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AGRICULTURAL, METEOROLOGIC AND HYDROLOGIC DROUGHT RELATIONS

Krishan P. Singh
Principal Scientist

Ganapathi S. Ramamurthy
Assoc. Professional Scientist

Illinois State Water Survey, Champaign, Illinois 61820, U.S.A.

SYNOPSIS

Agricultural and hydrologic droughts affect a large segment of the population. Both have their roots in meteorologic drought. Meteorologic drought occurs when precipitation over a large area is much below average for an extended period of time. Hydrologic drought (caused by low precipitation, substantial soil moisture deficits, ad high temperatures) occurs when streamflow in a given basin is much below average for several months and available water withdrawals are inadequate. Meteorologic and hydrologic factors can combine to substantially reduce crop yields, leading to an agricultural drought. Interrelationships among these droughts are investigated using long term historical data on precipitation, temperature, streamflow, and crop yields.

1.0 INTRODUCTION

1.1 The term *drought* usually refers to a meteorologic drought which occurs when precipitation over a large area is much below average for an extended period of time. However, there are also hydrologic and agricultural droughts, which have their roots in meteorologic drought. Hydrologic drought, caused by low precipitation combined with substantial soil moisture deficits and higher than average temperatures, occurs when streamflow in a given basin is much below average for several months and water available for withdrawals is inadequate. Meteorologic and hydrologic factors can combine to significantly reduce crop yields, leading to an agricultural drought. Agricultural and hydrologic droughts affect a large segment of the population. They cause economic distress to the farming community and affect the general lifestyle of the people living in the drought area.

1.2 In this paper, a framework for investigating the interrelationships among agricultural, hydrologic, and meteorologic droughts is suggested. A proper understanding of these relationships is essential for evaluating public policy programs designed to mitigate some of the problems associated with droughts, and for determining the economics of such programs. A database is developed that consists of time-series data on precipitation, temperature, streamflow, and crop yields for several basins and areas in Illinois.

1.3 To keep the analytical and statistical models simple and effective, the data set should be homogeneous or pertain to the same population. Thirteen hydrologically and meteorologically homogeneous regions in Illinois were identified on the basis of physiography, glaciations, soil types, and hydrology. A total of 23 drainage basins in Illinois were selected for this study. Relationships between agricultural yields and meteorologic factors are explored informally and regression equations relating runoff to meteorologic factors are developed for 4 study basins. Finally, some concluding comments and suggestions for future research are provided.

2.0 REGIONS FOR DROUGHT INDEX ANALYSIS

2.1 Physiography, glaciations, soil types, and hydrology were considered in delineating 13 regions for drought index analysis. The physiographic divisions of Illinois [3] and other information such as glaciations and drift thickness covering Illinois and generalized soil permeability were used to develop the regions. Hydrologic information available in publications [1,5,6] was also considered in the delineation of the drought regions. The 13 regions identified are shown in Figure 1. Twenty-three drainage basins were selected for analysis: three basins in region 5; two basins in each of regions 1, 2, 3, 4, 6, 8, 10, and 12; and one basin in each of regions 7, 9, 11, and 13. The locations of the study basins are shown in Figure 2. The relevant information is given in Table 1. The basin drainage areas vary from a minimum of 31.3 to a maximum of 2751 sq km.

Table 1. Basins: Selected Stream and Gaging Stations

Basin No	*Region*	*Stream and Gaging Stations*	*USGS No.*	*D.A., km²*	*Period of Record*
1	1	Hayes Creek at Glendale	03385000	49.5	10/50-9/75
2	1	Cache River at Forman	03612000	632	10/24-9/83
3	2	Beaucoup Creek near Matthews	05599000	756	10/45-9/80
4	2	Bonpas Creek at Browns	03378000	591	10/40-9/83
5	3	N.F. Embarras River near Oblong	03346000	823	10/40-9/83
6	3	Indian Creek at Wanda	05588000	95.0	10/40-9/83
7	4	Lake Fork near Cornland	05579500	554	10/48-9/83
8	4	Spring Creek at Springfield	05577500	277	10/49-9/83
9	5	Kickapoo Creek at Waynesville	05580000	588	10/48-9/83
10	5	Vermilion River at Pontiac	05554500	1500	10/42-9/83
11	5	Blackberry Creek near Yorkville	05551700	182	10/60-9/83
12	6	La Moine River at Colmar	05584500	1696	10/44-9/83
13	6	Bear Creek near Marcelline	05495500	904	10/44-9/83
14	7	Crane Creek near Easton	05582500	68.6	10/49-9/83
15	8	Spoon River at London Mills	05570000	2751	10/42-9/83
16	8	Pope Creek near Keithsburg	05467000	451	10/34-9/83
17	9	Terry Creek near Custer Park	05526500	31.3	10/49-9/75
18	10	Hickory Creek at Joliet	05539000	277	10/44-9/83
19	10	Poplar Creek at Elgin	05550500	91.2	10/51-9/83
20	11	Green River near Geneseo	05447500	2598	10/36-9/83
21	12	Coon Creek at Riley	05438250	220	10/61-9/82
22	12	Elkhorn Creek near Penrose	05444000	378	10/39-9/83
23	13	Apple River near Hanover	05419000	640	10/34-9/83

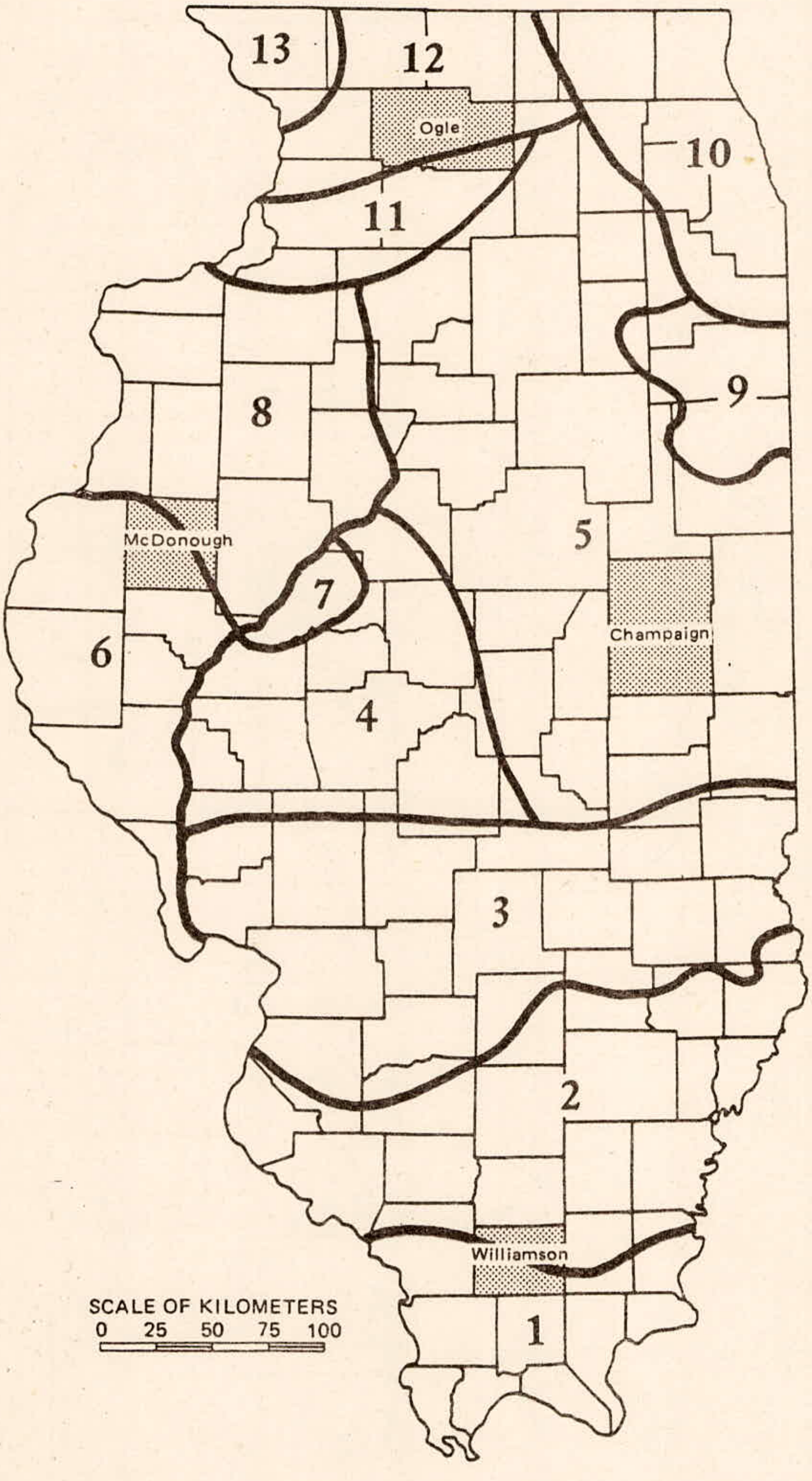

Figure 1. Regions identified for drought study

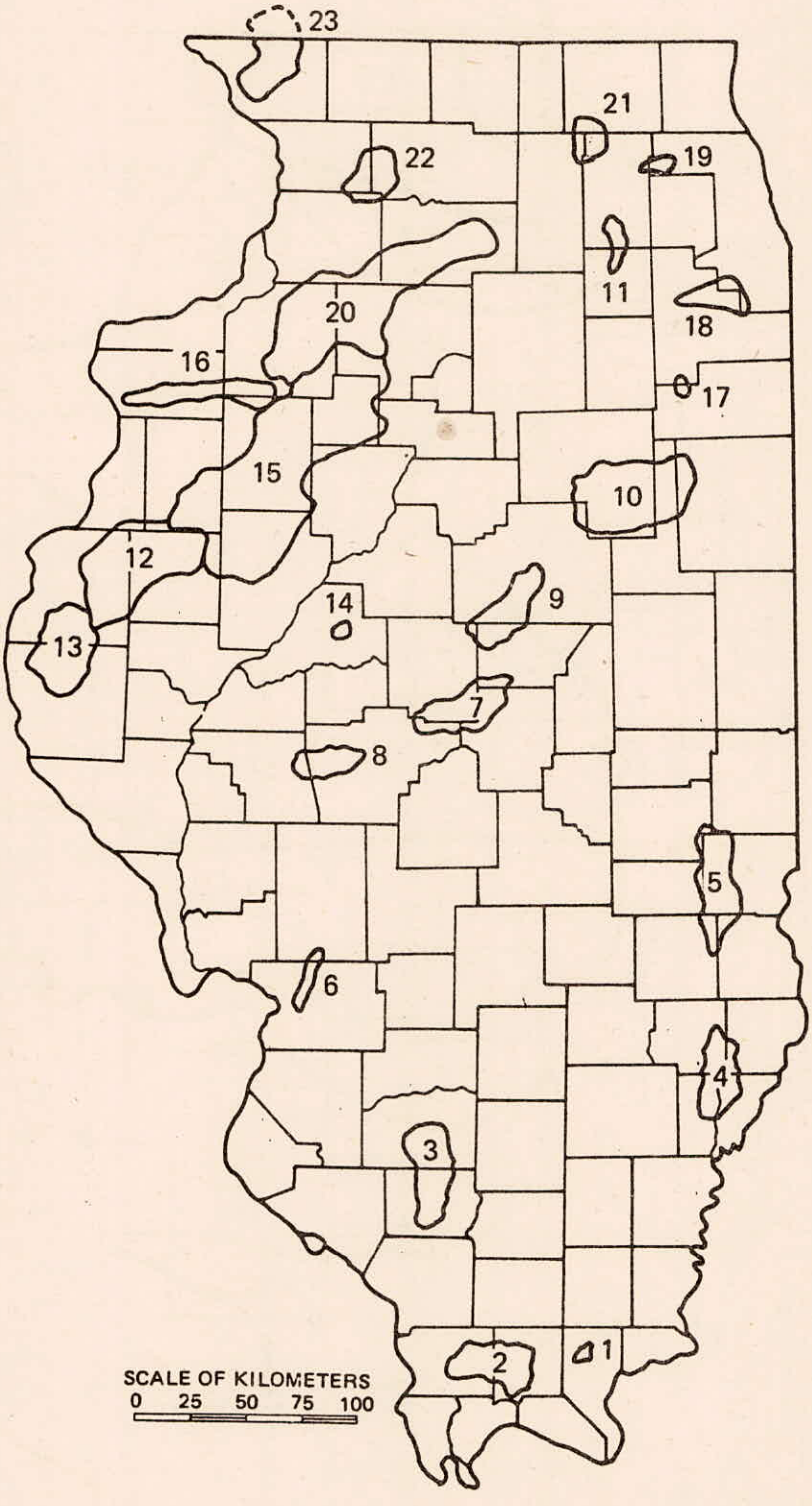

Figure 2. Locations of 23 study basins in Illinois

3.0 TEMPORAL RUNOFF DISTRIBUTIONS IN STUDY BASINS

3.1 The daily flow records available from the U.S. Geological Survey for the 23 study basins vary from a minimum of 23 years to a maximum of 59 years. A computer program was developed to read the daily flow data stored on tape and to calculate mean monthly and annual discharges in cms (cubic meters per second) for each year of record for each of the 23 study basins. Precipitation and temperature during the months of July and August significantly affect crop yields. To provide more information about runoff distribution in these two months, average discharges for the first half of both July and August were also calculated.

3.2 Monthly, annual, and semimonthly values of runoff in milimeters were calculated from the corresponding discharge in cms from the following expressions:

$$\text{Monthly runoff in mm} = \frac{\text{avg monthly discharge} \times \text{days in months} \times 86.4}{\text{D.A.}}$$

$$\text{Annual runoff in mm} = \sum_{i=1}^{12} (\text{monthly runoff in mm})_i$$

$$\text{Semimonthly runoff in mm} = \frac{\text{semimonthly avg discharge} \times 15 \times 86.4}{\text{D.A.}} \quad \text{(for July and August)}$$

3.3 The mean runoff for each month was calculated from the monthly runoff values for the years of record for each of the study basins. The ratios of monthly runoff to mean monthly runoff were calculated. These ratios are a measure of the variability of runoff about the mean value and thus indicate dry or wet conditions. The means of the annual runoffs were used in calculating ratios of annual runoff to mean annual runoff. Similarly, ratios were calculated for the first half of July and August.

4.0 TEMPORAL PRECIPITATION AND TEMPERATURE DISTRIBUTIONS IN STUDY BASINS

4.1 Values of daily precipitation and temperature from 55 raingage stations were used in this study. Forty-nine stations are long-term stations with records of 70 years or more, and six have 35 years of record. The monthly precipitation for each year of record at each of the 55 stations, as well as semimonthly precipitation for July and August, were computed. Similar information was developed for average maximum and minimum monthly (and semimonthly) temperatures.

4.2 Basin values of monthly (and semimonthly) precipitation and maximum/minimum temperatures were computed by using the Thiessen weights [4] for the raingage station values pertinent to a particular study basin. The precipitation ratios, or the ratio of precipitation for a particular month to the long-term average precipitation for that month, were developed for each month over the period of record for a study basin. The departures of a month's average maximum or minimum temperature from the long-term average maximum or minimum for that month were also computed.

4.3 The precipitation ratios provide information on above-normal or below-normal precipitation. The sequence of such ratios within a year or from one year to another indicates whether rainfall was average, above average, or below average for that month or year. The relative excess or deficit is indicated by the values of the ratio. Similarly, the temperature departures (equal to a month's average maximum/minimum temperatures minus the long-term average maximum/minimum temperatures) provide information on normal, relatively warm, or relatively cold months. Precipitation and temperature significantly affect runoff, other conditions being similar.

5.0 TEMPORAL DISTRIBUTION OF CROP YIELDS IN STUDY BASINS

5.1 Corn and soybean yields in terms of kilograms/hectare (kg/ha) for each of the 102 counties in Illinois were developed from the data on crop production and acreage published by the Illinois Cooperative Crop Reporting Service for the years 1927 through 1985. As an example, the crop yield versus year curves for Champaign, Williamson, Ogle, and McDonough counties are shown in Figure 3 for corn. These curves show the temporal and spatial variation in crop yield in Illinois. The corn yield varied from a low of 2007 to a high of 8254 kg/ha in Ogle County in northern Illinois, and from 565 to 6529 kg/ha in Williamson County in southern Illinois. The soybean yield varied from 740 to 2959 kg/ha in Ogle County and from 471 to 2065 kg/ha in Williamson County. The yields in drought years were depressed by varying amounts from one county to another. The avearge crop yields have tripled or quadrupled over a period of 60 years because of advances in agricultural practices, land management, fertilizers and seeds.

5.2 To assess the crop yield for each basin, counties were weighted according to the ratio of county area in a basin to the total basin area. If the percent of a county's area in a basin was very small, the weight for that county was neglected. The corn and soybean yields for each year of record were compiled for each of the 23 study basins on the basis of the applicable county weights and yield data.

6.0 AGRICULTURAL AND METEOROLOGIC DROUGHT ANALYSES

6.1 The information developed on the temporal distributions of precipitation, temperature, and crop yields in the 23 study basins was used to examine cause-and-effect relationships between meteorologic factors and crop yields. The objective of the analyses was to establish various sets of meteorologic conditions that caused abnormal departures from expected or normal crop yields, both positive (higher than normal) and negative (lower than normal). The problem has been approached in a rather informal and exploratory manner.

6.2 Crop yield trends for each basin for the period of record were developed to establish expected yield curves and to identify years in which the observed or realized crop yields were much lower or much higher than the value provided by the expected yield curve. Several trend models were examined. The model found to be best in terms of adjusted R^2 (coefficient of determination) and standard error of the estimate was the second degree polynomial of the form:

$$y = a + bx + cx^2$$

in which

y = crop yield in kg/ha
x = year ($x = 1$ for 1927; $x = 56$ for 1982)
a, b, c = regression constants

The 2nd degree equation was found to fit the data better than the 1st degree and 3rd degree polynomial equations for all 23 study basins.

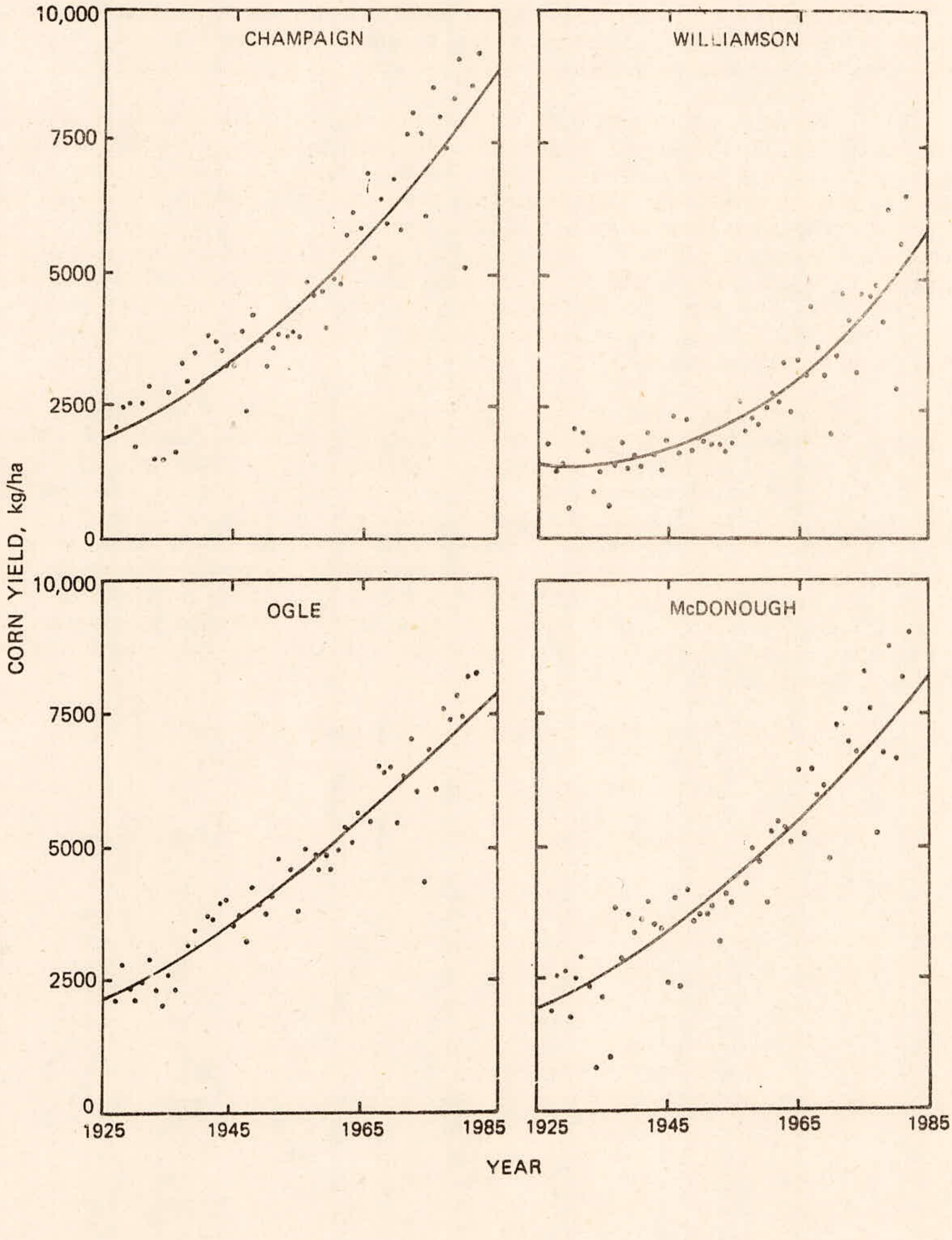

Figure 3. Corn yields for 4 counties in Illinois

6.3 The difference between observed and expected yield is termed the departure in yield. This departure can be positive or negative. Departures in corn yields for each of the 23 study basins for the period of record were determined. The absolute values of the departures for each study basin were ranked in descending order of magnitude. The five highest yield departures were selected for each basin for further analyses.

6.4 The data set consists of 5 observations for each basin, or a total of 115 observations for the 23 basins. As an example, relevant data pertaining to the analyses are given in Table 2 for Basin 2 -- Cache River at Forman. In this table DY refers to departure in corn yields; the negative signs refers to yield deficits. The relevant period for corn production is from March through September. The precipitation ratio PR, the temperature deviation DT in °C, and the runoff ratio QR are given for each month for the period March through September. Since July and August represent a critical period in corn production, the semimonthly values for the first half of these months are reported under J1 and A1. These ratios and deviations are calculated with respect to long-term averages, as explained earlier.

6.5 Out of this total of 115 observations 15 cases had missing data. The remaining 100 observations were analyzed case by case to classify the meteorologic conditions prevalent during May through September. The precipitation and temperature statistics for each month were categorized as low, average, or high. Six distinct groups were identified for classification of negative departures (deficit yields) and four groups for positive departures (surplus yields). These groups are represented as G1- to G6- and G1+ to G4+ in Figure 4. G6- contains events that did not fit any group G1- to G5-. This group may perhaps represent a combination of conditions pertaining partially to two or more groups, as well as other factors such as crop diseases, that lead to severe agricultural yield deficits. Similarly, group G4+ may represent a partial combination of conditions pertaining to groups G1+ to G3+.

Table 2. Corn Yield Departures and Climate and Runoff Conditions

Basin 2

*R**	*DY*	*Year*		*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Jul1*	*Aug1*
1	-2007	1980	PR	1.13	.67	.43	.70	.91	.13	.71	.66	0.00
			DT	-2.8	0	1.1	1.1	3.3	4.4	2.8	4.4	3.9
			QR	.90	.76	.08	.11	.39	.07	.15	.50	.08
2	-1756	1970	PR	1.32	1.59	1.32	1.85	.34	.69	.93	.22	.88
			DT	-3.3	1.1	2.2	-1.1	-0.6	0	1.7	-0.6	-0.6
			QR	1.44	2.06	1.99	1.66	.04	.21	.23	.05	.21
3	1317	1967	PR	.69	.43	1.23	.71	1.43	.78	.88	.73	1.09
			DT	3.3	2.2	-0.6	0	-2.2	-2.2	-1.7	-4.1	-2.2
			QR	.57	.09	.92	.11	1.99	2.94	.52	2.81	5.66
4	1254	1979	PR	1.52	1.62	.93	.78	1.58	.90	.57	1.23	.96
			DT	0	-1.1	-1.1	0	-1.7	-1.1	-0.6	-1.1	-1.1
			QR	2.19	2.87	1.03	.21	.34	.76	.22	.32	.97
5	-1129	1978	PR	1.34	.79	.45	.36	.59	2.15	.09	1.13	.37
			DT	-3.3	1.1	-0.6	0	0.6	1.1	1.1	-0.6	0
			QR	1.81	.46	.11	.07	.06	.89	1.05	.05	.08

*R denotes rank

G1- = Low P_1 & P_2, High T_1 & T_2

G2- = Low P_1, Avg or High T_1 and T_2

G3- = Low P2, Avg or High T_1 and T_2

G4- = High P1, Avg or High T_1 and T_2

G5- = High P3, Avg or High T_1 and T_2

G6- = Other Combinations

G1+ = Low T_1 & T_2

G2+ = High P_2, Low T_1 & T_2

G3+ = Low P_1, Low T_1 & T_2

G4+ = Other Combinations

P_1 May & June Precipitation

P_2 July & August Precipitation

P_3 September Precipitation

T_1 May & June Temperature

T_2 July & August Temperature

	PR	ΔT, C°
Low	<0.8	<-1.4
Avg	0.8 - 1.2	-1.4 - +1.4
High	>1.2	>+1.4

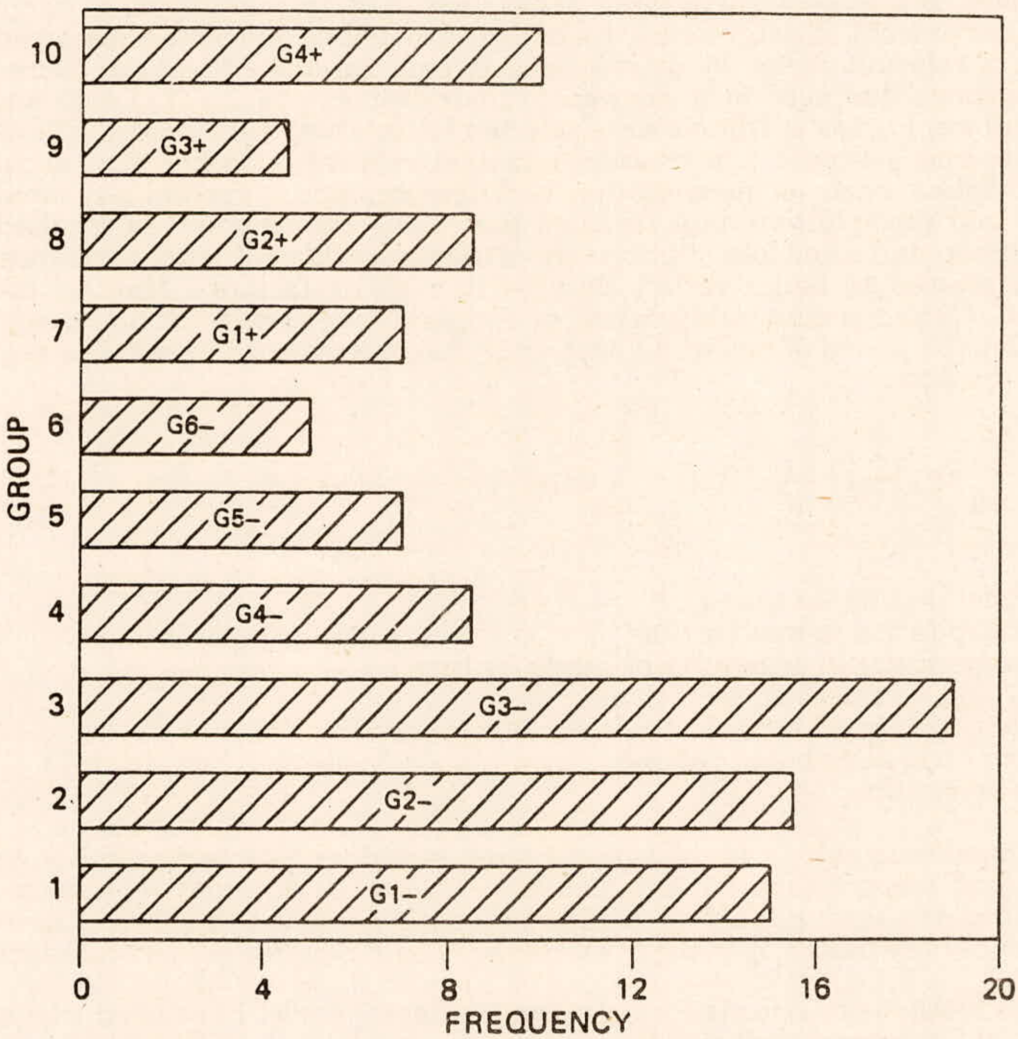

Figure 4. Classification of extreme corn-yield departures and associated frequencies

6.6 The results of the analyses are presented as a bar diagram in Figure 4. The classification of the events into 10 groups and the categorization of precipitation and temperature as low, average, or high are explained in that figure. As an example, consider group G3-, which has a frequency of 19. This means that out of the 100 cases examined, 19 of the events were due to low P2, or below-average precipitation during the months of July and August, in combination with average or high temperature during the period May through August. Similarly group G1+ has a frequency of 7. This means that 7 out of the 100 events were during a period of low T1 and T2 or lower-than-average temperatures during the period May through August, with average precipitation during the same period.

7.0 RELATIONS BETWEEN HYDROLOGIC AND METEOROLOGIC FACTORS IN STUDY BASINS

7.1 A hydrologic drought has its roots in meteorologic drought -- a prolonged period of very little or much-below-average rainfall. To what extent is a hydrologic drought affected by meteorologic factors? What level of carry-over effects of temperature and rainfall are present in determining hydrologic drought or deficient stream runoff? Is temperature a relevant factor in determining stream runoff? These are some of the empirical questions that need to be answered. Four drainage basins (2, 12, 18 and 20, in Table 1) in different areas of Illinois were selected for this empirical study. The objective was to define and estimate a regression equation relating monthly stream runoff to explanatory factors such as precipitation and temperature. Preliminary analysis of temperature and precipitation data revealed that using monthly values resulted in too much aggregation and some loss of information. Semimonthly values of temperature and precipitation seemed to better reflect changes in climatic factors. Monthly values of stream runoff (Q) and semimonthly values of temperature (T1 and T2) and precipitation (P1 and P2) for the period of record for each study basin were used to estimate regression equations of the form:

$$Q_j = a_j + \sum_{i=0}^{N} (b1_{j,i}\, P1_{j-i} + b2_{j,i}\, P2_{j-i}) + \sum_{i=0}^{N} (c1_{j,i}\, T1_{j-i} + c2_{j,i}\, T2_{j-i}) + e_j \qquad (\text{for } j = 1, 12)$$

where

- Q_j = runoff in mm for time j
- P_j = precipitation in mm for time j
- T_j = temperature in degrees Centigrade for time j
- a_j , $b_{j,i}$, $c_{j,i}$ = regression coefficients
- j = time period (j = 1 for Jan., j = 12 for Dec.)
- e = error term distributed $N(0,\sigma^2)$
- i = lag in months

Assuming a maximum carry-over of 3 months and including both semimonthly values of temperature and precipitation for any month, a total of 14 different regression models can be identified as shown in Table 3. These 14 models are estimated for each month for each of the four study basins by using the Ordinary Least Squares (OLS) procedure.

7.2 Various methods or criteria for selecting the "best" model have been suggested in the econometric literature. Some of the more common informal ad hoc decision rules or criteria are the adjusted R^2 or R^2 criterion, the Mallows (Cp) criterion, and the Amemiya Prediction criterion (PC) [2]. For selecting among models with the same dependent

Table 3. Combinations of Variables Used in the Development of Regression Models Relating Runoff to Climatic Factors

Model	*Variables included in the regression*
1	P1 P2
2	P1 P2 T1 T2
3	P1 P2 P3 P4
4	P1 P2 P3 P4 T1 T2
5	P1 P2 P3 P4 T1 T2 T3 T4
6	P1 P2 P3 P4 P5 P6
7	P1 P2 P3 P4 P5 P6 T1 T2
8	P1 P2 P3 P4 P5 P6 T1 T2 T3 T4
9	P1 P2 P3 P4 P5 P6 T1 T2 T3 T4 T5 T6
10	P1 P2 P3 P4 P5 P6 P7 P8
11	P1 P2 P3 P4 P5 P6 P7 P8 T1 T2
12	P1 P2 P3 P4 P5 P6 P7 P8 T1 T2 T3 T4
13	P1 P2 P3 P4 P5 P6 P7 P8 T1 T2 T3 T4 T5 T6
14	P1 P2 P3 P4 P5 P6 P7 P8 T1 T2 T3 T4 T5 T6 T7 T8

Note:

P1, P2, T1 and T2 refer to the semimonthly precipitation and temperature values for current month.
P3, P4, T3 and T4 refer to the semimonthly precipitation and temperature values with one month lag.
P5, P6, T5 and T6 refer to the semimonthly precipitation and temperature values with two months lag.
P7, P8, T7 and T8 refer to the semimonthly precipitation and temperature values with three months lag.

variable, the adjusted R^2 criterion is a simple yet adequate decision rule for selecting the 'best' model. This statistic is estimated by most major statistical programs and is therefore readily available.

7.3 The equations estimated for the four study basins provide some insight into the extent of carry-over effects of precipitation and temperature in determining stream runoff. The carry-over effects are generally more pronounced for larger drainage areas; however, they are also a function of drainage characteristics, soil type, and other channel properties. Seasonal effects are also evident, with the number of lagged precipitation and temperature variables required to determine runoff changing with time.

7.4 The regression equations estimated are linear and additive. Other structural forms relating runoff to precipitation and temperature were also examined. The log form of the models was estimated for one study basin and the results were not satisfactory. More complex structural forms with both additive and multiplicative components in the regression equations may provide better representation of the interactive effects of precipitation and temperature on runoff.

8.0 CONCLUSIONS

8.1 A framework for investigating the interrelationships among agricultural, hydrologic, and meteorologic droughts has been developed and applied to 23 study basins in Illinois. Data on daily precipitation, daily minimum and maximum temperatures, daily stream runoff, and annual corn and soybean crop yields for each of the 23 study basins were used in developing the interrelationships among the three types of drought. Some of the research findings are as follows:

8.2 1. There are some years in which crop yields have deviated significantly from expected trends depending on meteorologic conditions.

8.3 2. Stream runoff decreases at a faster rate than the decrease in precipitation. This decrease in runoff becomes more pronounced if prevailing temperatures are much higher than normal.

8.4 3. Agricultural and hydrologic drought depend on the severity and duration of the meteorologic drought. Agricultural drought causes considerable damage to crop production and yields. Hydrologic drought can cause problems in meeting different water demands such as for potable water, water based recreation, and irrigation.

8.5 4. Investigation of the effect of meteorologic factors on agriculture yielded a set of 10 scenarios of precipitation and temperature conditions during the months May through September that can cause abnormal departures in crop yields.

8.6 5. A set of regression equations relating monthly runoff to semimonthly precipitation and temperature were developed and estimated for each of four selected study basins. These equations reveal that the extent of carry-over effects of precipitation and temperature on runoff are different for different months and also vary across basins. Generally for large drainage areas the number of lagged variables needed to estimate runoff is higher than the number needed for small drainage areas.

8.7 The general framework developed in this study is simplistic and provides the first step in investigating the interrelationships among the three types of drought. The informal approach has obvious limitations. The models developed cannot be directly used to evaluate public policy programs designed to mitigate problems associated with drought. However, this approach will form the basis for the design of formal models, by allowing the researcher to understand the data and incorporate all available information in such models.

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