PLANNING IRRIGATION REQUIREMENTS

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For centuries, the farmer has depended on his horse-sense in the application of irrigation water to his field. The art of irrigating the cropped acres has passed on from generation to generation till, rather recently, the scientist stepped in to enquire into the true mechanism of plant growth and the real function performed by water for optimum crop production. With the increasing economic pressures caused by a rapid growth of world population, water has assumed an importance of great significance. Developed nations have actually started fearing that their sources of fresh water supply are inadequate and need to be augmented to keep pace with their advancement. In less developed countries, more and more water is needed to grow food and fibre to save their populations from starvation. Where due stress is being laid on water resources development, efforts are also being made to economize the use of water, especially the irrigation water. To recall a phrase, a nation, indifferent to efficient use of her water resources, will soon find confronted with serious economic problems.

Crop yields are seriously affected by too little and too much water application. The productivity of land is likely to be jeopardized if quality of water as well as its quantity are not properly controlled. The engineer is as responsible as the farmer in the most efficient management of water so that proper amounts of water of a suitable quality are made available at the proper time for optimum growth of plants. Any negligence in this regard is bound to result in a loss of valuable supply which, in its own turn, will cause other problems entailing increased financial outlays. It is high time for the engineer to understand a little about the agricultural technology and problems of the farmer in the latter's struggle for survival. It is unfortunate that water resources development planning is influenced by other considerations more than the irrigation requirements of the farmer who is the backbone of economy of developing countries.

Estimation of irrigation requirements involves many complex problems all of which require a cool-headed consideration before embarking on any water supply project. It is generally understood that the process of irrigation is meant primarily for storage of water in the root zone of plants to supply for their evapo-transpiration requirements. The foremost problem, therefore, is the soil factor requiring investigation into the properties of the soil *viz.*, its capacity to retain moisture, permeability, structure, texture, composition, organic and inorganic matter present in the soil etc. Next, the problem of estimating the consumptive use by the plant for a vigorous growth requires an accurate appraisal of the transpiration process and the climatic factors controlling evaporation such as heat, humidity, wind etc. The factors concerning the topography, environments, methods and efficiency of land and water management, distribution of irrigation supplies etc., also greatly influence the design of an adequate irrigation system. The planner, in addition, should also investigate the drainage requirement of an irrigated area and make provision for additional water that may be needed to maintain a favourable salt balance in the soil. Adequate precautions need also be taken in regard to flood control and excessive leakage of water supply from the distribution system. This article serves the purpose of understanding the problem and assists the planner in providing optimum irrigation supplies to support a vigorous agricultural activity in the area under his jurisdiction.

The Soil Factor

Detailed soil investigations are necessary to arrive at a decision whether agriculture in a certain area is an economic proposition. These investigations should be aimed at determining the maximum productivity and financial outlay for developing the land. Broadly, the soils may be classified as coarse medium and fine textured. Sandy soils are coarse, loamy soils are medium and clayey soils are fine textured. The soil texture has an important bearing on flow of soil water, air circulation and rate of chemical transformation all of which control the plant life. The size of soil particles will determine as to how much water can be stored in the root zone for use by the plant. The arrangement of soil particles governs the soil structure which is fundamentally built by alternate wetting and drying, freezing and thawing or both. The roots of plants by penetrating into the soil assist in the building up of a suitable soil structure, so vital for plant fertility. Presence of organic matter improves soil structure. The pore space in most irrigated soils varies from 35% to 45% of the total volume. Reduction in pore space by as little as 10% would seriously hamper the plant growth.

Soils should not have excessive soluble salts or excessive exchangeable sodium. Excessive amounts of such plant nutrients as sodium and potassium nitrates are likely to become toxic to plants. Excess of soluble salts in soils is invariably found in arid and semi-arid areas where rainfall is inadequate to wash them down. It would, therefore, be appreciated that application of additional water is necessary to avoid the hazards of salinity and alkalinity in irrigated soils. The drainage of this additional water is also imperative to eliminate subsequent waterlogging problems.

Soil Moisture

The soil moisture is of three kinds :—

(*i*) *Hygroscopic Moisture*

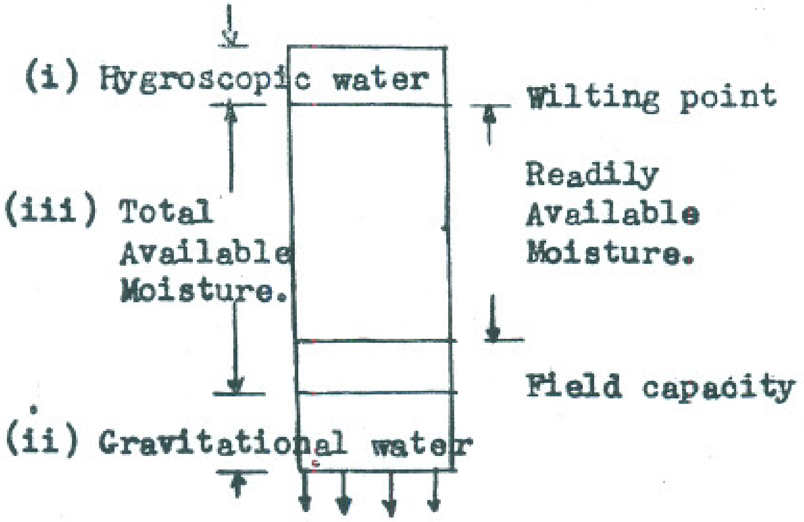
Hygroscopic moisture is contained in the molecular structure of the soil particles and thus cannot be extracted by a plant.

(*ii*) *Gravitational Water*

Gravitational water is the amount of water released by a completely saturated soil under action of gravitational force and is therefore not available to the plant. The pore spaces vacated by gravitational water are filled up by air. A heavy (such as clay) soil may have little gravitational water. When saturated, such soil has little or no air in the root zone which is detrimental to plant growth.

(*iii*) *Capillary Water*

Capillary water is the amount of water retained in the minute spaces between soil particles due to capillary action (surface tension) and is available to the plant for evapo-transpiration.



Field Capacity of a soil is defined as the soil moisture content when gravitational water has completely drained off. The field capacity should be determined 2 days after an irrigation and an adjustment be made for the water transpired by the plant in this period.

Permanent Wilting Point is reached when all available moisture has been transpired by the plant. Temporary wilting may occur in certain crops on a hot and windy day but the plant would recover during the cooler part

PLATE-I

NOMOGRAPH FOR BLANEY - CRIDDLE CONSUMPTIVE USE FORMULA

u = kf = k(t.p)

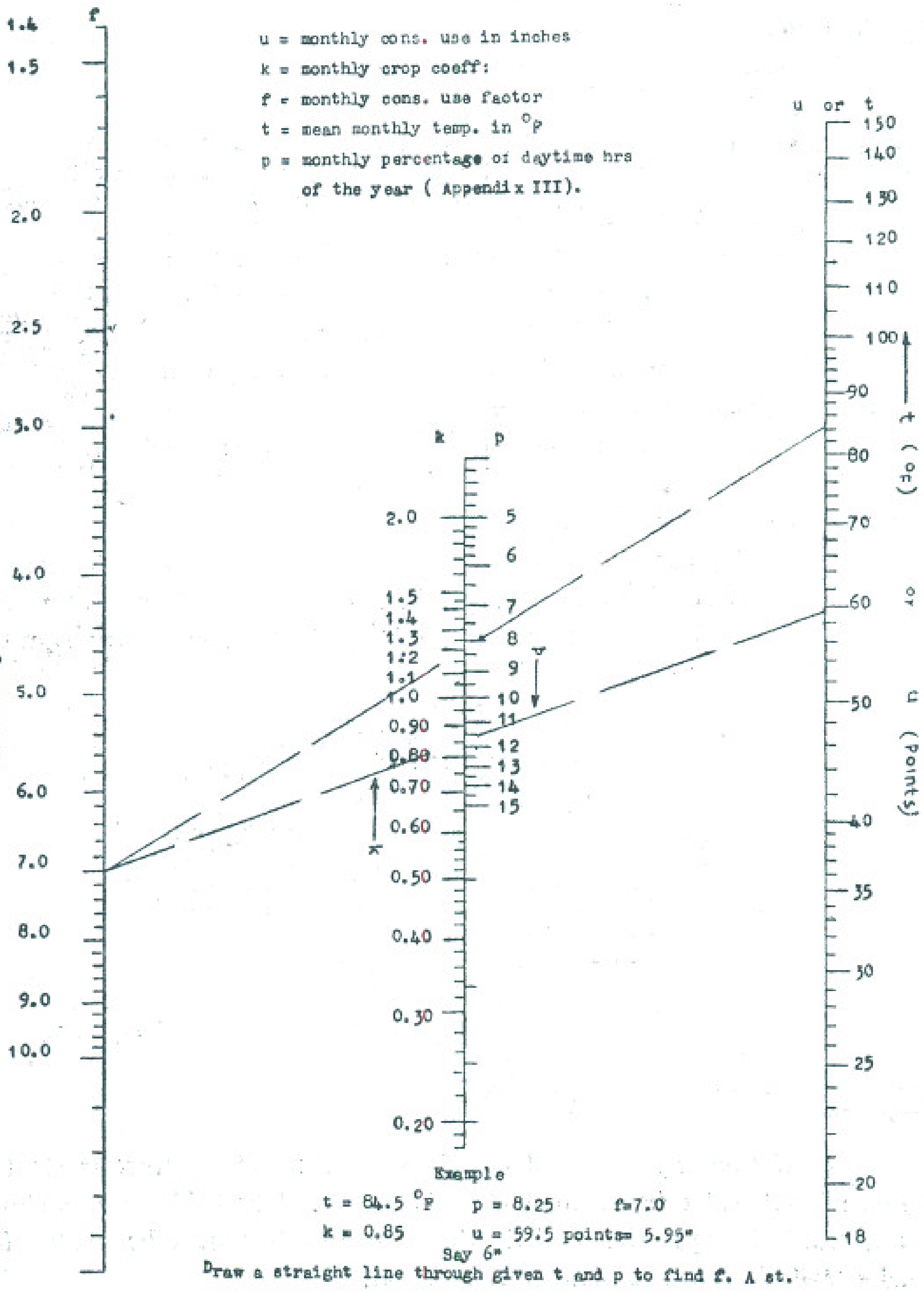
u = monthly cons. use in inches

k = monthly crop coeff:

f = monthly cons. use factor

t = mean monthly temp. in °F

p = monthly percentage of daytime hrs of the year (Appendix III).



Example

t = 84.5 °F p = 8.25 f=7.0

k = 0.85 u = 59.5 points= 5.95"

Say 6"

Draw a straight line through given t and p to find f. A st. line drawn through f and given k will give value of u in points.

(1 point = $\frac{1}{10}$ inch)

of the day. Wilting, permanent or temporary, is governed by the rate of evapo-transpiration, the depth of root zone and the field capacity of the soil. Permanent wilting of a plant may take place one week after irrigation in sandy soils and after 4 weeks or more, in clayey soils. In practice, permanent wilting percentage may be taken as 1/4th to 1/5th of field capacity.

The total available moisture is the amount of capillary water available for evapo-transpiration. 70 to 75% of this is readily available moisture (R.A.M.) The total available moisture and R.A.M. may be expressed as a percentage moisture, percentage volume or in terms of depth depending on the convenience of the planner. Representative physical properties of soils are shown in Appendix I.

The irrigated lands in West Pakistan are generally loamy having good permeability and moisture holding capacities. Root zones are not restricted. Soil deficiency in plant nutrients can be made good where necessary by application of natural or artificial fertilizers. Adequately extensive data for precise land classification, however, is not available. Considerable work is needed to investigate this aspect to facilitate efficient planning of irrigation operations in West Pakistan.

Consumptive Use

Consumptive use (evapotranspiration or E_t) is defined as the quantity of water per annum used by cropped or natural vegetation by transpiration together with water evaporated from adjacent soil. Consumptive use therefore is the sum of two terms namely :—

(*a*) *Transpiration i.e.*, the passage of water through the plant from roots to leaves. In this process, this water is partly used up in building up the plant tissues and partly lost to the atmosphere by evaporation at the surface of the plant leaves.

(*b*) *Evaporation* from the adjacent soil, water surfaces or surface of the plant leaves; light rain, dew etc., directly evaporated without entering the plant is a part of the consumptive use.

Consumptive use is influenced by a number of factors some of which are as follows :—

(*a*) The plant itself *viz.*, the type of foliage, nature of leaves, root system and depth of root zone.

(*b*) Stage of development of plant.

(*c*) Climatic factors such as temperature, humidity, wind movements, vapour pressure, precipitation, intensity and duration of sun light etc.

(*d*) Location factor (geographical location and elevation above mean sea level).

(*e*) Land and water management practices (size of farm, irrigation practice, farm management etc.)
(*f*) Length of growing season.
(*g*) Plant diseases and pests.
(*h*) Cropping pattern and rotation of crops.
(*i*) Availability of water.
(*j*) Depth to ground water table.
(*k*) Weeds and noxous plants.

It is generally noticed that like humans, the plants adjust their consumptive use according to the availability of water. For example, in southern Arizona, U.S.A. net delivery to farmers in 1964 varied from 3.79 to 13.49 acre feet per irrigated acre while in California, U.S.A., net delivery to farms in the same year varied from 0.97 to 3.12 af/acre. The average gross crop value per irrigated acre in these two states was respectively $372.54 and $361.44. The great diversity of water use in the two states is due to large differences in the developed water potential, problems peculiar to the areas irrigated, water rights of the two states and of course land and water management practices.

Evaporation from Free Water Surfaces

Evaporation depends on temperature, wind velocity, atmospheric pressure, dissolved solids, nature and shape of surface etc. Several formulae have been suggested for evaluating evaporation all of which are based on Dalton's Law :—

$E = C\,(e_w - e_a)$ where E = evaporation in inches/day
e_w and e_a are respectively max and actual vapour pressures.

Mayer suggested (1915) the following formulae :—

$E = C\,(e_w - e_a)\,\psi$ where $y\,\psi = 1 + 0.1w$
w = mean monthly wind velocity (mph)
C = 15 for small, shallow water.
C = 11 for large, deep water.
E = evaporation rate in inches/month.

Field Measurement of evaporation may be accomplished by installing U.S. Weather Bureau Class A Land Pan which is 48" diam. 10" deep with its bottom raised 6" above ground. Water surface in the pan is kept 2" to 3" below its rim and is measured daily with a hook gauge in a stilling well. The observations are multiplied by 0.7 (pan coeff. 0.6 to 0.8) to arrive at evaporation in the larger water body. Evaporation pans of other sizes and shapes may be correlated to the standard pan.

Evaporation from Soils

Evaporation from soils where depth to water table is small (about 2 feet or less) nearly equals that from free water surface. As the depth to water table increases, evaporation from soil markedly decreases till it becomes nil when the capillary fringe of water table does not reach the ground surface.

Significant amounts of water applied by flood irrigation and light showers of rainfall are lost to atmosphere by direct evaporation without passing through the plant. This direct evaporation is, however, beneficially used as it reduces the water which would have been used otherwise by transpiration.

Transpiration

Water passes from the soil to the plant through roots and travels up through the stems and leaves till it is finally evaporated. The process is defined as transpiration. Normally the velocity of the flowing water ranges from 0.2 to 1.2 inches per hour but may be accelerated on hot and windy days. The transpiration rate depends on the solar energy. A light rainfall shower may decrease transpiration by a corresponding amount since the water deposited on the plant leaves will absorb a part of solar energy for direct evaporation.

Estimating Evapotranspiration

The consumptive use may be estimated by the following methods :—

(*a*) *Evaporation Pan Method*

$U = k\,(E+2.70)$ where U = monthly crop consumptive use.
k = monthly crop consumptive use factor.
E = monthly standard pan evap. in inches.

k is a coeff. depending largely on the extent of ground coverage by crop.

The above formula was developed by Hargreaves who maintains that crop consumptive use is closely related to standard (U.S. Weather Bureau) Pan evaporation.

(*b*) *Atmometer Method*

The difference of evaporation (D) between the black and white atmometers is highly correlated with the intensity of solar radiation. As evapotranspiration is a function of solar radiation the following simple equation was developed by Halkias and others (1955) to determine monthly crop consumptive use:

Consumptive use $U = S.\,D.$ where S is the slope of regression line between U (inches) and D (cm^3). The values of S are given in Table 1.

(*c*) Crop Consumptive use has also been measured in the field by soil-moisture sampling, lysimeter, inflow—outflow measurements, integration methods, energy balance method and by observing ground water fluctuations. For details, a study of selected references would be useful.

TABLE 1

Crops	*S*
Tomatoes	0.0082
Grapes	0.0086
Sugar beets	0.0096
Cotton	0.0105
Peaches	0.0110
Apricots	0.0120
Alfalfa	0.0134

(*d*) *Empirical Equations*

Several attempts have been made at estimating the crop consumptive use (U) by using climatic data. Only three such equations, which could possibly be used in the arid and semi-arid areas of West Pakistan will be described here :—

(*i*) Lowry-Johnson Equation (1942) used by U.S. Bureau of Reclamation in Western U.S.A.

$U = 0.8 + 0.156\ F$

U = annual consumptive use in ft.

F = Accumulated 1000-degree days of max. daily temp. above 32°F.

The result so arrived at is applicable to a valley rather than to individual farms.

(*ii*) *Blaney-Criddle Formula* (1950)

This formula has been extensively used in the Western United States by the Soil Conservation Service and also in many arid/semi-arid countries. The Lowry-Johnson equation does not take account of the individual crops or length of the growing season. Blaney-Criddle Formula does so with surprisingly accurate results.

$u = k.f \qquad f = p.\ t$

where u= monthly crop consumptive use *in inches.*

k=monthly crop coefficient.

f=monthly consumptive use factor = $p.\ t.$

p=Ratio of monthly daylight hours to annual daylight hours.

t=mean monthly temperature in °F

$$U = KF \qquad F = \sum_{1}^{m} f. \quad = \sum_{1}^{m} p.t.$$

where U = Seasonal crop consumptive use in inches
K = Seasonal crop coefficient
F = Seasonal C.U. factor = Accumulated monthly consumptive use factors for *m* No. of months

$$= \sum_{1}^{m} p.t.$$

The seasonal crop coefficient K is fairly constant for a given crop. Slight variations are however noticed depending on stage of crop growth and means monthly temperature of the area. Experimental values, after Blaney and Criddle are shown in Appendix II. Appendix III shows the % monthly daylight hours of the year from 10 to 40 degrees North lattitude.

Plate I is a nomograph to evaluate the monthly crop consumptive use in inches depth of water. The values of *p*, *t* and *k* are plotted on the appropriate scales of the nomograph and lines down through the plotted points. Monthly consumptive use is read directly on the C. U. scale. Seasonal use may be determined in a like manner by drawing a straight line through K and F plotted on the appropriate scales of the nomograph and reading the value of seasonal consumptive use directly on the C. U. scale.

Blaney-Criddle method for estimating crop consumptive use has been used extensively throughout the arid and semi-arid zones of the world with considerable success. Its popularity is obviously due to :—

(*a*) Its simplicity of form.

(*b*) The formula makes use pf simple climatic data which is generally available for sufficiently long periods for all important localities.

(*c*) The crop coefficients for any zone may be determined by simple experiments; in case it cannot be done, published data for zones of similar climatic/geographical characteristics may be used.

Blaney-Criddle formula has certain drawbacks because it does not account for the effect on consumptive use due to wind movements, humidity, land and water management practices etc. In certain localities, these factors may have a marked influence on the crop consumptive use. It must, however, be admitted that evapo-transpiration is governed to a very large extent by temperature, duration of sunlight and nature of crops. Other factors influencing consumptive use may be taken care of by crop coefficients. Determination of this coefficient would require detailed investigation at site using a score of methods now available for the purpose. In spite of these deficiencies, however, Blaney-Criddle method does provide an excellent procedure for estimating the evapo-transpiration requirements of an irrigated area.

(iii) *Hargreaves Methods*

Hargreaves analysed the data available in U.S.A. by correlating evapo-transpiration and Class-A evaporation pan data. As a result of this effort, values of crop consumptive use coefficients (shown in Appendix IV) were determined. The consumptive use for a given crop at any stage of growth may be estimated by the following formula :—

$$U = k.E_p$$

where U = consumptive use in inches

K = crop consumptive use coeff. (Appendix IV)

E_p = class-A evaporation pan observation in inches

Where class-A evap. pan observations are not available, the value of Γ_p may be calculated as follows :—

$$E_p = 0.38d\,(1.0-H)\,(T-32)$$

where d = ratio of day length for the month to 12 hours (Appendix V)

H = mean monthly relative humidity *at noon* expressed in decimal form. (Average humidity at 1300 hrs. or average of humidities at 1100 and 1700 hours may also be used for H)

T = mean monthly temp. in °F.

Christiansen has suggested improvement of the above equation by introducing factors of wind, sunshine and elevation. Hargreaves formula in metric units will thus become :—

$$Ep = 17.4\,d.T.\ F_H \cdot F_W \cdot F_S \cdot F_E \cdot$$

where E_p = Class-A evap. pan reading in m.m.

d = Ratio of day length for the month to 12 hours (Appendix V)

T = Mean monthly temp. in °C.

$F_H = 0.59—0.55H^2$ H = mean monthly relative humidity at noon.

$F_W = 0.75+0.0255\sqrt{W}$ W = wind velocity in K*m*/day

$= 0.75+0.125\sqrt{W}$ W = wind velocity in K*m*/Hr.

$F_S = 0.478+0.58\ S$ S = sunshine percentage expressed in decimal form.

$F_E = 0.950+0.0001\ E$ E = Elevation above mean sea level in meters

Hargreaves' formula, modified by Christiansen includes the influence of practically all climatic factors as well as the stage of crop growth and is thus an improvement on Blaney-Criddle formula. Consumptive use can be determined directly when Class-A evap. pan observations are available; otherwise these may be worked out by equations given above. Consumptive use for any period of time may be estimated by interpolation.

Hargreaves suggests the following formula for estimating irrigation requirements :

$$\frac{u}{e} = \mathrm{I}r.$$

Where u = consumptive use during a given period in inches.

e = irrigator's efficiency of water management (0.6-0.8)

$\mathrm{I}r$ = Irrigation requirement during the period in inches.

Irrigation Requirements of West Pakistan

Blaney and Criddle in their report on the "Irrigation Requirements for West Pakistan" (1957) have pointed out the inadequacy of irrigation water in the following words :—

> "The major cause of low production seems to be an insufficient quantity of irrigation water applied on the fields. This has resulted in an inefficient use of available water in terms of productivity. This is readily borne out by a comparison of historic deliveries in West Pakistan with those made for similar crops under similar conditions in those countries where production is more than double that of Pakistan. In general it may be said that water deliveries in West Pakistan are about half of what is considered necessary in other parts of the world, where climatic conditions are similar for optimum production."

The report further states :—

> "Low yields are not the only results of water applications inadequate to meet the consumptive requirements. Inadequate waterings have also adversely affected plant growth by contributing to the salinization of top soil."

Blaney and Criddle have proposed to divide West Pakistan in 6 climatic zones with the monthly consumptive use factors shown in Appendix VI. The proposed crop coefficients for some major crops grown in West Pakistan are given in the following table :—

TABLE 2—*Monthly crop co-efficients k*

Crop/months	1	2	3	4	5	6	7	8	9	10	11	12
Citrus	.5	.55	.55	.6	.6	.65	.7	.7	.65	.6	.55	.55
Cotton	..	..	..	.5	.6	.75	.9	.85	.75	.55	.5	.5
Maize	..	..	..	.5	.6	.7	.8	.8	.6	.5	..	..
Rice	..	..	..	.85	1.0	1.15	1.3	1.25	1.1	.9	..	..
Sugarcane	.75	.8	.85	.85	.9	.95	1.0	1.0	.95	.9	.85	.75
Tobacco	..	.65	.7	.8	.85	.75	..	..	..	..	..	..
Vegetables	.5	.55	.6	.65	.7	.75	.8	.8	.7	.6	.55	.5
Wheat	.5	.7	.75	.7	..	..	..	..	..	.7	.6	.6

Using their formula Blaney and Criddle worked out the following consumptive uses and irrigation requirements for different crops on L.C.C. system :—

TABLE 3.—*Irrigation requirements of crops grown in L.C.C. Command (Blaney Criddle)*

Crop		*Consumptive Use*	*Irrigation Requirement*
(Depth of application in inches/annum)			
Rice	..	45.78	29.86
Cotton	..	40.75	31.74
Sugarcane	..	63.65	58.22
Vegetables	..	52.04	41.41 Year round 3 crops
Maize	..	19.40	14.67
Orchards	..	52.31	46.88
Wheat	..	18.96	16.79
Fodder (Burseem)	..	38.29	35.81
Tobacco	..	26.23	21.18

The total irrigation requirements (Net consumptive use after adjustment for effective rainfall) of West Pakistan, excluding minor projects, works out to 57.99 MAF. Accounting for conveyance losses from canal headworks to farms, Blaney & Criddle have estimated the following annual diversion requirements compared with allocations and 5 year average withdrawals ending 1956-57 :—

TABLE 4

Project	Blaney & Criddle		Allocation & Withdrawals			
	Assumed Irrigated Area (1000 Acres)	Annual Diversion Reqt. (MAF)	Mean Allocation (MAF)	Av. 5 Yr. W/D ending 1956-57 (MAF)	Max. Withdrawal MAF	Max. Withdrawal Year
1	2	3	4	5	6	7
Kotri ..	2004.6	19.059	11.40	4.0	8.653	1966-67
Sukkur ..	6320.5	40.045	25.30	21.2	24.811	1966-67
Gudu ..	1827.9	19.224	9.80	5.2	8.001	1966-67
Taunsa ..	1417.0	7.632	4.47	3.5	5.262	1966-67
Thal ..	1401.0	5.505	3.59	2.8	4.314	1966-67
Indus Projects ..	12971.0	91.465	54.56	36.7	51.041	1966-67
Haveli ..	1082.5	4.861	3.82	3.3	3.889	1965-66
Panjnad ..	1079.5	5.410	3.74	4.2	5.024	1961-62
Haveli & Panjnad	2162.0	10.271	7.56	7.5	..	..
U. J. C. ..	426.4	1.522	..	..	2.966	1958-59
L. J. C. ..	986.5	3.752	..	..	3.314	1963-64
U. J. C. ..	908.7	4.829	..	18.7	4.203	1965-66
L. C. C. ..	2829.0	12.544	..	..	7.648	1964-65
L. B. D. C. ..	1452.3	6.364	..	..	4.653	1964-65
5 Lined Canals ..	6602.9	29.111	..	18.7	..	..
C. B. D. C. ..	661.2	2.664	..	1.2	1.765	1962-63
Suleimanki ..	2050.4	8.630	..		6.665	1958-59
Islam ..	916.3	3.898	11.20	10.5	3.945	1958-59
D. C. C. ..	693.0	2.900	..		1.825	1958-59
Eastern Canals ..	4320.9	18.092	..	11.7	..	..
Grand Total ..	26055.8	148.939	..	74.6	..	..

A comparison of irrigation requirements at farm site (Nakkas) with the sanctioned water allowances for various projects in West Pakistan is shown in the following table :—

TABLE 5.—*Irrigation requirements of farms and sanctioned water allowances in West Pakistan*

Project	Blaney-Criddle			Max. Sanctioned Water Allowances	
	Annual Irrigation Requirements MAF	Area Irrigated per annum million acres	Average depth of application (Ft.)	Perennial	Non-Perennial
1	2	3	4	5	6
Kotri ..	7.186	2.005	3.59	NA	NA
Sukkur ..	14.913	6.320	2.36	2.99/4.27	17.6 (Rice Canal)
Guddu ..	6.852	1.828	3.75	NA	NA
Taunsa ..	2.998	1.417	2.12	..	9.0 (Muzaffargarh Canal)
Thal ..	2.751	1.401	1.97	3.18	..
Indus Projects ..	34.700	12.971	2.68	..	..
Haveli ..	2.000	1.082	1.85	3.0	4.8
Panjnad ..	2.195	1.080	2.01	4.2	5.5
Haveli and Panjnad	4.195	2.162	1.94	..	..
U. J. C. ..	0.623	0.426	1.46	3.03	3.25
L. J. C. ..	1.599	0.987	1.62	2.84	4.3
U. C. C. ..	1.642	0.909	1.81	2.73	5.09
L. C. C. ..	5.177	2.829	1.83	3.77	5.19
L. B. D. C. ..	2.651	1.452	1.83	3.33	3.33
5 Linked Canals ..	11.692	6.603	1.77	..	..
C. B. D. C. ..	1.087	0.661	1.65	3.22	3.57
Suleimanki ..	3.578	2.051	1.75	5.5	5.5
Islam ..	1.605	0.916	1.75	4.0	5.5
Depalpur Canal ..	1.135	0.693	1.64	..	5.6
Eastern Canal ..	7.405	4.321	1.71	..	..
Grand Total ..	57.992	26.650	2.22	..	..

N.A.=Not Available.

Note.—Water allowance is defined as the discharge in cusecs allowed for irrigating 1000 acres of culturable irrigable area at out let head. Assuming 300 days of full supply per annum, the quantity delivered at outlet head would be 600 acre ft. for each cusec of water allowance. Assuming further an intensity of 100% (Kharif-Rabi ratio=1 : 1), the area irrigated per annum would be 1000 acres per cusec at outlet head. The average depth of application per cusec (water allowance) would, therefore, be 0.6 ft. at outlet head or 0.45 ft. at farm site allowing for 25% water-course losses. Thus a water allowance of 3 cusec /1000 acres is equivalent to an application of less than 18″ depth of water on the irrigated fields per annum. Designed intensity of irrigation for West Pakistan canals rarely exceeds 100%. Any increase of intensity would, therefore, result in reduced water applications due to restriction in canal capacities. Public and private tubewell projects which are coming up fairly rapidly are expected to make up such shortages. This analysis brings us to the following conclusions :—

(*i*) There is a need for developing storage reservoirs to increase the No. of full supply days in a year.

(*ii*) Increase in canal capacities appears to be essential in view of the increasing intensities of irrigation on most canal systems in West Pakistan.

(*iii*) Water allowances sanctioned at present should be enhanced to provide adequate water supply to the farmers for optimum production of food and fibre.

(*iv*) Conservation of fresh water resources of West Pakistan by resorting to lining and/or piped water supply system deserves top priority. In addition, the need of education to the farmer for improved water management practices must not be overlooked.

It would thus appear that water development in West Pakistan has lagged far behind the development of land. This is but obvious considering the rapid growth of population in this country. The total potential fresh water (river run-off) resource allocated to West Pakistan under the Indus Water Treaty 1960 works out to 136 MAF (average of 25 years). The dependable water supply is said to be about 110 MAF. Up to end of 1967-68 we have been able to divert about 85 MAF to our elaborate canal system per annum which would yet seem grossly inadequate keeping in view our aspirations not only for self-sufficiency in food and fibre but also for export. To fulfil our national goals, we must develop something like 60 MAF either by exploiting ground water resource, or by conserving water by lining our canal systems. As a matter of fact an effort in both directions would be needed in addition to improved water management practices. Ignoring any one aspect of this problem would mean accentuating the spread of salinity which would drastically reduce our C.C.A. in the end.

In their investigation of the problem, Blaney and Criddle assumed certain interim and ultimate cropping patterns and irrigated areas. Both of these parameters may vary greatly with time. The engineer, therefore, must take a stock of the situation at frequent intervals to determine and provide for the irrigation requirements in the area under his jurisdiction. Improved seeds have been recently introduced into West Pakistan Agriculture, the success of which might depend greatly on the adequacy of irrigation water supply. It is true that optimum crop yields depend on many other factors beside adequate water supply yet the latter is probably the most important in the success of sustained agricultural activity of an irrigated area. Paucity of funds has to a great extent, hindered the development of water resources in Pakistan and elsewhere in the South-east Asian countries. This difficulty may be partly overcome by curbing tendencies of extravagance and insincerity towards national interests. Conservation of water and improvement in our management efficiencies must be reviewed by our engineers constantly to stabilize our economic situation.

Extent and Frequency of Irrigation Water Application

The structure, texture, permeability, moisture holding capacity etc. of soil and the consumptive use requirements of crops play an important role in the overall planning of water application to the irrigated fields. Estimation of consumptive use has been discussed in some detail in the foregoing paragraphs. We shall now investigate the problem of the actual application of water. Irrigator's efficiency depends largely on his method of irrigation. It has been proved now that flooding the fields for purposes of irrigation through the cheapest method available to the farmer, results in excessive loss due to direct evaporation from free water surface and wet soil beside non-uniform application. Furrow irrigation, sprinklers and sub-irrigation would greatly reduce such losses and consequently improve upon the irrigation efficiency. A considerable seepage and evaporation loss takes place in open water courses. Valuable water supply can be saved from going waste into deep ground and atmosphere by resorting to lining of water courses or aluminium pipe conveyance channels.

Part of the water applied to the irrigated land drains quickly into deeper ground and thus becomes unavailable to the plant. The remaining water is held in the capillary spaces of the soil from where it is absorbed by the plant roots for evapo-transpiration, as and when necessary. Continued researches have proved that the plant does not extract water uniformly from each foot depth of the root zone. Plants' capacity to extract moisture from the soil depends entirely on its root system which is rather elaborate at the top and rapidly thins down with greater depth of the root zone. The next irrigation application becomes due when permanent wilting point is reached in any layer of the root zone. Spread of the root system depends firstly on the plant itself and secondly on the depth to water table. The depth of root zone is drastically curtailed by high water table. No doubt, the plant may extract water for beneficial use from an aquifer, capillary fringe of which encroaches upon the plant root zone, but water table reaching within 3 ft. from the ground surface is generally harmful to the plant growth by partly filling up the useful air space in the root zone. In such cases, corrective measures must be taken to deplete the water table to at least 5 ft. depth from ground surface. Further depletion of water table is warranted if quality of ground water is too bad and/or poor drainage conditions exist. A high water table is additionally harmful to plant growth by disturbing the salt balance of a productive soil. This is caused by evaporation of ground water leaving behind its dissolved salts in the root zone. Application of irrigation water in excess of crop consumptive use would be required to wash down the harmful salts accumulated in the root zone. While planning for irrigation requirements, this aspect should not be ignored by the engineer.

Depending on the crop and climate, the depth of roots varies from 12 to 18 inches depth per month of active growth. Thus crops matured in 2 months would noι penetrate by more than 2-3 ft. below ground. The depth of root zone of crops matured in 3-4 months is 3-5 ft. and crops requiring 6 months to mature may penetrate 6 to 10 ft. into the soil. Trees and perennial crops may have a root system extending to as much as 50-60 ft. below ground provided favourable and unrestricted root zone exists.

As has been stated earlier, different crops at different stages of their growth, extract moisture from each layer of the root zone at a variable rate depending on the spread of their root system. For arid zone, it has been observed that plants extract 40%, 30%, 20% and 10% of their total requirements from the first, second, third and the last quarter of their root zone respectively. This may only be a rough guide for planning irrigation. Detailed investigation should be carried out for better results.

The maximum depth of readily available moisture (RAM) for each foot depth of root zone has been observed to be 1.2, 1.7 and 2.2 inches for coarse (sandy), medium (loamy) and fine (clayey) textured soils respectively. Detailed soil investigations would be required in this connection to serve as a basis for an efficient management of irrigation water.

Consider a medium textured loamy soil with a field capacity (total available moisture) of 25% by volume or $\frac{25}{100} \times 12 = 3''$ depth of water per foot depth of root zone. Taking 60% of field capacity as readily available moisture only 1.8″ per foot would be available for plant use. Let the root zone extend to 4 ft. depth. Therefore, the total RAM of root zone would be 7.2″ depth of moisture after the first irrigation. Next let the average crop consumptive use for the period be 0.3″ per day. Assuming that the plant extracts 35%, 30%, 25% and 10% of its requirements from each successive quarter of the root zone we arrive at the following rates of moisture extraction from the soil per day :—

0 — 1 ft.	$= 0.35 \times 0.3$	$= 0.105''$
1 — 2 ft.	$= 0.30 \times 0.3$	$= 0.090''$
2 — 3 ft.	$= 0.25 \times 0.3$	$= 0.075''$
3 — 4 ft.	$= 0.10 \times 0.3$	$= 0.030''$
	Total C. U.	$= 0.30''$ per day.

RAM from 0-1 ft. amounts to 1.8″. Therefore the plant will reach the wilting point $\frac{1.8}{0.105} = 17$ days after the first irrigation. It is worthwhile to note that the lower layers from 1—4 ft. will still have some available moisture, but to safeguard against damage to the plant, irrigation water must be applied 17 days after the previous irrigation. The depth of this irrigation is determined from the amount of moisture depleted during the 17 days period *viz.*,

Moisture extracted by plant	0—1 ft. $= 17 \times .105$	$= 1.78''$
	1—2 ft. $= 17 \times .090$	$= 1.53''$
	2—3 ft. $= 17 \times .075$	$= 1.28''$
	3—4 ft. $= 17 \times .030$	$= 0.51''$
Next irrigation due after 17 days.	Total	5.10″

Thus a depth of 5.1″ must be applied 17 days after the previous irrigation to bring the root zone soil to its field capacity. Some irrigators might like to reduce the frequency of irrigation to 7 or 10 days. In such cases they are advised to cut down the depth of next irrigation on a pro rata basis. Due consideration should be given for irrigators' efficiency and loss of water.

Drainage Requirements

In arid and semi-arid climatic conditions, the crop yields are likely to be affected due to salt imbalance in the root zone soil. This is true especially if adequate irrigation water is not supplied to wash down the harmful salts, Drainage of excessive water applications must receive due consideration. Unfavourable salt content in soils may be corrected and the land may be kept in perpetual beneficial use by the process of leaching. Excessive salt content reduces the permeability of soil so that flow of moisture in the root zone is obstructed. Irrigation with high T.D.S. water (such as ground water) will necessitate a certain percentage of irrigation water to be leached through the root zone to maintain soil salinity at a favourable level. The leaching requirement (LR) may be estimated from the following formula :—

$$LR = \frac{D_d}{D_i} = \frac{EC_i}{EC_d} \text{ expressed in decimal form}$$

where D_d and EC_d are, respectively, the depth and electrical conductivity of drainage water and D_i and EC_i are the depth and electrical conductivity of the irrigation water.

The U.S. Bureau of Reclamation uses the following formula for determining leaching requirements :—

$$\frac{Q_f}{Q_c} = \frac{S_r}{S_r - S_f}$$

where Q_f ... reqd. farm delivery
Q_c ... Consumptive use
S_f ... Salinity of flow supply
S_r ... Salinity of soil (or of return flow).

$$\therefore \text{ leaching reqt.} = \frac{Q_f - Q_c}{Q_c} = \frac{S_f}{S_r - S_f} \text{ expressed in decimal form.}$$

Leaching reqts. of an irrigated area should be estimated separately and added to consumptive use reqts. to determine the net delivery of irrigation water to the farm.

Conclusion

The present methods and planning of irrigation in West Pakistan on the part of both the farmer and the engineer are based on factors far removed from realistic crop-consumptive use reqts. The so-called water allowances, sanctioned from time to time, are inadequate and need immediate revision in the light of information available today. The irrigation engineer has yet to play a vital role to improve the general economy of Pakistan. Providing adequate irrigation supplies to over 28 million irrigated acres in West Pakistan appears to be a gigantic task but is by no means an impossible one. With the completion of the Indus Basin Project, we would have accomplished solution of a major part of the formidable problem. Substantial development of water resources is coming up in the shape of thousands of tubewells installed all over in West Pakistan's irrigated area. The engineer at the same time should divert his attention to the much neglected aspect of water conservation. This involves more efficient canal water distribution and control of the enormous losses of valuable fresh water supplies by seepage evaporation and evapo-transpiration through noxous weeds. Research should be launched with a view to achieving these objectives at a competitive cost. It will not be out of place to mention that with the development of irrigation in West Pakistan we are also heading towards a stage where the basic legislation and country's water policies will need drastic modifications for accommodating the revolution in our water resources development. For example, our present water rates structure is grossly inadequate to sustain maintenance of works and generate enough funds to permit further developments. The procedures for economic appraisal of water projects would require enlargement to incorporate the public welfare in general. The sooner we realize the impact of modern times, the better it would be in the larger national interest.

Appendix I

Representative Physical Properties of Soil

(Average and Range of Values)

Soil Classification	Porosity %	Field capacity %	Total Available moisture in./ft.	Intake rate in./hr.	Apparent S_p sp. gravity
Sandy	38 (32-42)	9 (6-12)	1.0 (0.8-1.2)	2 (1-10)	1.65 (1.55-1.80)
Sandy loam	43 (40-47)	14 (10-18)	1.4 (1.1-1.8)	1 (0.5-3)	1.50 (1.40-1.60)
Loam	47 (43-49)	22 (18-26)	2.0 (1.7-2.3)	0.5 (0.3-0.8)	1.4 (1.35-1.5)
Silty clay	51 (49-53)	31 (27-35)	2.5 (2.2-2.8)	0.1 (0.01-0.2)	1.30 (1.25-1.35)
Clay loam	49 (47-51)	27 (23-31)	2.3 (2.0-2.6)	0.3 (0.1-0.6)	1.35 (1.30-1.40)
Clay	53 (51-55)	35 (31-39)	2.7 (2.4-3.0)	0.2 (0.05-0.4)	1.25 (1.20-1.30)

Note :— (*a*) *Readily available moisture 70—75% of total available moisture.*
(*b*) *Intake rates are greatly influenced by soil structure.*

Appendix II

Seasonal and Max. monthly crop coefficient (K & k) for Blaney Criddle formula

Crop		Length of season (Months)	Seasonal Crop Coeff. K	Max. monthly crop Coeff. *k*
Alfalfa	..	Frost-free	0.80—0.85	0.95—1.25
Beans	..	3	0.60—0.70	0.75—0.85
Corn (Maize)	..	4	0.75—0.85	0.80—1.20
Cotton	..	7	0.65—0.75	0.75—1.10
Grain (Small)	..	3	0.75—0.85	0.85—1.00
Orchards				
Citrus	..	7	0.50—0.65	0.65—0.75
Deciduous	..	Frost-free	0.60—0.70	0.70—0.95
Walnut	..	,,	0.60—0.70	
Pasture (Grass, hay, annuals)	..	,,	0.75	0.85—1.15
Potatoes	..	3½	0.65—0.75	0.85—1.00
Rice	..	3—5	1.00—1.20	1.10—1.30
Sugarbeets	..	6	0.65—0.75	0.85—1.00
Tomatoes	..	4	0.70	..
Vegetables (small)	..	3	0.60	..

Note :— (*a*) *Lower and higher values of K, k are respectively for coastal and arid areas.*

(*b*) *Crop coefficients depend on mean monthly temperatures and stage of growth.*

Appendix III

Monthly Daytime Hours expressed as percentage of Annual Daylight Hours (*To be used in Blaney Criddle formula*)
U. S. Weather Bureau (1905).

Latitude Deg. N	MONTHS											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
10	8.13	7.47	8.45	8.37	8.81	8.60	8.86	8.71	8.25	8.34	7.91	8.10
15	7.94	7.36	8.43	8.44	8.98	8.80	9.05	8.83	8.28	8.26	7.75	7.88
20	7.74	7.25	8.41	8.52	9.15	9.00	9.25	8.96	8.30	8.18	7.58	7.66
25	7.53	7.14	8.39	8.61	9.33	9.23	9.45	9.09	8.32	8.09	7.40	7.42
30	7.30	7.03	8.38	8.72	9.53	9.49	9.67	9.22	8.33	7.99	7.19	7.15
35	7.05	6.88	8.35	8.83	9.76	9.77	9.93	9.37	8.36	7.87	6.91	6.80
40	6.76	6.72	8.33	8.95	10.02	10.08	10.27	9.54	8.39	7.75	6.72	6.52

Appendix IV

Consumptive Use coefficient (k) for use in Hargreaves' equation

$$U = k\ E_p$$

Crop	Percentage of crops growing season										
	0	10	20	30	40	50	60	70	80	90	100
Alfalfa ..	0.55	0.60	0.70	0.80	0.90	0.95	0.95	0.95	0.90	0.80	0.65
Beans ..	0.20	0.30	0.40	0.65	0.85	0.90	0.90	0.80	0.60	0.35	0.20
Citrus ..	0.50	0.45	0.45	0.45	0.45	0.45	0.50	0.55	0.60	0.55	0.50
Corn ..	0.20	0.30	0.50	0.65	0.80	0.90	0.90	0.85	0.75	0.60	0.50
Cotton ..	0.10	0.20	0.40	0.55	0.75	0.90	0.90	0.85	0 75	0.55	0.35
Deciduous ..	0.20	0.30	0.50	0.65	0.70	0.75	0.70	0.60	0.50	0.40	0.20
Grain Spring ..	0.15	0.20	0.25	0.30	0.40	0.55	0.75	0.85	0.90	0.90	0.30
Grain Winter ..	0.15	0.25	0.35	0.40	0.50	0.60	0.70	0.80	0.90	0.90	0.30
Grapes ..	0.15	0.15	0.20	0.35	0.45	0.55	0.55	0.45	0.35	0.25	0.20
Peanuts ..	0.15	0.25	0.35	0.45	0.55	0.60	0.65	0.65	0.60	0.45	0.30
Potatoes ..	0.20	0.35	0.45	0.65	0.80	0.90	0.95	0.95	0.95	0.90	0.90
Rice ..	0.80	0.95	1.05	1.15	1.20	1.30	1.30	1.20	1.10	0.90	0.50
Sugar Beets ..	0.25	0.45	0.60	0.70	0 80	0.85	0.90	0.90	0.90	0.90	0.90
Sugarcane ..	Varies from 0.55 to 1.00 depending on rate and stage of growth.										
Vegetable Deeproot	0.20	0.20	0.25	0.35	0.50	0.65	0.70	0.60	0.45	0.35	0.20
Vegetable shallow root.	0.10	0.20	0.40	0.50	0.60	0.60	0.60	0.55	0.45	0.35	0.30

Appendix V

Monthly daytime coefficient (d) for use in Hargreaves' equation

$$E_p = 0.38\, d\, (1.0 - H)\, (T\text{-}32)$$

Lat. Deg. North	MONTHS											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
60	0.56	0.68	0.97	1.16	1.41	1.49	1.48	1.29	1.03	0.84	0.61	0.50
55	0.65	0.72	0.98	1.13	1.34	1.39	1.40	1.24	1.02	0.87	0.67	0.60
50	0.72	0.76	0.99	1.11	1.28	1.31	1.32	1.20	1.01	0.89	0.73	0.68
45	0.76	0.78	0.99	1.08	1.24	1.26	1.27	1.17	1.01	0.91	0.77	0.74
40	0.81	0.81	1.00	1.07	1.20	1.21	1.24	1.15	1.01	0.93	0.81	0.78
35	0.84	0.82	1.00	1.06	1.17	1.17	1.20	1.13	1.00	0.94	0.83	0.82
30	0.88	0.84	1.01	1.05	1.14	1.14	1.16	1.11	1.00	0.96	0.86	0.86
25	0.90	0.86	1.01	1.03	1.12	1.11	1.13	1.09	1.00	0.97	0.88	0.89
20	0.93	0.87	1.01	1.02	1.10	1.08	1.11	1.07	1.00	0.98	0.91	0.95
15	0.95	0.88	1.01	1.01	1.08	1.06	1.08	1.06	0.99	0.99	0.93	0.96
10	0.97	0.89	1.01	1.01	1.06	1.03	1.06	1.05	0.99	0.99	0.95	0.97

Appendix VI

Monthly consumptive use factor (f) for use in Blaney Criddle Formula

Zone	MONTHS											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
I.	4.89	4.91	6.48	7.29	8.38	8.39	8.37	7.77	7.04	6.69	5.48	4.95
II.	4.72	4.82	6.54	7.57	8.84	8.84	8.77	8.16	7.36	6.82	5.46	4.82
III.	4.32	4.54	6.22	7.38	8.94	9.14	9.11	8.46	7.92	6.57	5.14	4.48
IV.	4.22	4.42	6.12	7.29	8.85	9.12	9.11	8.44	7.74	6.48	5.03	4.36
V.	3.94	4.12	5.80	7.00	8.65	9.08	9.07	8.40	7.32	6.23	4.96	4.02
VI.	3.92	4.10	5.73	6.94	8.55	8.98	8.92	8.27	7.21	6.20	4.72	4.03

Note :— (1) *Blaney Criddle divided West Pakistan into 6 climatic zones for working out irrigation requirements for West Pakistan.*

These are :—

Zone I. *Karachi, Hyderabad, Chhore.*
Zone II. *Hyderabad, Chhore, Sukkur, Naushera.*
Zone III. *Sukkur, Jacobabad.*
Zone IV. *Sukkur, Jacobabad, Multan.*
Zone V. *Multan, Khushab, D. I. Khan.*
Zone VI. *Lahore, Lyallpur, Montgomery.*

(2) *Monthly C. U. factor* $= p. t./100$.
where $p = \%$ *monthly daytime hours of the year.*
$t =$ *mean monthly temp. in* °*F.*

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