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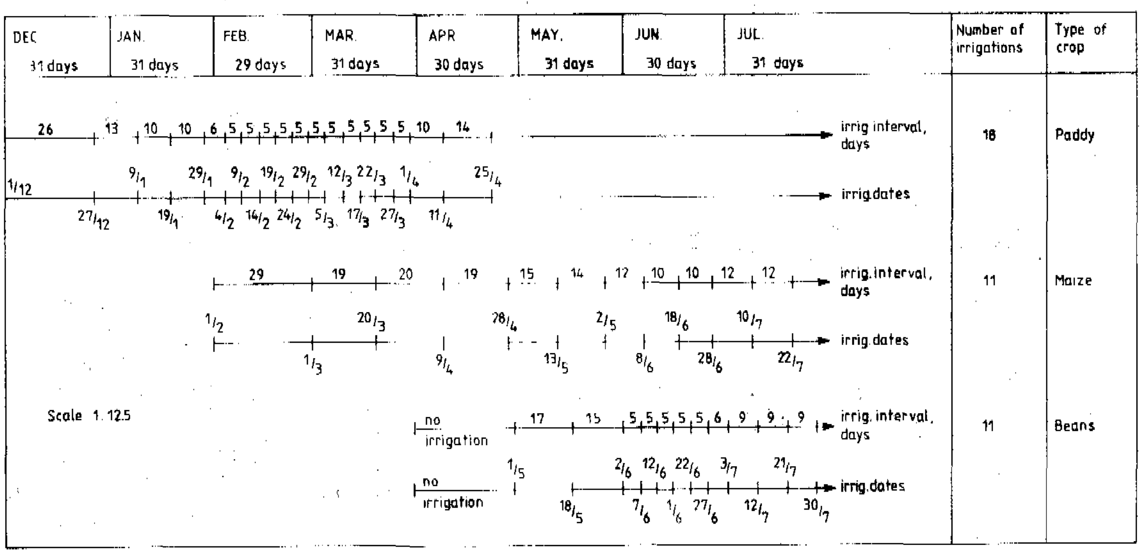
Thadei Simon Y

Irrigation Scheduling



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IRRIGATION SCHEDULING

by

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University of Technology, Finland
in partial fulfillment of the
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IRRIGATION SCHEDULING

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ABSTRACT

This thesis deals with irrigation scheduling under rotational water supply. First, irrigation scheduling is defined and the general review of the principles, factors, methods, and scheduling techniques which must be considered before scheduling is given. This includes crop water requirements, factors affecting crop water requirements and methods for determining crop water requirements. Then soil waterholding capacity, irrigation requirements (efficiencies and leaching requirements), amount of water for irrigation, availability of water supply, and scheduling techniques are reviewed.

Also, Tanzania's case study is given for two projects: Mbarali (a state farm) and Mombo (village owned farm).

Finally, irrigation schedule is prepared for Mombo irrigation scheme.

1. INTRODUCTION

Irrigation scheduling is a planning and decision making activity that the farmer or operator of an irrigation farm is involved in before and during most of the growing season for each crop that is grown (Jensen, 1981). Alternatively, irrigation scheduling can be defined as determining when to irrigate and how much water to apply (Israelsen and Hamsen, 1962). The required decision making criteria includes (Jensen, 1975):

1. the current level and expected change in available soil water for each field over the subsequent 5 to 10 days,
2. current estimates of the probable latest date of the next irrigation on each field to avoid adverse effects of plant water stress and the earliest date that the next irrigation can be given to permit efficient irrigation with the existing system,
3. the amount of water that should be applied to each, if the irrigator is able to control or measure that amount, which will achieve a high irrigation efficiency and the targeted soil water level,
4. some indication of the adverse effects of irrigating a few days early or late, or applying too little or too much water, or perhaps terminating irrigation for the season. These adverse effects would be mainly on the marketable value of the crop involved.

In addition, irrigation scheduling may require consideration of irrigation costs, including electrical load management (if water is pumped) to limit demand charges, salinity control, optimizing soil moisture for harvesting root crops, providing adequate soil moisture for planting the next crop, and maximizing the potential soil water storage capacity to retain seasonal precipitation.

Another important basic concept of irrigation scheduling with most irrigation systems is that the soil water reservoir, and not plant water stress is being managed. Lead time is always important. As a general rule, the farmer would like to know the tentative date of the next irrigation, or possibly of the next two irrigations, immediately after an irrigation. The amount of water to be applied is often a secondary consideration because the time schedule can be modified to fit that amount using the existing system (Jensen, 1981). The major considerations which influence the time of irrigation are

1. crop water requirements (evapotranspiration),
2. water-holding capacity of the root zone soil,
3. effective rainfall,
4. amount of water for irrigation,
5. irrigation requirements and
6. the availability of water with which to irrigate.

2. LITERATURE REVIEW

2.1 Crop water requirements

Crop water requirements are sometimes called crop evapotranspiration, ETcrop. Crop water requirements are defined as the depth of water needed to meet the water loss through evapotranspiration of a disease - free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977). The factors which affect crop water requirements are: 1) climate, 2) soil water, 3) method of irrigation and 4) cultural practices.

2.1.1 Climate

It is a common practice to use mean climatic data for determining mean ETcrop (crop water requirement). However, due to weather changes, ETcrop will vary from year to year and for each season within the year. For example, from year to year the monthly values of radiation can show extreme variations in Mid-latitude climates. In areas having distinct dry and wet seasons, the transition month shows significant differences from year to year depending on the onset of the rains.

Daily values ETcrop can vary drastically, with low values on days that are rainy, cloudy, humid and calm and with high values on dry, sunny and windy days.

Consequently to obtain for each month a measure of crop water requirements with the selected irrigation supply, monthly ETcrop should be calculated for each year of climatic record (Doorenbos and Pruitt, 1977).

In a given climatic zone, ETcrop will vary with altitude; this is not caused by difference in altitude as such but mainly by associated changes in temperature, humidity and wind. Also radiation at high altitudes may be different to that in low lying areas.

2.1.2 Soil water

Published data on depth over which the crop extracts most of its water show great differences. With salt free soil water in ample supply, water uptake for most field crops has been expressed as 40 per cent of total water uptake over the first one fourth of total rooting depth, 30 per cent over the second one fourth, 20 per cent over the third and 10 per cent over the last. However, movement of soil water will take place inside and to the root zone when portions become dry. Also water can be supplied to the roots from ground water.

If plants are sufficiently anchored and there are proper growing conditions, including available water and nutrients, soil aeration, soil temperature and soil structure, ETcrop is not affected even when rooting depth is severely restricted. Consequently water management practices should be adjusted accordingly (Doorenbos and Pruitt, 1977).

After irrigation or rains, the soil water content will be reduced primarily and evapotranspiration. As the soil dries, the rate of water transmitted through the soil will reduce. When at same stage the rate of flow falls below the rate needed to meet ETcrop, ETcrop will fall below its predicted level. The effect of soil water content on evapotranspiration varies with crop and is conditioned primarily by type of soils and waterholding characteristics, crop rooting characteristics and the meteorological factors determining the level of transpiration (Doorenbos and Pruitt, 1977).

With moderate evaporative conditions whereby ETcrop does not exceed 5 mm/day, for most field crops ETcrop is likely to be little affected at soil water tensions up to one atmosphere (corresponding approximately to 30 volume percentage of available soil water for clay, 40 for loam, 50 for sandy loam, and 60 for loamy sand). When evaporative conditions are lower the crop may transpire at the predicted ET rate even though available soil water depletion is greater, when higher, ETcrop will be reduced if the rate of water supply to the roots is not able to cope with transpiration losses. This will be more pronounced in heavy textured than in light textured soils.

Since reduction in evapotranspiration affects crop growth and/or crop yields, timing and magnitude of reduction in ETcrop are important criteria for irrigation practices. Following an irrigation the crop will transpire at the predicted rate during the days immediately following irrigation. With time the soils become drier and the rate will decrease, more so under high as compared to low evaporative conditions. This is shown in figure 1 for cotton grown in Egypt on fine textured soil.

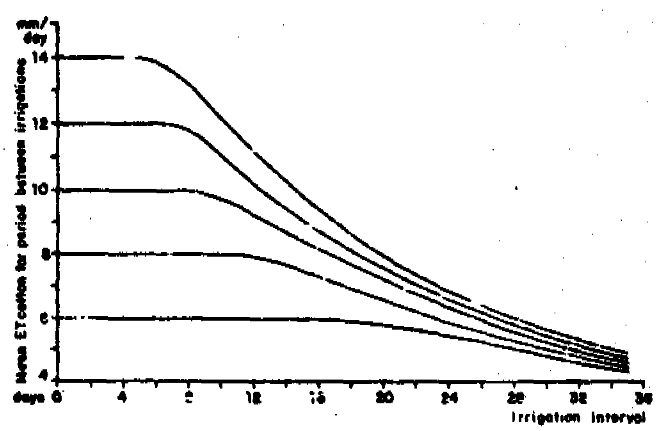


Fig. 1. Mean actual ET cotton over the irrigation interval for different durations of irrigation interval and for different ET cotton levels (Rijtema and Aboukhaled, 1975).

Whether or not the reduction in ETcrop is permissible during part or whole growing season can be determined only when the effect of soil water stress on yield during various stages of growth is known (Doorenbos and Pruitt, 1977).

For most crops, growth and consequently ETcrop will be affected when ground water is shallow or the soil is waterlogged. For example, in cooler climates wet soils warm up slowly, causing delay in seed germination and plant development, land preparation may be delayed, resulting in later planting. Consequently different ETcrop values apply during the remainder of the season. Some crops tolerate waterlogging and shallow ground water conditions more than others. The tolerance of some crops to these conditions is given in table 1.

Table 1. Tolerance levels of crops to high ground water tables and waterlogging (Doorenbos and Pruitt, 1977).

Tolerance level	Ground water at 50 cm	Waterlogging
high tolerance	sugarcane, potatoes, broad beans	rice, willow, strawberries, plums and various grasses
medium tolerance	sugarbeet, wheat, barley, oats, peans, cotton	citrus, bananas, apples, pears, blackberries, onions
sensitive	maize, tobacco	peaches, cherries, date, palms, olives, peas, beans

Higher ground water tables are generally permitted in sandy rather than loam and clay soils due to the difference in capillary fringe above the ground water table. For most crops minimum depth of ground water table required for maximum yield has been expressed as: for sand, rooting depth + 20 cm; for clay rooting depth + 40 cm; for loam rooting depth + 80 cm. No correction on ETcrop will be required (Doorenbos and Pruitt, 1977).

ETcrop can be affected by soil salinity since the soil water uptake by the plant can be drastically reduced due to higher osmotic potential of the saline ground water. Poor crop growth may be due to adverse physical characteristics of some saline soils. Some salts cause toxicity and affect growth. The relative extent to which each of these factors affect ETcrop cannot be distinguished (Westcot and Ayers, 1976).

The effect of timing and duration of water shortage on some crops is very pronounced during certain periods of growth; figure 2.2 shows that for maize yields are negligible when ETcrop is severely restricted during the tasselling stage; figure 2.3 shows that prolonged reduction in ET sugarcane during the period of active growth has a more pronounced negative effect on yield than when experienced during late growth.

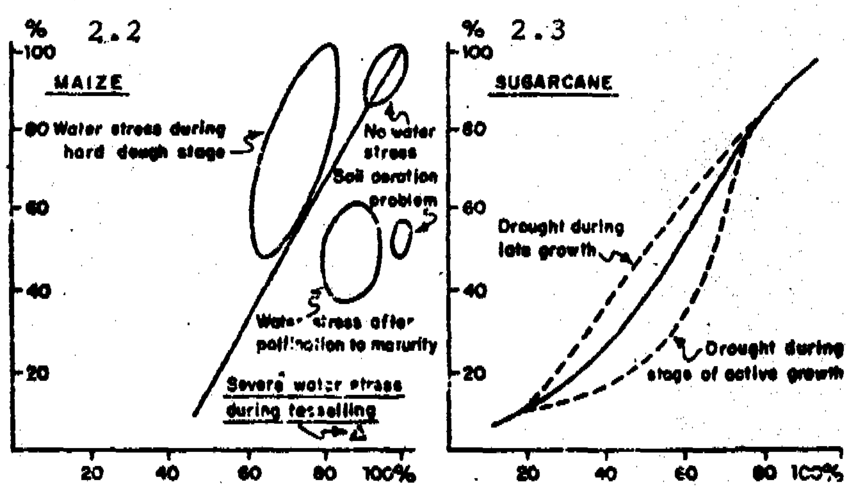


Fig. 2. Relationships between relative yield and relative ETcrop for non-forage crops, corn and virgin cane (Downey, 1972; Chang, 1963).

Reduction in ETcrop is particularly critical when the crop is sensitive to soil water stress and could drastically affect yields. Sensitive stages for some crops are given in table 2.

Table 2. Critical periods for soil water for different crops (Doorenbos and Pruitt, 1977).

Alfalfa	just after cutting for hay and at the start of flowering for seed production
Apricots	period of flower and bud development
Barley	early boot stage > soft dough stage > onset of tillering or ripening stage
Beans	flowering and pod setting period > earlier > ripening period. However, ripening period > earlier if not prior water stress.
Broccoli	during head formation and enlargement
Cabbage	during head formation and enlargement
Castor bean	requires relatively high soil water level during full growing period
Cauliflower	requires frequent irrigation from planting to harvesting
Cherries	period of rapid growth of fruit prior to maturing
Citrus	flowering and fruit setting stages; heavy flowering may be induced by withholding irrigation just before flowering stage (lemon); "June drop" of weaker fruits may be controlled by high soil water levels
Cotton	flowering and boll formation > early stages of growth > after boll formation
Groundnuts	flowering and seed development stages > between germination and flowering and end of growing season
Lettuce	requires wet soil particularly before harvest
Maize	pollination period from tasselling to blister kernel stages > prior to tasselling > grain filling periods; pollination period very critical if no prior water stress
Oats	beginning of ear emergence possibly up to heading
Olives	just before flowering and during fruit enlargement
Peaches	period of rapid fruit growth prior to maturity
Peas	at start of flowering and when pods are swelling
Potatoes	high soil water levels; after formation of tubers, blossom to harvest
Radish	during period of root enlargement
Sunflower	possibly during seeding and flowering - seed development stage
Small grains	boot to heading stage
Sorghum	secondary rooting and tillering to boot stage > heading, flowering and grain formation > grain filling period
Soybeans	flowering and fruiting stage and possibly period of maximum vegetative growth
Strawberries	fruit development to ripening
Sugarbeet	3 to 4 weeks after emergence
Sugarcane	period of maximum vegetative growth
Tobacco	knee high to blossoming
Tomatoes	when flowers are formed and fruits are rapidly enlarging
Turnips	when size of edible root increases rapidly up to harvesting
Water melon	blossom to harvesting
Wheat	possibly during booting and heading and two weeks before pollination

However, slight, timely ET reduction by withholding water may have a positive effect on yields such as improved quality in apples, peaches and plums, aromatic quality of tobacco, oil content of olives, and sugar content in sugarcane (Kozlowski, 1968).

2.1.3 Methods of irrigation

The method of irrigation has little effect on ETcrop if the system is properly designed, installed and operated. The advantages of one method over another are therefore not determined by differences in total irrigation water supplied but by the adequacy and effectiveness with which crop requirements can be met.

Different methods imply different rates of water application. When comparing the various methods in terms of water efficiency in meeting crop demand the apparent superiority of one method over another may be merely the result of too much or too little water being applied. There may be no fault in the actual method of irrigation, only practices thought to affect ETcrop are as follows (Doorenbos and Pruitt, 1977).

2.1.3.1 Surface irrigation

Reducing the area wetted by alternate furrow irrigation generally has little effect on ETcrop. The positive effect on crop growth sometimes noticed should be attributed to other factors such as better soil aeration. Reduction on evaporation from the soil surface is obtained in the case of incomplete crop cover (less than 60 per cent) and/or by wetting only a relatively small area less than 30 per cent. This latter is practised in orchards and vineyards by irrigating near the trunks; the net reduction in seasonal ETcrop will in general not be more than 5 per cent.

2.1.3.2 Sprinkler irrigation

Transpiration by the crop may be greatly reduced during application but will increase by increased evaporation from the wet leaves and soil surface. The combined effects do not greatly exceed predicted ETcrop. The effects of under-tree sprinkling on water savings are unlikely to be very great. With above-tree canopy sprinkling the micro-climate can change considerably but is, however, relatively short lived and little effect on ETcrop will be observed except possibly for centre-pivot systems with daily water application.

Evaporation losses from the spray are small and generally below 2 per cent. Losses due to wind drift may be considerable at higher wind speeds and can reach 15 per cent at 5 m/s. Strong winds also result in a poor water distribution pattern. Sprinkler irrigation should not normally be used when wind speeds are over 5 m/s.

2.1.3.3 Trickle irrigation

A well operated drip system allowing frequent application of small quantities of water can provide a nearly constant low tension soil water condition in the major portion of the root zone. The high water use efficiency can be attributed to improved water conveyance and water distribution to the root zone. ETcrop with near or full ground cover is not affected unless under-irrigation is practised. Only with widely spaced crops and young orchards will ETcrop be reduced since evaporation will be restricted to the area kept moist. For young orchards with 30 per cent ground cover on light, sandy soils and under high evaporation conditions requiring very frequent irrigations, a reduction in ETcrop of up to possibly 60 per cent has been observed. This reduction would be considerably lower for medium to heavy textured soils under low evaporative conditions requiring much less frequent irrigation.

2.1.3.4 Subsurface irrigation

With a subsurface water distribution system, depending on the adequacy of the water supply through upward water movement to the root zone, ETcrop should be little affected except for the early stage of growth of some crops when frequent irrigation is required.

2.1.4 Cultural practices

The cultural practices which affect ETcrop are application of fertilizers, plant density, tillage, mulching, windbreaks and anti-transpirants.

2.1.4.1 Fertilizers

The use of fertilizers has only a slight effect on ETcrop, unless crop growth was previously adversely affected by low soil nutrition delaying full crop cover. Irrigation imposes a greater demand on fertilizer nutrients; adequately fertilized soils produce much higher yields per unit of irrigation water than do poor soils, provided the fertilizer is at the level in the soil profile where soil water is extracted by the plant. The movement of soluble nutrients and their availability to the crop is highly dependent on method and frequency of irrigation (Doorenbos and Pruitt, 1977).

2.1.4.2 Plant population

The effect of plant population or plant density on ETcrop is similar to that of percentage of ground cover. When top soils are kept relatively dry, evaporation from the soil surface is sharply reduced and ETcrop will be less for low population crops than for high population crops. During the early stages of the crop a high population planting would normally require somewhat more water than low density planting due to quicker development of full ground cover.

In irrigated agriculture plant population has been considered of little importance in terms of total water needs (Hagan et al., 1967).

2.1.4.3 Tillage

Tillage produces little if any effect on ETcrop unless a significant quantity of weed is eliminated: rough tillage will accelerate evaporation from the plough layer; deep tillage may increase water losses when the land is fallow or when the crop cover is sparse. After the surface has dried, evaporation from the dry surface might be less than from an untilled soil. Other factors such as breaking up sealed furrow surfaces and improving infiltration may decide in favour of tillage. With soil ripping between crop rows the crop could be slightly set back due to root pruning (Doorenbos and Pruitt, 1977).

2.1.4.4 Mulching

In irrigated agriculture the use of a mulch of crop residues to reduce ETcrop is often considered of little net benefit, except for specific purposes such as reducing erosion, preventing soil sealing and increasing infiltration. Crop residues may even be a disadvantage where soils are intermittently wetted, the water absorbing organic matter remains wet much longer thus increasing evaporation. As a barrier to evaporation it is rather ineffective. The lower temperature of the covered soil and the higher reflected capacity of the organic matter are easily outweighed by evaporation of the often rewetted crop residue layer. There may be additional disadvantages such as the increased danger of pests and diseases, slower crop development due to lower soil temperatures, and problematic water distribution from surface irrigation. Polyethylene and perhaps also asphalt mulches are effective in reducing ETcrop when it covers more than 80 per cent of the soil surface and crop cover is less than 50 per cent of the total cultivated area. Weed control adds to the successful use of plastic (Doorenbos and Pruitt, 1977).

2.1.4.5 Windbreaks

Reduced wind velocities produced by artificial and vegetative windbreaks may reduce ETcrop by about 5 per cent under windy, warm, dry conditions at a horizontal distance equal to 25 times the height of the barrier downwind from it, increasing to 10 and sometimes up to 30 per cent at a distance of 10 times the height. ETcrop as determined by the overall climatic conditions and using the reduced wind speed data is not altered. In most cases shrubs and trees are used and, due to the transpiration of the vegetative windbreak, overall ET may be more.

2.1.4.6 Anti-transpirants

The use of anti-transpirants, natural or artificially induced variation in plant foliage properties and soil conditioners to reduce ETcrop continue to interest many investigators, but is still in the experimental stage.

2.1.5 Summary of factors affecting ETcrop

The main factors affecting ETcrop are climate, soil water, methods of irrigation and cultural practices. Climatic data (temperature, relative humidity, sunshine hours, wind speed, radiation and rainfall) are the major factors which affect ETcrop. Climatic data excluding rainfall are major components used to predict ETcrop; therefore if there is a change of climate, ETcrop will also change. Effective rainfall (discussed in section 2.4) will reduce ETcrop because part of crop water requirements will be satisfied by it (see section 2.6.1).

When the evaporative conditions are high, ETcrop will be reduced if the rate of water supply to the roots is not able to cope with transpiration. If the evaporative conditions are low, the crop may transpire at the predicted ETcrop rate. Soil salinity also affects ETcrop since the water uptake by plant can be reduced due to higher osmotic potential of the saline ground water. Only one method of irrigation, surface irrigation, is used in Tanzania (hence only this method is emphasized). The effect of surface irrigation on ETcrop is little. Evaporation (part of ETcrop) is higher at the initial stage of plant growth and decreases towards the development stage (due to increase of crop cover), thus affecting ETcrop in the same way. During complete crop cover surface irrigation has little effect on ETcrop.

The main cultural practices which have little effect on ETcrop are plant population (due to percentage of ground cover), rough tillage (increase of evaporation from the plough layer) and windbreaks (reduce wind velocity which accelerates evaporation of water from leaf surfaces).

2.2 Methods for determining ETcrop

After the discussion of factors affecting ETcrop, methods for determining ETcrop should be known. There are two groups: direct and indirect methods. The direct methods are lysimeters, soil moisture studies, integration method, and inflow-outflow for large areas. The indirect methods (recommended by FAO) are Penman, Radiation, Blaney-Criddle, Pan Evaporation, and Jensen-Haise methods.

2.2.1 Direct methods

Direct field measurements are very expensive and are therefore mainly used to provide data for calibrating the indirect methods which use climatological and crop data to estimate ETcrop. These methods measure the components of water balance represented by the following equation:

$$\Delta w = Pe + I - R - D - ETcrop \quad \text{(Kijne, 1980)}$$

where Δw = change in water content in the root zone during a certain period

Pe = precipitation (rainfall)

I = irrigation water

R = run-off

D = deep percolation

ETcrop= crop evapotranspiration.

From this equation, if all components are measured (except ETcrop), crop evapotranspiration can be calculated. The methods used in direct measurements of ETcrop are lysimeters (soil tanks), soil moisture studies, integration method, and inflow-outflow for large areas (Israelsen and Hansen, 1962).

2.2.1.1 Lysimeters

Lysimeters are large containers of soil set in natural surroundings with the least possible discontinuity between the crop on the lysimeters and that in the surrounding field. Figure 3 shows an example of lysimeter with suction control at the bottom.

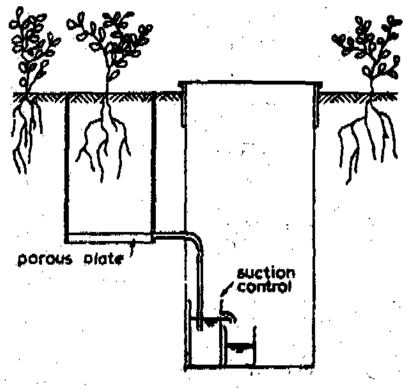


Fig. 3. Non-weighable lysimeter with suction control at the bottom (Kijne, 1980).

The effective use of lysimeters is limited to situations in which the vegetation community under study can be simulated within the lysimeter itself, without, for instance, any restriction of root development. Lysimeters which can be weighed either by means of pressure transducers or because they can float in water or some liquid provide a means of accurately determining the water loss due to evapotranspiration, provided the temperature sensitivity of the weighing system is properly taken into consideration. A reliable measurement of the components of the water balance is only obtained if the potential profile in the lysimeter is the same as in the surrounding field. This condition can be satisfied if the lysimeter is provided with a drainage system and a system to maintain the water potential at the bottom of the soil in the lysimeter at the same level as the water potential in the adjacent field. When however, the object is to determine the maximum evapotranspiration rate, the moisture condition in the soil column is not critical as long as root growth is normal. These lysimeters should then be irrigated frequently, for instance every 4 or 5 days, unless rainfall intervenes. A fairly reliable estimate of potential evapotranspiration rate for periods of a week or more should then be possible. The use of constant water table lysimeters for the measurement of potential evapotranspiration rate for short periods is questionable, since under conditions of high evaporative demand, the movement of water from the water table into the root zone may not be rapid enough to equal the potential evapotranspiration rate (Kijne, 1980).

2.2.1.2 Soil moisture studies

Crop water requirements (ETcrop) for various crops can be determined by intensive moisture studies. Soil moisture is determined before and after each irrigation with some measurements between irrigation in the major root zone. The volume (ha-mm) of water extracted per day from the soil is computed for each period. When the rate of use is plotted against time, a curve can be drawn from which the seasonal use (ETcrop) can be obtained (Israelsen and Hansen, 1962). Soil moisture is determined by gravimetric method, neutron probe and porous blocks.

2.2.1.3 Integration method

The integration method is the summation of the products of unit evapotranspiration for each crop times its area, the unit of evapotranspiration of native vegetation times its area, water surface evaporation times water surface area, and evaporation from bare land times area (Israelsen and Hansen, 1962).

Before this method can successfully be applied, it is necessary to know the unit evapotranspiration of water and the areas of various classes of agricultural crops, native vegetation, bare land and water surfaces. By means of aerial maps and field surveys areas of various types of native vegetative cover, bare land and water surfaces can be determined. Table 3 shows the results of determination of evapotranspiration by this method in Mesilla Valley, New Mexico.

Table 3. Areas of different crops and crop water requirements (ETcrop) of water in Mesilla Valley area, New Mexico, as estimated by integrated method, 1936 (Israelsen and Hansen, 1962).

Land classification	1936 area, ha	Consumptive use unit mm	Consumptive use Annual ha mm
Irrigated crops:			
Alfalfa and clover	17 077	4,0	68 308
Cotton	54 513	2,5	136 282
Native hay and irrigated pasture	216	2,3	497
Miscellaneous crops	11 117	2,0	22 234
Entire irrigated area	82 923	2,74	227 321
Natural vegetation:			
Grass	2 733	2,3	6 286
Brush	6 933	2,5	17 332
Trees - Bosque	3 532	5,0	17 660
Entire area	13 198	3,13	41 278
Miscellaneous:			
Temporarily out of cropping	5 569	1,5	8 354
Towns	1 523	2,0	3 046
Water surfaces, pooled, river and canals	4 081	4,5	18 364
Bare lands, roads, etc.	3 124	0,7	2 187
Total (entire area)	110 418	2,72	300 550

2.2.1.4 Inflow-outflow for large areas

Applying this method, valley consumptive use ETcrop is equal to the water that flows into the valley during a 12 month year, I, plus yearly precipitation on the valley floor, Pe, plus water in ground storage at the beginning of the year, Gs, minus water in ground storage at the end of the year, Ge, and minus yearly outflow, R, - all volumes measured in ha-cm. Thus

$$ETcrop = (I + Pe) + (Gs - Ge) - R$$

(Israelsen and Hansen, 1962).

The difference between storage of capillary water at the beginning of the year and at the end of the year is usually considered to be negligible. The quantity (Gs - Ge) is considered as a unit so that evaluation of either Gs or Ge is unnecessary, only the difference (ΔG) being needed. This is the product of the difference in the average depth of water table during the year measured in centimetres and multiplied by the specific yield (the total pore space of the soil less the moisture content at field capacity, both expressed as volume percentage of the total soil volume) of the soil and area of the valley floor. The quantity Pe is obtained by multiplying the average annual precipitation in centimetres and the area of the valley floor in hectares. The unit consumptive use of the entire valley is in hectare-centimetre per hectare of the valley floor.

2.2.2 Indirect methods

Numerous equations that require meteorological data have been developed, and several are commonly used to estimate ETcrop for periods of one day or more. These equations are all empirical to various extents; the simplest requiring only average air temperature, day length and a crop factor. The generally better performing equations require daily radiation, temperature, vapour pressure and wind data (Burman, 1980).

These equations give potential evapotranspiration (reference crop evapotranspiration ETo) which can be used to estimate the actual evapotranspiration, ETcrop by using coefficients to account for the effect of soil moisture status, stage of growth and maturity of a crop.

The weather records that are used by the equations to calculate evapotranspiration should not be used indiscriminately without knowledge of the weather station, site exposure and the care with which the station was maintained (Jensen, 1968).

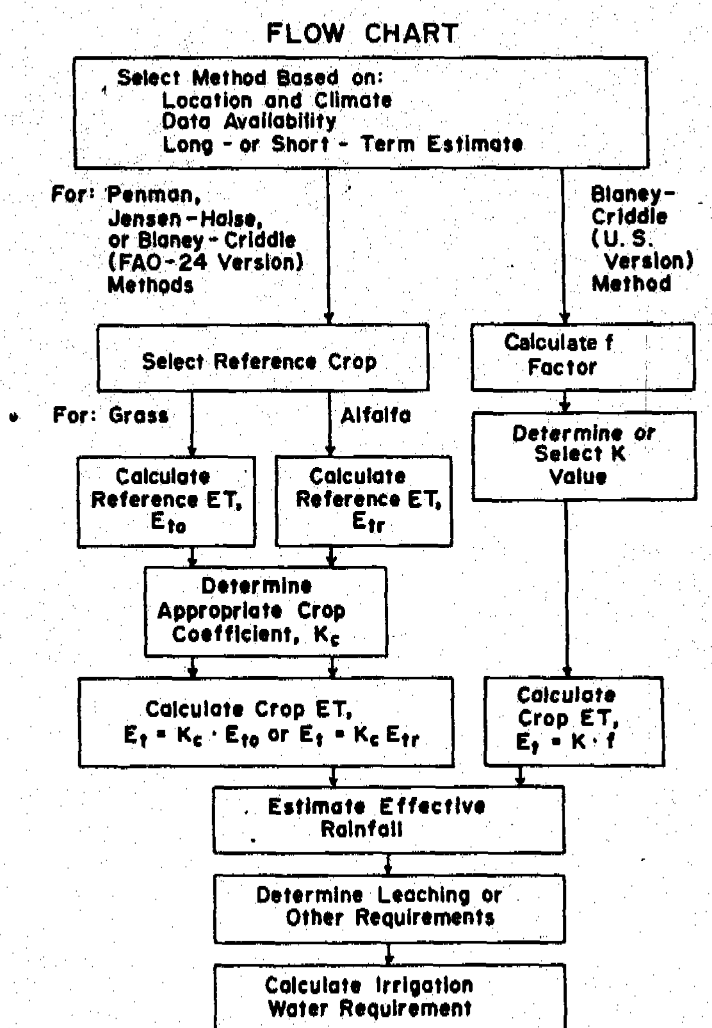


Fig. 4. Typical flow chart for estimation of irrigation water requirements from climatic data (Burman, 1980).

The methods used in estimating potential evapotranspiration from climatic data are numerous, but the most commonly used ones are Penman, Radiation, Blaney-Criddle, Pan evaporation and Jensen-Haise methods.

2.2.2.1 Penman method

Penman method is a combination method derived from combination of emergy balance and aerodynamic term (mass transport). For areas where measured data on temperature, humidity, wind and sunshine duration or radiation are available, an adaptation of Penman method is suggested; compared to the other methods it is likely to provide the most satisfactory results (Doorenbos and Pruitt, 1977).

Climate data required are: mean temperature (^{O}C), mean relative humidity (Rh in per cent), total wind run (U in km/day at 2 m height) and mean actual sunshine duration (n in hour/day) or mean radiation (Rs or Rn equivalent evaporation in mm/day). Also measured or estimated data on mean maximum relative humidity (RHmax in per cent) and mean daytime wind speed must be available. Reference evapotranspiration (potential evapotranspiration, ETo) representing the mean value in mm/day, over the period considered, is obtained by

$$ETo = c \left[W \times Rn + (1 - w) \times f(U) \times (ea - ed)\right]$$

(Kassam and Doorenbos, 1979), where

ETo = reference crop evapotranspiration in mm/day
W = temperature related weighing factor
Rn = net radiation in equivalent evaporation in mm/day
f(U) = wind related function
(ea - ed) = difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air, both in mbs
c = adjustment factor to compensate for the effect of day and night weather conditions

Description of variables

a) Vapour pressure (ea - ed)

Air humidity affects ETo. Humidity is expressed here as saturation vapour pressure deficit (ea - ed): the difference between the mean saturation water vapour pressure (ea) and the mean actual water vapour pressure (ed).

Air humidity data are reported as relative humidity (RHmax and RHmin in percentage), as psychrometric readings ($T^{o}C$ of dry and wet bulb) from either ventilated or non ventilated wet and dry bulb thermometers, or dew point temperature (Tdewpoint, ^{o}C). Time of measurement is important but is often not given. Fortunately actual vapour pressure is a fairly constant element and even one measurement per day may suffice for the type of application envisaged (Doorenbos and Pruitt, 1977). Tables 4 and 5 give values ea and ed from available climatic data.

Table 4. Saturation vapour pressure (ea) in mb as a function of mean air temperature in °C (Doorenbos and Kassam, 1979).

Temperature °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ea mbar	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6*	22.0
Temperature °C	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
ea mbar	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7	37.8*	40.1	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

1/ Also actual vapour pressure (ed) can be obtained from this table using available Tdewpoint data.
(Example: Tdewpoint is 18°C; ed is 20.6 mbar)

Table 5. Actual vapour pressure (ed) in mb from dry and wet bulb temperature in ^{o}C - aspirated psychrometer (Doorenbos and Pruitt, 1979).

Depression wet bulb T°C altitude 0-1 000 m												drybulb	Depression wet bulb T°C altitude 1 000-2 000 m											
0	2	4	6	8	10	12	14	16	18	20	22	T°C	0	2	4	6	8	10	12	14	16	18	20	22
73.8	64.9	56.8	49.2	42.2	35.8	29.8	24.3	19.2	14.4	10.1	6.0	40	73.8	65.2	57.1	49.8	43.0	41.8	31.0	25.6	20.7	16.2	12.0	8.1
66.3	58.1	50.5	43.6	37.1	31.1	25.6	20.5	15.8	11.4	7.3		38	66.3	58.2	50.9	44.1	37.9	36.7	26.8	21.8	17.3	13.2	9.2	5.7
59.4	51.9	44.9	38.4	32.5	26.9	21.8	17.1	12.7	8.6	4.9		36	59.4	52.1	45.2	39.0	33.3	32.1	23.0	18.4	14.3	10.4	6.8	3.5
53.2	46.2	39.8	33.8	28.3	23.2	18.4	14.0	10.0	6.2			34	53.2	46.4	40.1	34.4	29.1	24.1	19.6	15.4	11.5	8.0	4.6	1.5
47.5	41.1	35.1	29.6	24.5	19.8	15.4	11.3	7.5	4.0			32	47.5	41.3	35.5	30.2	25.3	20.7	16.6	12.6	9.1	5.8	2.6	
42.4	36.5	30.9	25.8	21.1	16.7	12.6	8.8	5.3				30	42.4	36.7	31.3	26.4	21.9	17.7	13.8	10.2	6.9	3.8	0.9	
37.8	32.3	27.2	22.4	18.0	14.0	10.2	6.7	3.4				28	37.8	32.5	27.5	23.0	18.9	14.9	11.4	8.0	4.9	2.1		
33.6	28.5	23.8	19.4	15.3	11.5	8.0	4.7	1.6				26	33.6	28.7	24.1	20.0	16.1	12.5	9.2	6.0	3.2	0.5		
29.8	25.1	20.7*	16.6	12.8	9.3	6.0	2.9					24	29.8	25.3	21.1	17.2	13.9	10.3	7.2	4.3	1.6			
26.4	22.0	18.0	14.2	10.6	7.4	4.3	1.4					22	26.4	22.3	18.3	14.3	11.5	8.3	5.5	2.7	0.2			
23.4	19.3	15.5	12.0	8.7	5.6	2.7						20	23.4	19.5	15.9	12.6	9.5	6.6	3.9	1.3				
20.6	16.8	13.3	10.0	6.9	4.1	1.4						18	20.6	17.1	13.7	10.6	7.8	5.0	2.5	0.1				
18.2	14.6	11.4	8.3	5.4	2.7							16	18.2	14.9	11.7	8.9	6.2	3.6	1.3					
16.0	12.7	9.6	6.7	4.0	1.5							14	16.0	12.9	10.0	7.3	4.8	2.4	0.3					
14.0	10.9	8.1	5.3	2.8								12	14.0	11.2	8.4	5.9	3.6	1.4						
12.3	9.4	6.7	4.1	1.7								10	12.3	9.6	7.0	4.7	2.6	0.4						
10.7	8.0	5.5	3.1	0.8								8	10.7	8.2	5.8	3.7	1.6							
9.3	6.8	4.4	2.1									6	9.3	7.0	4.8	2.7	0.7							
8.1	5.7	3.4	1.6									4	8.1	6.0	3.8	1.8								
7.1	4.8	2.8	0.8									2	7.1	5.0	2.9	1.0								
6.1	4.0	2.0										0	6.1	4.1	2.1									

b) Wind function

The effect of wind on ETo has been studied for different climates resulting in a revised wind function and defined as:

$$f(U) = 0{,}27(1 + \frac{U}{100}) \quad \text{(Doorenbos and Pruitt, 1977)}$$

where U is 24 h wind run in km/day at 2 m height. This expression is valid when (ea - ed) is expressed in mbs. Table 6 gives the values of f(U) for wind run at 2 m height.

Table 6. Values at wind function $f(U) = 0{,}27(1 + \frac{U_2}{100})$ for wind run at 2 m height in height in km/day (Doorenbos and Pruitt, 1977).

Wind km/day	0	10	20	30	40	50	60	70	80	90
	-	.30	.32	.35	.38	.41	.43	.46	.49	.51
100	.54	.57	.59	.62	.65	.67	.70	.73	.76	.78
200	.81	.84	.86	.89*	.92	.94	.97	1.00	1.03	1.05
300	1.08	1.11	1.13	1.16	1.19	1.21	1.24	1.27	1.30	1.32
400	1.35	1.38	1.40	1.43	1.46	1.49	1.51	1.54	1.57	1.59
500	1.62	1.65	1.67	1.70	1.73	1.76	1.78	1.81	1.84	1.90
600	1.89	1.92	1.94	1.97	2.00	2.02	2.05	2.08	2.11	2.15
700	2.16	2.19	2.21	2.24	2.27	2.29	2.32	2.35	2.38	2.40
800	2.43	2.46	2.48	2.51	2.54	2.56	2.59	2.62	2.64	2.65
900	2.70									

Where wind data are not collected at 2 m height, the appropriate corrections for wind measurements taken at different heights are given below (Doorenbos and Pruitt, 1977):

Measurement height in m	0,50	1,00	1,50	2,00	3.00	4,00	5,00	6,00
Correction factor	1,35	1,15	1,06	1,00	0,93	0,98	0,85	0,83

c) Weighting factor (W)

W is the weighting factor for the effect of radiation on ETo. Table 7 gives value of W as related to temperature and altitude.

d) Net radiation (Rn)

Net radiation is the difference between all incoming and outgoing radiation. It can be measured, but such data are seldom available. Rn can be calculated from solar radiation or sunshine hours (or degree of cloud cover) temperature and humidity data (Doorenbos and Pruitt, 1977).

A schematic illustration of the component to be considered in daytime net radiation is shown in figure 5.

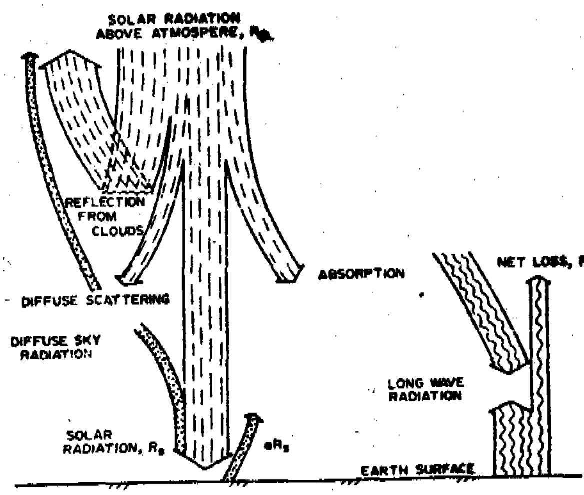


Fig. 5. Schematic representation of the daytime radiation balance (Jensen, 1973).

The amount of radiation received at the top of the atmosphere (Ra) is dependent on latitude and the time of the year only; values of Ra are given in table 8.

Table 7. Value of weighting factor (W) for the effect of radiation on ETo at different temperatures and altitudes (Doorenbos and Pruitt, 1977).

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
W at altitude m																				
0	0.43	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77*	.78	.80	.82	.83	.84	.85
500	.44	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1 000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2 000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3 000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88	.89
4 000	.54	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.89	.90	.90

Table 8. Extra terrestial radiation (Ra) expressed in equivalent evaporation in mm/day (Doorenbos and Pruitt, 1977).

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Part of Ra is absorbed and scattered when passing through the atmosphere. The remainder including some that is scattered but reaches the earth's surface, is identified as solar radiation (Rs) is dependent on Ra and the transmission through the atmosphere, which is largely dependent on cloud cover. Part of Rs is reflected back directly by the soil and crop and is lost to the atmosphere. Reflectivity (α) depends on the nature of the surface cover and is approximately 5 to 7 per cent for water and around 15 to 25 per cent for most crops. This fraction varies with degree of crop cover and the wetness of the exposed soil surface. That which remains is net shortwave solar radiation (Rns).

Additional loss at the earth's surface occurs since the earth radiates part of its absorbed energy back through the atmosphere as longwave radiation. This is normally greater than the downcoming longwave atmospheric radiation. The difference between outgoing and incoming longwave radiation is called net longwave radiation (Rnl). Since outgoing is greater than incoming, Rnl represents net energy loss (Jensen, 1968).

Total net radiation, Rn is equal to the difference between Rns and Rnl, or $Rn = Rns - Rnl = (1 - \alpha)\ Rs - Rnl$ (Jensen, 1968).

Radiation here is given as equivalent evaporation in mm/day. To calculate total net radiation, Rn, the different steps involved are (Doorenbos and Pruitt, 1977):

1. If measured solar radiation, Rs is not available, select Ra value in mm/day from table 10 for given month and latitude.
2. To obtain solar radiation, Rs, correct Ra value for ratio of actual, n, to maximum sunshine hours, N; $Rs = (0{,}25 + 0{,}50\ \frac{n}{N})Ra$. Values of N for a given month and latitude are given in table 9.

Table 9. Mean daily duration of maximum possible sunshine hours, N, for different months and latitudes (Doorenbos and Pruitt, 1977).

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

Both n and N are expressed in hours as mean daily values for the period considered.

When only visual cloud observations are available, they can be used to calculate Rs. Several daily visual observations of cloudness over a sufficiently long period are needed. Cloudness is expressed in oktas (0 to 8) and sometimes in the tenths (0 to 10) which must first be converted into equivalent values of n/N. Table 10 can be used as a rough guide.

Table 10. Relationship between cloudness and n/N ratio (Doorenbos and Pruitt, 1977).

Cloudness oktas	0	1	2	3	4	5	6	7	8
n/N ratio	0,95	0,85	0,95	0,65	0,55	0,45	0,30	0,15	-

Cloudness in tenths	0	1	2	3	4	5	6	7	8	9	10
n/N ratio	0,95	0,85	0,80	0,75	0,65	0,55	0,50	0,40	0,30	0,15	-

3. To obtain net shortwave radiation, Rns, the solar radiation, Rs, must be corrected for reflectiveness of the crop surface, or $Rs = (1 - \alpha)Rs$. For most crops $\alpha = 0,25$.

4. Net longwave radiation, Rnl, can be determined from available temperature, T, vapour pressure, ed, and n/N ratio data. Values for the function f(T), f(ed) and f(n/N) are given in tables 11, 12 and 13 respectively (Doorenbos and Pruitt, 1977).

Table 11. Effect of temperature, f(T), on longwave radiation, Rnl.

T^oC	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
$f(T) = \sigma Tk^4$	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3*	16.7	17.2	17.7	18.1

Table 12. Effect of vapour pressure, f(ed) on longwave radiation.

ed mbar	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$f(ed) = 0.34 - 0.044\sqrt{ed}$	0.23	.22	.20	.19	.18	.16	.15	.14	.13*	.12	.12	.11	.10	.09	.08	.08	.07	.06

Table 13. Effect of the ratio of actual and maximum bright sunshine hours, f(n/N) on longwave radiation (Rnl).

n/N	0	.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
$f(n/N) = 0.1 + 0.9\, n/N$	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82*	.87	.91	.96	1.0

5. To obtain total net radiation, Rn, the algebraic sum of net shortwave radiation, Rns, and net long-wave radiation, Rnl, is calculated. Rnl always constitutes a net loss so, Rn = Rns - Rnl.

e) Adjustment factor (c)

The Penman equation given assumes the most common conditions where radiation is medium to high, maximum relative humidity is medium to high and moderate daytime wind about double the nighttime wind. However, these conditions are not always met. For instance, coastal areas with pronounced sea breezes and calm nights generally have day/night wind ratio of 3 to 5; parts of the Middle East have dry winds during the night with maximum relative humidity approaching 100 per cent. For such conditions correction to the Penman equation is required (Doorenbos and Pruitt, 1977).

Table 14 gives the values of adjustment factors c, for different conditions of RHmax, Rs, Uday and Uday/Unight.

Table 14. Adjustment factor, c, in presented Penman equation (Doorenbos and Pruitt, 1977).

	RHmax = 30%				RHmax = 60%				RHmax = 90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec	Uday/Unight = 4.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
	Uday/Unight = 3.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
	Uday/Unight = 2.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99*	1.05*	.89	.98	1.10*	1.14*
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
	Uday/Unight = 1.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94*	.99*	.85	.92	1.01*	1.05*
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

The information for using table 14 may be difficult to obtain from available climatic records but it can usually be derived for the different seasons from published weather descriptions or from local services.

2.2.2.2 Radiation method

Climatic data required by radiation method are mean air temperature, Tmin in ^{o}C, and mean actual sunshine duration, n in hours/day, or mean incoming shortwave radiation, Rs in mm/day. Knowledge of general levels of relative humidity and wind is required, and these should be estimated using published weather descriptions, extrapolations from nearby areas or from local sources.

Relationships are given between the radiation formula and reference crop evapotranspiration, ETo, taking into account general levels of mean relative humidity and daytime wind (figure 6).

Radiation method should be more reliable than the Blaney-Criddle approach. In fact, in equatorial zones, on small islands or at high altitudes, the radiation method may be more reliable even if measured sunshine or cloudiness data are not available, in this case solar radiation maps prepared for most locations in the world should provide the necessary solar radiation data (Doorenbos and Pruitt, 1977).

Reference evapotranspiration, ETo, representing the main daily value over the period considered is obtained by:

$$ETo = c\ (W \times Rs)\ \text{mm/day}$$ (Kassam and Doorenbos, 1979)

where Rs = measured mean incoming shortwave radiation in mm/day

W = weighting factor which depends on temperature and altitude

c = adjustment factor which depends on mean humidity and daytime wind conditions.

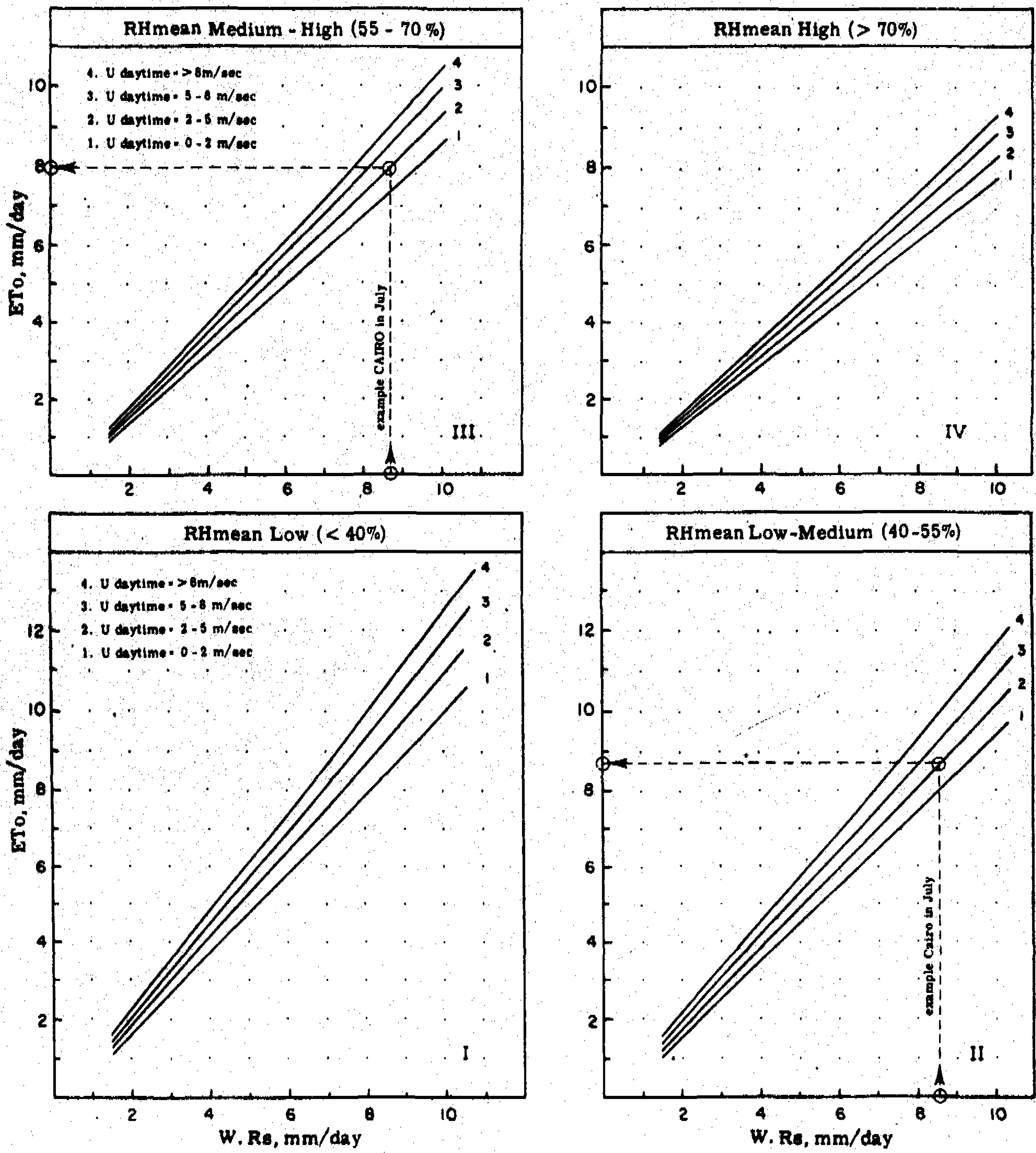


Fig. 6. Prediction of ETo from W x Rs for different conditions of mean relative humidity and daytime wind (Kassam and Doorenbos, 1979).

To calculate solar radiation, Rs, from sunshine duration or cloudiness data, to determine the weighting factor, W, from temperature and altitude data, and to select the appropriate adjustment factor, c, as given by the relationship between product, w x Rs and ETo in figure 4 for different mean relative humidity and daytime wind conditions, the following procedure is suggested (Doorenbos and Pruitt, 1977):

a) Solar radiation (Rs)

Solar radiation (Rs) is discussed under section 2.2.2.1 d).

b) Weighting factor (W)

The weighting factor, W, reflects the effect of temperature and altitude on the relationship between Rs and ETo. Values of W as related to temperature are given in table 7. Temperature reflects the mean air temperature in ^{o}C for the period considered.

c) Adjustment factor (c)

The adjustment factor , c, is given by the relationship between the radiation term, W x Rs, and reference crop evapotranspiration, ETo, and is shown graphically in figure 4. It depends greatly on general levels of mean relative humidity and daytime wind (07.00 - 19.00 hours) at 2 m height above the soil surface (Doorenbos and Pruitt, 1977).

An example of determining ETo using radiation method is given in appendix 4 a. Also, additional considerations for radiation method are found in appendix 4 b.

2.2.2.3 Blaney-Criddle method

The original Blaney-Criddle equation (Blaney and Criddle, 1950) involves the calculation of the consumptive use factor, f, from mean temperature, T, and percentage, P, of total annual daylight hours occurring during the period being considered. An empirically determined consumptive use crop coefficient, K, is then applied to establish the consumptive water requirements, CU, or $CU = K \times f = K \times (P \times T)/100$ with T in ^{o}F. The effect of climate on crop water requirements is, however, insufficiently defined by temperature and day length, crop water requirements will vary widely between climates having similar values of T and P. Consequently, the consumptive use crop coefficient, K, will need to vary not only with the crop but also very much with climatic conditions (Israelsen and Hansen, 1962).

For a better definition of the effect of climate on crop water requirements, but still employing the Blaney-Criddle temperature and day length related f factor a method is presented to estimate reference crop evapotranspiration, ETo. Using measured temperature data as well as general levels of humidity, sunshine and wind, an improved prediction of the effect of climate on evapotranspiration should be obtainable. The relationship recommended by FAO, representing mean value over the given month, is expressed as:

$$ETo = c \times P\ (0{,}46T + 8) \quad \text{mm/day}$$ (Doorenbos and Pruitt, 1977)

where ETo = reference crop evapotranspiration for the month considered, mm/day

T = mean daily temperature over the month considered, ^{o}C

P = mean daily percentage of total daytime hours obtained from table 5 for given month and latitude

c = adjustment factor which depends on minimum relative humidity, sunshine hours and daytime wind estimates.

Table 15. Mean daily percentage, P, of annual daytime hours for different latitudes (Burman, 1980).

Latitude North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
58	.16	.21	.26	.32	.37	.40	.39	.34	.28	.23	.18	.15
56	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.17
52	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
50	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48	.20	.23	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
44	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42	.21	.24	.27	.30	.33	.34	.33	.31	.28	.25	.22	.21
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31*	.30	.28	.26	.24	.23
25	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

The value of f, P(0,46T + 8) is given on the X-axis and the value of ETo can be read directly from the Y-axis. Relationships are presented in figure 7 for three levels of minimum humidity, RHmin; three levels of the ratio actual to maximum possible sunshine hours, n/N; and three ranges of daytime wind conditions at 2 m height, Uday. Information on general monthly or seasonal weather conditions and approximate range of RHmin, n/N and Uday for a given site may be obtained from published weather descriptions, from extrapolation from nearby areas or from local information. Example 2 in appendix 4 a shows how to determine ETo using Blaney-Criddle method.

Figure 7 can be used to estimate ETo graphically using calculated values of P(0,46T + 8).

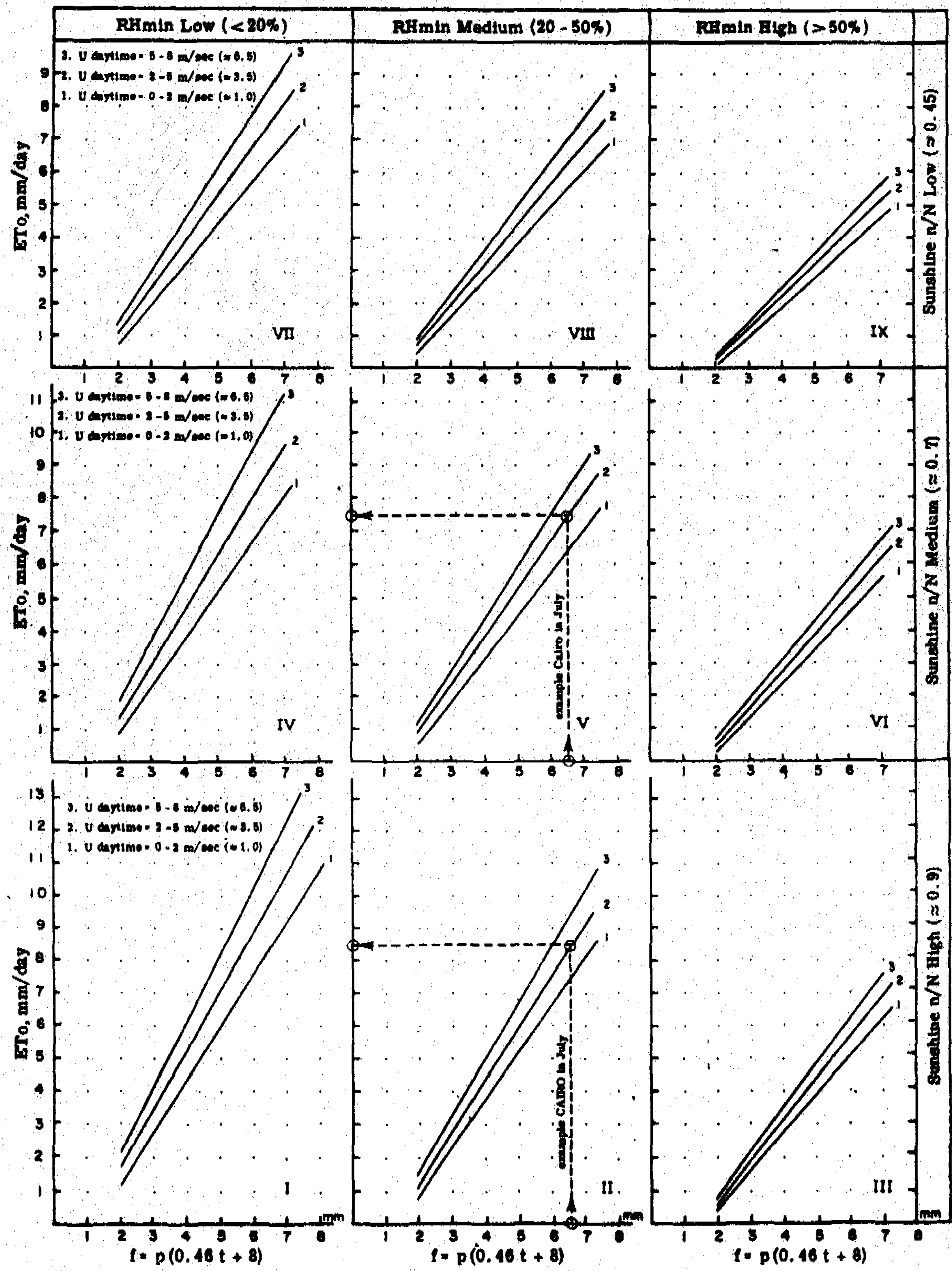


Fig. 7. Prediction of ETo from Blaney-Criddle factor for different conditions of minimum relative humidity, sunshine duration and daytime wind (Doorenbos and Pruitt, 1977).

2.2.2.4 Pan evaporation method

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface. In a similar fashion the plant responds to the same climatic variables but several major factors may produce significant difference in loss of water. Reflecting of solar radiation from a water surface is only 5 - 7 per cent, from most vegetative surfaces 20 - 25 per cent, storage of heat within the pan can be appreciable and may cause almost equal evaporation during night and day, most crops transpire only during daytime. Also the difference in water losses from pan and from crop can be caused by differences in turbulence, temperature and humidity of the air immediately above the surfaces. Heat transfer through the sides of the pan can occur, which may be severe for sunken pan. Also the colour of the pan and the use of screens will affect water losses. The siting of the pan and the pan environment influence the measured results, especially when the pan is placed in fallow rather than cropped fields (Doorenbos and Pruitt, 1977).

Notwithstanding these deficiencies, with proper siting the use of pan to predict crop water requirements for periods of 10 days or longer is still warranted. From the many different types of pans, the use of the U.S. class A pan and the Colorado sunken pan is given here. To relate pan evaporation, Epan, to reference crop evapotranspiration, ETo, empirically derived coefficients, Kp, are given which take into account climate and environment. If measured data from other types of sunken pans are available, such data should first be related to sunken Colorado pan data (table 16).

Table 16. Ratios between evaporation from sunken pans mentioned and from Colorado sunken pan for different climatic conditions and pan environments (Doorenbos and Pruitt, 1977).

Climate		Ratio Epan mentioned and Epan Colorado: Humid-temperate climate		Ratio Epan mentioned and Epan Colorado: Arid to semi-arid (dry season)	
Groundcover surrounding pan (50 m or more)	Pan area m^2	Short green cover	Dry fallow	Short green cover	Dry fallow
CGI 20 dia. 5 m, depth 2 m (USSR)	20	1.0	1.1	1.05	1.25*
Sunken pan dia. 12 ft, depth 3.3 ft. (Israel)	10.5				
Symmons pan 6 ft^2, depth 2 ft (UK)	3.3				
BPI dia. 6 ft, depth 2 ft (USA)	2.6				
Kenya pan dia. 4 ft, depth 14 in	1.2				
Australian pan dia. 3 ft, depth 3 ft	0.7		1.0		1.0
Aslyng pan 0.33 m^2, depth 1 m (Denmark)	0.3			1.0	
CGI 3000 dia. 61.8 cm, depth 60-80 cm (USSR)	0.3				
Sunken pan dia. 50 cm, depth 25 cm (Netherlands)	0.2	1.0	.95	1.0	.95

Reference crop evapotranspiration, ETo, can be obtained from:

$$ETo = Kp \times Epan$$

where Epan = pan evaporation and represents the mean daily value of the period considered, mm/day, and

Kp = pan coefficient.

Values for Kp are given in table 17 for the class Apan and in table 18 for the sunken Colorado pan for different humidity and wind conditions and pan environment.

Table 17. Pan coefficient Kp for class A pan for different ground cover and levels of mean relative humidity and 24 hour wind (Burman, 1980).

CASE A Class A pan		Pan surrounded by short green crop			CASE B Pan surrounded by dry-fallow land			
RH mean %		Low < 40	Medium 40-70	High > 70		Low < 40	Medium 40-70	High > 70
Wind km/day	Upwind distance of crop (m)				Upwind distance of dry fallow (m)			
Light < 175	0	0.55	0.65	0.75	0	0.70	0.80	0.85
	10	0.65	0.75	0.85	10	0.60	0.70	0.80
	100	0.70	0.80	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.50	0.60	0.70
Moderate 175-425	0	0.50	0.60	0.65	0	0.65	0.75	0.80
	10	0.60	0.70	0.75	10	0.55	0.65	0.70
	100	0.65	0.75	0.80	100	0.50	0.60	0.65
	1000	0.70	0.80	0.80	1000	0.45	0.55	0.60
Strong 425-700	0	0.45	0.50	0.60	0	0.60	0.65	0.70
	10	0.55	0.60	0.65	10	0.50	0.55	0.65
	100	0.60	0.65	0.70	100	0.45	0.45	0.60
	1000	0.65	0.70	0.75	1000	0.40	0.45	0.55
Very strong > 700	0	0.40	0.45	0.50	0	0.50	0.60	0.65
	10	0.45	0.55	0.60	10	0.45	0.50	0.55
	100	0.50	0.60	0.65	100	0.40	0.45	0.50
	1000	0.55	0.60	0.65	1000	0.35	0.40	0.45

Table 18. Pan coefficient, Kp, for Colorado sunken pan for different ground cover and levels of relative humidity and 24 hour wind (Doorenbos and Pruitt, 1977).

Sunken Colorado	Case A: Pan placed in short green cropped area				Case B 1/ Pan placed in dry fallow area			
RHmean %		low <40	medium 40-70	high >70		low <40	medium 40-70	high >70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.75	.75	.8	1	1.1	1.1	1.1
	10	1.0	1.0	1.0	10	.85	.85	.85
	>100	1.1	1.1	1.1	100	.75	.75	.8
					1 000	.7	.7	.75
Moderate 175-425	1	.65	.7	.7	1	.95	.95	.95
	10	.85	.85	.9	10	.75	.75	.75
	>100	.95	.95	.95	100	.65	.65	.7
					1 000	.6	.6	.65
Strong 425-700	1	.55	.6	.65	1	.8	.8	.8
	10	.75	.75	.75	10	.65	.65	.65
	>100	.8	.8	.8	100	.55	.6	.65
					1 000	.5	.55	.6
Very strong >700	1	.5	.55	.6	1	.7	.75	.75
	10	.65	.7	.7	10	.55	.6	.65
	>100	.7	.75	.75	100	.5	.55	.6
					1 000	.45	.5	.55

1/ For extensive areas of bare-fallow soils and no agricultural development, reduce Kpan by 20% under hot, windy conditions; by 5-10% for moderate wind, temperature and humidity conditions.

The Kp values relate to pans located in an open field with no crops taller than 1 m within some 50 m of the pan. Immediate surrounding within 10 m are covered by a green frequently mowed grass cover or by bare soils. The pan station is placed in an agricultural area. The pan is increased. Case A and B are explained in detail in appendix 4 c.

2.2.2.5 Jensen-Haise method

Jensen-Haise method uses solar radiation, air temperature and coefficients based on elevation and long term mean temperature. This method gives an estimate of reference crop evapotranspiration, ETo (potential evapotranspiration). The estimation of ETo and the crop coefficients must be based on the same reference crop. The Jensen-Haise method is as follows:

$$ETo = 10 \times CT\ (T - Tx)\ \frac{Rs}{L} \quad \text{(Jensen et al., 1970)}$$

where ETo = reference crop evapotranspiration, mm/day

CT = air temperature coefficient which is constant for a given area

T = mean daily temperature, ^{o}C

Tx = constant for the given area and it is merely the linear equation intercept on the temperature axis

Rs = daily solar radiation, langleys/day

L = 595 - 0,51 T (Burman, 1980), latent heat of vaporization, cal/g.

If accurate evapotranspiration data are available for an area, CT and Tx can be determined by calibration. But if calibration data is not available, then at normal mean temperatures, CT in $^{o}C^{-1}$ may be calculated using

$$CT = \frac{1}{C_1 + 7{,}3\ CH} \quad \text{(Jensen et al., 1970)}$$

$$CH = \frac{50\ mb}{e_2 - e_1} \quad \text{(Jensen et al., 1970)}$$

where e_2 is the saturation vapour pressure of water, mb, at the mean monthly maximum air temperature of the warmest month in the year (long term climatic data), and e_1 is the saturation vapour pressure of water, mb, at the mean monthly minimum air temperature of the warmest month in the year. C_1 in the equation for CT varies with elevation as

$$C_1 = 38 - \frac{2EL}{305} \quad \text{(Burman, 1980)}$$

where EL = the site elevation, m.

Tx in the equation for ETo is given by

$$Tx = -2{,}5 - 0{,}14\ (e_2 - e_1) - \frac{EL}{550} \quad \text{(Burman, 1980)}.$$

2.2.2.6 Selection of crop coefficients

The five methods described in part 2.2.2 predict the effect of climate on reference crop evapotranspiration ETo. To account for the effect of the crop characteristics on crop water requirements, crop coefficients are presented to relate ETo to crop evapotranspiration, ETcrop. The kc value relates to evapotranspiration of a disease-free crop grown in large fields under optimum soil water and fertility conditions and achieving full production potential under the given growing environment. ETcrop can be found by:

ETcrop = kc x ETo (Wright, 1981)

where kc = dimensionless crop coefficient for a particular crop at a given stage and soil moisture conditions

ETcrop = daily crop evapotranspiration, mm/day

ETo = reference evapotranspiration, mm/day.

The crop coefficient (kc = ETcrop/ETo) includes the effects of evaporation from both plant and soil surfaces, and is thus dependent upon soil water availability within the root zone and the wetness of the exposed soil surface. Soil evaporation is proportionally greater during the portions of the growing season when the crop canopy is at less than effective full cover. The time-scale of kc is, of course, dependent upon that of ETcrop and ETo.

Changes in soil water content with time are commonly used to obtain ETcrop. Gravimetric sampling and neutron probe methods produce 3 - 5 day averages but even in carefully planned studies uncertainty exists concerning the significance of upward or downward movement of water and extraction by deep roots. Weighing lysimeters can provide daily ETcrop data which are not subject to errors in assessing soil water movement and the relative proportion of soil evaporation and transpiration can be estimated.

Factors affecting the value of the crop coefficient, kc, are mainly the crop characteristics, crop planting or sowing data, rate of crop development, length of growing season and climatic conditions. Particularly following sowing and during the early growth stage, the frequency of rain or irrigation is important.

The steps needed to arrive at the kc values for the different stages are as follows (Doorenbos and Pruitt, 1977):

i) establish planting or sowing data from local information or from practices in similar climatic zones;

ii) determine total growing season and length of crop development stage from local information (for approximation see table 20);

iii) initial stage: predict irrigation and/or rainfall frequency, for predetermined ETo value, obtain kc from figure 8 plot kc value as shown in figure 9;

iv) mid-season stage: for given climate (humidity and wind) select kc value from table 19 and plot as a straight line;

v) late season stage: for time of full maturity (or harvest within a few days), select kc value from table 19 for given climate (humidity and wind) and plot the value at the end of growing season or full maturity. Assume straight line between kc values at end of mid-season period and at end of growing season;

vi) development stage: assume straight line between kc value at end of initial to the start of mid-season stage.

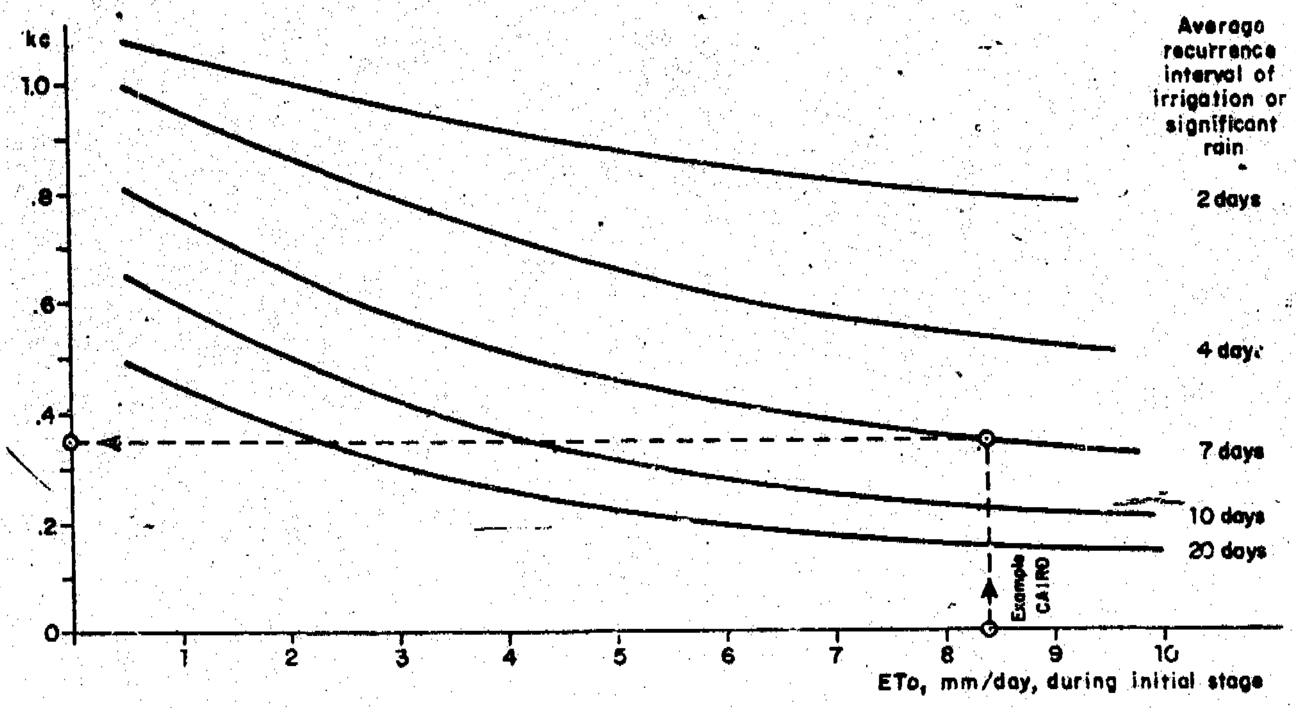


Fig. 8. Average kc value for initial crop development stage as related to level of ETo and frequency of irrigation and/or significant rain (Doorenbos and Pruitt, 1977).

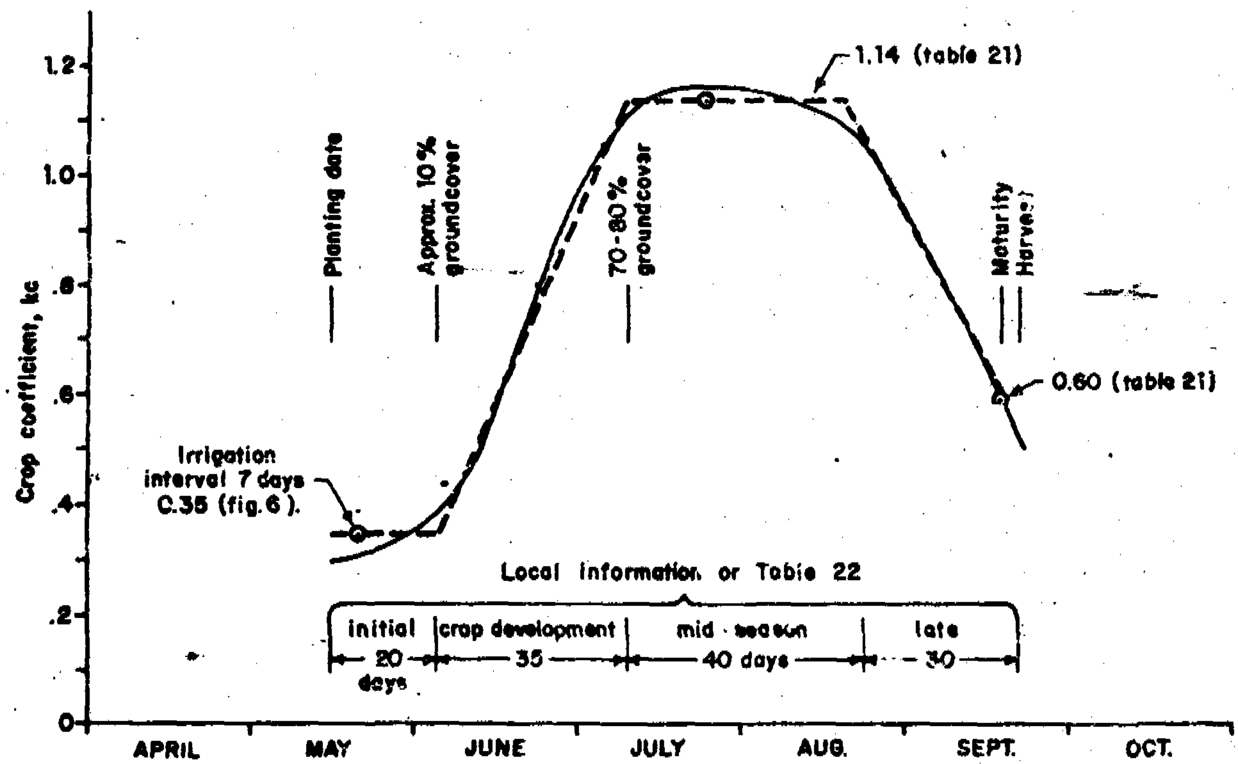


Fig. 9. Example of crop coefficient curve (Doorenbos and Pruitt, 1977).

For each 10 or 30 day period the kc values can be obtained from the prepared graph. A smoothed curve might first be drawn as indicated in figure 9, although this may have little effect in terms of accuracy added.

Table 19. Crop coefficient, kc, for field and vegetable crops for different stages of crop growth and prevailing climatic condition (Doorenbos and Pruitt, 1977).

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
	Crop stage					
All field crops	initial	1	Use Fig. 7			
"	crop dev.	2	by interpolation			
Artichokes (perennial-clean cultivated)	mid-season	3	.95	.95	1.0	1.05
	at harvest or maturity	4	.9	.9	.95	1.0
Barley		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Beans (green)		3	.95	.95	1.0	1.05
		4	.85	.85	.9	.9
Beans (dry)		3	1.05	1.1	1.15	1.2
Pulses		4	.3	.3	.25	.25
Beets (table)		3	1.0	1.0	1.05	1.1
		4	.9	.9	.95	1.0
Carrots		3	1.0	1.05	1.1	1.15
		4	.7	.75	.8	.85
Castorbeans		3	1.05	1.1	1.15	1.2
		4	.5	.5	.5	.5
Celery		3	1.0	1.05	1.1	1.15
		4	.9	.95	1.0	1.05
Corn (sweet)		3	1.05	1.1	1.15	1.2
(maize)		4	.95	1.0	1.05	1.1
Corn (grain)		3	1.05	1.1	1.15*	1.2
(maize)		4	.55	.55	.6 *	.6
Cotton		3	1.05	1.15	1.2	1.25
		4	.65	.65	.65	.7
Crucifers (cabbage, cauliflower, broccoli,		3	.95	1.0	1.05	1.1
Brussels sprout)		4	.80	.85	.9	.95
Cucumber		3	.9	.9	.95	1.0
Fresh market		4	.7	.7	.75	.8
Machine harvest		4	.85	.85	.95	1.0
Egg plant		3	.95	1.0	1.05	1.1
(aubergine)		4	.8	.85	.85	.9
Flax		3	1.0	1.05	1.1	1.15
		4	.25	.25	.2	.2
Grain		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lentil		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lettuce		3	.95	.95	1.0	1.05
		4	.9	.9	.9	1.0
Melons		3	.95	.95	1.0	1.05
		4	.65	.65	.75	.75
Millet		3	1.0	1.05	1.1	1.15
		4	.3	.3	.25	.25

Table 19. Cont'd.

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
Oats	mid-season	3	1.05	1.1	1.15	1.2
	harvest/maturity	4	.25	.25	.2	.2
Onion (dry)		3	.95	.95	1.05	1.1
		4	.75	.75	.8	.85
(green)		3	.95	.95	1.0	1.05
		4	.95	.95	1.0	1.05
Peanuts (Groundnuts)		3	.95	1.0	1.05	1.1
		4	.55	.55	.6	.6
Peas		3	1.05	1.1	1.15	1.2
		4	.95	1.0	1.05	1.1
Peppers (fresh)		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Potato		3	1.05	1.1	1.15	1.2
		4	.7	.7	.75	.75
Radishes		3	.8	.8	.85	.9
		4	.75	.75	.8	.85
Safflower		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Sorghum		3	1.0	1.05	1.1	1.15
		4	.5	.5	.55	.55
Soybeans		3	1.0	1.05	1.1	1.15
		4	.45	.45	.45	.45
Spinach		3	.95	.95	1.0	1.05
		4	.9	.9	.95	1.0
Squash		3	.9	.9	.95	1.0
		4	.7	.7	.75	.8
Sugarbeet		3	1.05	1.1	1.15	1.2
		4	.9	.95	1.0	1.0
	no irrigation last month	4	.6	.6	.6	.6
Sunflower		3	1.05	1.1	1.15	1.2
		4	.4	.4	.35	.35
Tomato		3	1.05	1.1	1.2	1.25
		4	.6	.6	.65	.65
Wheat		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2

NB: Many cool season crops cannot grow in dry, hot climates. Values of kc are given for latter conditions since they may occur occasionally, and result in the need for higher kc values, especially for tall rough crops.

Table 20. Length of growing season and crop development stage of selected field crops; some indications (Doorenbos and Pruitt, 1977).

Artichokes	Perennial, replanted every 4-7 years; example Coastal California with planting in April 40/40/250/30 and (360)1/; subsequent crops with crop growth cutback to ground level in late spring each year at end of harvest or 20/40/220/30 and (310).
Barley	Also wheat and oats; varies widely with variety; wheat Central India November planting 15/25/50/30 and (120); early spring sowing, semi-arid, 35°-45° latitudes and November planting Rep. of Korea 20/25/60/30 and (135); wheat sown in July in East African highlands at 2 500 m altitude and Rep. of Korea 15/30/65/40 and (150).
Beans (green)	February and March planting California desert and Mediterranean 20/30/30/10 and (90); August-September planting California desert, Egypt, Coastal Lebanon 15/25/25/10 and (75).
Beans (dry) Pulses	Continental climates late spring planting 20/30/40/20 and (110); June planting Central California and West Pakistan 15/25/35/20 and (95); longer season varieties 15/25/50/20 and (110).
Beets (table)	Spring planting Mediterranean 15/25/20/10 and (70); early spring planting Mediterranean climates and pre-cool season in desert climates 25/30/25/10 and (90).
Carrots	Warm season of semi-arid to arid climates 20/30/30/20 and (100); for cool season up to 20/30/80/20 and (150); early spring planting Mediterranean 25/35/40/20 and (120); up to 30/40/60/20 and (150) for late winter planting.
Castorbeans	Semi-arid and arid climates, spring planting 25/40/65/50 and (180).
Celery	Pre-cool season planting semi-arid 25/40/95/20 and (180); cool season 30/55/105/20 and (210); humid Mediterranean mid-season 25/40/45/15 and (125).
Corn (maize) (sweet)	Philippines, early March planting (late dry season) 20/20/30/10 and (80); late spring planting Mediterranean 20/25/25/10 and (80); late cool season planting desert climates 20/30/30/10 and (90); early cool season planting desert climates 20/30/50/10 and (110).
Corn (maize) (grains)	Spring planting East African highlands 30/50/60/40 and (180); late cool season planting, warm desert climates 25/40/45/30 and (140); June planting sub-humid Nigeria, early October India 20/35/40/30 and (125); early April planting Southern Spain 30/40/50/30 and (150).

1/ 40/40/250/30 and (360) stand respectively for initial, crop development, mid-season and late season crop development stages in days and (360) for total growing period from planting to harvest in days.

Table 20. Cont'd.

Cotton	March planting Egypt, April-May planting Pakistan, September planting South Arabia 30/50/60/55 and (195); spring planting, machine harvested Texas 30/50/55/45 and (180).
Crucifers	Wide range in length of season due to varietal differences; spring planting Mediterranean and continental climates 20/30/20/10 and (80); late winter planting Mediterranean 25/35/25/10 and (95); autumn planting Coastal Mediterranean 30/35/90/40 and (195).
Cucumber	June planting Egypt, August-October California desert 20/30/40/15 and (105); spring planting semi-arid and cool season arid climates, low desert 25/35/50/20 and (130).
Egg plant	Warm winter desert climates 30/40/40/20 and (130); late spring-early summer planting Mediterranean 30/45/40/25 and (140).
Flax	Spring planting cold winter climates 25/35/50/40 and (150); pre-cool season planting Arizona low desert 30/40/100/50 and (220).
Grain, small	Spring planting Mediterranean 20/30/60/40 and (150); October-November planting warm winter climates; Pakistan and low deserts 25/35/65/40 and (165).
Lentil	Spring planting in cold winter climates 20/30/60/40 and (150); pre-cool season planting warm winter climates 25/35/70/40 and (170).
Lettuce	Spring planting Mediterranean climates 20/30/15/10 and (75) and late winter planting 30/40/25/10 and (105); early cool season low desert climates from 25/35/30/10 and (100); late cool season planting, low deserts 35/50/45/10 and (140).
Melons	Late spring planting Mediterranean climates 25/35/40/20 and (120); mid-winter planting in low desert climates 30/45/65/20 and (160).
Millet	June planting Pakistan 15/25/40/25 and (105); central plains U.S.A. spring planting 20/30/55/35 and (140).
Oats	See Barley.
Onion (dry)	Spring planting Mediterranean climates 15/25/70/40 and (150); pre-warm winter planting semi-arid and arid desert climates 20/35/110/45 and (210).
(green)	Respectively 25/30/10/5 and (70) and 20/45/20/10 and (95).
Peanuts (groundnuts)	Dry season planting West Africa 25/35/45/25 and (130); late spring planting Coastal plains of Lebanon and Israel 35/45/35/25 and (140).
Peas	Cool maritime climates early summer planting 15/25/35/15 and (90); Mediterranean early spring and warm winter desert climates planting 20/25/35/15 and (95); late winter Mediterranean planting 25/30/30/15 and (100).

Table 20. Cont'd.

Peppers	Fresh - Mediterranean early spring and continental early summer planting 30/35/40/20 and (125); cool coastal continental climates mid-spring planting 25/35/40/20 and (120); pre-warm winter planting desert climates 30/40/110/30 and (210).
Potato (Irish)	Full planting warm winter desert climates 25/30/30/20 and (105); late winter planting arid and semi-arid climates and late spring-early summer planting continental climate 25/30/45/30 and (130); early-mid spring planting central Europe 30/35/50/30 and (145); slow emergence may increase length of initial period by 15 days during cold spring.
Radishes	Mediterranean early spring and continental summer planting 5/10/15/5 and (35); coastal Mediterranean late winter and warm winter desert climates planting 10/10/15/5 and (40).
Safflower	Central California early-mid spring planting 20/35/45/25 and (125) and late winter planting 25/35/55/30 and (145); warm winter desert climates 35/55/60/40 and (190).
Sorghum	Warm season desert climates 20/30/40/30 and (120); mid-June planting Pakistan, May in mid-West U.S.A. and Mediterranean 20/35/40/30 and (125); early spring planting warm arid climates 20/35/45/30 and (130).
Soybeans	May planting Central U.S.A. 20/35/60/25 and (140); May-June planting California desert 20/30/60/25 and (135); Philippines late December planting, early dry season - dry: 15/15/40/15 and (85); vegetables 15/15/30/- and (60); early-mid June planting in Japan 20/25/75/30 and (150).
Spinach	Spring planting Mediterranean 20/20/15/5 and (60); September-October and late winter planting Mediterranean 20/20/25/5 and (70); warm winter desert climates 20/30/40/10 and (100).
Squash (winter) pumpkin	Late winter planting Mediterranean and warm winter desert climates 20/30/30/15 and (95); August planting California desert 20/35/30/25 and (110); early June planting maritime Europe 25/35/35/25 and (120).
Squash (zucchini) crookneck	Spring planting Mediterranean 25/35/25/15 and (100+); early summer Mediterranean and maritime Europe 20/30/25/15 and (90+); winter planting warm desert 25/35/25/15 and (100).
Sugarbeet	Coastal Lebanon, mid-November planting 45/75/80/30 and (230); early summer planting 25/35/50/50 and (160); early spring planting Uruguay 30/45/60/45 and (180); late winter planting warm winter desert 35/60/70/40 and (205).
Sunflower	Spring planting Mediterranean 25/35/45/25 and (130); early summer planting California desert 20/35/45/25 and (125).
Tomato	Warm winter desert climates 30/40/40/25 and (135); and late autumn 35/45/70/30 and (180); spring planting Mediterranean climates 30/40/45/30 and (145).
Wheat	See Barley.

Table 21. Kc values for crops at different crop development stages (Kassam and Pruitt, 1979).

CROP	Crop Development stages					Total growing period
	Initial	Crop develop-ment	Mid-season	Late season	At harvest	
Banana						
tropical	0.4 -0.5	0.7 -0.85	1.0 -1.1	0.9 -1.0	0.75-0.85	0.7 -0.8
subtropical	0.5 -0.65	0.8 -0.9	1.0 -1.2	1.0 -1.15	1.0 -1.15	0.85-0.95
Bean						
green	0.3 -0.4	0.65-0.75	0.95-1.05	0.9 -0.95	0.85-0.95	0.85-0.9
dry	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7 -0.8
Cabbage	0.4 -0.5	0.7 -0.8	0.95-1.1	0.9 -1.0	0.8 -0.95	0.7 -0.8
Cotton	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.9	0.65-0.7	0.8 -0.9
Grape	0.35-0.55	0.6 -0.8	0.7 -0.9	0.6 -0.8	0.55-0.7	0.55-0.75
Groundnut	0.4 -0.5	0.7 -0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3 -0.5	0.7 -0.9	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
grain	0.3 -0.5*	0.7 -0.85*	1.05-1.2*	0.8 -0.95	0.55-0.6*	0.75-0.9*
Onion						
dry	0.4 -0.6	0.7 -0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8 -0.9
green	0.4 -0.6	0.6 -0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4 -0.5	0.7 -0.85	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
Pepper, fresh	0.3 -0.4	0.6 -0.75	0.95-1.1	0.85-1.0	0.8 -0.9	0.7 -0.8
Potato	0.4 -0.5	0.7 -0.8	1.05-1.2	0.85-0.95	0.7 -0.75	0.75-0.9
Rice	1.1 -1.15	1.1 -1.5	1.1 -1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.7	0.2 -0.25	0.65-0.7
Sorghum	0.3 -0.4	0.7 -0.75	1.0 -1.15	0.75-0.8	0.5 -0.55	0.75-0.85
Soybean	0.3 -0.4	0.7 -0.8	1.0 -1.15	0.7 -0.8	0.4 -0.5	0.75-0.9
Sugarbeet	0.4 -0.5	0.75-0.85	1.05-1.2	0.9 -1.0	0.6 -0.7	0.8 -0.9
Sugarcane	0.4 -0.5	0.7 -1.0	1.0 -1.3	0.75-0.8	0.5 -0.6	0.85-1.05
Sunflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.7 -0.8	0.35-0.45	0.75-0.85
Tobacco	0.3 -0.4	0.7 -0.8	1.0 -1.2	0.9 -1.0	0.75-0.85	0.85-0.95
Tomato	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.95	0.6 -0.65	0.75-0.9
Watermelon	0.4 -0.5	0.7 -0.8	0.95-1.05	0.8 -0.9	0.65-0.75	0.75-0.85
Wheat	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.2 -0.25	0.8 -0.9
Alfalfa	0.3 -0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4 -0.6

First figure : Under high humidity (RHmin >70%) and low wind (U <5 m/sec).
Second figure: Under low humidity (RHmin <20%) and strong wind (>5 m/sec).

2.2.3 Choice of method for estimating potential evapotranspiration, ETo

The method selected for a particular use may depend on the availability and accuracy of available meteorological data, the training and experience of the user, and the general acceptance of previous estimates. Many evaluations of the presented methods clearly indicate that no single existing method using meteorological data is universally adequate under all climatic regions, especially for tropical areas and for high elevations, without some local or regional calibration (Jensen, 1973).

Availability of meteorological data alone should not be the sole criterion in selecting a method since some of the needed data can be estimated with sufficient accuracy by trained and experienced engineers and scientists to permit using one of the better estimating methods. If reliable and accurate ETcrop data such as that obtained from weighing lysimeter are available in a region, local calibration is recommended.

In general, energy balance or energy balance - aerodynamic equations (Penman) will provide the most accurate results of the various meteorological methods since they are based on physical laws and rational relationships. Evaporation data is relatively easy to obtain and can be very reliable if the evaporation site is maintained in a suitable and consistent manner. Evaporation data collected in poorly maintained installation may not produce estimates as accurate as these based on good meteorological data (Jensen, 1973).

Concerning the accuracy of the methods, only approximate possible errors can be given since no base-line type of climate exists. Penman method would offer the best results with minimum possible error of ± 10 per cent and up to

20 per cent under low evaporative conditions. Pan evaporation method can be graded next with possible error of 15 per cent depending on the location of the pan. The radiation method, in extreme condition, involves a possible error of up to 20 per cent. The Blaney-Criddle method should only be applied for periods of one month or longer, in humid, windy, mid-latitude water conditions, an over and under prediction of up to 25 per cent has been noted (Doorenbos and Pruitt, 1977).

Furthermore, more estimates of ETo with Penman equation are reliable for periods of 1 day to 1 month, while estimates obtained by using Jensen-Haise method are reliable for periods of 5 days to 1 month, and estimates from FAO Blaney-Criddle (revised Blaney-Criddle) gives reliable estimates for periods of from 10 days to 1 month. If ET of shorter periods is required then Penman method is the best choice, followed by Jensen-Haise, radiation, and FAO Blaney-Criddle methods respectively. The absence of complete climatic data limits the use of Penman equation (Doorenbos and Pruitt, 1977). Based on the above discussion and the availability of reliable meteorological data in Tanzanian projects, Penman method is strongly recommended to be used in Mbarali and Mombo irrigation projects.

2.3 Water holding capacity of the root zone soil

The capacity of a soil to retain water available to plants has a direct bearing on the required depth and frequency of irrigation. There are three important terms to be considered in relation to waterholding capacity: field capacity, wilting percentage and available moisture.

2.3.1 Field capacity

When the soil is saturated and thereafter the water is drained, the moisture content decreases. The process (drainage) continues under the action of gravity until a moisture content is reached which corresponds to a matric potential at equilibrium with the gravity potential. This moisture content is considered as field capacity (mm/m) which is the maximum moisture content that can be maintained by the soil suction. The corresponding suction (matric potential) at field capacity ranges between 100 to 300 cm (Stackman, 1980).

2.3.2 Wilting percentage or point

If the matric potential of the soil reaches a value of 16 000 cm (i.e. PF = 4,2), the plants cannot extract any soil moisture and suffer the lack of water in the soil. This limit of soil moisture is called the wilting point (mm/m).

2.3.3 Available moisture

The difference in moisture content at field capacity and at wilting point is called the available moisture (mm/m). Generally, about 50 to 75 % of the available moisture can be considered easily obtainable by the plants and this is called readily available moisture (FAO, 1979).

2.4 Effective rainfall

Not all rainfall is effective and part may be lost by surface runoff, deep percolation or evaporation. Only a portion of heavy and high intensity rains can enter and be stored in the root zone and the effectiveness is consequently low. Frequent light rains intercepted by plant foliage with full ground cover are close to 100 per cent effective. With a dry soil surface and little or no vegetative cover, rainfall up to 8 mm/day may all be lost by evaporation; rains of 25 to 30 mm may be only 60 per cent effective with a low percentage of vegetative cover (Burman, 1980). Effective rainfall can be estimated by the evapotranspiration/precipitation ratio method.

Table 22. Average monthly effective rainfall as related to the average monthly ETcrop and mean monthly rainfall (Burman, 1980).

Monthly mean rainfall mm	Mean monthly consumptive use mm													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
	Mean monthly effective rainfall mm													
12.5	7.5	8.0	8.7	9.0	9.2	10.0	10.5	11.2	11.7	12.5	12.5	12.5	12.5	12.5
25.0	15.0	16.2	17.5	18.0	18.5	19.7	20.5	22.0	24.5	25.0	25.0	25.0	25.0	25.0
37.5	22.5	24.0	26.2	27.5	28.2	29.2	30.5	33.0	36.2	37.5	37.5	37.5	37.5	37.5
50.0	25	32.2	34.5	35.7	36.7	39.0	40.5	43.7	47.0	50.0	50.0	50.0	50.0	50.0
62.5	at 41.7	39.7	42.5	44.5	46.0	48.5	50.5	53.7	57.5	62.5	62.5	62.5	62.5	62.5
75.0		46.2	49.7	52.7	55.0	57.5	60.2	63.7	67.5	73.7	75.0	75.0	75.0	75.0
87.5		50.0	56.7	60.2	63.7	66.0	69.7	73.7	77.7	84.5	87.5	87.5	87.5	87.5
100.0		at 60.7	63.7	67.7	72.0	74.2	78.7	83.0	87.7	95.0	100	100	100	100
112.5			70.5	75.0	80.2	82.5	87.2	92.7	98.0	105	111	112	112	112
125.0			75.0	81.5	87.7	90.5	95.7	102	108	115	121	125	125	125
137.5			at 122	88.7	95.2	98.7	104	111	118	126	132	137	137	137
150.0				95.2	102	106	112	120	127	136	143	150	150	150
162.5				100	109	113	120	128	135	145	153	160	162	162
175.0				at 160	115	120	127	135	143	154	164	170	175	175
187.5					121	126	134	142	151	161	170	179	185	187
200.0					125	133	140	145	158	168	178	188	196	200
225					at 197	144	151	160	171	182				
250						150	161	170	183	194				
275						at 240	171	181	194	205				
300							175	190	203	215				
325							at 287	198	213	224				
350								200	220	232				
375								at 331	225	240				
400									at 372	247				
425										250				
										at 412				
450	25	50	75	100	125	150	175	200	225	250				

Where the net depth of water that can be stored in the soil at the time of irrigation is greater or less than 75 mm, the correction factor to be used is:

Effective storage	20	25	37,5	50	62,5	75	100	125	150	175	200
Storage factor	0,73	0,77	0,86	0,93	0,97	1,00	1,02	1,04	1,06	1,07	1,08

2.5 Irrigation requirements

Other than for meeting the net irrigation requirement (In = ETcrop - precipitation), water is needed to compensate for water losses during conveyance and application, and for leaching salts from the root zone. Leaching requirements, LR, and irrigation efficiency, E, are included as a fraction of the net irrigation requirements.

Water needed for land preparation may need to be considered in the case of paddy. At the planning stage normally no allowance is made for such needs for other crops; this applies similarly to water needs for cultural practices and aid to germination and quality control of the harvested yield. They are usually covered by adjusting irrigation schedules.

2.5.1 Irrigation efficiency

After determining net irrigation water requirements, an estimate of the expected irrigation efficiency is needed to determine gross irrigation water requirements. No irrigation system is capable of applying an exact amount of water with perfect uniformity. In addition, some water will be lost by evaporation during application, especially with sprinkler systems. Loss of water by evaporation during sprinkling may reduce the rate at which soil water normally would be extracted when not being irrigated so that this may not be a total loss (Burman, 1980).

Surface runoff, water spillage and leakage from the on-farm water distribution system also affect the expected farm irrigation efficiency. A major part of surface runoff and spillage may be recovered for use on a given farm if an effective reuse system is used.

Seepage from unlined farm ditches and deep percolation through the soil profile due to non-uniform and excessive water applications usually cannot be recovered for use on a given farm so as to affect the design irrigation efficiency.

Therefore, to account for losses of water incurred during conveyance and application to the field, an efficiency factor should be included when calculating the project irrigation requirements. Project efficiency is normally subdivided into three stages, each of which is affected by different set of conditions: conveyance efficiency, Ec, field canal efficiency, Eb and field application efficiency, Ea.

2.5.1.1 Conveyance efficiency

Conveyance efficiency is the ratio of the volume of water received at inlet to a block of fields and that released at the project headworks (Doorenbos and Pruitt, 1977). Conveyance efficiency can be stated as follows:

$$Ec = 100 \frac{Wf}{Wr} \quad (\%)$$ (Israelsen and Hansen, 1962).

where Ec = conveyance efficiency, per cent

Wf = water delivered to the farm, m^3/s

Wr = water diverted from the river or reservoir, m^3/s.

2.5.1.2 Field canal efficiency

Field canal efficiency, Eb, is the ratio between water received at the field inlet and that received at the inlet of the block of fields.

2.5.1.3 Field application efficiency, Ea

Field application efficiency is the ratio between water directly available to the crop and that received at the field inlet. This efficiency can be stated as:

$$Ea = 100 \frac{Ws}{Wf} \quad \text{(Israelsen and Hansen, 1962)}$$

where Ea = application efficiency, %
Ws = water stored in the soil root zone during irrigation
Wf = water delivered to the farm.

2.5.1.4 Project efficiency

Project efficiency is the ratio between water made directly available to the crop and that released at the headworks, or Ep = Ea x Eb x Ec.

2.5.2 Leaching requirements

Soil salinity is mainly affected by water quality, irrigation methods and practices, soil condition, and rainfall. Salinity levels in the soil generally increase as the growing season advances. Leaching can be practised during, before or after the crop season depending on available water supply, but provided that salt accumulation in the soil does not exceed the crop tolerance level. Table 23 can be used to evaluate the effect of the quality of the irrigation water on soil salinity, permeability and toxicity.

Table 23. Effect of irrigation water quality on soil salinity, permeability and toxicity (Ayers and Westcot, 1976).

	none	moderate	severe
Salinity			
ECw (mmhos/cm)	< 0.75	0.75 - 3.0	> 3.0
Permeability			
ECw (mmhos/cm)	> 0.5	0.5 - 0.2	< 0.2
adj. SAR			
Montmorillonite	< 6	6 - 9	> 9
Illite	< 8	8 - 16	> 16
Kaolinite	< 16	16 - 24	> 24
Toxicity (most tree crops)			
sodium (adj. SAR)	< 3	3 - 9	> 9
chloride (meq/l)	< 4	4 - 10	> 10
boron (mg/l)	< 0.75	0.75 - 2	> 2

The crop tolerance levels given in table 24 can be used to determine the leaching requirements for a given quality of irrigation water.

Crop tolerance levels are given as electrical conductivity of the soil saturation extract, Ece, in mmhos/cm. With poor quality water, frequent irrigation and excessive leaching water may be required to obtain acceptable yields. In table 24 values of quality of irrigation water are given which also relate to commonly experienced yield levels.

Leaching requirement, LR, is the minimum amount of irrigation water supplied that must be drained through the root zone to control soil salinity at the given specific level (Doorenbos and Pruitt, 1977). For sandy loam to clay loam soils with good drainage and where rainfall is low the leaching requirement can be obtained from:

for surface irrigation methods (including sprinklers)

$$LR = \frac{Ecw}{5Ece - Ecw}$$ (Doorenbos and Pruitt, 1977)

for drip and high frequency sprinkler (near daily)

$$LR = \frac{Ecw}{2maxEce}$$ (Doorenbos and Pruitt, 1977)

where Ecw = electrical conductivity of irrigation water, mmhos/cm

Ece = electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction (table 24), mmhos/cm

maxEce = maximum tolerable electrical conductivity of the soil saturation extract for a given crop (table 24).

When the leaching efficiency, Le, is 100 per cent the water needed to satisfy both ETcrop and Le is equal to (ETcrop - Pe)/(1 - LR), where Pe = rainfall. The leaching efficiency has been shown to vary with the soil type, and particularly with the internal drainage properties of the soil and the field (Doorenbos and Pruitt, 1977).

2.6 Amount of water for irrigation

2.6.1 Net water requirement

With known water requirements, ETcrop, and effective rainfall, Pe, of a given period, the net irrigation requirements, In, can be calculated from:

In = Etcrop - Pe (Vierhout, 1979).

Net irrigation requirement is the amount of water needed to supply the root zone with sufficient moisture.

Table 24. Crop salt tolerance levels for different crops (Ayers and Westcot, 1976).

Crop	Yield potential 100%		90%		75%		50%		Max. ECe
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	
Field crops									
Barley 1/	8.0	5.3	10.0	6.7	13.0	8.7	18.0	12.0	28
Beans (field)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	7
Broad beans	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Cotton	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0	27
Cowpeas	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	9
Flax	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Groundnut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	7
Rice (paddy)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	12
Safflower	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	15
Sesbania	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17
Sorghum	4.0	2.7	5.1	3.4	7.2	4.8	11.0	7.2	18
Soybean	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
Sugarbeet	7.0	4.7	8.7	5.8	11.0	7.5	15.0	10.0	24
Wheat 1/	6.0	4.0	7.4	4.9	9.5	6.4	13.0	8.7	20
Vegetable crops									
Beans	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	7
Beets 2/	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
Broccoli	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14
Cabbage	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12
Cantaloupe	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
Carrot	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
Cucumber	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
Lettuce	1.3	0.9	2.1	1.4	3.2	2.1	5.2	3.4	9
Onion	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	8
Pepper	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	9
Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Radish	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	9
Spinach	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
Sweet corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet potato	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11
Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13
Forage crops									
Alfalfa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16
Barley hay 1/	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20
Bermuda grass	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	23
Clover, berseem	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
Corn (forage)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	16
Harding grass	4.6	3.1	5.9	3.9	7.9	5.3	11.1	7.4	18
Orchard grass	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18
Perennial rye	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
Soudan grass	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
Tall fescue	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8.9	23
Tall wheat grass	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13.0	32
Trefoil, big	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	8
Trefoil, small	5.0	3.3	6.0	4.0	7.5	5.0	10.0	6.7	15
Wheat grass	7.5	5.0	9.0	6.0	11.0	7.4	15.0	9.8	22
Fruit crops									
Almond	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7
Apple, pear	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8
Apricot	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6
Avocado	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6
Date palm	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12.0	32
Fig, olive, pomegranate	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
Grape	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Grapefruit	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8
Lemon	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Orange	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8
Peach	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	7
Plum	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Strawberry	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4
Walnut	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8

1/ During germination and seedling stage ECe should not exceed 4 or 5 mmhos/cm. Data may not apply to new semi-dwarf varieties of wheat.

2/ During germination ECe should not exceed 3 mmhos/cm.

2.6.2 Field water requirement

To account for the losses of water incurred during conveyance and application to the field, the net irrigation requirement is divided by the application efficiency. Therefore, the field water requirement is given by:

$$If = \frac{In}{Ea} \quad \text{(Vierhout, 1979)}$$

where If = field water requirement mm/period
In = net irrigation requirement, mm/period
Ea = application efficiency.

When the field water requirement and the area to be irrigated are known, the amount of water to be supplied to the field is determined by

$$Q = 10 \times If \times A \quad \text{(Breuer and Netzband, 1980)}$$

where Q = amount of water (m^3/period)
If = field water requirement (mm/period)
A = area, ha.

2.7 Availability of water supply

An important element in the evaluation of crop production under irrigation is the available and required water supply over time and acreage. When the available water supply is adequate and fully meets crop water requirements, the production is maximum and the required supply depends on the crop selected, the length of the growing season and the irrigated acreage. When the available water supply is limited, the production is determined by the extent to which full water requirements can be met by the available water water supply over the total growing season (Kassam and Doorenbos, 1979).

To plan, design and operate the water supply and distribution system for the project in relation to the available water and water requirements, the procedure must consider i) selection of crops and cropping pattern, ii) monthly (or ten-day) and peak supply requirements, and iii) schedule of irrigation water supply over the growing season (Kassam and Doorenbos, 1979).

2.7.1 Selection of crops and cropping patterns

When water supply is adequate, crops and cropping patterns that can be considered suitable will be those whose climatic requirements are met by the prevailing climatic conditions and the length of the growing season (table 25).

When data on crop yields are not available for the given location, a first estimate can be made with the help of table 26 or can be calculated by the yield prediction methods.

Table 25. Climatic, soil and water requirements for crops (Kassam and Doorenbos, 1979).

Crop	Total growing period (days)	Temperature requirements for growth, °C optimum[1]/(range)	Daylength requirements for flowering	Specific climatic constraints/ requirements	Soil requirements
Alfalfa	100-365	24-26 (10-30)	Day neutral	Sensitive to frost; cutting interval related to temp.; requires low RH in warm climates	Deep, medium-textured, well-drained, pH = 6.5-7.5
Banana	300-365	25-30 (15-35)	Day neutral	Sensitive to frost; temp. <8°C for longer periods causes serious damage; requires high RH, wind < 4 m/sec	Deep, well-drained loam without stagnant water: pH = 5-7
Bean	fresh: 60-90 dry : 90-120	15-20 (10-27)	Short day/ day neutral	Sensitive to frost; excessive rain, hot weather	Deep, friable soil, well-drained and aerated; opt. pH = 5.5-6.0
Cabbage	100-150+	15-20 (10-24)	Long day	Short periods of frost (-6 to -10°C) are not harmful; opt. RH = 60-90%	Well-drained; opt. pH = 6.0-6.5
Citrus	240-365	23-30 (13-35)	Day neutral	Sensitive to frost (dormant trees less), strong wind, high humidity; cool winter or short dry period preferred	Deep, well-aerated, light to medium-textured soils, free from stagnant water; pH 5-8
Cotton	150-180	20-30 (16-35)	Short day/ day neutral	Sensitive to frost; strong or cold winds; temp. req. for boll development: 27-32°C (18-38); dry ripening period required	Deep, medium to heavy-textured soils; pH = 5.5-8.0 with opt. pH = 7.0-8.0
Grape	180-270	20-25 (15-30)		Resistant to frost during dormancy (down to -18°C) but sensitive during growth; long, warm to hot, dry summer and cool winter preferred/ required	Well-drained, light soils are preferred
Groundnut	90-140	22-28 (18-33)	Day neutral	Sensitive to frost; for germination temp. >20°C	Well-drained, friable, medium-textured soil with loose top soil; pH = 5.5-7.0
Maize	100-140+	24-30 (15-35)	Day neutral/ short day	Sensitive to frost; for germination temp. >10°C; cool temp. causes problem for ripening	Well-drained and aerated soils with deep water table and without waterlogging; opt. pH = 5.0-7.0
Olive	210-300	20-25 (15-35)		Sensitive to frost (dormant trees less); low winter temp. required (< 10°C) for flower bud initiation	Deep, well-drained soils free from waterlogging
Onion	100-140 (+30-35 in nursery)	15-20 (10-25)	Long day/ day neutral	Tolerant to frost; low temp. (< 14-16°C) required for flower initiation; no extreme temp. or excessive rain	Medium-textured soil; pH = 6.0-7.0
Pea	fresh: 65-100 dry : 85-120	15-18 (10-23)	Day neutral	Slight frost tolerance when young	Well-drained and aerated soils; pH = 5.5-6.5
Pepper	120-150	18-23 (15-27)	Short day/ day neutral	Sensitive to frost	Light to medium-textured soils; pH = 5.5-7.0
Pineapple	365	22-26 (18-30)	Short day	Sensitive to frost; requires high RH; quality affected by temperature	Sandy loam with low lime content; pH = 4.5-6.5
Potato	100-150	15-20 (10-25)	Long day/ day neutral	Sensitive to frost; night temp. < 15°C required for good tuber initiation	Well-drained, aerated and porous soils; pH = 5-6
Rice	90-150	22-30 (18-35)	Short day/ day neutral	Sensitive to frost; cool temp. causes head sterility; small difference in day and night temp. is preferred	Heavy soils preferred for percolation losses, high tolerance to O_2 deficit; pH = 5.5-6.0
Safflower	spring: 120-160 autumn: 200-230	early growth: 15-20 later growth: 20-30 (10-35)		Tolerant to frost; cool temp. req. for good establishment and early growth	Fairly deep, well-drained soils, preferably medium-textured; pH = 6-8
Sorghum	100-140+	24-30 (15-35)	Short day/ day neutral	Sensitive to frost; for germination temp. > 10°C; cool temp. causes head sterility	Light to medium/heavy soils relatively tolerant to periodic waterlogging, pH = 6-8
Soybean	100-130	20-25 (18-30)	Short day/ day neutral	Sensitive to frost; for some var. temp. >24°C required for flowering	Wide range of soil except sandy, well-drained; pH = 6-6.5
Sugarbeet	160-200	18-22 (10-30)	Long day	Tolerant to light frost; toward harvest mean daily temp. <10°C for high sugar yield	Medium to slightly heavy-textured soils, friable and well-drained; pH = 6-7
Sugarcane	270-365	22-30 (15-35)	Short day/ day neutral	Sensitive to frost; during ripening cool (10-20°C), dry, sunny weather is required	Deep, well aerated with ground water deeper than 1.5-2 m but rel. tolerant to periodic high water tables and O_2 deficit; pH = 5-8.5; opt pH = 6.5
Sunflower	90-130	18-25 (15-30)	Short day/ day neutral	Sensitive to frost	Fairly deep soils; pH = 6-7.5
Tobacco	90-120 (+40-60 in nursery	20-30 (15-35)	Short day/ day neutral	Sensitive to frost	Quality of leaf depends on soil texture; pH = 5-6.5
Tomato	90-140 (+25-35 in nursery)	18-25 (15-28)	Day neutral	Sensitive to frost, high RH, strong wind; opt. night temp. 10-20°C	Light loam, well-drained without waterlogging; pH = 5-7
Watermelon	80-110	22-30 (18-35)	Day neutral	Sensitive to frost	Sandy loam is preferred; pH = 5.8-7.2
Wheat	spring: 100-130 winter: 180-250	15-20 (10-25)	Day neutral/ long day	Spring wheat: sensitive to frost; Winter wheat: resistant to frost during dormancy (> -18°C), sensitive during post-dormancy period; requires a cold period for flowering during early growth. For both, dry period required for ripening	Medium-texture is preferred; relatively tolerant to high water table; pH = 6-8

[1] mean daily temperatures

Table 25. Cont'd.

Sensitivity to salinity	Fertilizer requirements N : P : K kg/ha/growing period	Water requirements mm/growing period	Sensitivity to water supply (ky)	Water utilization efficiency for harvested yield, Ey, kg/m³ (% moisture)	Crop
moderately sensitive	0-40 : 55-65 : 75-100	800-1600	low to medium-high (0.7-1.1)	1.5 - 2.0 hay (10-15%)	Alfalfa
sensitive	200-400: 45-60 : 240-480	1200-2200	high (1.2-1.35)	plant crop: 2.5-4 ratoon : 3.5-6 fruit (70%)	Banana
sensitive	20-40 : 40-60 : 50-120	300-500	medium-high (1.15)	lush : 1.5-2.0 (80-90%) dry : 0.3-0.6 (10%)	Bean
moderately sensitive	100-150: 50-65 : 100-130	380-500	medium-low (0.95)	12-20 head (90-95%)	Cabbage
sensitive	100-200: 35-45 : 50-160	900-1200	low to medium-high (0.8-1.1)	2-5 fruit (85%, lime: 70%)	Citrus
tolerant	100-180: 20-60 : 50-80	700-1300	medium-low (0.85)	0.4-0.6 seed cotton (10%)	Cotton
moderately sensitive	100-160: 40-60 : 160-230	500-1200	medium-low (0.85)	2-4 fresh fruit (80%)	Grape
moderately sensitive	10-20 : 15-40 : 25-40	500-700	low (0.7)	0.6-0.8 unshelled dry nut (15%)	Groundnut
moderately sensitive	100-200: 50-80 : 60-100	500-800	high (1.25)	0.8-1.6 grain (10-13%)	Maize
moderately tolerant	200-250: 55-70 : 160-210	600-800	low	1.5-2.0 fresh fruit (30%)	Olive
sensitive	60-100: 25-45 : 45-80	350-550	medium-high (1.1)	8-10 bulb (85-90%)	Onion
sensitive	20-40 : 40-60 : 80-160	350-500	medium-high (1.15)	fresh: 0.5-0.7 shelled (70-80%) dry: 0.15-0.2 (12%)	Pea
moderately sensitive	100-170: 25-50 : 50-100	600-900 (1250)	medium-high (1.1)	1.5-3.0 fresh fruit (90%)	Pepper
	230-300: 45-65 : 110-220	700-1000	low	plant crop: 5-10 ratoon : 8-12 fruit (85%)	Pineapple
moderately sensitive	80-120: 50-80 : 125-160	500-700	medium-high (1.1)	4-7 fresh tuber (70-75%)	Potato
moderately sensitive	100-150: 20-40 : 80-120	350-700	high	0.7-1.1 paddy (15-20%)	Rice
moderately tolerant	60-110: 15-30 : 25-40	600-1200	low (0.8)	0.2-0.5 seed (8-10%)	Safflower
moderately tolerant	100-180: 20-45 : 35-80	450-650	medium-low (0.9)	0.6-1.0 grain (12-15%)	Sorghum
moderately tolerant	10-20 : 15-30 : 25-60	450-700	medium-low (0.85)	0.4-0.7 grain (6-10%)	Soybean
tolerant	150 : 50-70 : 100-160	550-750	low to medium-low (0.7-1.1)	beet : 6-9 (80-85%) sugar: 0.9-1.4 (0%)	Sugarbeet
moderately sensitive	100-200: 20-90 : 125-160	1500-2500	high (1.2)	cane : 5-8 (80%) sugar: 0.6-1.0 (0%)	Sugarcane
moderately tolerant	50-100: 20-45 : 60-125	600-1000	medium-low (0.95)	0.3-0.5 seed (6-10%)	Sunflower
sensitive	40-80 : 30-90 : 50-110	400-600	medium-low (0.9)	0.4-0.6 cured leaves (5-10%)	Tobacco
moderately sensitive	100-150: 65-110 : 160-240	400-600	medium-high (1.05)	10-12 fresh fruit (80-90%)	Tomato
moderately sensitive	80-100: 25-60 : 35-80	400-600	medium-high (1.1)	5-8 fruit (90%)	Watermelon
moderately tolerant	100-150: 35-45 : 25-50	450-650	medium-high (spring: 1.15 winter: 1.0)	0.8-1.0 grain (12-15%)	Wheat

1 kg P = 2.4 kg P_2O_5

1 kg K = 1.2 kg K_2O

Table 26. Good yield of high producing varieties adopted to the climatic conditions of the available growing season under adequate water supply and high level of agricultural inputs under irrigated farming conditions, ton/ha (Kassam and Doorenbos, 1979).

CROP		Climatic Regions					
		Tropics 1/		Subtropics 2/		Temperate 3/	
		<20°C 4/	>20°C	<20°C	>20°C	<20°C	>20°C
Alfalfa	hay	15		25		10	
Banana	fruit		40-60		30-40		
Bean: fresh	pod	6-8		6-8		6-8	
dry	grain	1.5-2.5		1.5-2.5		1.5-2.5	
Cabbage	head	40-60		40-60		40-60	
Citrus:							
grapefruit	fruit		35-50		40-60		
lemon	fruit		25-30		30-45		
orange	fruit		20-35		25-40		
Cotton	seed cotton		3-4		3-4.5		
Grape	fruit	5-10		15-30		15-25	
Groundnut	nut		3-4		3.5-4.5		1.5-2
Maize	grain	7-9	6-8	9-10	7-9		4-6
Olive	fruit			7-10			
Onion	bulb	35-45		35-45		35-45	
Pea: fresh	pod	2-3		2-3		2-3	
dry	grain	0.6-0.8		0.6-0.8		0.6-0.8	
Fresh pepper	fruit	15-20		15-25		15-20	
Pineapple	fruit		75-90		65-75		
Potato	tuber	15-20		25-35		30-40	
Rice	paddy		6-8		5-7		4-6
Safflower	seed			2-4			
Sorghum	grain	3-4	3.5-5	3-4	3.5-5		2-3
Soybean	grain	2.5-3.5		2.5-3.5			
Sugarbeet	beet			40-60		35-55	
Sugarcane	cane		110-150		100-140		
Sunflower	seed	2.5-3.5		2.5-3.5		2-2.5	
Tobacco	leaf		2-2.5		2-2.5		1.5-2
Tomato	fruit	45-65		55-75		45-65	
Water melon	fruit		25-35		25-35		
Wheat	grain	4-6		4-6		4-6	

1/ Semi-arid and arid areas only
2/ Summer and winter rainfall areas
3/ Oceanic and continental areas
4/ Mean temperature

Similarly an estimate of yield per unit water (Ey) for the climatically suitable crops can be obtained (table 26) to indicate the crop water requirements per unit of product. Calculation procedure:

a) Determine climatically suitable crops, collect available climatic data, evaluate climatic conditions in relation to crop requirements, select crops that are most suitable for the given climate and soil.

b) Determine cropping patterns. Determine most likely the length of growing periods of the selected crops in relation to the total growing season and time required for other farming operations.

c) Select optimum cropping pattern in relation to yield as determined by climate and select optimum cropping pattern and possible yields.

2.7.2 Monthly and peak supply requirements

The main variables in determining the monthly (or ten-day) and peak supply requirements are: the water requirements of the crops, the crop acreages, the efficiency of the supply and distribution system, and the leaching requirements. To minimize the design capacity of the system, adjustments in the crop calendar and crop practices may be required. These may vary from making optimum use of seasonal rainfall and water stored in the soil from pre-season rainfall to reducing peak supply requirements by shifting sowing dates so that different crops do not reach peak water requirements at the same time.

Calculation procedure of irrigation supply:

a) Crop water requirements, ETcrop
Calculate reference crop evapotranspiration, ETo, on a monthly or ten-day basis, select appropriate crop coefficient, kc, calculate crop water requirements, ETcrop = kc x ETo, in mm/period.

b) Net irrigation requirements, In
Determine effective rainfall, Pe, and ground water contribution, Ge, (normally Ge is assumed to be zero) to crop water requirements in mm/period, and actual depth of available soil water over the root depth at start of the growing period (Wb) in mm; calculate In = ETcrop - (Pe + Ge + Wb) in mm/period.

c) Irrigation supply requirements, Q
Determine leaching requirements and conveyance, Ec, field canal, Eb, and field application efficiency or project efficiency (Ep = Ec x Eb x Ea) as fraction, calculate for acreage (A):

$$Q = \frac{10}{Ep} \times \frac{A \times In}{1 - LR}, \ m^3/\text{period.}$$

2.7.3 Schedule for irrigation water supply over the growing season

For high crop production, the design and operation of the supply and distribution system of the project must be geared toward delivering water to the fields at the predetermined interval and depth of irrigation, which meets the changing water requirements of the crops over the growing season. The supply schedule within the supply and distribution system must be based on the supply requirements of the individual field. The supply requirements at the field level are expressed in irrigation interval, i, and in net irrigation depth, d, in mm.

2.7.3.1 Net irrigation depth

Net irrigation depth is the depth of water that can be stored within the root zone between soil field capacity, Sfc, and the allowable level the soil water can be depleted for crop, soil and climate. Data on type of soil and its water holding characteristics should be collected at site. The available soil water is expressed in mm/m soil depth (Doorenbos and Pruitt, 1977).

Not all water in the root zone held between soil field capacity, Sfc, and soil wilting point, Sw, is readily available to the crop. The level of maximum soil water depletion tolerated to maintain potential crop growth varies with type of crop. The depth of water readily available to the crop, w, is defined as:

$$w = P \times Sa$$ (Doorenbos and Pruitt, 1977)

where Sa = total available soil water, Sfc - Sw, mm/m

P = the fraction of the total available soil water which can be used by the crop without affecting its evapotranspiration and/or growth.

The value of P depends mainly on type of crop and evaporative demand. The net irrigation depth, d, is equal to the readily available soil water, w, over the root zone and is equal to w x D, where D is rooting depth. General information is given in table 27 for different crops on rooting depth, D, on fraction of total available soil water allowing optimal crop growth, P, and on readily available soil water, P x Sa for different soil types.

Table 27. Generalized data on rooting depth of full grown crops, fraction of available soil water, P, and readily available soil water, P x Sa, for different soil types (Doorenbos and Pruitt, 1977).

Crop	Rooting depth (D) m	Fraction (p) of available soil water 1/	Readily available soil water (p.Sa) mm/m 1/ fine	medium	coarse
Alfalfa	1.0 - 2.0	0.55	110	75	35
Banana	0.5 - 0.9	0.35	70	50	20
Barley 2/	1.0 - 1.5	0.55	110	75	35
Beans 2/	0.5 - 0.7	0.45	90	65	30
Beets	0.6 - 1.0	0.5	100	70	35
Cabbage	0.4 - 0.5	0.45	90	65	30
Carrots	0.5 - 1.0	0.35	70	50	20
Celery	0.3 - 0.5	0.2	40	25	10
Citrus	1.2 - 1.5	0.5	100	70	30
Clover	0.6 - 0.9	0.35	70	50	20
Cacao	-	0.2	40	30	15
Cotton	1.0 - 1.7	0.65*	130	90*	40
Cucumber	0.7 - 1.2	0.5	100	70	30
Dates	1.5 - 2.5	0.5	100	70	30
Dec. orchards	1.0 - 2.0	0.5	100	70	30
Flax 2/	1.0 - 1.5	0.5	100	70	30
Grains small 2/	0.9 - 1.5	0.6	120	80	40
winter 2/	1.5 - 2.0	0.6	120	80	40
Grapes	1.0 - 2.0	0.35	70	50	20
Grass	0.5 - 1.5	0.5	100	70	30
Groundnuts	0.5 - 1.0	0.4	80	55	25
Lettuce	0.3 - 0.5	0.3	60	40	20
Maize 2/	1.0 - 1.7	0.6	120	80	40
silage		0.5	100	70	30
Melons	1.0 - 1.5	0.35	70	50	25
Olives	1.2 - 1.7	0.65	130	95	45
Onions	0.3 - 0.5	0.25	50	35	15
Palm trees	0.7 - 1.1	0.65	130	90	40
Peas	0.6 - 1.0	0.35	70	50	25
Peppers	0.5 - 1.0	0.25	50	35	15
Pineapple	0.3 - 0.6	0.5	100	65	30
Potatoes	0.4 - 0.6	0.25	50	30	15
Safflower 2/	1.0 - 2.0	0.6	120	80	40
Sisal	0.5 - 1.0	0.8	155	110	50
Sorghum 2/	1.0 - 2.0	0.55	110	75	35
Soybeans	0.6 - 1.3	0.5	100	75	35
Spinach	0.3 - 0.5	0.2	40	30	15
Strawberries	0.2 - 0.3	0.15	30	20	10
Sugarbeet	0.7 - 1.2	0.5	100	70	30
Sugarcane 2/	1.2 - 2.0	0.65	130	90	40
Sunflower 2/	0.8 - 1.5	0.45	90	60	30
Sweet potatoes	1.0 - 1.5	0.65	130	90	40
Tobacco early	0.5 - 1.0	0.35	70	50	25
late		0.65	130	90	40
Tomatoes	0.7 - 1.5	0.4	180	60	25
Vegetables	0.3 - 0.6	0.2	40	30	15
Wheat	1.0 - 1.5	0.55	105	70	35
ripening		0.9	180	130	55
Total available soil water (Sa)			200	140	60

1/ When ETcrop is 3 mm/day or smaller increase values by some 30%; when ETcrop is 8 mm/day or more reduce values by some 30%, assuming non-saline conditions (ECe < 2 mmhos/cm).

2/ Higher values than those shown apply during ripening.

2.7.3.2 Irrigation application interval

Correct timing of irrigation applications is of over-riding importance. Delayed irrigations particularly when the crop is sensitive to water stress, could affect yields, which cannot be compensated for by subsequent over-watering. Timing of irrigation should conform to soil water depletion requirements of the crop which are shown to vary considerably with evaporative demand, rooting depth and soil type as well as with stages of crop growth. Therefore, rather than basing irrigation interval on calendar or fixed schedules, considerable flexibility in time and depth of irrigation should be maintained to accommodate distinct differences in crop water needs during the crops growing cycle. The irrigation interval can be obtained from:

$$i = \frac{(P \times Sa) \times D}{In} \quad \text{(Doorenbos and Pruitt, 1977)}$$

where i = irrigation interval, days
D = rooting depth
In = net irrigation requirement.

2.8 Irrigation scheduling techniques

2.8.1 Irrigation scheduling with soil instruments

Tensiometers, resistance blocks, thermoconductivity sensors, neutron probes have been occasionally used in automatically starting irrigation at some given water potential. These instruments measure parameters related to soil moisture content.

At present time, a farmer may schedule irrigation with soil water potential instruments. Based on experience, he will extrapolate the soil water change expected in the next few days and arrive at a projected date for irrigation. The recent evolution of microprocessors suggests that a system might be designed that would automatically read soil water potential and predict the day to irrigate using an appropriate algorithm (Jensen and Wright, 1978).

The general patterns of change in soil water potential with time at a given depth are as shown in figure 10.

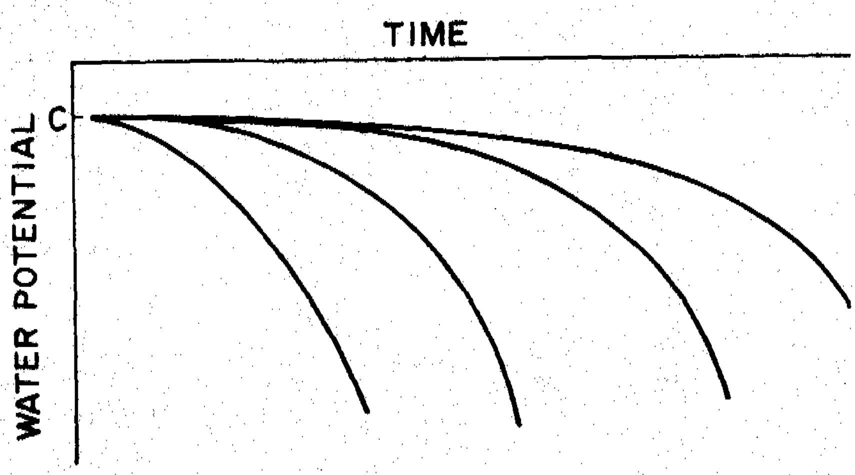


Fig. 10. A family of curves illustrating the effects of various evapotranspirations rates on the relation between time and soil water potential matrix, τ , at a given depth (Cary, 1981).

This family of curves can be approximated by the empirical function:

$$\tau = at^n + c$$

where τ = soil matrix potential, kPa

t = time, days

n = constant which depends on soil pore size distribution and type of sensor

a = constant which is affected by rate of soil water depletion

c = the intercept at $t = 0$, for instance, immediately following irrigation.

2.8.2 Irrigation scheduling using climate crop-soil data

In order to apply this technique first crop evapotranspiration, ETcrop, and net irrigation depth, d, must be determined. Crop evapotranspiration is estimated from meteorological data as discussed in section 3.2. The net irrigation depth is determined by depth of root zone, water-holding capacity of the soil and the degree of drying up of the soil at the time of irrigation. The other factor to be estimated is the effective rainfall which when subtracted from crop evapotranspiration, net crop water requirement is obtained.

After obtaining net irrigation depth and net crop requirement, irrigation interval or frequency can be determined by dividing net irrigation depth by net crop water requirement.

2.8.3 Irrigation scheduling with thermal infrared techniques and spectral remote sensing inputs

Field studies on grain sorghum have been conducted to evaluate the use of spectral reflectance and thermal infrared to the crop water use and crop water stress. These studies have been conducted for three years on Yolo loam soil with various rooting volumes to limit water availability (Hatfield, 1981).

Data shows that the stress degree day provides a valid indicator of crop stress and the leaf air temperature difference increases rapidly about zero degrees centigrade when more than 65 per cent of the available water is depleted. The leaf air temperature difference is also related to leaf water potential, with an increase above zero when the potential decreases below -12,5 bars. Vegetative indices as developed from spectral reflectance, track the leaf area of the crop both in the growth stages and in changes caused by water stress but are a result of water stress and not a valid early warning method. There appears to be promise in the use of infrared thermometry in irrigation scheduling and it could replace other more labor and time-intensive methods, in addition to covering large areas quickly and reliably (Hatfield, 1981).

The main irrigation scheduling techniques among the three groups are irrigation scheduling with soil instruments and irrigation scheduling using climate crop soil data. Irrigation scheduling with thermal infrared techniques and spectral remote sensing input is still being studied and tested. Therefore infrared techniques and spectral remote sensing inputs are not put into practice yet.

The soil instruments which are used in irrigation scheduling are tensiometers, electrical blocks and neutron probes. These instruments have their limitations, for example the limitations of tensiometers are: they require pre-installation preparation, careful installation, frequent readings and service, need multiple sites, have limited water tension range (0 to 800 cm), and the apparatus is fragile. The limitations of the electrical blocks (porous blocks) are: they require careful installation, calibration and frequent readings, not sufficiently sensitive in coarse textured soils, short block life, and need multiple sites, sensitive to temperature and salt. Both tensiometers and electrical blocks are affected by hysteresis effect (Stackman, 1980). The limitations of neutron probe are: they need calibration, danger of radiation exposure and careful installation of access tube.

The limitations of scheduling using climate crop soil data are: they require reliable weather data and soil laboratory for soil analysis. These limitations are not pronounced in Tanzania since weather data is well recorded by trained meteorological technicians and soil laboratories are present in various institutions in the country where soil samples are sent for analysis. Also since soil analysis is not needed frequently, the available soil laboratories are enough to analyze soil samples from various projects of the country. Based on these limitations of irrigation scheduling techniques, scheduling using climate crop soil data is strongly recommended to be used in Tanzania.

2.9 Tanzania's case study

Among the visited projects (Mbarali, Madibira, Dakawa and Mombo - all rice projects), two representative projects are selected and presented here. These projects are Mbarali (state farm) and Mombo irrigation scheme (village owned).

2.9.1 Mbarali rice farm

The existing scheme area under cultivation now is over 1600 ha and is still being expanded. The area under the scheme is situated in the Rufiji basin, latitude about $8^{o}42'$ south and longitude $34^{o}15'$ east. It lies in the valley of the Mbarali river, a tributary of Rufiji river, 5 - 6,25 km above its confluence with great Ruaha.

Mbarali situated in the low latitude is characterized by its tropical highland climate with warm and dry weather, strong radiation of sunshine, great difference of diurnal temperature, low relative humidity and rainy and dry seasons. According to the meteorological data, the annual mean temperature is 22,9 ^{o}C, the difference of diurnal temperature is 10 - 15 ^{o}C, the temperature in November is high, the average of which is 25,7 ^{o}C; the temperature in July is low, its average being 20,2 ^{o}C. The absolute maximum temperature is 38,8 ^{o}C, and the absolute minimum temperature is 5,3 ^{o}C (Technical Team of the People's Republic of China = TTPRC, 1975).

The annual mean precipitation is 634 mm; the rainy season starts from November to April with precipitation consisting 89,5 per cent of the whole year, and the maximum daily rainfall is 151 mm. The dry season starts from May to October with little rainfall. The annual mean evaporation capacity is 2440 mm, being 3,85 times the amount of the annual precipitation. The relative humidity is 70 - 80 per cent in the rainy season and 50 - 60 per cent in the dry season. The annual sunshine hours are about 3100 hours. Southeastern winds prevail. The annual mean wind speed is 8,25 km/hr (TTPRC, 1975).

According to the data obtained from Igawa Gauging station from 1955 to 1958, the perennial mean flow is 16,90 m^3/s. The mean discharge is 27,5 m^3/s for high flow year and 7,89 m^3/s for the low flow year. The discharge in the rainy season is high, floods rise and fall rapidly. The river water is low at the end of dry season and the beginning of the rainy season, the minimum mean discharge in 10 days being only 2,03 m^3/s. The quality of the water is good. For a long period in history the masses on the plain have been diverting the water of Mbarali river to grow paddy, vegetables etc. (TTPRC, 1975).

The farm area is in an alluvial plain with a mean gradient of 1/350 - 1/450. The soils are of the neoteric alluvium from the Mbarali river. As the course of the river has under-gone many changes, the layers of clayey and sandy soil are intersected with the predominance of clayey soils and sandy bonds and segments appearing occassionally. The fertility of the soil is medium, containing organic matter of about 0,8 - 1,3 per cent, total nitrogen content about 0,05 - 0,08 per cent, available phosphorus content less than 100 mg/l and total potassium content is about 1,79 - 2,27 per cent (TTPRC, 1975).

The soil is partially alkaline; the pH value of some deep seated soil reaches up to 8 - 9. Surface vegetation cover is mainly the shrub, the grass (gramineae), the composite, the night-shade etc. (TTPRC, 1975).

Irrigation scheduling in Mbarali irrigation project is based on Chinese experience and partly on trials of production taken. According to report prepared by the Chinese Technical Team in order to meet the needs of moisture for germination or emergence, it is essential to solve the contradictions between shortage of oxygen during flooding and demand of oxygen during germination; and between the emergence of young seedlings from the soil and the hard surface crust of the soil, thus creating advantages for young seedlings to emerge early and with enough temperature.

The principal measures are: the method of quick irrigation and quick drainage can solve the contradiction between water and oxygen causing flooding, avoiding or reducing the shortage of oxygen in the soil and the occurrence of crust on the soil surface. In general the second flooding is necessary five days after initial irrigation because the seedlings are germinating and the top soil dries out. After the second flooding, the root buds of seedlings develop rapidly and are able to penetrate the soil surface within 4 - 5 days. Then third flooding follows and most of the seedling can emerge from the soil which is softened by water, and additional floodings can be applied, depending on the emergence rate, until the seedlings have four leaves.

When paddy plants grow to a height of 5 centimetres with four leaves after emergence of regular seedlings, timely water retaining (water is retained at a certain depth above soil surface) is necessary in each plot to promote the growth of paddy seedlings, control weed growth and prevent ants from eating seedlings. At the beginning of water retaining, actual conditions of the plots and seedlings should be considered, and the depth of water above the soil surface should not be allowed to be greater than 3 cm.

Due to less rainfall and greater evaporation in the farm area, paddy seedlings are likely to wilt, weeds are liable to grow and alkaline conditions are likely to appear on some plots at the seedling stage. For this reason the water in the plots should be retained at a certain depth above the soil surface. The water depth is dependent on the plant growth. Shallow water (3 - 5 cm) is for tillering stage, wet soil (0 - 3 cm) for jointing, deep water (5 - 10 cm) for earing and running water for milking. No deep flooding for a long time is allowed for healthy development of paddy plants.

At the end of tillering stage, all water in those plots where plants are growing well should be drained off in due time and make the plots sunned completely in order to control the growth of some parts of the plants above the ground and promote the growth of their root systems. To what extent sunning of a plot is done depends on the soil and plant types. Generally reflooding is needed when the soil starts to crack or curling leaves appear in some sections of the plots. Irrigation is stopped 25 to 30 days after full heading. The main problem faced by the Mbarali project is that the project does not have any water meters such as weirs, Parshall flumes or current metres for water management purposes (for assessment of irrigation efficiencies and determination of the amount of water which enters the plots).

2.9.2 Mombo irrigation scheme

Mombo irrigation scheme is located in the flood plains of the Mkomazi river, latitude 4°55' south and longitude 38°17' east. The project area is 400 meters above sea level just below the southern escarpments of the Western Usambara mountains (see map Appendix 1.1) close to Mombo village (RADO and TIRDEP, 1977).

Mombo irrigation scheme differs from other Tanzanian projects in that it is owned by the farmers of the four villages: Mombo, Jitengeni, Mwisho wa Shamba, and Mlembule; while others are state farms. The Governement constructed the irrigation infrastructure (system) and continues to provide them with staff who give them technical advice.

Each farmer who has been admitted to the scheme is allotted a plot of 0,5 ha for individual use. The rights and obligations of the farmer are subject to the rules and regulations approved by the Regional Tanga Irrigation Committee and laid down in the by-laws of the scheme. A scheme manager appointed by the Regional Development Director of Tanga Region is responsible for the observance of the by-laws.

Climate and particularly rainfall are affected by the Usambara mountain range and rainfall decreases rapidly with increasing distance from the mountain scarp.

An adequate and realistic climatic data of the scheme can be obtained from the meteorological data measured and recorded at the Mombo Aerodrome, which is situated in the vicinity of the scheme (see map, Appendix 1.3). Rainfall and meteorological data are given in table 28.

Table 28. Rainfall and meteorological data of Mombo Aerodrome (RADO and TIRDEP, 1977).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean rainfall, mm	49,0	46,0	86,0	132,0	101,0	26,0	20,0	30,0	24,0	26,0	61,0	61,0
Mean temp., ^{o}C	27,3	27,2	27,3	25,8	24,1	22,7	22,2	22,7	23,6	24,8	26,3	26,9
RH $09^{h}00$	77,0	77,0	78,0	83,0	85,0	83,0	84,0	81,0	76,0	72,0	73,0	75,0
RH $15^{h}00$	46,0	46,0	49,0	60,0	62,0	56,0	53,0	48,0	45,0	45,0	50,0	48,0
Class "A" Pan evaporation, mm/day	6,5	7,0	6,8	5,7	4,4	4,5	4,6	6,1	7,3	8,0	6,5	6,3
Sunshine hours, hrs/day	7,4	8,3	8,1	4,8	5,6	5,5	6,8	7,8	8,1	9,8	8,0	8,5

where RH $09^{h}00$ means relative humidity (RH) recorded at 09.00 a.m.
RH $15^{h}00$ means relative humidity (RH) recorded at 03.00 p.m.

Annual rainfall varies from about 320 mm to 1000 mm, with average of 650 mm. Rainfall is highly concentrated in March - May period (main rainy season), which receives an average of 49 per cent of the total annual rainfall. The second rainy season is less pronounced and appears to be the November - December period, receiving an average of 20 per cent of the total annual rainfall. The July - September period may be regarded as the dry season (RADO and TIRDEP, 1977).

The maximum wind speed occurs in the period of July - October and ranges from 5 - 7,5 m/s, blowing from a prevailing south to south-east direction. The soils mainly found in the project area are shown in the soil and irrigation suitability map (Appendix 1.2) and are as follows according to the FAO classification (RADO and TIRDEP, 1977):

- chromic and pollic vertisol,
- mollic gleysol,
- haphlic phaeozen,
- chromic cambisol, and
- orthic solonchak.

The dominant soils in the scheme area are vertisol and gleysol (see soil map of Mombo irrigation scheme Appendix 1.4). A detailed description of four soil profiles is given in Appendix 1.5. Profiles number 4 and 5 are located in the scheme area and the other two profiles, number 111 and 114, are situated in the vicinity of the scheme.

The soil samples of the four profiles were analysed in the laboratory of the National Soil Service at Mlingano and the results are given in Appendix 1.6. The characteristics of the soils in the scheme area are:
Texture - sandy clay to heavy clay, 46,8 - 50,8 per cent clay
Colour - dark coloured.

The moisture holding capacity of profiles 4 and 5 were determined in the water laboratory at Ubungo (Ministry of Water Development and Energy). The results are shown in table 29.

Table 29. Weight per cent moisture in relation to soil water suction (RADO and TIRDEP, 1977).

Profile	pF value		
No.	2,0	3,0	4,18
4.1	33,48	31,17	25,76
4.2	36,82	34,28	24,28
5.1	22,91	17,59	13,61
5.2	32,59	33,83	26,57

The determined bulk densities of these soils are given in table 30.

Table 30. Bulk densities of the four profiles (RADO and TIRDEP, 1977).

Profile No.	Type of soil	Bulk density
4.1	Clay (57,5 % clay)	1,30 g/cm^3
4.2	Clay (67,5 % clay)	1,25 g/cm^3
5.1	Sandy clay (32,5 % clay)	1,35 g/cm^3
5.2	Clay (67,5 % clay)	1,25 g/cm^3

Figure 11 gives the pF curve drawn from the results given in tables 29 and 30.

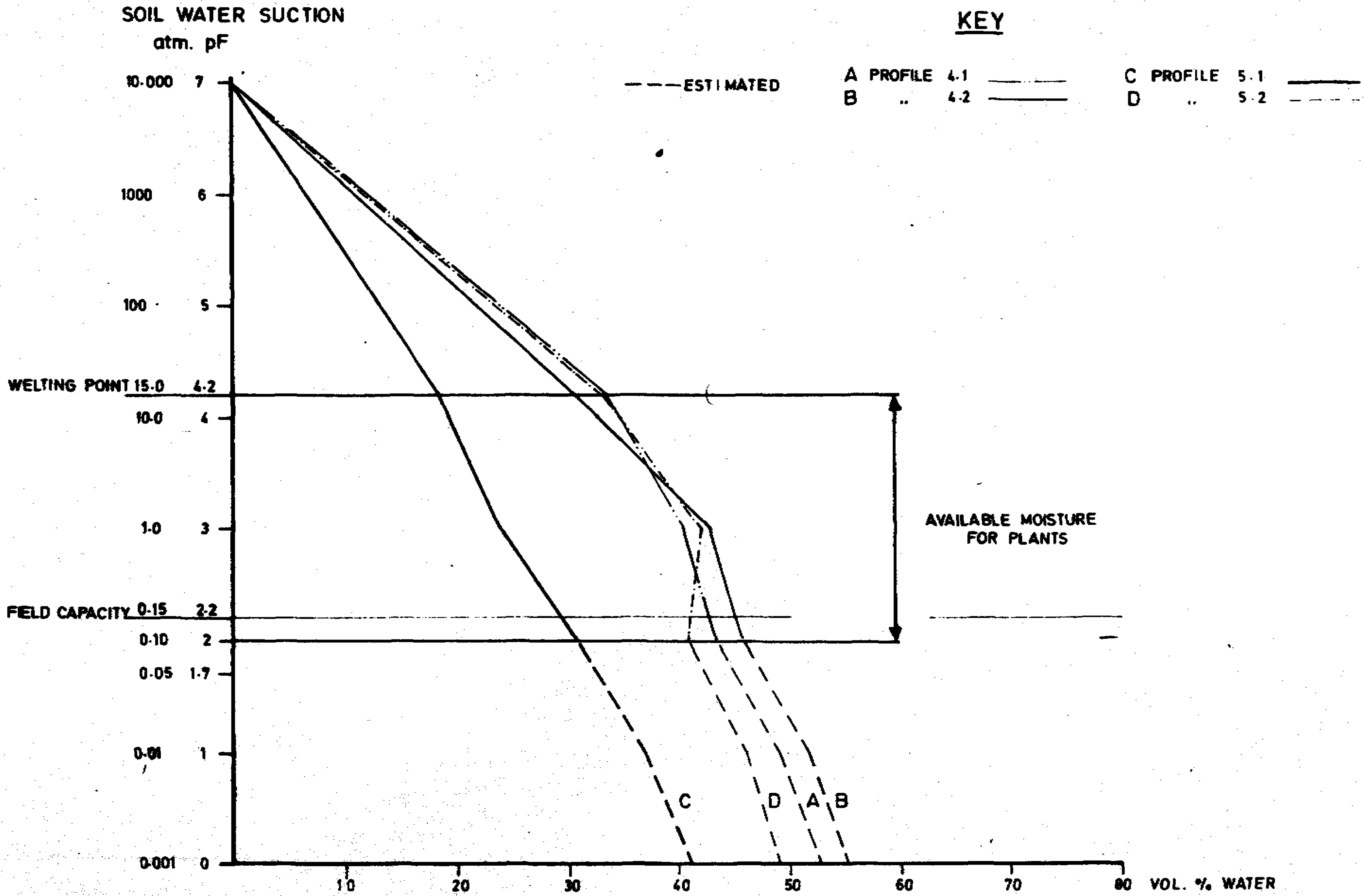


Fig. 11. pF curves (RADO and TIRDEP, 1977).

The pF curve shows that the available moisture for plants is between 34 per cent moisture by volume (wilting point pF 4.2) and 44 per cent moisture by volume (field capacity pF 2.2) amounts to 100 mm over a soil depth of 1 m.

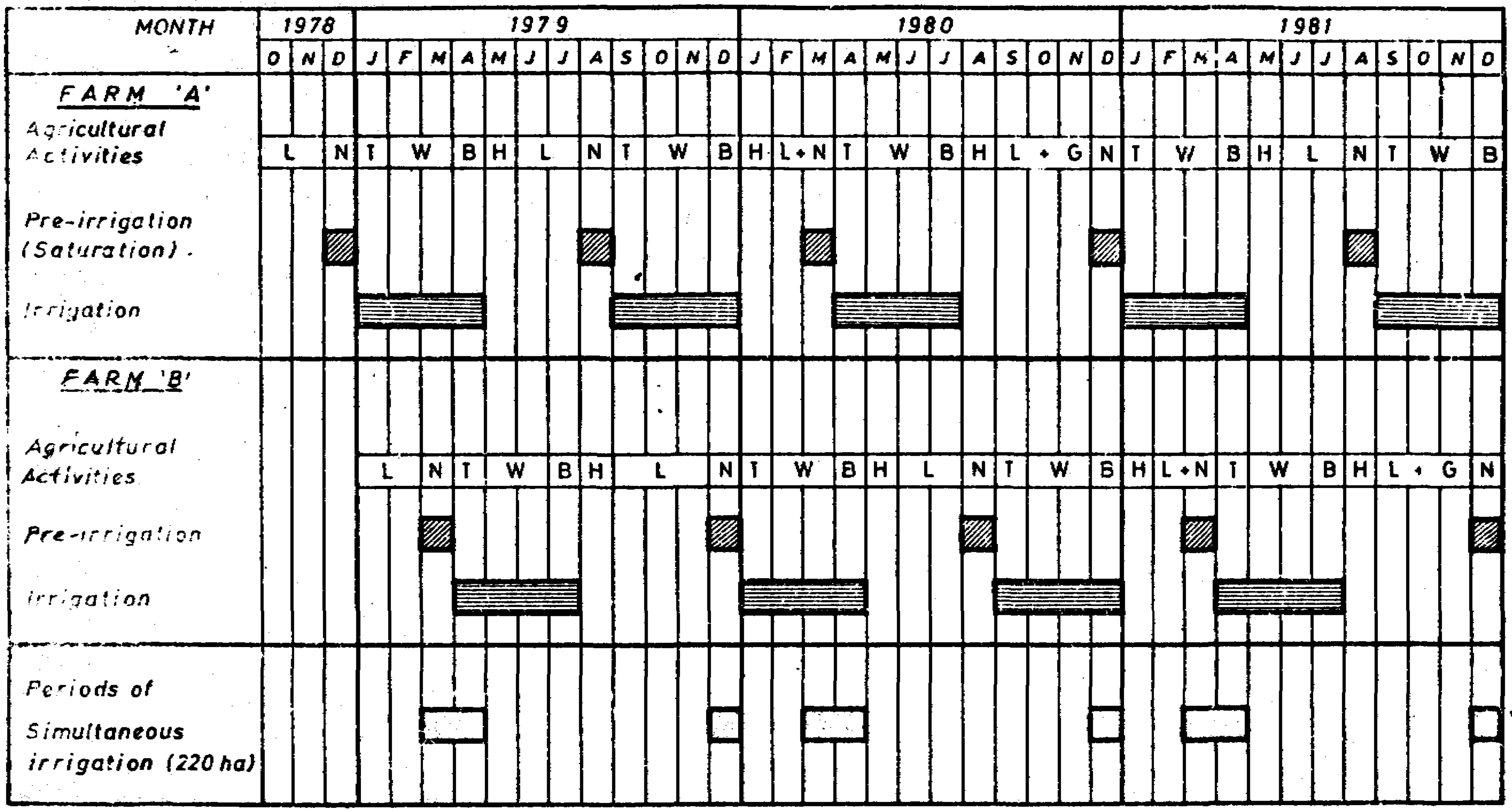
The present land use of the Mombo irrigation scheme is mainly for cultivation of paddy. Some maize and beans are however grown as well, but due to the heavy waterlogged soils, these upland crops are not suitable for the scheme.

The cropping pattern of irrigated crops is determined by the cultivation of paddy and maize. For paddy, a single cropping pattern is used. Maize, beans and bananas are the major dry land crops.

As far as irrigation scheduling is concerned the German Technical Team prepared a crop calendar, shown in figure 12, based on the concept of staggered crop season.

The scheme has been divided in two sub-areas of about 110 ha each, farm A and B (see general layout map, Appendix 2). Each plot is cultivated 3 times in 2 years, i.e. a double cropping intensity of 150 per cent can be achieved more easily, with more time available for land preparation (Vierhout, 1979).

For convenience, the crop seasons (sowing in the nurseries) have been assumed to start at the first day of the month, for instance, 1st of December, 1st of March and 1st of August. The time of preirrigation, saturation and eventually puddling should fall in the nursery period, which is assumed to take on the average of about 4 weeks. Irrigation of the transplanted paddy plants continues up to about 15 days before harvest. The total length of the irrigation has been taken as 5 months and may vary with plus or minus one or two weeks. Simultaneous irrigation of farm A and B is only required during three months a year, March, April and December.



L : Land preparation W : Weeding G : Fine Grading (land plane)

N : Nurseries B : Bird scaring

T : Transplanting H : Harvest

Fig. 12. Crop calendar (Vierhout, 1979).

The average irrigation interval used is about 11 days. There is no distinct upper limit, but 14 days is found to be in practice a suitable one. The practical lower limit of irrigation interval is determined by the minimum rotation interval which is technically feasible. Figure 12 suggests application time of 10 hours per day with an irrigation interval of 11 days. Mombo irrigation scheme is selected for further studies of scheduling because it has both climatic and soil data available.

3. METHOD OF MATERIALS

3.1 Location and topography of Mombo irrigation scheme

The location and topography of Mombo irrigation scheme is discussed in section 2.9.2. The situation of traffic for the project area is good. The project area is 2 km south-east of Mombo (see map, Appendix 1.3). Mombo is directly located on the main tarmac road which connects Moshi (via Korogwe) to Tanga or to Dar es Salaam. In addition, the railway line Tanga-Moshi passes through Mombo. A railway station is located in Mombo town and is easily accessible from the project area.

Mombo is located directly on the southern slopes of the Western Usambaras. The entire traffic from and to the Western Usambaras (Soni-Lushoto-Malindi) passes through Mombo. Mombo irrigation scheme draws water from the Soni river which is a tributary of the Mkomazi river.

3.2 Measuring methods

3.2.1 Weather data measurements

In order for weather data to be used to predict crop water requirements (crop evapotranspiration), the data must be the average of meteorological data (monthly or yearly) measured and recorded for over 10 years (Doorenbos and Pruitt, 1977). Therefore row data cannot reliably be used to estimate crop evapotranspiration.

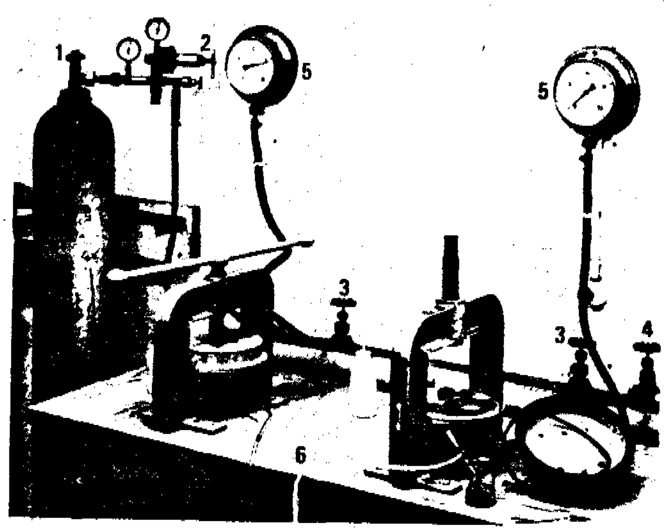
Mombo Aerodrome is equipped with most instruments: rain gauge, maximum and minimum thermometers, dry and wet bulb thermometers, evaporation class A pan, anemometers and Campbell Stokes sunshine recorder, which measure precipitation, temperature, relative humidity, evaporation rate, wind speed and sunshine hours respectively.

Daily weather records for Mombo Aerodrome are available since 1958 and is discussed in section 2.8.2. According to German Technical Team the meteorological data measured and recorded at the Mombo Aerodrome is relatively adequate and realistic (RADO and TIRDEP, 1977). The meteorological data is presented in table 30.

3.2.2 Water holding capacity measurement

Water holding capacity of the soils of Mombo irrigation scheme was determined in the water laboratory at Ubungo by pressure membrane apparatus. The results which are soil moisture, bulk densities and pF curve are discussed in section 2.9.2. From the pF curve, the water holding capacity was deduced as 100 mm/m of root zone depth.

The soil samples for determining water holding capacities of the soil were taken by pF-rings.



1 VALVE OF GAS CYLINDER
2 ADJUSTING SCREW OF REDUCING VALVE
3 VALVE BETWEEN CONDUIT PIPE AND APPARATUS
4 OUTLET VALVE
5 PRESSURE-GAUGE
6 BURETTE

Fig. 13. Pressure membrane apparatus.

3.2.3 Discharge measurements

Mombo irrigation scheme is equipped with diversion weir across the Soni river, parshall flume on the main canal and check weirs on the existing laterals to measure the discharge of the canal system. These structures are also used to assess the efficiency of the canal system and to measure the water being applied in the field plots.

3.3 Method of analysis

3.3.1 Relationship between crop evapotranspiration and meteorological data

Penman method (discussed in section 2.2.2.1) is used to determine reference crop evapotranspiration, ETo, from meteorological data. Then crop coefficients, kc, for different stages of growth are used to convert reference crop evapotranspiration to crop evapotranspiration, ETcrop. See results in sections 4.1.1, 4.1.2 and 4.1.3.

3.3.2 Relationship between soil moisture and matric potential

The soil moisture content by volume was plotted against the corresponding matric potential (tension) called pF (logarithm to base 10 of the matric potential measured in cm = pF) to obtain the moisture retention curve or pF-curve (see figure 11). From the pF-curve water holding capacity was determined. The difference of soil moisture from the pF-curve between pF 2.2 (field capacity) and pF 4.2 (wilting point) multiplied by one metre of root depth was equal to the water holding capacity of the soil sample. The result was 100 mm/m of root depth.

4. RESULTS AND DISCUSSION

4.1 Crop water requirements

4.1.1 Reference crop evapotranspiration

Climate data was analysed by Penman equation and table 31 gives the results of reference crop evapotranspiration obtained.

Table 31. Reference crop evapotranspiration, ETo, determined from climatic data.

Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
ETo mm/day	7,46	7,40	7,69	7,38	5,36	4,83	4,81	5,17	6,07	6,97	7,89	7,23

The Penman equation used to predict ETo is given by

$$ETo = c \times \left[W \times Rn + (1 - W) \times f(U) \times (ea - ed)\right].$$

The ETo values determined are not used for a particular crop, but are values for a reference crop which can be used for any crop by changing them to crop evapotranspiration, ETcrop, values. Monthly ETo values were high from December (proceeding year) to March (following year) and they fell gradually from April to June where they again gradually increased to December. These changes of ETo values were similar to the temperature changes (see table 30).

4.1.2 Crop coefficients

After selecting growing seasons for paddy, maize and beans and developing crop coefficient curves (see Appendix 2.1 b) average monthly kc values for the respective crops were determined. Table 32 shows those kc values.

Table 32. Kc values according to the growing seasons of the crops.

MONTH	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY
Kc paddy	0.35	0.60	1.02	1.28	1.05			
Kc maize			0.34	0.62	1.04	1.25	1.15	0.85
Kc bean					0.40	0.80	1.25	0.70

The growing periods were selected in such way that the dates of irrigation of one crop did not coincide with others. This method of seasoning is called staggered crop seasoning. Staggering crop seasoning would also provide the farmers with more time for land preparation (2 months or more) and would leave a wider margin to shift the season (in both directions) should circumstances beyond control require it. Also staggered planting times reduce the total irrigation requirements per unit of time to meet the capacity of the channels. In addition to inducing irrigation requirements, during periods of water shortage, staggered planting would make the distribution of the deficit equally over the fields easier.

4.1.3 Crop evapotranspiration and net irrigation requirement

The crop evapotranspiration was determined by the following relationship: ETcrop = kc x ETo, and net irrigation requirements, In, were obtained by subtracting effective rainfall from crop evapotranspiration. Table 33 shows the results.

Table 33. Crop evapotranspiration and net irrigation requirements.

Months	Dec.	Jan.	Feb.	Mar	Apr	May	Jun	Jul
Paddy ETcrop mm/day	2.60	4.40	7.80	9.40	5.60			
Maize ETcrop mm/day			2.60	4.60	5.60	6.00	5.50	4.40
Beam ETcrop mm/day					2.10	3.90	6.00	3.60
Effective rainfall for paddy mm/day	1.35	1.22	1.14	2.82	3.30			
Effective rainfall for maize, mm/day			1.10	2.10	3.30	2.60	0.70	0.49
Effective rainfall for beans, mm/day					2.72	2.30	0.70	0.47
Paddy irrigation requirement, mm/day	1.25	3.20	6.90	6.60	2.30			
Maize irrigation requirement, mm/day			1.50	2.50	2.30	3.40	4.8	3.90
Beam irrigation requirement, mm/day					-	1.60	5.30	3.10

The crops paddy, maize and beans were assumed to be sown on 1st December, 1st February and 1st April respectively and their values for crop evapotranspiration and irrigation requirements started at the respective sowing dates. From table 33 it can be seen that irrigation for beans was not required in the first month, April, because rainfall was enough to satisfy the crop requirements. For every crop, the irrigation requirement was low at the initial stage of the crop and increased as the crop grew and then started to decrease from mid-season towards the late season (see kc development, Appendix 2.1 b).

4.1.4 Net irrigation depth

The net irrigation depth was determined by the following relationship: d = P x Sa x D (see section 2.5.3.1). The results of the calculations are shown in table 34.

Table 34. Net irrigation depths for paddy, maize and beans.

Type of crop	Paddy	Maize	Beans
Net irrigation depth, mm	32,5	48,0	27,0

The net irrigation depths for paddy, maize and beans were different because their rooting depths and fractions of the available soil water were different being higher for maize than the rest.

4.2 Rotational irrigation scheduling

The irrigation intervals were obtained from the following formula:

$$i = \frac{d}{In}$$

where i = irrigation interval, days
d = net irrigation depth, mm
In = net irrigation requirement, mm/day.

Combining the planting dates (using staggered planting, see section 4.1.2) with irrigation interval, the irrigation scheduling for the three crops, paddy, maize and beans, was obtained. The irrigation scheduling was as shown in figure 14.

Paddy has the highest irrigation frequency with low frequency in the establishment stage of growth. The low irrigation frequency is caused by rainfall (increases from November to April the next year) which reduces the crop evapotranspiration.

From the schedule (figure 14) the irrigation frequencies (for three crops) increase towards the critical periods (stages of growth) for these crops (see table 2).

When scheduling for paddy, it should be noted that paddy is normally grown under conditions of near soil saturation and submersion (waterlogging) and hence loss of water through percolation should be minimal. Appendix 3 gives the four practices for paddy. The schedule (figure 14) just described is water saving practice. This schedule can be simplified within plus or minus one or two days for practical operations without affecting crop yield.

The effects of this irrigation scheduling if followed will be i) increased profits and ii) secondary benefits. The increased profits can be realized from increased crop yield and quality. Experience in Salt River Project, California, has shown that yields can be increased from one tenth to one third per hectare with this scheduling technique (Jensen et al., 1970). Timing of irrigation application also has an influence on the yield of the crop. It has been shown that a delay of four or five days at the reproductive stage of corn on sandy soil may reduce grain by about 1245 kilograms per hectare or more.

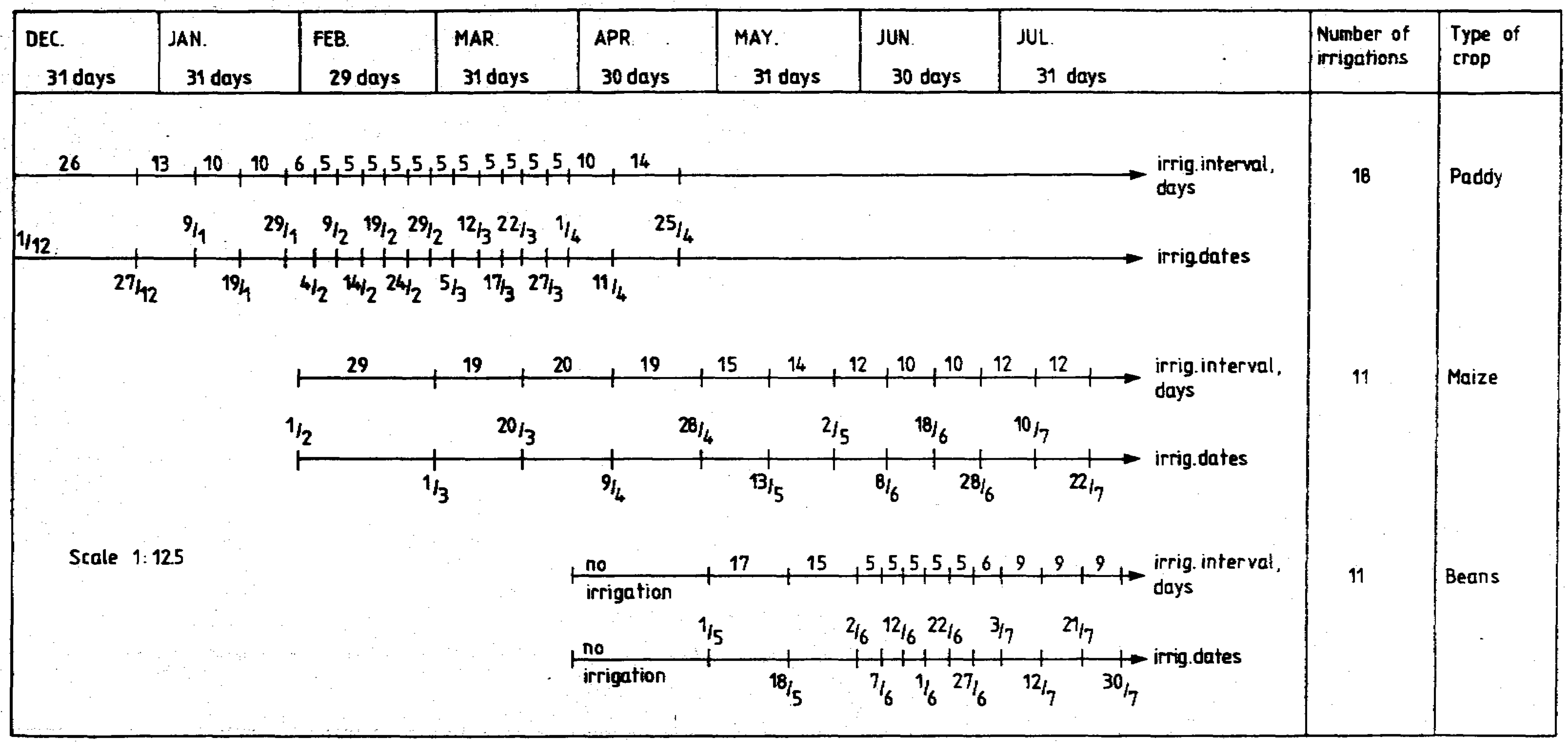


Fig. 14. Rotational irrigation scheduling.

Secondary benefits are: increased water use efficiency, reduction in irrigation labour costs and the elimination of detrimental effects associated with poor irrigation practices. One of the detrimental effects is waterlogged soils, a condition which decreases yields and results in increased costs for water, fertilizer and drainage.

This irrigation schedule will enable the farmer to use water efficiently and resulting in the decrease of water storage requirements per hectare, which will in turn result in reduced storage costs per hectare or the ability to serve more land with the given amount of storage (water is saved). Pilot projects in Nebraska indicated that about 170 mm of water per season may be saved by scheduling. If this water is lifted 30 m out of the ground water reservoir, 109 litres/ha of diesel can be saved annually with gated pipe surface irrigation (Fischbach, 1980).

This scheduling (staggered scheduling) enables the farmer to do other operations (weeding, applying fertilizers etc.) between irrigations without causing crop stress by delaying irrigation. This schedule will allow crop rotation and cultivation of the farm two times a year (two harvests a year).

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Irrigation scheduling is the application of the right amount of water at the right time. In order to prepare a good schedule, the following major considerations which influence the timing of irrigation must be determined or taken into account: crop water requirements, soil water holding capacity of the root zone soil, effective rainfall, amount of water for irrigation and the availability of water with which to irrigate.

Before understanding the methods for determining crop water evapotranspiration one has to know the factors affecting it (ETcrop). The major factors affecting ETcrop are climate, soil water, methods of irrigation and cultural practices.

The methods of determining ETcrop are divided into two groups: direct and indirect methods. The direct methods are lysimeters, soil moisture studies, integration methods and inflow-outflow for large areas. Direct methods are used to calibrate indirect methods. The indirect methods are Penman, radiation, Blaney-Criddle, pan evaporation and Jensen-Haise methods. These methods use climatic data to predict crop evapotranspiration (crop water requirements). Under this study, Penman method is recommended to be used in Tanzania.

Among the three groups of irrigation scheduling techniques, scheduling using climate crop soil data can be used in Tanzania with fewer problems than the other techniques.

Penman method was used to predict crop evapotranspiration and after determining effective rainfall, the final schedule for Mombo irrigation scheme was prepared using climate crop soil data.

The main benefits of irrigation scheduling are increased crop yield and quality (net returns), increased water use efficiency, reduction in irrigation labour costs and decreased costs for water, fertilizer and drainage. The water saved by irrigation scheduling will enable the farmer to serve more land (expand the farm).

5.2 Recommendations

Based on this study and its conclusion, I strongly recommend the following:

1. Irrigation scheduling should be integrated in all farming operations.

2. Penman method should be used to determine ETcrop in Tanzania.

3. Scheduling using climate crop soil data should be used to prepare irrigation schedules in Tanzania.

4. Irrigation scheduling requires efficient water control, therefore simple water measurement structures such as weirs and Parshall flumes should be constructed within Tanzania.

5. Tanzanian staff of the projects should learn how to prepare irrigation schedules rather than depend on foreign technical teams only.

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GLOSSARY

1. ACTUAL VAPOUR PRESSURE (ed): pressure exerted by water vapour contained in the air; millibar.

2. ALLOWABLE SOIL WATER DEPLETION (p x Sa): depth of soil water in the root zone readily available to the crop for given soil and climate allowing unrestricted evapotranspiration as the fraction p of the total soil water between field capacity (Sfc) and wilting point (Sw); mm/m soil depth.

3. AVAILABLE SOIL WATER (Sa): depth of water stored in the root zone between field capacity (Sfc) and wilting point (Sw); mm/m soil depth.

4. CANOPY INTERCEPTION: depth of precipitation caught and held by plant foliage and lost by evaporation without reaching the ground surface; mm or sometimes as percentage of rainfall.

5. CLOUDINESS: degree of cloud cover, usually mean of several observations per day; expressed in oktas (in eights) of sky covered, or in tenths of sky covered.

6. CONTINUOUS SUPPLY: method of water delivery with continuous but often variable discharge in water distribution system up to inlet of individual farm or field.

7. CONVEYANCE EFFICIENCY (Ec): ratio between water received at the inlet to a block of fields and that released at the project's headworks.

8. CRITICAL PERIODS: periods during crop growth when soil water stress will have a lasting effect on crop growth and yields.

9. CROP COEFFICIENT (kc): ratio between crop evapotranspiration (ETcrop) and the reference crop evapotranspiration (ETo) when crop is grown in large fields under optimum growing conditions.

10. CROP EVAPOTRANSPIRATION (ETcrop): rate of evapotranspiration of a disease-free crop growing in a large (one or more ha) field under optimal soil conditions, including sufficient water and fertilizer and achieving full production potential of that crop under the given growing environment, includes water loss through transpiration by the vegetation and evaporation from the soil surface and wet leaves; mm/day.

11. CROPPING PATTERN: sequence of different crops grown in regular order on any particular field or fields.

12. CROP WATER REQUIREMENTS (see crop evapotranspiration).

13. DAY LENGTH FACTOR (P): percentage P of total annual daylight hours occurring during the period being considered; percentage.

14. DEVELOPMENT STAGE: for a given crop the period between end of initial (emergence) stage and full ground cover or when ground cover is between 10 and 80 %; days.

15. DISTRIBUTION EFFICIENCY (Ed): ratio of water made directly available to the crop and that released at the inlet of a block of fields; Ed = Eb x Ea.

16. EFFECTIVE FULL GROUND COVER: percentage of ground cover by the crop when ETcrop is approaching maximum - generally 70 % to 80 % of surface area; percentage.

17. EFFECTIVE RAINFALL (Pe): rainfall useful for meeting crop water requirements, it excludes deep percolation, surface runoff and interception; mm/period.

18. EFFECTIVE ROOTING DEPTH (D): soil depth from which the full grown crop extracts most of the water needed for evapotranspiration; m.

19. ELECTRICAL CONDUCTIVITY (EC): the property of a substance to transfer an electrical charge (reciprocal of resistance). It is measured in ohms of a conductor which is 1 cm long and 1 cm^2; electrical conductivity is expressed as the reciprocal of Ohms/cm (mhos/cm); 1 mhos/cm = 1000 mmhos/cm.

20. ELECTRICAL CONDUCTIVITY OF IRRIGATION WATER (ECw): is used as a measure of the salt content of the irrigation water; mmhos/cm.

21. ELECTRICAL CONDUCTIVITY, MAXIMUM (ECmax): is used as a limit of the salt concentration of the soil saturation paste (ECe) beyond which growth would stop (zero yield); mmhos/cm.

22. ELECTRICAL CONDUCTIVITY, SATURATION EXTRACTS (ECe): is used as a measure of the salt content of an extract from a soil when saturated with water, under average conditions ECe is approximately half the salinity of the soil water to which the crop is actually exposed in the soil; mmhos/cm.

23. EVAPORATION (E): rate of water loss from liquid to vapour phase from an open water or wet soil surface by physical processes; mm/day.

24. EVAPOTRANSPIRATION: rate of water loss through transpiration from vegetation plus evaporation from the soil; mm/day.

25. EXTRA TERRESTIAL RADIATION (Ra): amount of solar radiation received on a horizontal at the top of the atmosphere; equivalent evaporation mm/day.

26. FIELD APPLICATION EFFICIENCY (Ea): ratio of water made directly available to the crop and that received at the field inlet.

27. FIELD CANAL EFFICIENCY (Eb): ratio between water received at the field inlet and that at the inlet of a block of fields.

28. FIELD CAPACITY (Sfc): depth of water held in the soil after ample irrigation or heavy rain when the rate of downward movement has substantially decreased, usually 1 to 3 days after irrigation or rain, soil water content at soil water tension of 0,2 to 0,3 atmosphere; mm/m soil depth.

29. FIELD SUPPLY SCHEDULE: stream size, duration and interval of water supply to the individual field or farm.

30. GROWING SEASON: for a given crop the time between planting or sowing and harvest; days.

31. INITIAL DEVELOPMENT STAGE: for a given crop the time during germination or early growth when ground cover is less than 10 %; days.

32. IRRIGATION INTERVAL (i): time between the start of successive field irrigation applications on the same field; days.

33. IRRIGATION REQUIREMENTS: depth of water required for meeting crop evapotranspiration minus effective precipitation, ground water, stored soil water, required for normal crop production plus leaching requirement, and water losses and operational wastes, sometimes called gross irrigation requirements; mm/period.

34. LATE SEASON STAGE: time between the end of the mid-season stage and harvest or maturity; days.

35. LEACHING EFFICIENCY (Le): fraction of the irrigation water applied for salt control (leaching) which was effective.

36. LEACHING REQUIREMENTS (Lr): fraction of the irrigation water entering the soil that effectively must flow through and beyond the root zone in order to prevent salinity build-up. This value is the minimum amount of water necessary to control salts.

37. MAXIMUM NUMBER OF BRIGHT SUNSHINE HOURS (N): number of bright sunshine hours for a 24-hour day with no cloud cover; hours.

38. MID-SEASON STAGE: for a given crop the period between effective full ground cover and the onset of maturity (i.e. leaves start to discolour or fall off); days.

39. NET IRRIGATION REQUIREMENT (In): depth of water required for meeting evapotranspiration minus effective rainfall; mm/period.

40. NET LONGWAVE RADIATION (Rnl): balance between all outgoing and incoming longwave radiation, almost always a negative value, equivalent evaporation; mm/day.

41. NET RADIATION (Rn): balance between all incoming and outgoing short and longwave radiation, Rn = Rns - Rnl; equivalent evaporation mm/day.

42. NET SOLAR RADIATION (Rns): difference between shortwave radiation received on the earth's surface and that reflected by the soil, crop or water surface; equivalent evaporation mm/day.

43. PAN COEFFICIENT (kp): ratio between reference evapotranspiration ETo and water loss by evaporation from an open surface of a pair or ETo = kp x Epan.

44. PAN EVAPORATION (Epan): rate of water loss by evaporation from an open water surface of a pan; mm/day.

45. PEAK SUPPLY PERIOD: water use period for a given crop or cropping pattern during the month or period thereof of highest water requirements; mm/day.

46. PLANT POPULATION: number of plants per unit of crop area.

47. PROJECT EFFICIENCY (Ep): ratio between water made available to the crop and that released at the project headworks; Ep = Ea x Eb x Ec.

48. PSYCHROMETER: device to measure air humidity, normally consisting of two standard thermometers, one whose bulk is surrounded by wet muslin bag and is called net-bulk thermometer, both should normally be force-ventilated and shielded against radiation (Assman type).

49. READILY AVAILABLE SOIL WATER (p x Sa): depth of soil water available for given crop, soil and climate allowing unrestricted evapotranspiration and crop growth, equals allowable soil water depletion; mm/m soil depth.

50. REFERENCE CROP EVAPOTRANSPIRATION (ETo): rate of evapotranspiration from an extended surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water; mm/day.

51. REFLECTION COEFFICIENT, also called albedo (α): ratio between the amount of shortwave radiation received at the earth's surface and that reflected back.

52. RELATIVE HUMIDITY (RH, RHmax, RHmin): actual amount of water vapour in the air relative to the amount of water vapour the air would hold when saturated at the same temperature, mean of maximum RH of each day over the period considered, RHmin: mean of minimum RH of each day over the period considered; percentage.

53. ROTATIONAL WATER SUPPLY: supply of water rotated among field inlets at varied intervals.

54. SATURATION VAPOUR PRESSURE (ea): upper limit of vapour pressure at or when air is saturated at given air temperature; millibar.

55. SOIL INTAKE (INFILTRATION) RATE: instantaneous rate at which water will enter the soil.

56. SOIL BULK DENSITY (As): ratio of the weight of water free soil to its volume; g/cm^3.

57. SOIL STRUCTURE: arrangement of soil particles into aggregates which occur in a variety of recognised shapes, sizes and strengths.

58. SOIL TEXTURE: characterization of soil in respect to its particle size and distribution.

59. SOIL WATER CONTENT: depth of water held in the soil; mm/m soil depth.

60. SOIL WATER DEPLETION FRACTION (p): fraction of available soil water (Sfc - Sw) that can be taken by the crop permitting unrestricted evapotranspiration and crop growth.

61. SOIL WATER STRESS: sum of soil water tension and osmotic pressure to which water must be subjected to be in equilibrium with soil water, also called soil water potential; atmosphere.

62. SOIL WATER TENSION: force at which water is held by the soil or negative pressure or suction that must be applied to bring the water in a porous cup into static equilibrium with the water in the soil, soil water tension is also called matric potential; atmosphere.

63. SOLAR RADIATION (Rs): amount of shortwave radiation received on a horizontal plane at the earth's surface; equivalent evaporation mm/day.

64. STORED SOIL WATER (Wb): depth of water stored in the root zone from earlier rains or irrigation applications which partly or fully meets crop water requirements in the following periods; mm.

65. STREAM SIZE: flow selected for supply to field inlet or irrigation block; l/s or m^3/s.

66. SUNSHINE HOURS (n): number of hours of bright sunshine per day, also sometimes defined as the duration of traces or burns made on a chart by Campbell-Stokes recorder; hours.

67. TENSIOMETER: a device for measuring the tension of soil water in the soil consisting of a porous, permeable ceramic cup connected through a tube to a manometer or vacuum gauge.

68. TOTAL AVAILABLE SOIL WATER (Sa = Sfc - Sw): depth of soil water available in the root zone to the crop, difference between field capacity and wilting point; mm/m soil depth.

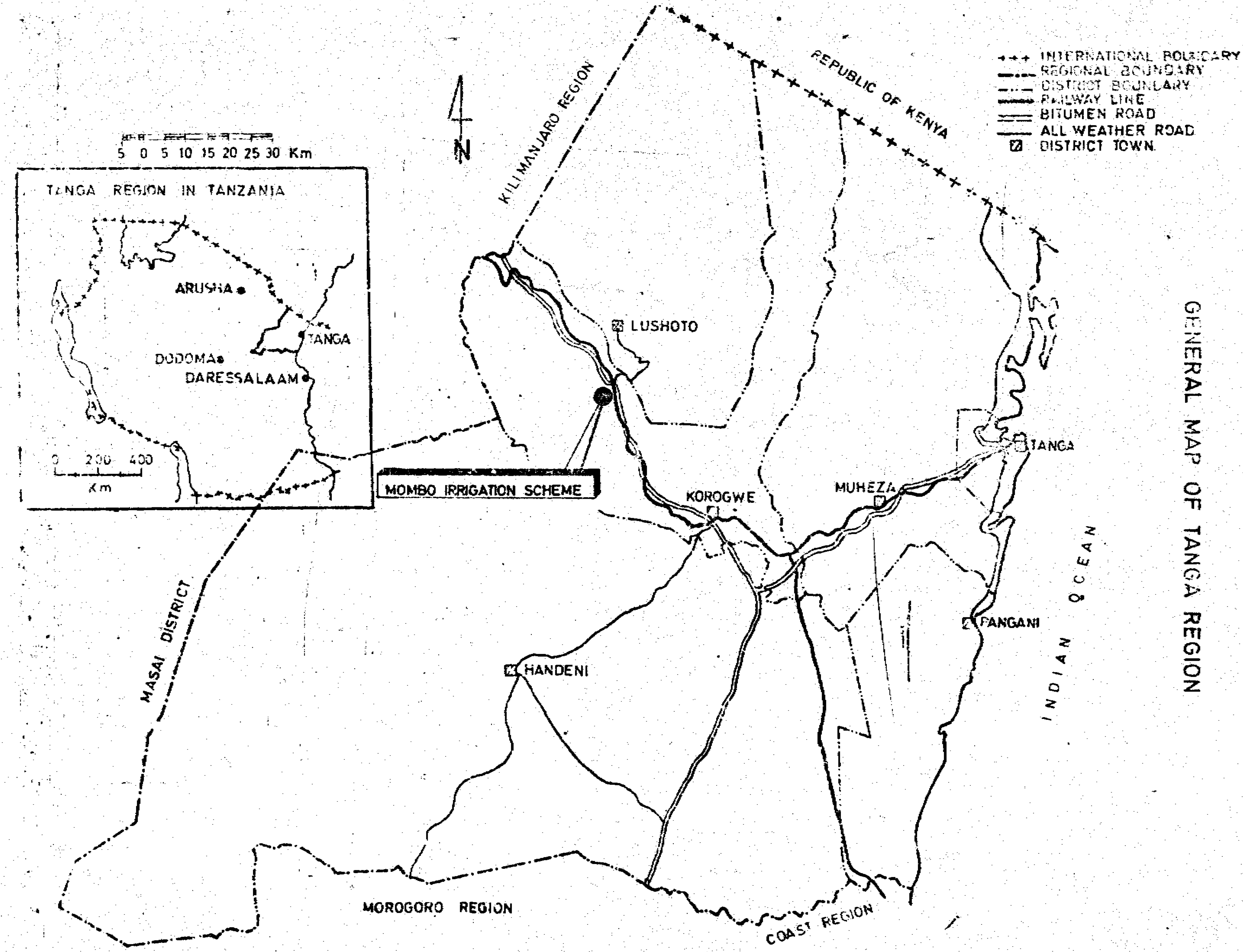
69. TRANSPIRATION: rate of water loss through the plant which is regulated by physical and physiological processes; mm/day.

70. WILTING POINT (Sw): depth of soil water below which the plant cannot effectively obtain water from the soil, soil water content at 15 atmospheres soil water tension; mm/m soil depth.

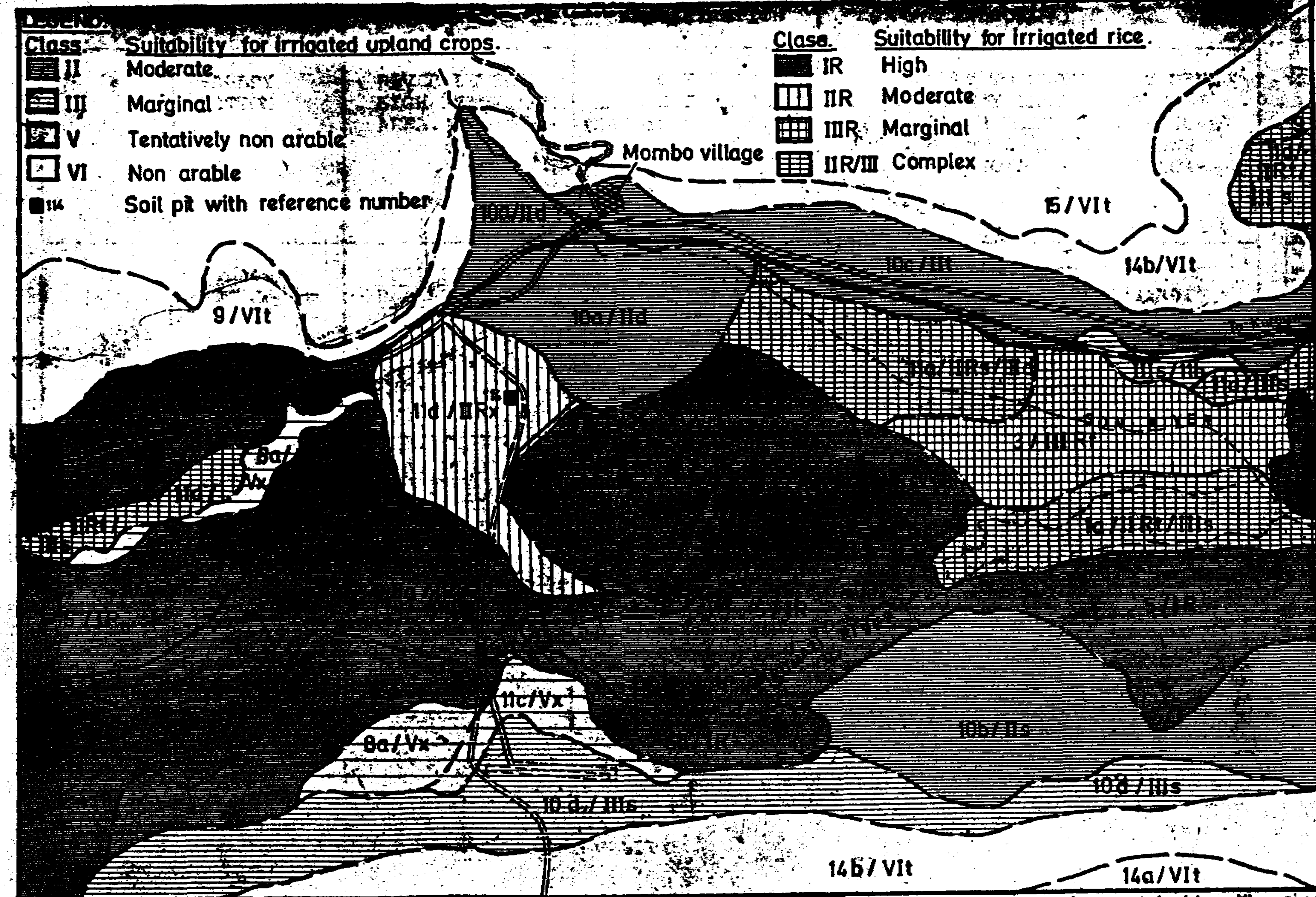
71. WINDSPEED (U): speed of air movement at 2 m above ground surface in unobstructed surroundings; mean in m/s over the period considered, or total wind run in km/day.

APPENDIX 1.1

GENERAL MAP OF TANGA REGION



SOIL AND IRRIGATION SUITABILITY MAP



(Reconnaissance study of lower Mkomazi valley)

LEGEND FOR SOIL AND IRRIGATION SUITABILITY MAP

Source: RECONNAISSANCE STUDY LOWER MKOMAZI VALLEY

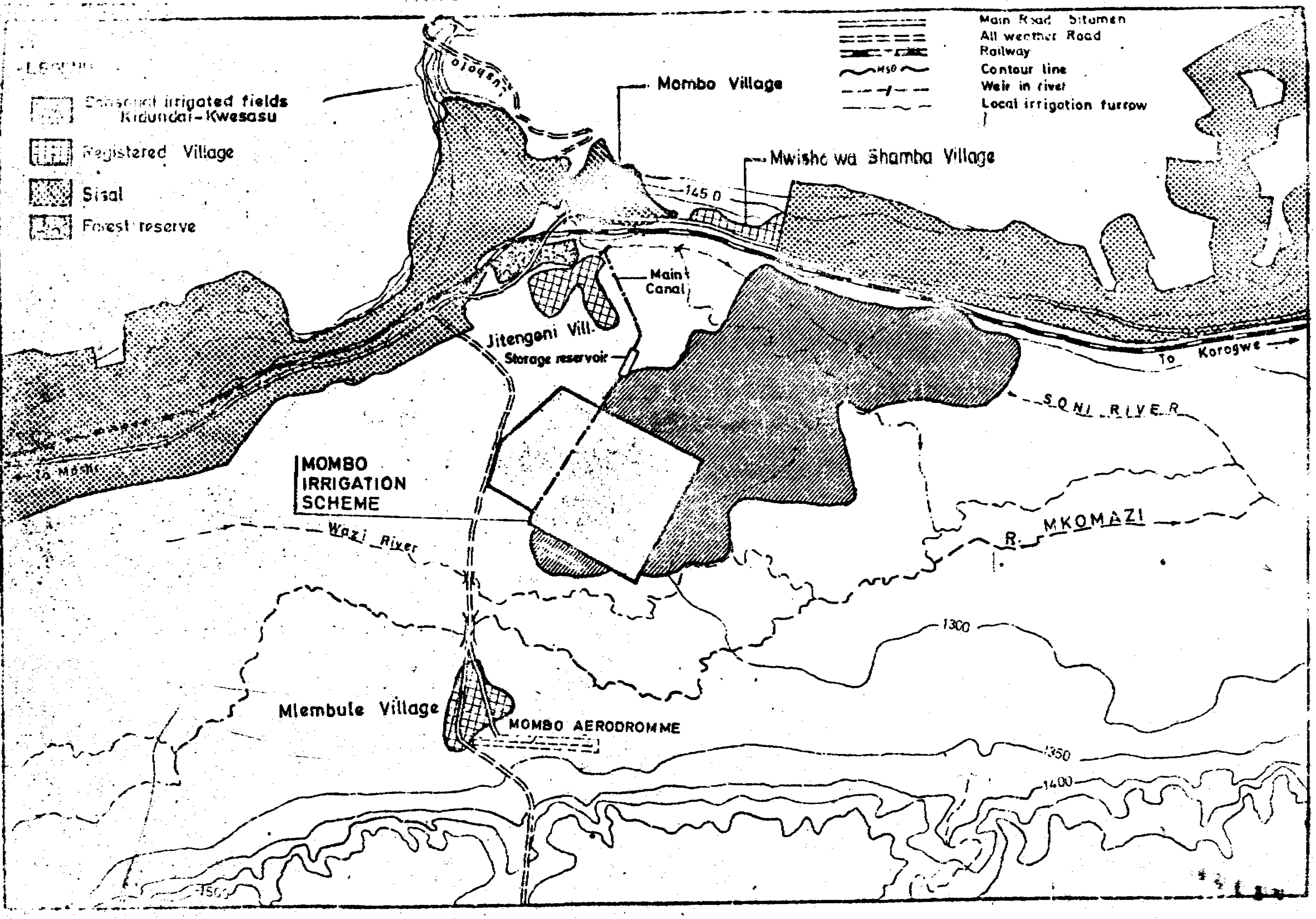
SYMBOL	MAIN UNIT	PHYSIOGRAPHY	CLASSIFICATION	SOIL
1a	VALLEY BOTTOM	RIVER LEVEES, HIGH RAINFALL AREA.	EUTRIC FLUVISOL HAPLIC PHAEOZEM (HAPLIC CHERNOZEM)	IMPERFECTLY TO MODERATELY WELL DRAINED SANDY CLAY LOAMS TO CLAYS WITH A DARK TOPSOIL 40-61 cm THICK AND A GREYISH BROWN MOTTLED SUBSOIL, OFTEN CALCAREOUS. NON SALINE.
3	VALLEY BOTTOM	VERY LOW LYING BLACKSWAMPS	MOLLIC GLEYSOL	VERY POORLY TO POORLY DRAINED CLAYS. SOMETIMES WITH SANDY LAYERS. WITH A DARK, THEN, HUMIC OR PEATY CLAY TOPSOIL AND A GREY MOTTLED SUBSOIL, SOMETIMES CONTAINING LIME SPOTS. NON SALINE.
4	VALLEY BOTTOM	CLAY PLAINS, GRASS VEGETATION.	MOLLIC GLEYSOL PELLIC VERTISOL CHROMIC VERTISOL	POORLY DRAINED CLAYS AND SANDY CLAYS WITH DARK TOPSOIL 20-40 cm THICK AND DARK GREYISH BROWN MOTTLED SUBSOIL, SOMETIMES CALCAREOUS. NON TO SLIGHTLY SALINE.
5	VALLEY BOTTOM	CLAY PLAINS, VEGETATED WITH GRASS AND FEW SMALL TREES.	MOLLIC GLEYSOL PELLIC VERTISOL CHROMIC VERTISOL	POORLY TO IMPERFECTLY DRAINED CLAYS WITH DARK TOPSOIL, 20-50 cm THICK, SOMETIMES HUMIC, AND VERY DARK GREYISH BROWN TO DARK BROWN MOTTLED SUBSOILS, SOMETIMES CALCAREOUS. NON TO SLIGHTLY SALINE.
6a	VALLEY BOTTOM	HIGH RAINFALL AREA	PELLIC VERTISOL CHROMIC VERTISOL MOLLIC GLEYSOL	IMPERFECTLY TO POORLY DRAINED CLAYS WITH A DARK TOPSOIL 10-40 cm THICK AND A VERY DARK GREYISH BROWN TO DARK GREY MOTTLED SUBSOIL, SOMETIMES CALCAREOUS. NON TO SLIGHTLY SALINE.
7	VALLEY BOTTOM	IRRIGATED LOWLANDS	MOLLIC GREYSOL VERTIC CAMBISOL PELLIC VERTISOL CHROMIC VERTISOL	POORLY TO IMPERFECTLY DRAINED SOIL WITH A DARK TOPSOIL, SOMETIMES HUMIC, OF SANDY CLAY TO CLAY TEXTURE 15-50 cm THICK AND A DARK BROWN TO VERY DARK GREY MOTTLED SUBSOIL OF CLAY TO SANDY CLAY LOAM TEXTURE. NON TO MODERATELY SALINE.
8	VALLEY BOTTOM	SALT FLATS WITH SCATTERED SUEDA SHRUBS.	ORTHIC SOLONCHAK GLEYIC SOLONCHAK	IMPERFECTLY DRAINED SOILS WITH A VERY DARK BROWN TO DARK REDDISH BROWN TOPSOIL WITH TEXTURES VARYING FROM SAND TO CLAY AND A VERY DARK BROWN TO DARK RED SANDY CLAY LOAM TO SUBSOIL, MOSTLY MOTTLED AND CALCAREOUS. STRONGLY TO EXTREMELY SALINE.

SYMBOL	MAIN UNIT	PHYSIOGRAPHY	CLASSIFICATIONS	SOIL
9	ALLUVIAL FANS	UPPER PARTS ALLUVIAL FANS 4-10%.	LUVIC PHAEOZEM HAPLIC PHAEOZEM CHROMIC CAMBISOL	WELL DRAINED SHALLOW TO DEEP SANDY LOAMS TO SANDY CLAY LOAMS WITH A DARK BROWN TO BLACK TOPSOIL AND A REDDISH BROWN SUBSOIL. NON SALINE.
10a	ALLUVIAL FANS	NEARLY LEVEL WITH GROUND-WATER SUPPLY SLOPES 0.5-2%	HAPLIC PHAEOZEM	MODERATELY WELL DRAINED, DEEP, SANDY LOAMS TO SANDY CLAY LOAMS, SOMETIMES WITH SANDY LAYERS IN THE SUBSOIL, WITH A VERY DARK BROWN TOPSOIL AND A DARK BROWN TO DARK REDDISH BROWN SUBSOIL, SOMETIMES MOTTLED, AND CALCAREOUS IN LOW RAINFALL AREA. NON TO SLIGHTLY SALINE.
10b	ALLUVIAL FANS	NEARLY LEVEL WITHOUT GROUNDWATER SUPPLY SLOPES 0.5-2%	CHROMIC CAMBISOL HAPLIC PHAEOZEM EUTRIC REGOSOL	WELL DRAINED, DEEP SANDY LOAMS TO SANDY CLAY, SOMETIMES WITH SANDY LAYERS IN THE SUBSOIL, WITH A VERY DARK BROWN TO DARK REDDISH BROWN TOPSOIL, AND A DARK BROWN TO DARK RED SUBSOIL, SOMETIMES CALCAREOUS. NON TO MODERATELY SALINE.

SYMBOL	MAIN UNIT	PHYSIOGRAPHY	CLASSIFICATION	SOIL
10c	ALLUVIAL FANS	GENTLY SLOPING WITH GROUND-WATER SUPPLY SLOPES 2-6%	HAPLIC PHAEOZEM EUTRIC FLUVISOL	WELL DRAINED DEEP SANDY LOAMS TO SANDY CLAYS WITH A VERY DARK BROWN TOPSOIL AND DARK BROWN TO REDDISH SUBSOIL. NON SALINE.
10d	ALLUVIAL FANS	GENTLY SLOPING WITHOUT GROUND-WATER SUPPLY SLOPES 2-6%	CHROMIC CAMBISOL HAPLIC PHAEOZEM EUTRIC REGOSOL	WELL AND MODERATELY WELL DRAINED DEEP LOAMY SOILS, SOMETIMES WITH SANDY LAYERS, WITH A VERY DARK BROWN TO DARK REDDISH BROWN TOPSOIL AND A DARK REDDISH BROWN TO YELLOWISH RED SUBSOIL. NON SALINE.
11a	ALLUVIAL FANS	NEARLY LEVEL WITH HIGH GROUNDWATER, SLOPES 0-1%	EUTRIC FLUVISOL HAPLIC PHAEOZEM	IMPERFECTLY TO MODERATELY WELL DRAINED SOILS WITH VERY DARK BROWN HUMIC TOPSOILS OF VARYING TEXTURE AND DARK GREY TO DARK BROWN LOAMY MOTTLED SUBSOILS OFTEN WITH SANDY LAYERS. NON TO SLIGHTLY SALINE.

SYMBOL	MAIN UNIT	PHYSIOGRAPHY	CLASSIFICATION	SOIL
11c	ALLUVIAL FANS	GENTLY SLOPING, HIGH RAINFALL AREA, SLOPES 2-6-%	HAPLIC PHAEOSEM	IMPERFECTLY TO MODERATELY WELL DRAINED SOILS WITH A VERY DARK BROWN TO BLACK SANDY CLAY LOAM TOPSOIL AND A DARK GREYISH BROWN, MOTTLED, CALCAREOUS, COMPACT SANDY CLAY SUB-SOIL. NON TO SLIGHTLY SALINE.
11c	ALLUVIAL FANS	NEARLY LEVEL, LOW RAINFALL AREA, SLOPES 0-2%	ORTHIC SOLONCHAK	MODERATELY WELL TO WELL DRAINED SOILS WITH A DARK BROWN TO YELLOWISH RED SANDY LOAM TO SANDY CLAY TOPSOIL AND A DARK REDDISH BROWN TO YELLOWISH RED, CALCAREOUS, CLAY LOAM TO CLAY SUBSOIL. STRONGLY SALINE.
11d	ALLUVIAL FANS	NEARLY LEVEL CLAY PLAINS SLOPES 0-2%	PELLIC VERTISOL CHROMIC VERTISOL VERTIC CAMBISOL HAPLIC PHAEOZEM	IMPERFECTLY DRAINED SOILS WITH A DARK BROWN TO VERY GREY TOPSOIL WITH TEXTURE VARYING FROM SANDY LOAM TO CLAY AND A VERY DARK BROWN TO VERY DARK GREY SANDY CLAY TO CLAY SUBSOIL THAT IS GENERALLY COMPACT, IMPER-MEABLE AND CALCAREOUS. NON TO MODERATELY SALINE.

SYMBOL	MAIN UNIT	PHYSIOGRAPHY	CLASSIFICATION	SOILS
14a	HIGHER LAND	UPLANDS AND MOUNTAIN FOOT-SLOPES 2-8%	RHODIC FERRALSOL CHROMIC LUVISOL	WELL DRAINED DEEP AND MODE-RATELY DEEP RED AND YELLOWIS RED CLAY LOAMS AND CLAYS. NON SALINE.
14b	-	ROLLING AND HILLY SLOPES 8-30%	CHROMIC LUVISOL	WELL DRAINED DEEP AND MODE-RATELY DEEP RED AND YELLOWISH RED CLAY LOAMS AND CLAYS. NON SALINE.
15		MOUNTAINS, LARGE RANGE IN ELEVATION	CHROMIC LUVISOL LITHOSOL	WELL TO EXCESSIVELY DRAINED SHALLOW AND MODERATELY DEEP RED AND YELLOWISH RED, GRAVELLY CLAY LOAMS AND CLAYS WITH COMMON ROCK OUTCROPS. NON SALINE.

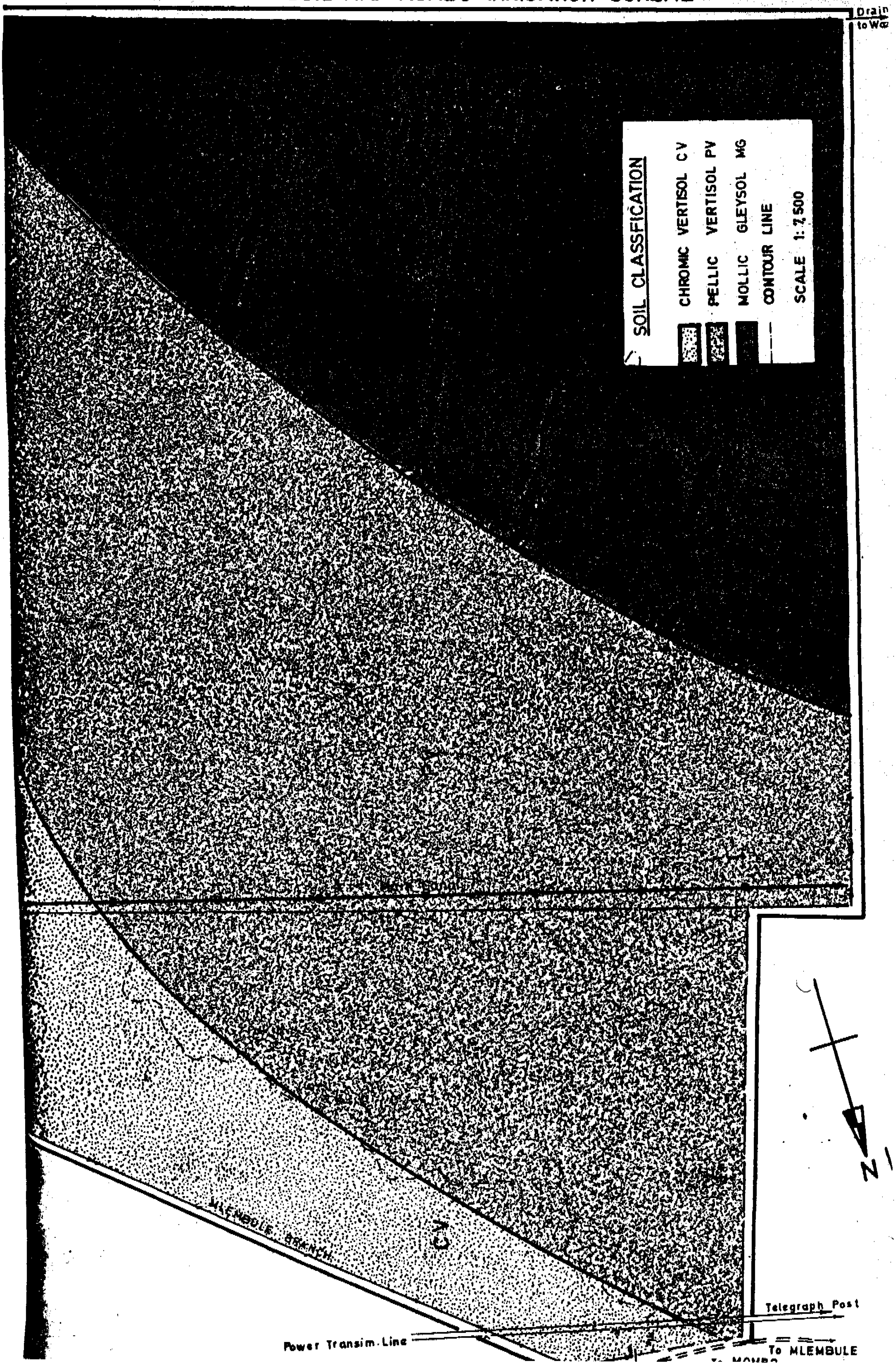


APPENDIX 1.3

LOCATION OF MOMBO IRRIGATION SCHEME (SCALE 1: 50,000)

APPENDIX 1.4

SOIL MAP MOMBO IRRIGATION SCHEME



DESCRIPTION OF SOIL PROFILES

Profile No. 4

Date of survey	21.1.1977
Location	Mombo Irrigation Scheme Right side of the road, see soil and irrigated suitability map, Appendix 1.2
Elevation	400 m above sea level
Physiographic position of the site	Valley bottom
Land form or land use	Rice fields
Moisture condition	Very dry hard soil
Brief description of the profiles	Very poor drainable to imperfectly drained black clay soil (Mbuga soil) with open vertical cracks 2 - 3 cm wide. Extremely hard when dry.

Description of soil horizon

AC	0 - 20 cm	Grey black clay soil Many fine rests, very hard when dry. Top soil slightly brown colour.
C	20 - 100 cm	Very dark grey clay with big wide vertical cracks (1 - 5 cm). Extremely hard when dry. Few fine roots. Strong very prismatic structures.

Classification (FAO)	Pellic vertical
Parent material	Alluvial clay
Suitability	Suitable for rice cultivation. Not suited for upland crops.

Profile No. 5

Date of survey	21.1.1977
Location	Mombo Irrigation Scheme Left side of the road approximately 250 m distance from profile No. 4
Elevation	400 m above sea level
Physiographic position of the site	Valley bottom
Land form	Flat. Slope of the site is approximately 0,1 - 1 %.
Vegetation or land use	Rice fields
Moisture condition	Very dry soil
Brief description of the profile	Very poorly to imperfectly drained black clay soil with wide open cracks similar to profile No. 4. Extremely hard when dry, sticky and plastic when wet.

Description of soil horizon

AC	0 - 30 cm	Sandy clay with a brown black colour. Many fine roots. Very hard when dry.
C	30 - 100 cm	Grey black clay with wide open vertical cracks. Extremely hard when dry. Few fine roots. Strong prismatic structure.

Soil classification (FAO)	Pellic vertical
Parent material	Alluvial clay
Suitability	Not suitable for upland crops, well suited for rice cultivation.

Profile No. 111

Date of survey	17.10.1975
Location	On the road from Mombo to Mombo Air-field, see soil and irrigation suitability map, Appendix 1.2
Land form	Flat. Slope on which profile is sited approximately 0 %.
Vegetation or land use	Short grazed grass tall herbs common small shrubs acacia trees
Moisture condition	Dry tall 50 cm slightly moist below
Brief description of the profile	Poorly to imperfectly drained cracking clay soil with black clayey top soil, with very coarse prismatic structure and common brown mottles.

Description of soil horizon

AC	0 - 40 cm	Black clay common fine and medium dark brown mottles. Very hard when dry. Very fine roots, wide open cracks.
C	40 - 95 cm	Very dark grey clay, very strong coarse prismatic structure. Very hard when dry, very firm when moist, common to many fine roots, many open cracks.

Classification (FAO)	Pellic vertical
Parent material	Alluvial clay
Drainage class	Poorly to imperfectly drained
Suitability	Not suited for upland crops. Well suited for irrigation rice cultivation.

Profile No. 114

Date of survey	18.10.1975
Location	On the road from Mombo to Kwalukonge Estate, see soil and irrigation suitability map, Appendix 1.2
Elevation	405 m above sea level
Physiographic position of the site	Alluvial fans, plain
Land form	Flat. Slope on which profile is sited approximately 2 %.
Vegetation or land use	Grass with scattered shrubs and some acacia trees
Moisture condition	Dry to 80 cm, slightly moist below
Brief description of the profile	Imperfectly drained sandy clay soil with a sandy clay loam top soil and slightly vertic characteristics. Layer 7 - 50 cm is extremely hard.

Description of soil horizon

AC	0 - 7 cm	Dark brown sandy clay loam with common fine and medium distinct mottles. Hard when dry, sticky and plastic when wet. Many fine roots.
C_1	7 - 50 cm	Dark brown sandy clay with few fine faint brown mottles. Strong very coarse prismatic and moderate coarse prismatic and moderate coarse angular blocky structure. Extremely hard when dry, few fine roots, slightly saline

C_2	50 - 80 cm	Dark brown sandy clay with few medium faint brown mottles. Strong very prismatic structure. Hard when dry, common fine roots, strongly saline.
C_3	80 - 135 cm	Dark reddish brown sandy clay with fine red mottles. Firm when moist, plastic when wet. Few fine tubular pores, few fine roots, no cracks, strongly saline.

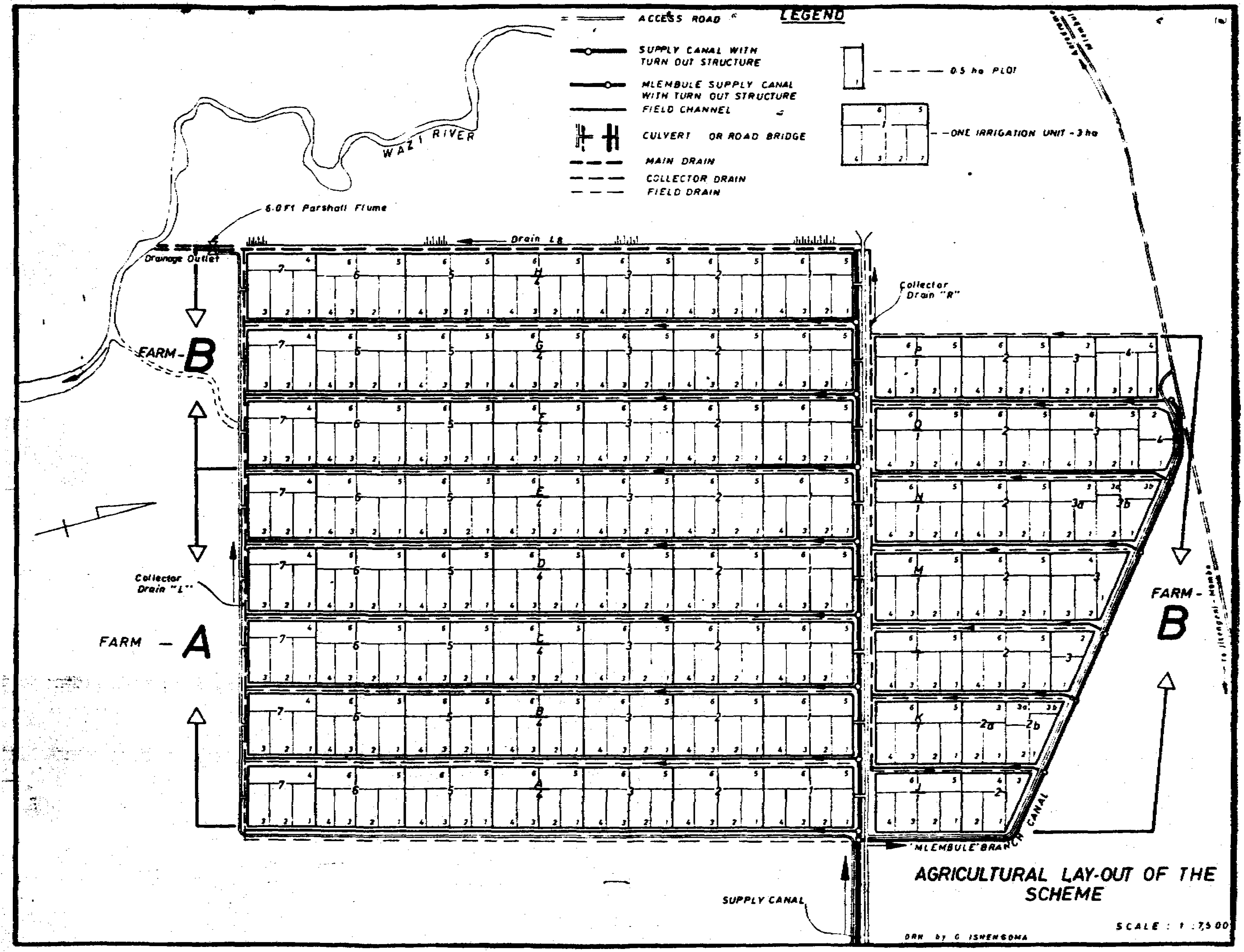
Classification (FAO)	Vertic cambisol
Parent material	Alluvial/colluvial material from the Usambaras
Drainage class	Imperfectly drained
Suitability	Not suitable for animal crops, moderately suited for upland crops. Moderately suited for rice cultivation.

APPENDIX 1.6

Analyse Data of the Soil Samples

PROFILE NO	DEPTH IN CMS	MECHANICAL ANALYSES & SEPARATES 2-0.05	0.05 - 0.02	0.02-0.002	0.002	pH H_2O 1.2.5	Ca Cl_2 1.2.5	WALKEY AND BLACK % C	KJEL-DAHL % N	C/N
4	0-20	35.2	6.0	12.0	46.8	7.6	2.8	-	-	-
	20-100	33.2	4.0	12.0	50.8	6.3	5.8	-	-	-
5	0-30	53.2	8.0	6.0	32.8	6.7	6.1	-	-	-
	30-100	35.2	6.0	10.0	48.8	6.6	6.0	-	-	-
111	0-40	23.2	11.0	7.0	52.8	6.4	6.0	0.50	0.005	8
	40-95	31.2	9.0	4.0	55.8	7.7	7.1	0.15	0.036	4
114	0-7	41.2	11.0	9.4	28.4	6.9	6.2	1.85	0.145	13
	7-50	45.2	11.0	4.0	41.8	5.5	4.8	0.44	0.025	18
	50-80	43.2	11.0	5.0	40.8	7.4	7.0	0.28	0.025	12
	80-100	47.2	8.0	4.0	40.8	7.1	6.5	0.09	0.015	8

PROFILE NO	ppm P	CONDUC-TIVITY mmhos/	EXCHANGEABLE LONS milliequivalents/100 g Na	K	Ca	Hg	TOTAL BASES	H	CEC
4	-	-	0.29	0.71	-	-			
	-	-	1.45	0.21	-	-			
5	-	-	0.05	0.23	-	-			
	-	-	2.32	0.19	-	-			
111	9.5	0.4	3.75	0.13	19.80	28.20	51.88	0.036	51.88
	3.0	0.83	4.65	0.14	21.80	36.80	63.39	0.036	63.43
114	472.0	0.3	2.13	0.32	11.40	5.60	19.45	0.084	19.53
	355.0	1.1	11.60	0.06	20.00	8.40	40.06	-	40.06
	257.0	3.9	2.40	0.06	22.20	9.40	24.66	0.020	34.68
	328.5	4.7	0.03	8.20	24.20	12.20	44.63	0.004	44.63


LEGEND
ACCESS ROAD
SUPPLY CANAL WITH TURN OUT STRUCTURE
MLEMBULE SUPPLY CANAL WITH TURN OUT STRUCTURE
FIELD CHANNEL
CULVERT OR ROAD BRIDGE
MAIN DRAIN
COLLECTOR DRAIN
FIELD DRAIN
0.5 ha PLOT
ONE IRRIGATION UNIT - 3 ha
WAZI RIVER
6.0 Ft Parshall Flume
Drainage Outlet
Drain Lg
Collector Drain "R"
Collector Drain "L"
FARM - B
FARM - A
FARM - B
'MLEMBULE' BRANCH CANAL
SUPPLY CANAL
AGRICULTURAL LAY-OUT OF THE SCHEME
SCALE : 1 : 7,500
DRN by G ISHENGOMA

APPENDIX 2

Reference crop evapotranspiration,
ETo determination

Months	Jan.	Feb.	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec.
T mean, °C	20.4	20.6	20.8	20.9	19.6	17.4	16.8	16.6	16.9	18.0	19.6	20.2
RHmean	61.5	61.5	63.5	71.5	73.5	69.5	68.5	64.5	60.5	58.5	61.5	61.5
Wind speed Km/day	5	-		7.	5 m/	sec =	mean	6.25	m/sec	= 540	km/day	
Sunshine hours, n	7.4	8.3	8.1	4.8	5.6	5.5	6.8	7.8	8.1	9.8	8.0	8.5
N	12.3	12.3	12.1	12.0	11.9	11.8	11.8	11.9	12.0	12.2	12.3	12.4
Ra, mm/day	15.7	15.9	15.6	14.8	13.6	13.0	13.3	14.2	15.1	15.7	15.7	15.6
n/N	0.60	0.67	0.67	0.4	0.47	0.47	0.58	0.65	0.68	0.80	0.65	0.69
Rs mm/day	8.64	9.30	9.13	6.66	6.60	6.30	7.18	8.24	8.91	10.21	9.03	9.28
Rns, mm/day	6.48	6.98	6.85	5.00	4.95	4.73	5.39	6.18	6.68	7.66	6.77	6.96
Rnl, mm/day	1.68	1.77	1.70	1.03	1.20	1.34	1.60	1.80	1.77	2.16	1.80	1.84
Rn mm/day	4.80	5.20	5.15	3.97	3.75	3.40	3.79	4.40	4.90	5.50	4.97	5.10
W	0.702	0.704	0.706	0.707	0.692	0.662	0.656	0.654	0.657	0.668	0.692	0.700
(1 - W)	0.298	0.296	0.294	0.293	0.308	0.338	0.344	0.346	0.343	0.332	0.308	0.300
f(U)	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
W.Rn	3.37	3.66	3.62	2.81	2.60	2.25	2.49	2.88	3.22	3.67	3.44	3.57
ea	24.0	24.3	24.6	24.75	22.84	19.88	19.16	18.92	19.28	20.6	22.84	23.70
ed	14.76	14.94	15.62	17.90	16.79	13.82	13.12	12.20	11.66	12.05	14.05	14.[illegible]
ea - ed	9.24	9.36	8.98	7.05	6.05	6.06	6.04	6.72	7.62	8.55	8.79	9.10
Uday/Unight	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
RHmax	77.	77.	78.	83.0	85.0	83.0	84.0	81.0	76.0	72.0	73.0	75.0
Uday	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
C	0.91	0.91	0.90	0.84	0.83	0.83	0.85	0.88	0.90	0.92	0.89	0.90
ETo mm/day	7.40	7.69	7.38	5.36	4.83	4.81	5.17	6.07	6.97	7.89	7.23	7.46

Note: Uday = 7.5m/s and Unight = 5m/s

CALCULATIONS FOR THE ETo DETERMINATION

Given for January (for example)

Tmean = 20,4 ^{o}C and RHmean = 61,5 %

From table 4,

ea = 24,0 mbar at 20,4 ^{o}C

ed = ea x $\frac{RHmean}{100}$ = 24,0 mbar x $\frac{61,5}{100}$ = 14,76 mbar

Uav = 6,25 m/s = 540 km/day,

From table 6 f(U) = 1,73

Tmean = 20,4 %, altitude = 400 m,

From table 7 W = 0,702

Latitude is 4^{o}55', altitude = 400 m, Tmean = 20,4 ^{o}C,

RHmean = 61,5 %, sunshine nmean = 7,4 hours/day,

From table 8 Ra = 15,7 mm/day

From table 9 N = 12,3 hours/day

Rs = (0,25 + 0,50 x $\frac{n}{N}$) Ra = 8,64 mm/day

α = 0,25

Rns = (1 - α) Rs = 6,48 mm/day

From table 11, f(T) = 14,6

From table 12, f(ed) = 0,17

From table 13, f($\frac{n}{N}$) = 0,64

Rnl = f(T) x f(ed) x f($\frac{n}{N}$) = 1,68 mm/day

Rn = Rns - Rnl = 6,48 - 1,68 mm/day = 4,80 mm/day

Rs = 8,64 mm/day, RHmax = 77 %, Uday/Unight = 1,5,

Uday = 7,5 m/s

From table 14, c = 0,91

ETo = c $\left[(W \times Rn) + (1 - W) \times f(U) \times (ea - ed)\right]$

= 0,91 $\left[(0,702 \times 4,80) + (1 - 0,702) \times 1,73 \times (24,0 - 14,76)\right]$ mm/day = 7,40 mm/day

The same steps are repeated to calculate ETo for the other months.

DEVELOPMENT OF CROP COEFFICIENT FOR PADDY, MAIZE AND BEANS

Steps:

I Establish planting date or sowing date from local information or from practices in similar climatic zones.

II Determine total growing season and length of crop development stages from local information or see table 20.

III Initial stage: predict irrigation and/or rainfall frequency; for predetermined ETo value, obtain kc from figure 6 and plot kc value as shown in figure 7.

IV Mid-season stage: for the given climate (humidity, wind) select kc values from table 19 and plot a straight line.

V Late-season stage: for time full maturity (or harvest within a few days) select kc from table 19 for given climate (humidity and wind) and plot value at the end of the growing season or full maturity. Assume straight line between kc values at the end of mid-season period and at the end of growing season.

VI Development stage: assume a straight line between kc value at the end of initial to start of mid-season stage.

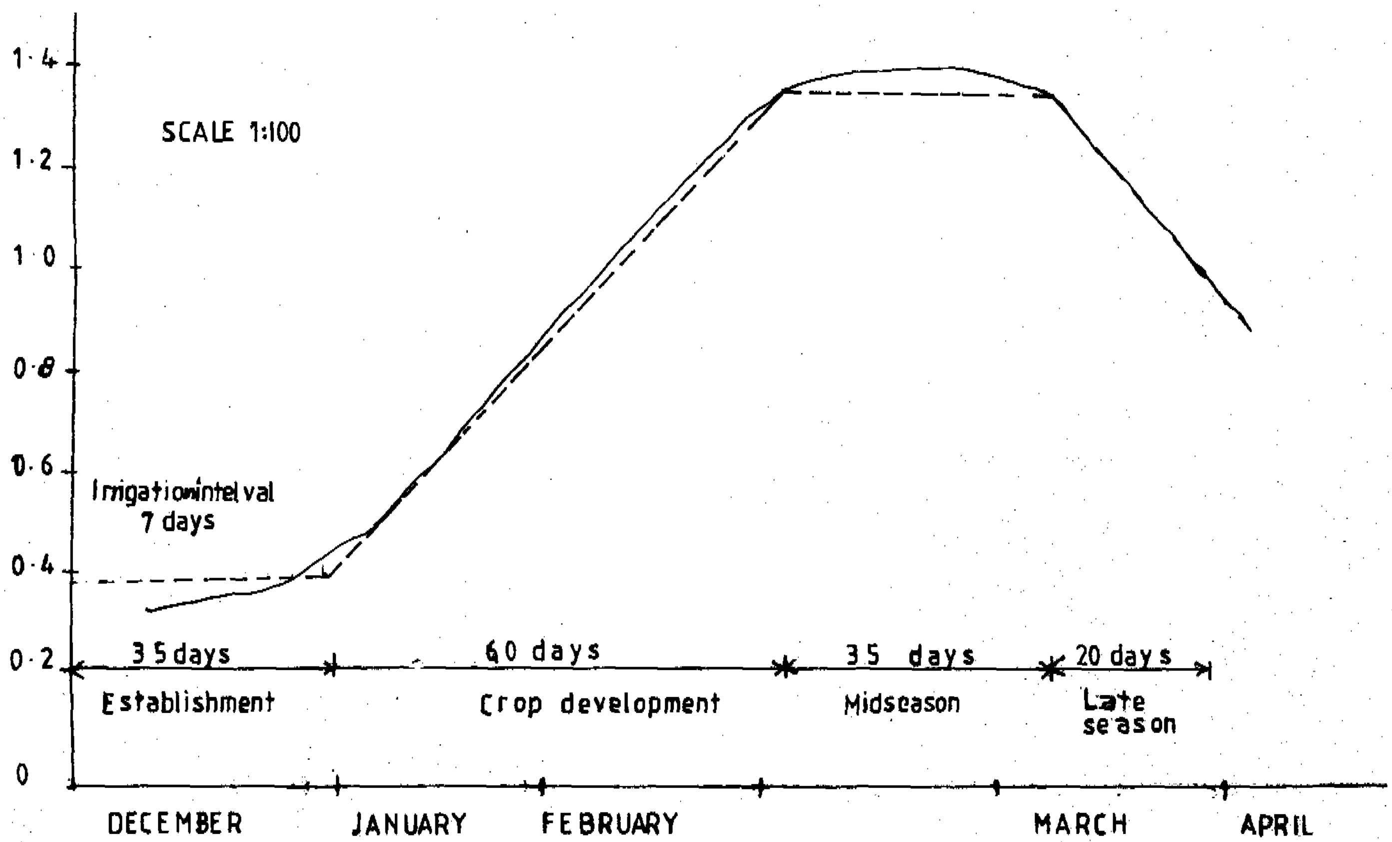
Given: Mombo Irrigation Scheme paddy planted 1st December, winds moderate 5,0 - 7,5 m/s, RHmin = 40 - 60 %, ETo initial stage = 7,50 mm/day, irrigation frequency at initial stage is 7 days.

I Planting date 1st December

II Length of growth stages (Appendix 3):

Establishment (Nursery-fellows)	35 days
Crop development (vegetative and flowering)	60 days
Mid season	35 days
Late season	20 days

Average irrigation interval = 7 days, kc = 0,37



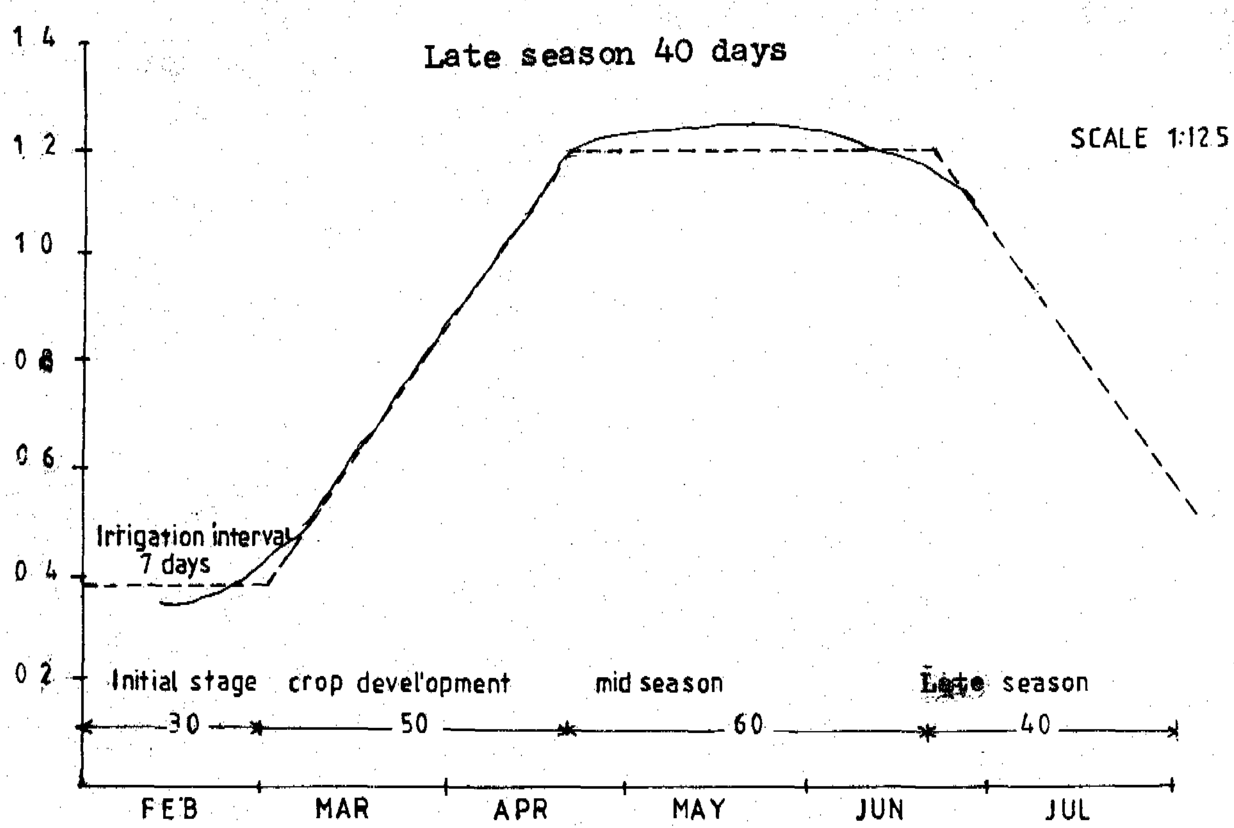
Paddy crop coefficient curve.

Given: maize planted 1st February, winds moderate 5,0 - 7,5 m/s, RHmin 40 - 60 %, ETo initial stage = 7,40 mm/day, irrigation frequency at initial stage is 7 days.

I Planting date 1st February

II Length of growing season (table 20):

Initial stage	30 days
Crop development	50 days
Mid season	60 days

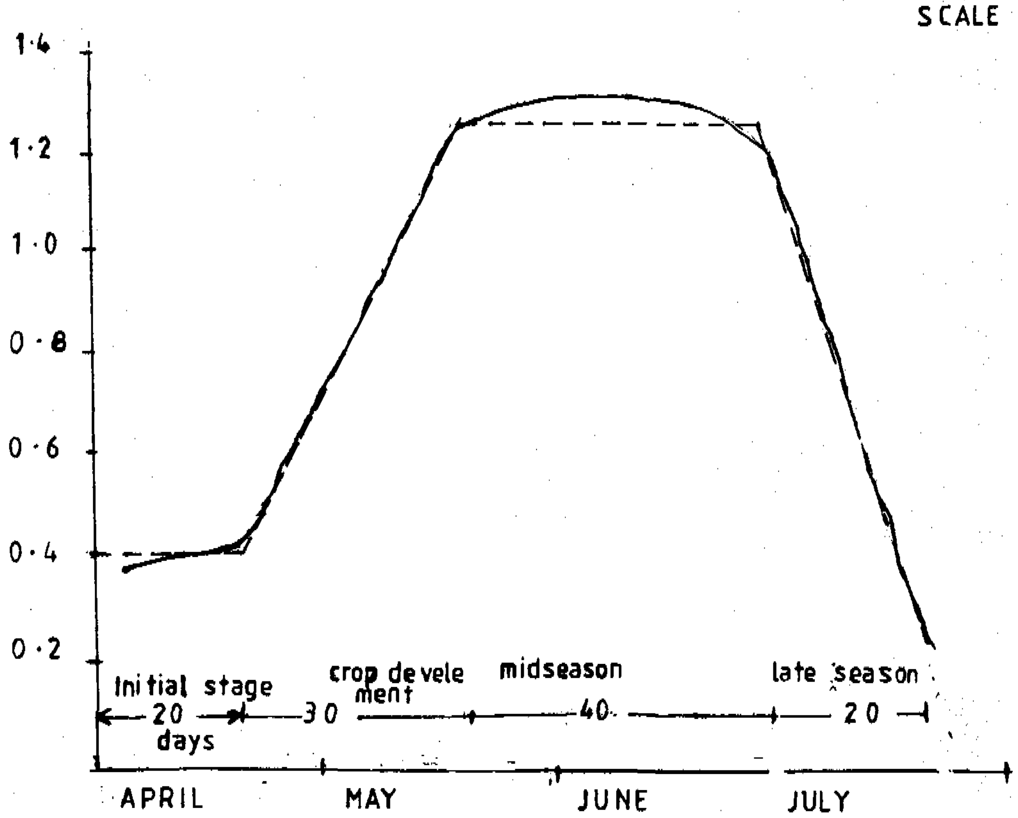


Maize crop coefficient.

Given: Beans planted 1st April, winds moderate 5,0 - 7,5 m/s, RHmin = 40 - 60 %, ETo at initial stage = 5,40 mm/day, irrigation frequency at initial stage is 7 days.

I	Planting date 1st April	
II	Length of growing stages (table 20)	
	Initial stage	20 days
	Crop development	30 days
	Mid season	40 days
	Late season	20 days

SCALE 1:100



Bean crop coefficient curve.

Determination of crop evapotranspiration ETcrop using the developed crop coefficients.

ETcrop = kc x ETo

kc is obtained from the curves above

ETcrop in mm/day

MONTH	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
ETo mm/day	7.46	7.40	7.69	7.38	5.36	4.83	4.81	5.17
Paddy kc	0.35	0.60	1.02	1.28	1.05			
Maize kc			0.34	0.62	1.04	1.25	1.15	0.85
Bean kc					0.40	0.80	1.25	0.70
Paddy ETcrop	2.60	4.40	7.80	9.40	5.60			
Maize ETcrop			2.60	4.60	5.60	6.0	5.50	4.40
Bean ETcrop					2.10	3.90	6.0	3.6

Determination of effective rainfall from the given rainfall. For paddy - effective rainfall and net irrigation requirement.

MONTH	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
Mean rainfall mm/month	61.0	49.0	46.0	86.0	132.0	101.0	26.0	20.0
Monthly Paddy ETcrop mm/month	80.90	136.4	226.2	291.4	168.0			
effective rainfall mm/month	41.95	38.0	32.20	87.50	98.9			
Net Irrigation requirement mm/month	38.95	98.4	193.0	203.9	69.1			
Net Irrigation Requirement mm/day	1.25	3.20	6.90	6.60	2.30			

For maize - effective rainfall and net irrigation requirement.

MONTH	JAN	FEB	MAR	APR.	MAY	JUN	JUL
Mean monthly rainfall mm	49.0	46.0	86.0	132.0	101.0	26.0	20.0
Monthly Maize ETcrop mm		75.40	142.60	168.0	186.0	165.0	136.4
Effective rainfall mm/month		31.80	64.30	98.90	81.30	21.0	15.25
Net irr. requir. mm/month		43.60	78.30	69.10	104.70	144.0	121.10
Net irrig. require. mm/day		1.50	2.50	2.30	3.40	4.8	3.90

For beans - effective rainfall and net irrigation requirement.

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL
Mean Month Rainfall mm	49.0	46.0	86.0	132.0	101.0	26.0	20.0
Monthly Bean Etcrop mm				63.0	120.9	180.0	111.60
Effective Rainfall mm/month				81.80	71.80	21.60	14.60
Net irrig. Require. mm/month				-	49.1	158.4	97.0
Net Irrig. Require. mm/day				-	1.60	5.30	3.10

ROTATIONAL IRRIGATION SCHEDULING

a) Basic data

1. Irrigable area 220 ha

2. Cropping pattern
   Paddy 110 ha
   Maize 55 ha
   Beans 55 ha

3. Hydraulic characteristics of soils
   Water holding capacity = 100 mm/m
   Root depth of paddy = 0,65 m
   Root depth of maize = 0,80 m
   Root depth of beans = 0,60 m
   Fraction of available soil water for rice = 0,50
   Fraction of available soil water for maize = 0,60
   Fraction of available soil water for beans = 0,45

4. Irrigation requirements (mm)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Paddy IrrigRe mm/day	3.20	6.90	6.60	2.30								1.25
Maize Irr.Req mm/day		1.50	2.50	2.30	3.40	4.80	3.90					
Beans Irr.Req mm/day				-	1.60	5.30	3.10					

b) Depth of irrigation water

The depth of irrigation $d = P \times Sa \times D$

For rice, $d = 0{,}50\ m \times 100\ mm/m \times 0{,}65 = 32{,}5\ mm$

For maize, $d = 0{,}60\ m \times 100\ mm/m \times 0{,}8 = 48{,}0\ mm$

For beans, $d = 0{,}45\ m \times 100\ mm/m \times 0{,}6 = 27{,}0\ mm$

c) Irrigation intervals

$$\text{Irrigation interval, } I = \frac{d}{\text{Irrigation requirement}}$$

Irrigation requirement mm/day and I in days.

Irrigation intervals for rice:

$$I_1 = \frac{32{,}50\ mm}{1{,}25\ mm/day}$$

I_1 = 26 days, within December

For I_2

$1{,}25\ (31 - 26) + 3{,}20\ \Delta = 32{,}50$, where Δ = days from the following month

$\Delta = 8{,}2$ days

$I_2 = 5 + 8{,}20 = 13$ days, January.

$$I_3 = \frac{32{,}50\ mm}{3{,}2\ mm/day}$$

I_3 = 10 days, within January

I_4 = 10 days, within January

For I_5

$3{,}2\ (31 - 28) + 6{,}90\ \Delta = 32{,}50$

$\Delta = 3{,}3$ days of February

$I_5 = 3 + 3{,}3 = 6$ days

$$I_6 = \frac{32{,}50 \text{ mm}}{6{,}90 \text{ mm/day}}$$

I_6 = 5 days

I_7, I_8, I_9, I_{10} = 5 days, respectively, within February

For I_{11}

$$6{,}90\ (29 - 28) + 6{,}60\ \Delta = 32{,}50$$
$$\Delta = 4 \text{ days}$$

I_{11} = (1 + 4) days = 5 days part of March

$$I_{11} = \frac{32{,}50 \text{ mm}}{6{,}60 \text{ mm/day}}$$

I_{11} = 5 days

I_{12}, I_{13}, I_{14}, I_{15} = 5 days respectively

For I_{16}

$$6{,}60\ (31 - 29) + 2{,}30\ \Delta = 32{,}50$$
$$\Delta = 8 \text{ days}$$

I_{16} = 2 + 8 = 10 days - April

$$I_{16} = \frac{32{,}50 \text{ mm}}{2{,}30 \text{ mm/day}}$$

= 14 days - last day of irrigation

The intervals for other crops are calculated similarly.

FOUR PRACTICES OF SCHEDULING FOR PADDY (Doorenbos and Pruitt, 1977)

1. Continuous submersion with intermittent drainage is the most promising method.

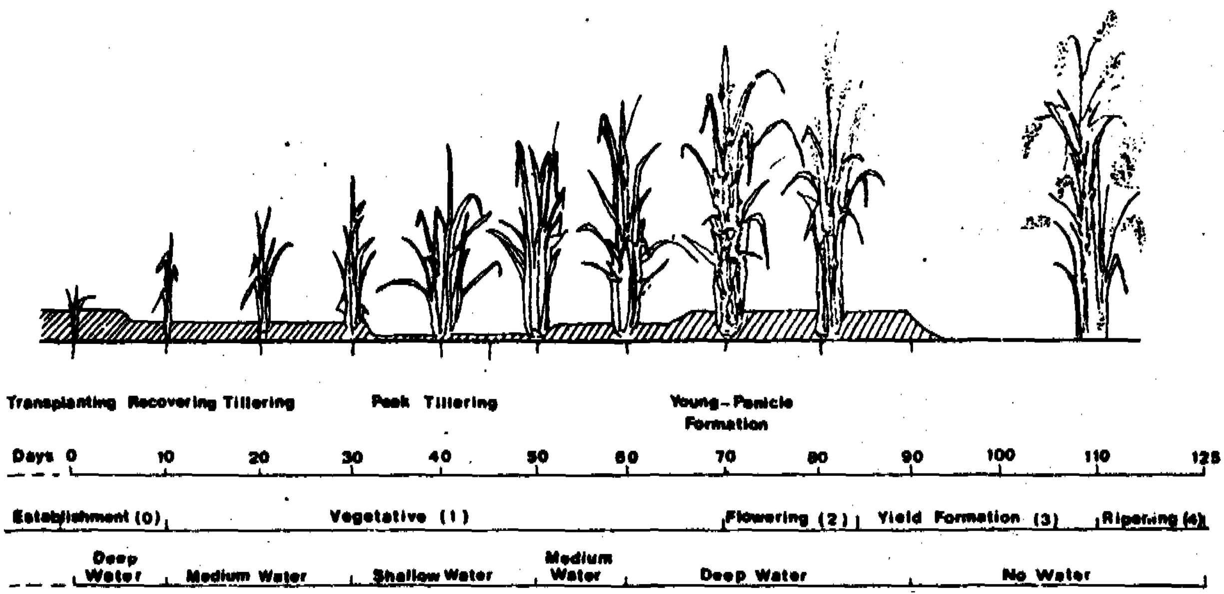


Fig. 15. Controlled water depth in paddy field (Kung, 1971).

During and immediately after transplanting the water is kept at 10 cm for about a week to secure healthy growth of seedlings. In the following tillering period, submergence is shallow (maximum 3 cm) to maintain high soil temperature. Drainage and drying of the top soil is practised during this period since paddy can tolerate a water shortage and root development is enhanced.

Drainage must be completed 30 days prior to heading. From this time onward, adequate water supply during head development through flowering is essential. Continuous flow irrigation and renewal of water once or twice during this period is sometimes practised.

During opening period fields should gradually be drained to facilitate harvest operations. Usually fields are completely drained 30 to 45 days after heading, with shorter period for early paddy varieties and the longer for late varieties.

2. Intermittent irrigation: with this method, soil water during the non-submersion period must be adequate. When the soil water content falls slightly below saturation. Water added until a shallow submergence is attained.

3. Heading stage submersion: with this method the soil is kept at saturation or is lightly submerged during almost the whole growing period, except for a period of 25 days prior to about 10 days after heading when paddy fields are submerged to a depth of 10 cm.

4. Water saving irrigation: when water saving is essential, the field after puddling and transplanting is supplied with water to keep soil water content in the root depth at not less than 75 per cent of full saturation throughout the growing period. Moderate submergence is only practised during a period of 30 days starting at head initiation till the end of flowering.

Compared to continuous submersion, water savings are estimated:

	Water applied	Yield
continuous submersion	100 %	100 %
intermittent irrigation	80 %	50 %
leading stage submersion	60 %	75 %
water saving irrigation (controlled)	75 %	110 %

Mbarali Rice State Farm uses continuous submersion practice (see section 2.8.1). The schedule given in figure 12 is based on water saving irrigation practice which seeks to increase the yield per unit of water applied.

THE DETERMINATION OF ETo

Example 1. Using radiation method.

Given: Mombo Irrigation Scheme, latitude 4°55', January, sunshine hours (n) = 7,4 hours/day, altitude 400 m, Tmean = 20,4 °C, wind daytime = 7,5 m/s, RHmean = 61,5 %

Calculation:
From table 8, Ra = 15,7 mm/day
From table 9, N = 12,3 hours/day

$$Rs = 0,25 + 0,5 \times \frac{7,4}{12,3} \times 15,7 \text{ mm/day}$$

Rs = 8,65 mm/day

From table 7 (given altitude and Tmean), W = 0,702
W x Rs = 0,702 x 8,65 mm/day
W x Rs = 6,07 mm/day

From figure 4, given W x Rs = 6,07 mm/day, Udaytime = 7,5 m/s, RHmean = 61,5 %, using the first block III, curve 3,
ETo = 5,90 mm/day

Example 2. Blaney-Criddle method.

Given: Mombo Irrigation Scheme, latitude 4°55', January, sunshine hours (n) = 7,4 hours/day, altitude 400 m, Tmean = 20,4 °C, wind daytime = 7,5 m/s, RHmean = 61,5 %

Calculation:
Tmean = 20,4 °C
From table 15 (for latitude 4°55'), P = 0,275
P (0,46 x T + 8) = 0,275 (0,46 x 20,4 + 8)
P (0,46 x T + 8) = 4,80 mm/day

Using Rmin = 46,0 %, $\frac{n}{N} = \frac{7,4}{12,3} = 0,60$

U_2 daytime = 7,5 m/s

From figure 7, line 3, Block V, ETo = 6,0 mm/day

∴ ETo = 6,0 mm/day

From the two exapmles, radiation method and Blaney-Criddle method give similar values of ETo.

ADDITIONAL CONSIDERATIONS

for radiation method with the inclusion of calculated or measured radiation and with partial consideration of temperature, only general level of daytime wind and mean relative humidity need to be selected. Except for equatorial zones climatic conditions for each month or shorter period vary from year to year, and consequently ETo varies. Calculations should preferably be made for each month or period for each year of record rather than using mean radiation and mean temperature data based on several years of record. A value of ETo can then be obtained to ensure that water equivalents will be met a reasonable degree of certainty.

ADDITIONAL CONSIDERATIONS OF BLANEY-CRIDDLE METHODS

Since the empiricism involved in any ETo prediction method using a single weather factor is inevitably, this method should be used when temperature data are the only measured weather data available. It should be used with scepticism (i) in equatorial regions where temperatures remain fairly constant but other weather parameters will change, (ii) for small islands and coastal areas where air temperature is affected by the sea temperature having little response to seasonal change in radiation, (iii) at high altitudes due to fairly low mean daily temperatures (cold nights) even though daytime radiation levels are high, and (iv) in climates with a wide variability in sunshine hours during transition months (e.g. monsoon climates, mid latitude climates during spring and autumn). The radiation method is preferable under these conditions even when the sunshine or radiation data need to be obtained from regional or global maps in the absence of any actual measured data (Doorenbos and Pruitt, 1977). At high latitudes (55° or more) the days are relatively long but radiation is lower as compared to low and medium latitude areas having the same day length values. This results in an undue weight being given to the day length related P factor. Calculated ETo value should be reduced by up to 15 per cent for areas at latitudes of 55° or more. Concerning altitude, in semiarid and arid areas ETo values can be adjusted downwards some 10 per cent for each 1000 m altitude change above sea level.

Calculation of mean daily ETo should be made for periods not shorter than one month. Since for a given location climatic conditions and consequently ETo may vary greatly from year to year, ETo should preferably be calculated for each calendar month for each year of record rather than by using mean temperatures based on several years' record.

The use of crop coefficient, k, employed in the original Blaney-Criddle approach is rejected because (i) the original crop coefficients are heavily dependent on climate, and the wide variety of K values reported in literature makes the selection of the correct value difficult; (ii) the relationship between P (0,46 T + 8) values and ETo can be adequately described for a wide range of temperatures for areas having only minor variation in RHmin, n/N and U; and (iii) once ETo has been determined the crop coefficients, kc, can be used to determine ETcrop (Burman, 1980).

ADDITIONAL CONSIDERATION OF PAN EVAPORATION METHOD

In selecting the appropriate value of kp to relate class A and Colorado sunken pan data to ETo, it is necessary to consider the ground cover of the pan station, that of the surroundings and general wind and humidity conditions.

When the pan is located at a station with very poor grass cover, dry bare soil or undesirably, a concrete or asphalt apron, air temperature at pan level may be 2 to 5 °C higher and relative humidity 20 to 30 per cent lower. This will be most pronounced in aid and semi-arid climates during all but the rainy periods. This effect has been accounted for in the figures of tables 21 and 22. However, in areas with no agricultural development and extensive areas of bare soils - as are found under desert conditions the values of kp given for arid, windy areas may need to be reduced by up to 20 per cent; for areas with moderate level of wind, temperature and relative humidity by 5 to 10 per cent; no or little reduction in kp is needed in humid and cool conditions.

In tables 17 and 18 a separation is made for pairs located within cropped plots surrounded by or downwind from dry surface areas, case A, and for pans located within a dry or fallow field but surrounded by irrigated or rainfed upwind cropped areas, case B. Figure 16 shows these two cases.

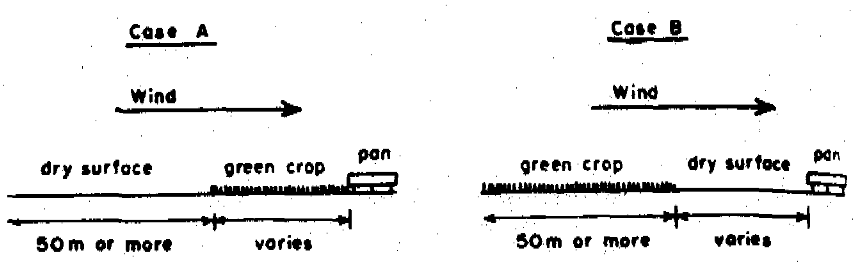


Fig. 16. Visual interpretation of cases A and B for tables 21 and 22 (Jensen, 1973).

Where pans are placed in a small enclosure but surrounded by tall crops, for example 2,5 m high maize, the coefficients in tables 21 and 22 will need to be increased by up to 30 per cent for dry, windy climates, whereas only a 5 to 10 per cent increase is required for calm and humid conditions. The pan coefficients given in tables 21 and 22 apply to galvanized pans annually painted with aluminium. Little difference in Epan will show when inside and outside surfaces of the pan are painted white. An increase in Epan of up to 10 per cent may occur when they are painted black. The material from which the pan is made may account for variations of only a few per cent.

The level at which the water is maintained in the pan is very important; resulting errors may be up to 15 per cent when water levels in class A pans fall 10 cm below the accepted standard of between 5 and 7,5 cm below the rim. Screens mounted over pans will reduce Epan by up to 10 per cent. In an endeavour to avoid pans being used by birds for drinking, a pan filled to the rim with water can be placed near the class A pan; birds may prefer to use the fully filled pan. Turdidity of the water in the pan does not affect Epan data by more than 5 per cent. Overall variation in Epan is not constant with time because of ageing, deterioration and repainting (Jensen, 1980).

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