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IRRIGATION WATER REQUIREMENTS

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SOIL CONSERVATION SERVICE

ENGINEERING DIVISION

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IRRIGATION WATER REQUIREMENTS

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U. S. Department of Agriculture
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IRRIGATION WATER REQUIREMENTS

Introduction

It is essential that the water requirements and consumptive use of water be known in irrigation planning for soil conservation and irrigation districts and for individual farms. Conservation of water supplies, as well as of soils, is of first importance in the agricultural economy. In basin-wide investigations of water utilization and in water conservation surveys, consumptive water requirement is one of the most important factors to be considered. There is an urgent need for information on irrigation requirements in connection with farm planning programs for areas where few data are available.

A knowledge of consumptive use is necessary in planning farm irrigation system layouts and improving irrigation practices. Irrigation and consumptive water requirement data are used more and more widely by water superintendents as well as state, federal, and other agencies responsible for the planning, construction, operation and maintenance of multiple-purpose projects and by those responsible for guiding and assisting farmers in the solution of their irrigation problems.

Scope

This release covers the procedures used to estimate irrigation water requirements on a farm or on a project. Irrigation application efficiencies are discussed briefly. More detailed information is presented in applicable chapters of Section 15 of the National Engineering Handbook. Procedures for measuring losses in existing farm distribution and project conveyance systems and for estimating losses in such systems as may be proposed are included. Irrigation water storage requirements may be estimated by use of the procedure contained in Technical Release No. 19.

Definition of Terms

Some of the terms used in this release are defined as follows:

Consumptive Use.

Consumptive use, often called evapo-transpiration, is the amount of water used by the vegetative growth of a given area in transpiration and building of plant tissue and that evaporated from adjacent soil or intercepted precipitation on the plant foliage in any specified time. If the unit of time is small, consumptive use is usually expressed as acre inches per acre or depth in inches, whereas, if the unit of time is large, such as a growing season or a 12-month period, it is usually expressed as acre feet per acre or depth in feet.

Consumptive Water Requirement.
The amount of water potentially required to meet the evapo-transpiration needs of vegetative areas so that plant production is not limited from lack of water.

Effective Rainfall.
Precipitation falling during the growing period of the crop that is available to meet the consumptive water requirements of crops. It does not include such precipitation as is lost to deep percolation below the root zone nor to surface runoff.

Consumptive Irrigation Requirement.
The depth of irrigation water, exclusive of precipitation, stored soil moisture, or ground water, that is required consumptively for crop production.

Net Irrigation Requirement.
The depth of irrigation water, exclusive of precipitation, stored soil moisture, or ground water, that is required consumptively for crop production and required for other related uses. Such uses may include water required for leaching, frost protection, etc.

Peak Period Consumptive Use.
Peak period consumptive use is the average daily rate of use of a crop occurring during a period between normal irrigations when such rate of use is at a maximum.

Irrigation Efficiency.
The percentage of applied irrigation water that is stored in the soil and available for consumptive use by the crop. When the water is measured at the farm headgate, it is called farm-irrigation efficiency; when measured at the field, it is designated as field-irrigation efficiency; and when measured at the point of diversion, it may be called project-efficiency.

Irrigation Water Requirement.
The net irrigation water requirement divided by the irrigation efficiency.

Field Capacity.
The moisture percentage, on a dry weight basis, of a soil after rapid drainage has taken place following an application of water, provided there is no water table within capillary reach of the root zone. This moisture percentage usually is reached within two to four days after an irrigation, the time interval depending on the physical characteristics of the soil.

Wilting Point.
The wilting point is the moisture percentage, also on a dry weight basis, at which plants can no longer obtain sufficient moisture to satisfy moisture requirements and will wilt permanently unless moisture is added to the soil profile.

Carryover Soil Moisture.
Moisture stored in soils within root zone depths during the winter, at times when the crop is dormant, or before the crop is planted. This moisture is available to help meet the consumptive water needs of the crop.

Influence of Various Factors on Water Use

Many factors operate singly or in combination to influence the amounts of irrigation water consumed by plants. Their effects are not necessarily constant but may differ with locality and fluctuate from time to time. The more important influences are climate, water supply, and plant growth characteristics.

Precipitation.
The amount and rate of precipitation will have an effect on the amount of irrigation water consumptively used during any season. Under certain conditions, precipitation may be a series of frequent, light showers during the hot summer. Such showers may add little or nothing to the soil moisture for use by the plants through transpiration but do decrease the withdrawal from the stored moisture. The precipitation may be largely lost by evaporation directly from the surface of the plant foliage and from the land surface. Some of the precipitation from heavy storms may be lost by surface runoff. Where storms occur within a relatively short period after completion of an irrigation, a high percentage of precipitation is lost due to surface runoff, deep percolation or both. Other storms may be of such intensity and amount that a large percentage of their precipitation will enter the soil and become available for plant transpiration. Such a condition materially reduces the amount of irrigation water needed.

Temperature.
The rate of consumptive use of water by crops in any particular locality is probably affected more by temperature, which for long-time periods is a good measure of solar radiation, than by any other factor. Abnormally low temperatures may retard plant growth and unusually high temperatures may produce dormancy. Consumptive use may vary even in years of equal accumulated temperatures because of deviations from the normal seasonal distribution. Transpiration is influenced not only by temperature but also by the area of leaf surface and the physiologic needs of the plant, both of which are related to stage of maturity.

Growing Season.
The growing season, which is tied rather closely to temperature, has a major effect on the seasonal use of water by plants. It is frequently considered to be the period between killing frosts, but for many annual crops, it is shorter than the frost-free period, as such crops are usually planted after frosts are past and mature before they recur.

For most perennial crops, growth starts as soon as the maximum temperature stays well above the freezing point for an extended period of days, and continues throughout the season despite later freezes.

Sometimes growth persists after the first so-called killing frost in the fall. In the spring, and to less extent in the fall, daily minimum temperatures may fluctuate several degrees above and below 32° F. for several days before remaining generally above or below the freezing point. The hardier crops survive these fluctuations and continue unharmed during a few hours of subfreezing temperature. In fact, many hardy crops, especially grasses, may mature even though growing season temperatures repeatedly drop below freezing. Although the frost-free season may be used as a guide for estimating consumptive use, actual dates of planting and crop maturity are important in determining the consumptive irrigation requirements of the crops.

<u>Latitude and Sunlight</u>.
Because of the earth's movement and axial inclination, the hours of daylight during the summer are much greater in the higher latitudes than at the Equator. Since the sun is the source of all energy used in crop growth and evaporation of water, this longer day may allow plant transpiration to continue for a longer period each day and to produce an effect similar to that of lengthening the growing season.

<u>Other Climatic Factors</u>.
Other climatic factors that have an effect on the amount of irrigation water consumed by plants are as follows:

Humidity.--Evaporation and transpiration are accelerated on days of low humidity and slowed during periods of high humidity. If the average relatively humidity percentage is low during the growing season, a greater use of water by vegetation may be expected.

Wind movement.--Evaporation of water from land and plant surfaces takes place more rapidly when there is moving air than under calm air conditions. Hot, dry winds and other unusual wind conditions during the growing period will affect the amount of water consumptively used. However, there is a limit in the amount of water that can be utilized. As soon as the land surface is dry, evaporation practically stops and transpiration is limited by the ability of the plants to extract and convey the soil moisture through the plants.

Advection.--Crops grown in irrigated areas surrounded by large arid or semi-arid areas can receive additional energy for vaporization of water by advection. A high percentage of net solar radiation received in arid areas is used in heating the atmosphere. As this warm air mass moves over irrigated areas that are generally cooler, energy contained in the air as sensible heat can be used to evaporate water by vertical turbulent transfer. Thus an "oasis" effect is created. This evaporation of water by vertical turbulent transfer may cause a considerable increase in normal consumptive use in arid areas. It is not believed to be of significance in humid areas.

<u>Stage of Plant Growth</u>.
Other factors being equal, the stage of a crop's growth has a very

considerable influence on its consumptive-use rate. This is particularly true for annual crops which generally have three rather distinct stages of growth. These are (1) emergence and development of complete vegetative cover during which time the consumptive-use rate increases rapidly from a low value and approaches its maximum; (2) the period of maximum vegetative cover during which time the consumptive-use rate may be near or at its maximum if abundant soil moisture is available and (3) crop maturation where, for most crops, the consumptive-use rate begins to decrease. During the maturation period, the plant becomes the limiting factor in the transpiration rate.

Available Irrigation Water Supply.
All the above-mentioned factors influece the amount of water that potentially can be consumed in a given area. However, there are other factors that also cause important differences in the consumptive-use rates. Naturally, unless water is available from some source (precipitation, natural ground water, or irrigation), there can be no consumptive use. In those areas of the arid and semi-arid West where the major source is irrigation, both the quantity and seasonal distribution of the available supply will affect consumptive use. Where water is plentiful and cheap, there is a tendency for farmers to over-irrigate. If the soil surface is frequently wet and the resulting evaporation is high, the combined evaporation and transpiration or consumptive use may likewise increase. Also, under more optimum soil moisture conditions, yields of crops may be higher than average and more water consumed.

Quality of Water.
Some investigations have shown that, besides the quantity and seasonal distribution of the water supply, the quality of the water also has a minor effect on the consumptive use. Whether or not plants require more or less water, if the supply is highly saline may be debatable.

Soil Fertility.
If a soil is made more fertile through the application of manure or by some other means, the yields may be expected to increase with an accompanying increase in water use. However, this increase is so small that it is seldom considered when estimating consumptive use.

Estimating Consumptive Use

In areas for which few or no measurements of consumptive use are available, it is usually necessary to estimate consumptive use of crops from climatological data. For this purpose the Soil Conservation Service uses the Blaney-Criddle method with some modifications.

Blaney and Criddle found that the amount of water consumptively used by crops during their normal growing season was closely correlated with mean monthly temperatures and daylight hours. They developed coefficients that can be used to transpose the consumptive use data for a given area to other areas for which only climatological data are available. The net amount of irrigation water necessary to satisfy consumptive use is found by subtracting the effective precipitation from the consumptive water requirement during the growing or irrigation season.

As previously indicated, numerous factors must be taken into consideration if the consumptive use of water is to be determined accurately. Of the climatic factors, the effect of temperature and sunshine upon plant growth as measures of solar radiation is without doubt the most important. Temperature and precipitation records are more readily available than most other climatic data. Records of actual sunshine are not generally available, but the effect of sunshine is very important on the rate of plant growth and the amount of water plants will consume.

The effect of sunshine can be introduced by using the length of days during the crop-growing season at various latitudes. As an example, the length of the daytime at the Equator varies little throughout the year, whereas at 50° N. latitude, the length of the day in summer is much longer than in winter. Thus, at equal temperatures, photosynthesis can take place for several hours longer each June day at the north latitude than at the Equator. Crop growth and water consumption vary with the opportunity for photosynthesis.

The Blaney-Criddle procedure has generally given sufficiently accurate results when used for the purpose for which it was originally developed, that is for estimating seasonal consumptive use. However, the design of irrigation systems, distribution systems, and water storage facilities require that estimates of consumptive use be made for short-time periods of from 5 to 30 days. It has been found that the seasonal crop coefficients previously mentioned are not constant for consecutive short periods throughout the growing season of a crop. Thus it became necessary to make two modifications in the original procedure in order to obtain reasonably accurate estimates of short-period consumptive use.

One modification requires the use of climatic coefficients that are directly related to the mean air temperature for each of the consecutive short periods which constitute the growing season. The other requires the use of coefficients which reflect the influence of the crop growth stages on consumptive-use rates. Both of these modifications are explained in more detail in later paragraphs.

The Blaney-Criddle Formula

Disregarding many influencing factors, consumptive use varies with the temperature, length of day, and available moisture regardless of its source (precipitation, irrigation water, or natural ground water.) Multiplying the mean monthly temperature (t) by the possible monthly percentage of daytime hours of the year (p) gives a monthly consumptive-use factor (f). It is assumed that crop consumptive use varies directly with this factor when an ample water supply is available. Expressed mathematically $u = kf$ and $U = \text{sum of } kf = KF$ where,

U = Consumptive use of the crop in inches for the growing season.

K = Empirical consumptive-use crop coefficient for the growing season. This coefficient varies with the different crops being irrigated.

F = Sum of the monthly consumptive-use factors for the growing season (sum of the products of mean monthly temperature and monthly percentage of daylight hours of the year).

u = Monthly consumptive use of the crop in inches.

k = Empirical consumptive-use crop coefficient for a month (also varies by crops).

f = Monthly consumptive-use factor (product of mean monthly temperature and monthly percentage of daylight hours of the year).

$f = \frac{t \times p}{100}$, where

t = Mean monthly air temperature in degrees Fahrenheit.

p = Monthly percentage of daylight hours in the year. Values of (p) for latitudes 0 to 65 degrees north of the Equator are shown in Table 1.

Note: Values of (t), (p), (f), and (k), can also be made to apply to periods of less than a month.

Following are modifications made in the original formula:

$k = k_t \times k_c$, where,

k_t = A climatic coefficient which is related to the mean air temperature (t).

$k_t = .0173t - .314$. Values of k_t for mean air temperatures from 36 to 100 degrees are shown in table 4.

k_c = A coefficient reflecting the growth stage of the crop. Values are obtained from crop growth stage coefficient curves such as those shown in figures 1 and 2.

The consumptive-use factor (F) may be computed for areas for which monthly temperature records are available, if the percentage of hours that is shown in table 1 is used. Then, the total crop consumptive use (U) is obtained by multiplying (F) by the empirical consumptive-use crop coefficient (K). This relationship allows the computation of seasonal consumptive use at any location for those crops for which values of (K) have been experimentally established or can be estimated.

Seasonal Comsumptive-Use Coefficients.
Consumptive-use coefficients (K) have been determined experimentally at

numerous localities for most crops grown in the western states. Consumptive-use values (U) were measured and these data were correlated with temperature and growing season. Crop consumptive-use coefficients (K) were then computed by the formula, K = U/F. The computed coefficients varied somewhat because of the diverse conditions (such as soils, water supply, and methods) under which the studies were conducted. These coefficients were adjusted where necessary after the data were analyzed. The resulting coefficients are believed to be suitable for use under normal conditions.

While only very limited investigations of consumptive use have been made in the eastern or humid-area states, studies made thus far fail to indicate that there should be any great difference between the seasonal consumptive-use coefficients used there and those used in the western states.

Table 2 shows the values of seasonal consumptive-use crop coefficients currently proposed by Blaney and Criddle for most irrigated crops. It will be noted that ranges in the values of these coefficients are shown. These, however, are not all inclusive limits. In some circumstances K values may be either higher or lower than shown.

Monthly or Short-Time Consumptive-Use Coefficients.
Although seasonal coefficients (K) as reported by various investigators show some variation for the same crops, monthly or short-time coefficients (k) show even greater variation. These great variations are influenced by a number of factors which must be given consideration when computing or estimating short-time coefficients. Although these factors are numerous, the most important are temperature and the growth stage of the crop. These factors are discussed in succeeding paragraphs.

Growing Season.
In utilizing the Blaney-Criddle formula for computing seasonal requirements, the potential growing season for the various crops is normally considered to extend from frost to frost or from the last killing frost in the spring to the end of a definite period of time thereafter. For most crops, this is adequate for seasonal use estimates, but a refinement is necessary to more precisely define the growing season when monthly or short-time use estimates are required. In many areas, records are available from which planting, harvesting and growth dates can be determined. These should be used where possible. In other areas, temperature data may be helpful for estimating these dates. Table 3 contains some guides which may be helpful in determining these dates.

Since the spring frost date corresponds very nearly with a mean temperature of 55 degrees, it is obvious that many of the common crops use appreciable amounts of water prior to the last frost in the spring and may continue to use water after the first frost in the fall.

Climatic Coefficient (k_t).
While it is recognized that a number of climatological factors have an

Table 1.--Monthly percentage of daytime hours (p) of the year for latitudes 18° to 65° north of the equator.

Latitude North	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
65°	3.52	5.13	7.96	9.97	12.72	14.15	13.59	11.18	8.55	6.53	4.08	2.62
64°	3.81	5.27	8.00	9.92	12.50	13.63	13.26	11.08	8.56	6.63	4.32	3.02
63°	4.07	5.39	8.04	9.86	12.29	13.24	12.97	10.97	8.56	6.73	4.52	3.36
62°	4.31	5.49	8.07	9.80	12.11	12.92	12.73	10.87	8.55	6.80	4.70	3.65
61°	4.51	5.58	8.09	9.74	11.94	12.66	12.51	10.77	8.55	6.88	4.86	3.91
60°	4.70	5.67	8.11	9.69	11.78	12.41	12.31	10.68	8.54	6.95	5.02	4.14
59°	4.86	5.76	8.13	9.64	11.64	12.19	12.13	10.60	8.53	7.00	5.17	4.35
58°	5.02	5.84	8.14	9.59	11.50	12.00	11.96	10.52	8.53	7.06	5.30	4.54
57°	5.17	5.91	8.15	9.53	11.38	11.83	11.81	10.44	8.52	7.13	5.42	4.71
56°	5.31	5.98	8.17	9.48	11.26	11.68	11.67	10.36	8.52	7.18	5.52	4.87
55°	5.44	6.04	8.18	9.44	11.15	11.53	11.54	10.29	8.51	7.23	5.63	5.02
54°	5.56	6.10	8.19	9.40	11.04	11.39	11.42	10.22	8.50	7.28	5.74	5.16
53°	5.68	6.16	8.20	9.36	10.94	11.26	11.30	10.16	8.49	7.32	5.83	5.30
52°	5.79	6.22	8.21	9.32	10.85	11.14	11.19	10.10	8.48	7.36	5.92	5.42
51°	5.89	6.27	8.23	9.28	10.76	11.02	11.09	10.05	8.47	7.40	6.00	5.54
50°	5.99	6.32	8.24	9.24	10.68	10.92	10.99	9.99	8.46	7.44	6.08	5.65
49°	6.08	6.36	8.25	9.20	10.60	10.82	10.90	9.94	8.46	7.48	6.16	5.75
48°	6.17	6.41	8.26	9.17	10.52	10.72	10.81	9.89	8.45	7.51	6.24	5.85
47°	6.25	6.45	8.27	9.14	10.45	10.63	10.73	9.84	8.44	7.54	6.31	5.95
46°	6.33	6.50	8.28	9.11	10.38	10.53	10.65	9.79	8.43	7.58	6.37	6.05
45°	6.40	6.54	8.29	9.08	10.31	10.46	10.57	9.75	8.42	7.61	6.43	6.14
44°	6.48	6.57	8.29	9.05	10.25	10.39	10.49	9.71	8.41	7.64	6.50	6.22
43°	6.55	6.61	8.30	9.02	10.19	10.31	10.42	9.66	8.40	7.67	6.56	6.31
42°	6.61	6.65	8.30	8.99	10.13	10.24	10.35	9.62	8.40	7.70	6.62	6.39
41°	6.68	6.68	8.31	8.96	10.07	10.16	10.29	9.59	8.39	7.72	6.68	6.47
40°	6.75	6.72	8.32	8.93	10.01	10.09	10.22	9.55	8.39	7.75	6.73	6.54
39°	6.81	6.75	8.33	8.91	9.95	10.03	10.16	9.51	8.38	7.78	6.78	6.61
38°	6.87	6.79	8.33	8.89	9.90	9.96	10.11	9.47	8.37	7.80	6.83	6.68
37°	6.92	6.82	8.34	8.87	9.85	9.89	10.05	9.44	8.37	7.83	6.88	6.74
36°	6.98	6.85	8.35	8.85	9.80	9.82	9.99	9.41	8.36	7.85	6.93	6.81
35°	7.04	6.88	8.35	8.82	9.76	9.76	9.93	9.37	8.36	7.88	6.98	6.87
34°	7.10	6.91	8.35	8.80	9.71	9.71	9.88	9.34	8.35	7.90	7.02	6.93
33°	7.15	6.94	8.36	8.77	9.67	9.65	9.83	9.31	8.35	7.92	7.06	6.99
32°	7.20	6.97	8.36	8.75	9.62	9.60	9.77	9.28	8.34	7.95	7.11	7.05
31°	7.25	6.99	8.36	8.73	9.58	9.55	9.72	9.24	8.34	7.97	7.16	7.11
30°	7.31	7.02	8.37	8.71	9.54	9.49	9.67	9.21	8.33	7.99	7.20	7.16
29°	7.35	7.05	8.37	8.69	9.50	9.44	9.62	9.19	8.33	8.00	7.24	7.22
28°	7.40	7.07	8.37	8.67	9.46	9.39	9.58	9.17	8.32	8.02	7.28	7.27
27°	7.44	7.10	8.38	8.66	9.41	9.34	9.53	9.14	8.32	8.04	7.32	7.32
26°	7.49	7.12	8.38	8.64	9.37	9.29	9.49	9.11	8.32	8.06	7.36	7.37
25°	7.54	7.14	8.39	8.62	9.33	9.24	9.45	9.08	8.31	8.08	7.40	7.42
24°	7.58	7.16	8.39	8.60	9.30	9.19	9.40	9.06	8.31	8.10	7.44	7.47
23°	7.62	7.19	8.40	8.58	9.26	9.15	9.36	9.04	8.30	8.12	7.47	7.51
22°	7.67	7.21	8.40	8.56	9.22	9.11	9.32	9.01	8.30	8.13	7.51	7.56
21°	7.71	7.24	8.41	8.55	9.18	9.06	9.28	8.98	8.29	8.15	7.55	7.60
20°	7.75	7.26	8.41	8.53	9.15	9.02	9.24	8.95	8.29	8.17	7.58	7.65
19°	7.79	7.28	8.41	8.51	9.12	8.97	9.20	8.93	8.29	8.19	7.61	7.70
18°	7.83	7.31	8.41	8.50	9.08	8.93	9.16	8.90	8.29	8.20	7.65	7.74

Table 1.--Monthly percentage of daytime hours (p) of the year for latitudes 0° to 20° north of the equator

Latitude North	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
20°	7.75	7.26	8.41	8.53	9.15	9.02	9.24	8.95	8.29	8.17	7.58	7.65
19°	7.79	7.28	8.41	8.51	9.12	8.97	9.20	8.93	8.29	8.19	7.61	7.70
18°	7.83	7.31	8.41	8.50	9.08	8.93	9.16	8.90	8.29	8.20	7.65	7.74
17°	7.87	7.33	8.42	8.48	9.04	8.89	9.12	8.88	8.28	8.22	7.68	7.79
16°	7.91	7.35	8.42	8.47	9.01	8.85	9.08	8.85	8.28	8.23	7.72	7.83
15°	7.94	7.37	8.43	8.45	8.98	8.81	9.04	8.83	8.27	8.25	7.75	7.88
14°	7.98	7.39	8.43	8.43	8.94	8.77	9.00	8.80	8.27	8.27	7.79	7.93
13°	8.02	7.41	8.43	8.42	8.91	8.73	8.96	8.78	8.26	8.29	7.82	7.97
12°	8.06	7.43	8.44	8.40	8.87	8.69	8.92	8.76	8.26	8.31	7.85	8.01
11°	8.10	7.45	8.44	8.39	8.84	8.65	8.88	8.73	8.26	8.33	7.88	8.05
10°	8.14	7.47	8.45	8.37	8.81	8.61	8.85	8.71	8.25	8.34	7.91	8.09
9°	8.18	7.49	8.45	8.35	8.77	8.57	8.81	8.68	8.25	8.36	7.95	8.14
8°	8.21	7.51	8.45	8.34	8.74	8.53	8.78	8.66	8.25	8.37	7.98	8.18
7°	8.25	7.53	8.46	8.32	8.71	8.49	8.74	8.64	8.25	8.38	8.01	8.22
6°	8.28	7.55	8.46	8.31	8.68	8.45	8.71	8.62	8.24	8.40	8.04	8.26
5°	8.32	7.57	8.47	8.29	8.65	8.41	8.67	8.60	8.24	8.41	8.07	8.30
4°	8.36	7.59	8.47	8.28	8.62	8.37	8.64	8.57	8.23	8.43	8.10	8.34
3°	8.40	7.61	8.48	8.26	8.58	8.33	8.60	8.55	8.23	8.45	8.13	8.38
2°	8.43	7.63	8.49	8.25	8.55	8.29	8.57	8.53	8.22	8.46	8.16	8.42
1°	8.47	7.65	8.49	8.23	8.52	8.25	8.53	8.51	8.22	8.48	8.19	8.46
0°	8.50	7.67	8.49	8.22	8.49	8.22	8.50	8.49	8.21	8.49	8.22	8.50

Table 2.--Seasonal consumptive-use crop coefficients (K)
for irrigated crops

Crop	Length of Normal Growing Season or Period 1/	Consumptive-use coefficient (K) 2/
Alfalfa	Between frosts	0.80 to 0.90
Bananas	Full year	.80 to 1.00
Beans	3 months	.60 to .70
Cocoa	Full year	.70 to .80
Coffee	Full year	.70 to .80
Corn (Maize)	4 months	.75 to .85
Cotton	7 months	.60 to .70
Dates	Full year	.65 to .80
Flax	7 to 8 months	.70 to .80
Grains, small	3 months	.75 to .85
Grain, sorghums	4 to 5 months	.70 to .80
Oilseeds	3 to 5 months	.65 to .75
Orchard crops:		
Avocado	Full year	.50 to .55
Grapefruit	Full year	.55 to .65
Orange and lemon	Full year	.45 to .55
Walnuts	Between frosts	.60 to .70
Deciduous	Between frosts	.60 to .70
Pasture crops:		
Grass	Between frosts	.75 to .85
Ladino whiteclover	Between frosts	.80 to .85
Potatoes	3 to 5 months	.65 to .75
Rice	3 to 5 months	1.00 to 1.10
Soybeans	140 days	.65 to .70
Sugar beet	6 months	.65 to .75
Sugarcane	Full year	.80 to .90
Tobacco	4 months	.70 to .80
Tomatoes	4 months	.65 to .70
Truck crops, small	2 to 4 months	.60 to .70
Vineyard	5 to 7 months	.50 to .60

1/ Length of season depends largely on variety and time of year when the crop is grown. Annual crops grown during the winter period may take much longer than if grown in the summertime.

2/ The lower values of (K) for use in the Blaney-Criddle formula, $U = KF$, are for the more humid areas, and the higher values are for the more arid climates.

effect on consumptive use by crops, seldom is complete climatological data on relative humidity, wind movement, sunshine hours, pan evaporation, etc., available for a specific site. Thus it is necessary to rely on records of temperature which are widely available.

In 1954 J. T. Phelan attempted to correlate the monthly consumptive-use coefficient (k) with the mean monthly temperature (t). It was noted that a loop effect occurred in the plotted points; the computed values of (k) were higher in the spring than in the fall for the same temperature. The effects of this loop were later corrected by the development of a crop growth stage coefficient (k_c). The relationship between (k) and (t) was adopted for computing values of (k_t), the temperature coefficient. This relationship is expressed as $k_t = .0173_t - .314$. Table 4 gives values of (k_t) for temperatures ranging from 36 to 100 degrees Fahrenheit.

Crop Growth Stage Coefficients (k_c).

As previously stated, another factor which causes consumptive use to vary widely throughout the growing season is the plant itself. Stage of growth is a primary variable that must be recognized since it is obvious that plants in the rapid growth stage will use water at a more rapid rate than will new seedlings. It is also obvious that these variations in consumptive use throughout the growing season will be greater for annual crops than for perennial crops such as alfalfa, permanent pasture grasses and orchards.

In order to recognize these variations in consumptive use, crop growth stage coefficients (k_c) have been introduced into the formula. Values of these coefficients are calculated from research data. When values of (k_c) are plotted against time or stage of growth, curves similar to those shown in figures 1 and 2 will result. Such curves are used to obtain values of (k_c) which, when used with appropriate values of (k_t), will permit a determination of values of monthly or short-time consumptive-use coefficients (k).

It is also recognized that value of (k_c) might, to some extent, be influenced by factors other than the characteristics of the plant itself. For this reason, it is not expected that these curves can be used universally. They should, however, be valid over a considerable area and certainly should be of value in areas where no measured consumptive-use data is available.

With annual crops, such as corn, values of the coefficient (k_c) are best plotted as a function of a percentage of the growing season. Figure 1 shows the suggested values of (k_c) for corn.

With perennial crops, values of the coefficient (k_c) are usually best plotted on a monthly basis. Figure 2 shows the plotting of such values for alfalfa. Crop growth stage coefficient curves for all crops for which data are available are contained in the appendix.

Table 3.--A guide for determining planting dates, maturity dates and lengths of growing seasons as related to mean air temperature

Crop	Earliest moisture-use or planting date as related to mean air temperature	Latest moisture-use or maturing date as related to mean air temperature	Growing Season Days
Perennial Crops			
Alfalfa	50° mean temp.	28° frost	Variable
Grasses, cool	45° mean temp.	45° mean temp.	Variable
Orchards, decid.	50° mean temp.	45° mean temp.	Variable
Grapes	55° mean temp.	50° mean temp.	Variable
Annual Crops			
Beans, dry	60° mean temp.	32° frost	90 - 100
Corn	55° mean temp.	32° frost	140 - Max.
Cotton	62° mean temp.	32° frost	240 - Max.
Grain, spring	45° mean temp.	32° frost	130 - Max.
Potatoes, late	60° mean temp.	32° frost	130 - Max.
Sorghum, grain	60° mean temp.	32° frost	130 - Max.
Sugar beets	28° frost	28° frost	180 - Max.
Wheat, winter			
(Fall season)		45° mean temp.	
(Spring season)	45° mean temp.		

Assumptions in Applying the Formula.
In order to apply results of a consumptive-use-of-water study in one area to other areas, it is usually necessary to make certain assumptions. As previously indicated, if sufficient basic information is available locally, such actual data should be used. But rarely are all needed data known in sufficient detail. Where necessary information is lacking, the following assumptions must be made in applying the consumptive-use formula to transfer data between areas:

1. Seasonal consumptive use (U) of water varies directly with the consumptive-use factor (F).

2. Crop growth and yields are not limited by inadequate water at any time during the growing season.

3. Growing periods for alfalfa, pasture, orchard crops, and "natural" vegetation, although usually extending beyond the frost-free periods, are usually indicated by such periods. Yields of crops dependent only upon vegetative growth vary with the length of the growing period.

Application to Specific Areas.
The application of the Blaney-Criddle formula to specific areas can best be illustrated by examples. Two have been chosen for this purpose. The first is an annual crop, corn, grown in a humid area, Raleigh, North Carolina. The second is a perennial crop, alfalfa, grown in an arid area, Denver, Colorado.

Corn at Raleigh, N. C.--The procedure for estimating the average daily, monthly and seasonal consumptive use by corn at this location is shown in Sample Calculation No. 1. The average length of the growing season for corn grown in the vicinity of Raleigh is 120 days beginning about April 20.

The estimate is made on a monthly basis, the months and fractions thereof being shown in column 1. The midpoint date for each month or fraction is shown in column 2. The accumulated number of days from the planting date, April 20, to the midpoint of each month or period is shown in column 3. The percentage of the 120-day growing season represented by these midpoint dates is shown in column 4. Thus Col. 4 = Col. 3 ÷ 120.

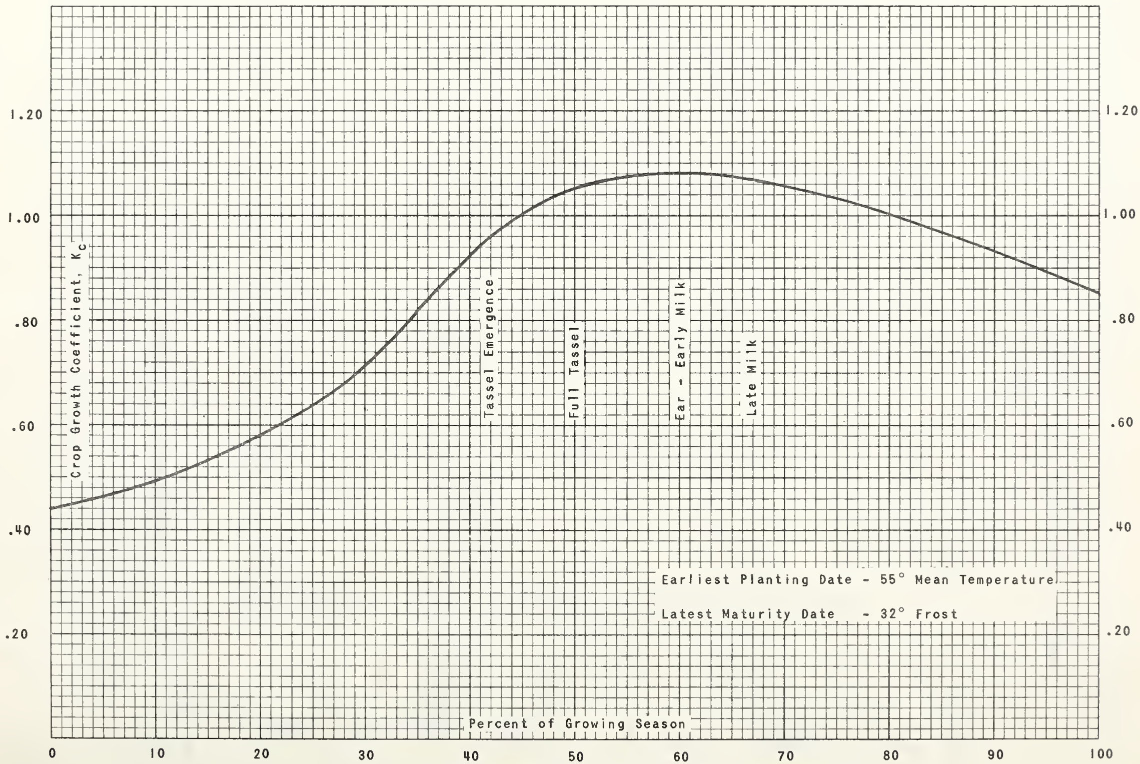
Mean monthly air temperature values, shown in column 5, are taken from Weather Bureau records. The mean temperature is assumed to occur on the 15th day of each month. The mean air temperature for a part of a month can be obtained mathematically or graphically by assuming that the increase or decrease in temperature between the 15th day of any consecutive month is a straight-line relationship. For example, at Raleigh, the mean monthly air temperature for April is 60.6° and that

Table 4.--Values of the climatic coefficient, k_t, 1/ for various mean air temperature, t.

t °F	k_t	t °F	k_t	t °F	k_t
36	.31	61	.74	86	1.17
37	.33	62	.76	87	1.19
38	.34	63	.78	88	1.21
39	.36	64	.79	89	1.23
40	.38	65	.81	90	1.24
41	.40	66	.83	91	1.26
42	.41	67	.85	92	1.28
43	.43	68	.86	93	1.30
44	.45	69	.88	94	1.31
45	.46	70	.90	95	1.33
46	.48	71	.91	96	1.35
47	.50	72	.93	97	1.36
48	.52	73	.95	98	1.38
49	.53	74	.97	99	1.40
50	.55	75	.98	100	1.42
51	.57	76	1.00		
52	.59	77	1.02		
53	.60	78	1.04		
54	.62	79	1.05		
55	.64	80	1.07		
56	.66	81	1.09		
57	.67	82	1.11		
58	.69	83	1.12		
59	.71	84	1.14		
60	.72	85	1.16		

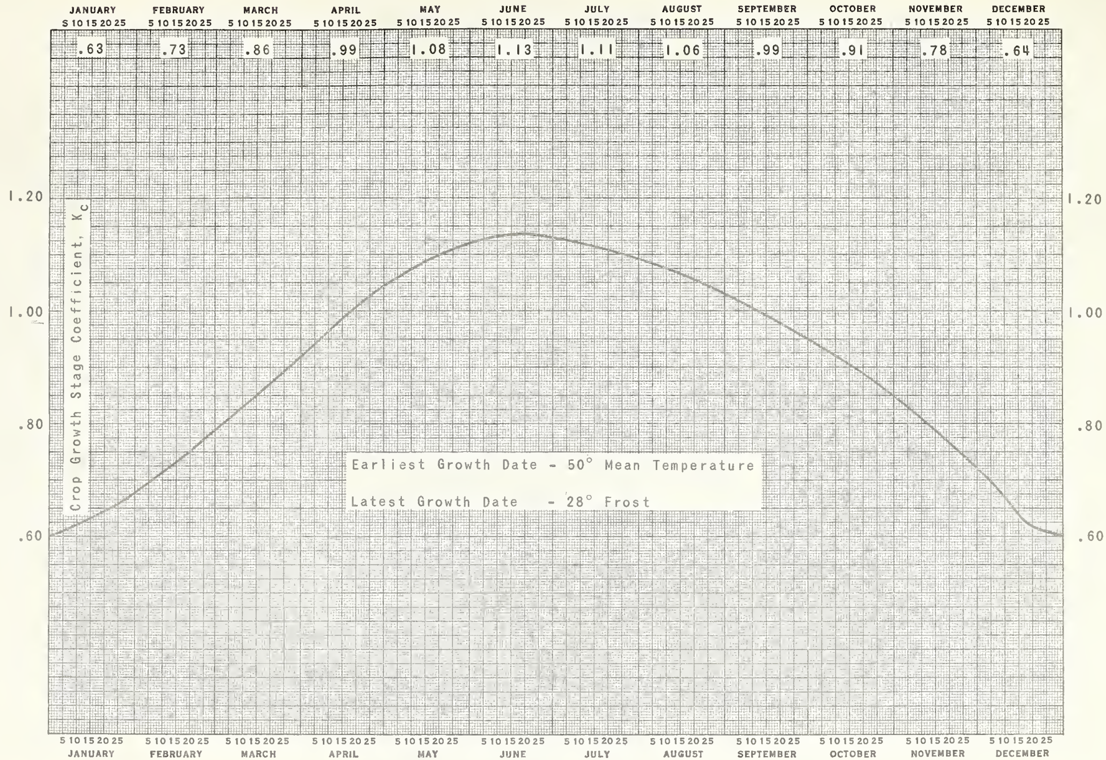
1/ Values of (k_t) are based on the formula, $k_t = .0173\ t - .314$

for mean temperatures less than 36°, use $k_t = .300$.



Crop growth stage coefficient curve for corn (grain)

Curve No. 1



Crop growth stage coefficient curve for alfalfa

Curve No. 2

for May is 69.2°. The mean air temperature for the midpoint date is calculated as follows:

$$60.6° + \frac{10 \text{ days } (69.2° - 60.6°)}{30 \text{ days}} = 63.5°$$

Raleigh is located at Latitude 35° - 47' N. The monthly percentages of daylight hours, shown in column 6, are taken from table 1. For parts of a month the values of these percentages can be obtained in a similar manner as described for mean air temperatures. For example, at Raleigh, the monthly percentage of daylight hours for April is 8.84 and that for May is 9.79. For the period April 20 through April 30, the monthly percentage of daylight hours is calculated as follows:

$$\left[8.84\% + \frac{10 \text{ days } (9.79\% - 8.84\%)}{30 \text{ days}}\right] \frac{10 \text{ days}}{30 \text{ days}} = 3.05\%$$

The values of consumptive use factors (f) shown in column 7 are the product of (t) and (p) divided by 100. Values of the climatic coefficient (k_t), shown in column 8, are taken from table 4. Values of the crop growth stage coefficient (k_c), shown in column 9, are taken from the curve shown in figure 1. The values of the monthly consumptive-use coefficient (k), shown in column 10, are the product of (k_t) and (k_c). Values of monthly consumptive use (u), shown in column 11, are the product of values of (k) and (f). The average daily rates of consumptive use shown in column 12 are the monthly values of (u) (column 11) divided by the number of days in the month.

Alfalfa at Denver, Colo.--The procedure for estimating the average daily, monthly and seasonal consumptive use by alfalfa in this location is shown in Sample Calculation No. 2. The growing season for alfalfa grown near Denver is considered to be that period from the date corresponding to 50° mean temperature in the spring to the date corresponding to 28° frost in the fall. This period is from April 24 to October 25.

The procedure illustrated by Sample Calculation No. 2 is the same as that heretofore described for corn and illustrated by Sample Calculation

No. 1. The values of the crop growth stage coefficient, (k_c), shown in column 8 are taken from the curve for alfalfa shown in figure 2.

Peak Period Consumptive Use

Information on peak period rates of consumptive use is needed to properly design irrigation systems. It is used to determine the minimum capacity requirements of main and lateral canals, pipelines, and other water conveyance or control structures. The peak period rates of water use by crops also influence the administration of streams and reservoirs from which irrigation water supplies are obtained.

In irrigation project design, the peak period of consumptive use is the period during which the weighted average daily rate of consumptive use of the various crops grown in the project area is at a maximum. Different crops may have their peak rates of use at different times. Therefore, some crops may not be using water at their maximum rate during the project peak period. In fact, some of the crops may not even be grown during this period.

Factors Influencing Peak Period Use Rates.

While other factors may have a minor influence on peak period rates of consumptive use, peak period air temperature and net depth of irrigation application have the greatest influence.

Temperature.--An analysis of daily mean air temperature records for any month at any location will show that the mean temperature for the warmest consecutive 5-day period will be greater than that for the warmest 10-day period. Likewise, the mean temperature for the warmest consecutive 10-day period will be greater than that for the warmest 15-day period, and so on. All will be greater than the mean monthly temperature. Since consumptive use, as estimated by the Blaney-Criddle formula, is directly related to air temperature, it is obvious that the shorter the peak period is in days, the greater will be the mean temperature and therefore the greater will be the consumptive-use rate.

Net irrigation application.--The length of the peak period is that number of days in which the normal net irrigation application will last under the peak rate of use for the period. Thus smaller net irrigation applications will last for smaller periods of time and, as shown above, will result in greater peak period-use rates. Conversely, higher net irrigation applications will result in lower peak period-use rates.

Table 5 shows peak-period average daily consumptive-use rates as related to estimated monthly use and net irrigation application. As an illustration of the use of this table, the case of alfalfa irrigated near Denver may be used. From Sample Calculation No. 2, it will be noted that the peak-use month is July and that the average consumptive use for that month is 7.8 inches. From the Colorado irrigation guide, it

Sample Calculation No. 1.--Estimate of average daily, monthly and seasonal consumptive-use
by
Corn at Raleigh, North Carolina
(Harvested for grain)

Lat. 35° 47' North

(1) Month or Period	(2) Midpoint of Period	(3) Accum. Days to Midpoint	(4) Percent of Growing Season	(5) Mean Air Temp. t. ° F.	(6) Daylight Hours p. Percent	(7) Cons. Use Factor f.	(8) Climatic Coeff. k_t	(9) Growth Stage Coeff. k_c	(10) Cons. Use Coeff. k	(11) Monthly Cons. Use u. Inches	(12) Daily Cons. Use u. In./Day
Apr. 20											
	Apr. 25	5	4.2	63.5	3.05	1.94	.79	.46	.36	.70	.070
May											
	May 15	25	20.8	69.2	9.79	6.77	.88	.59	.52	3.52	.114
June											
	June 15	56	46.7	76.9	9.81	7.54	1.02	1.02	1.04	7.84	.261
July											
	July 15	86	71.7	79.4	9.98	7.92	1.06	1.05	1.11	8.79	.284
Aug.											
	Aug. 9	111	92.5	78.3	5.52	4.32	1.04	.91	.95	4.10	.228
Aug. 18											
Season Total										24.95	

Sample Calculation No. 2.--Estimate of average, daily, monthly and seasonal consumptive-use by Alfalfa at Denver, Colorado

Lat. 39° 40' North

(1) Month or Period	(2) Midpoint of Period	(3) Days in Period	(4) Mean Air Temp. t. ° F.	(5) Daylight Hours p. Percent	(6) Cons. Use Factor f	(7) Climatic Coeff. k_t	(8) Growth Stage Coeff. k_c	(9) Cons. Use Coeff. k	(10) Monthly Cons. Use u Inches	(11) Daily Cons. Use u In./Day
Apr. 24 – May	Apr. 27	6	51.1	1.87	.96	.57	1.03	.59	.57	.095
May – June	May 15	31	56.3	9.99	5.62	.66	1.08	.71	3.99	.129
June – July	June 15	30	66.4	10.07	6.69	.84	1.13	.95	6.36	.212
July – Aug.	July 15	31	72.8	10.20	7.43	.95	1.11	1.05	7.80	.252
Aug. – Sept.	Aug. 15	31	71.3	9.54	6.80	.92	1.06	.98	6.66	.215
Sept. – Oct.	Sept. 15	30	62.7	8.39	5.26	.77	.99	.76	4.00	.133
Oct. – Oct. 25	Oct. 12	25	53.5	6.31	3.38	.61	.91	.56	1.89	.076
Season Total									31.27	

is determined that the net irrigation application is 4.2 inches. Thus, by interpolation from the table, the peak-period use rate is found to be 0.28 inch per day.

A suggested procedure for using table 5 to estimate project peak period consumptive-use requirements is outlined below and is illustrated by Sample Calculation No. 3.

1. Determine the net irrigation applications (I) required for the crops in the project area.

2. Determine the monthly consumptive-use rate (u_m) for each crop in the project area for the month of greatest overall water use. (Note that if some crop is using water for only a portion of the month, its rate of use must be computed by dividing the estimated requirement by the fraction of the month when water is used).

3. From table 5, using appropriate values of (I) and (u_m), determine the peak period consumptive-use rate (u_p) for each of the three crops.

4. Using the crop and soil distribution patterns established for the project, compute the weighted peak period consumptive-use rate for the project.

Effective Rainfall

Effective rainfall supplies a portion of the consumptive use by crops. It may be a nearly insignificant portion in arid areas such as the Salt River Valley of Arizona or it may be a major portion in humid areas such as the Atlantic Coastal Plain of the Carolinas. The engineer engaged in estimating irrigation water requirements of a crop is confronted with the problem of determining what portion of total consumptive use will be furnished by effective rainfall and what portion will have to be supplied by irrigation. Since there are no records of effective rainfall available, it is necessary to utilize total rainfall records and estimate the portion of total rainfall that is effective. A procedure for doing this is described in succeeding paragraphs.

Factors Influencing Rainfall Effectiveness.

Total rainfall.--In arid areas where total growing season precipitation is light, the moisture level in the soil profile at the time precipitation occurs is usually such that almost all of it enters the soil profile and becomes available for consumptive use. Losses due to surface runoff or to percolation below the crop root zone are usually negligible. Thus the effectiveness of rainfall in these areas is relatively high.

In humid areas, storms of large magnitude and high intensity occur frequently during the growing season. These storms often produce water in excess of that which can be stored in the soil profile for consumptive

Table 5.--Peak period average daily consumptive use rates (u_p) as related to estimated actual monthly use (u_m)

Net Irrigation Application I (Inches)	Computed Peak Monthly Consumptive Use Rate (u_m) in Inches 1/																
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
	Peak Period Daily Use Rate (u_p) in Inches per Day																
1.0	.15	.18	.20	.22	.24	.26	.28	.31	.33	.35	.37	.40	.42	.44	.46	.49	.51
1.5	.15	.17	.19	.21	.23	.25	.27	.29	.32	.34	.36	.38	.41	.43	.45	.47	.50
2.0	.15	.16	.18	.20	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.44	.46	.48
2.5	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.39	.41	.43	.45	.47
3.0	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44	.46
3.5	.14	.16	.18	.19	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.44	.46
4.0	.14	.15	.17	.19	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.43	.45
4.5	.14	.15	.17	.19	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.43	.45
5.0	.13	.15	.17	.19	.21	.23	.25	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44
5.5	.13	.15	.17	.19	.21	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44
6.0	.13	.15	.17	.19	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.41	.43

1/ Based on the formula $u_p = 0.034\ u_m^{1.09}\ I^{-.09}$ where
u_p = Average daily peak period consumptive use in inches.
u_m = Average consumptive use for the peak month in inches.
I = Net irrigation application in inches.

Sample Calculation No. 3.--Estimate of project peak consumptive use rates for a project near Boise, Idaho

Item		Unit	Soil Mapping Units		
			1 M 3	1 S 6	Total
Soil Areas		Acres	930	570	1500
		Percent	62	38	100
Available Moisture Holding Capacity		In./ft.	2.2	1.4	
Crops					
Alfalfa		Acres			975
Small grain		Acres			375
Potatoes		Acres			150
Crop Root Zone Depths					
Alfalfa		Ft.	5	5	
Small grain		Ft.	4	4	
Potatoes		Ft.	3	3	
Net Irrigation Application (I)					
Alfalfa		In.	5.5	3.5	
Small grain		In.	4.4	2.8	
Potatoes		In.	2.6	1.7	
Consumptive Use Rate for Peak Month (u_m)					
Alfalfa		In./mo.	8.5	8.5	
Small grain (1.89" in 17 days)		In./mo.	3.4	3.4	
Potatoes		In./mo.	7.4	7.4	
Peak Period Consumptive Use Rates (u_p) (from table 5)					
Alfalfa		In./day	.30	.31	
Small grain		In./day	.13	.13	
Potatoes		In./day	.28	.29	
Weighted for crop distribution					
Alfalfa	65%	In./day	.195	.202	
Small grain	25%	In./day	.033	.033	
Potatoes	10%	In./day	.028	.029	
All crops	100%	In./day	.256	.264	
Weighted for soils distribution		In./day	.159	.100	.259

use. This excess is lost either to surface runoff or to percolation below the root zone depth. When such storms occur soon after an application of irrigation water has been made, almost all of the rainfall may be lost. Thus in areas of high total growing season rainfall, the effectiveness of rainfall is low by comparison.

For example at Albuquerque, New Mexico, where the average total growing season rainfall is only 8.0 inches, the average rainfall effectiveness is 92 percent. At Baton Rouge, Louisiana, the average total growing season rainfall is 39.4 inches but the average rainfall effectiveness is only 64 percent.

Consumptive-use rate.--Where the consumptive-use rate of a crop is high, available moisture in the soil profile is depleted rapidly, thus providing storage capacity at a relatively rapid rate for receiving rainfall. Should a substantial storm occur, the amount of water required to bring the moisture in the profile back to the field capacity level would be relatively large and the losses due to runoff and/or deep percolation would be relatively small. Conversely, where the consumptive-use rate is low, storage capacity for rainfall is provided at a slower rate. When a storm occurs, there is less capacity in the profile available to receive water and thus the losses will be relatively large. Said briefly, the higher the rate of consumptive use, the greater will be the rainfall effectiveness. Conversely, the lower the rate of consumptive use, the lower will be the effectiveness of rainfall.

Net irrigation application.--As previously stated, the net irrigation application is dependent upon the capacity of the soil profile at root zone depth to store readily available moisture for plant use. When this capacity is low and a storm of considerable magnitude occurs, only a small percentage of the precipitation may be needed to fill the soil profile to field capacity and the resulting rainfall effectiveness will be low. Conversely, if the capacity is high, all or most of the rainfall resulting from such a storm might be stored in the profile before the field capacity level is reached. In this case, the effectiveness of rainfall would be relatively high.

Monthly Effective Rainfall.

Curves and tables have been developed to show the relationship between effective rainfall and the three variable factors discussed previously (see figure 3 and table 6). Either the curves or the table may be used with the same result and both are presented in order to give the user a choice. The curves and the table show the relationship between average monthly effective rainfall (r_e), mean monthly rainfall (r_t), and average monthly consumptive use (u). The values of (r_e) are based on a 3-inch net irrigation application. Factors for converting to other net depths of application are presented. For example, a crop of corn grown on a sandy soil has a net depth of application of 2.0 inches. Average consumptive use for the month of July is 8.79 inches and mean July rainfall is 5.85 inches. From figure 3 or table 6, the average effective rainfall for July is 4.78 x 0.93 = 4.45 inches.

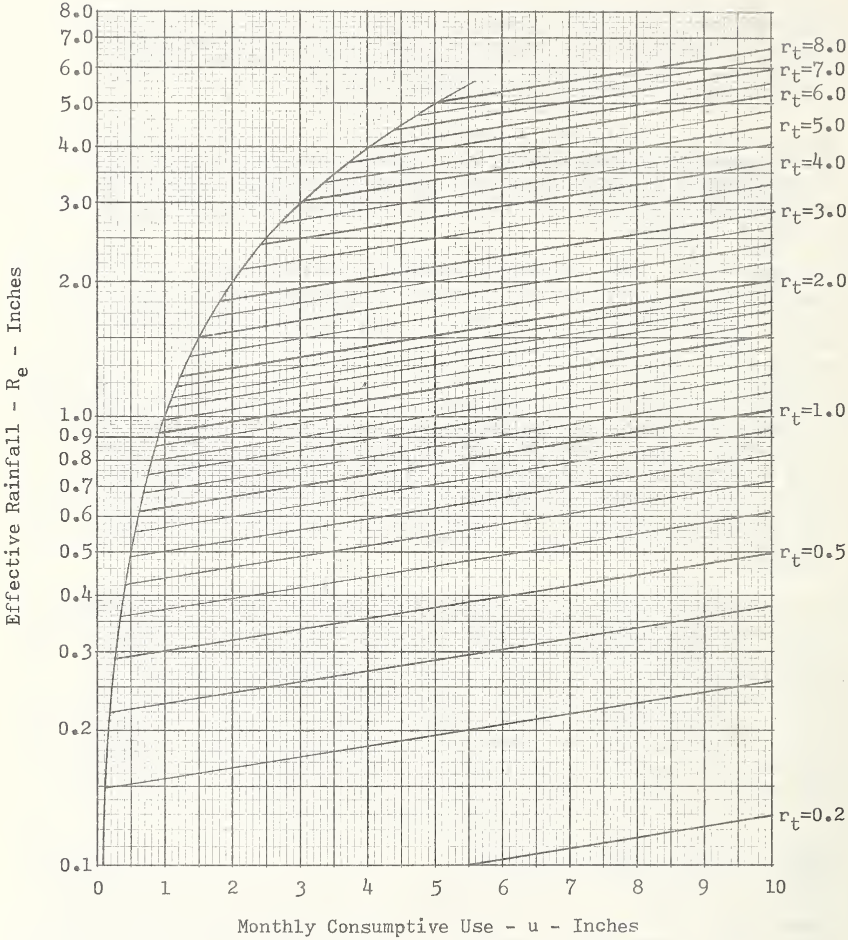


Figure 3 - Average monthly effective rainfall[1/] as related to mean monthly rainfall and average monthly consumptive use.

1/ Based on 3-inch net depth of application. For other net depths of application, multiply by the factors shown in Table 6.

Table 6.--Average monthly effective rainfall[1/] as related to mean monthly rainfall and average monthly consumptive use

Monthly Mean Rainfall r_t Inches	Average Monthly Consumptive Use, u, in Inches										
	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.00
	Average Monthly Effective Rainfall, r_e, in Inches										
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.45	0.47	0.50
1.0	0.59	0.63	0.66	0.70	0.74	0.78	0.83	0.88	0.93	0.98	1.00
1.5	0.87	0.93	0.98	1.03	1.09	1.16	1.22	1.29	1.37	1.45	1.50
2.0	1.14	1.21	1.27	1.35	1.43	1.51	1.59	1.69	1.78	1.88	1.99
2.5	1.39	1.47	1.56	1.65	1.74	1.84	1.95	2.06	2.18	2.30	2.44
3.0		1.73	1.83	1.94	2.05	2.17	2.29	2.42	2.56	2.71	2.86
3.5		1.98	2.10	2.22	2.35	2.48	2.62	2.77	2.93	3.10	3.28
4.0		2.23	2.36	2.49	2.63	2.79	2.95	3.12	3.29	3.48	3.68
4.5			2.61	2.76	2.92	3.09	3.26	3.45	3.65	3.86	4.08
5.0			2.86	3.02	3.20	3.38	3.57	3.78	4.00	4.23	4.47
5.5			3.10	3.28	3.47	3.67	3.88	4.10	4.34	4.59	4.85
6.0				3.53	3.74	3.95	4.18	4.42	4.67	4.94	5.23
6.5				3.79	4.00	4.23	4.48	4.73	5.00	5.29	5.60
7.0				4.03	4.26	4.51	4.77	5.04	5.33	5.64	5.96
7.5					4.52	4.78	5.06	5.35	5.65	5.98	6.32
8.0					4.78	5.05	5.34	5.65	5.97	6.32	6.68

Note: Values below line exceed monthly consumptive use and are to be used for interpolation only.

1/ Based on 3-inch net depth of application. For other net depths of application, multiply by the factors shown below.

Net Depth of Application (D)	.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
Factor (f)	.72	.77	.86	.93	.97	1.00	1.02	1.04	1.06	1.07

Note: Average monthly effective rainfall cannot exceed average monthly rainfall or average monthly consumptive use. When the application of the above factors results in a value of effective rainfall exceeding either, this value must be reduced to a value equal the lesser of the two.

$$r_e = (0.70917\, r_t^{0.82416} - 0.11556)(10)^{0.02426u}\ (f)$$

where $f = (0.531747 + 0.295164D - 0.057697D^2 + 0.003804D^3)$

Seasonal Effective Rainfall.
Average growing season effective rainfall is determined by adding the values of average effective rainfall for the several months and fractions thereof that cover the total growing season of the crop in question. (See Sample Calculations No. 4 and No. 5.)

Caution in the Use of the Curves and the Table.
Figure 3 and table 6 are the result of a comprehensive analysis of 50 years of precipitation records at each of 22 Weather Bureau stations so selected that all climatic conditions throughout the 48 continental states were represented. These studies were made by using the daily soil moisture balance procedure whereby a soil moisture balance is computed for each day by subtracting consumptive use and adding effective rainfall and/or irrigation to the previous day's balance. This procedure necessarily fails to consider two factors which, in some instances, may have a bearing on the effectiveness of rainfall. These factors, soil intake rates and rainfall intensities, are not considered for two reasons: (1) sufficient data are not available; and (2) the complexity involved in their consideration would make such a study impractical. In some areas where soil intake rates are low and rainfall intensities are consistently high, large percentages of rainfall may be lost to surface runoff without the moisture level in the soil profile being raised appreciably. In such areas the values obtained from figure 3 and table 6 may need to be modified.

Frequency Distribution of Effective Rainfall.
It can safely be assumed that, for any given crop at a particular location, monthly and seasonal consumptive use will vary only slightly from year to year provided the crop is planted at about the same time each year. On the other hand, monthly and seasonal effective rainfall can be expected to vary widely from year to year. Since by definition the net irrigation requirement is that portion of total consumptive use not supplied by effective rainfall or other natural sources, it will also vary widely from year to year as effective rainfall varies.

In view of this wide variation in net irrigation requirements from year to year, it is obvious that the development of a dependable water supply cannot be based on average requirements, since this would provide an adequate supply approximately half the time. It is common practice, therefore, to estimate effective rainfall and irrigation water requirements on a probability basis, the percent chance of occurrence used being an economic consideration. For example, it might be economical to provide a water supply that is adequate in nine out of ten years for a high-value vegetable crop or tobacco. For a low-value hay crop or pasture, it may not be economical to provide an adequate supply in more than six out of ten years.

The procedure for determining the frequency distribution of effective rainfall is based on the assumption that, for any fixed period of time or growing season at a given location, other factors being equal, effective rainfall will vary from year to year in direct proportion to the variance in total rainfall. Thus the frequency distribution of total rainfall may be used as a measure of the frequency distribution of effective rainfall. The procedure is as follows:

For the growing season of any given crop at a particular location, Weather Bureau records are used to determine the total rainfall that occurred during the growing season for each year over a period of 25 years or longer. These growing-season rainfall totals are then ranked in order of magnitude and plotted on log-normal probability paper as illustrated by figure 4. A straight line that most nearly fits all of the plotted points is drawn to establish the frequency distribution of growing-season total rainfall. Instructions for plotting the points and drawing the frequency distribution line are contained in the SCS National Engineering Handbook, Section 4, Supplement A, Part 3.18.

The desired percent chance of the developed water supply being equaled or exceeded by the gross irrigation water requirements of the crop is then selected. In the case of corn grown near Raleigh, North Carolina, as illustrated by Sample Calculation No. 4, this selected chance is 20 percent. Thus the developed water supply would be adequate in 8 years out of 10 or 80 percent of the time. The ratio of 80 percent chance growing-season rainfall to average growing-season rainfall is then determined. It will be noted in figure 4 that the 80 percent chance growing-season rainfall is 14.0 inches. From Weather Bureau records, it is determined that the average rainfall for the growing season for corn is 17.87 inches. Thus the aforementioned ratio is 14.0/17.87 or .783. This ratio, when applied to the monthly and seasonal average rainfall values, as shown in column 3 of Sample Calculation No. 4, determines the 80 percent chance monthly and seasonal rainfall values shown in column 9 of the same calculation.

The monthly effective rainfall that can be expected for any frequency of occurrence can be estimated by the use of figure 3 or table 6 when monthly consumptive use and monthly total rainfall for that frequency of occurrence are known. Again using Sample Calculation No. 4 as an example, the monthly consumptive-use values shown in column 2 and the 80 percent chance monthly total rainfall shown in column 9 are used with figure 3 or table 6 to obtain the 80 percent chance monthly effective rainfall shown in column 10.

An Alternate Procedure.

In cases where the degree of accuracy desired does not warrant the time required to plot a growing season rainfall frequency distribution curve for each crop under consideration, an alternate procedure may be used. This procedure involves the application of an average ratio to the average growing season effective rainfall to obtain the growing season effective rainfall for any given percent chance of occurrence. These average ratios vary with the desired percent chance of occurrence and with average annual rainfall values as shown in table 7.

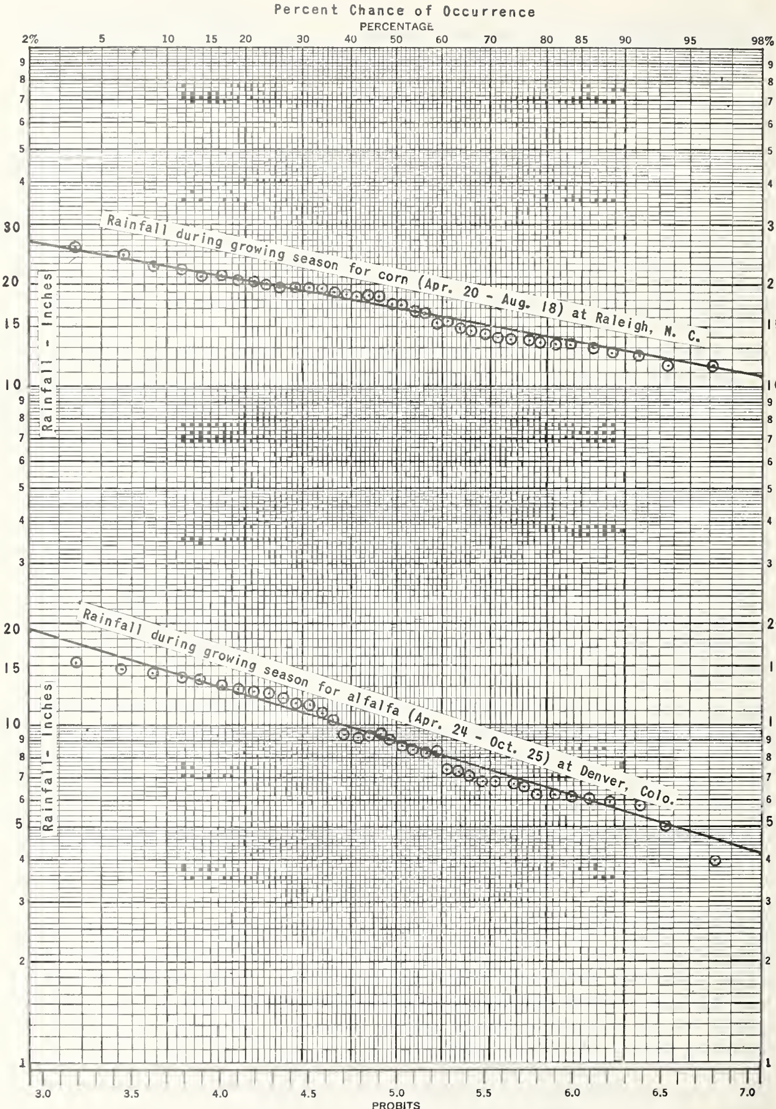


Figure 4 - Frequency distribution of growing season rainfall.

Again using corn at Raleigh, North Carolina, as an example, it is desired to find the growing season effective rainfall that will have an 80 percent chance of occurrence. Average total annual rainfall at Raleigh is 45.92 inches and it has been determined that the average growing season effective rainfall for corn is 12.72 inches (see Sample Calculation No. 4 on page 35). From table 7 it will be noted that the average ratio applicable to effective rainfall is .842. Thus the growing season effective rainfall that may be expected to occur or be exceeded in eight out of ten years would be .842 x 12.58 or 10.59 inches.

The frequency distribution of effective rainfall for months or other short-time periods may be determined by applying these same ratios shown in table 7.

Irrigation Water Requirements

Consumptive-use data are used in estimating the irrigation water requirements of existing or proposed projects and for crop production on individual farms. The consumptive irrigation water requirement is dependent not only on the total consumptive need, but also on the amount of moisture contributed from such natural sources as effective growing-season rainfall, carryover soil moisture from winter rains and any contribution from ground water. Effective rainfall has been discussed in preceding paragraphs. The other two natural sources are discussed below.

Carryover Soil Moisture.

The contribution of carryover soil moisture resulting from winter rains to the seasonal water requirements is difficult to estimate. In some areas, winter precipitation is sufficient to bring the soil moisture in the root zone depth of the profile up to field capacity. This is particularly true in the humid area states where it is the custom to deduct this readily available moisture (equivalent to the net irrigation application) from seasonal consumptive use when estimating seasonal consumptive irrigation requirements. Where late-season water supplies are short, (usually arid areas) the soil moisture is often well below field capacity and possibly down to the wilting point in the fall.

For crops with a 6-foot root zone, the amount of usable water that could be stored might range from 1 to 2 inches of water per foot depth of soil, or 6 to 12 inches in the 6-foot root zone. This is a major part of the annual requirement of some crops and can be supplied by winter precipitation in some areas in wet years. However, in areas where irrigation water is plentiful, it is not unusual to find the soil moisture content at the end of the season nearly as high as at the beginning. Thus, there is no storage capacity left in the root zone and the contribution from winter precipitation is negligible. Nevertheless, the quantity of moisture carried over in the soil from winter precipitation tends to offset any deficiency in the estimated irrigation water requirements.

Table 7.--Average ratios applicable to effective rainfall

Average Annual Rainfall (Inches)	Percent Chance of Occurrence 50	60	70	80	90
3	0.80	0.68	0.56	0.45	0.33
4	.84	.72	.61	.50	.38
5	.87	.76	.65	.54	.42
6	.88	.78	.68	.57	.45
7	.89	.79	.69	.60	.48
8	.90	.81	.71	.62	.51
9	.91	.82	.73	.63	.53
10	.92	.83	.75	.65	.55
12	.93	.85	.78	.69	.58
14	.94	.86	.79	.71	.61
16	.95	.88	.81	.73	.63
18	.95	.89	.82	.74	.65
20	.96	.90	.83	.75	.67
22	.96	.90	.84	.77	.69
24	.97	.91	.84	.78	.70
26	.97	.92	.85	.79	.71
28	.97	.92	.86	.80	.72
30	.97	.93	.87	.81	.73
35	.98	.93	.88	.82	.75
40	.98	.94	.89	.83	.77
45	.98	.94	.90	.84	.78
50	.98	.95	.91	.85	.79
55	.99	.95	.91	.86	.80
60	.99	.95	.91	.87	.81
70	.99	.95	.92	.88	.83
80	.99	.95	.92	.89	.85
90	.99	.96	.93	.90	.86

Example of Use.
It is desired to find the growing season effective rainfall that will occur or be exceeded in 8 out of 10 years at a location where the average total annual rainfall is 30 inches and for a growing season where the average effective rainfall is 12 inches. From the table, the applicable ratio is found to be 0.81. Thus the 80% chance growing season effective rainfall is 0.81 x 12 = 9.72 inches.

Ground Water Contribution.
In areas of high natural ground water, the irrigation requirement may be materially less than if ground water were not available. However, if the high ground water is the result of excess irrigation, the overall demand on the irrigation supply by the crops is not decreased. In such a case, part of the irrigation is obtained by underground methods. As an example, studies in San Fernando Valley in Southern California indicated a consumptive use of water by alfalfa of 37 inches during the irrigation season. In areas of high water table in this valley, only 24 inches of surface irrigation water was required to produce a good yield of alfalfa. The additional 13 inches came from underground water supplies and a small amount of summer precipitation. As with carryover soil moisture, the contribution of ground water to seasonal water requirements is difficult to estimate.

Net Field Irrigation Requirements.
Net field irrigation water requirements for any period of time are estimated by subtracting from potential consumptive and other uses that moisture that is supplied by one or more of the three natural sources previously mentioned.

As previously stated, the effective rainfall studies were made by using the daily soil moisture balance method in which a balance is computed for each day by subtracting consumptive use and adding effective rainfall and/or irrigation to the previous day's balance. In using this method, daily balances are calculated from an assumed soil moisture level at the beginning of the growing season. In these studies, it was assumed that this level was field capacity. In using figure 3 or table 6 to determine net irrigation water requirements, an estimate of anticipated soil moisture conditions at the start of the growing season must be made. The depth of water, if any, required to bring the moisture level in the soil profile up to field capacity must be added to the irrigation water requirements obtained from the use of figure 3 or table 6.

Sample Calculation No. 4 illustrates the procedure for estimating both average net irrigation requirements and those net requirements than can be expected to be equaled or exceeded in two out of ten years using a crop of corn grown in an area near Raleigh, North Carolina. In this case it has been assumed that winter precipitation will bring the soil moisture level up to field capacity and provide 2.0 inches of carryover soil moisture. This 2.0 inches represents the amount of moisture between the 50 percent level and field capacity and is also equivalent to the net depth of application. It has been assumed that each farmer in a project starts irrigating when the soil moisture reaches the 50 percent level and applies enough water to bring the moisture level up to field capacity. Then, at any given time the average soil moisture level over the entire project area will approximate 75 percent. The amount of moisture between the 50 and 75 percent levels (equivalent to one-half the net depth of application or 1.00 inch in this case) has been carried over from month to month and finally consumed at the end of the growing season as shown in the calculation. This leaves the moisture in the soil profile at approximately the 50 percent level at that time. The procedure for estimating gross irrigation requirements is also illustrated.

Sample Calculation No. 5 illustrates the same procedures using a crop of alfalfa grown in an area near Denver, Colorado. In this instance it has been assumed that winter precipitation will provide 2.0 inches of carryover soil moisture and that a net pre-irrigation of 2.2 inches will be needed to bring the soil moisture level up to field capacity. The sum of the carryover moisture and the pre-irrigation, or 4.2 inches, is the net depth of application. As in the previous calculation, one-half the net depth of application or 2.1 inches has been carried through the growing season and used at its end.

<u>Field Application Efficiencies.</u>
Due to unavoidable losses, no field application of irrigation water can ever be 100 percent efficient. Thus more water than is needed to satisfy net irrigation requirements must be applied. A reasonably accurate estimate of field application efficiencies must therefore be made in order to estimate gross field irrigation requirements.

Application losses include evaporation, deep percolation, and surface runoff. The extent of such losses will depend on a number of different factors. The principal ones are discussed in succeeding paragraphs.

Intake characteristics of soils.--In general, considerable loss of water due to deep percolation may be expected when coarse-textured soils with high intake rates are irrigated by surface methods. On the other hand, when fine-textured soils with very low intake rates are irrigated by these methods, considerable losses will occur in the form of excess surface runoff. In either case, field application efficiencies are adversely affected.

Variations in soil intake rates are also a factor in lowering application efficiencies. The intake rate of most soils on which a rotation of crops is grown will vary widely both throughout the growing season and from year to year within the rotation period. Unless considerable flexibility is designed into the irrigation system and the irrigator has the skill required to adjust stream sizes to these changing intake rates, field application efficiences will be materially lowered.

Topography.--It is more difficult to control the flow of water on sloping land than it is on level or near-level land. When relatively steep slopes are irrigated by either of the furrow, corrugation, border or contour ditch methods, excessive surface runoff can be expected where enough water is applied to meet crop requirements. Highest application efficiencies are attained where the land is nearly level and all irregularities are removed by land leveling.

Where fields are subirrigated, the difficulty in maintaining a water table approximately parallel to the land surface increased rapidly as

SAMPLE CALCULATION NO. 4

Estimate of monthly and seasonal irrigation requirements
by
Corn at Raleigh, North Carolina

(1) Month	(2) Average Monthly Cons. Use, u. Inches	(3) Mean Monthly Rainfall, r_t Inches	(4) Average Monthly Effective Rainfall r_e, Inches	(5) Average Carryover Soil Moisture Inches	(6) Average Net Irrig. Requirement i_n, Inches	(7) Estimated Field Appl. Efficiency Percent	(8) Average Gross Irrig. Requirement i_g, Inches	(9) 80% Chance Monthly Rainfall, r_t, Inches	(10) 80% Chance Monthly Effective Rainfall r_e, Inches	(11) 80% Chance Carry-over Soil Moisture, Inches	(12) 20% Chance Net Irrig. Require. i_n Inches	(13) 20% Chance Gross Irrig. Require. i_g, Inches
				2.00						2.00		
Apr. 20	0.70	1.20	0.67		None	70	None	0.94	0.54		None	None
				1.97						1.84		
May	3.52	3.62	2.19		0.36	70	0.51	2.83	1.76		0.92	1.31
				1.00						1.00		
June	7.84	4.05	3.07		4.77	70	6.81	3.17	2.48		5.36	7.66
				1.00						1.00		
July	8.79	5.85	4.45		4.34	70	6.20	4.58	3.60		5.19	7.41
				1.00						1.00		
Aug. 18	4.10	3.15	2.20		0.90		1.29	2.47	1.78		1.32	1.89
				0.00						0.00		
Season Totals	24.95	17.87	12.58	2.00	10.37	70	14.81	13.99	10.16	2.00	12.79	18.27

Note: Explanation of column headings appears on the reverse side of this page.

EXPLANATION OF COLUMN HEADINGS - SAMPLE CALCULATION NO. 4

(2) Consumptive-use values shown in this column are taken from Sample Calculation No. 1, column 11.

(3) Mean monthly rainfall values are taken from Weather records.

(4) Values of monthly effective rainfall are obtained by using the values shown in columns 2 and 3 together with table 6 (using a 2.0-inch net depth of application for corn at Raleigh, N.C.). Values in table 6 are for whole months only. To obtain a value for a part of a month, the values shown in columns 2 and 3 must first be converted proportionately to whole month values and table 6 then used to obtain effective rainfall for the entire month. This latter value is then converted back proportionately to obtain the effective rainfall for the actual number of days involved.

(5) Carryover soil moisture must be estimated. In this case it is assumed the winter rains will bring the soil profile up to field capacity, thus the amount of carryover soil moisture will be equal to the net depth of application or 2.0 inches. On an average, one-half of this carryover soil moisture will be consumptively used before irrigation is started and one-half will be carried over for use at the end of the growing season.

(6) The average net irrigation requirement for any month is obtained by subtracting the sum of the values shown in columns 4 and 5 from the value shown in column 2.

(7) Values of obtainable field application efficiencies are taken from the conservation irrigation guide covering the area concerned.

(8) Gross irrigation requirements are obtained by dividing the values shown in column 6 by those shown in column 7.

(9) Values of monthly rainfall for any frequency of occurrence are obtained by first plotting a rainfall frequency distribution curve (see curve for Raleigh, N. C., figure 4) and then obtaining from the curve the value of the growing season rainfall for the desired frequency of occurrence, in this case 8 out of 10 years. This latter value divided by the average growing season rainfall will give a percentage factor which, when applied to the values shown in column 3, will give the values of monthly rainfall shown in column 9 on a frequency basis.

(10) The values of monthly effective rainfall shown in this column are obtained by using the values shown in columns 2 and 9 together with table 6. See explanation of column 4.

(11) See explanation of column 5.

(12) The net irrigation requirements for any month are obtained by subtracting the sum of the values shown in columns 10 and 11 from the value shown in column 2.

(13) Gross irrigation requirements are obtained by dividing the values shown in column 12 by those shown in column 7.

SAMPLE CALCULATION NO. 5

Estimate of monthly and seasonal irrigation requirements

Alfalfa at Denver, Colorado

(1) Month	(2) Average Monthly Cons. Use, u. Inches	(3) Mean Monthly Rainfall, rt Inches	(4) Average Monthly Effective Rainfall re, Inches	(5) Average Carryover Soil Moisture Inches	(6) Average Net Irrig. Requirement in, Inches	(7) Estimated Field Appl. Efficiency Percent	(8) Average Gross Irrig. Requirement ig, Inches	(9) 80% Chance Monthly Rainfall, rt Inches	(10) 80% Chance Monthly Effective Rainfall re, Inches	(11) 80% Chance Carryover Soil Moisture Inches	(12) 20% Chance Net Irrig. Require. in, Inches	(13) 20% Chance Gross Irrig. Require. ig, Inches
				2.00						2.00		
Pre-Irrigation					2.20	75	2.93				2.20	2.93
				4.20						4.20		
Apr. 24	0.57	0.49	0.33		None	75	None	0.34	0.24		None	None
				3.96						3.86		
May	3.99	2.70	1.91		0.22	75	0.29	1.87	1.37		0.86	1.15
				2.10						2.10		
June	6.36	1.44	1.23		5.13	75	6.84	1.00	0.87		5.49	7.32
				2.10						2.10		
July	7.80	1.53	1.41		6.39	75	8.52	1.06	1.00		6.80	9.07
				2.10						2.10		
Aug.	6.66	1.28	1.11		5.55	75	7.40	0.89	0.78		5.88	7.84
				2.10						2.10		
Sept.	4.00	1.13	0.85		2.38	75	3.18	0.78	0.59		2.82	3.76
				1.33						1.51		
Oct. 25	1.89	0.81	0.56		--			0.56	0.38		--	
				0.00						0.00		
Season Totals	31.27	9.38	7.40	2.00	21.87	75	29.16	6.50	5.23	2.00	24.05	32.07

Note: Explanation of column headings appears on the reverse side of this page.

EXPLANATION OF COLUMN HEADINGS - SAMPLE CALCULATION NO. 5

(2) Consumptive-use values shown in this column are taken from Sample Calculation No. 2, Column 10.

(3) Mean monthly rainfall values are taken from Weather Bureau records.

(4) Values of monthly effective rainfall are obtained by using the values shown in columns 2 and 3 together with table 6 (using a 4.2-inch net depth of application for alfalfa at Denver, Colorado). Values in table 6 are for whole months only. To obtain a value for a part of a month, the values shown in columns 2 and 3 must first be converted proportionately to whole month values and table 6 then used to obtain effective rainfall for the entire month. This latter value is then converted back proportionately to obtain the effective rainfall for the actual number of days involved.

(5) In this case it is assumed that there is a 2.0-inch soil-moisture carryover and that a 2.2-inch net irrigation will be required to bring the moisture level in the profile up to field capacity. The sum of these, or 4.2 inches, will equal the net depth of application and is treated as carryover moisture in the calculations. On the average, one-half of this carryover soil moisture will be consumptively used before irrigation is started and one-half will be carried over for use at the end of the growing season.

(6) The average net irrigation requirement for any month is obtained by subtracting the sum of the values shown in columns 4 and 5 from the value shown in column 2.

(7) Values of obtainable field application efficiencies are taken from the conservation irrigation guide covering the area concerned.

(8) Gross irrigation requirements are obtained by dividing the values shown in column 6 by those shown in column 7.

(9) Values of monthly rainfall for any frequency of occurrence are obtained by first plotting a rainfall frequency distribution curve (see curve for Denver, Colorado, figure 4) and then obtaining from the curve the value of the growing season rainfall for the desired frequency of occurrence, in this case 8 out of 10 years. This latter value divided by the average growing season rainfall will give a percentage factor which, when applied to the values shown in column 3, will give the values of monthly rainfall shown in column 9 on a frequency basis.

(10) The values of monthly effective rainfall shown in this column are obtained by using the values shown in columns 2 and 9 together with table 6. See explanation of column 4.

(11) See explanation of column 5.

(12) The net irrigation requirements for any month are obtained by subtracting the sum of the values shown in columns 10 and 11 from the value shown in column 2.

(13) Gross irrigation requirements are obtained by dividing the values shown in column 12 by those shown in column 7.

slopes increase above one-half percent.

Climate.--In arid and semi-arid areas where air temperatures and wind velocities are high, appreciable losses may be expected from the resulting evaporation. These tend to lower application efficiencies of all methods of irrigation except subirrigation. Sprinkler irrigation is particularly affected. High wind velocities so distort the distribution pattern that high application efficiencies are not attainable.

Net depth of irrigation.--The amount of water applied at one irrigation and stored in the soil profile for plant use will affect the application efficiency with some methods of irrigation. In the case of sprinklers, for example, the water retained on the plant foliage and that evaporated from the ground surface while sprinkling is in process will be approximately the same regardless of the depth of application. Thus these losses will be greater percentage-wise for light applications. In the case of graded furrows or corrugations, the amount of water lost to deep percolation will be approximately equal for both light and heavy applications. Generally speaking, then, with these methods, lighter applications will be made at lower efficiencies than will heavier applications.

Irrigation methods.--Relatively high application efficiencies can be attained by most methods of irrigation where the soils, topographic, and climatic conditions are favorable. However, for any given set of conditions, usually a higher application efficiency can be attained with one method than can be attained with another. For example, a close-growing crop on a near-level field where wind velocities exceed 15 miles per hour could be irrigated by the border method with a high application efficiency. Under the same conditions a sprinkler system would have a much lower application efficiency. If the same crop were to be irrigated on a sloping field with relatively calm wind conditions, the sprinkler system would prove to be more efficient. Thus in order to attain a high application efficiency, it is important that the most adaptable method of irrigation be selected.

Adequacy of system design and installation.--In order to attain a high application efficiency, any irrigation system, regardless of method, must be adequately designed and properly installed. The system must include all structures and other devices necessary for controlling the irrigation stream. The extent to which this is accomplished will, in large measure, determine the application efficiency that can be reached.

Skill of the irrigator.--A most important factor influencing field application efficiency is the skill of the irrigator and his interest in using that skill to practice good water management. All of the influential factors mentioned above may be favorable but, unless the irrigator operates the system according to plan, applying water as needed by the crop and at a rate commensurate with the soil intake rate, a high application efficiency will not be attained.

Tailwater recovery systems.--In some instances where the graded furrow and border methods of irrigation are used, relatively large percentages of surface runoff cannot be avoided due to low soil intake rates. In such cases, field application efficiencies are low. Approximately 50 to 65 percent of these losses can be recovered, however, for re-use where tailwater recovery systems are installed. These are systems whereby the runoff from graded furrow and border systems is collected and either pumped back for re-use on the same field or allowed to flow by gravity onto other fields of lower elevation. The use of such a system will materially increase the overall application efficiency on the farm.

Estimating field application efficiencies.--After all of the aforementioned influential factors have been given due consideration, field application efficiencies may best be estimated by referring to that chapter of Section 15 of the SCS National Engineering Handbook covering the specific method of irrigation contemplated or by referring to applicable local irrigation guides.

Gross field irrigation requirements.--Sample Calculations Nos. 4 and 5 also illustrate the procedure involved in estimating gross field irrigation requirements. To determine average gross requirements, the average net requirements shown in column 6 are divided by the estimated field application efficiency shown in column 7. To determine the gross field requirements that can be expected to be equaled or exceeded 20 percent of the time, the 20 percent net requirements shown in column 12 are divided by the same estimated field application efficiency shown in column 7.

Requirements for Related Purposes

In irrigated agriculture, there are occasions where water is needed for purposes other than irrigation but where irrigation systems must be used to apply the water. Where water is used for these additional purposes, their annual requirements must be estimated and added to those for irrigation. Water requirements for the more important of these related purposes are discussed in succeeding paragraphs.

Leaching Requirements

The removal of harmful soluble salts from the crop root zone is essential in irrigated soils if sustained high crop production is to be maintained. Without removal, salts accumulate in direct proportion to the salt content of the irrigation water and the depth of water applied. The concentration of the salts in the soil solution results principally from the extraction of moisture from the soil by the processes of evaporation and transpiration. Such salt concentrations can only be removed by passing enough water through the soil profile to dissolve the harmful soluble salts and transport them, by the downward movement of the water, out of or beyond the crop root zone. This process is known as leaching.

Physical characteristics of the soil profile, particularly the degree of drainage, sometimes place a restriction on the practice of leaching. Unless drainage is adequate, attempts at leaching may not be successful for the reason that leaching requires the unrestricted passage of water through and out of the root zone. Where drainage is inadequate, water applied for leaching may cause the water table to rise so that soluble salts will quickly return to the root zone. Thus saline waters should not be used on soils with restricted internal drainage.

In humid and subhumid areas (mean annual rainfall exceeding 30 inches), salt-free water is usually passed through the soil profile naturally in sufficient quantities to dissolve and remove salt accumulations and thus leaching is seldom required. In arid and semiarid areas, rainfall may be insufficient to accomplish this purpose and water in excess of crop needs must be applied through irrigation systems. Where leaching is required, the problem is to determine the depth of water, in excess of crop needs, that must be applied annually to maintain the salt content at a level that will assure sustained crop production.

The annual leaching requirement may be defined as that depth of irrigation water in excess of crop needs that must be passed annually through the root zone to control soil salinity at any specified acceptable level. The leaching requirement will depend upon the salt concentration of the irrigation water and upon the maximum concentration permissible in the soil solution for the crop being irrigated. The maximum concentration, except for salt crusts formed by surface evaporation, will occur at the bottom of the root zone and will be the same as the concentration of the drainage water from a soil where irrigation water is applied with areal uniformity and with no excess leaching.

The maximum salt concentration that is permissible for a given crop is an indicator of the relative salt tolerance of that crop and is expressed in terms of electrical conductivity or millimhos per centimeter. The relative tolerance of crop plants to salt may be taken from table 8. The salt-tolerance lists are arranged according to major crop divisions and, in each division, crops are listed in three groups. Within each group, the crops are listed in the order of decreasing salt tolerance. For example, for field crops with medium salt tolerance, EC_{dw} values of 10 mmhos/cm. occur at the top of the column and 6 mmhos/cm. at the bottom. This indicates that rye or wheat will tolerate a salt concentration of 10 mmhos/cm. in the lower portion of the root zone while castor beans will tolerate a salt concentration of only 6 mmhos/cm. in the same location. EC_{dw} values having similar significance have been shown for each group of plants for which data are available.

The salt content of the irrigation water is obtained from a chemical analysis in which the amounts of the various salts present are usually expressed in parts per million. Some salts of low solubility, such as magnesium carbonate, calcium carbonate, calcium bicarbonate, and calcium sulphate, are not considered to be harmful. Thus the amounts of

Table 8 - Relative tolerance of crop plants to salt

FRUIT CROPS

High salt tolerance	Medium salt tolerance	Low salt tolerance
Date palm	Pomegranate	Pear
	Fig	Apple
	Olive	Orange
	Grape	Grapefruit
	Cantaloup	Prune
		Plum
		Almond
		Apricot
		Peach
		Strawberry
		Lemon
		Avocado

VEGETABLE CROPS

EC_{dw} = 12 mmhos/cm.	EC_{dw} = 10 mmhos/cm.	EC_{dw} = 4 mmhos/cm.
Garden beets	Tomato	Radish
Kale	Broccoli	Celery
Asparagus	Cabbage	Green beans
Spinach	Bell pepper	
	Califlower	
	Lettuce	
	Sweet corn	
	Potatoes (White Rose)	
	Carrot	
	Onion	
	Peas	
	Squash	
	Cucumber	
EC_{dw} = 10 mmhos/cm.	EC_{dw} = 4 mmhos/cm.	EC_{dw} = 3 mmhos/cm.

FORAGE CROPS

High salt tolerance	Medium salt tolerance	Low salt tolerance
EC_{dw} = 18 mmhos/cm.	EC_{dw} = 12 mmhos/cm.	EC_{dw} = 4 mmhos/cm.
Alkali sacaton	White sweetclover	White Dutch clover
Saltgrass	Yellow sweetclover	Meadow foxtail
Nuttall alkaligrass	Perennial ryegrass	Alsike clover
Bermudagrass	Mountain brome	Red clover
Rhodesgrass	Strawberry clover	Ladino clover
Rescuegrass	Dailisgrass	Burnet
Canada wildrye	Sudangrass	
Western wheatgrass	Hubam clover	
Barley (hay)	Alfalfa (California common)	
Bridsfoot trefoil	Tall fescue	
	Rye (hay)	
	Wheat (hay)	
	Oats (hay)	
	Orchardgrass	
	Bluegrama	
	Meadow fescue	
	Reed canary	
	Big trefoil	
	Smooth brome	
	Tall meadow oatgrass	
	Cicer milkvetch	
	Sourclover	
	Sickle milkvetch	
EC_{dw} = 12 mmhos/cm.	EC_{dw} = 4 mmhos/cm.	EC_{dw} = 2 mmhos/cm.

FIELD CROPS

EC_{dw} = 16 mmhos/cm.	EC_{dw} = 10 mmhos/cm.	EC_{dw} = 4 mmhos/cm.
Barley (grain)	Rye (grain)	Field beans
Sugar beet	Wheat (grain)	
Rape	Oats (grain)	
Cotton	Rice	
	Sorghum (grain)	
	Corn (field)	
	Flax	
	Sunflower	
	Castorbeans	
EC_{dw} = 10 mmhos/cm	EC_{dw} = 6 mmhos/cm.	

Reference: Agriculture Handbook No. 60, Diagnosis and Improvement of Saline and Alkali Soils, February 1954.

these salts should not be considered in arriving at the total harmful salt content of the water. For use in computing leaching requirements the harmful salt content of irrigation water is expressed in terms of electrical conductivity or millimhos per centimeter. To convert to millimhos per centimeter, parts per million are divided by 640.

For estimating annual leaching requirements information is needed on the consumptive use of the crop and that portion of consumptive use that can be expected to be supplied by effective rainfall. The values of average annual consumptive use, U, and average annual effective rainfall, R_e, may be computed as shown in Sample Calculations Nos. 1 and 4. That portion of average annual consumptive use that must be supplied by irrigation water, D_{cw}, or net irrigation requirements, is computed by the formula:

$$D_{cw} \text{ (in inches)} = U - R_e$$

With values of the aforedescribed factors known or estimated, the average net annual leaching requirement may be computed by the following formulas:

$$LR = \frac{D_{iw}EC_{iw}}{(D_{rw} + D_{iw})EC_{dw}}, \text{ and}$$

$$L_n = \frac{U}{1 - LR} - (D_{rw} + D_{cw}), \text{ where:}$$

LR = Leaching requirement expressed as the ratio of the equivalent depth of the drainage water to the depth of irrigation water.

D_{iw} = Depth of irrigation water required in inches to satisfy both consumptive use and leaching requirements.

EC_{iw} = Electrical conductivity of the irrigation water in millimhos per centimeter.

D_{rw} = Depth of rainwater entering the soil profile annually in inches (Equals total average annual precipitation less average annual runoff and evaporation from the soil surface during the non-growing season).

EC_{dw} = Maximum permissible electrical conductivity of the drainage effluent for the crop being irrigation in millimhos per centimeter. (See table 8.)

L_n = Average net annual leaching requirement in inches.

In almost all irrigated areas, some part, however small, of the waters entering the soil profile and used to satisfy consumptive use and leaching requirements is supplied by rainfall. Such waters include both irrigation water, D_{iw}, and rainfall, D_{rw}. To determine D_{rw}, both average annual surface runoff and surface evaporation are deducted from the average annual rainfall, R_a.

The value of average annual runoff will have to be determined locally. Where local information on evaporation from the soil surface is available, it should be used. Where such information is not available, figure 5, Evaporation from Land Areas for Various Temperatures and Rates of Rainfall, may be used to prepare a reasonable estimate. Some care and judgment must be exercised in the use of figure 5. While the chart is based on average soil and climatic conditions existing in the upper Midwest, it can and has been used successfully in other regions of the United States by applying suitable coefficients reflecting differences in humidity, character of the soil, type of vegetal cover and topography. The coefficients normally used vary from a low of 9.6 for areas having rapidly permeable soils and high humidity to 1.2 for relatively flat areas having slowly permeable soils and low humidity.

Since, for all practical purposes, the electrical conductivity of rain water is zero, a weighted average of the electrical conductivity of all of these waters entering the soil profile must be used. This necessitates the use of a trial and adjustment procedure to determine the average annual net leaching requirement, L_n. Such trial and adjustment procedure is illustrated in Sample Calculation No. 6.

Since it is impossible to obtain total areal uniformity in distribution of the leaching water by whatever method is used, the field application efficiency, E, must be considered in determining the average annual gross leaching requirement, L_g. Field application efficiencies, as discussed in preceding paragraphs, should be taken from applicable chapters of Section 15 of the SCS National Engineering Handbook or from local irrigation guides.

$$L_g = \frac{L_n}{E}$$

Sample Calculation No. 6 has been prepared to illustrate the procedure for estimating average annual gross leaching requirements. For further information on the subject of leaching, the reader is referred to Agriculture Handbook No. 60, Diagnosis and Improvement of Saline and Alkali Soils, U. S. Department of Agriculture, February 1954.

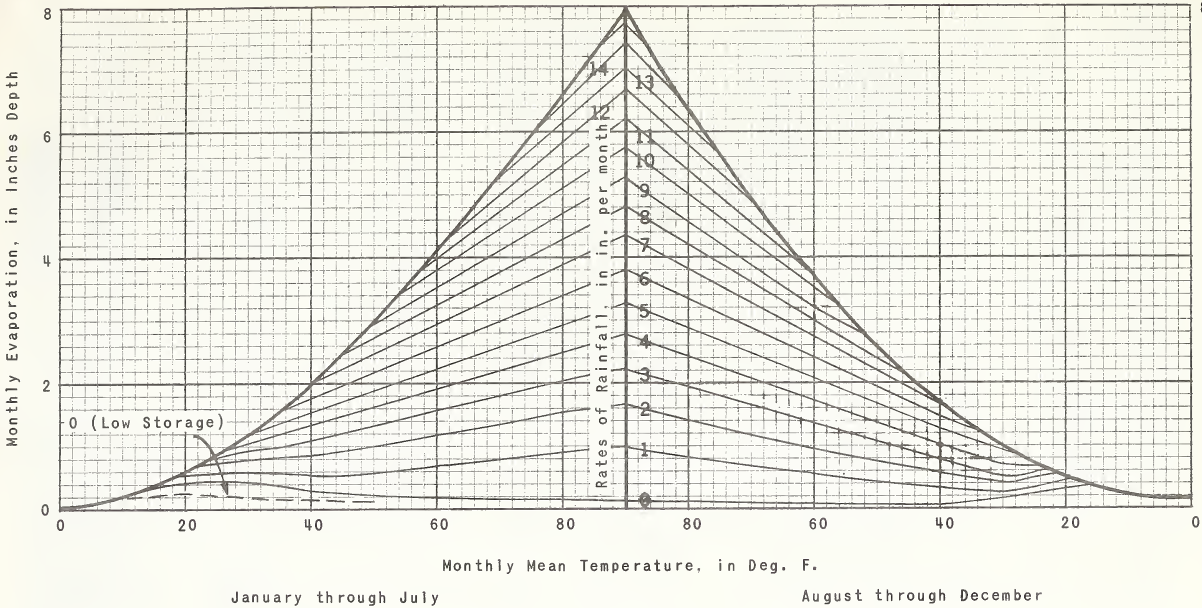


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Figure 5 - Evaporation from land areas for various temperatures and rates of rainfall

SAMPLE CALCULATION NO. 6

Estimate of Leaching Requirement for Grain Sorghum
at
Fort Stockton, Texas

Given:

Grain sorghum irrigated by the furrow method at Fort Stockton, Texas.

Seasonal consumptive use	U	=	23.9 inches
Average annual rainfall	R_a	=	14.9 inches
Average growing season rainfall	R_t	=	8.6 inches
Average growing season effective rainfall	R_e	=	6.7 inches
Average annual surface runoff		=	0.8 inches
Field application efficiency	E	=	75 percent
Harmful salt content of irrigation water		=	2,050 p.p.m.

Find:

The average annual gross leaching requirement that will maintain the salt content of the soil solution at a level that will permit the sustained successful growth of grain sorghum.

Calculation:

First find D_{cw}, that portion of consumptive use that must be supplied by irrigation.

$$D_{cw} = U - R_e = 23.9 - 6.7 = 17.2 \text{ inches}$$

From table 8, note that the maximum permissible electrical conductivity of the saturation extract for grain sorghum, EC_{dw}, is 8.0 millimhos per centimeter.

Calculate the electrical conductivity of the available irrigation water, EC_{iw}, to be:

$$\frac{\text{2050 parts per million}}{\text{640 (a constant)}} = \text{3.2 millimhos per centimeter}$$

Next, determine the average depth of rainwater entering the soil profile annually, D_{rw}, as follows:

Average annual rainfall	R_a =	14.9 inches
Less average annual runoff	=	0.8 inches
Less surface evaporation in non-growing season (from figure 5)	=	4.9 inches
D_{rw}	=	9.2 inches

Next, assume that no irrigation water is to be added for leaching purposes and compute the leaching requirement ratio, LR.

$$LR = \frac{D_{iw}EC_{iw}}{(D_{rw} + D_{iw})EC_{dw}} = \frac{17.2 \times 3.2}{(9.2 + 17.2)8.0} = .261$$

Now compute the average annual net leaching requirement, L_n, as shown:

$$L_n + \frac{U}{1 - LR} - (D_{rw} + D_{cw}) = \frac{23.9}{1 - .261} - (9.2 + 17.2) = 5.9 \text{ inches}$$

Thus it becomes obvious from these calculations that more than 5.9 inches of irrigation water will have to be added for leaching purposes.

Next assume that 10.0 inches of irrigation water are to be added and repeat the above calculations.

$$LR = \frac{27.2 \times 3.2}{(9.2 + 27.2)8.0} = .299$$

$$L_n = \frac{23.9}{1 - .299} - (9.2 + 17.2) = 7.7 \text{ inches}$$

Thus it is obvious that there is no need to add as much as 10.0 inches of irrigation water for leaching purposes. The required value of L_n will lie between 5.9 and 7.7 inches and can be determined by interpolation as follows:

$$\frac{L_n}{L_n - 5.9} = \frac{10.0}{7.7 - 5.9}$$

$$1.8\, L_n = 10\, L_n - 59.0$$

$$-8.2\, L_n = -59.0$$

$$L_n = \frac{59.0}{8.2} = 7.2 \text{ inches}$$

The average annual gross leaching requirement is equal to the net requirement divided by the field application efficiency, or,

$$L_g = \frac{L_n}{E} = \frac{7.2}{.75} = 9.6 \text{ inches}$$

Requirements for Protection Against Sub-Freezing Temperatures

Growing crops may be protected against sub-freezing temperatures by a number of means, however, when water is used it is usually applied through sprinkler irrigation systems. The sprinkler heads are small and widely spaced resulting in a low application rate, usually from 0.10 to 0.20 inch per hour. The systems are usually turned on in the late afternoon or evening when the temperature at plant level drops to 34 degrees F. Sprinkling is continuous until the ice melts from the plants the next day.

Sprinkling utilizes the latent heat of fusion released when water changes from a liquid to a solid state. Sprinklers discharge water in small droplets and the latent heat of fusion is released when the water freezes on plant or tree surfaces. Theoretically, the heat thus released maintains ice temperatures around 32 degrees F. and the ice acts as a buffer against cooling of plant surfaces by radiation or contact with the cold air. This theory is valid and the process is effective as long <u>and only so long</u> as the water application and subsequent ice formation continues.

A word of caution seems appropriate here. The sprinkling process becomes ineffective when a combination of extremely low temperatures (below 20 degrees F.), low humidity, and strong winds prevail. Entire groves of citrus trees have been lost in Florida when sprinkling was undertaken under these conditions.

The amount of water, expressed in acre-inches per acre, that should be made available annually for protection against freeze damage will depend on the design application rate of the sprinkler system and the total number of hours during the growing season in which the temperature may be expected to remain below 34 degrees F. The total expected seasonal hours of operation should be determined on a frequency basis using the maximum number that can be expected to occur once in 10 or once in 20 years.

Local records of temperatures taken at plant level should be analyzed where such records are available. The only alternative is to make an analysis of available Weather Bureau records. These are not too satisfactory since the Bureau measurements are not generally taken at plant level. However, the Bureau temperatures are consistently lower than those that would prevail at plant level; thus the resulting volume calculations would result in the provision of a water supply somewhat in excess of actual needs.

The volume of water that should be made available annually can be estimated by the formula:

$$\text{Vol.} = IH, \text{ where,}$$

- Vol. is the volume of water to be made available in acre inches per acre
- I is the design sprinkler application rate
- H is the total expected number of operating hours per season based on some predetermined frequency of occurrence.

Where it is desirable to express the water requirement as a rate rather than a volume, the rate of flow that should be made available is estimated as follows:

Q in gallons per minute per acre = 453I

Conveyance Losses

It has been estimated that, in the western states, from one-third to one-half of the water diverted for irrigation purposes is lost between the source and the point of use. A large percentage of this water is lost in conveyance. These losses may be incurred both on the farm and in project facilities. Conveyance losses result primarily from three causes: (1) seepage in ditches, canals and pipelines, (2) leakage through and around headgates and other structures, and (3) consumptive use by phreatophytes. Some loss in conveyance is unavoidable, however, losses may be greatly reduced by lining earth ditches and canals, wholly or in part, by repairing and maintaining pipelines, headgates and other structures, and by destroying or removing phreatophytes in the vicinity of canals. In any case, losses in conveyance facilities must be measured or estimated and the results must be considered in any estimate of annual irrigation water requirements.

It is the purpose of this release to discuss the factors contributing to these losses and to present methods of measuring them in existing facilities and estimating them in proposed facilities.

Seepage Losses in Unlined Canals

Factors affecting seepage losses.--Seepage takes place under the combined influence of the forces of gravity and the soil moisture-tension gradient. When water is first turned into a dry canal the force of the moisture-tension gradient may exceed that of gravity, however as the soil approaches saturation the force arising from it becomes small. Consequently the canal may, at first, loose a large amount of water, not only by the percolation of water through the pores in the soil under the action of gravity but also by moisture-tension gradients. The loss due to the latter soon decreases, however, and is overshadowed by that caused by percolation. The force associated with the tension gradient may act in any direction and may cause the soil water to rise above the water surface in the canal. Frequently it carries water upward to the root zone of plants or to the soil surface. Then, water is lost through the transpiration of plants or through evaporation from the soil. Such losses are generally small in comparison with the overall seepage losses from canals.

The factors most important in determining rate of seepage is the permeability of the material forming the bed of the canal. Permeability is a porous medium's capacity for transmitting water. It is influenced both by pore size and by percentage of pore space, or porosity, but as pore size decreases permeability decreases in approximately the same ratio as the square of pore diameter. This is the reason for the relative imperviousness of clays, which have high porosity but very small pore diameter. Soils consisting of a mixture of gravel and clay are almost completely impervious. The permeability of gravel depends on the size and the size gradation of the gravel particles. Gravel with a good range of particle sizes and good size distribution is less permeable than gravel of uniform particle size. Laboratory tests by the Geological Survey have shown that coarse gravel may transmit water 450 million times as fast as clayey silt. The wide range of possible seepage losses is apparent from this fact.

Seepage rate is determined in part by the head available to drive the water through the soil. This factor depends not only on the depth of water in the canal but also on the depth to ground water and the nature of the material composing the canal bed. If the ground-water level is above the water surface in the canal, water will seep into the canal from the surrounding area. If it is below the bottom of the canal, the effective head depends on the depth of water in the canal and the length of the soil column required to use up the available head. For intermediate ground-water levels, the effective head is equal to the difference in level between the water table and the water surface in the canal.

If the soil underlying an irrigation canal bed is less permeable than the bed, water lost by seepage spreads laterally as it percolates downward. In more permeable soil, water lost by seepage moves downward as a film of moisture on soil particles in the zone directly beneath the canal. In this case a tension gradient occurs in the unsaturated soil and supplements the force of gravity in causing the downward movement.

Darcy's law may be useful in showing the relationship between these principal factors that affect the seepage rate. According to Darcy, the velocity of flow through water-bearing materials is directly proportional to the head consumed and also to the permeability of the material. In terms of these factors involved in the study of seepage, Darcy's law is expressed by the formula

$$Q = \frac{KhA}{\ell}, \text{ in which}$$

- Q is the quantity lost in unit time
- K is the coefficient of permeability
- h is the total head-producing seepage
- ℓ is the length of the column of material, through which seepage is taking place under the head, h
- A is the wetted area of the canal bed and banks

Darcy's law is generally regarded as unsatisfactory for computing seepage losses due to the difficulty in determining the hydraulic gradient, $\frac{h}{\ell}$, and the permeability for the section of canal under consideration.

There are numerous other factors that are known to affect seepage rates to a lesser degree. Some of these are:

Length of time the canal is in operation
Amount of sediment contained in the canal water
Temperature of the water and the soil
Capillary tension of the soil
Barometric pressure
Salt content of the soil and water
Percentage of entrained air in the soil
Certain biological factors.

Since all the factors acts simultaneously, and some of them tend to counteract each other, it is difficult to segregate the effect of any one of them. Because of the many variables involved and the complexity of their relations, no entirely satisfactory formula for computing seepage losses in canals has ever been developed.

Measuring seepage losses in existing canals.--Currently accepted methods of measuring the quantity of water lost by seepage from existing canals are limited to ponding, inflow-outflow, and seepage meter determination. Each method has its advantages and limitations and no single method is adapted to all conditions encountered in the field.

In normal operation of a canal, evaporation losses are generally considered negligible. The loss of water due to evaporation is small in comparison to the volume carried and usually represents only a fraction of one percent of the flow.

(a) The ponding method requires the measurement of the rate of drop in the water surface of a pool formed in the section of canal being tested. This rate of drop and the ratio of the water surface area of the pool to the wetted area of the section provide the data necessary to compute the seepage loss in cubic feet per square foot of wetted area per 24 hours.

Temporary water-tight dikes or bulkheads are used to isolate a reach of the canal and form the pool to be tested. Staff or hook gages should be used to measure the rate of drop in the pool. To obtain satisfactory results the ponded reach must be selected so as to avoid any inflow or outflow that cannot be accurately measured. Ponding tests are normally suspended during periods of precipitation, however, if they are not, the precipitation must be accurately measured and the results considered in determining the seepage rate.

A modification of the ponding method involves the addition of water to the pond to maintain a constant water surface elevation. The volume of added water is carefully measured and is considered to be equal to the seepage loss. The rate of loss is established by the elapsed time.

The ponding method produces the best results, and measurements obtained with it are generally used as the standard of comparison for seepage measurements obtained otherwise. This method is particularly useful in measuring small seepage losses. However, it has serious disadvantages. Ponding tests can be made only when the canal is not in use. Constructing dikes to form the pools is expensive. Providing water to fill the pools sometimes involves difficulties, particularly when the pools must be filled several times before the seepage rate becomes stabilized. Filling the pools, also, is a problem. If pools are to be filled by pumping, expensive pumps must be installed. For these reasons, the ponding method is not used unless the importance of the tests warrants fairly large expenditures. Furthermore, although the ponding method gives the average seepage from a pool, it does not show the variation in the rates from different parts of the pool.

(b) The inflow-outflow method utilizes flow measurements made at the upstream and downstream ends of the reach of canal being studied. The quantities of water flowing into and out of the reach are carefully measured and the difference is attributed to seepage. The rate of seepage is established by the elapsed time.

Current meters are generally used to measure the flow in large canals. Weirs or Parshall flumes should be used to measure the flow in farm laterals and small ditches. The stage of the canal should be kept constant during the test period in order to eliminate the effect of bank and channel storage. Failure to take account of this factor may introduce large errors into the results. Reaches in which there are few diversions and no appreciable inflow from higher lands should be selected. Diversions should be carefully measured with a weir or Parshall flume. Leaks that cannot be eliminated can best be measured volumetrically with a calibrated can. If the test is made during periods of precipitation, the precipitation must be measured and considered in computing seepage losses.

The inflow-outflow method is best adapted to measuring seepage in long sections of canals in which there are few diversions and in which the rate of seepage is appreciable. It can be used in short sections of canals in which seepage is taking place at a high rate. Inflow-outflow measurements can be made rather easily and do not interfere with the operation of the canal. The results are no better than the accuracy of the measurements and it is difficult to attain a degree of accuracy that will reflect the true losses in the canal.

(c) The falling-head seepage meter measures rates of seepage in small segments of a canal under normal operating conditions. For any reach of canal being tested, readings are taken at several points and the results are averaged.

The field equipment consists essentially of three parts: (1) the seepage bell, (2) the falling-level reservoir, and (3) a device for measuring the rate of all of the water level in the falling-level reservoir. These are shown in figure 6.

The cylinder part of the bell is pushed a small distance into the canal bottom. If the pressure head inside the seepage meter equals that in the canal, the outflow from the meter is a measure of the seepage of that portion of the bottom enclosed by the meter. Thus, the principle of measuring seepage with seepage meters is to maintain a pressure inside the meter that is equal to that outside the meter and to measure, at the same time, the outflow from the meter.

Because of the difficulty in maintaining a head inside the seepage meter that is exactly equal to the head in the canal, a falling-head technique, whereby the seepage meter is connected to a falling-level reservoir is used. Before the seepage is measured, the water level in this reservoir is raised an inch or so above the water surface in the canal. The subsequent fall of the water level in the reservoir is measured by means of a vacuum inverted U-tube manometer which is placed on the canal bank. One leg of the manometer is connected to the seepage meter interior, the other to the free water in the canal. The water level in the manometer tube connected to the seepage meter will fall, whereas that in the tube connected to the free water surface in the canal will rise. At any time, however, the difference between the water levels in the manometer tubes is equal to the pressure difference between the seepage meter and the outside canal, even if the water level in the canal is fluctuating during the time of the measurements.

The field measurements consist of taking time and water-level readings of the water levels in the manometer. From these data, seepage can be calculated graphically or analytically with a falling-head equation. The graphical procedure is the easiest. It consists of plotting the manometer and time readings on graph paper. At the point of intersection of the two resulting curves, the pressure inside the meter equals that outside the canal, and the angle between the curves at their point of intersection can be converted into the seepage from the meter.

If the water surface in the falling-level reservoir is permitted to fall sufficiently long, it will reach an equilibrium position whereby the original outflow from the seepage meter due to seepage is compensated by an inflow component into the seepage meter caused by a lower pressure in the meter than in the canal. This condition has been called the balanced-flow condition. The corresponding pressure difference between the meter and the canal is the balanced-flow differential head.

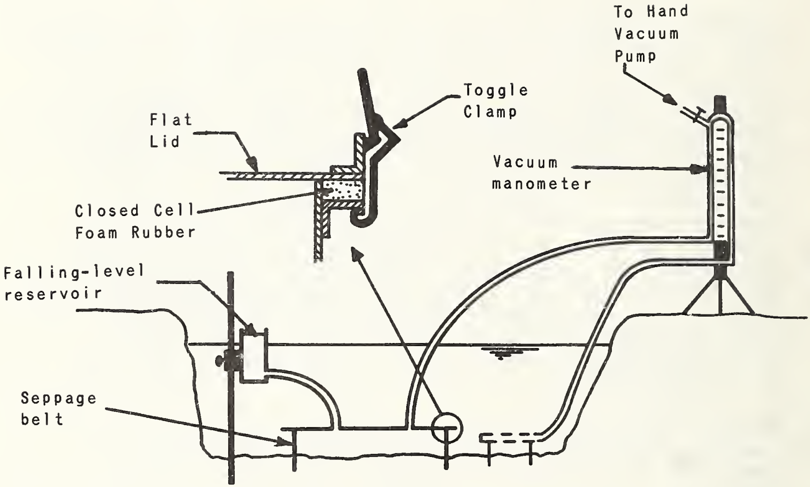


Figure 6 - Sketch of seepage meter equipment in canal

The balanced-flow differential head, which can be measured rapidly in the field by closing the valve between the seepage meter and the falling-level reservoir, is an indication of the seepage gradient in the bottom material below the seepage meter. Since the seepage and the balanced-flow differential head are known, the hydraulic conductivity of the bottom material can be calculated through the aid of dimensionless flow factors which were evaluated with the resistance network analog. Graphs from which those flow factors can be determined for a particular seepage meter installation have been prepared by Bouwer and Rice.1/ The calculation of the hydraulic conductivity of canal bottom material is applicable if the bottom is uniform to rather large depths or if the bottom material is underlain by soil of much higher or much lower hydraulic conductivity. The depth of the material of different conductivity may vary.

Dividing the seepage by the hydraulic conductivity of the bottom material yields the seepage gradient, which can be a clue as to the conditions under which the seepage takes place. Knowledge of seepage gradients may enable one to predict how seepage will react to changes in water depth in the canal or in water table positions in the soil adjacent to the canal.

Falling-head seepage meters have some advantages. They are quickly and easily installed and give reasonably satisfactory results for the conditions existing at the test site. They are particularly useful in locating short reaches of a canal where seepage is excessive and where lining should be considered. Normal procedure is to obtain meter readings only in the bottom of a canal ignoring bank seepage. This can lead to serious errors particularly where there are significant differences in the texture of the bank material and the bed material.

Seepage meters should be installed with the least possible disturbance of the bed material. Because of disturbance of the bed material, the seepage meter usually overregisters if measurements are made immediately after the meter is installed. The meter cannot be used in very gravelly soil, because of the difficulty of forcing the bell into the bed of the canal, and in sandy soil it is likely to be washed away by the current.

Predicting losses in proposed canals.--The usual procedure for predicting seepage losses in canals before they are constructed consists of estimating or measuring the permeability of the soil into which the canal is to be excavated and then using the resulting data as a basis for determining seepage losses. The difficulty in this procedure lies in the fact that no satisfactory formula

1/ Bouwer, Herman and Rice, R. C. - 1963. Use of Seepage Meters in Seepage and Recharge Studies. - Jour. Irr. and Drain. Div. - Am. Soc. Civ. Eng. - Proc. 89:17-42.

for converting permeability rates to rates of seepage has thus far been developed. Permeability rates do serve, however, as satisfactory indicators of whether or not seepage losses in a canal will be excessive and for determining the necessity for lining.

The two most common methods of determining the permeability of canal subgrade materials are the well permeameter method and the laboratory permeability method.

(d) Because seepage is directly proportional to soil permeability, a well permeameter can be used to measure the permeability of the soil along the axis of a proposed canal and thus obtain a basis for predicting the seepage from the canal.

The well permeameter consists of a calibrated supply tank equipped with an indicator glass and an outlet pipe equipped with a float mechanism that controls the water level in the well. The wells in which it is used are holes 4 to 6 inches in diameter and of a depth that varies with the horizon to be tested but must be 10 or more times the radius. The hole is partly filled with highly permeable sand or gravel to reduce erosion and prevent caving, and the upper part, in which the float is to be installed, is cased with screen.

A constant water level, usually corresponding in elevation to the high-water line of the proposed canal is maintained in the hole by the float and valve mechanism. The discharge required to maintain this constant water level is determined from the drop in the water surface in the calibrated tank. Since the loss from the well decreases with time, readings must be taken over a period of days to get the best results. It is important that the well be kept filled continuously during the test, because breaks in the continuity of the data make it difficult to interpret them.

The loss from the well in unit time can be computed from the time interval between observations and the calibrated-tank readings. These data, plotted against elapsed time, show how the rate of loss changes with time. From this information, the diameter of the well, and the depth of water in the well the permeability of the soil is computed, and from this the prospective seepage from a canal in the same soil can be computed. Because the formulas required for these conversions are based on theoretical analyses and electrical-analogy studies, and because various assumptions have to be made that may not be justified by conditions in nature, seepage computations from well-permeameter data cannot be expected to agree closely with seepage rates based on ponding tests. The method, however, is probably accurate enough under favorable conditions for estimating the seepage from proposed canals.

Well permeameters have serious limitations in addition to those already mentioned. They require a considerable supply of water. As the tests must frequently be made in desert areas, far from a source of water, this may be a serious handicap. The tanks must be closely watched to avoid having them go dry, which would spoil the tests. Because each test has to continue for several days, the tanks should be watched 24 hours a day, and enough men to handle day and night shifts should be assigned to the job.

(e) Laboratory tests of the permeability of soil along the line of a proposed canal may be made on samples of either disturbed or undisturbed material. A large soil auger is generally used to collect disturbed samples, which are later dried and pulverized. Undisturbed samples are taken by cutting out cylindrical blocks of the soil. Samples are taken at various depths, so as to include material from the different soil horizons into which the canal would be excavated. The material is placed in a glass or plastic cylinder, according to a definite procedure. Water is allowed to flow through the samples under a definite head, usually for a week or more, and at intervals during this period the rate of flow through the soil is determined. A plot of the rate of flow against elapsed time shows how the rate changes. At first the rate decreases rapidly. After a time, for most soils, it becomes practically constant; for a few soils it may increase. The rate at which the curve starts to flatten out is used for computing permeability. The seepage from the proposed canal is then computed in the same manner as in well-permeameter tests.

Seepage rates based on permeabilities of undisturbed samples should be reasonably accurate if a large number of samples have been tested, although a satisfactory formula for converting permeability into seepage is lacking. The difficulty of obtaining representative samples and of sealing them in the permeameters makes the method time consuming and expensive.

Seepage rates computed on the basis of permeability data for disturbed samples of soil are not accurate. Even though the soil in the sample is otherwise representative of that in the canal bed, the stratification and compaction of the sample after it has been dried, pulverized, and placed in the permeameter for testing may differ widely from those of the soil in its natural state. Permeability computed by use of a disturbed sample is likely to indicate fairly well the fundamental property of the soil, but it may have no relation to the property of the soil under natural conditions.

(f) Measurements made of seepage rates in nearby canals excavated in similar material may be used to estimate seepage losses in proposed canals. Where such measurements are used they should be checked or compared with the estimate of seepage rates obtained by use of one of the two procedures aforementioned.

<u>Seepage Losses in Lined Canals</u>.
Seepage losses in lined canals will depend upon (1) the type of lining used, and (2) the care taken in installing and maintaining the lining.

While no lining is totally impervious, the water losses to seepage through the lining are usually insignificant. Thus seepage losses will depend almost entirely on the state of repair of the lining. When the lining is maintained in a good state of repair, seepage losses may be considered to be negligible. Seepage losses in existing canals may be measured by the ponding method afore-described. Estimates of losses in proposed canals may be made by taking some small arbitrary percentage of the flow.

Seepage Losses in Pipelines.
Losses in pipelines almost always occur at faulty or broken joints. Where pipelines are maintained in a good state of repair, seepage losses may be considered to be negligible.

Leakage Around Gates and Other Structures.
Another type of conveyance loss occurs around gates, turnouts and other structures. These losses can become considerable where structures are improperly designed or installed or are inadequately maintained. However, where well designed structures are adequately maintained, these losses will be insignificant.

Losses to Phreatophytes and Hydrophytes.
On large unlined canals considerable quantities of water may be lost to the consumptive use by phreatophytes and hydrophytes where these water-loving plants are allowed to grow along the canal banks, berms and in adjacent areas.

Phreatophytes are plants that habitually grow where they can send their roots down to the water table or the capillary fringe immediately overlying the water table. They range in size from small natural vegetation to large saltcedar and cottonwood trees. Hydrophytes are plants that live wholly or partly submerged in water, or with roots in saturated soil that is intermittently submerged, such as tules, cattails and other marsh plants.

The moisture requirements of these natural plants are usually satisfied before water becomes available for irrigation or other purposes. Measurements of consumptive use indicate that some water-loving natural vegetation uses from 50 to 100 percent more water than most field crop plants. On projects where moisture use by these plants can be expected to be a significant percentage of the total available water, this use should be considered a conveyance loss and its rates should be estimated on a monthly basis.

Estimates of consumptive use by phreatophytes and hydrophytes may be made by use of the Blaney-Criddle procedure as described in this release or by use of the pan-evaporation method when the relations between the consumptive use of the plant and pan-evaporation values are known. Detailed procedures for making estimates of the consumptive use by these plants are contained in "Consumptive Use and Water Waste by Phreatophytes", by Harry F. Blaney, Proceedings No. 2929, American Society of Civil Engineers, September 1961.

Storage Losses

Storage of water in on-farm irrigation reservoirs may be necessitated by several conditions. Where intermittent streams must be relied upon to provide irrigation water, as is the case in many humid areas, flow in such streams is oftentimes very low or non-existent during the irrigation season. In such cases runoff from the watershed must be stored throughout the year for use during the irrigation season. Where water is received from a project, the delivery schedules to the farm headgate may be such that water is not always received when and in the amount needed to satisfy farm irrigation requirements. Water may be received at rates which are too small to provide an irrigation stream that is adequate to operate the farm irrigation system efficiently. In either case storage reservoirs should be provided. In the latter case the reservoirs are referred to as regulating reservoirs.

Storage of water in project irrigation reservoirs is needed to store water during periods of over-supply for use in periods where the normal supply is inadequate to meet on-farm irrigation requirements. Storage is also needed to provide a satisfactory means of distributing stream flow to the various farms in the enterprise as needed.

When water is stored in a reservoir, either on a farm or in a project, certain unavoidable losses will be incurred. These losses must be considered when estimating either farm or project irrigation requirements. The losses are discussed below.

Seepage Losses in Reservoirs.
The principal factors influencing seepage losses in reservoirs are the permeability and thickness of the soil layers in the ponded area and the total head of water producing seepage. The same difficulties in determining seepage rates as heretofore described for unlined canals are present in the case of determining seepage rates in reservoirs.

Seepage rates in existing reservoirs can be measured by the ponding method. The procedure is similar to that described for unlined canals except that, in the case of reservoirs, evaporation rates must be estimated and subtracted from the total rate of loss. Seepage meters, of the type previously discussed for measuring seepage rates in canals, can also be used for measuring reservoir seepage.

Predicting or estimating seepage loss rates in proposed reservoirs involves primarily a knowledge of the permeability rates of the soils over which water is to be impounded. Permeability rates can be determined by the well permeameter method or the laboratory permeability method as previously described for determining seepage losses in proposed canals. Procedures for determining permeability rates and coefficients are discussed in Chapter 2, Section 8, "Engineering Geology", National Engineering Handbook. The procedure for estimating seepage loss rates is contained in Chapter 9, Section 4, "Hydrology" of the same handbook.

Evaporation Losses in Reservoirs.
Several methods of estimating daily and monthly evaporation rates are presented in Chapter 9, Section 4 of the National Engineering Handbook. Of these, the two procedures most practical for Service use are (1) the use of generalized maps and (2) the relationships of lake evaporation to evaporation from a Class A Weather Bureau pan.

Where the first method is used, the mean annual evaporation value for the area in which the reservoir is located is obtained from Weather Bureau Technical Publication 37. This annual value is broken down into mean monthly values by the application of monthly distribution percentages obtained from Drawing ES-1016, Sheets 2 through 13.

Where more accurate results are desired, the second method can be used. Where data from a Weather Bureau pan that is considered to be representative is available, Drawing ES-1018 may be used to convert pan evaporation to lake evaporation. Data needed in addition to pan evaporation are daily wind movement above the pan, approximate mean sea level elevation, pan water temperature, and air temperature.

Losses to Phreatophytes and Hydrophytes.
Where these water-loving plants are allowed to grow around the banks or in the shallow waters of an irrigation reservoir, their consumptive use may cause a considerable loss of water. Where these plants cannot be eliminated economically, the water lost to their consumptive use should be considered. The method used for estimating the consumptive use by phreatophytes and hydrophytes is the same as that discussed for these losses in canals.

Operational Losses

Operational water losses are created during the delivery of water by sluicing, breaks in the conduits, and diversions or deliveries in excess of demands. Canal operational losses are dependent on conditions of various kinds which may be quite different from project to project.

Water deliveries in excess of the scheduled rate of flow results in excess deliveries to turnouts and spills at wasteways. Also when the demand for water is abruptly decreased due to a general rainfall, water is often discharged from wasteways before the flow in the system can be reduced. These losses are sometimes termed regulatory losses. They are often substantial even for the most efficiently constructed and managed system. On large projects, with normal management, regulatory losses have run from 5 to 30 percent of the diversion amount. On carefully managed projects these losses can usually be held below 10 percent of the diversion.

Gate leakage on large canals is usually not significant, however, as the volume of flow decreases and the number of gates increase this loss may become more meaningful. Estimates of this value will vary widely depending on the type of gates, maintenance program, and the degree of enforcement of closing regulations.

Project Water Requirements

The total water requirements for a project are the summation of (1) the gross field requirements of the crops to be irrigated, (2) the water requirements for related purposes such as leaching or protection against subfreezing temperatures, (3) losses incurred in conveyance of the water, (4) losses incurred when water is stored, (5) losses due to use by phreatophytes, and (6) losses incurred in the operation of the project. These losses, items (3) through (6) may occur either on the farms or within the project or both. This summation, usually prepared on a monthly basis, represents the demand upon the water source, whether the water is diverted from a stream or released from a reservoir or both. Project water requirements are usually expressed in acre feet.

The procedure for estimating project water requirements can best be illustrated by use of an example. Sample Calculation No. 7 is presented for this purpose. In this example a fictional project near Amarillo, Texas has been chosen where water is released from a reservoir to irrigate 9,600 acres of alfalfa, winter wheat and grain sorghum. The problem is to estimate the maximum monthly demand on the reservoir that can be expected to occur once in five years.

SAMPLE CALCULATION NO. 7

Estimate of Project Water Requirements
for a fictional project near

Amarillo, Texas

Given:

Crops to be irrigated are	Alfalfa	1,152 acres
	Winter Wheat	3,840 acres
	Grain Sorghum	4,608 acres

Irrigation is by adapted surface methods.
Estimated field irrigation efficiency 70%

No water is required for related purposes.

On-farm conveyance losses have been determined to be 16%

No on-farm storage is required.

No water is lost on-farm to phreatophytes.

No water is lost on-farm due to operation of the farm systems.

Conveyance losses in unlined project canals have been determined to be 14%

There are no regulating or storage reservoirs in the project (except the main reservoir).

Water losses to phreatophytes in the project are negligible.

Project operation losses have been estimated to be 20%

Find:

The estimated maximum monthly water requirements (demand) to be expected to occur once in five years (20% chance).

Calculation:

First find the 20% chance monthly gross field irrigation requirements for each crop in inches by using the procedures presented in Sample Calculations Nos. 1, 2, 4, and 5. The results are tabulated as shown in columns 2, 3, and 4 of the first of the following tabulation sheets. These requirements are then converted to acre feet for each crop as shown in columns 5, 6, and 7. The total monthly field irrigation requirements for all crops. (Σ columns 5, 6, and 7) are shown in column 8.

Monthly field irrigation requirements are then converted to farm irrigation requirements by considering the 16% on-farm conveyance losses. These farm irrigation requirements are shown in column 3 of the second tabulation sheet.

Finally the monthly farm irrigation requirements are converted to project irrigation requirements by considering both the 14% conveyance losses in project canals and the 20% project operational losses. These monthly project irrigation requirements are shown in column 4.

GROSS FIELD IRRIGATION REQUIREMENTS
for a fictional project near

Amarillo, Texas

Month (1)	20 Percent Chance Gross Field Irrigation Requirements						
	Alfalfa (2)	Winter Wheat (3)	Grain Sorghum (4)	Alfalfa 1,152 Ac. (5)	Winter Wheat 3,840 Ac. (6)	Grain Sorghum 4,608 Ac. (7)	Total All Crops 9,600 Ac. (8)
	inches	inches	inches	acre feet	acre feet	acre feet	acre feet
March	5.71 1/	2.97		548	950		1,498
April		7.06			2,259		2,259
May	3.30	8.26		317	2,643		2,960
June	9.01	5.26	5.71 1/	865	1,683	2,193	4,741
July	10.67		.69	1,024		265	1,289
August	9.07		9.16	871		3,517	4,388
September	5.93		5.41	569		2,077	2,646
October	3.11	5.71 1/	1.89	299	1,827	726	2,852
Annual	46.80	29.26	22.86	4,493	9,362	8,778	22,633

1/ Denotes pre-planting irrigation.

PROJECT IRRIGATION REQUIREMENTS
for a fictional project near

Amarillo, Texas

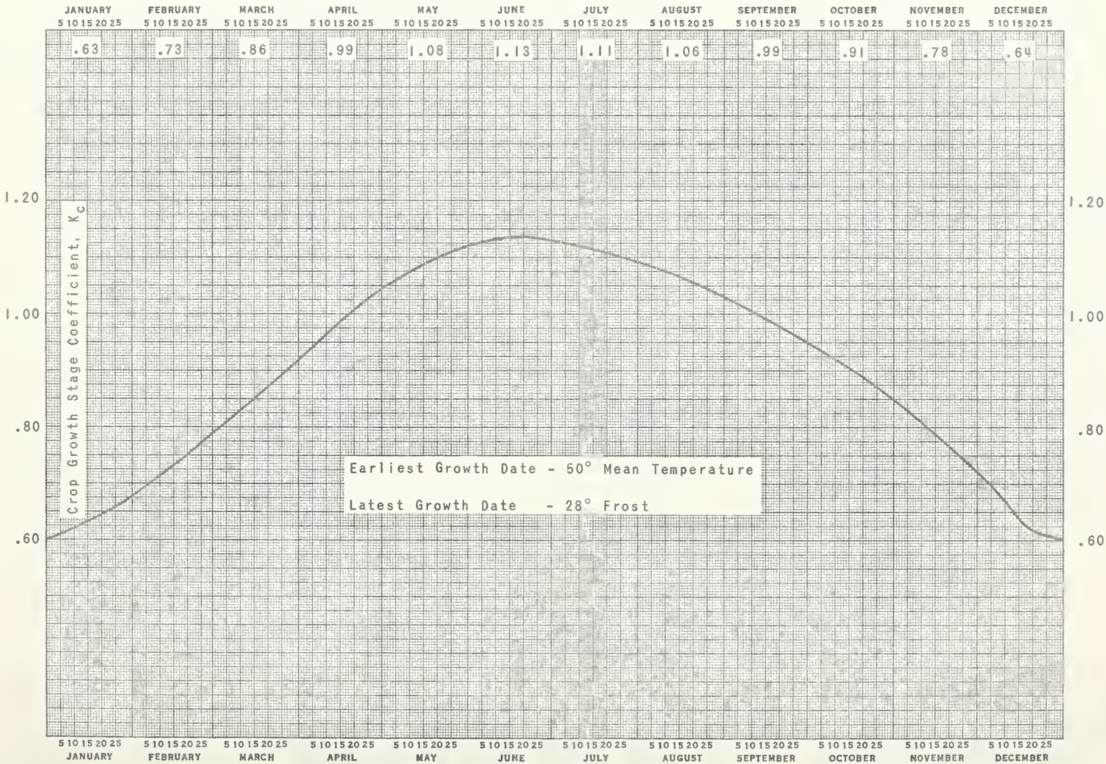
Month (1)	Field Irrigation Requirements (2)	Farm Irrigation 1/ Requirements (3)	Project Irrigation 2/ Requirements (4)
	acre feet	acre feet	acre feet
March	1,498	1,783	2,702
April	2,259	2,689	4,074
May	2,960	3,524	5,339
June	4,741	5,644	8,552
July	1,289	1,535	2,326
August	4,388	5,224	7,915
September	2,646	3,150	4,773
October	2,852	3,395	5,144
Annual	22,633	26,944	40,824

1/ Farm Requirements $= \frac{\text{Field Requirements}}{(1 - 16\% \text{ loss})}$

2/ Project Requirements $= \frac{\text{Farm Requirements}}{(1 - 14\% \text{ loss} - 20\% \text{ loss})}$

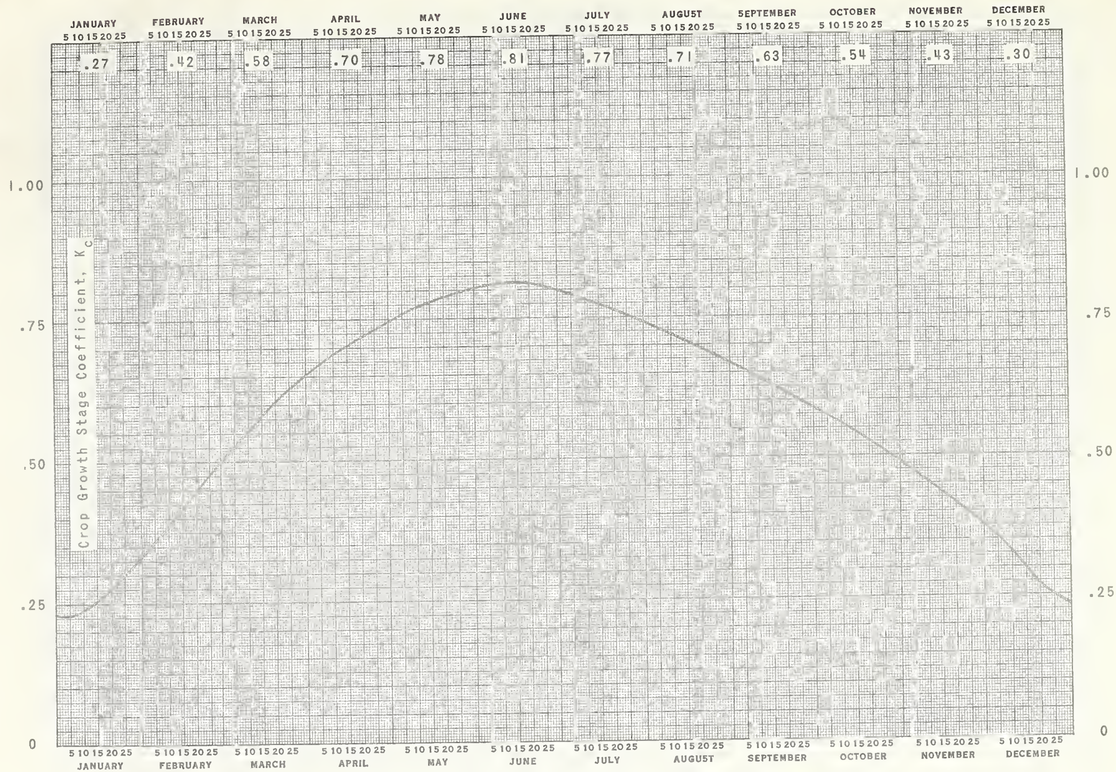
Appendix

List of Crop Growth Stage Coefficient Curves



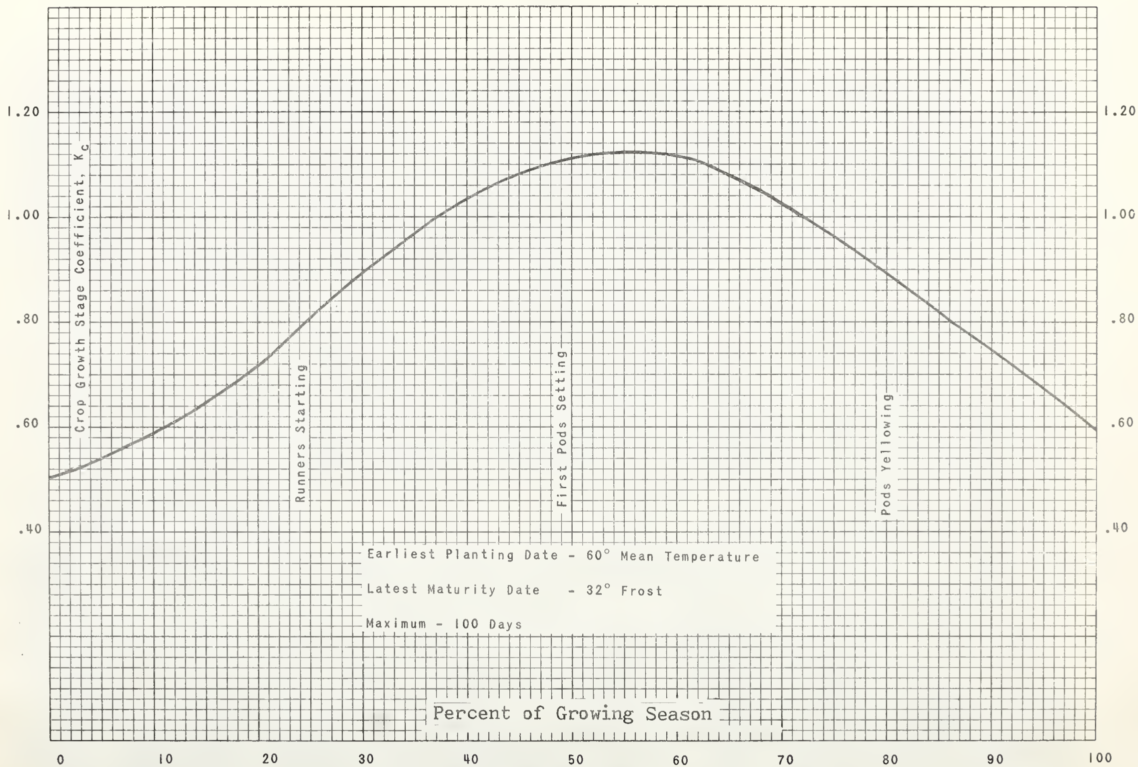
Crop growth stage coefficient curve for alfalfa

Curve No. 2



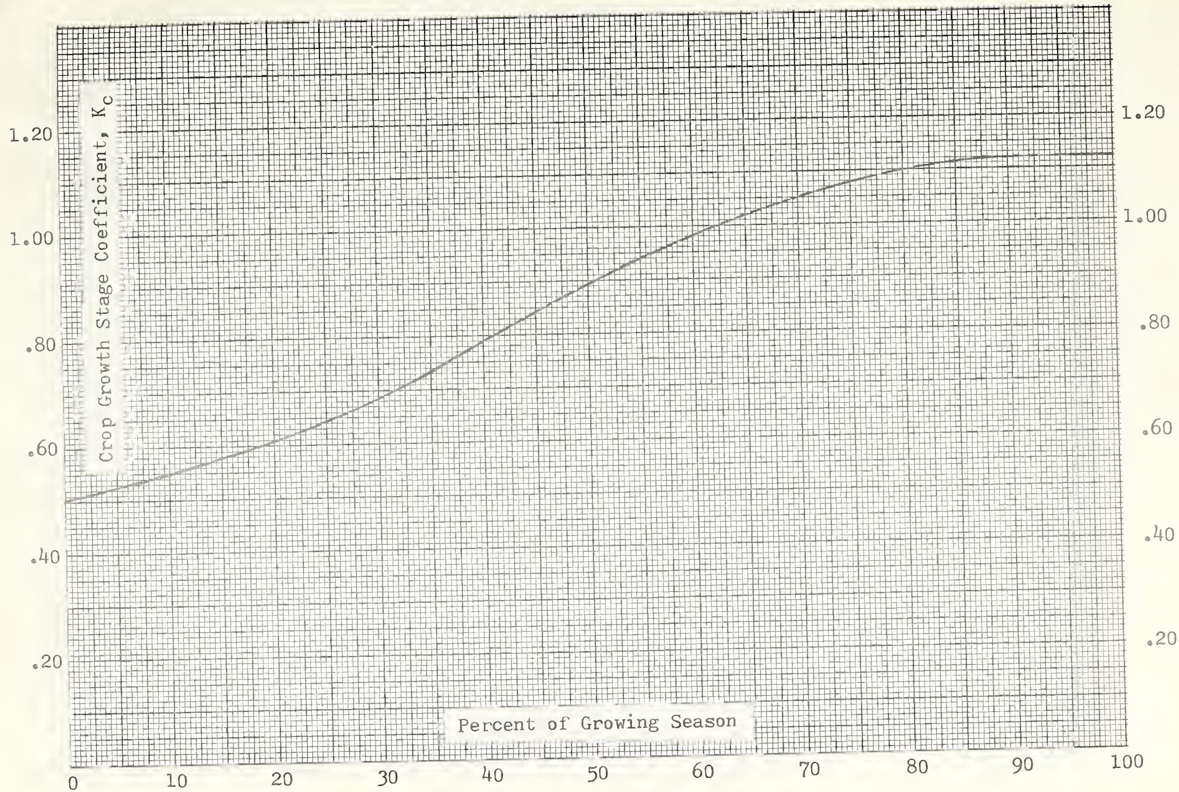
Crop growth stage coefficient curve for avocados

Curve No. 7



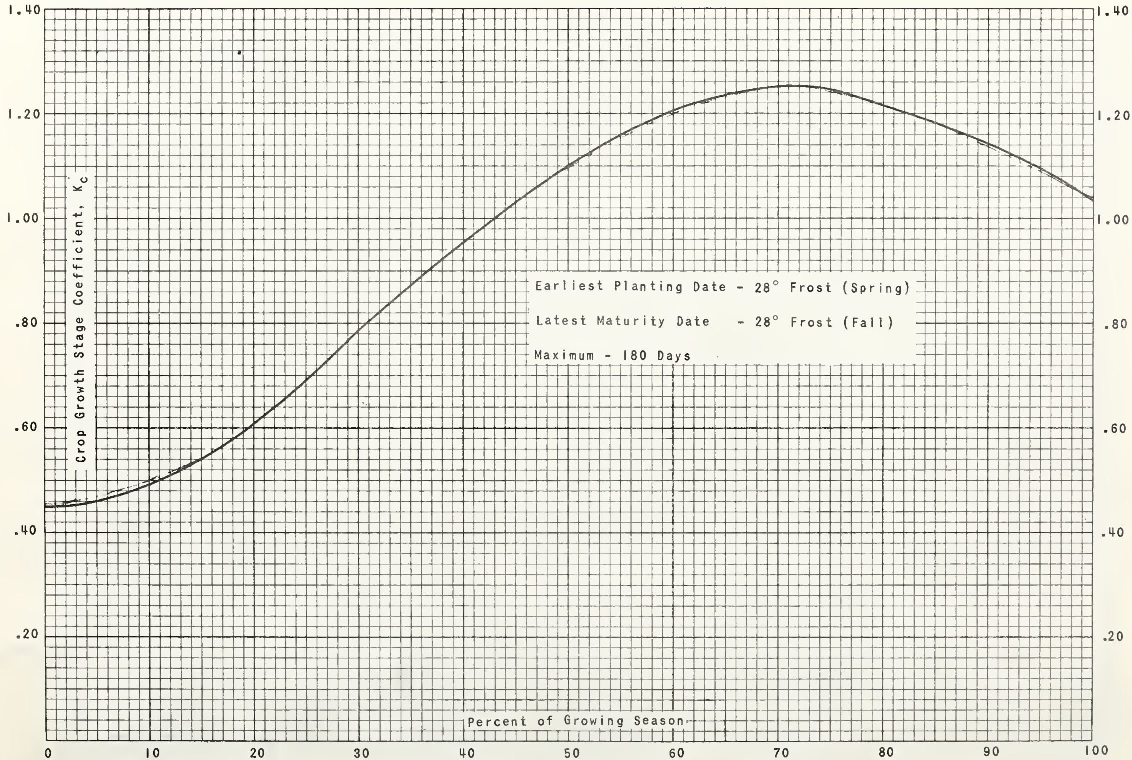
Crop growth stage coefficient curve for dry beans

Curve No. 8



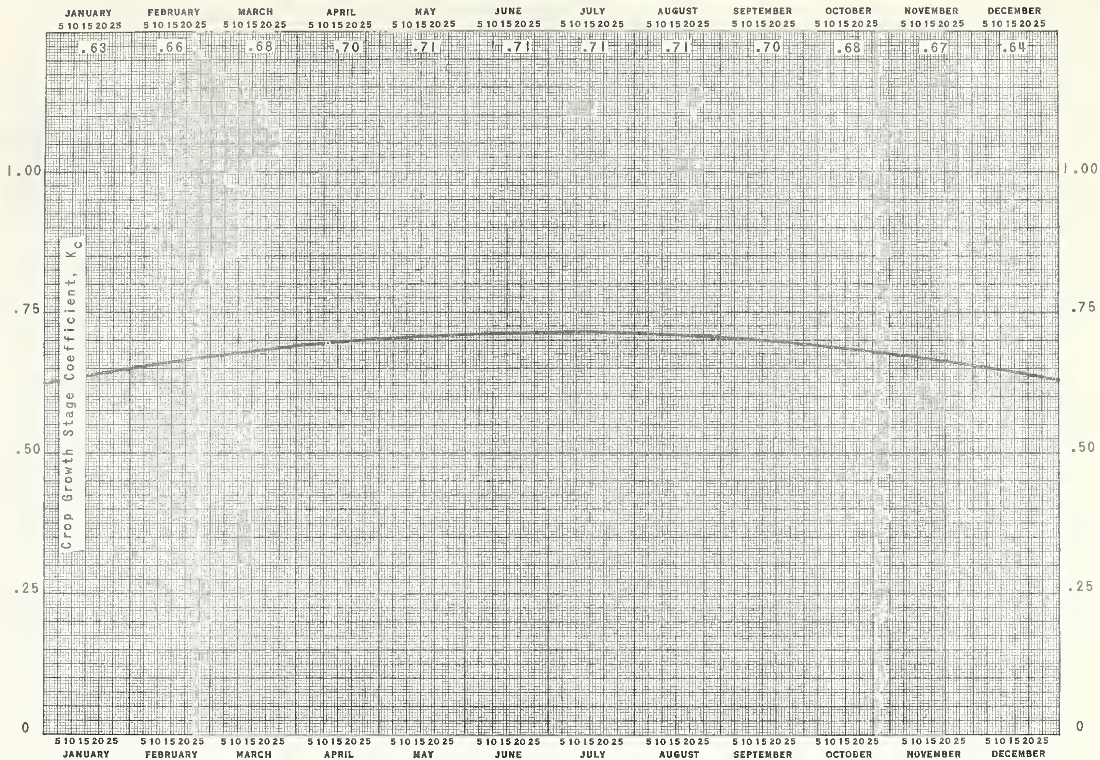
Crop growth stage coefficient curve for snap beans

Curve No. 3



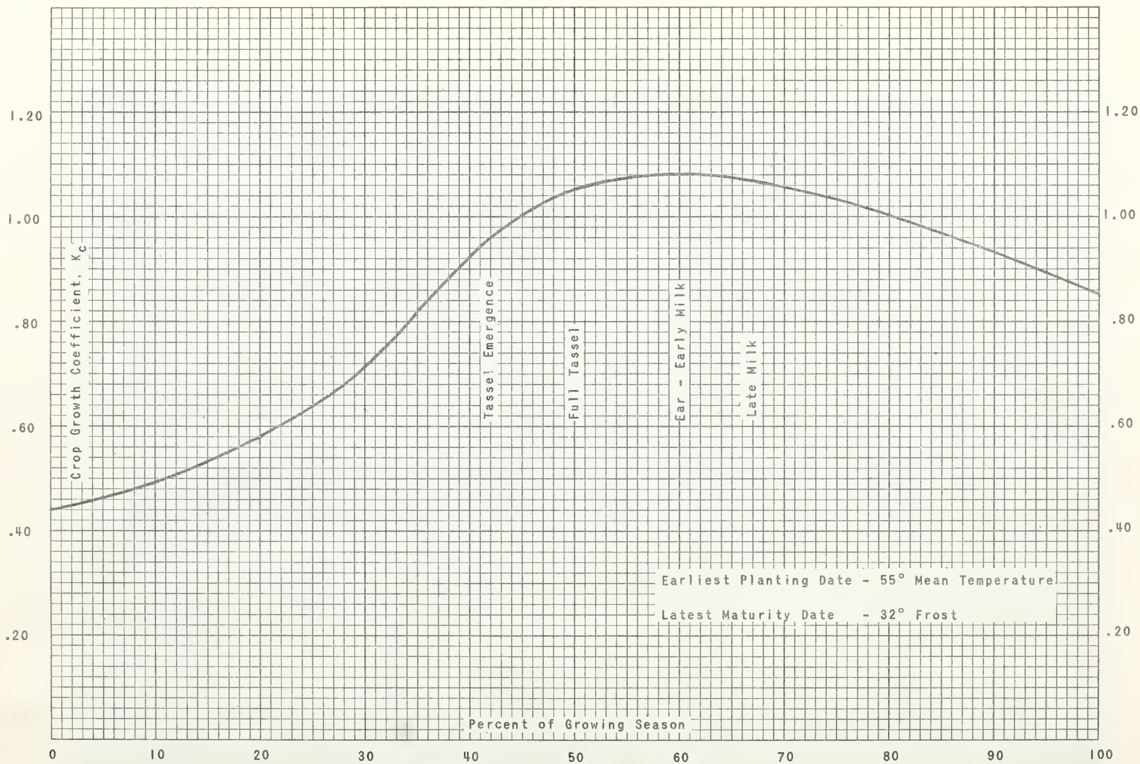
Crop growth stage coefficient curve for sugar beets

Curve No. 9



Crop growth stage coefficient curve for citrus

Curve No. 10

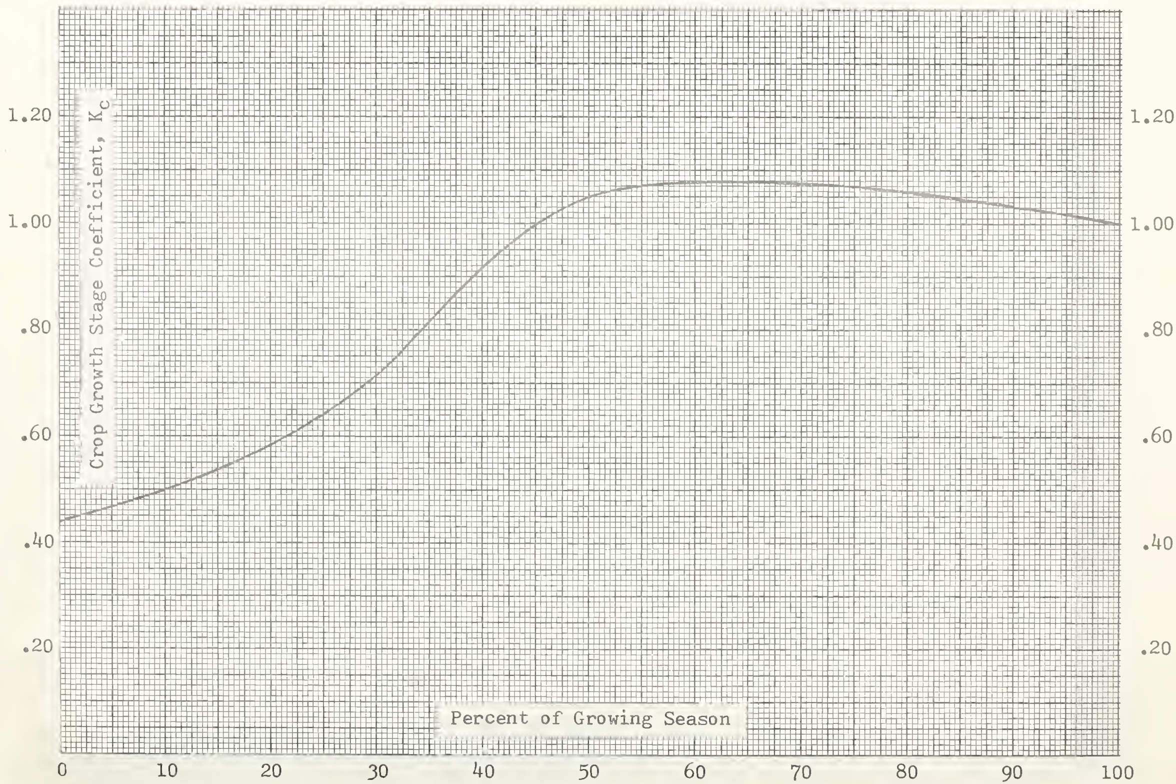


Crop growth stage coefficient curve for corn (grain)

Curve No. 1

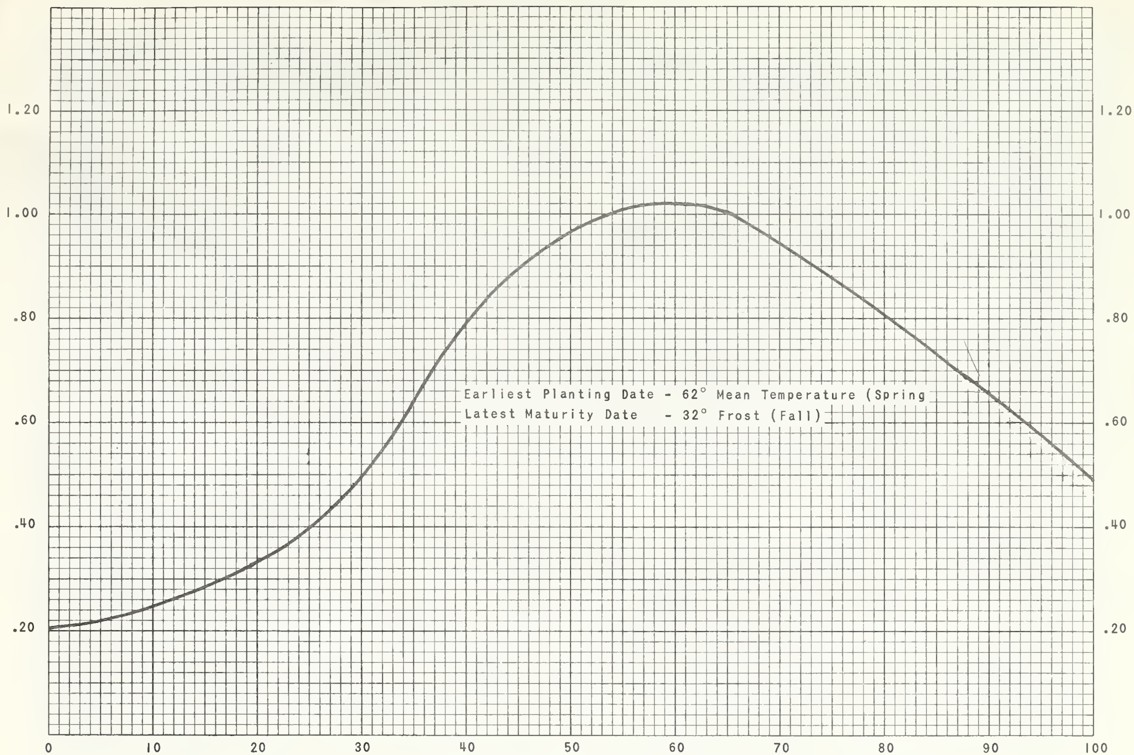
Crop growth stage coefficient curve for corn (silage)

Curve No. 11



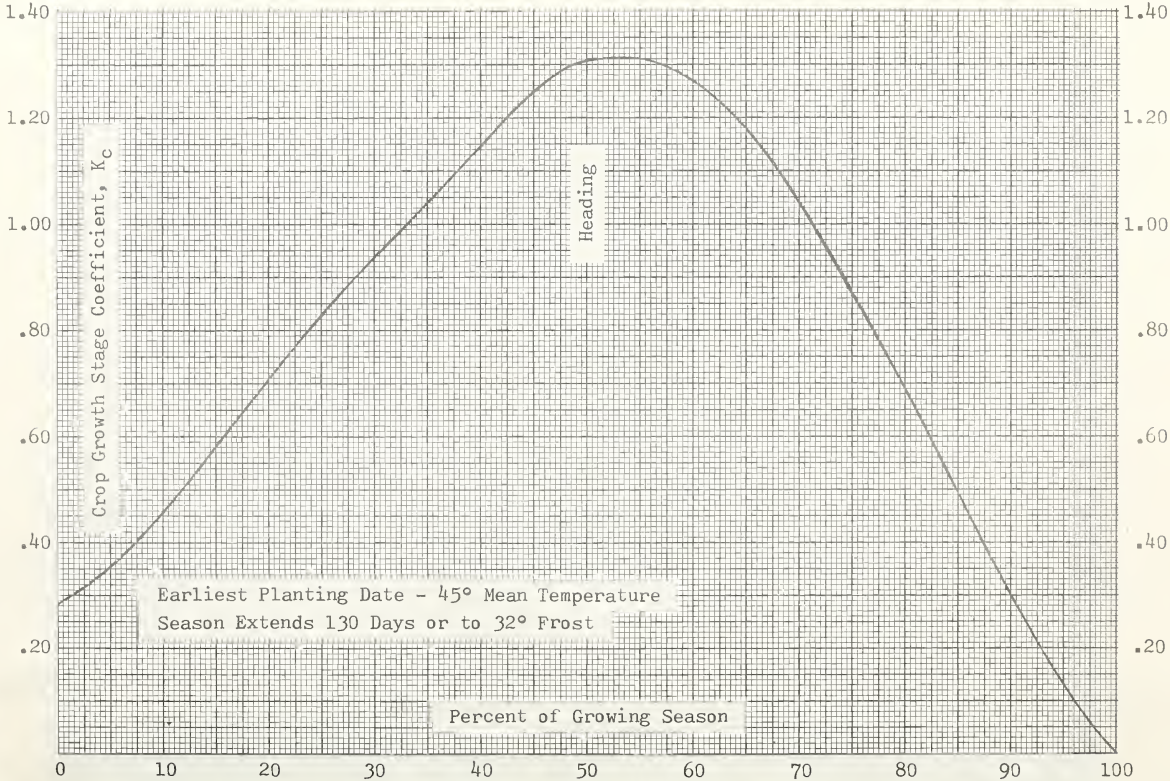
Crop growth stage coefficient curve for sweet corn

Curve 5



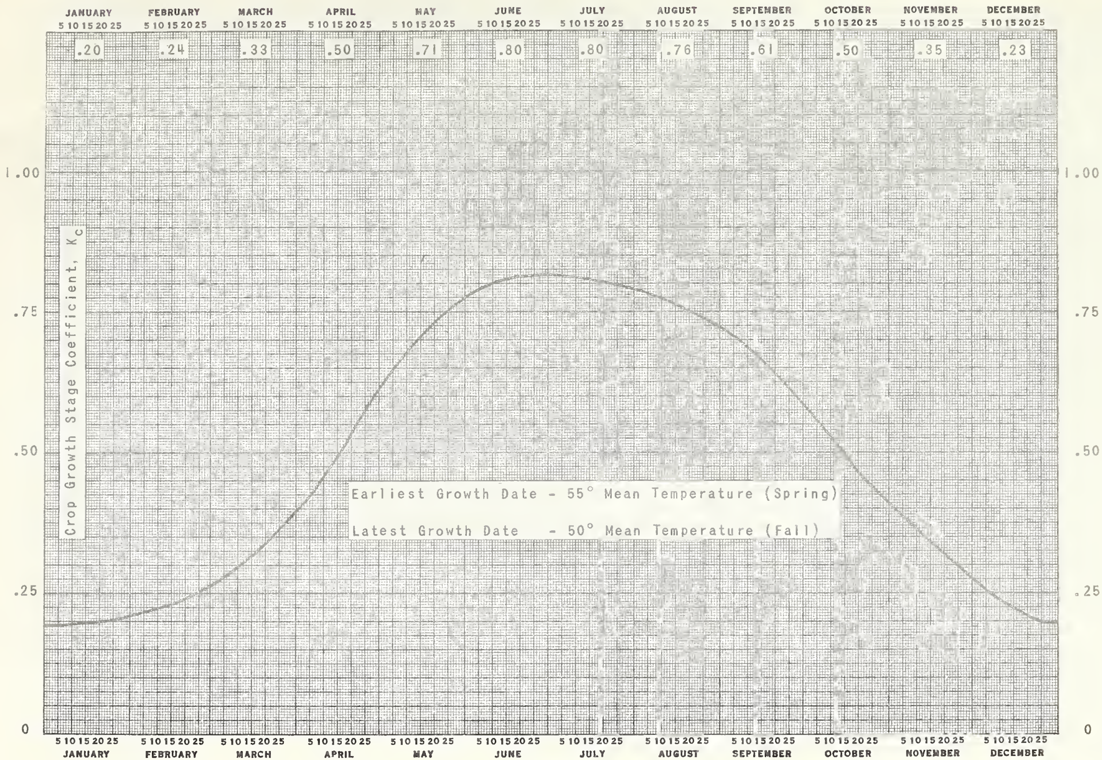
Crop growth stage coefficient curve for cotton

Curve No. 12



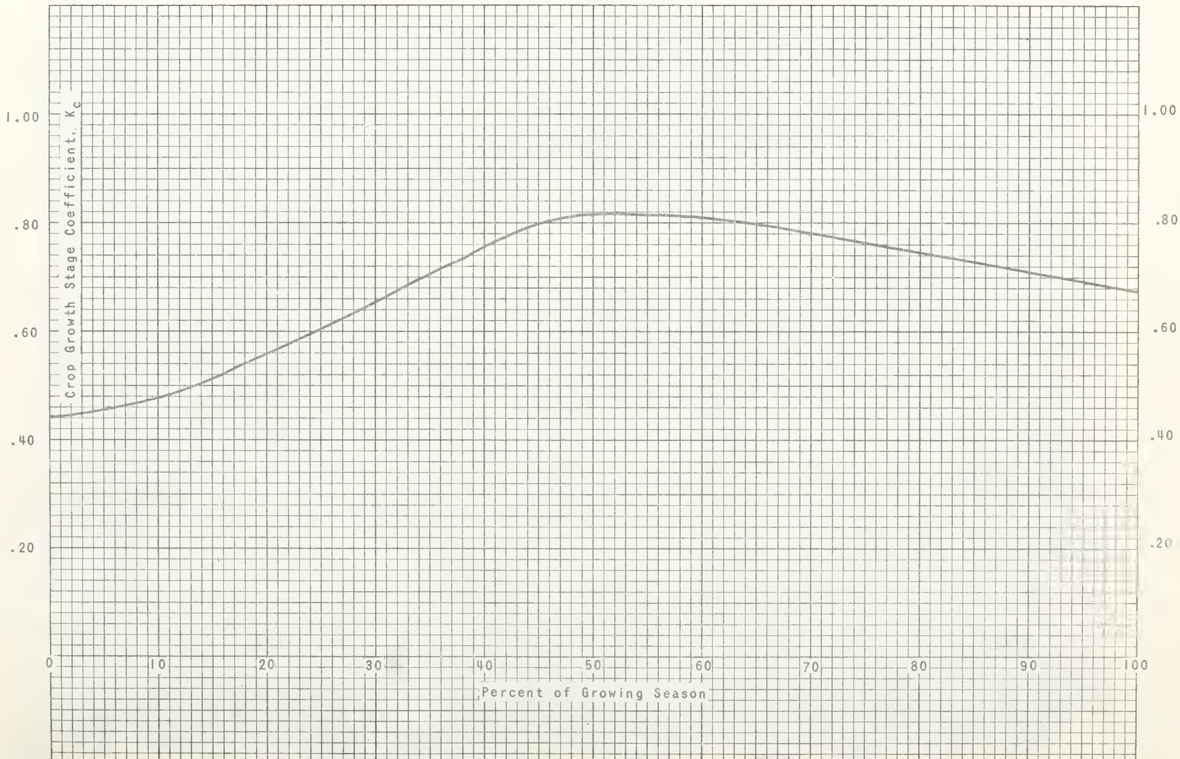
Crop growth stage coefficient curve for spring grain

Curve No. 13



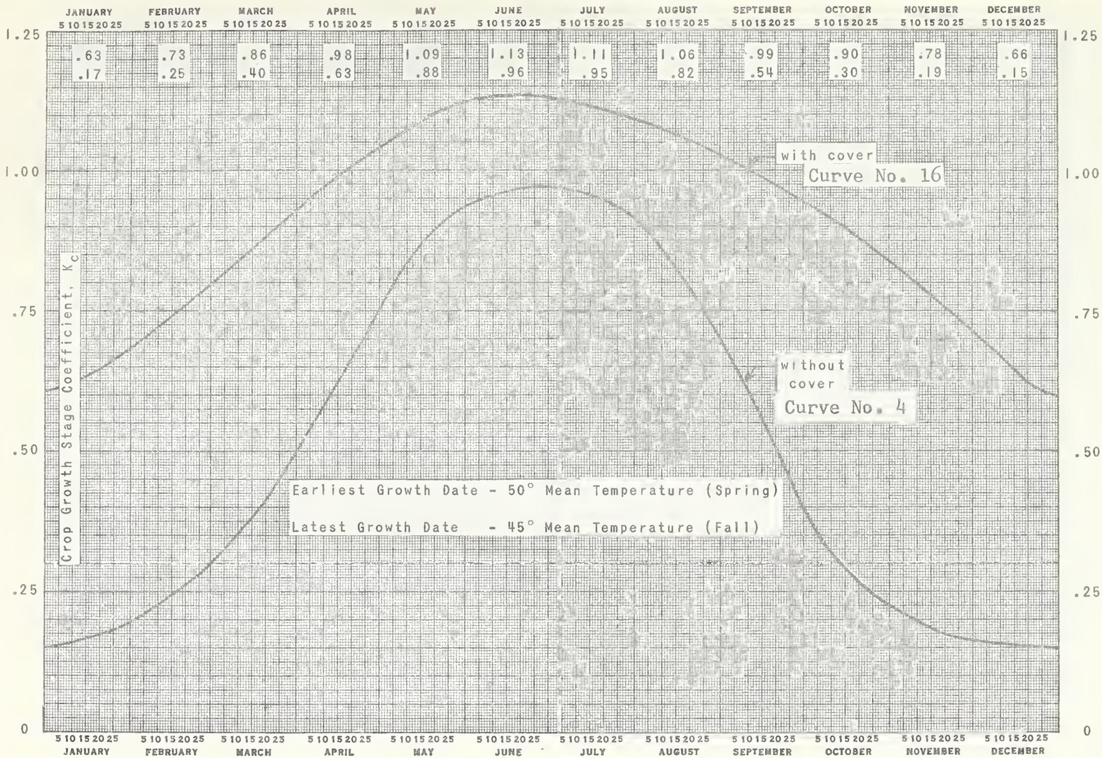
Crop growth stage coefficient curve for grapes

Curve No. 14

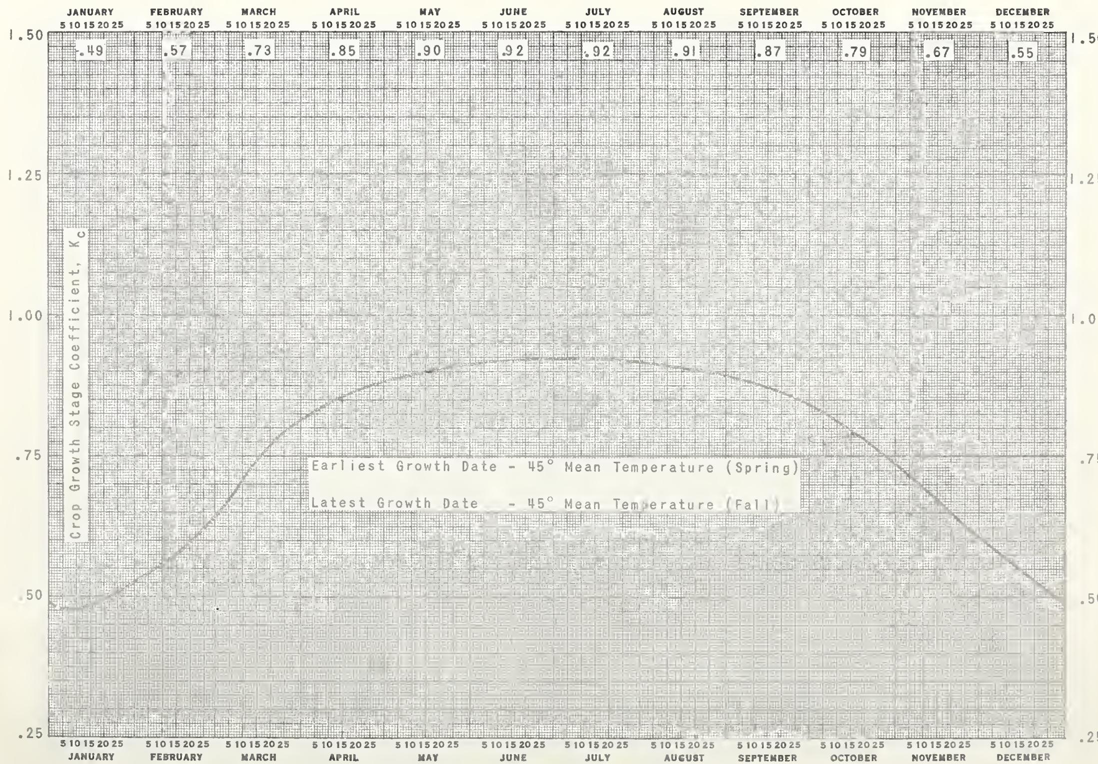


Crop growth stage coefficient curve for melons and cantaloupes

Curve No. 15

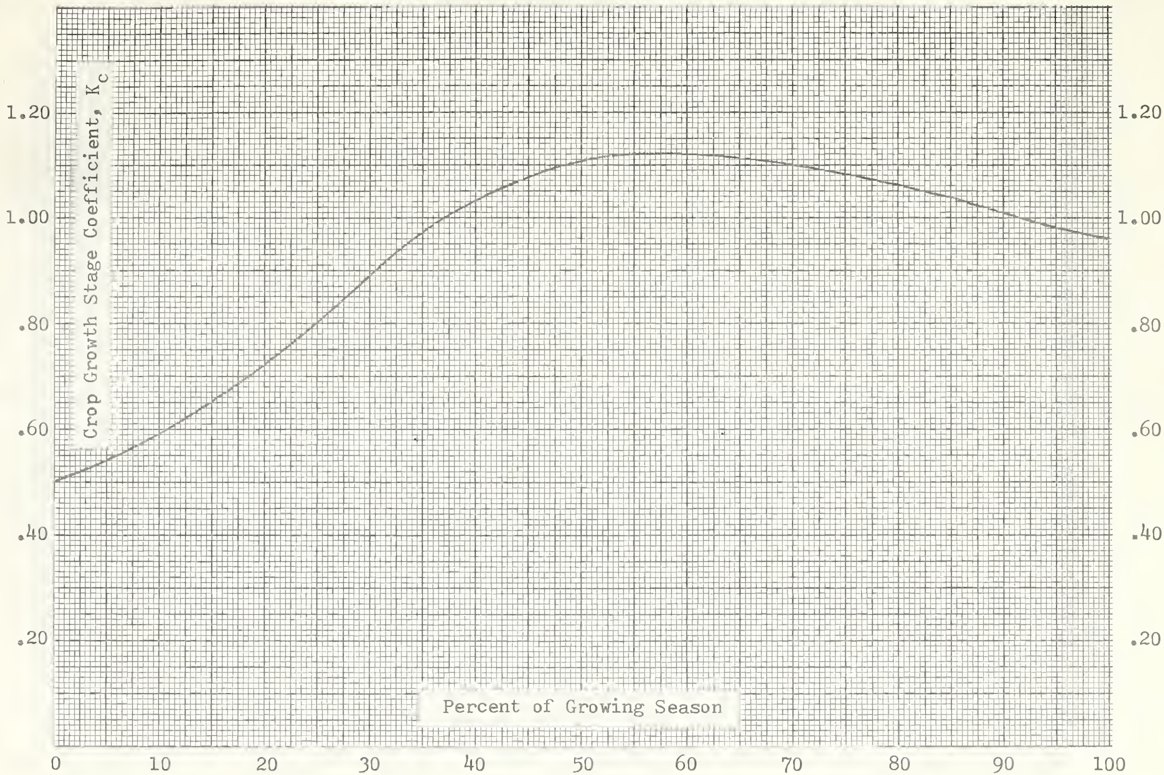


Crop growth stage coefficient curve for deciduous orchards
Curves No. 4 & No. 16



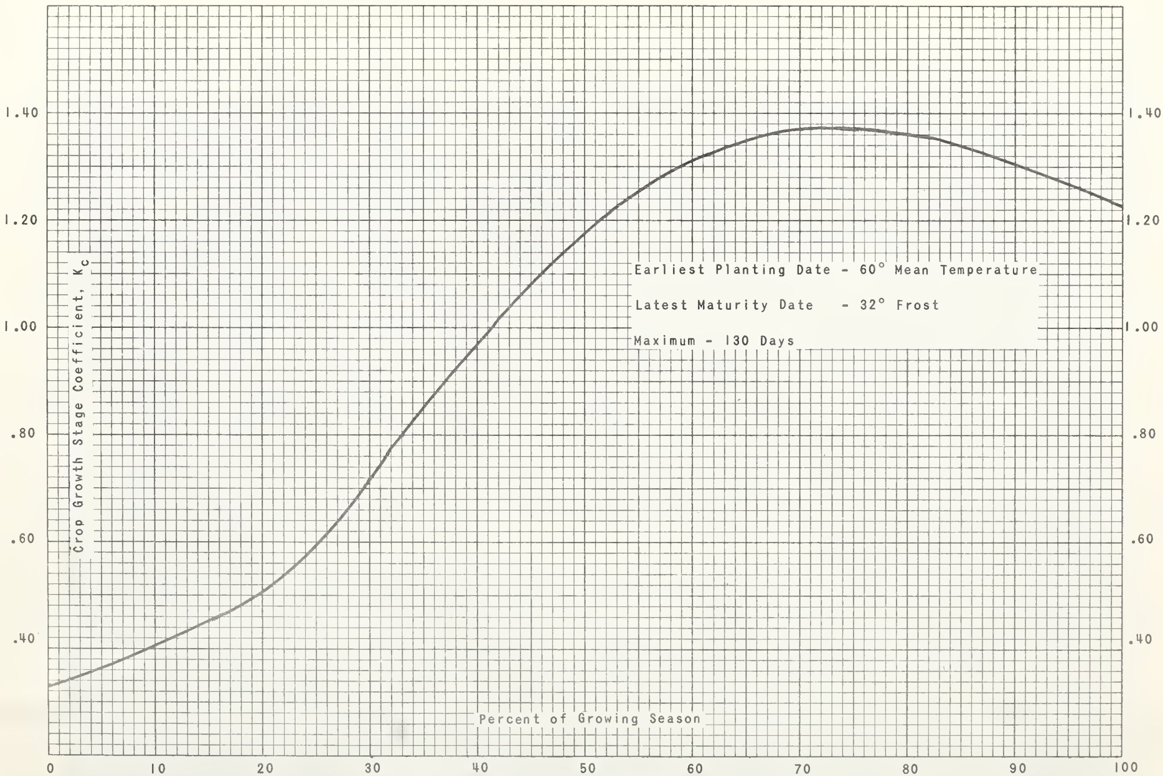
Crop growth stage coefficient curve for pasture grasses

Curve No. 17



Crop growth stage coefficient curve for peas

Curve No. 6



Crop growth stage coefficient curve for Irish potatoes

Curve No. 18

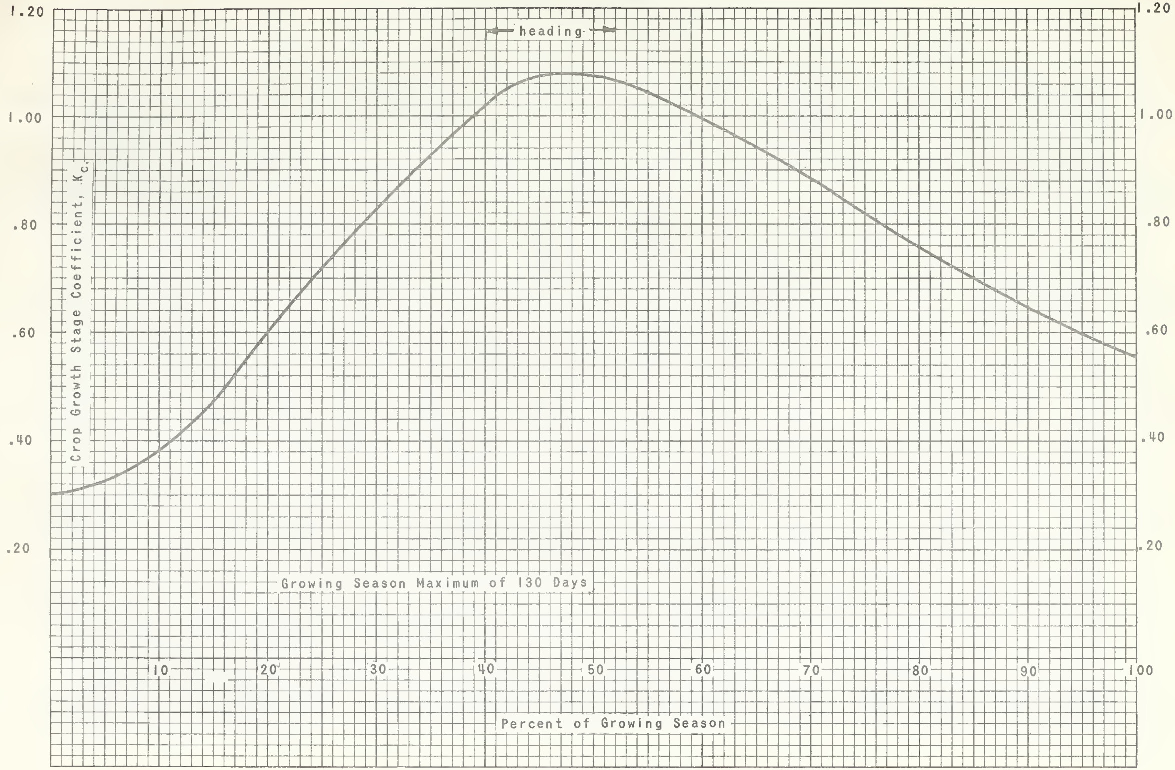
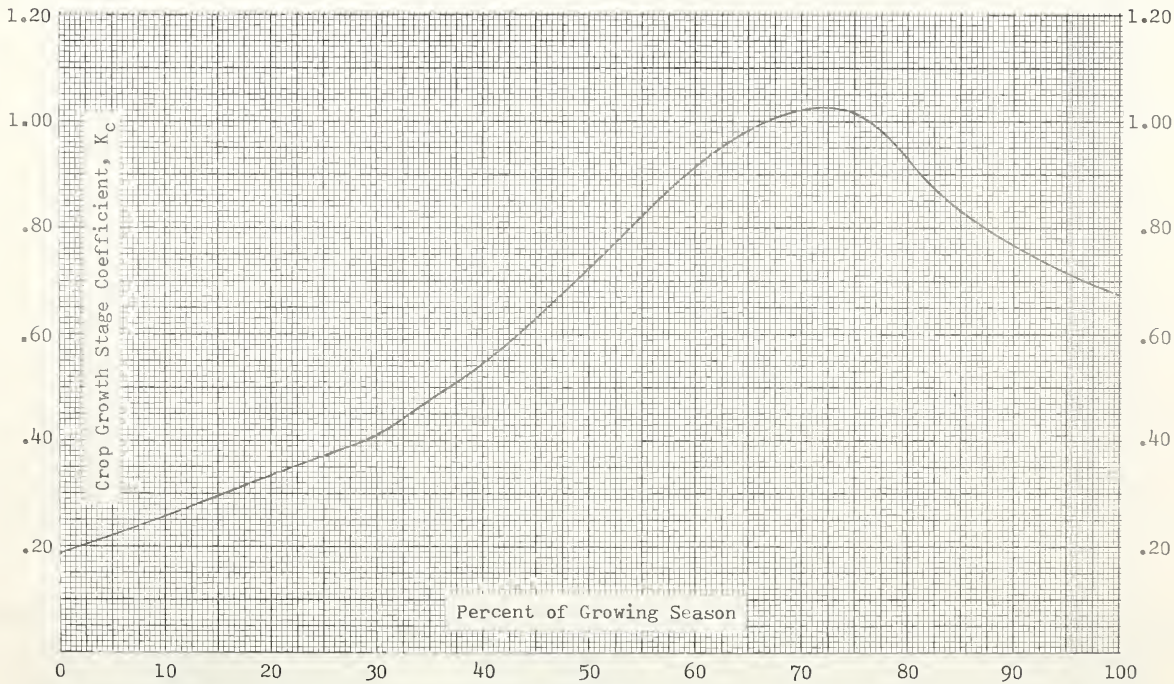


Figure 19 - Crop growth stage coefficient curve for grain sorghum

Curve No. 19

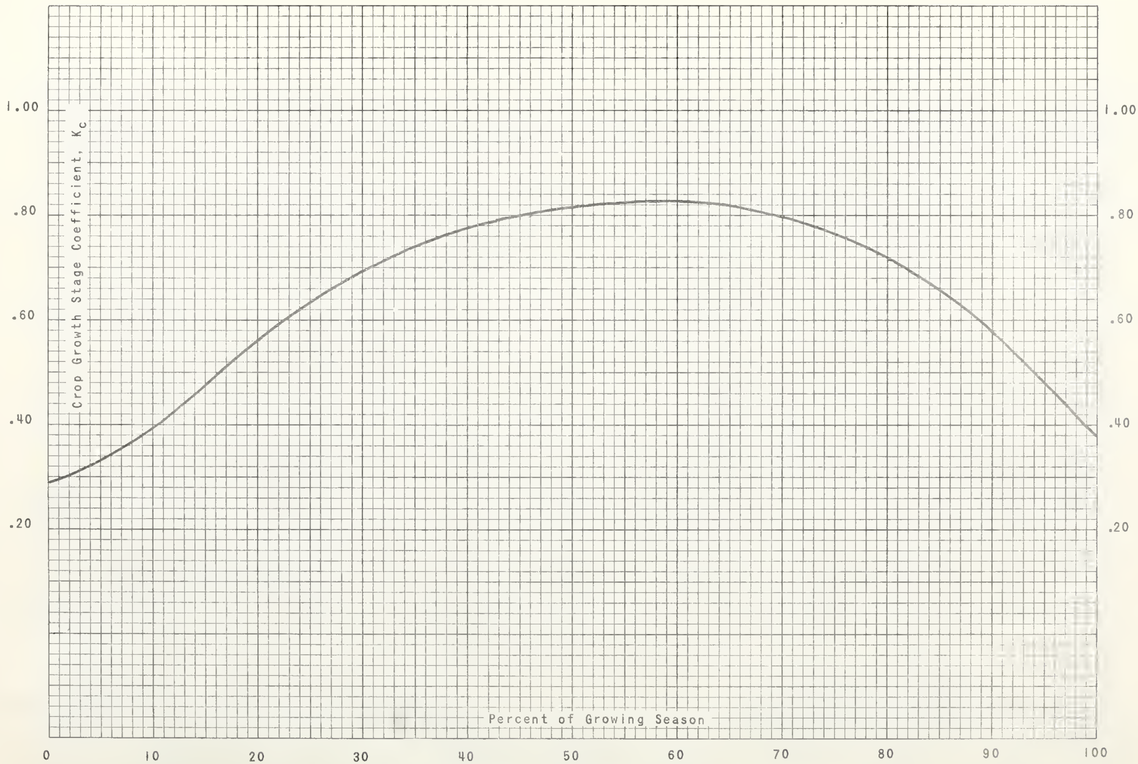


Crop growth stage coefficient curve for soybeans

Curve No. 20

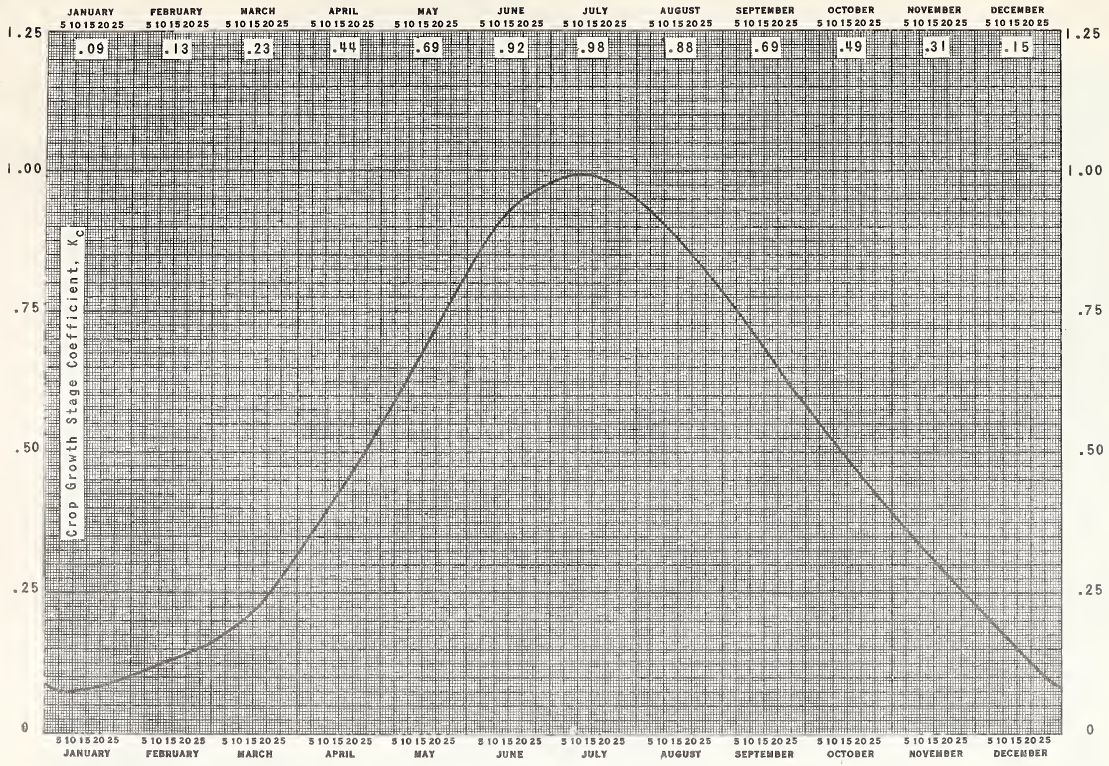
Crop growth stage coefficient curve for tomatoes

Curve No. 21

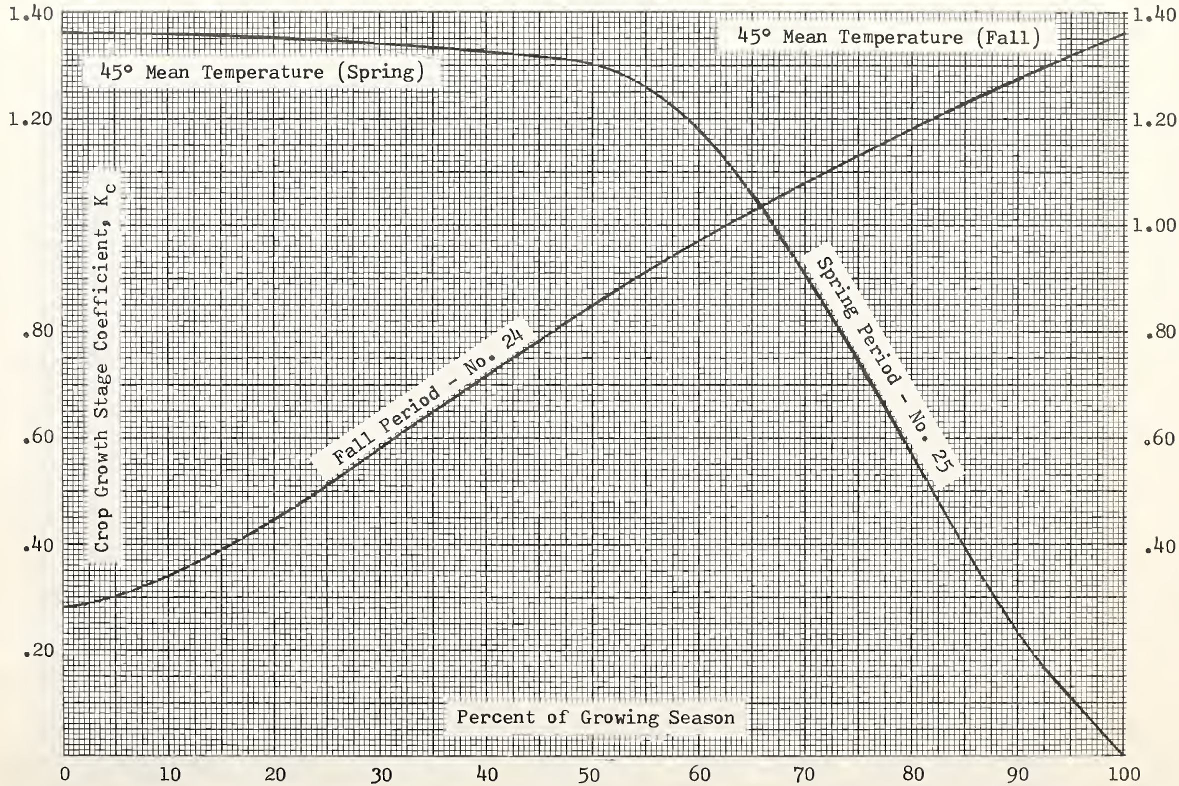


Crop growth stage coefficient curve for small vegetables

Curve No. 22



Crop growth stage coefficient curve for walnuts
Curve No. 23



Crop growth stage coefficient curves for winter wheat

Curves No. 24 and 25

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