MIOMCO model output operating schedule is given (Fig 5.15).This operating schedule is based on an outlet inflow rate of 5000m^3 /day .The schedule indicate that it is possible to operate the canal using only two groups which requires a canal capacity of 10000m^3 /day .

Farbrother (1974). Reported that the actual water course inflow rate is practically less than design value. It may drop down to 3500 m3/ day. Therefore the case of the reduced inflow rate. was formulated as (8X14) matrix (Fig 5.16) and consequently solved by the model to obtain the optimum operating schedule. The generated operating schedule given in Fig (5.17) show that under such critical condition four groups of out lets (Abu XX) can operate simultaneously . These four groups require maximum canal capacity of 20,000m3/ day, which is still less than design canal capacity .

It is to be recalled that the canal is designed with a capacity capable of operating half the number of its outlets (Abu XX) together. This result implies that more area can be irrigated thus reducing the fallow area.

2- Peak season

At peak season (watering 10) Ugud data was formulated in matrix form (7 X 13) as shown in figure (5.18) and solved by the model .The operating schedule is given in figure (5.19) using an outlet inflow rate of 5000m^3/day . The schedule indicates that it is possible to operate the Minor canal at its design capacity.

Reducing the outlet inflow rate to 3500m^3/day will increase the outlet working days greatly, table (5.12). When data is subjected to model as shown in Figure (5.20), the result was an infeasible solution as shown in Fig. (5.21). but if the outlet working hours per day are extended to18 hours a practical operation schedule is possible. It is worth while to mention that the outlets are 24 hours open at the present time.

Fig 5.14

Fig. 5.15

Fig. 5.16

Fig. 5.17

Fig. 5.18

Fig. 5.19

Table 5.12 Ugud working days for w10- inflow 3500 m^3/day

Out lets	Working Days
Outlet 1	10.4
Outlet 2	10.4
Outlet 3	10.1
Outlet 4	10.1
Outlet 5	9.9
Outlet 6	7.1
Outlet 7	7.1
Outlet 8	8.7
Outlet 9	8.7
Outlet 10	9.6
Outlet 11	9.6
Outlet 12	6.8
Outlet 13	6.8

Fig. 5.20

Fig 5.21

Fig 5.21 : Ugud Watering 10 Outlet Inflow Rate 3500M3/ day

Optimization Report Invisible Solution

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What'sBest! 6.0 Status Report

  Solver memory allocated:   16384




  Model Type: LINEAR / INTEGER
    CLASSIFICATION STATISTICS      Current /    Maximum
    ---------------------------------------------------
    Numeric                            336 /      10000
    Adjustable                          91 /       2000
    Constraints                         20 /       1000
    Integers                            91 /        200
    Optimizable                        132
    Nonlinear                            0 /        200
    Coefficients                       334
  Best integer value: NONE @ 0 tries. Theoretical limit: - 0.10000E+31
  Solution Status: NO FEASIBLE SOLUTION FOUND.
  There is no solution that satisfies all of the constraints.
  Check to make sure all of the constraints were properly
  formulated.  Consider easing constraints in the returned
  model that are either not satisfied or tight.
  WARNING: The answer returned is not feasible, therefore the
  value of the objective function is NOT optimal. The solution
  returned is only for the purpose of illustrating a scenario
  with violated constraints so the model can be corrected.
  Solution Time:    0 Hours  0 Minutes  1 Seconds
  End of report.
```

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1- Conclusoin

Sudan Meteorological data format was used as direct input to calculate ETo using Penman-Montieth equation. Actual vapour pressure“ea” was calculated from temperature and relative humidity data. Wind speed in miles per hour at $U_{15}$was also entered as it is.

ET_o was computed by model and the .results are shown in a graphical form and statistical paired t-test .

The calculated Kcin differs significantly from that of Farbrother’s (19) and Adam’s(1993) especially during the initial stage .

Significantly lower Kc values result in considerable water savings during early season . These savings can be made use of during the peak demand period for agricultural expansion and industrial uses.

Anew procedure for indenting based on demand is used under diversified cropping system.

The model was found to be valid when compared to published data

The model was applied successfully for canal operation and gave good advice during the early and peak demand seasons of Sunni Minor and Ugud canal which resembls wet central Gezira and the northern dry Gezira respectively.

Optimization of canal operation was performed at two levels of FOP inflow:The designed inflow of 5000m^3/day and 3500m^3/day –(actual inflow). The results show that the model may be used as a teaching tool for capacity building

6.2 – Recommendations

The model offers a decision aid to upgrade management through better indenting and better canal operation.

Since the program was made user friendly, it provides a means for management transfer to water user associations

Future database is needed concerning information such as crop growth stages, root depth particularly of main crops should be worked out.

To implement such model further research on gate calibration is required.

This model is targeted towards better indenting and management at the level of the Minor canals Further research work within Minor gates control is needed as well as water management at the farm level for appropriate complete perfomance..

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Appendices

Appendix I

Steps for calculating Eto using Penman-Montieth equation

$$ETo = \frac{0.408\,\Delta\,(Rn - G) + \gamma \left(\frac{900}{T + 273}\right) U_2 \;(e_s - e_a)}{\Delta + [\,\gamma\,(1 + 0.34\,U_2)]}$$

Where:

ET_o = Reference Evapotranspiration (mm day^{-1}),

R_n = Net radiation at the crop surface (MJ m^{-2} day^{-1}),

G = Ground heat flux density (MJ m^{-2} day^{-1}),

U_2 = Wind speed at 2 m height (ms^{-1}),

e_s = Saturation vapor pressure (kPa),

e_a = Actual vapor pressure (kPa),

$e_s - e_a$ = Saturation vapor pressure deficit (kPa),

Δ = Slope vapor pressure curve (kPa $^oC^{-1}$),

= psychometric constant (kPa $^oC^{-1}$)

Step 1

Calculation of the mean daily air temperature (T mean) in degrees Celsius or Fahrenheit can be made from one to another.

Saturation water vapor pressure (e_a T max) in (k Pa)

Saturation vapor pressure (e_s T min) in (k Pa)

Mean saturation vapor pressure (e_s avg) in (k Pa)

Using input data:

Mean maximum air temperature (T max) in (ºC)

Mean minimum air temperature (T min) in (ºC)

a) $e_s\, T\, max = 0.611\, e^{x\, max}$

$$x\, max = \frac{17.27\, (T\, max)}{T\, max + 273.3}$$

b) $e_s\, T\, min = 0.611\, e^{x\, min}$

$$x\, min = \frac{17.27\, (T\, min)}{T\, min + 273.3}$$

c) $$e_s\, avg = \frac{e_s\, T\, max + T\, min}{2}$$

d) $$T\, mean = \frac{T\, max + T\, min}{2}$$

Step 2

Calculation of the slope of saturation vapor pressure curve (Δ) at air temperature (T) in (kPa ºC^{-1}).

Using input data:- e_s avg and T mean.

$$\Delta = \frac{4099\, e_s}{(T\, mean + 237.3)^2}$$

$$= \frac{4099\left(0.6108\, \exp\left[\frac{17.27\, T}{T+237.3}\right]\right)}{(T + 237.3)^2}$$

T: air temperature (ºC)

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

Step 3

Calculation of psychometric constant (γ) in (kPa $^oC^{-1}$).

Using input data:

Elevation above sea level (Z) in (m) and (T mean)

$$\gamma = \frac{0.00163 \ p}{\lambda}$$

a) $$p = \frac{101.3 \ (293 - 0.0065 \ Z)}{293}$$

b) $\lambda = 2.501 - [\ 2.361 * 10]^{-3} * T \ mean$

p = atmospheric pressure (kPa)

λ = latent heat of vaporization (kPa)

Step 4

Calculation of mean actual water vapor pressure (e_a avg) in (kPa)

Using input data:

- RH mean: Mean relative humidity (RH) in (percent)
- e_s avg; e_s T max; e_s T max

(a) $$RH \ mean = \frac{RH \ max + RH \ min}{2}$$

(b) $$e_a \ avg = \frac{RH \ mean}{\frac{50}{e_a \ T \ max} + \frac{50}{e_a \ T \ min}}$$

Step 5

Calculation of saturation vapor pressure deficit (e_s - e_a) in (kPa)

Using input data: e_s avg and e_a avg

= (e_s avg - e_a avg)

Step 6

Calculation of the number of the day in the year (J)(1 ⟶ 365 or 366)

Using input data:

Number of the month in the year (M) (1 ⟶ 12)

J = (30.5 M – 14.6)

The value of (J) is an integer

Step 7

Calculation of:

The inverse relative distance Earth-Sun (dr)

δ the solar declination (δ)

Using input data: (J) Julian day.

$$dr = 1 + 0.033 \cos\left(\frac{2\pi J}{365}\right)$$

$$dr = (1 + 0.033 \cos(0.0172 J)$$

$$\delta = 0.409 \sin\left[\frac{2\pi J - 1.39}{365}\right]$$

$$\delta = 0.409 \sin (0.0172 J - 1.39)$$

(J) in radians

Step 8

Calculation of:

The sunset hour angle: ωs:

Using input data:

Latitude Qr

Solar declination angle δ

$\omega s = \arccos (- \text{Tan } Qr * \text{Tan } \delta)$

Step 9

Calculation of relative sunshine duration ($^n/_N$) and day light hours (N)

Using input data: - sunset hour angle (ωs) and actual duration of sunshine (n)

a) $N = 7.64 * \omega s$

b) Relative sunshine duration $= \dfrac{n}{N}$

Step 10

Calculation of extraterrestrial radiation (Ra) in (MJ m^{-2} min^{-1})

using input data:

dr, ωs, Qr, and δ

$Ra = 37.6\ dr\ [\ (\omega s \sin Qr \sin \delta) + (\cos Qr \cos \delta \sin \omega s)\ ]$

dr and ωs are in radian

Step 11

Calculated of solar or shortwave radiation (Rs) in (MJ m^{-2} day^{-1})

using input data:

Ra and $\frac{n}{N}$

$$Rs = \left(0.25 + 0.5\frac{n}{N}\right) Ra$$

Step 12

Calculation of net solar or net shortwave radiation (Rns) in (MJ m^{-2} day^{-1})

using input data: Rs

$$Rns = 0.77\ Rs$$

Step 13

Calculation of net long wave radiation (Rnl) in (MJ m^{-2} day^{-1})

using input data:

$\frac{n}{N}$, e_a, T max, k, T min, k

Where: T max k = T max + 273.16

T min k = T min + 273.16

$$Rnl = -2.45 * 10^{-9} \left(0.9\frac{n}{N} + 0.1\right)\left(0.34 – 0.14\sqrt{ea}\right)\left(T\ max\ k^4 + T\ min\ k^4\right)$$

Step 14

Calculation of net radiation (Rn) in (MJ m^{-2} day^{-1})

using input data:

Rns and Rnl

$$Rn = (Rns – Rnl)$$

Step 15

Substitute calculated values in ETo equation.

$$ETo = \frac{0.408\,\Delta\,(Rn - G) + \gamma\left(\frac{900}{T+273}\right) U_2 \quad (e_s - e_a)}{\Delta + [\gamma(1 + 0.34\,U_2)]}$$

Calculation sheet for ETo (FAO Penman-Montieth) using meteorological data.

Parameters

Tmax		ºC			
Tmin		ºC	Tmean = (Tmax + Tmin)/2		ºC
Tmean		ºC	Δ (Table 2.4 of Annex 2)		kPa/ ºC
Altitude		M	γ (Table 2.2 of Annex 2)		kPa/ ºC
u_2		m/s	$(1 + 0.34\ u_2)$		
$\Delta / [\Delta + \gamma\ (1 + 0.34\ u_2)]$					
$\gamma / [\Delta + \gamma (1 + 0.34\ u_2)]$					
$[900 / (Tmean + 273)]\ u_2$					
Vapour pressure deficit:					
Tmax		ºC	E^o(Tmax) (Table 2.3)		kPa
Tmin		ºC			kPa
Saturation vapour pressure $e_s = [(e^o\ (Tmax) + e^o\ (Tmin)]/^2$					kPa
e_a derived from dew point temperature:					
Tdew		ºC	$e_a = e^o$ (Tdew) (Table 2.3)		kPa
OR e_a derived from maximum and minimum relative humidity:					
RHmax		%	e^o (Tmin) RHmax/100		kPa
RHmin		%	e^o (Tmax) Rhmin/100		kPa
			e_a (average)		kPa
OR e_a derived from maximum relative humidity: (recommended if there are errors in Rhmin)					
RHmax		%	$e_a = e^o$ (Tmin) RHmax/100		kPa
OR e_a derived from mean relative humidity: (less recommended due to non-linearities)					
RHmean		%	$e_a = e_s$ RHmean/100		kPa
Vapour pressure deficit			$(e_s - e_a)$		kPa

Latitude	**Radiation**				
Day			Ra (Table 2.6)		MJ m^{-2} d^{-1}
Month			N (Table 2.7)		Hours
N		Hours	n/N		
If no R_2 data available: $R_s = (0.25 + 0.50\ n/N)\ R_a$					
R_s / R_{so}					
$R_{ns} = 0.77\ R_s$					MJ m^{-2} d^{-1}
Tmax			σ Tmax.K^4 (Table 2.8)		MJ m^{-2} d^{-1}
Tmin			σ Tmin.K^4 (Table 2.8)		MJ m^{-2} d^{-1}
$(\sigma \text{ Tmax.}K^4 + \sigma \text{ Tmin.}K^4)/2$					MJ m^{-2} d^{-1}
e_a		kPa	$(0.34 - 0.14 \sqrt{e_a})$		
R_s/R_{so}			$(1.35\ R_s/R_{so} - 0.35)$		
$R_{n1} = (\sigma \text{ Tmax.}K^4 + \sigma \text{ Tmin.}K^4)/2\ (0.34 - 0.14\sqrt{e_a})\ (1.35\ R_s/R_{so} - 0.35)$					MJ m^{-2} d^{-1}
$R_n = R_{ns} - R_{n1}$					MJ m^{-2} d^{-1}
Tmonth		ºC	Gday (assume)		MJ m^{-2} d^{-1}
Tmonth-1		ºC	Gmonth = 0.14 (Tmonth-Tmonth-1)		MJ m^{-2} d^{-1}
$R_n - G$					MJ m^{-2} d^{-1}
$0.408\ (F_n - G)$					mm/day
Grass reference Evapotranspiration					
$\dfrac{\Delta}{\Delta + \gamma(1 + 0.34u_2)}\ [0.408\ (R_n - G)]$					mm/day
$\dfrac{\gamma}{\Delta + \gamma(1 + 0.34\ u_2)}\ \dfrac{900}{T + 273}\ u_2\ (e_s - e_a)$					mm/day
$ETo = \dfrac{0.408\ \Delta\ (R_n - G) + \gamma\ \dfrac{900}{T + 273}\ u_2\ (e_s - e_a)}{\Delta + \gamma(1 + 0.34\ u_2)}$					mm/day

Farbrother crop-water-requirements in cubic meters per feddan per day for Acala cotton .Farbrother(1977).

	Actually planted in these periods				
	Jul 21-31	**Aug 1-10**	**Aug 11-20**	**Aug 21-31**	**Sep 1-10**
Jul. 21-31	PD				
Aug 1-10	14.3	PD			
Aug 11-20	13.6	13.6	PD		
Aug 21-31	15.8	13.8	13.8	PD	
Sep 1-10	19.2	16.3	14.3	14.3	PD
Sep 11-20	24.6	19.4	16.5	14.5	14.5
Sep 21-30	28.7	24.6	19.4	16.5	14.5
Oct 1-10	32.0	28.3	24.3	19.2	16.3
Oct 11-20	33.2	31.0	27.4	23.5	18.6
Oct 21-31	32.3	32.3	30.1	26.6	22.9
Nov 1-10	31.5	31.2	31.2	29.1	25.7
Nov 11-20	30.2	30.5	30.2	30.2	28.2
Nov 21-30	26.8	29.3	29.5	29.3	29.3
Dec 1-10	21.6	25.8	28.2	28.4	28.2
Dec 11-20	17.0	20.9	25.0	27.2	27.5
Dec 21-30	15.6	17.2	21.1	25.2	27.5
Jan 1-10	16.2	15.7	17.3	21.2	25.4
Jan 11-20	18.8	16.4	16.0	17.6	21.6
Jan 21-31	22.7	20.0	17.6	17.1	18.9
Feb 1-10	26.9	24.2	21.5	18.8	18.3
Feb 11-20	28.6	28.6	25.7	25.7	20.0
Feb 21-28	29.8	29.8	29.8	29.8	26.8
Mar 1-10	31.1	31.1	31.1	31.1	31.1
Mar 11-20	31.9	31.9	31.9	31.9	31.9
Mar 21-31	33.2	33.2	33.2	33.2	33.2

Crop-water-requirements in m^3/fed/day.
Cotton (All barbadense varieties).

	Actually planted in these periods					
	Jul. 11-20	Jul. 21-31	Aug. 1-10	Aug. 10-20	Aug. 21-31	
Jul. 11-20	PD					
" 21-31	15.4	PD				
Aug. 1-10	14.3	14.3	PD			
" 11-20	14.4	13.6	13.6	PD		
" 21-31	16.1	14.7	13.8	13.8	PD	
Sep. 1-10	18.6	16.6	15.2	14.3	14.3	
" 11-20	23.5	18.8	16.8	15.4	14.5	
" 21-30	29.3	23.5	18.8	16.8	15.4	
Oct. 1-10	31.5	28.9	23.2	18.6	16.6	
" 11-20	31.5	30.5	28.0	22.4	18.0	
" 21-30	31.5	30.5	29.6	27.2	21.8	
Nov.1-10	31.2	30.4	29.4	28.6	26.3	
" 11-20	29.7	30.2	29.5	28.5	27.7	
" 21-30	28.3	28.8	29.3	28.5	27.6	Liable to reduction in a 'short' season; and to inflation in a 'long' season.
Dec.1-10	27.0	27.3	27.7	28.2	27.5	
" 11-20	25.2	26.3	26.3	26.8	27.2	
" 21-31	22.9	25.4	26.3	26.6	27.0	
Jan. 1-10	21.9	23.1	25.6	26.6	26.8	
" 11-20	20.2	22.3	23.5	26.1	27.0	
" 21-31	19.4	21.7	23.9	25.2	27.0	
Feb.1-10	18.3	20.7	23.1	25.6	26.9	
" 11-20	19.4	19.4	22.0	24.6	27.2	
" 21-28		20.3	20.3	22.9	25.6	
Mar.1-10			21.1	21.1	23.9	
" 21-20				21.7	21.7	

Crop-water-requirements in m^3/fed/day.

Wheat mexi-varieties.

	Actually planted in these periods					
	Oct. 11-20	Oct. 21-31	Nov. 1-10	Nov. 11-20	Nov. 21-30	Dec. 1-10
Oct. 11-20	PD					
“ 21-31	13.4	PD				
Nov. 1-10	18.2	13.0	PD			
“ 11-20	22.9	17.6	12.6	PD		
“ 21-30	26.1	22.2	17.1	12.2	PD	
Dec. 1-10	28.2	25.1	21.4	16.4	11.8	PD
“ 11-20	27.9	27.2	24.3	20.6	15.9	11.4
“ 21-31	25.9	28.2	27.5	24.5	20.8	16.0
Jan. 1-10	21.9	26.1	28.4	27.7	24.7	21.0
“ 11-20	18.8	22.3	26.6	28.9	28.2	25.1
“ 21-31		20.2	23.9	28.5	31.0	30.2
Feb. 1-10		18.8	21.5	25.6	30.4	33.1
“ 11-20		15.1	16.1	22.9	27.2	32.3
“ 21-28		13.4	14.3	17.3	23.8	28.3
Mar. 1-10						24.9

Crop-water-requirements in m^3/fed/day.

Dura short and medium term varieties (90-110 days).

	Actually planted in these periods

	Jun. 21-30	Jul. 1-10	Jul. 11-20	
Jan. 21-30	PD			
Jul. 1-10 “ 11-20 “ 21-31	17.8 18.3 21.5	PD 16.6 16.9	 PD 15.4	
Aug. 1-10 “ 11-20 “ 21-31	26.9 30.0 31.0	20.0 25.7 30.5	15.7 19.1 26.0	
Sep. 1-10 “ 11-20 “ 21-30	31.5 31.9 30.2	32.0 31.9 31.9	31.5 32.5 31.9	
·····························				→
Oct. 1-10 “ 11-20 “ 21-31	25.4 18.0	29.7 24.6 17.5	31.5 28.8 23.9	Arbitrary date of “water-stop”, according to SGB administrative circulars to Block Inspectors.
Nov. 1-10			16.9	Water may be with-held over the last 20 days, without significant loss of yield.

Crop-water-requirements in m^3/fed/day.
Groundnut and all long-term spreading varieties.

	Actually planted in these periods					
	Jun. 1-10	Jun. 11-20	Jun. 21-30	Jul. 1-10	Jul. 11-20	
Jun. 1-10	PD					
" 11-20	20.2	PD				
" 21-30	20.5	19.3	PD			
Jul. 1-10	21.1	18.9	17.8	PD		
" 11-20	22.6	19.6	17.6	16.6	PD	
" 21-31	23.9	20.9	18.1	16.3	15.4	
Aug. 1-10	26.0	22.3	19.4	16.9	15.2	
" 11-20	27.6	24.8	21.3	18.6	16.1	
" 21-31	30.2	28.0	25.2	21.6	18.8	
Sep. 1-10	31.5	31.2	28.9	26.0	22.3	
" 11-20	31.0	31.9	31.6	29.3	26.4	
" 21-30	29.9	31.0	31.9	31.6	29.3	
Oct. 1-10	25.4	29.5	30.6	31.5	31.2	
" 11-20	22.2	24.6	28.5	29.6	30.5	
" 21-30		21.5	23.9	27.7	28.8	Arbitrary date of "water-stop", according to SGB administrative circulars.
Nov. 1-10			20.8	23.1	26.8	
" 11-20				20.2	22.4	
" 21-30					19.5	
Dec. 1-10						
" 11-20						GRS research now recommends "with holding water" after 130 days. (Ref. Dr. H.Ishag)

Appendix II

Lengths of crop development stages* for various planting periods and climatic regions (days).

Crop	**Init. (L_{ini})**	**Dev. (L_{dev})**	**Mid. (L_{mid})**	**Late. (L_{late})**	**Total**	**Plant date**	**Region**
a. Small vegetables							
Broccoli	35	45	40	15	135	Sept	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi) Arid
	25	40	45	15	125	April	Mediterranean
	30	55	105	20	210	Jan	(Semi) Arid
Crucifers [1]	20	30	20	10	80	Apr	Mediterranean
	25	35	25	10	95	Feb	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	Oct	Arid Region
	30	55	55	40	180	March	Calif. USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apri;Sep/Oct	Mediterranean
	20	30	40	10	100	Nov	Arid Region
Radish	5	10	15	5	35	Mar/Apr	Medit.; Europe
	10	10	15	5	40	Winter	Arid Region
b. Vegetables – Solanum Family (*Solanaceae*)							
Egg plant	30	40	40	20	130/1	Oct	Arid Region
	30	45	40	25	40	May/June	Mediterranean
Sweet	25/30	35	40	20	125	Apr/June	Europe and Medit.
peppers (bell)	30	40	110	30	210	Oct	Arid Region
Tomato	30	40	40	25	135	Jan	Arid Region
	35	40	50	30	155	Apr/May	Calif., USA
	25	40	60	30	155	Jan	Calif. Desert, USA
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
c. Vegetables – Cucumber Family (cucurbitaceae)							
Cantaloupe	30	45	35	10	120	Jan	Calif., USA
	10	60	25	25	120	Aug	Calif., USA
Cucumber	20	30	40	15	105	June/Aug	Arid Region
	25	35	50	20	130	Nov/Feb	Arid Region
Pumpkin,	20	30	30	20	100	Mar, Aug	Mediterranean
Winter squash	25	35	35	25	120	June	Europe
Squash,	25	35	25	15	100	Apr; Dec	Medit.; Arid Reg.
Zucchini	20	30	25	15	90	May/June	Medit.; Europe

* Lengths of crop development stages provided in this table are indicative of general conditions, but may vary substantially from region to region, with climate and cropping conditions, and with crop variety. The user is strongly encouraged to obtain appropriate local information.

[1] .

Table continued.

Crop	**Init. (L_{ini})**	**Dev. (L_{dev})**	**Mid. (L_{mid})**	**Late. (L_{late})**	Total	Plant date	Region
Sweet melons	25	35	40	20	120	May	Mediterranean
	30	30	50	30	140	March	Calif., USA
	15	40	65	15	135	Aug	Calif. Desert, USA
	30	45	65	20	160	Dec/Jan	Arid Region
Water melons	20	30	30	30	110	April	Italy
	10	20	20	30	80	Mar/Aug	Near East (desert)
d. Roots and Tubers							
Beets, table	15	25	20	10	70	Apr/May	Mediterranean
	25	30	25	10	90	Feb/Mar	Mediterranean & Arid
Cassava: year 1	20	40	90	60	210	Rainy	Tropical regions
year 2	150	40	110	60	360	Season	
Potato	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid Climate
	25	30	45	30	130	May	Continental Climate
	30	35	50	30	145	April	Europe
	45	30	70	20	165	Apr/May	Idaho, USA
	30	35	50	25	140	Dec	Calif. Desert, USA
Sweet potato	20	30	60	40	150	Apr	Mediterranean
	15	30	50	30	125	Rainy season	Tropical regions
Sugarbeet	30	45	90	15	180	Mar	Calif.; USA
	25	30	90	10	155	June	Calif.; USA
	25	65	100	65	255	Sept	Calif. Desert, USA
	50	40	50	40	180	Apr	Idaho, USA
	25	35	50	50	160	May	Mediterranean
	45	75	80	30	230	Nov	Mediterranean
	35	60	70	40	205	Nov	Arid Regions
e. Legumes (*Leguminosae*)							
Beans (green)	20	30	30	10	90	Feb/Mar	Calif., Mediterranean
	15	25	25	10	75	Aug/Sep	Calif., Egypt, Lebanon
Beans (dry)	20	30	40	20	110	May/June	Continental Climates
	15	25	35	20	95	June	Pakistan, Calif.
	25	25	30	20	100	June	Idaho, USA
Faba bean,	15	25	35	15	90	May	Europe
broad bean	20	30	35	15	100	Mar/Apr	Mediterranean
- dry	90	45	40	60	235	Nov	Europe
- green	90	45	40	0	175	Nov	Europe
Green gram, cowpeas	20	30	30	20	110	March	Mediterranean
Groundnut	25	35	45	25	130	Dry season	West Africa
	35	35	35	35	140	May	High Latitudes
	35	45	35	25	140	May/June	Mediterranean
Lentil	20	30	60	40	150	April	Europe
	25	35	70	40	170	Oct/Nov	Arid Region
Peas	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
	35	25	30	20	100	April	Idaho, USA
Soybeans	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	140	May	Central USA
	20	25	75	30	150	June	Japan
f. perennial vegetables (with winter dormancy and initially bare or mulched soil)							
Artichoke	40	40	250	30	360	Apr (1st yr)	California
	20	25	250	30	325	May (2nd yr)	(cut in May)
Asparagus	50	30	100	50	230	Feb	Warm winter
	90	30	2000	45	365	Feb	Mediterranean

Table cont.

Crop	**Init. (L_{ini})**	**Dev. (L_{dev})**	**Mid. (L_{mid})**	**Late. (L_{late})**	Total	Plant date	Region
g. Fibre crops							
Cotton	30 45 30 30	50 90 50 50	60 45 60 55	55 45 55 45	195 225 195 180	Mar-May Mar Sept April	Egypt; Pakistan; Calif. Calif. Desert, USA Yemen Texas
Flax	25 30	35 40	50 100	40 50	150 220	April Oct	Europe Arizona
h. Oil crops							
Castor beans	25 20	40 40	65 50	50 25	180 135	March Nov	(Semi) Arid Climates Indonesia
Safflower	20 25 35	35 35 55	45 55 60	25 30 40	125 145 190	Apr Mar Oct/Nov	California, USA High Latitudes Arid Region
Sesame	20	30	40	20	100	June	China
Sunflower	25	35	45	25	130	April/May	Medit.; California
i. Cereals							
Barley/Oats/ Wheat	15 20 15 40 40	25 25 30 30 60	50 60 65 40 60	30 30 40 20 40	120 135 150 130 200	Nov March/Apr July Apr Nov	Central India 35-45 ºL East Africa
Winter Wheat	20 20[2] 30 160	50 60[2] 140 75	60 70 40 75	30 30 30 25	160 180 240 335	Dec Dec Nov Oct	Calif. Desert, USA Calif., USA Mediterranean Idaho, USA
Grains (small)	20 25	30 35	60 65	40 40	150 165	April Oct/Nov	Mediterranean Pakistan; Arid Reg.
Maize (grain)	30 25 20 20 30 30	50 40 35 35 40 40	60 45 40 40 50 50	40 30 30 30 30 50	180 140 125 125 150 170	April Dec/Jan June Oct April April	East Africa (alt.) Arid Climate Nigeria (humid) India (dry, cool) Spain (spr, sum.); Calif Idaho, USA
Maize (sweet)	20 20 20 30	20 25 30 30	30 25 50/30 30	10 10 10 10[3]	80 80 90 110	March May/June Oct/Dec April	Philippines Mediterranean Arid Climate Idaho, USA
	20	40	70	10	140	Jan	Calif. Desert, USA
Millet	15 20	25 30	40 55	25 35	105 140	June April	Pakistan Central USA

2 These periods for winter wheat will lengthen in frozen climates according to days having zero growth potential and wheat dormancy. Under general conditions and in the absence of local data, fall planting of winter wheat can be presumed to occur in northern temperate climates when the 10-day running average of mean daily air temperature decreases to 17oC or December 1. Whichever comes first. Planting of spring wheat can be presumed to occur when the 10-day running average of mean daily air temperature increases to 5oC. spring planting of maize-grain can be presumed to occur when the 10-day running average of mean daily air temperature increases to 13oC.
3 The late season for sweet maize will be about 35 days if the grain is allowed to mature and dry.

Table continued.

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid. (L_{mid})	Late. (L_{late})	Total	Plant date	Region
Sorghum	20 20	35 35	40 45	30 30	130 140	May/June Mar/April	USA, Pakis., Med. Arid Region
Rice	30 30	30 30	60 80	30 40	140 180	Dec; May May	Tropics, Mediterranean Tropics
j. Forages							
Alfalfa, total season[4]	10	30	Var.	Var.	Var.		Last –4ºC in spring until first –4ºC in fall
Alfaalfa[4] 1st cutting cycle	10 10	20 30	20 25	10 10	60 75	Jan Apr(last –4ºC)	Calif., USA Idaho, USA
Alfalfa[4] other Cutting cycles	5 5	10 20	10 10	5 10	30 45	Mar June	Calif., USA Idaho, USA
Bermuda for seed	10	25	35	35	105	March	Calif. Desert, USA
Bermuda for hay (several cuttings)	10	15	75	35	135	-	Calif. Desert, USA
Grass pasture[4]	10	20	-	-	-		7 days before last –4ºC spring until 7 days after first –4ºC in fall
Sudan, 1st cutting cycle	25	25	15	10	75	Apr	Calif. Desert, USA
Sudan, other cutting cycles	3	15	12	7	37	June	Calif. Desert, USA
k. Sugar Cane							
Sugarcane, virgin	35 50 75	60 70 105	190 220 330	120 140 210	405 480 720		Low Latitudes Tropics Hawaii, USA
Sugarcane, ratoon	25 30 35	70 50 105	135 180 210	50 60 70	280 320 420		Low Latitudes Tropics Hawaii, USA
l. Tropical Fruits and Trees							
Banana 1st yr	120	90	120	60	390	Mar	Mediterranean
Banana 2nd yr	120	60	180	5	365	Feb	Mediterranean
Pineapple	60	120	600	10	790		Hawaii, USA
m. Grapes and Berries							
Grapes	20 20 20 30	40 50 50 60	120 75 90 40	60 60 20 80	240 205 180 210	April Mar May April	Low Latitudes Calif., USA High Latitudes mid Latitudes (wine)
Hops	25	40	80	10	155	April	Idaho, USA
n. Fruit Trees							
Citrus	60	90	120	95	365	Jan	Mediterranean
Deciduous Orchard	20 20 30	70 70 50	90 120 130	30 60 30	210 270 240	March March March	High Latitudes Low Latitudes Calif., USA

[4] In climates having killing frosts, growing seasons can be estimated for alfalfa and grass as:
alfalfa: last –4ºC in spring until first –4ºC in fall (Everson, D.O., M. Faubion and D.E. Amos 1978. -Freezing temperatures and growing seasons in Idaho. – Univ. Idaho Agric. Exp. station bulletin 494. 18 p.
grass: 7 days before last –4ºC in spring and 7 days after last –4ºC in fall (Kruse E.G. and Haise, H.R. 1974. "Water use by native grasses in high altitude Colorado meadows" USDA Agric. Res. Service, Western Region Report ARS-W-6-1974. 50 p.

Source: FAO Irrigation and Drainage Paper No. 56, 1998

Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates (RH_{min} = 45%, u_2 m/s) for use with the FAO Penman-Monteith ET_o.

Crop	$K_{c\ ini}$[1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h) (m)
a. Small Vegetables	0.7	1.05	0.95	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions – dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables - Solanum Family (*Solanaceae*)	0.6	1.15	0.80	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables – Cucumber Family (*Cucurbitaceae*)	0.5	1.00	0.80	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber - Fresh Market	0.6	1.00[2]	0.75	0.3
- Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	0.5	1.10	0.95	
Beets, table		1.05	0.95	0.4
Cassava - year 1	0.3	0.80[3]	0.30	1.0
- year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70[5]	0.5

[1] These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\ ini}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30, or Equation 7-3 in Anne 7, or using the dual $K_{cb\ ini} + K_e$.

[2] Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_c values need to be taken. For green beans, peppers and cucumbers, 1.15 can be taken, and for tomatoes, dry beans and peas, 1.20. Under these conditions h should be increased also.

[3] The midseason values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\ end}$ values account for domancy during the dry season.

[4] The $K_{c\ end}$ value for potatoes is about 0.40 for long season potatoes with vine kill.

[5] The $K_{c\ end}$ value is for no irrigation during the last month of the growing season. The $K_{c\ end}$ value for sugar beets is higher, up to 1.0, when irrigation or significant rain occurs during the last month.

Table continued.

Crop	$K_{c\ ini}$[1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h)(m)
e. Legumes (*Leguminosae*)	0.4	1.15	0.55	
Beans, green	0.5	1.05[2]	0.90	0.4
Beans, dry and Pulses	0.4	1.15[2]	0.35	0.4
Chick pea		1.00	0.35	0.4
Fababean (broad bean) - Fresh - Dry/Seed	0.5 0.5	1.15[2] 1.15[2]	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[6]	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[2] 1.15	1.10 0.30	0.5 0.5
Soybeans		1.15	0.50	0.5-1.00
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	0.5	1.00	0.80	
Artichokes	0.5	1.00	0.95	0.7
Asparagus	0.5	0.95[7]	0.30	0.2-0.8
Mint	0.60	1.15	1.10	0.6-0.8
Strawberries	0.40	0.85	0.75	0.2
g. 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[8]		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	0.35	1.15	0.35	
Castorbean (*Ricinus*)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15[9]	0.35	0.6
Safflower		1.0-1.15[9]	0.25	0.8
Sesame		1.10	0.25	1.00
Sunflower		1.0-1.15[9]	0.35	2.00
i. Cereals	0.3	1.15	0.40	
Barley		1.15	0.25	1.00
Oats		1.15	0.25	1.00
Spring Wheat		1.15	0.25-0.4[10]	1.00
Sinter Wheat - with frozen soils - with non-frozen soils	0.4 0.7	1.15 1.15	0.25-0.4[10] 0.25-0.4[10]	1.00
Maize, Field (grain) (*field corn*)		1.20	0.60,0.35[11]	2.00
Maize, Sweet (sweet corn)		1.15	1.05[12]	1.5
Millet		1.00	0.30	1.5
Sorghum - grain - sweet		1.0-1.10 1.20	0.55 1.05	1.2 2.4
Rice	1.05	1.20	0.90-0.60	1.00

[6] The first $K_{c\ end}$ is for harvested fresh. The second value is for harvested dry.

[7] The K_c for asparagus usually remains at $K_{c\ ini}$ during harvest of the spears, due to sparse ground cover. The $K_{c\ mic}$ value is for following regrowth of plant vegetation following termination of harvest of spears.

[8] K_c for sisal depends on the planting density and water management (e.g., intentional moisture stress).

[9] The lower values are for rainfed crops having less dense plant populations.

[10] The higher value is for hand-harvested crops.

[11] The first $K_{c\ end}$ value is for harvest at high grain moisture. The second $K_{c\ end}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis).

[12] 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.

Table continued.

Crop	$K_{c\ ini}$[1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h) (m)
j. Forages				
Alfalfa Hay - averaged cutting effects	0.40	0.95[13]	0.90	0.70
- individual cutting periods	0.40[14]	0.20[14]	1.15[14]	0.70
- for seed	0.40	0.50	0.50	0.70
Bermuda hay - averaged cutting effects	0.55	1.00[13]	0.85	0.35
- spring crop for seed	0.35	0.90	0.65	0.40
Clover hay, Berseem - averaged cutting effects	0.40	0.90[13]	0.85	0.60
- individual cutting periods	0.40[14]	1.15[14]	1.10[14]	0.60
Rye Grass hay - averaged cutting effects	0.95	1.05	1.00	0.30
Sudan Grass hay (annual) - averaged cutting effects	0.50	0.90[14]	0.85	1.20
- individual cutting periods	0.50[14]	1.15[14]	1.10[14]	1.20
Grazing Pasture - Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10
Turf grass - cool season[15]	0.90	0.95	0.95	0.10
- warm season[15]	0.80	0.85	0.85	0.10
k. Sugar Cane	0.40	1.25	0.75	3.00
l. Tropical Fruits and Trees				
Banana - 1st year	0.50	1.10	1.00	3.00
- 2nd year	1.00	1.20	1.10	4.00
Cacao	1.00	1.05	1.05	3.00
Coffee - bare ground cover	0.90	0.95	0.95	2-3
- with weeds	1.05	1.10	1.10	2-3
Date Palms	0.90	0.95	0.95	8.00
Palm Trees	0.95	1.00	1.00	8.00
Prineapple[16] - bare soil	0.50	0.30	0.30	0.6-1.2
- with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber Trees	0.95	1.00	1.00	10.00
Tea - non-shaded	0.95	1.00	1.00	1.50
- shaded[17]	1.10	1.15	1.15	2.00
m. Grapes and Berries				
Berries (bushes)	0.30	1.05	0.50	1.50
Grapes - Table or Raisin	0.30	0.85	0.45	2.00
- Wine	0.30	0.70	0.45	1.5-2.00
Hops	0.30	1.05	0.85	5.00

[13] This $K_{c\ mid}$ coefficient for hay crops is an overall average $K_{c\ mid}$ coefficient that average K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

[14] These K_c coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods.

[15] Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermoda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced and rapid growth is not required, K_c's for turf can be reduced by 0.10.

[18] The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil. The $K_{c\ mid}$ < $K_{c\ ini}$ since $K_{c\ mid}$ occurs during full ground cover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, K_c's given can be reduced by 0.10.

[17] Includes the water requirements of the shade trees.

Table continued.

Crop	$K_{c\ ini}$[1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h) (m)
n. Fruit Trees				
Almonds, no ground cover	0.40	0.90	0.65[18]	5.00
Apples, Cherries, Pears[19]				
- no ground cover, killing frost	0.45	0.95	0.70[18]	4.00
- no ground cover, no frosts	0.60	0.95	0.75[18]	4.00
- active ground cover, killing frost	0.50	1.20	0.95[18]	4.00
- active ground cover, no frosts	0.80	1.20	0.85[18]	4.00
Apricots, Peaches, Stone Fruit[19, 20]				
- no ground cover, killing frost	0.45	0.90	0.65[18]	3.00
- no ground cover, no frosts	0.55	0.90	0.65[18]	3.00
- active ground cover, killing frost	0.50	1.15	0.90[18]	3.00
- active ground cover, no frosts	0.80	1.15	0.85[18]	3.00
Avocado, no ground cover	0.60	0.85	0.75	3.00
Citrus, no ground cover[21]				
- 70% canopy	0.70	0.65	0.70	4.00
- 50% canopy	0.65	0.60	0.65	3.00
- 20% canopy	0.50	0.45	0.55	2.00
Citrus, with active ground cover or weeds[22]				
- 70% canopy	0.75	0.70	0.75	4.00
- 50% canopy	0.80	0.80	0.80	3.00
- 20% canopy	0.85	0.85	0.85	2.00
Conifer Trees[23]	1.00	1.00	1.00	10.00
Kiwi	0.40	1.05	1.05	3.00
Olives (40 to 60% ground coverage by canopy)[24]	0.65	0.70	0.70	3-5
Pistachios, no ground cover	0.40	1.10	0.45	3-5
Walnut Orchard[19]	0.50	1.10	0.65[18]	4-5

[18] These $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$ to 0.80 for actively growing ground cover.

[19] Refer to Eq. 94, 97 or 98 and footnotes 21 and 22 for estimating K_c for immature stands.

[20] Stone fruit category applies to peaches, apricots, pears, plums and pecans.

[21] These K_c values can be calculated from Eq. 98 for K_c min = 0.15 and $K_{c\ full}$ = 0.75, 0.70 and 0.75 for the initial, mid season and end of season periods, and $f_{c\ eff} = f_c$ where f_c = fraction of ground covered by tree canopy (e.g., the sun is presumed to be directly overhead). The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. The midseason value is lower than initial and ending values due to the effects of stomatal closure during periods of peak ET. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ end}$ can be increased by 0.1 – 0.2, following Rogers *et al.* (1983).

[22] These K_c values can be calculated as $K_c = f_c\ K_{c\ ngc} + (1 = f_c)\ K_{c\ cover}$ where $K_{c\ ngc}$ is the K_c of citrus with no active ground cover (calculated as in footnote 21), $K_{c\ cover}$ is the K_c for the active ground cover (0.95), and f_c is defined in footnote 21. The value listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. Alternatively, K_c for citrus with active ground cover can be estimated directly from Eq. 98 by setting $K_{c\ min} = K_{c\ cover}$. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini,}$ $K_{c\ mid,}$ and $K_{c\ end}$ can be increased by 0.1 – 0.2, following Rogers *et al.* (1983).

For non-active or only moderately active ground cover (active indicates green and growing ground cover with LAF > about 2 to 3), K_c should be weighted between K_c for no ground cover and K_c for active ground cover, with the weighting based on the "greenness" and approximate leaf area of the ground cover.

Source: FAO Irrigation and Drainage Paper No. 56, 1998

END

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Determination of Eto with mean monthly data Given the monthly average climatic data of April of Bangkok (Thailand) located at 13° 44 N and at an elevation of 2 m:			
- - - Measured at 2m - For April For March	Monthly average daily maximum (Tmax)= Monthly average daily minimum (Tmin)= Monthly average daily vapour (ea)= Monthly average daily wind speed (u2)= Monthly average sunshine duration (n)= Mean monthly average (Tmonth,i) = Mean monthly average temperature(Tmonth,i	34.8 25.6 2.85 2 8.5 30.2 29.2	^{o} C ^{o} C kPa M/s Hours\day ^{o} C ^{o} C
Determination according to outline of box 11 (calculation sheet Eto)			
parameters			
- from table 2.4oreq.13:	Tmean = [(Tmax = 34.8)+(Tmin 25.6)]= Δ=	30.2 0.246	^{o} C kPa/ ^{o} C
From table2.1and Table2.2orEq.7 andEq.8:	Altitude = P = γ =	2.00 101.3 0.0674	M KPa KPa/ ^{o} C
-	(1+0.34 u2) =	1.68	-
-	Δ/[Δ+γ(1+0.34u2)]=0.246/[(0.246+0.0674 (1.68)]	0.685	-
-	Δ/[Δ+γ(1+0.34u2)]=0.0667/[0.246+0.0674 (1.68)] =	0.188	-
-	900/(Tmean+273)u2 =	5.94	-
Vapour pressure deficit			
From Table 2.3orEq.11:	Tmax= E(Tmax)=	34.8 5.56	^{o} C Kpa
From Table 2.3orEq.11:	Tmin E(Tmin)	25.6 3.28	^{o} C Kpa
- Given	es=(5.56+3.28)/2= ea=	4.42 2.85	Kpa Kpa
-	Vapour pressure Deficit (es-ea)=4.42-2.85)=	1.57	Kpa

Radiation (for month = April)			
From table 2.6 or 2.5 or Eq.21	J = (for 15 April) Latitud3144N=(13+44/60)= Ra=	105 13.37 38.06	- N Mjm-2day-1
N(Table2.7 orEq.34):	Daylength N=	12.31	Hours
- - - - -	n/N=(8.5/12.31)= Rs=(.25+.50(0.69))38.06= Rso=(0.75+2(2)/100000)38.06= Rs/Rso=(22.65/28.54)= Rns=0.77(22.65)=	0.69 22.65 28.54 0.79 17.44	- Mjm-2day-1 Mjm-2 day-1 - Mjm

Determination of Eto with mean monthly data Given the monthly average climatic data of April of Bangkok (Thailand) located at 13° 44 N and at an elevation of 2 m:			
-	Monthly average daily maximum (Tmax)=	34.8	ºC
-	Monthly average daily minimum (Tmin)=	25.6	ºC
-	Monthly average daily vapour (ea)=	2.85	kPa
Measured at 2m	Monthly average daily wind speed (u2)=	2	M/s
-	Monthly average sunshine duration (n)=	8.5	Hours\day
For April	Mean monthly average (Tmonth,i) =	30.2	º C
For March	Mean monthly average temperature (Tmonth,i)=	29.2	º C
Determination according to outline of box 11 (calculation sheet Eto)			
parameters			
- from table eq. :	Tmean = [(Tmax = 34.8)+(Tmin 25.6)]= Δ=	30.2 0.246	º C kPa/ º C
From table	Altitude = P = γ =	2 101.3 0.0674	M KPa KPa/ º C
-	(1+0.34 u2) =	1.68	-
-	Δ/[Δ+γ(1+0.34u2)]=0.246/[(0.246+0.0674 (1.68)]	0.685	-
-	Δ/[Δ+γ(1+0.34u2)]=0.0667/[0.246+0.0674 (1.68)] =	0.188	-
-	900/(Tmean+273)u2 =	5.94	-
Vapor pressure deficit			
From Table 2.3or Eq.11:	Tmax= E(Tmax)=	34.8 5.56	C Kpa
From Table 2.3or Eq.11:	Tmin E(Tmin)	25.6 3.28	C Kpa
- Given	Es=(5.56+3.28)/2= Ea=	4.42 2.85	Kpa Kpa
-	Vapour pressure Deficit (es-ea)=4.42-2.85)=	1.57	Kpa

Irrigated and cultivated areas of Tayba Major.

Minor	Area	Dura	Cotton	Fallow	Garden	G/nut & wheat	Water intent
Tayba left	842	210	140	177	140	175	20,000
El Suni	1227	220	130	338	110	359	15,000
Ibrahim	1531	352	256	252	420.5	250.5	20,000
Tayba right	935	192	118	201	190	234	20,000
Elhakoma	305	95	-	75	75	60	10,000
Tayba 3	439	66	85	96	96	96	10,000
Tayba 4	415	115	90	30	90	90	10,000
Tayba east	5350	1126	904	1056	1206	1058	110,000
Tayba north east	2320	332	454	531	443	560	110,000
Branch	1449.5	282	132.5	307	292	1058	20,000
Tayba 1	2542	462	650	480	478	478	40,000
Tayba 2	2604	446	548	540	540	530	40,000
Total							315,000

Source: Tayba office, Sudan Gezira Board.

Planting data	Kc Comparison Table For Ground Nuts					
	Decade	Decade No	Far brother	H.Adam	Cropwat	Computer model
	1	1				
June	2	2	0.5	0.6	.40	.26
	3	3	.53	0.6	.47	.26
	1	4	.59	0.7	.68	.26
July	2	5	.68	0.8	.96	.48
	3	6	.78	0.9	1.15	.70
	1	7	0.91	1.0	1.20	.93
August	2	8	1.01	1.1	1.20	1.15
	3	9	1.09	1.2		1.1528
	1	10	1.10	1.2		1.1528
Sept	2	11	1.07	1.2		1.1528
	3	12	1.03	1.1		1.1528
	1	13	0.89	1.0		1.1528
Oct	2	14	0.80	.9		.60
	3	15	0.69	.8		.60
	1	16	.60	0.7		.61
Nov	2	17				
	3	18				