National and Regional Water Production Functions Reflecting Weather Conditions

. . .Miscellaneous Report

By Burton C. English
and Dan Dvoskin

THE CENTER FOR
AGRICULTURAL AND RURAL DEVELOPMENT
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Errata Sheet

page 19 Equation 8 should read
$f = 0.531747 + 0.295164D - 0.057697D^2 + 0.003804D^3$

page 22 The regression equations' variable YP should be Yp

page 27 Equation 19 YP should be Yp

page 29 Equation 32 and 33 YP should be Yp

page 57 Should read Hexem, Roger, and Earl O. Heady

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The Center for Agricultural and Rural Development
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TABLE OF CONTENTS

PREFACE

Water, of course, is one of the major components of agricultural production. Forty years of increased agricultural production in the Western states has been based on the expanding use of water through irrigation. Today, one of every seven crop acres in the United States is irrigated. More than half of the crop acres in the Western states receives some irrigation water. Since 1972, increased energy prices accompanied by increased demands for U.S. agricultural products, have led to a re-examination of the economic viability of irrigation farming.

This study adds another dimension to the research that has been underway at the Center for Agricultural and Rural Development and which is being concentrated on various agricultural resource uses. The purpose of this report is to suggest a procedure that relates water use or consumption of crops to weather situations. It is hoped that the information reported herein will encourage further work and comment related to this topic.

Many people at the Center and elsewhere have been involved in the project: Nancy Melton was responsible for the computer programming work. Howard Hogg and Roger Hexem of the Economic Research Service, U.S. Department of Agriculture, and Dan Yaron, Hebrew University, Israel, reviewed earlier versions of the work and made useful comments to the authors. The authors, however, are solely responsible for any errors or omissions that still remain in the text.

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I. INTRODUCTION

Modern agriculture, such as that in the United States, relies heavily on irrigation farming, but irrigated agriculture is an energy-intensive process. For example, delivering water to the field sometimes requires more energy than all other field operations combined. Six acres of land under a pumped irrigation system has about the same annual electrical energy requirement as an average American home. In California, for example, more than 60 percent of the energy used in agriculture is for irrigation (Batty, et al. 1975).

In 1929, there were only 19.5 million acres under irrigation in the United States (Bureau of the Census, 1932). By 1976 irrigated acreage had increased 2.8 times (Irrigation Journal, 1976). There were 4 million acres under sprinkler systems in 1960 (Batty, et al. 1975). But by 1976, sprinkler systems irrigated an estimated 15.7 million acres (Irrigation Journal, 1976).

Energy has been and will continue to be a scarce resource in the near future. Energy demands have been exceeding energy supplies. This situation has caused shortages of some forms of energy and has increased the cost of energy to farmers.

To facilitate the analysis of the impacts of rising energy costs on irrigated agriculture, a water production function must be developed. Previous national agricultural models at the Center for Agricultural and Rural Development (CARD) did not allow for a reduction in water applied to irrigated land. The production functions developed in this report accomplish this task.

Objectives

The objective of this work is to develop a procedure for the derivation of general production functions for various crops. Those functions are converted to regional water production functions by using regional weather information and the characteristics of the crops grown in the region. This procedure is then applied in regions where sufficient weather data exist but little or no information exists on regional crop response to change in water applications.

Literature Review

There are many pertinent studies in the area of water use by crops. To maintain brevity, a complete literature review will not be attempted. The research reported in this section includes only those that directly pertain to this study.

Four major research efforts are used throughout this study. Three of these studies contain production functions having, as a composite variable, available water divided by the potential amount of water needed to attain maximum yield. The fourth source developed specific production functions for a single site and year.

Hexem (1974) derives two types of production functions. The first includes generalized equations for five major crops - corn grain, corn silage, wheat, sugar beets, and cotton. The data on which these production functions are based include such items as amount of water and nitrogen applied, crop yield, plant population, pH and electrical conductivity of the soil, available water-holding capacity, and critical pan evaporation. Water, nitrogen, and in some cases plant population are allowed to vary in the field experiments. The other variables could not be controlled and therefore they only reflect the state of nature. The functions are based on data from several different states including Kansas, Texas, Arizona, Colorado, and California.

The second type of production function derived by Hexem includes nitrogen and water as the changing variables and is based on a specific site and growing season. The functional forms reported are listed below (Hexem, 1974):

Quadratic

$$Y = \beta_0 + \beta_1 W + \beta_2 N + \beta_3 W^2 + \beta_4 N^2 + \beta_5 (WN)^2 \quad (1)$$

Three-halves

$$Y \ \beta_0 + \beta_1 W + \beta_2 N + \beta_3 W^{1.5} + \beta_4 N^{1.5} + \beta_5 (WN)^{1.5} \quad (2)$$

Square-root

$$Y = \beta_0 + \beta_1 W + \beta_3 W^{.5} + \beta_4 N^{.5} + \beta_5 N^{.5} W^{.5} \quad (3)$$

where:

Y is the estimated yield;

W is the water applied;

N is the nitrogen applied;

$\beta_{0,1,\ldots,5}$ are regression coefficients.

Chang, et al. (1963) studied the relationship between water and sugarcane yield in Hawaii. They found that the maximum cane yield is obtained when water is applied at the same rate as potential evapotranspiration[1] depleted it. Assuming that water is the only limiting factor, the yield obtained when water is applied at the evapotranspiration rate, equals the potential yield. Their function is:

$$\frac{Ya}{Yp} = -.61 + 2.70A - 1.09A^2 \qquad (4)$$

where:

$$A = \frac{\text{actual evapotranspiration}}{\text{potential evapotranspiration}}$$

Ya is the actual yield; and

Yp is the potential yield.

Hargreaves uses a similar procedure as Chang, et al. He summarizes data from various studies. Yield data are obtained from Hawaii, California, Utah, Israel, and other locations. Available moisture is either calculated or estimated and includes moisture stored before the growing season plus the amount of precipitation and irrigation water during the growing season. Most of the data analyzed are expressed by the equation :

$$Y = 0.8X + 1.3X^2 - 1.1X^3$$

where:

Y is the ratio of actual yield divided by potential yield; and

X is the ratio of available moisture over the amount of moisture needed to attain maximum yield (Hargreaves, 1974).

The economic range of any production function (such as above) is that range in which the marginal productivity is declining but positive. For

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[1]Evapotranspiration is the combination of evaporation of water from the soil and transpiration of water from plants. Potential evapotranspiration is the amount of water that potentially could leave the field for a specific crop at a specific location and time.

the above production function the economic range for X is between 0.394 and 0.976. Thus, a rational producer would always apply water, such that X would be greater than 0.394 but less than 0.976.

Hogg and Vieth (1976) use a model that includes weather variability. Their model is based on Hargreaves work and on data generated from sugarcane in Hawaii. A quadratic function is fitted so that the composite variable equals one when the potential yield of sugarcane is attained. The function is:

$$\frac{Ya}{Yp} = 1.7429 + 5.4858W - 2.7429W^2 \qquad (6)$$

where:

Ya is the actual yield;

Yp is the potential; and

W is the water adequacy ratio.

The water adequacy ratio (W) is the ratio of available moisture over the moisture needed to achieve maximum yield. It can be written as:

$$W = \frac{Ea}{Ep} = \frac{(N \times S) + Re}{Ep} \qquad (7)$$

where:

Ea is the actual evapotranspiration;

Ep is the potential evapotranspiration;

N is the number of irrigation rounds applied to the field;

S is the available soil moisture storage associated with the soil type in each field; and

Re is the effective rainfall.[1]

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[1]Effective rainfall is that fraction of total precipitation useful for meeting crop water requirements.

In comparing the quadratic form above to Hargreaves' cubic form, Hogg and Vieth found that the cubic form was unnecessary because the inflection point attributed to the cubic form occurred when W is quite small. Also, the economic range of the function is between the inflation point and the maximum yield point.

II. GENERAL PRODUCTION FUNCTIONS

This chapter describes the procedures involved in obtaining the general production functions. The word general, in this case, means that the functions are not regionally specific. However, the general production functions are varied between crops. A schematic flow chart diagram of the procedure used is presented in Appendix A.

Primary Data Needed

The information needed for estimating the general quadratic production functions includes yield response, effective rainfall, and potential evapotranspiration.

Yield response

The production functions developed by Hexem (1974) serve as the basic source for the yield response data. These production functions are specified by crop, site, and season. Crop, sites, and growing seasons for the functions chosen are presented in Table 1. The average nitrogen levels assumed and water maximization points[1] are reported in Table 2.

[1] The water maximization point is the amount of water required to attain maximum crop yield.

Table 1. Place, year, and growing season by crop for data used in developing general production functions

Function Number	Crop	Place	Year	Growing Season
1	Cotton	Shafter, CA	1968	April 15-October 24
2	Cotton	Shafter, CA	1967	May 3-October 17
3	Cotton	Tempe, AZ	1971	March 26-November 8
4	Cotton	Yuma Meza, AZ	1971	April 20-September 9
5	Sugar Beets	Mesa, AZ	1971	September 24, 1970-May 4, 1971
6	Sugar Beets	Mesa, AZ	1971	September 14, 1970-July 5, 1971
7	Sugar Beets	Mesa, AZ	1972	September 23, 1971-July 7, 1972
8	Wheat	Yuma Valley, AZ	1972	December 15, 1971-May 11, 1972
9	Wheat	Mesa, AZ	1971	November 15, 1970-May 19, 1971
10	Corn Silage	Mesa, AZ	1970	April 11-August 21
11	Corn Silage	Yuma Mesa, AZ	1970	March 3-July 12
12	Corn Silage	Ft. Collins, CO	1968	May 9-September 18
13	Corn	Mesa, AZ	1970	April 11-August 21
14	Corn	Ft. Collins, CO	1968	May 9-September 18
15	Corn	Colby, KS	1971	May 7-October 29
16	Corn	Davis, CA	1970	May 22-September 28
17	Corn	Davis, CA	1969	May 22-September 26
18	Corn	Colby, KS	1970	May 5-November 2
19	Corn	Plainview, TX	1970	April 24-October 10

Table 2. Production functions used in developing the general production functions

Function Number	Production Function	Average Nitrogen Level	Water Maximization Point	R^2
		(lbs./acre)	(inches/acre)	
	COTTON:			
1	$Y = -837.13 + 99.93 + 1.56N - 1.40W^2 - 0.003N^2 - 0.027WN$	125	34.58	.821
2	$Y = 1103.62 + 118.35W + 2.85N - 1.63W^2 - 0.004N^2 - 0.045WN$	125	34.56	.850
3	$Y = -15848.70 + 911.97W - 2.28N - 12.22W^2 + 0.002N^2 + 0.045WN$	150	37.60	.580
4	$Y = -728.17 + 57.31 - 0.96N - 0.52W^2 - 0.002N^2 + 0.042WN$	300	66.97	.627
	SUGARBEETS:			
5	$Y = 1.51 + 1.21W + 0.036N - 0.03W^2 - 0.00009N^2 + 0.0009WN$	180	20.60	.468
6	$Y = 14.55 + 0.67W + 0.06N - 0.01W^2 - 0.00019N^2 + 0.00095WN$	180	38.39	.616
7	$Y = 4.97 + 1.12W + 0.04N - 0.01W^2 - 0.00017N^2 + 0.00084WN$	180	42.42	.759
	WHEAT:			
8	$Y = -9906.46 + 856.73W + 8.34N - 12.92W^2 - 0.032N^2 + 0.093WN$	175	33.52	.762
9	$Y = -8772.43 + 889.98W + 29.35N - 16.63W^2 - 0.112N^2 + .565WN$	150	29.32	.931

Table 2. Continued

Function Number	Production Function	Average Nitrogen Level	Water Maximization Point[a]	R^2
		(lbs./acre)	(inches/acre)	
	CORN SILAGE:			
10	$Y = -35{,}848.66 + 2733.81 + 84.74N - 28.54W^2 - 0.31N^2 + 1.40WN$	160	51.80	.754
11	$Y = -422{,}002.25 + 27800.70W - 228.87N - 430.64W^2 - 0.04N^2 + 7.62WN$	225	34.27	.437
12	$Y = 14{,}929.75 + 2934.50W + 115.62N - 54.97W^2 - 0.38N^2 - 1.66WN$	100	25.18	.592
	CORN:			
13	$Y = -4546.37 + 249.09W + 1.65N - 2.71W^2 - 0.02N^2 + 0.21WN$	160	52.25	.749
14	$Y = 973.52 + 856.67W + 10.62N - 29.96W^2 - 0.03N^2 + 0.06WN$	100	14.40	.634
15	$Y = -5206.79 + 598.71W + 37.09N - 11.03W^2 - 0.08N^2 + 0.39WN$	180	33.17	.936
16	$Y = 145.10 + 702.80W + 3.41N - 13.28W^2 - 0.01W^2 - 0.03WN$	150	26.28	.922
17	$Y = 2493.66 + 466.28W + 3.30N - 8.86W^2 + 0.003N^2 - 0.12WN$	160	25.25	.843
18	$Y = -7068.72 + 815.80W + 6.96N - 13.16W^2 - 0.03N^2 + 0.032WN$	180	33.17	.748
19	$Y = -20{,}672.27 + 1695.31W - 3.17N - 27.20W^2 - 0.004N^2 + 0.19WN$	170	31.76	.702

SOURCE: [Hexem, 1974].

[a]Water maximization point is the amount of water applied corresponding to maximum yield possible.

The information available from the functions in Table 2 is pooled together by using a least squares regression method. This is done by projecting corresponding yield and water data for each of these functions.

Climatological data

The climatological data necessary for the development of these water response functions include monthly rainfall and monthly Class A pan evaporation.[1] These data are collected from various weather stations reported by the U.S. Environmental Data Service (1968). Both crop site and year are used in obtaining the climatological data (Tables 3 and 4) corresponding to the production functions in Table 2. The data, however, must be converted to potential monthly evapotranspiration and to monthly effective rainfall.

Processed Weather Data

The two components of the composite variable used in the general production functions are potential evapotranspiration and effective rainfall. These components are derived from monthly Class A pan evaporation and monthly rainfall.

Potential evapotranspiration

The potential evapotranspiration of a given crop is the amount of water that leaves the crop surface and the area surrounding the crop. Radiative and aerodynamic properties of the crop surface modify the

[1]Class A evaporation is the amount of water that evaporates from a circular pan having dimensions of 47.6 inches (121 cm) in diameter and 10 inches (25.5 cm) deep.

Table 3. Monthly Class A pan evaporation by location

	Ft. Collins, CO	Mesa, AZ	Colby, KS		Davis, CA		Plainview, TX[a]	Yuma Mesa, AZ
	1968	1970	1970	1971	1969	1970	1970	1970
				(inches)				
January	NA[b]	3.12	NA	NA	1.46	1.65	NA	3.63
February	NA	4.99	NA	NA	1.70	2.33	4.21	4.74
March	NA	6.58	NA	NA	5.11	7.28	4.20	7.14
April	NA	9.78	8.40	8.02	7.85	8.14	8.97	9.34
May	NA	13.17	11.34	8.28	12.32	12.66	10.16	12.85
June	4.68	14.41	12.79	13.59	11.24	12.26	10.47	14.17
July	6.60	(14.69)[c]	13.96	12.92	13.07	13.71	9.43	14.69
August	6.60	11.93	14.15	12.60	11.99	11.59	9.24	13.16
September	5.00	9.80	10.10	9.99	8.76	9.78	7.17	11.15
October	NA	7.12	NA	NA	6.70	6.44	5.05	NA
November	NA	4.67	NA	NA	2.86	2.58	4.66	5.06
December	NA	2.74	NA	NA	1.42	0.79	4.15	3.06

SOURCE: [U.S. Environmental Data Service, 1968].

[a]Data from Clovis, New Mexico.

[b]NA indicates that data were not available.

[c]Data from Yuma Mesa, Arizona.

Table 4. Monthly precipitation by location

	Ft. Collins, CO	Mesa, AZ	Colby, KS		Davis, CA		Plainview, TX[a]	Yuma Mesa, AZ
	1968	1970	1970	1971	1969	1970	1970	1970
				(inches)				
January	0.09	0.00	0.04	0.27	9.60	6.79	0.00	0.01
February	0.60	0.38	0.01	1.04	6.11	1.13	0.00	0.72
March	0.90	1.65	0.83	0.39	1.46	1.75	2.35	1.05
April	1.85	0.02	1.02	3.73	0.93	0.04	0.53	0.00
May	3.20	0.00	4.73	2.86	0.01	0.05	1.03	0.00
June	0.86	0.00	2.93	2.13	0.13	0.42	0.96	0.00
July	2.05	0.04	1.76	2.51	0.00	T[a]	0.28	0.00
August	2.11	0.46	2.08	0.85	0.00	0.00	1.30	0.70
September	0.09	1.77	2.21	1.47	0.05	0.00	0.65	0.17
October	0.65	0.77	1.12	1.11	0.89	0.92	1.66	0.05
November	0.78	T	0.41	1.38	0.56	6.87	0.12	0.02
December	0.13	0.21	T	0.13	5.36	4.38	T	T

SOURCE: [U.S. Environmental Data Service, 1968].

[a]Trace.

meteorological conditions around the crop. Potential evapotranspiration, therefore, will vary from crop to crop (Fuchs, 1973).

Several methods are available to estimate potential evapotranspiration. These include solar radiation, plant aerodynamics, temperature, and evaporation-pan. These methods, discussed in Fuchs (1973), Chang (1968), Doorenbos and Pruitt (1975), have different data requirements.

The method chosen depends in part on the available data. Since the objective of this work is to derive water production functions over the western United States, data must be available for all regions in the western United States. Thus, the evaporation-pan method seems to be most applicable.

Hargreaves (1966) summarizes numerous formulations for using evaporation-pan data. He also derives a table for converting pan evaporation to potential evapotranspiration[1] (Table 5). This table categorizes crops into eight groups (Table 6).

To use Table 5, the cumulative percentage of the growing season must be derived. This derivation is shown in Table 7. Potential evapotranspiration then is K (Table 5) times the observed pan evaporation (PE). An example of this procedure for Colby, Kansas, is found in Table 8. Monthly potential evapotranspiration is summed over the growing season to yield the annual potential evapotranspiration.

Effective rainfall

Effective rainfall is that fraction of total precipitation useful for meeting crop water requirements. Consequently, effective rainfall

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[1]Here, our terminology differs from that used by Hargreaves. Hargreaves used the term evapotranspiration instead of potential evapotranspiration.

Table 5. Potential evapotranspiration coefficients

Percentage of Growing Season	Potential Evapotranspiration Coefficients, K to be Multiplied by Class A Pan Evaporation							
	Group A	Group B	Group C	Group D	Group E	Group F	Group G	Rice
0	0	0	0	0	0	0	0	0
5	0.20	0.15	0.12	0.08	1.00	0.60	0.55	0.90
10	0.36	0.27	0.22	0.15	1.00	0.60	0.60	0.92
15	0.50	0.38	0.30	0.19	1.00	0.60	0.65	0.95
20	0.64	0.48	0.38	0.27	1.00	0.60	0.70	0.98
25	0.75	0.56	0.45	0.33	1.00	0.60	0.75	1.00
30	0.84	0.63	0.50	0.40	1.00	0.60	0.80	1.03
35	0.92	0.69	0.55	0.46	1.00	0.60	0.85	1.06
40	0.97	0.73	0.58	0.52	1.00	0.60	0.90	1.08
45	0.99	0.74	0.60	0.58	1.00	0.60	0.95	1.10
50	1.00	0.75	0.60	0.65	1.00	0.60	1.00	1.10
55	1.00	0.75	0.60	0.71	1.00	0.60	1.00	1.10
60	0.99	0.74	0.60	0.77	1.00	0.60	1.00	1.10
65	0.96	0.72	0.58	0.82	1.00	0.60	0.95	1.10
70	0.91	0.68	0.55	0.88	1.00	0.60	0.90	1.05
75	0.85	0.64	0.51	0.90	1.00	0.60	0.85	1.00
80	0.75	0.56	0.45	0.90	1.00	0.60	0.80	0.95
85	0.60	0.45	0.36	0.80	1.00	0.60	0.75	0.90
90	0.46	0.35	0.28	0.70	1.00	0.60	0.70	0.85
95	0.28	0.21	0.17	0.60	1.00	0.60	0.55	0.80
100	0	0	0	0	0	0	0	0

SOURCE: Hargreaves (1966).

Table 6. Listing of crops by crop group

Group							
A	B	C	D	E	F	G	Rice
Beans	Dates	Melons	Asparagus	Pangola pasture	Oranges	Sugarcane	Rice
Corn	Olives	Onions	Barley	Clover pasture	Lemons	Alfalfa	
Cotton	Peaches	Carrots	Celery	Trenza pasture	Grapefruit		
Potatoes	Plums	Hops	Flax	Orchard[a]			
Sugar beets	Walnuts	Grapes	Oats	Bananas			
Grain sorghum[b]	Dwarf sorghum	Almonds	Wheat	Plantain			
Peas			Other small grains				
Tomatoes							

SOURCE: (Hargreaves, 1966).

[a]Orchard with cover crop.

[b]Grain sorghum also appears in group D.

Table 7. An example of the estimation procedures used in determining the corn growing season for Colby, Kansas, 1971[a]

Time Period	Growing Season Days in Month	Growing Season Accumulated Unadjusted[b]	Growing Season Midpoint[c]
	(number of days)	(percent)	(percent)
May	24	13.71	6.86
June	30	30.86	22.28
July	31	48.57	39.72
August	31	66.29	57.43
September	30	83.43	74.86
October	29	100.00	91.72
Total	175		

[a]The period from planting to harvesting is May 7 to October 29, 1971.

[b]Accumulated adjusted column is the accumulated sum divided by the length of the growing season. For example,

$$\frac{24 + 30}{175} \times 100 = 30.86.$$

[c]The midpoint of each month is found by taking the difference in the accumulated unadjusted column of adjacent months; dividing that difference by 2, and summing the result to the previous months accumulated unadjusted percent. For example,

$$\frac{30.85 - 13.71}{2} + 13.71 = 22.28.$$

Table 8. Calculation of potential evapotranspiration for corn in Colby, Kansas, 1971

Period	Potential Evapotranspiration Coefficient[a] K	Pan Evaporation[b] (PE)	Estimated Potential Evapotranspiration[c] (Ep)
		(inches)	(inches)
May	.2595	6.41[d]	1.66
June	.6902	13.59	9.38
July	.9671	12.92	12.49
August	.9948	12.60	12.53
September	.8519	9.99	8.51
October	.3984	5.65[e]	2.25
Total		61.16	46.83

[a]Linear interpolation used on Table 5 data to compute intermediate values.

[b]Table 3.

[c]K x PE = Ep.

[d]A partial monthly figure $\frac{24}{31} \times 8.02 = 6.41$

[e]Estimated.

excludes deep drainage, run-off, and evaporation from the soil (Doorenbos and Pruitt, 1975).

The Soil Conservation Service (1967) suggests using equation (8) to derive monthly effective rainfall. The equation related effective rainfall to monthly rainfall, potential evapotranspiration, and the depth of water application.

The equation is:

$$Re = [(0.70917)\ (R^{0.82416}) - 0.11556]\ [10^{0.02426E_p}]\ [f] \qquad (8)$$

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

where:

Re is the effective rainfall;

R is the total rainfall;

E is the potential evapotranspiration; and

D is the net depth water of application.

In areas where soil intake rates are low and rainfall intensities are high, modification of the effective rainfall results may be desired.[1] Large data requirements are necessary for modification of this type. Also, the areas under study are located in the Western United States. These areas do not receive much rain during the growing season, and for the most part, are characterized with sandy soil types. For these reasons, it was decided not to undertake such modifications. Table 9 shows the effective rainfall calculated for Colby, Kansas.

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[1]A large percentage of the rainfall may be lost due to large amounts of runoff without an increase in the moisture level in the soil profile.

Table 9. An example of the calculation of effective rainfall for corn at Colby, Kansas, 1971

Month	Potential Evapotranspiration[a]	Total Rainfall[b]	Effective Rainfall
		(inches)	
May	1.66	2.86	1.66
June	9.38	2.13	2.04
July	12.49	2.51	2.51
August	12.53	0.85	0.85
September	8.51	1.47	1.38
October	2.25	1.11	.97
Total	46.83	10.93	9.41

[a]Table 8.

[b]Table 4.

Deriving the General Production Functions

The general production functions are derived by regressing the ratio of actual yield over potential yield on the adequacy of water applied using ordinary least squares.

Assume that we have the following quadratic equation:

$$\frac{Ya}{Yp} = \beta_0 + \beta_1 A + \beta_2 A^2 \qquad (9)$$

$$A = \frac{W + Re}{Ep} \qquad (10)$$

where:

Ya is the actual yield;

Yp is the potential yield;

β's are the ordinary least square regression coefficients;

A is the water adequacy ratio;

W is the amount of water applied;

Re is the effective rainfall; and

Ep is the potential evapotranspiration.

If we let the adequacy ratio (A) be equal to one then:

W = Ep - Re

Further, if A is equal to one, actual yield (Ya) must equal potential yield. This implies that the sum of the regression coefficients $\beta_0 + \beta_1 + \beta_2$ must also be equal to 1.

Because of problems arising from using two different data sources,[1] an adjustment of the adequacy ratio is needed. This adjustment requires

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[1]The water applied (W) is obtained from Hexem, but Ep and Re are obtained from weather information.

the adequacy ratio (A) to equal one where the ratio of actual to potential yield is equal to one. The adjustment is then applied to all other adequacy ratios (A) associated with the crop, site, and growing season.

For each water application, the adjusted adequacy ratio (Z) is obtained from Z = A x F. The adjustment factor (F) is calculated as F = EP/(W + Re) when the actual yield (Ya) equals the potential yield (Yp).

The adjusted adequacy ratio with their associated potential and actual yields are used in deriving the regression coefficients of the model:

$$Ya = \beta_0 Y_p + \beta_1 Y_p Z + \beta_2 Y_p Z^2.$$

The regression equations for corn, cotton, sugar beets, and wheat are shown below.

CORN

$$Ya = -0.1442 \times YP + 2.0307 \times YP \times Z - 0.8911 \times YP \times Z^2 \qquad (11)$$

COTTON

$$Ya = -0.7702 \times YP + 3.3800 \times Z \times YP - 1.6395 \times YP \times Z^2 \qquad (12)$$

SUGAR BEETS

$$Ya = 0.2836 \times YP + 1.3075 \times YP \times Z - 0.6782 \times YP \times Z^2 \qquad (13)$$

WHEAT

$$Ya = -1.0739 \times YP + 3.9694 \times YP \times Z - 1.8839 \times YP \times Z^2 \qquad (14)$$

Regional Water Response Functions

The regression equations derived in the previous section are only the national equations for a given crop. Water production functions reflecting regional climatological data are now developed.

Processing of climatological data

Weather conditions vary greatly between years. This study, however, reflects the "normal" or the average weather situation in each region. With this in mind, local weather data are collected and processed so that a regional average condition can be stated. These procedures can be amended for any type weather condition desired. For instance, if expected yearly rainfall is lower than normal, then the weather data can be processed to meet this assumption. This study, however, assumes a "normal" rainfall and pan evaporation at a given site.

The collection sites chosen depend on the location of the weather station and the number of years for which records are available. Average monthly precipitation is collected (only from weather stations having records for at least the past 20 years). Only stations located in the Western United States (producing areas 48 to 105, Figure 1) are included. Approximately 2,800 weather stations are represented in the data base.

For Class A pan evaporation, the same procedure is followed. Only 200 weather stations are incorporated into the data because many weather stations do not report Class A pan evaporation.

The weather stations' climatological data are aggregated to the county level by taking a simple average of the stations in the county. These data are further aggregated to the producing area by using a weighted

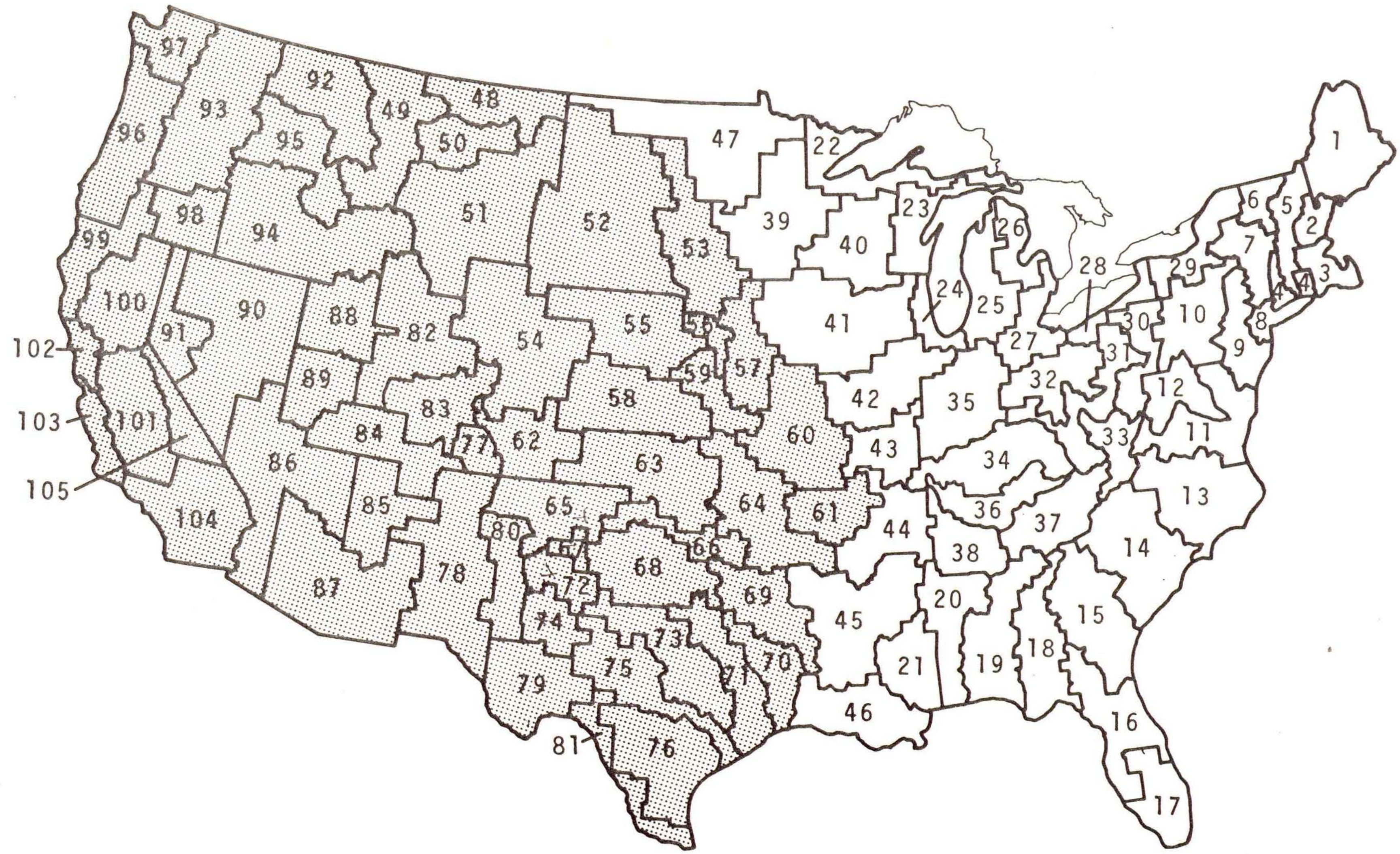

Figure 1. The 105 producing areas with irrigated lands in the West (producing areas 48-105)

average procedure. The weights are based on the number of irrigated acres in the county divided by the total number of irrigated acres in the producing area (Table 10). This procedure is used for both rainfall and Class A pan evaporation (Appendix C).

Deriving regional water production functions

Assume that we have the following national production function:

$$\frac{Ya}{Yp} = \beta_0 + \beta_1 Z + \beta_2 Z^2 \qquad (15)$$

where:

$$Z = \frac{W + Re}{Ep} \qquad (16)$$

Ya is the actual yield;

Yp is the potential yield;

W is the amount of water applied;

Re is the effective rainfall during the growing season;

Ep is the crop evapotranspiration; and

β_0, β_1, and β_2 are the national regression response coefficients derived previously (Chapter II).

By substituting (16) into (15) we get:

$$\frac{Ya}{Yp} = \beta_0 + \beta_1 \left[\frac{W + Re}{Ep}\right] + \beta_2 \left[\frac{W_2 + 2WRe + Re^2}{Ep^2}\right] \qquad (17)$$

If we expand (17), collect terms, and factor out W, we get:

$$\frac{Ya}{Yp} = \beta_0 + \frac{\beta_1 Re}{Ep^2} + \frac{\beta_2 Re^2}{Ep^2} + \left[\frac{\beta_1}{Ep} + \frac{2\beta_2 Re}{EP^2}\right] W + \left[\frac{\beta_2}{EP^2}\right] W^2 \qquad (18)$$

Thus, the regional water production function can be written as:

Table 10. Weights applied to each county in deriving data for producing area 101 (Central California)

County Name	Irrigated Land	County Weight[a]
	(acres)	(ratio)
Amador	5,224	0.0013
Calaveras	4,897	0.0013
Fresno	1,033,439	0.2644
Kern	671,512	0.1718
Kings	349,041	0.0893
Madera	208,451	0.0533
Mariposa	3,037	0.0008
Merced	343,590	0.0879
San Joaquin	441,370	0.1129
Stanislaus	295,900	0.0757
Tulure	548,525	0.1404
Tuolumne	3,068	0.0008
Total	3,908,054	

SOURCE: (Bureau of Census, 1972).

[a]Rounded to four decimal places.

$$Ya = \left[\alpha_0 + \alpha_1 W + \alpha_2 W^2\right] \quad YP \tag{19}$$

where:

$$\alpha_0 = \beta_0 + \frac{\beta_1 Re}{Ep} + \frac{\beta_2 Re^2}{Ep^2} \tag{20}$$

$$\alpha_1 = \frac{\beta_1}{Ep} + \frac{2\beta_2 Re}{Ep^2} \tag{21}$$

$$\alpha_2 = \frac{\beta_2}{Ep^2} \tag{22}$$

For each region and crop, effective rainfall (Re) and evapotranspiration (Ep) are determined from weather data. β_0, β_1, and β_2 are derived in previous sections. Therefore, we can express the actual yield (Ya) as a function of the water applied (W) and the potential yield (Yp).

III. APPLICATIONS

The application of the water production functions, developed in the previous sections, could be extended to many areas. This section presents three such applications. The first application allows us to derive a regional production function relating reduction in crop yield to a given reduction in water application. The second application derives a regional demand function for water by crop, and the third application demonstrates how this type of production function could be incorporated into linear programming models to derive crop production activities under various quantities of water and nitrogen application.

Reduced Water Application Functions

In many cases it might be desired to know the expected yield reduction for a given reduction in water applied. Thus, if farmers reduce their water application, say, by 50 percent, we would like to know the expected yield reduction in each region.

Assume that water applied is reduced by (1-R) percent. Then, the amount of water applied is:

$$W = (Ep - Re)R \tag{23}$$

where:

W, Ep, Re, and R have been defined previously.

From (19) we get:

$$\alpha_0 = \beta_0 + \frac{\beta_2 Re^2}{Ep^2} + \frac{\beta_1 Re}{Ep} \tag{24}$$

$$\alpha_1 W = \frac{\beta_1}{Ep} + 2\,\frac{\beta_2 Re}{Ep^2}\ (Ep - Re)\ R \tag{25}$$

$$\alpha_2 W^2 = \frac{\beta_2}{Ep^2}\,(Ep - Re)^2 R^2 \tag{26}$$

If we let: $D = \frac{Re}{Ep}$

$$F = \frac{Re^2}{Ep^2}$$

and substitute D and F into (24), (24), and (26), we obtain:

$$\alpha_0 = \beta_0 + \beta_1 D + \beta_2 F \tag{27}$$

$$\alpha_1 W = \beta_1 R - \beta_1 RD + 2\beta_2 RD - 2\beta_2 RF \tag{28}$$

$$\alpha_2 W^2 = \beta_2 R^2 - 2\beta_2 R^2 D + \beta_2 R^2 F \tag{29}$$

By substituting (27), (28), and (29) into (19), we obtain:

$$Ya = \left[\beta_0 + \beta_1(D + R - RD) + \beta_2(F + 2RD - 2RF + R^2 - 2R^2D + R^2F)\right] Yp \quad (30)$$

This function expresses the crop yield as a function of the regional weather variables (Re and Ep) and the reduction of water applied (R). Note that when R = 1 (no reduction in water applied) we have

$$Ya = \left[\beta_0 + \beta_1 + \beta_2\right] Yp \quad (31)$$

But when R = 0 (no water applied as irrigation) we have

$$Ya = \left[\beta_0 + \beta_1 D + \beta_2 F\right] YP \quad (32)$$

or

$$Ya = \left[\beta_0 + \beta_1 \frac{Re}{Ep} + \beta_2 \frac{Re^2}{Ep^2}\right] YP \quad (33)$$

To demonstrate the usefulness of this application, the reduction in yields of irrigated corn grain for the western states are presented (Figure 2). The reductions shown assume normal weather situations and water applied is only one-half of the water needed by corn according to its regional evapotranspiration.

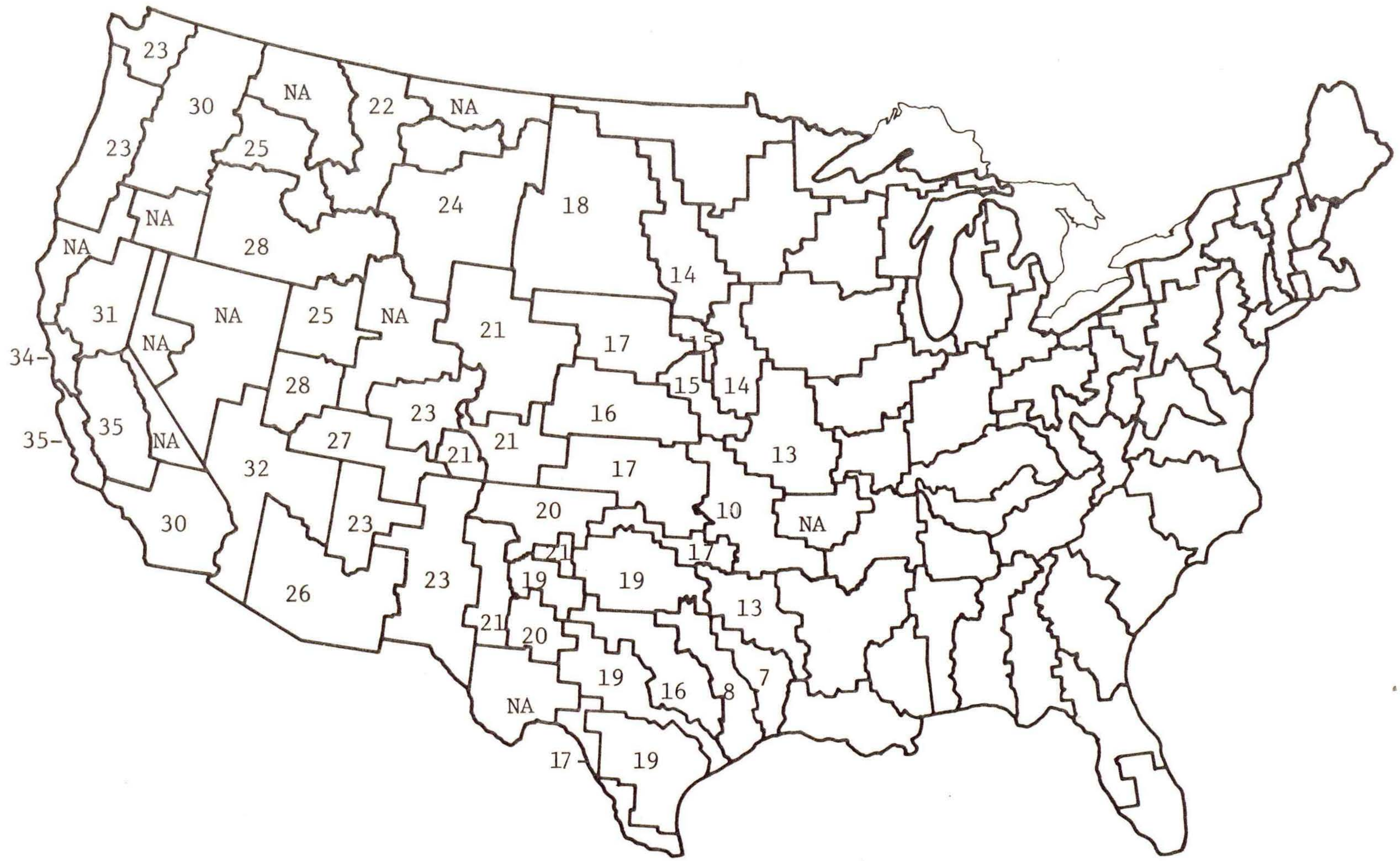

Figure 2. Percent reduction in irrigated corn yield under average weather conditions and a 50 percent reduction in water applied.

NA means Not Available.

Derived Demand Functions for Water

A demand function for water is very useful for determining water demanded by crop when crop or water prices change. Such a function would allow us to estimate the amount of water demanded in a given region when water prices are rising because of increased energy costs.

Assuming now that we have the following regional water production function (repeated equation 19):

$$Ya = (\alpha_0 + \alpha_1 W + \alpha_2 W^2) Yp \tag{34}$$

the marginal product of water is:

$$MP = \frac{\partial Ya}{\partial W} = (\alpha_1 + 2\alpha_2 W) Yp. \tag{35}$$

Profit maximization requires that farmers equate their marginal value product of water (MVP_w) to the price of water (Pw). Hence,

$$MVP_w = MP \times Py; \text{ and} \tag{36}$$

$$(\alpha_1 + 2\alpha_2 W) YP = \frac{Pw}{Py}; \tag{37}$$

where:

Py is the commodity price.

By substitution of α_1 and α_2 from equations (21) and (22), we obtain:

$$\left(\frac{\beta_1}{Ep} + \frac{2\beta_2 Re}{Ep^2} + \frac{2W\beta_2}{Ep^2} \right) YP = \frac{Pw}{Py} \tag{38}$$

Solving for W we get:

$$W = \left(\frac{Pw}{Py}\right) \times \left(\frac{Ep^2}{2\beta_2 YP}\right) - \frac{\beta_1 Ep}{2\beta_2} - Re \qquad (39)$$

Thus, the optimal amount of water applied is a function of the relative water to commodity prices, crop evapotranspiration, regional effective rainfall, and the potential crop yield. The above function is linear in prices. To demonstrate the use of the derived demand function, we use corn grain in region 101 (Central California).

Ep (yearly evapotranspiration) = 38.96 inches

Re (effective rainfall) = .34 inches

β_1 = 2.0307

β_2 = -0.8911

YP (estimated potential yield) = 99.96 bushels per acre

Using equation (39), the derived demand water function for corn in region 101 is:

$$W = 44.05 - \frac{8.52Pw}{Py}$$

Three water demand functions for corn price at $1.00 per bushel, $2.00 per bushel, and $3.00 per bushel, are shown in Figure 3. The demand for water is more elastic at the lower corn prices. But as corn prices increase the demand for water becomes more and more inelastic. Thus, as corn prices increase, we cannot expect farmers to substantially reduce the amount of water applied even when water prices increase substantially. For example, under $1.00 per bushel corn, doubling of water prices from $1.00 to $2.00 per acre-inch reduces water application by 32 percent.

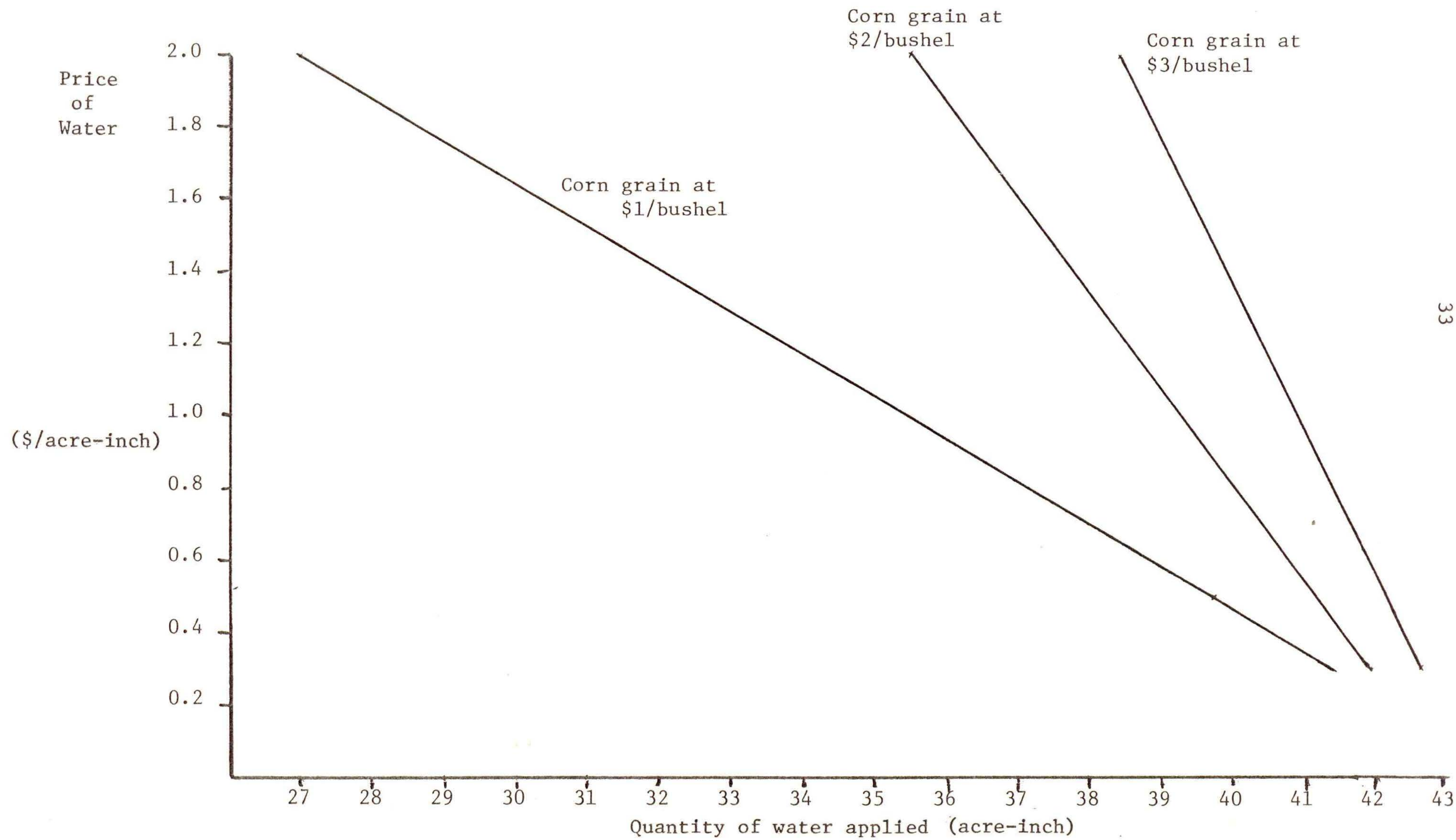

Figure 3. Derived demand functions for water under three corn grain prices for region 101 (Central California)

At the same time, with \$3.00 per bushel corn, increased water prices from \$1.00 to \$2.00 per acre-inch results in only a 7 percent reduction in the amount of water applied.

Application for Linear Programming Analysis

A major shortcoming of linear programming models (LP) is their assumed fixed technology. This is because many LP models define only one technology. For example, such a model might contain an irrigated corn activity in a given area requiring fixed levels of fertilizer and water. When the relative input prices change, farmers would use more of that input with the lower relative input price. If the relative input to output prices change, farmers would likely increase or decrease the level of inputs in response to the changes in the relative input-output prices. This application shows that we can approximate the input substitution relationships between inputs and outputs to derive the least cost technology.

Assume that two inputs (water and nitrogen fertilizer) are needed in the production of one output (irrigated corn grain). Under normal conditions, the two-variable production function can be presented as isoquants of increasing yields (Figure 4). To achieve the optimal quantity of each of the inputs used, their relative prices and the output price must be known. Unfortunately, under many LP formulations prices of inputs and outputs are endogenously determined by the model as shadow prices. Thus, prior to solving the model, it is not possible to know the optimal quantities or prices of the resources used.

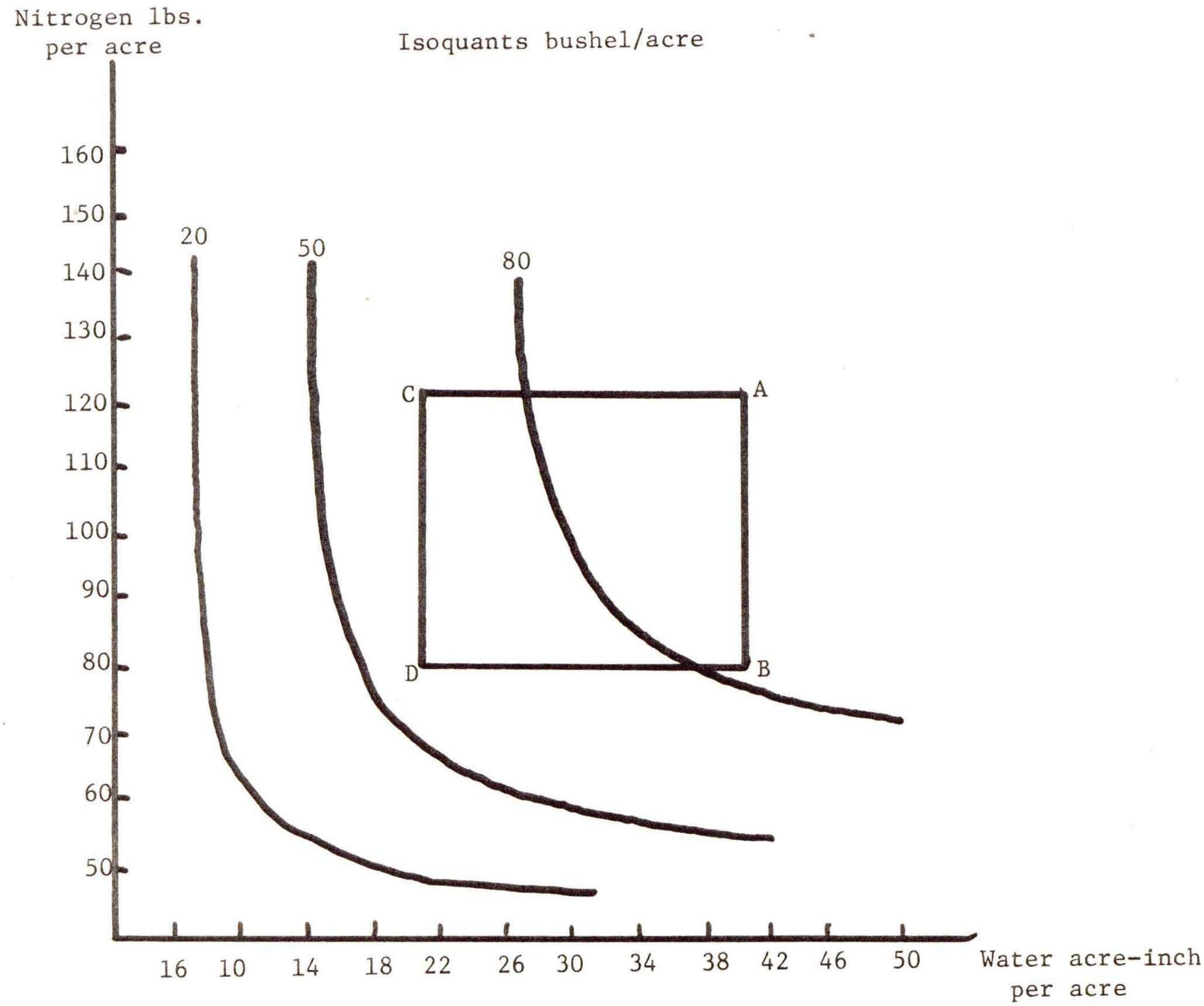

Figure 4. Corn production isoquants for water and nitrogen production function

If, however, we have a water production function and nitrogen production function we can define four different activities combining various rates of water and nitrogen application. For example, for producing area 101 we would obtain the following points (Table 11).

Table 11. Water-nitrogen and yield relationships for irrigated corn grain in producing area 101

Point	Water Applied (acre/inch/acre)	Nitrogen Applied (lbs./acre)	Corn Yield (bu./acre)
A	38.6	121.8	99.96
B	38.6	81.6	86.70
C	19.3	121.8	65.35
D	19.3	81.6	56.58

By varying the proportion of each of the above activities in the region, it is possible to approximate an activity with an optimal application of nitrogen fertilizer and water. This also would determine the optimal yield. For example, if 50 percent of the corn in the region is composed of activity A, 30 percent of activity B, and 20 percent of activity C, this would imply that the approximate optimum level of water applied is 34.7 acre-inch per acre; the approximate level of nitrogen fertilizer is 109.7 lbs. per acre; and the approximate optimum yield is 89.06 bushels per acre. Such a scheme would allow an approximation of any activity within the square ABCD (Figure 4). Even though the method is only an approximation, it still can be a substantial improvement for linear programming models with fixed coefficients.

IV. SUMMARY, LIMITATIONS, AND FUTURE RESEARCH

National water production functions are developed for four crops (corn, cotton, sugar beets, and wheat). These functions quantify the crop yield response to the amount of water applied. The functions are derived by regressing yield on a composite variable consisting of four components: potential yield, water applied, effective rainfall, and potential evapotranspiration.

The national functions are used in the development of regional water response equations which reflect regional climatological conditions. The regional functions are used in quantifying the impact of reduced water application on crop yield. Regional yield derived demand functions are also found. Finally, an illustration of how they can be used in a linear programming model is presented.

The regional functions developed in the study reflect average or "normal" weather conditions in the region. These functions might not be applicable for specific sites in the region or for a specific year as potential evapotranspiration and effective rainfall can vary greatly between sites and years. Also, the functions cannot deal with a specific water shortage during the growing season.

The functions quantify only the response of the crop yields to changes in water applied. Thus, they do not include interactions with other inputs such as fertilizers.

Additional research is needed before widespread use of these types of functions can be made. More experimental data are needed to improve the quantification of yield, effective rainfall, potential evapotranspiration, and potential yield.

Other characteristics of the functions should be explored. Water needs at various stages of the crop growth should be determined before functions such as these can be used in specific situations. It also would be useful to examine the applicability of these type equations to rainfed areas such as the Eastern United States. Finally, interaction between other limiting variables and water should be studied to determine if these interactions significantly affect the yield estimates.

APPENDIX A

Calculate Potential Evapotranspiration and Effective Rainfall

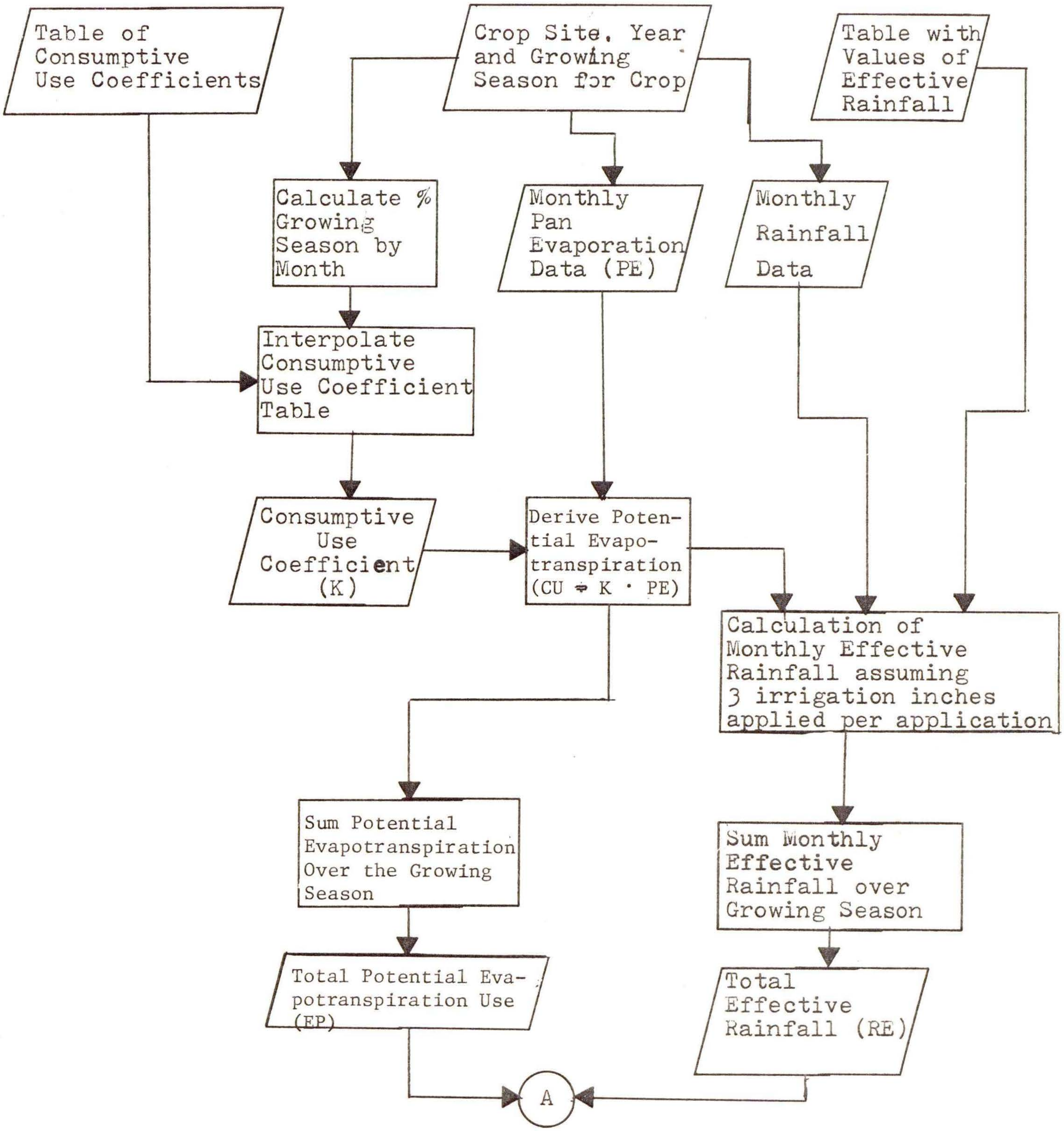

Figure A.1. Schematic diagram of the procedures used in deriving the general production functions

---- Derive General Production Functions ----

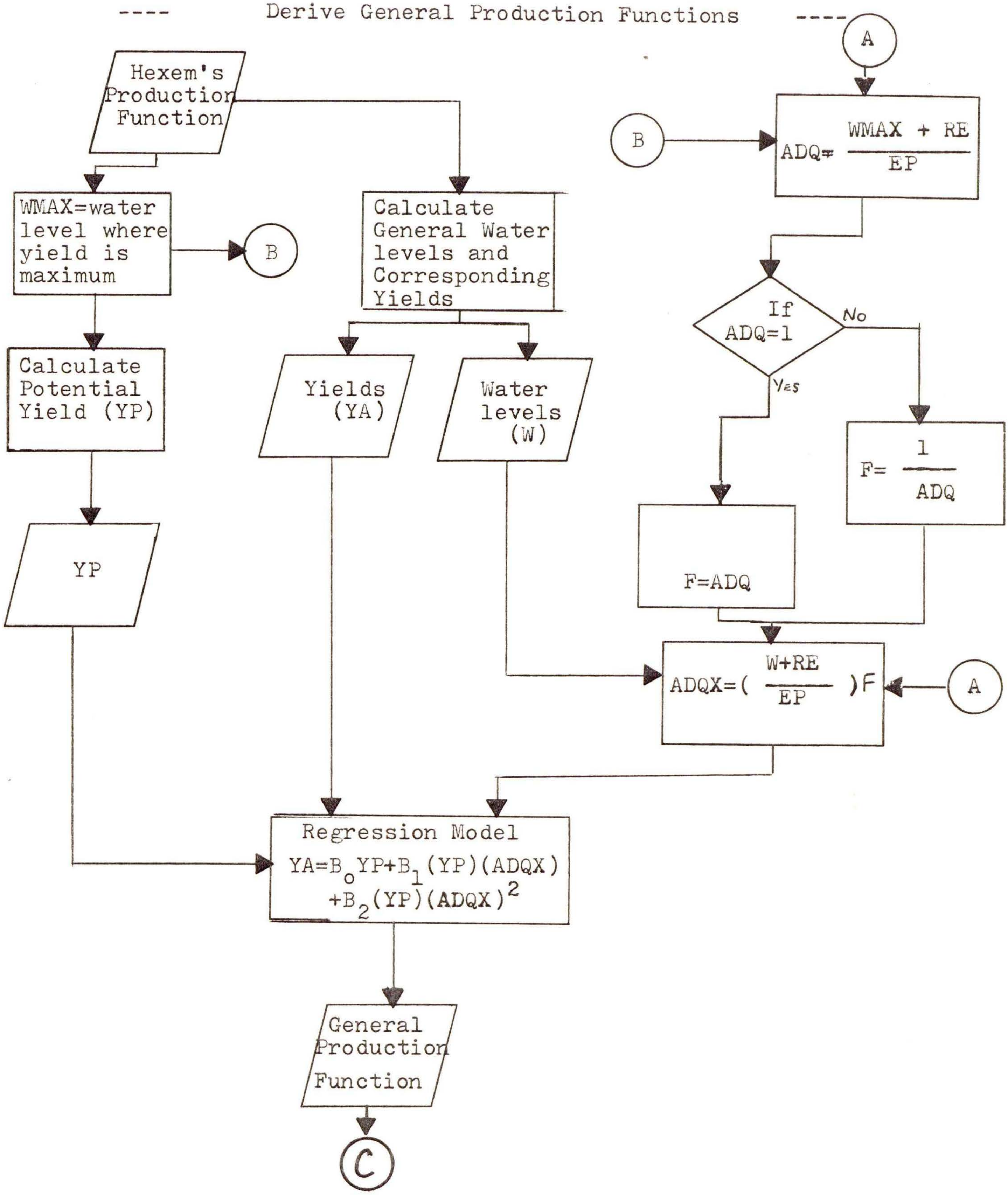

Figure A.1. Continued

APPENDIX B

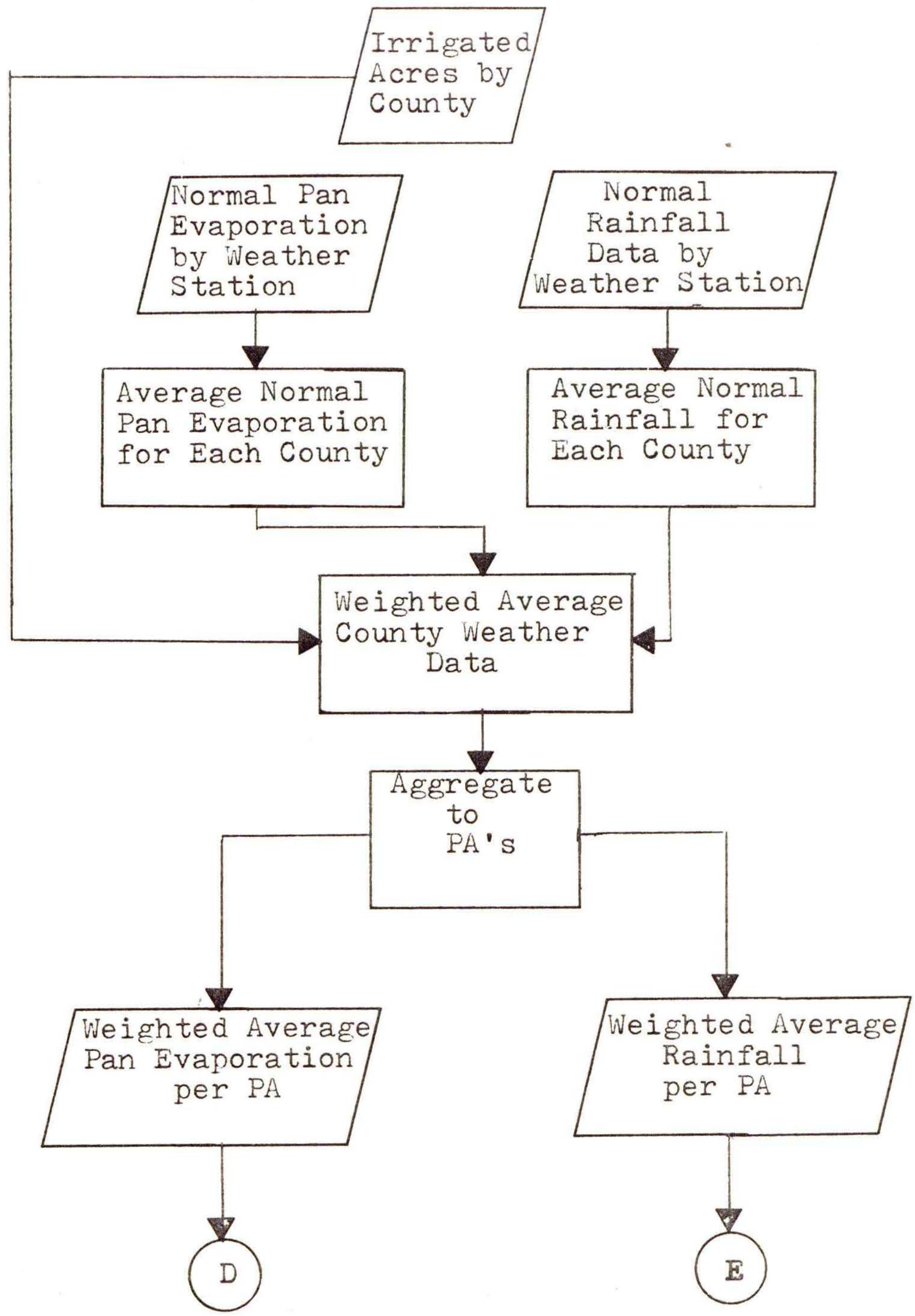

Figure B.1. Schematic diagram of the procedures used in determining regional production functions

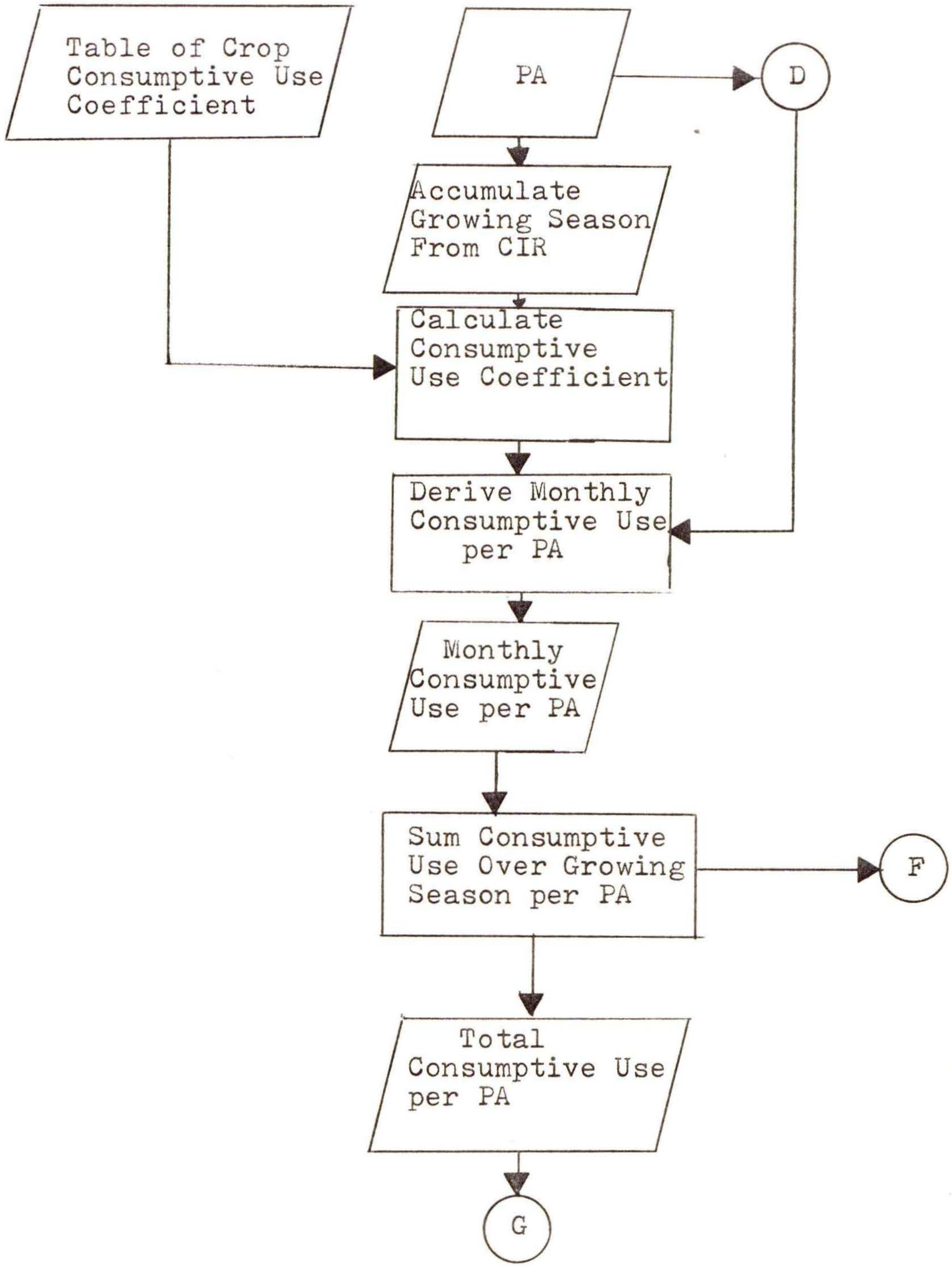

Figure B.1. Continued

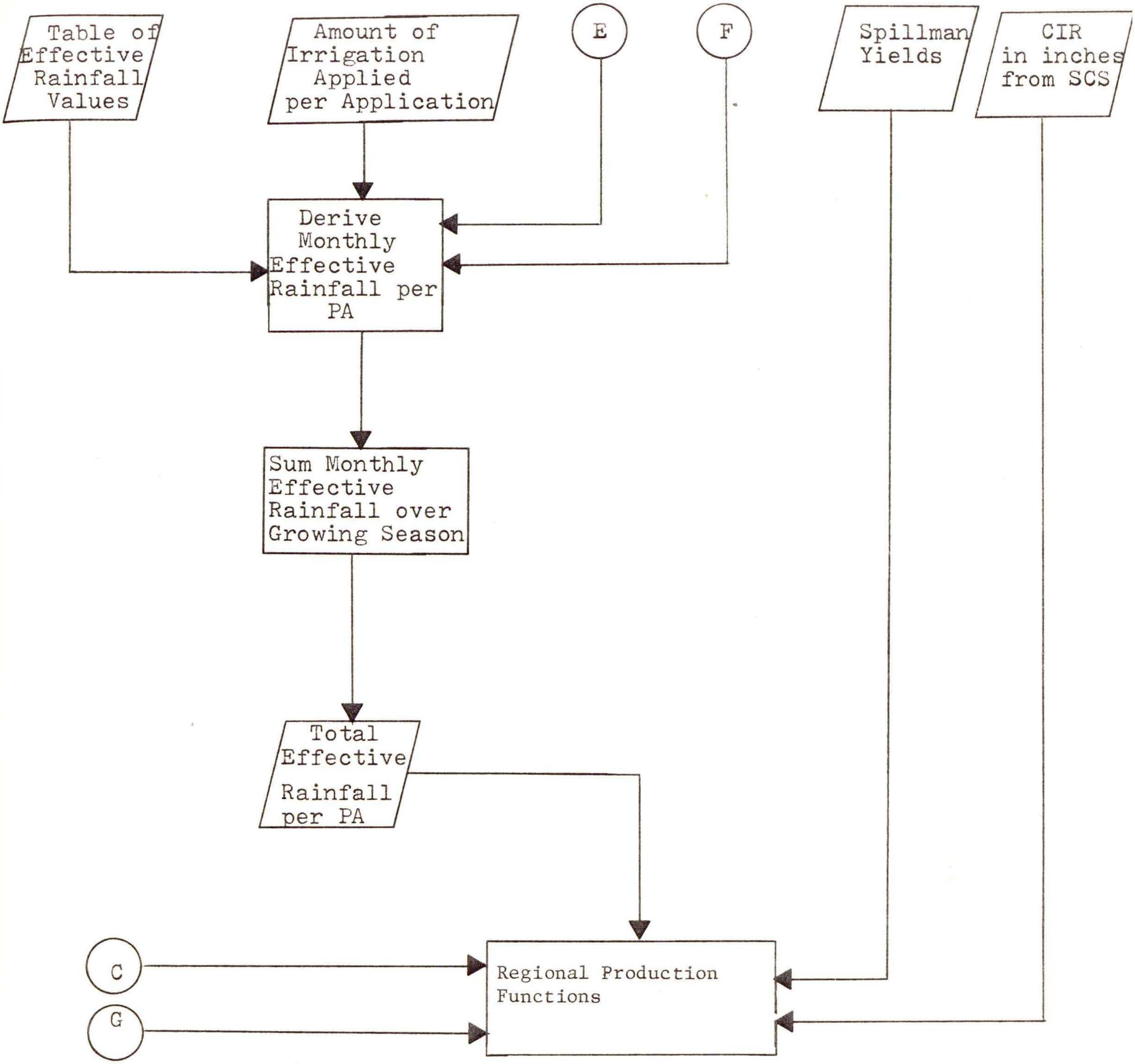

Figure B.1. Continued

APPENDIX C

Table C-1. Consumptive irrigation requirements[a] by producing area for the 12 major crops

Producing Area	Barley	Corn	Corn Silage	Cotton	Hay Legume	Hay Nonlegume	Oats	Grain Sorghum	Sorghum Silage	Soybeans	Sugar Beets	Wheat
					(acre feet per year)							
48	0.90	-[b]	1.10	-	1.60	1.50	0.90	-	-	-	1.50	0.90
49	0.90	1.10	0.99	-	1.45	1.34	0.90	-	-	-	1.40	0.90
50	0.90	-	0.90	-	1.40	1.30	0.90	-	-	-	-	0.90
51	1.07	1.30	1.24	-	1.81	1.61	1.07	-	-	-	1.76	1.04
52	0.66	0.93	0.82	-	1.37	1.24	0.65	1.10	1.00	1.10	1.02	0.68
53	0.65	0.93	0.78	-	1.30	0.90	0.62	0.97	0.90	0.85	-	0.59
54	0.74	1.18	1.07	-	1.70	1.50	0.85	1.11	1.06	0.80	1.62	0.77
55	0.80	1.30	1.23	-	1.80	1.40	0.80	1.10	1.10	0.70	1.80	0.88
56	0.70	1.30	1.30	-	1.80	1.30	0.70	1.00	1.00	0.80	1.70	0.70
57	-	1.19	1.19	-	1.77	1.30	0.70	1.00	-	0.74	-	0.69
58	0.70	1.23	1.10	-	1.73	1.48	0.77	0.87	0.89	0.70	1.45	0.72
59	-	1.29	1.28	-	1.80	1.30	0.70	0.99	0.97	0.80	-	0.68
60	-	0.79	0.81	-	1.28	-	0.60	0.72	-	0.60	-	0.59
61	-	0.90	0.90	0.72	1.30	-	0.70	0.80	-	0.60	-	0.70
62	0.80	1.30	1.30	-	2.00	1.80	0.80	1.20	0.80	-	1.80	0.80
63	0.80	1.25	1.12	-	1.81	1.70	-	0.96	0.82	-	1.38	0.81
64	-	0.80	0.76	0.91	1.22	-	-	0.71	-	0.84	-	0.57
65	1.02	1.42	1.05	1.27	2.33	2.35	1.11	1.10	1.09	1.10	0.80	1.03
66	-	1.40	1.11	1.02	2.01	-	-	1.10	1.10	1.10	-	1.00
67	2.10	1.70	1.30	1.30	3.90	3.90	2.10	1.30	1.30	1.30	1.30	2.10
68	-	1.50	1.32	1.26	2.74	-	-	1.37	1.35	1.24	-	1.62
69	-	0.89	0.76	0.78	1.40	1.69	0.60	0.90	-	0.56	-	0.88
70	-	0.68	-	0.79	-	1.70	-	0.70	-	-	-	-
71	-	0.92	0.75	0.90	1.80	2.30	-	1.37	2.02	-	-	-
72	1.61	1.79	1.02	1.30	3.49	1.80	1.95	1.02	1.06	1.30	1.40	1.84
73	-	1.07	1.80	1.20	2.31	2.79	-	1.22	1.15	0.90	-	1.69

Table C-1. Continued

Producing Area	Barley	Corn	Corn Silage	Cotton	Hay Legume	Hay Nonlegume	Oats	Grain Sorghum	Sorghum Silage	Soybeans	Sugar Beets	Wheat
						(acre inches per year)						
74	1.21	1.22	1.06	1.50	3.80	2.40	1.20	1.59	1.52	1.50	-	2.19
75	-	1.60	1.60	1.70	3.20	-	-	1.60	1.60	1.70	-	2.30
76	-	1.27	1.15	1.27	3.34	2.20	-	0.97	0.84	-	-	1.84
77	0.70	0.80	0.60	-	1.10	1.00	0.70	0.80	-	-	-	0.70
78	1.27	1.82	1.44	2.14	2.97	2.22	1.20	1.81	1.50	-	-	1.25
79	-	-	1.60	2.21	4.57	-	-	1.79	1.80	-	-	2.60
80	1.40	1.60	1.40	1.70	2.50	2.30	1.40	1.50	1.30	-	-	1.40
81	-	1.02	1.20	1.20	3.83	-	-	1.01	1.09	-	-	2.30
82	0.79	-	0.80	-	1.22	1.18	0.75	-	-	-	-	0.72
83	0.85	1.57	1.37	-	1.95	1.78	0.96	1.58	1.30	-	1.42	0.89
84	0.76	1.68	1.15	-	1.78	1.51	0.72	-	1.07	-	-	0.70
85	1.10	1.60	1.50	-	2.24	1.90	1.60	1.60	1.50	-	-	1.60
86	2.11	2.00	2.05	3.50	5.69	3.29	2.01	2.21	2.41	-	-	2.19
87	1.92	1.98	1.78	3.02	5.50	3.08	1.82	1.89	1.81	-	3.42	1.90
88	0.99	1.36	1.20	-	1.91	1.71	1.02	1.10	1.10	-	1.59	0.99
89	1.00	1.20	1.10	-	1.80	1.60	1.00	1.10	1.10	-	1.50	1.00
90	1.11	-	1.32	1.90	1.98	1.27	1.12	-	-	-	-	0.91
91	1.40	-	1.40	-	2.60	2.30	1.40	-	-	-	-	1.30
92	0.91	-	1.02	-	1.52	1.40	0.93	-	-	-	1.30	0.95
93	1.27	1.81	1.56	-	2.46	2.06	1.38	1.67	1.41	-	2.34	1.46
94	1.11	1.49	1.37	-	1.96	1.61	1.12	1.45	1.33	-	1.79	1.10
95	1.02	1.30	1.25	-	1.62	1.34	1.10	-	-	-	-	0.90
96	0.92	1.11	0.99	-	1.72	1.40	0.92	-	1.00	-	-	0.92
97	0.90	0.90	0.80	-	1.30	1.20	0.90	-	-	-	-	0.90
98	1.00	-	-	-	1.90	1.60	1.00	-	-	-	-	1.00
99	0.97	-	1.00	-	1.75	1.52	0.99	-	-	-	-	0.94

Table C-1. Continued

Producing Area	Barley	Corn	Corn Silage	Cotton	Hay Legume	Hay Nonlegume	Oats	Grain Sorghum	Sorghum Silage	Soybeans	Sugar Beets	Wheat
						(acre inches per year)						
100	0.40	1.10	1.00	2.00	2.80	2.80	0.40	1.10	1.00	-	2.00	0.40
101	0.86	1.59	1.65	2.50	3.04	2.21	0.76	1.66	-	-	2.45	0.85
102	0.50	1.50	1.50	1.50	2.00	1.90	0.50	1.50	-	-	1.50	0.60
103	0.50	1.70	1.50	2.50	1.90	1.90	0.50	1.70	-	-	1.60	0.50
104	3.16	2.70	2.50	3.10	5.33	-	2.75	2.70	2.70	-	3.00	2.57
105	-	-	-	-	4.00	3.90	2.70	-	-	-	-	2.70

SOURCE: (SCS, 1976).

[a]Consumptive irrigation requirements plus effective rainfall is equal to potential evapotranspiration.

[b]Not available.

Table C-2. Effective rainfall by producing area for the 12 major crops

Producing Area	Barley	Corn Grain	Corn Silage	Cotton	Legume Hay	Nonlegume Hay	Oats	Sorghum Grain	Sorghum Silage	Soybeans	Sugar Beets	Wheat
					(acre inches per year)							
48	5.63	-	7.01	-	7.59	7.36	5.63	-	-	-	7.58	5.63
49	5.00	4.82	4.82	-	6.73	6.42	4.99	-	-	-	6.49	5.00
50	5.77	-	3.35	-	7.82	7.49	5.77	-	-	-	-	5.77
51	3.65	4.73	4.48	-	5.15	4.96	3.62	-	-	-	4.78	3.56
52	6.75	6.43	6.43	-	9.40	10.31	6.77	6.46	6.46	6.57	6.66	6.75
53	6.86	9.69	9.68	-	14.15	13.55	6.81	8.57	8.56	9.77	-	6.69
54	5.36	5.60	5.58	-	6.96	7.35	5.36	4.89	4.85	3.34	7.25	5.39
55	7.53	9.92	9.92	-	12.73	12.14	7.55	9.78	9.78	6.05	12.24	7.55
56	8.40	11.88	11.88	-	16.32	14.32	8.40	10.73	10.73	7.41	12.15	8.40
57	-	12.84	12.88	-	18.39	15.87	8.66	11.44	-	12.22	-	11.34
58	9.25	10.50	10.38	-	14.25	12.58	9.70	10.19	10.10	6.71	12.82	13.28
59	-	12.06	12.06	-	17.65	15.17	8.51	11.04	11.04	7.63	-	10.37
60	-	9.62	9.52	-	16.24	-	8.11	12.09	-	9.13	-	13.81
61	-	7.75	7.75	9.58	15.47	-	7.85	9.53	-	9.54	-	7.85
62	4.95	6.76	6.76	-	8.99	8.57	4.95	5.80	5.66	-	8.25	4.95
63	7.14	9.28	9.17	-	13.95	12.17	-	9.57	9.46	-	10.67	13.93
64	-	14.18	11.63	11.22	17.92	-	-	11.09	-	10.75	-	10.96
65	11.46	7.88	7.82	7.66	15.10	14.27	11.30	7.42	7.53	7.40	9.23	11.30
66	-	10.26	8.07	9.67	23.97	-	-	7.40	7.42	9.66	-	18.09
67	7.30	8.67	5.71	7.57	16.19	15.49	7.30	5.71	5.71	7.57	9.36	7.30
68	-	9.06	9.20	8.65	20.39	-	-	9.01	8.88	8.66	-	13.01
69	-	11.10	10.88	13.75	10.88	22.14	10.05	7.56	-	13.91	-	10.18
70	-	17.45	-	14.18	-	25.29	-	13.40	-	-	-	-
71	-	20.44	20.43	15.17	26.19	24.86	-	25.46	25.27	-	-	-
72	8.15	10.49	8.89	9.34	17.18	13.09	8.13	8.45	8.71	8.03	9.91	8.13
73	-	8.84	8.20	7.84	18.46	19.13	-	8.44	8.54	7.23	-	12.91

Table C-2. Continued

Producing Area	Barley	Corn Grain	Corn Silage	Cotton	Legume Hay	Nonlegume Hay	Oats	Sorghum Grain	Sorghum Silage	Soybeans	Sugar Beets	Wheat
					(acre inches per year)							
74	4.39	7.01	6.95	6.66	13.91	11.40	4.44	6.90	6.91	6.65	-	6.29
75	-	10.03	10.03	10.23	25.57	-	-	10.03	10.03	10.09	-	13.86
76	-	7.79	7.79	7.84	20.13	16.48	-	7.89	7.92	-	-	8.49
77	2.94	3.77	3.22	-	4.11	4.36	2.94	3.25	-	-	-	2.94
78	3.07	6.85	6.21	6.79	8.97	6.90	1.01	6.57	5.79	-	-	4.74
79	-	-	5.22	8.22	11.63	-	-	5.91	5.91	-	-	3.77
80	4.67	7.63	6.11	9.63	9.78	9.39	4.67	8.65	7.48	-	-	4.67
81	-	7.91	7.79	7.42	17.99	-	-	9.47	9.41	-	-	7.01
82	3.19	-	3.29	-	4.52	4.33	3.18	-	-	-	-	3.18
83	4.73	5.98	4.95	-	7.39	7.81	4.80	4.31	4.88	-	4.47	4.83
84	4.17	4.03	4.60	-	5.54	4.61	4.17	-	3.99	-	-	4.17
85	2.81	6.20	6.17	-	7.81	7.48	1.16	6.22	6.18	-	-	1.16
86	2.11	1.78	1.72	1.84	2.62	2.20	2.12	1.77	1.33	-	-	3.04
87	2.14	5.68	5.65	5.79	7.08	6.62	2.15	5.70	5.63	-	4.80	2.84
88	3.28	4.34	4.34	-	5.46	6.25	3.28	4.25	3.09	-	4.24	3.28
89	2.25	2.43	2.46	-	3.99	3.93	2.25	2.46	2.46	-	3.01	2.25
90	3.92	-	2.91	2.88	4.74	3.89	3.93	-	-	-	-	3.51
91	1.56	-	1.53	-	1.95	1.88	1.56	-	-	-	-	2.14
92	5.40	-	5.64	-	7.00	6.68	5.39	-	-	-	5.88	6.39
93	3.53	2.66	2.25	-	4.46	4.30	3.52	2.25	2.26	-	3.52	4.17
94	3.13	3.10	3.10	-	4.63	4.37	3.13	3.07	3.09	-	3.66	3.12
95	3.63	3.95	3.95	-	5.55	4.73	3.62	-	-	-	-	5.17
96	3.85	4.30	4.34	-	8.67	8.28	3.85	-	3.75	-	-	3.85
97	3.72	3.52	3.52	-	7.16	6.85	3.72	-	-	-	-	3.72
98	2.35	-	-	-	3.65	3.49	2.35	-	-	-	-	2.35
99	2.90	-	2.52	-	4.15	3.99	2.84	-	-	-	-	2.97

Table C-2. Continued

Producing Area	Barley	Corn Grain	Corn Silage	Cotton	Legume Hay	Nonlegume Hay	Oats	Sorghum Grain	Sorghum Silage	Soybeans	Sugar Beets	Wheat
					(acre inches per year)							
100	4.15	1.21	1.22	2.41	6.20	6.00	4.15	1.31	1.22	-	2.41	2.58
101	1.44	0.34	0.31	1.68	4.16	3.04	1.44	0.36	-	-	1.37	3.97
102	0.41	0.45	0.45	1.73	4.56	4.36	0.41	0.45	-	-	1.73	1.54
103	3.34	0.30	0.26	0.49	4.05	3.87	3.34	0.30	-	-	1.54	3.34
104	5.10	3.74	7.89	1.70	3.75	-	5.14	4.02	0.30	-	1.57	5.18
105	-	-	-	-	3.12	2.95	2.58	-	-	-	-	2.58

Table C-3. Percent crop reduction by producing area for the 12 major crops

Producing Area	Barley	Corn Grain	Corn Silage	Cotton	Legume Hay	Nonlegume Hay	Oats	Sorghum Grain	Sorghum Silage	Soybeans	Sugar Beets	Wheat
						(percentage)						
48	26.0	-	19.0	-	24.0	24.0	28.0	-	-	-	15.0	26.0
49	28.0	22.0	21.0	-	24.0	24.0	28.0	-	-	-	16.0	28.0
50	25.0	-	24.0	-	22.0	22.0	25.0	-	-	-	-	25.0
51	35.0	24.0	24.0	-	29.0	29.0	35.0	-	-	-	18.0	35.0
52	18.0	18.0	17.0	-	20.0	18.0	18.0	19.0	19.0	-	14.0	19.0
53	18.0	14.0	13.0	-	14.0	11.0	17.0	16.0	15.0	14.0	-	16.0
54	23.0	21.0	21.0	-	26.0	24.0	26.0	22.0	22.0	-	16.0	24.0
55	19.0	17.0	16.0	-	20.0	17.0	19.0	16.0	16.0	17.0	14.0	19.0
56	16.0	15.0	15.0	-	17.0	14.0	16.0	14.0	14.0	16.0	14.0	16.0
57	-	14.0	14.0	-	15.0	13.0	15.0	13.0	-	10.0	-	12.0
58	14.0	16.0	15.0	-	18.0	17.0	15.0	13.0	13.0	16.0	13.0	10.0
59	-	15.0	15.0	-	16.0	14.0	15.0	13.0	13.0	16.0	-	12.0
60	-	13.0	13.0	-	13.0	-	-	10.0	-	-	-	8.0
61	-	-	-	-	-	-	-	-	-	-	-	-
62	26.0	21.0	21.0	-	25.0	24.0	26.0	21.0	18.0	-	16.0	26.0
63	20.0	17.0	16.0	-	18.0	19.0	-	14.0	13.0	-	13.0	11.0
64	-	10.0	11.0	15.0	11.0	-	-	11.0	-	-	-	10.0
65	17.0	20.0	17.0	25.0	21.0	21.0	18.0	18.0	18.0	20.0	12.0	17.0
66	-	17.0	17.0	19.0	13.0	-	-	18.0	18.0	17.0	-	10.0
67	35.0	21.0	22.0	25.0	26.0	26.0	35.0	22.0	22.0	22.0	14.0	35.0
68	-	19.0	18.0	23.0	19.0	-	-	18.0	18.0	20.0	-	22.0
69	-	13.0	11.0	12.0	18.0	12.0	11.0	16.0	-	6.0	-	16.0
70	-	7.0	-	12.0	-	11.0	-	9.0	-	-	-	-
71	-	8.0	7.0	12.0	11.0	14.0	-	9.0	12.0	-	-	-
72	29.0	19.0	16.0	22.0	24.0	19.0	32.0	16.0	16.0	21.0	14.0	31.0
73	-	16.0	22.0	23.0	18.0	20.0	-	18.0	17.0	18.0	-	23.0

Table C-3. Continued

Producing Area	Barley	Corn Grain	Corn Silage	Cotton	Legume Hay	Nonlegume Hay	Oats	Sorghum Grain	Sorghum Silage	Soybeans	Sugar Beets	Wheat
						(percentage)						
74	34.0	20.0	18.0	28.0	27.0	26.0	34.0	22.0	22.0	25.0	-	38.0
75	-	19.0	19.0	25.0	18.0	-	-	19.0	19.0	22.0	-	26.0
76	-	19.0	18.0	24.0	21.0	19.0	-	16.0	15.0	-	-	31.0
77	32.0	21.0	20.0	-	27.0	25.0	32.0	23.0	-	-	-	32.0
78	40.0	23.0	22.0	33.0	29.0	29.0	49.0	24.0	23.0	-	-	34.0
79	-	-	25.0	31.0	30.0	-	-	25.0	25.0	-	-	45.0
80	-	21.0	22.0	25.0	26.0	26.0	-	20.0	20.0	-	-	36.0
81	-	17.0	19.0	24.0	24.0	-	-	15.0	16.0	-	-	37.0
82	33.0	-	23.0	-	27.0	27.0	32.0	-	-	-	-	31.0
83	28.0	23.0	24.0	-	27.0	25.0	29.0	26.0	23.0	-	17.0	28.0
84	28.0	27.0	23.0	-	29.0	29.0	27.0	-	24.0	-	-	27.0
85	39.0	23.0	23.0	-	28.0	26.0	-	23.0	23.0	-	-	50.0
86	48.0	32.0	32.0	45.0	39.0	38.0	48.0	32.0	33.0	-	-	46.0
87	47.0	26.0	25.0	38.0	35.0	32.0	-	25.0	25.0	-	20.0	45.0
88	36.0	25.0	24.0	-	29.0	27.0	36.0	-	26.0	-	18.0	36.0
89	41.0	28.0	27.0	-	32.0	31.0	41.0	-	27.0	-	19.0	41.0
90	35.0	-	27.0	40.0	31.0	29.0	35.0	-	-	-	-	33.0
91	47.0	-	31.0	-	38.0	37.0	47.0	-	-	-	-	44.0
92	27.0	-	20.0	-	25.0	24.0	27.0	-	-	-	16.0	25.0
93	38.0	30.0	30.0	-	33.0	32.0	39.0	-	19.0	-	20.0	38.0
94	38.0	28.0	27.0	-	31.0	30.0	28.0	-	27.0	-	19.0	38.0
95	35.0	25.0	25.0	-	28.0	27.0	36.0	-	-	-	-	27.0
96	32.0	23.0	22.0	-	23.0	22.0	32.0	-	-	-	-	32.0
97	32.0	23.0	22.0	-	22.0	22.0	32.0	-	-	-	-	32.0
98	40.0	-	-	-	33.0	32.0	40.0	-	-	-	-	40.0
99	37.0	-	27.0	-	31.0	30.0	48.0	-	-	-	-	46.0

Table C-3. Continued

Producing Area	Barley	Corn Grain	Corn Silage	Cotton	Legume Hay	Nonlegume Hay	Oats	Sorghum Grain	Sorghum Silage	Soybeans	Sugar Beets	Wheat
						(percentage)						
100	18.0	31.0	31.0	41.0	32.0	32.0	18.0	31.0	31.0	-	20.0	25.0
101	44.0	35.0	35.0	45.0	35.0	35.0	43.0	35.0	-	-	22.0	31.0
102	50.0	44.0	44.0	42.0	31.0	31.0	50.0	44.0	-	-	21.0	39.0
103	25.0	35.0	35.0	48.0	32.0	32.0	25.0	35.0	-	-	21.0	25.0
104	44.0	30.0	29.0	45.0	38.0	-	43.0	30.0	45.0	-	33.0	42.0
105	-	-	-	-	37.0	37.0	49.0	-	-	-	-	49.0

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