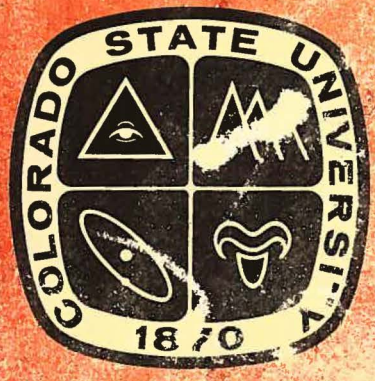
USE OF THE PALMER INDEX AND OTHER WATER SUPPLY INDEXES FOR DROUGHT MONITORING IN COLORADO

N. J. Doesken, J. D. Kleist, and T. B. McKee



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DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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Nolan J. Doesken, John D. Kleist, and Thomas B. McKee

Colorado Climate Center
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523

(303) 491-8545

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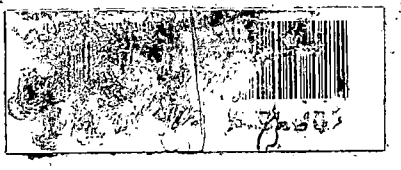

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Table of Contents

List of Figures

List of Tables

Use of the Palmer Index and Other
Water Supply Indexes for Drought Monitoring
In Colorado

Abstract

The Colorado Drought Response Plan of 1981 assigned drought monitoring responsibilities to a special intergovernmental technical working group called the Colorado Water Availability Task Force (WATF). The intent of this group is to use existing data sources and information products to monitor Colorado's water supplies. The information assembled and interpreted by the WATF is then used by State decision makers to guide State government's response to drought.

The Palmer Index, developed in the 1960's, has become a credible tool for monitoring drought and assessing drought severity on the national scale. It reasonably depicts soil moisture conditions using a simple hydrologic balance accounting for precipitation, evapotranspiration, runoff and soil moisture recharge. However, experiences of the WATF have revealed that Palmer Index values, currently generated weekly through the growing season by the National Climatic Data Center for 5 climatic divisions in Colorado, were only marginally useful for drought monitoring. The regions were too large and climatically diverse, and input temperature and precipitation data were not adequately controlled to produce consistent and meaningful results.

With the encouragement and cooperation of the WATF this project was undertaken to adapt the Palmer Index model to Colorado. The original program was brought to Colorado, the state was broken down into 25 climatically similar regions, and a simple routine for adjusting input data to correct for missing data and station moves was implemented. The

existing model was then used to generate 30 years of monthly Palmer Index values for all 25 regions of the state.

A thorough examination of these new Palmer Indexes has been performed. Comparisons with the original indexes show noticeable differences and considerable small scale detail which previously could not be resolved. With the new smaller regions it is now reasonable to use contour analysis of Palmer Index values to visually describe local variations in drought severity across Colorado. Two case studies were conducted to show how the new indexes compared to original index values during severe drought situations: 1) the end of the 1956 drought on the Eastern Plains, and 2) the 1976-1977 winter drought in the Colorado mountains.

A particular application of the Palmer Index was given special attention. Palmer Index values were correlated with dryland winter wheat yields. The best correlations with annual yields were obtained using June 1 or July 1 Palmer Index values. Good correlations were obtained in most of the major wheat growing areas but especially in the northeastern counties of Colorado. Better correlations were obtained using indexes calculated for the new areas than were obtaining using the original index values.

The WATF agreed that the capability to calculate Palmer Indexes here in Colorado, with our own choice of climatic divisions, greatly increases the utility of this drought monitoring tool. More refinements are possible, and further study conducted jointly with agricultural interests would be desirable. This index is already of sufficient value to the WATF to justify the low cost required to produce it on a routine monthly basis.

Use of the Palmer Index and Other Water Supply Indexes for Drought Monitoring in Colorado

I. INTRODUCTION

Drought is not a rarity in Colorado. It happens -- all too often. When it does occur it can have devastating effects.

Little skill has been shown in forecasting drought episodes long in advance. (Drought, for the purposes of this study shall be defined as any prolonged -- a few months or longer -- period of dry weather resulting in reduced supplies of available water.) Predicting local variations; the difference in drought severity between adjacent counties during a large scale drought period; is essentially impossible. It is possible, however, to monitor the emergence of drought and to anticipate possible impacts.

Serious droughts take months and sometimes even years to materialize. Hence, by monitoring the current status of water supplies -- precipitation, snowpack, streamflow, reservoir levels, soil moisture -- it is possible to detect developing drought, observe the areas most susceptible to impacts, and in some cases take action to avoid or minimize these impacts. This is the philosophy behind the Colorado Drought Response Plan (Lamm, 1981) -- a plan which was formulated during and after the severe winter drought of 1976-1977 in the West and which was completed during the lesser but equally alarming drought winter of 1980-1981.

A. Current Drought Monitoring Activities in Colorado.

The entire Plan hinges on information supplied to State government by the Water Availability Task Force (WATF); a special intergovernmental

mix of State and Federal agency representatives with access to weather, climate, and/or water supply information. This group (see Appendix A) which is chaired by the Colorado Division of Disaster Emergency Services has been operating continuously since early 1981, voluntarily sharing data, developing information products, disseminating appropriate information to State officials and others interested in Colorado's water concerns, and generally striving to attain an ongoining drought monitoring capacity for the State. The information supplied by the WATF is used to trigger various levels of action and decision making which compose the State's response to drought. So far since 1981, water supplies have remained very good in Colorado and little action has been required. The mechanism is in place, however, and will hopefully continue to be, as drought will most certainly reappear.

Several existing information products are currently used by the WATF. They include:

1) Colorado Climate -- a monthly summary report of precipitation and temperature prepared by the Colorado Climate Center, Colorado State University (Office of the State Climatologist),

2) Water Supply Outlook -- a monthly summary report published (January-May) by the U.S. Department of Agriculture, Soil Conservation Service (SCS) which summarizes mountain snowpack conditions, streamflows, and reservoir storage, and predicts summer streamflows in the State's major watersheds,

3) 30-day Outlook -- a bi-monthly forecast of temperature and precipitation for the entire country prepared by the National Weather Service.

In addition to these, wind erosion information compiled by the SCS, a new surface water supply index developed jointly by the Colorado Division of Water Resources and the SCS Snow Survey Unit (Shafer and Dezman, 1982), Palmer Index information calculated for 5 Colorado regions by the National Weather Service in cooperation with the U.S.

Department of Agriculture, and ground water data made available by the State Engineer and the U.S. Geological Survey, are all examined routinely by the WATF to monitor water supplies affecting all areas of Colorado's economy. All of this information is summarized in a brief monthly statement currently being developed by the Colorado Climate Center. If found useful, this statement called "Colorado Water Availability Status Report" (see example in Appendix B) will be produced regularly and will incorporate all current drought monitoring capabilities and information.

B. Directions for Development of Colorado's Drought Monitoring Capabilities

There is considerable room for improvement in State drought monitoring. Communication of pertinent data is currently painfully slow, often relying on mail service rather than high speed computer links. This is not a problem when water is plentiful, but when water is in short supply a crisis could emerge.

Communication links are very people dependent with the cooperation of key individuals in several agencies being prerequisite to a functional drought monitoring system. It is a credit to the present leadership and to the key individuals involved, that the current high level of cooperation has been maintained, even in times of plentiful water and scant budgets. Eventually a more formal, less individual-dependent, cooperation must be developed to assure ongoing drought monitoring and data dissemination. The idea of an interagency Water Availability Task Force was excellent. The continued existence of this working group is necessary if Colorado is to maintain a comprehensive

drought monitoring program taking fair advantage of the considerable expertise already available in the State.

Finally, a strong program of drought monitoring must be linked to ongoing research. Through applied research in Colorado and elsewhere, new data sources can be explored such as satellite imagery, new technology can be incorporated such as improved data transmission, and new information products can be developed similar to the water supply indexes currently being tested.

Colorado is fortunate to be at the headwaters of considerable water resources research. It is the State's responsibility to encourage this work and make use of it.

This particular research project described in the chapters which follow, examines the use of the Palmer Index for drought monitoring. This is just one small example of the opportunities to apply the results of research to policy-making and decision-making processes within Colorado.

II. THE PALMER INDEX

A. History and General Description

In the early 1960's, Wayne C. Palmer developed a methodology to quantitatively assess prolonged unusual wet and dry periods. The method, developed at the U.S. Weather Bureau's Office of Climatology, was described in detail in the paper "Meteorological Drought" published in 1965 (Palmer). The method was based on the concept of a simple water balance. Using measured precipitation, estimated evapotranspiration (Palmer and Havens, 1958) and by determining climatically characteristic runoff and soil moisture recharge in the topsoil and root zone, it is possible to perform hydrologic accounting. Partitioning the actual precipitation (on a weekly or monthly basis) and residual soil moisture into runoff, evapotranspiration, and recharge, yields much more information pertinent for assessing drought than would precipitation information alone. For example, an inch of precipitation in early spring when temperatures are cool adds much more moisture to the soil than an inch of rain in mid summer when temperatures are hot and evapotranspiration rates high. Similarly, an inch of rain when the ground is dry will contribute much more moisture to the soil than an inch of rain when the soil is saturated.

This hydrologic accounting procedure was originally tested by Palmer on three experimental areas: one in western Kansas, one in Iowa, and one in North Dakota. Using monthly temperature (to estimate evapotranspiration) and precipitation for these areas over periods ranging from 32 to 76 years, climatic characteristics of the water balance were calculated. These characteristics were expressed in terms of a series of coefficients (Table 1). The purpose of these

coefficients was to define the long term "normal" for a specific area for a specific time of year (weekly or monthly).

Table 1. Coefficients Used in the Calculation of Palmer Indexes

Coefficient	Definition
Coefficient of Evapotranspiration	average evapotranspiration divided by the average potential evapotranspiration.
Coefficient of Recharge	average recharge divided by the potential recharge.
Coefficient of Runoff	average runoff divided by the potential runoff.
Coefficient of Moisture Depletion	average depletion divided by the potential depletion.

Departures from the climatically "normal" state for a given area could then be defined as contributing to wet and dry periods. The magnitude and duration of these departures both need to be considered when assessing the severity of drought or wet periods. Palmer took these into account as he developed a weighting factor called the "Climatic Characteristic." This final coefficient was employed to adjust the results of the hydrologic accounting to produce an index which ranged from about -6 for extreme drought situations to +6 for extremely wet periods. The "Climatic Characteristic" was used to adjust different areas of the country with much different water balances to this same consistent scale (Figure 1). The final index value is what has become known as the Palmer Index.

Many details of Palmer's procedure are not mentioned here. His original paper is required reading for anyone seriously interested in the specifics of the procedure.

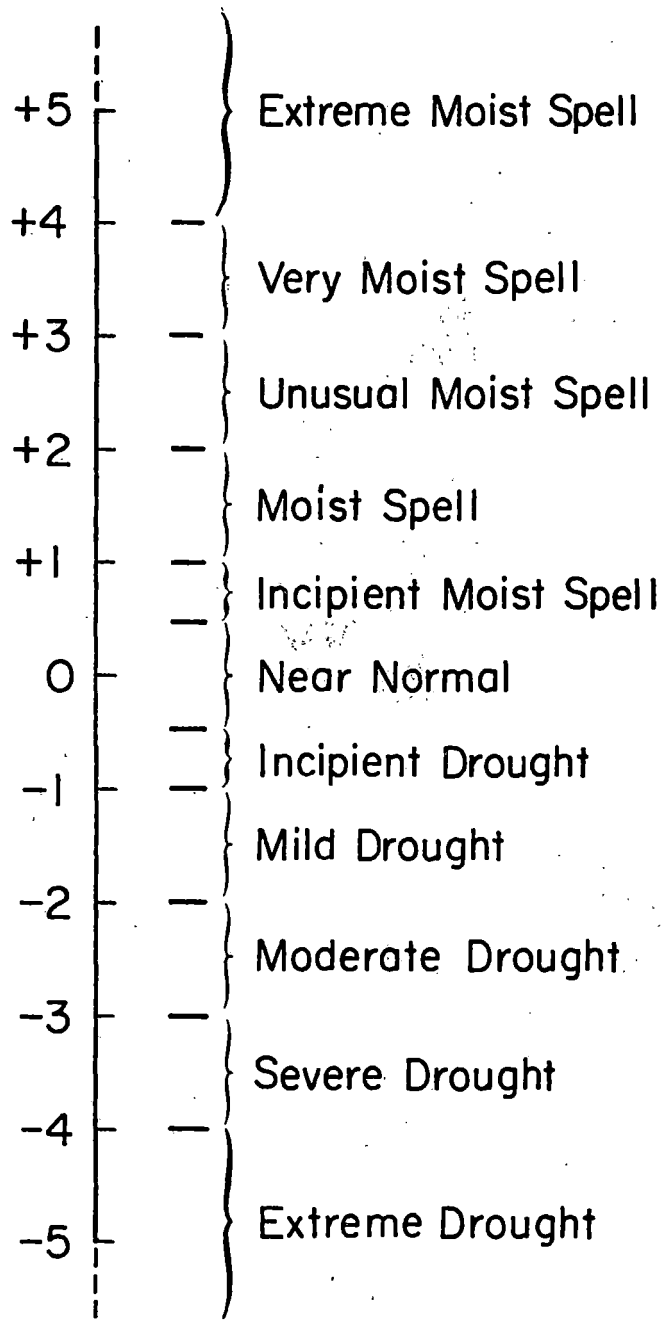


Figure 1. Interpretation scale for the Palmer Index.

The results of this original work for particular small areas of the country were very informative. Large negative values of the Palmer Index, when calculated from monthly temperature and precipitation data for the area, coincided with periods of documented drought with significant economic impacts. Based on this outcome, the method was deemed useful for the entire country. The country was broken down into 344 regions using the traditional climatic divisions constructed by the National Climatic Center in the 1940's (Figure 2). Coefficients were generated for each area based on monthly temperature and precipitation data obtained by averaging the data from all the reporting stations (both staffed weather stations and cooperative substations) in each division.

Due to the apparent usefulness of this index as a nationwide indicator of moisture excesses and deficits, the Palmer Index was eventually calculated and published on a routine basis. This activity has been carried out as a cooperative effort between the U.S. Department of Agriculture and the U.S. Department of Commerce, National Weather Service.

A second index called the Crop Moisture Index was developed after the Palmer Index. The Crop Moisture Index is very similar except that it focuses on the water balance in approximately the top one foot of top soil. It responds much quicker than the Palmer Index to changes in soil moisture that might affect vegetation and field operations. As a result, the Crop Moisture Index is considered a better indicator of drought for most agricultural applications.

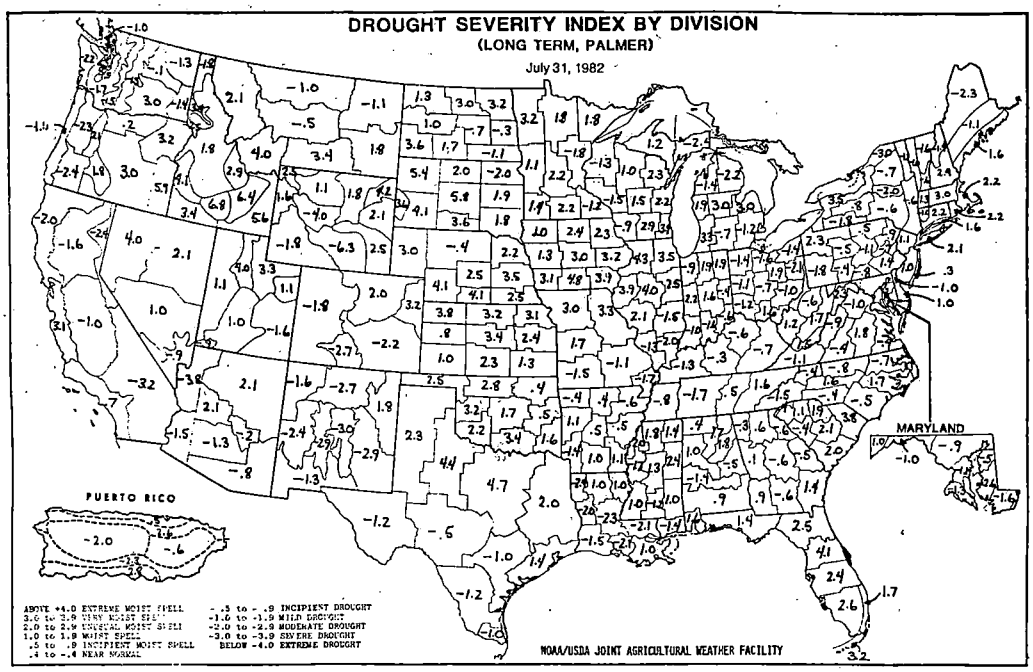


Figure 2. State Climatic Divisions for the United States and an example of weekly Palmer Index values, July 31, 1982 (NOAA/USDA, 1982).

B. Current Status

Both the Palmer and the Crop Moisture Index continue to be produced weekly for the March through October period for the entire country by the National Climatic Data Center. Input temperature and precipitation data are assembled for each of the nearly 350 climatic divisions in the contiguous United States by state forecast offices of the National Weather Service. Input data consist of the weekly mean temperature and total preciptation for each area as calculated from available daily data for a select set of stations within each area.

The calculated Palmer and Crop Moisture Indexes are made available to the National Weather Service by means of their regular facsimile communication circuit. General dissemination is accomplished by the publication, "Weekly Weather and Crop Bulletin" published jointly by the U.S. Department of Commerce and the U.S. Department of Agriculture.

C. The Palmer Index in Colorado

Of the nearly 350 areas nationwide for which index values are calculated, Colorado is divided into just 5 areas as shown in Figure 3. With the exception of the Kansas drainage, these areas all include dryland agricultural areas, irrigated areas, forested regions, and high rugged mountains.

Palmer Index values for Colorado by month have been calculated back to 1931. Considerable interest in this index in the 1960's and early 1970's has since given way to apathy. This apathy is understandable when you consider:

1) the apparent crudeness and subjectivity of the Palmer calculations when compared to current water budget models,

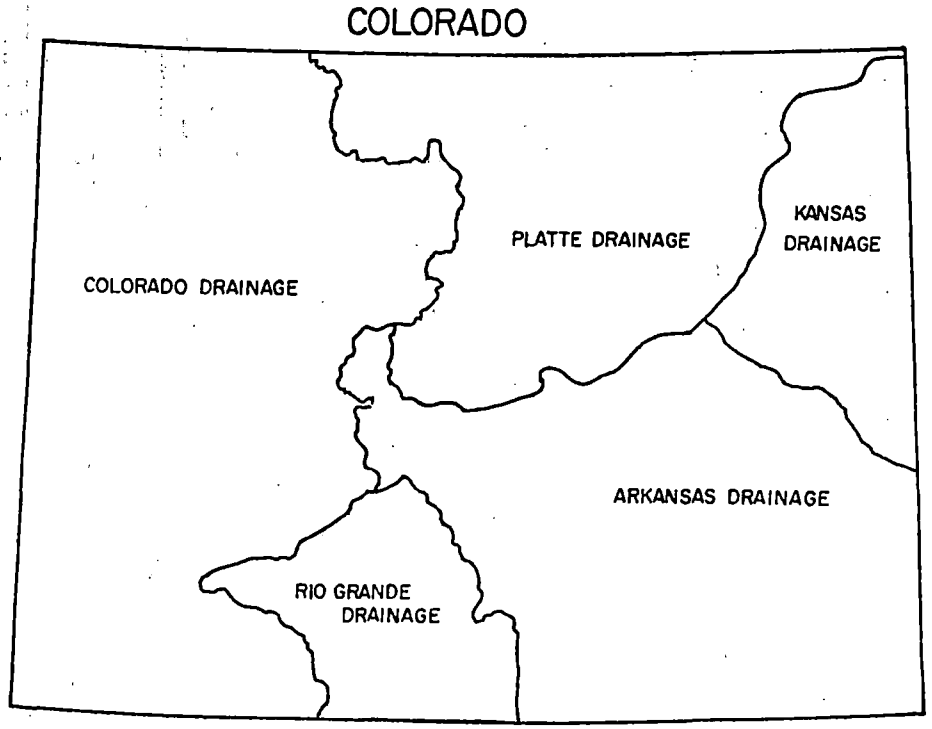


Figure 3. Original State Climatic Divisions for Colorado developed by the National Climatic Data Center, Asheville, North Carolina.

2) the climatic diversity which are apparent within the traditional climatic divisions. (The Colorado drainage, for example, includes areas which average less than 7 inches of precipitation annually and areas which average more than 60 inches per year. Likewise, average annual temperatures in the Colorado drainage range from below 30°F in the mountains to more than 52° in several western valley locations.)

3) the inconsistencies inherent in the input data. (With such climatic diversity it is impossible to select representative data points. Weekly input data is required for the national calculations, but most data are transmitted by mail, most data are collected by unpaid cooperative observers, and a strict time schedule is required to get data into the weekly calculations. The result is, the number of stations used to calculate division averages may be very few and the stations may vary from week to week.)

These are major weaknesses of the current method, particularly as it applies to Colorado. As a result, use of the index has been limited. Nevertheless, the Palmer Index has attained national recognition and credibility as a consistent, simple indexing method. Examination of 50 years of Palmer Index values for the 5 state climatic divisions shows that the Palmer Index does give a reasonable general picture of Colorado's moisture conditions which might be useful on a regional or national scale. However, spatial resolution is inadequate for in-state applications where local differences are important.

D. Goals of this Project

This project was undertaken with the overall goal of improving drought monitoring capabilities within the state of Colorado. Specific tasks included the following:

- Develop capability to calculate the Palmer Drought Index in Colorado.
- Verify index calculations against federal calculations.
- Develop new geographical subdivisions for the State of Colorado.

- Introduce the newly defined Palmer Drought Index for use by the WATF.
- Compare the Palmer Drought Index with winter wheat yield.

The last item was a change from the original proposal. Originally, other indexes were to be examined. However, interaction with the WATF lead to a concentrated effort to compare Palmer Index values with winter wheat yields to help demonstrate the benefits of using this type of index.

III. PROCEDURE -- PALMER INDEX CALCULATIONS FOR COLORADO

A. The Computer Program

No effort was made by the Colorado Climate Center to develop our own local version of the Palmer Index computer program. Instead, a copy of the computer program written in FORTRAN was obtained from the U.S. Department of Agriculture North Central Forest Experiment Station in East Lansing, Michigan. According to William Main (1982), who originally wrote this particular version of the program, and contacts at the National Climatic Data Center (Lewis, 1982), the U.S.D.A. model was consistent with the operational model being run at the National Climatic Data Center. Some minor differences were possible due to differences in computers. The U.S.D.A. model was also the version of the program used by the State of Kansas for special drought monitoring work (Brown, 1979a, 1979b).

The currently used values of the coefficients described in Section II.A. used for each climatic division in Colorado were obtained from the National Climatic Data Center (1982). Very little additional work was required to adapt the program to run on the Colorado State University, CDC mainframe computer.

B. Program Verification

To verify that the U.S.D.A. program was working properly, a simple test was performed. Using the original coefficients supplied by the National Climatic Data Center, monthly Palmer Index values were generated for the Kansas Drainage in east central Colorado. This area was chosen since it was the most climatically homogeneous of the 5 existing Colorado divisions and because there was only a handful of

input data points in the area. Monthly index values were calculated using monthly temperature and precipitation data for all weather stations in the area during the 1931 to 1972 period. Our results were then compared to the monthly index values previously generated for that area by the National Climatic Data Center.

The results of this comparison test are shown in Figure 4 for the 10-year period 1951-1960. Identical values were not obtained throughout the period. However, with few exceptions, differences were small enough (<0.2) to be considered trivial. From available information there is no way to fully explain the few instances such as early 1957 when significant differences occurred. It can probably be assumed that our input data at some time during that period was not identical to the original input data. This is a reasonable explanation since additions and corrections to the original data base have occurred over the years. There is no reason to expect, based on this test, that any differences or errors exist in the actual Palmer Index program adapted to Colorado.

C. Development of New State Climatic Divisions

A major element of this project was to devise a new, more appropriate, set of climatic divisions for the state. Originally a set of 12 areas was proposed including 3 plains regions, 2 foothills areas, 3 mountain regions and 4 western valley zones. Actual examination of climatic averages for weather stations within these 12 areas still indicated insufficient climatic similarity and uniformity (homogeneity). Finally, 25 separate areas were chosen (Figure 5). Table 2 names and identifies each of these areas. This breakdown most effectively separated climatically and economically different areas of the state.

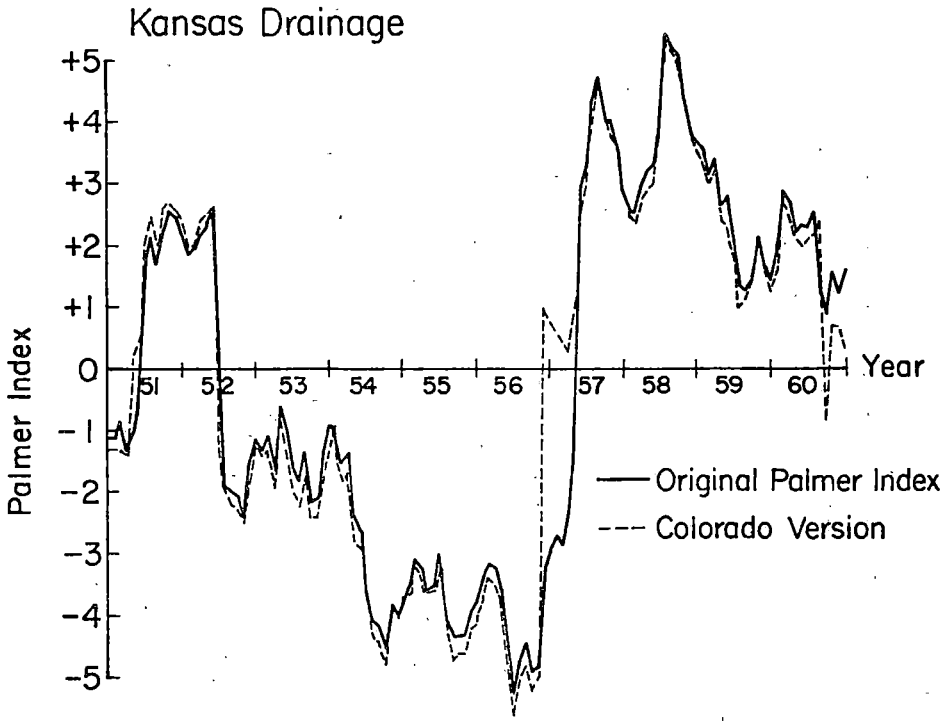


Figure 4. Monthly Palmer Index values, 1951-1960, for the Kansas Drainage. Original National Climatic Data Center values (solid line) compared to values calculated by the Colorado Climate Center (dashed line).

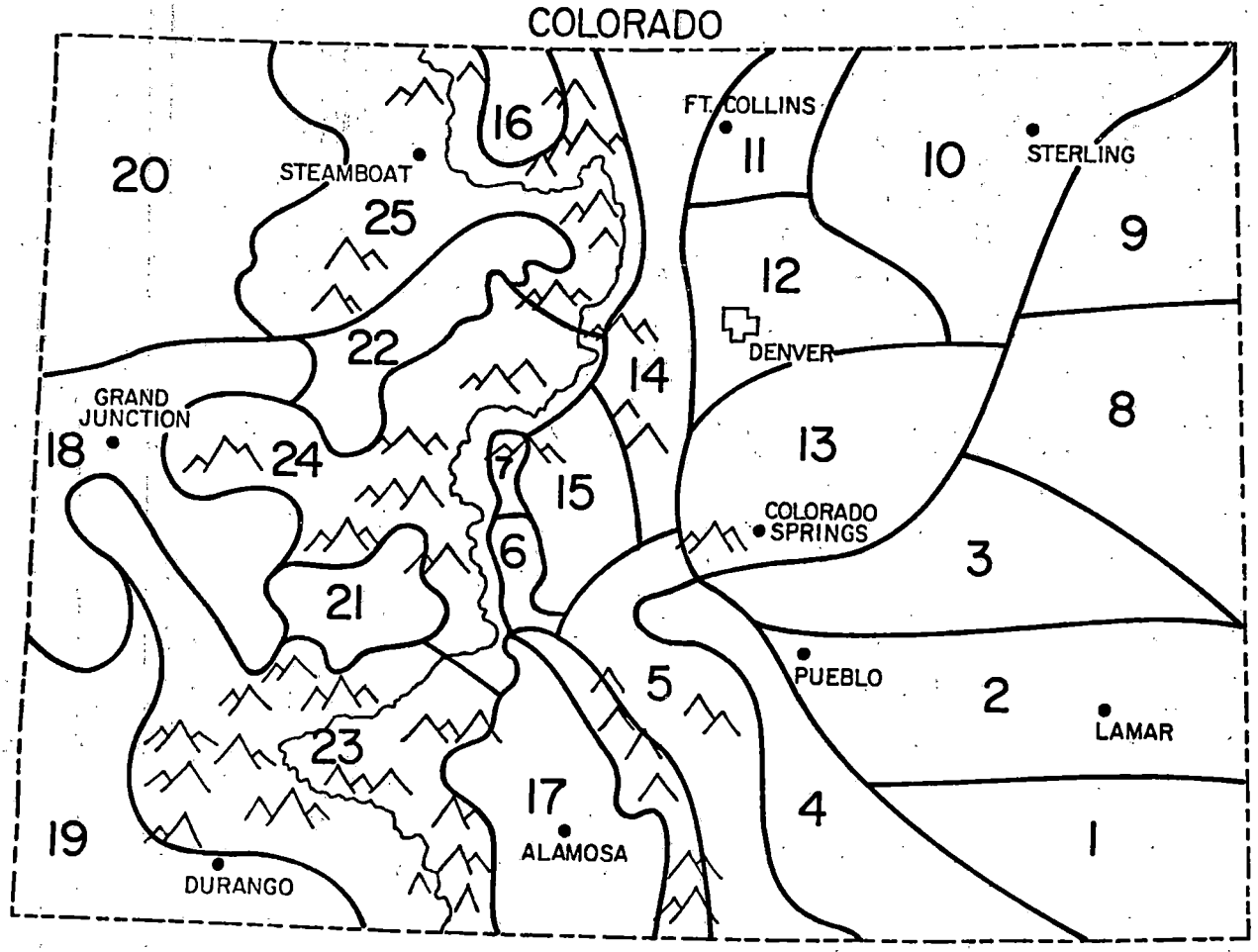


Figure 5. New climatic divisions for Colorado chosen for calculation of local Palmer Index values. Names and additional divisional information are given in Table 2.

TABLE 2.

Regions Selected for Calculation of Palmer Index

Region Number	Region Name[1]	Number of Weather Stations[2]	Average Latitude (deg. min.)[3]	Average Elevation (feet)[3]
1	Arkansas - Southeast Plains/Mesas	5	37°21'	4295
2	Arkansas - Valley Bottom	12	38 6	4132
3	Arkansas - Plains North of Valley	8	38 34	4631
4	Arkansas - Adjacent Plains/Mesas	9	37 30	5708
5	Arkansas - Foothills	5	37 53	7665
6	Arkansas - Collegiate Valley	2	34 42	7709
7	Arkansas - Upper Valley	3	39 11	9659
8	Kansas - Southern Plains	8	39 21	4457
9	Kansas - Northern Plains	6	40 19	4066
10	Platte - Northeast Plains	8	40 34	4531
11	Platte - North Front Range Adjacent Plains	6	40 35	5100
12	Platte - South Front Range Adjacent Plains	11	39 48	5378
13	Platte/Arkansas - Pikes Peak and Palmer Divide	12	39 04	6390
14	Platte - Foothills	13	39 51	7645
15	Platte - South Park	2	38 58	8718
16	Platte - North Park	2	40 36	8248
17	Rio Grande - San Luis Valley	10	37 36	7814
18	Colorado - Lower Valleys (Colorado, Gunnison, Dolores)	19	38 58	5408
19	Colorado - Lower Valleys (San Juan, Dolores, Animas)	10	37 27	6846
20	Colorado - Lower Valleys (Yampa, White)	8	40 18	6012
21	Colorado - Upper Valley - Gunnison	6	38 24	7890
22	Colorado - Upper Valley - Colorado	6	39 54	7251
23	Colorado/Rio Grande - San Juan Mountains	13	37 43	8607
24	Colorado/Arkansas - Central Mountains	12	39 12	8969
25	Colorado - Northern Mountains	7	40 08	8509

[1]Name based on traditional drainage basin name followed by description for local area.

[2]Weather station statistics based on active weather stations in each region as of 1 January 1983.

[3]Averages obtained by averaging latitudes and elevations of the weather stations used in each region.

It also complemented reasonably well the divisions already selected by the USDA-Soil Conservation Service and the Colorado Division of Water Resources for calculation of their new Surface Water Supply Index (SWSI).

D. Input Data

It was the expressed intent of this project to make use of only consistent input data to avoid the problems of the current national method. Currently divisional input data are formed by averaging the weekly or monthly data from a set of stations in each area. These stations may change over time as individual stations are moved or are terminated and new stations are added. While this may not be a problem in many areas of the country, this has contributed significantly to the lack of credibility of the Palmer Index in Colorado.

A simple procedure was developed to minimize this problem. First of all, by making the areas smaller and more climatically uniform, much of the problem goes away immediately. However, in making areas smaller, the number of stations averaged to produce the division input is also reduced. This can make the Palmer calculation even more sensitive to missing data or station moves. To deal with that problem, long-term monthly averages of temperature and precipitation for all currently reporting weather stations in Colorado were calculated based on the 1961-1980 period. If 20 years of data were not available, available averages were adjusted to 20-year averages using nearby stations. The result was a set of monthly averages for 203 regularly reporting weather stations. Twenty-year division averages were then calculated for each

of the 25 regions based on the reporting stations in each area (see Table 2).

Monthly input data were then generated for the period 1951 through 1980. Values were obtained for each area by calculating the temperature departure from the 20-year average for each station (degrees Fahrenheit). An average departure was calculated for any area by summing the individual station departures and dividing by the number of stations reporting that month. The average departure was then added to or subtracted from the long-term average for that month for the area as a whole. The end result was a single mean temperature for the area for the month, which was not affected adversely by missing data. Precipitation was handled in a similar way using percent of average rather than departure from average.

This is not the only and perhaps not even the best way to minimize the effects of station moves, changes, and missing data. It is a simple method, however, and an appropriate one for developing consistent input data for a model which is more sensitive to consistency than to absolute numbers.

E. Coefficients

The original coefficients required for the Palmer Index program were developed for the traditional state divisions. They were no longer appropriate for the new set of divisions. New coefficients are generated internally by the existing program simply by running the model on a long time series of data. This was done for each of the 25 regions using 1951 through 1980 monthly data.

The new coefficients will not be presented here. However, one example is appropriate to point out just how much climatic differences were hidden in the old division breakdown. Table 3 compares the 5 basic coefficients prerequisite for Palmer Index calculations for the several areas which compose the original Colorado basin. Major differences are apparent. Even without a good understanding of the exact meaning and interpretation of these coefficients, it is still obvious that the original values were not appropriate for specific subregions within the Colorado drainage basin.

F. Index Calculations

All the preliminary work described in the previous sections had to be completed before it was possible to begin the actual calculation of Palmer Index values. This final step was very straightforward and simple. Using the newly generated area coefficients and the carefully prepared input data, the program then generated monthly index values for the entire 1951 through 1980 record. An example of the output is shown in Figure 6. The program keeps track of all the hydrologic accounting and prints out these values monthly.

Estimates of the Crop Moisture Index are also generated by this program. Possible applications of these results will be discussed in a later chapter.

Index values were calculated for all months, 1951-1980 for all 25 areas except if no input data at all were available for a given region. The following chapter will examine some of the results.

TABLE 3.

Comparison of Palmer Index Coefficients
for Areas in the Colorado Basin for October

Area	Coef. of Evaporation	Coef. of Moisture Recharge	Coef. of Runoff	Coef. of Moisture Depletion	Climatic Characteristic
Original Values					
Entire Colorado Basin	.7482	.0406	.0000	.2237	2.4086
New Values					
18 Lower Valleys (Colorado, Gunnison, Dolores)	.5747	.0321	.0000	.4213	2.3077
19 Lower Valleys (San Juan, Dolores, Animas)	.7129	.1175	.0000	.2729	1.4903
20 Lower Valleys (Yampa, White)	.7067	.0479	.0000	.3133	2.2836
21 Upper Valley (Gunnison)	.6793	.0379	.0000	.3704	2.7489
22 Upper Valley (Colorado)	.7456	.0492	.0000	.3919	2.4475
23 San Juan Mountains	.9281	.2341	.0679	.1926	1.3244
24 Central Mountains	.8994	.1207	.0064	.1956	1.9946
25 Northern Mountains	.9419	.2251	.0280	.1465	1.7839

PALMER DROUGHT ANALYSIS

ARKANSAS DRAINAGE --- VALLEY BOTTOM

STATION 2 YEAR 1980	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
PRECIPITATION /INCHES/	.73	.28	2.21	4.14	3.32	.87	.98	1.45	.88	.04	.62	.09
TEMPERATURE /DEGREES F/	28.20	36.80	40.00	48.10	57.90	74.00	79.60	76.40	68.10	53.70	41.80	41.60
POTENTIAL EVAPOTRANSPIRATION	0.00	.18	.44	1.27	2.71	5.41	6.54	5.56	3.67	1.68	.48	.45
AVAILABLE SURFACE MOISTURE	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	.14	0.00
AVAILABLE SUBSURFACE MOISTURE	1.36	1.46	3.22	6.00	6.00	2.97	.61	.25	.15	.12	.12	.11
POTENTIAL MOISTURE LOSS	0.00	.18	.44	1.12	2.52	4.78	2.77	.49	.13	.04	.01	.15
POTENTIAL RECHARGE	5.37	4.64	4.54	2.78	0.00	0.00	4.03	6.39	6.75	6.85	6.88	6.74
MOISTURE RECHARGE	.73	.10	1.77	2.78	0.00	0.00	0.00	0.00	0.00	0.00	.14	0.00
MOISTURE LOSS	0.00	0.00	0.00	0.00	0.00	4.03	2.36	.36	.10	.04	0.00	.14
EVAPOTRANSPIRATION	0.00	.18	.44	1.27	2.77	4.90	3.34	1.81	.98	.08	.48	.23
RUNOFF	0.00	0.00	0.00	.10	.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EST. EVAPOTRANSPIRATION	0.00	.18	.41	1.05	2.20	2.77	3.09	2.39	1.42	.69	.38	.38
EST. MOISTURE RECHARGE	.29	.17	.36	.13	0.00	0.00	0.00	0.00	0.00	.07	.36	.26
EST. RUNOFF	.04	0.00	0.00	.01	.08	.03	0.00	0.00	0.00	0.00	0.00	0.00
EST. MOISTURE LOSS	0.00	.09	.13	.51	.84	3.45	1.83	.32	.08	.02	.00	.08
EST. PRECIPITATION	.33	.27	.64	.67	1.44	-.64	1.27	2.07	1.34	.74	.74	.56
MOISTURE DEPARTURE	.40	.01	1.57	3.47	1.88	1.51	-.29	-.62	-.46	-.70	-.12	-.47
MOISTURE ANOMALY INDEX	1.14	.04	3.45	6.88	3.06	2.53	-.55	-1.43	-1.10	-1.68	-.29	-1.39
PROBABILITY SPELL ENDED	0.00	2.49	0.00	0.00	0.00	0.00	5.05	18.24	30.88	50.62	57.84	76.63
MOISTURE NEEDED TO END SPELL	.99	-.11	3.19	6.73	2.91	2.38	-.70	-2.28	-3.53	-5.36	-5.80	-7.33
WET SEVERITY INDEX	0.00	.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DRY SEVERITY INDEX	0.00	0.00	0.00	0.00	0.00	0.00	-.18	-.64	-.94	-1.40	-1.36	-1.68
ESTABLISHED INDEX	2.18	1.97	2.92	4.91	5.43	5.71	4.94	3.95	3.18	2.29	1.96	1.30
FINAL INDEX	2.18	99.00	2.92	4.91	5.43	5.71	99.00	99.00	99.00	99.00	99.00	99.00
CROP MOISTURE INDEX	1.47	.21	3.81	7.02	3.14	2.56	-.55	-1.43	-1.09	-1.61	.07	-1.13

Figure 6. Example output produced by the Palmer Index computer program adapted to Colorado.

IV. RESULTS

A. Monthly Palmer Index Values

All of the monthly Palmer Index values for the 1951 through 1980 period will be published as a part of the Colorado Climate Center's Climatology Report Series. All values appeared to be reasonable and consistent with the input data. Most values fell in the range of -6 to +6, the normal range for Palmer Index results. Extreme values of the index corresponded well with documented records of extreme conditions of drought and excess moisture. By all general indications, the program produces realistic results for Colorado.

B. Geographical Variations

One of the reasons this research project was undertaken was to prove that the original basin size was too large to show local variations in moisture conditions. As expected, the smaller areas for index calculation did yield considerably more information.

Figure 7 compares monthly Palmer Index values for the smaller areas for a four year period (1965-1968) with the original PI calculated for the entire drainage basin of which they are a part. Significant differences are noted. In the Colorado River Basin for example (Figure 7a), the Northern Mountains and the Southwest Valleys seldom indicated similar moisture status relative to their long-term normals. During an extreme wet period in 1965 both areas experienced PI values above +3. The Southwest Valleys remained wetter than normal (PI > 0) throughout most of 1966 while the Northern Mountains quickly dropped to -2 and below. In the Platte Basin (Figure 7b) the northeastern plains experienced nearly an entire abnormally wet year from spring of 1967

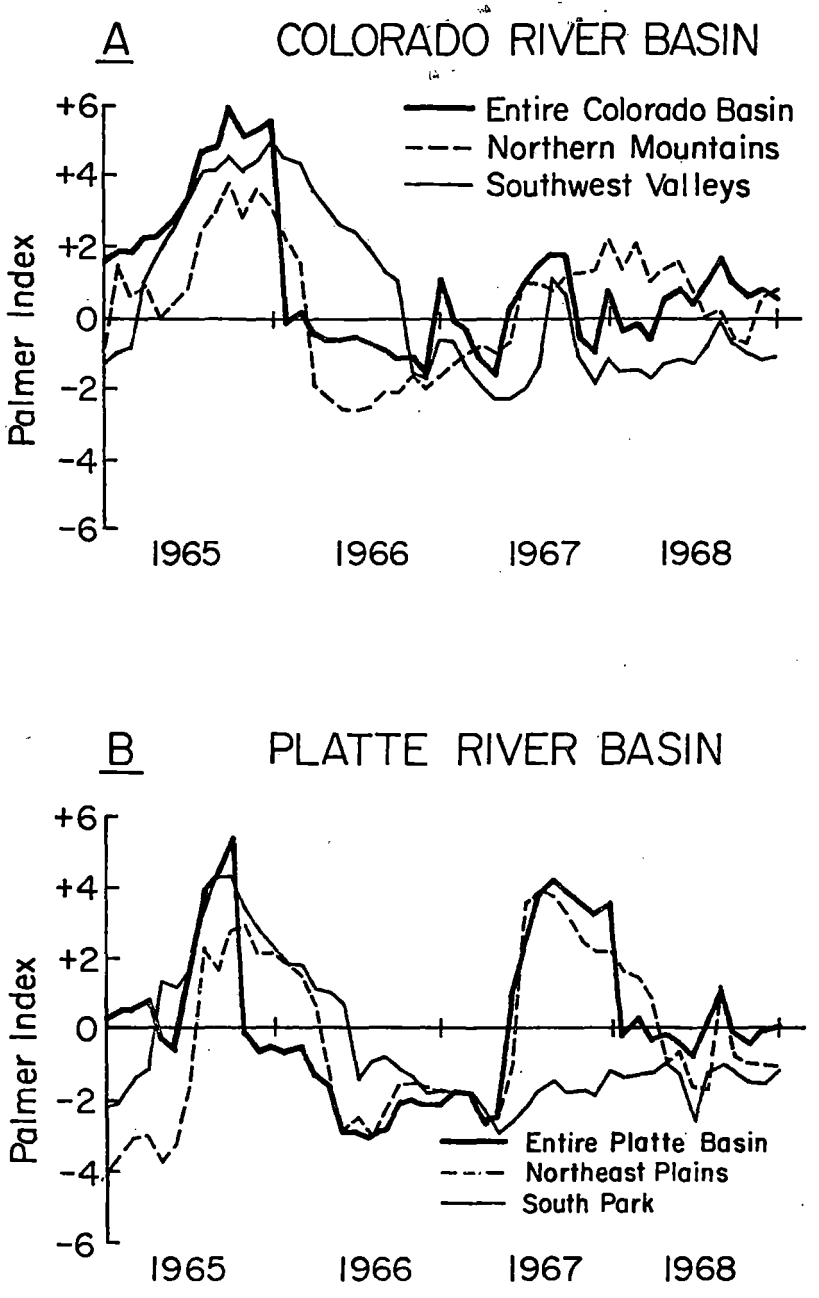


Figure 7. Monthly Palmer Index values 1965-1968, for the original large climatic divisions compared to values calculated for selected new small regions in the: a) Colorado River basin, and the b) Platte River basin.

into early 1968 while South Park approached moderate drought throughout the period. The original PI didn't even give a hint of the dry conditions occurring in that small area of the state.

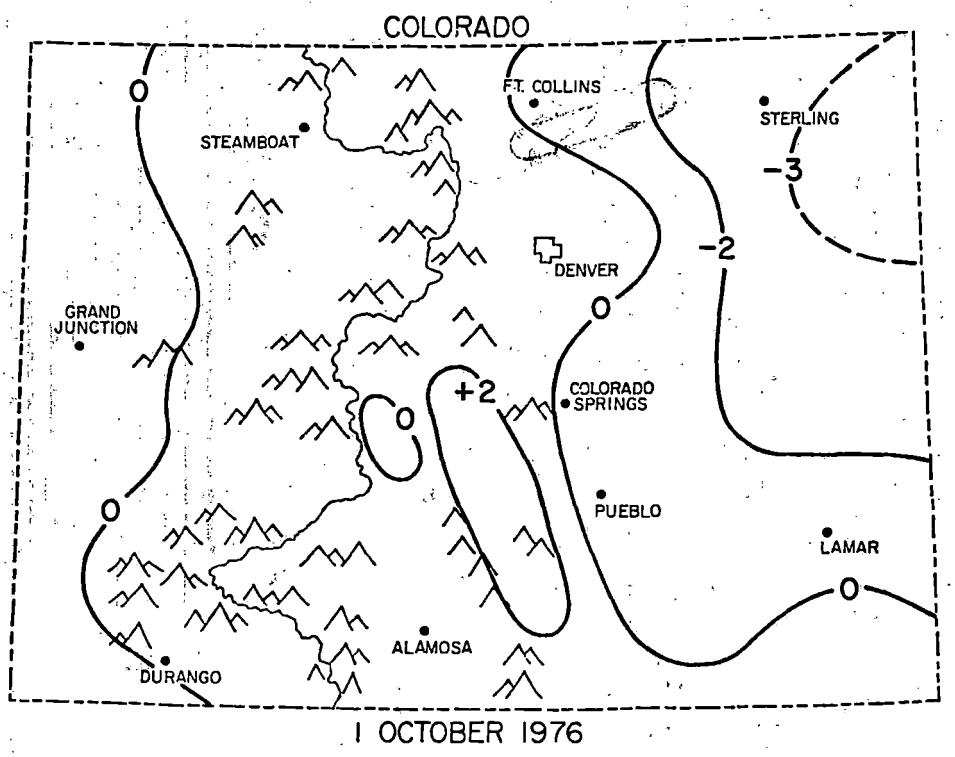
The magnitude differences of PI's within the large basins were typically 1 to 2 units but were sometimes more than 4. There were more than a few cases of PI values indicating moderately wet in one subregion while a nearby subregion indicated moderate drought. Assuming these calculations are correct, the implications for an effective drought monitoring program are significant.

C. Case Study: 1976-1977 Winter Drought

Another way to even more clearly examine the geographical variations across the state is by looking at the entire state at a series of specific times. Figure 8a-d follows the evolution of the severe winter drought of 1976-1977. When PI values are produced for 25 subregions of the state it becomes practical to use contour analysis to describe the statewide pattern. The national analyses of the PI is shown for comparison.

On October 1, 1976 (Figure 8a) much of the state indicated near normal moisture except for a small wet area in the mountains west of Pueblo and Colorado Springs. The national analysis was unable to resolve this small wet area. The moderate to severe drought area in northeast Colorado was more extensive than indicated by the national analysis.

By January (Figure 8b) conditions were rapidly deteriorating from the mountains westward. East of the mountains remained near average



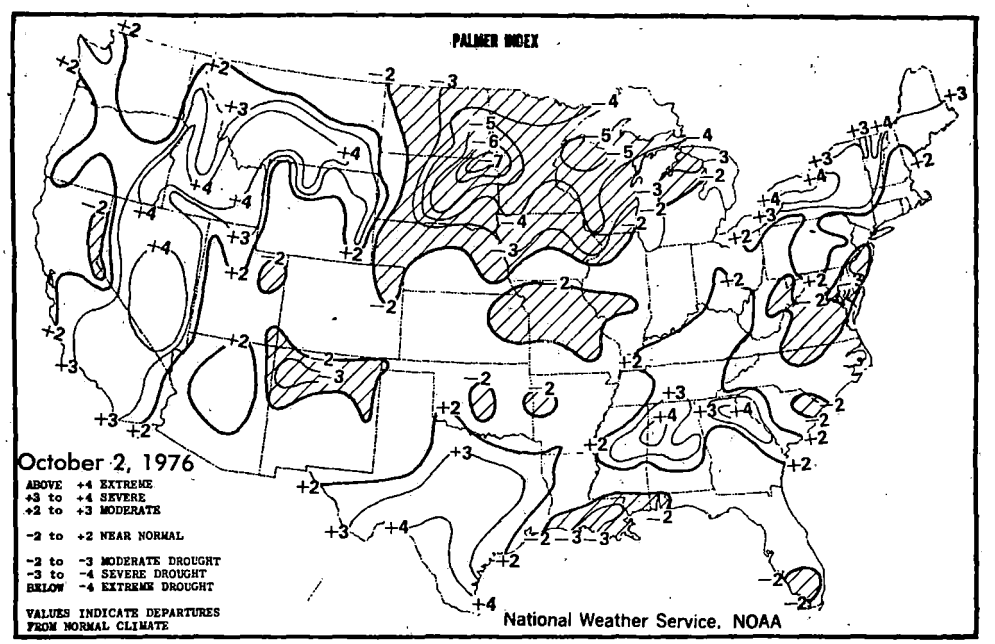
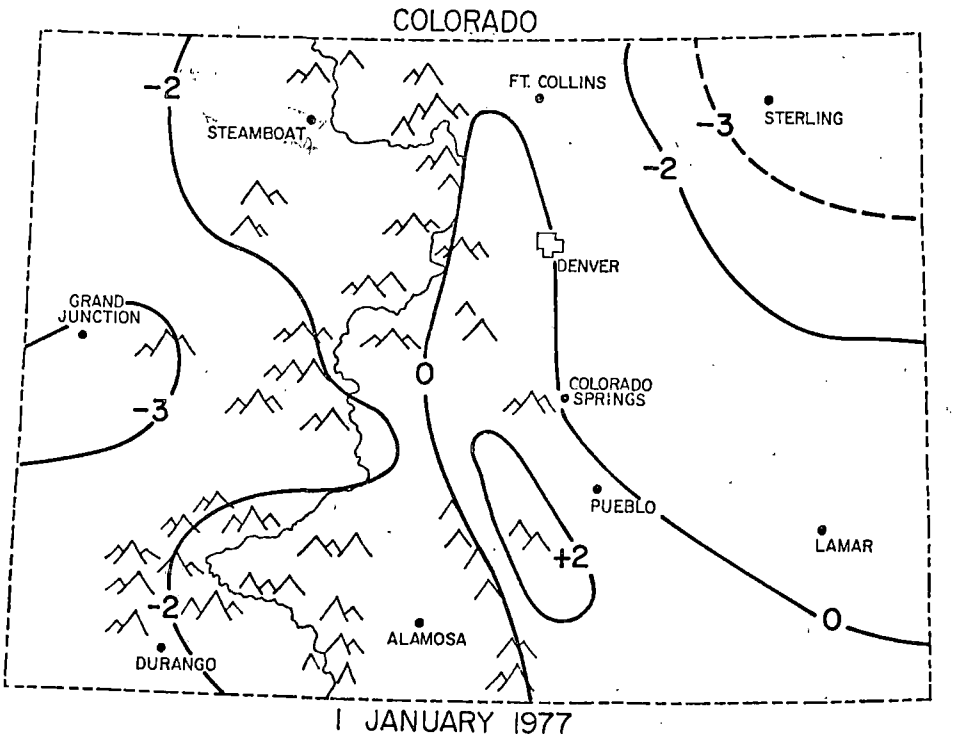


Figure 8a. Palmer Index pattern for Colorado for 1 October 1976 based on the 25 new regions (top) compared to the Palmer Index information for the entire U.S. derived from the original climatic divisions (bottom).



Not Available

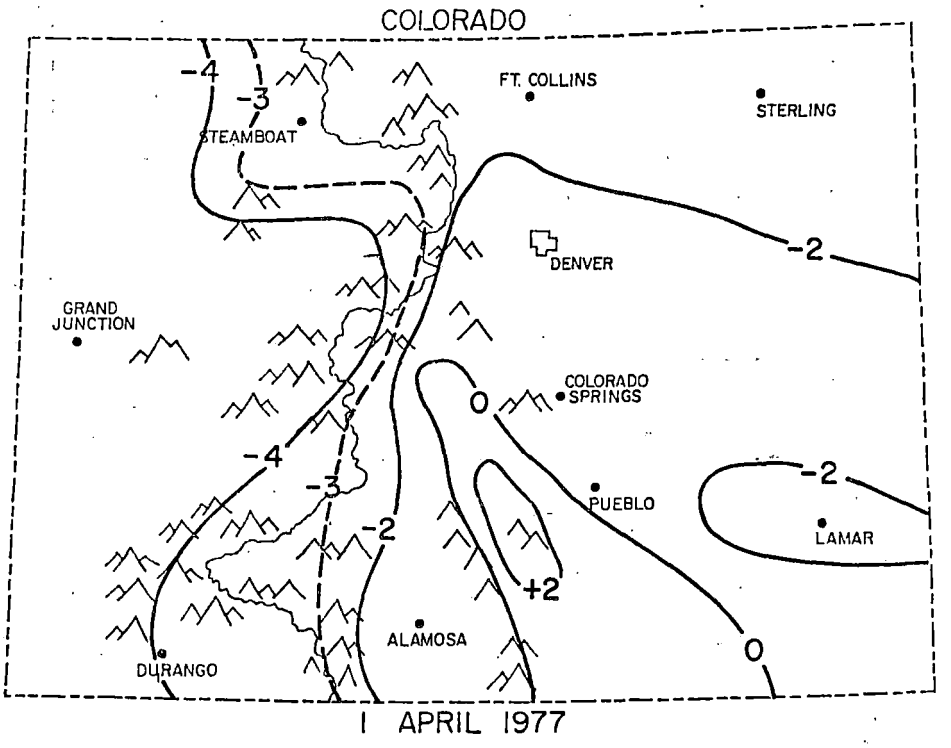
Figure 8b. Palmer Index pattern for Colorado for 1 January 1977 based on the 25 new regions. No U.S. information available.

except, again, for the northeast plains where moderate to severe drought conditions prevailed.

Already by April 1977 (Figure 8c), severe to extreme drought was indicated nearly everywhere along and west of the Continental Divide. Dry conditions prevailed in northeastern Colorado although not as severe as before. The moist area in the southeastern part of the state gradually shrunk.

The peak of the drought was reached in mid summer (Figure 8d) as the entire western portion of the state reached extreme drought levels with values approaching all time low figures. A smaller pocket of severe to extreme drought was observed along the Front Range northward from Denver. The remainder of eastern Colorado was in much better shape. Northeastern Colorado had actually improved somewhat since winter.

During this particular drought period, the national analyses were fairly consistent with the higher resolution Colorado data. However, the detail, and the confidence associated with that detail, was much greater with the local analyses. The national analyses were unable to pick out the variations in eastern Colorado. In fact, the national PI analysis for July 2, 1977 (Figure 8d) gave no indication at all of the local extreme drought area near Fort Collins. That analysis was very accurate and is clearly indicated in the accumulated precipitation map for Colorado presented in Figure 9 (Doesken and McKee, 1978). The July 1 PI pattern as a whole was very consistent with the pattern of the October 1976 - June 1977 accumulated precipitation as a percent of a average.



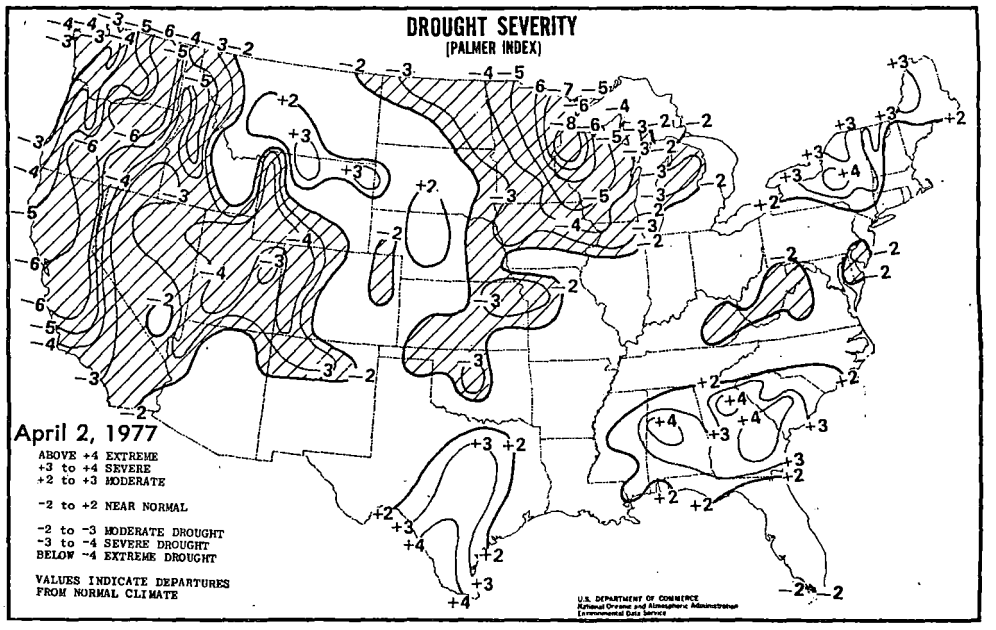


Figure 8c. Palmer Index pattern for Colorado for 1 April 1977 based on the 25 new regions (top) compared to the Palmer Index information for the entire U.S. derived from the original climatic divisions (bottom).

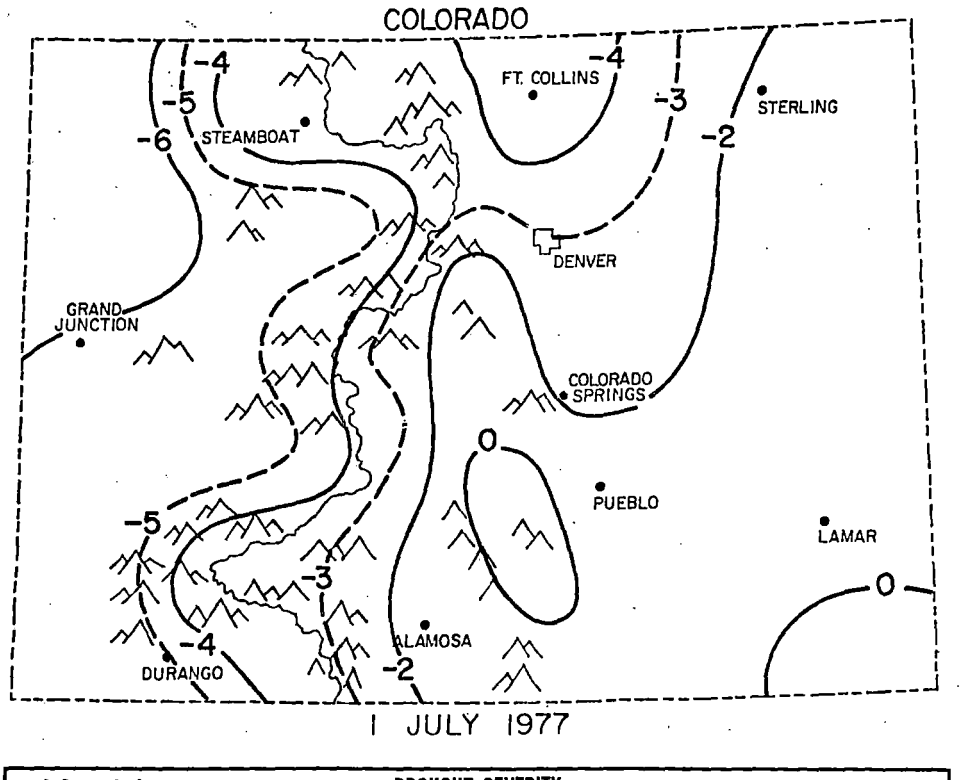


Figure 8d. Palmer Index pattern for Colorado for 1 July 1977 based on the 25 new regions (top) compared to the Palmer Index information for the entire U.S. derived from the original climatic divisions (bottom).

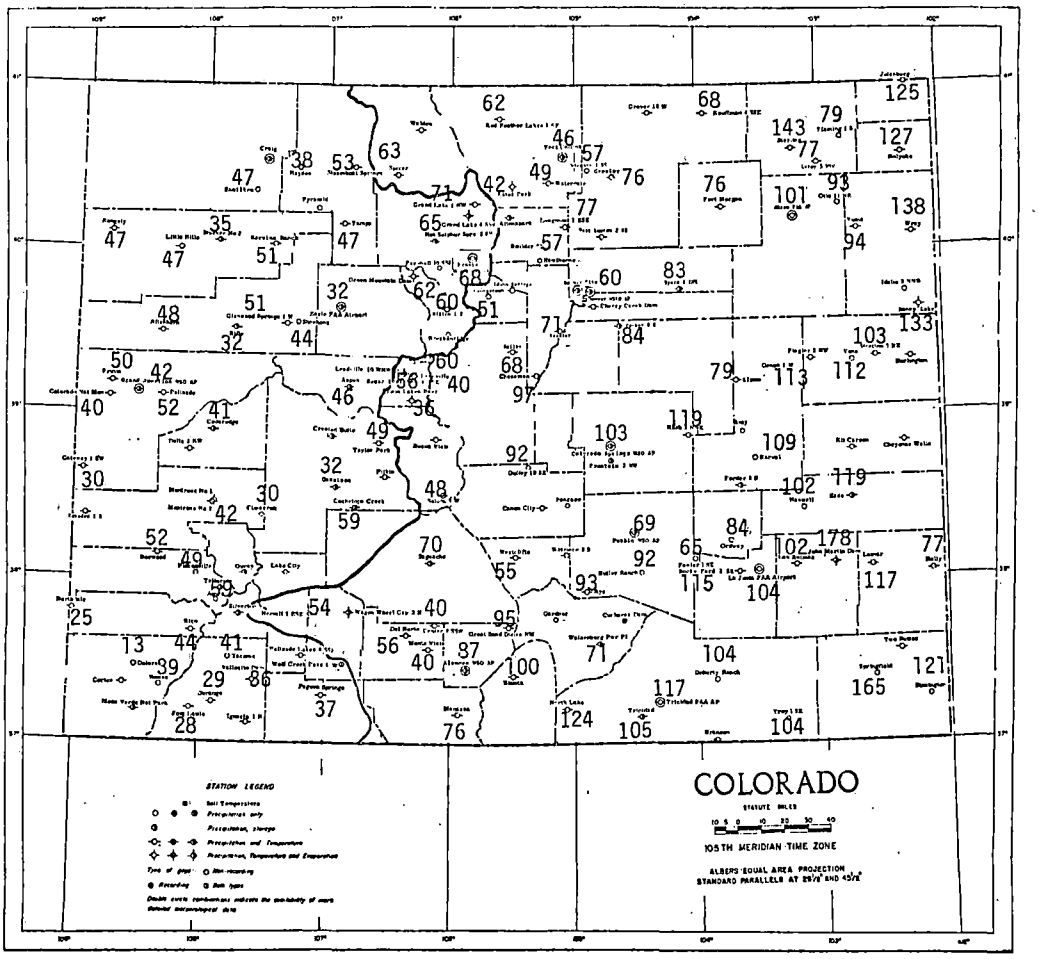
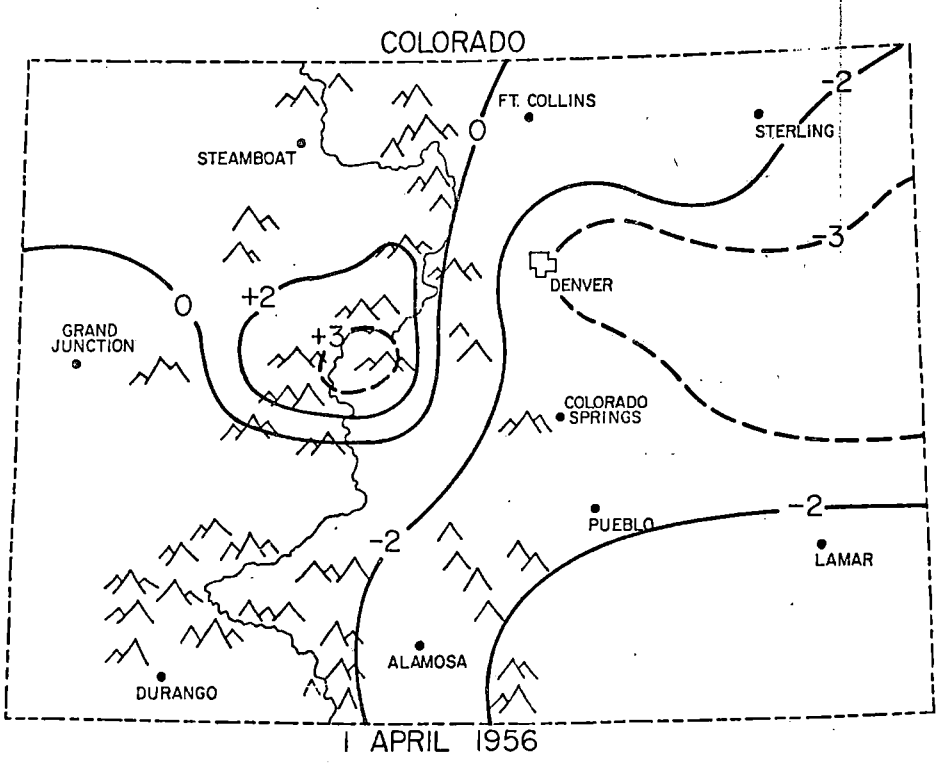


Figure 9. Precipitation for the period October 1976 through June 1977 as a percent of the 1951-1970 average.

D. Case Study: 1956-1957 End of the Mid-50's Drought on the High Plains

A second example of local variations and changes is shown in Figure 10a-f. National analyses are not available for that time period. Instead the index values for the specific state climatic divisions are shown for comparison. In this sequence, extreme drought develops during the summer of 1956 in east central Colorado (Figure 10a, b). Drought expands into southern and western parts of the state (c) and then begins to abate in the northeast (d). Moderate to severe drought conditions continued through the winter in the southeastern half of Colorado (e). Then along came a very wet spring which totally washed away the drought (f). During the 30 years of data used in this study, this was the most dramatic example of how abruptly serious droughts can be ended.

Once again, the original PI values gave an adequate large scale description of moisture conditions. However, the detail afforded by this special Colorado PI study gave much more information on the nature of this drought as it affected Colorado. For example, excellent winter precipitation in early 1956 in the Northern and Central Mountains and the upper Arkansas Valley showed up clearly on the local analysis while it was not at all apparent from the large basin PI values. Also, the large basin PI values did not show how the area of most severe drought continued westward from the Burlington area almost all the way to Denver and Colorado Springs, while the extreme northern and southern portions of the Colorado High Plains were only experiencing moderate drought.



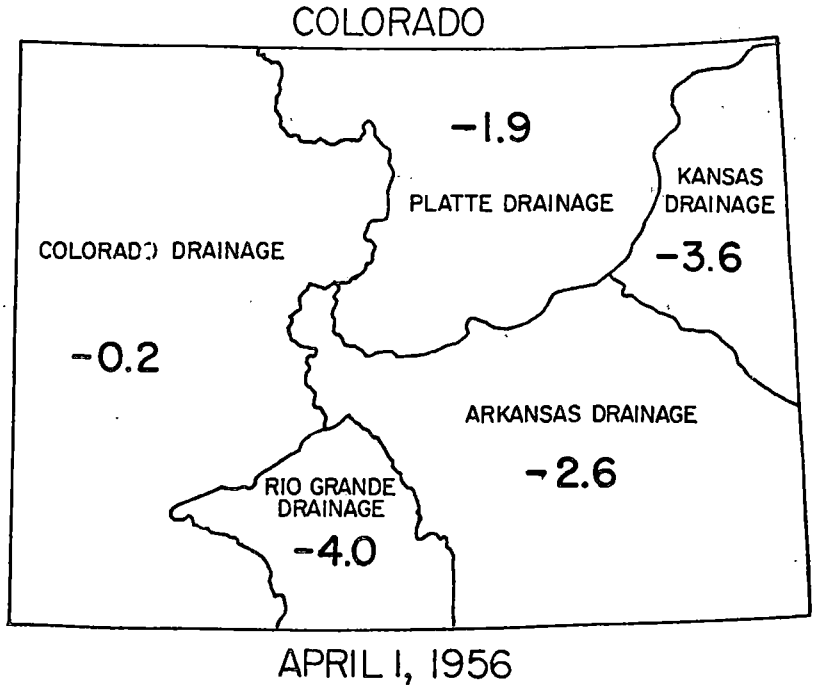
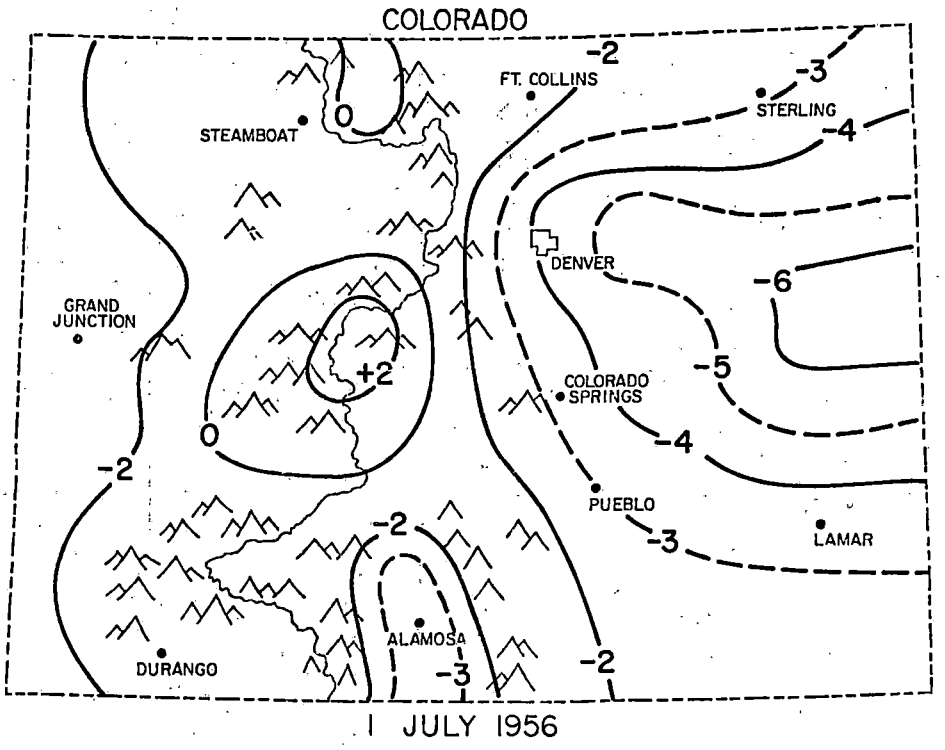


Figure 10a. Palmer Index pattern for Colorado based on the 25 new regions (top) and Palmer Index values for the 5 original divisions (bottom) for 1 April 1956.



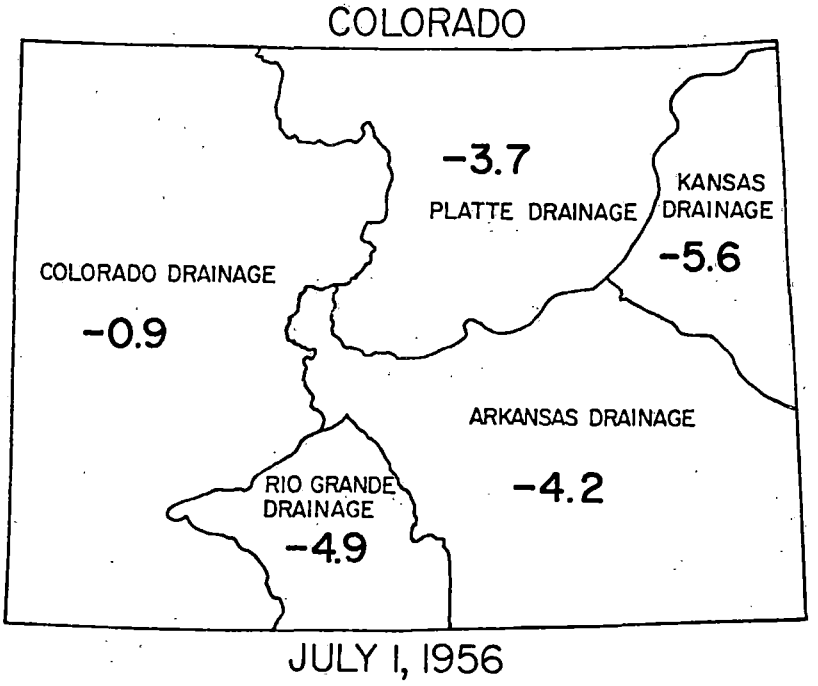
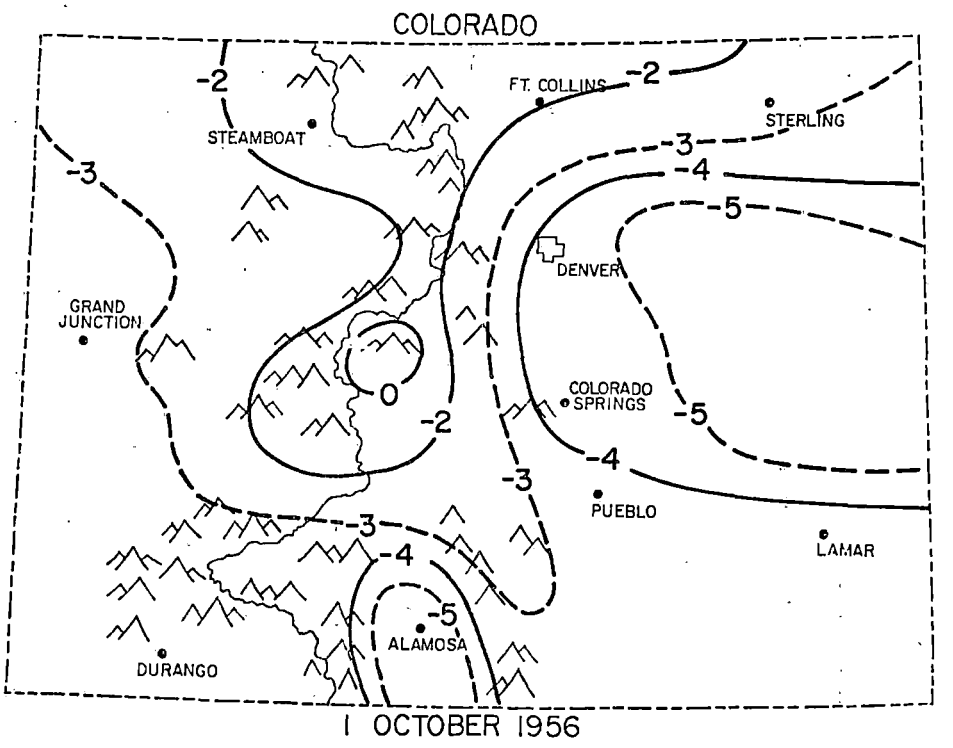


Figure 10b. Palmer Index pattern for Colorado based on the 25 new regions (top) and Palmer Index values for the 5 original divisions (bottom) for 1 July 1956.



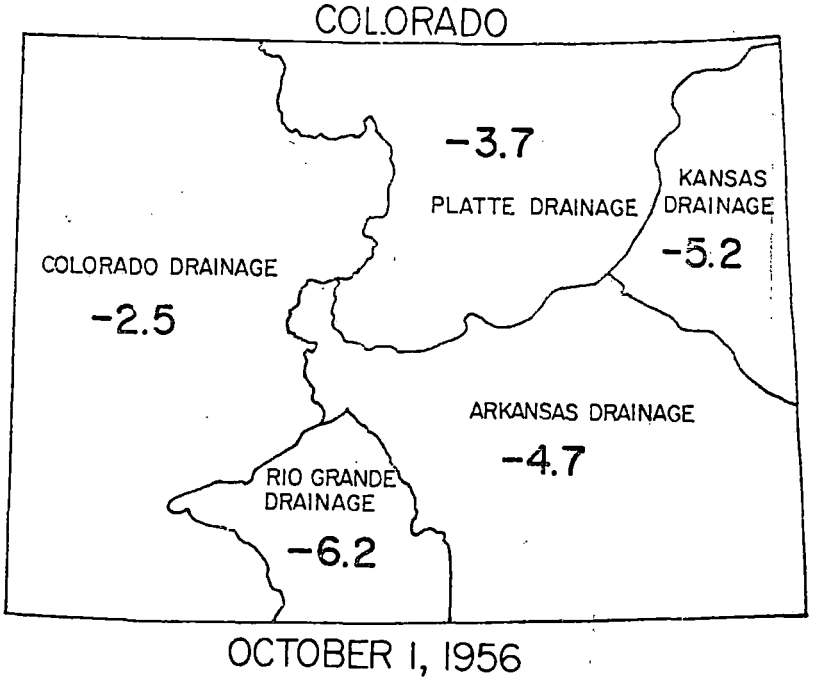
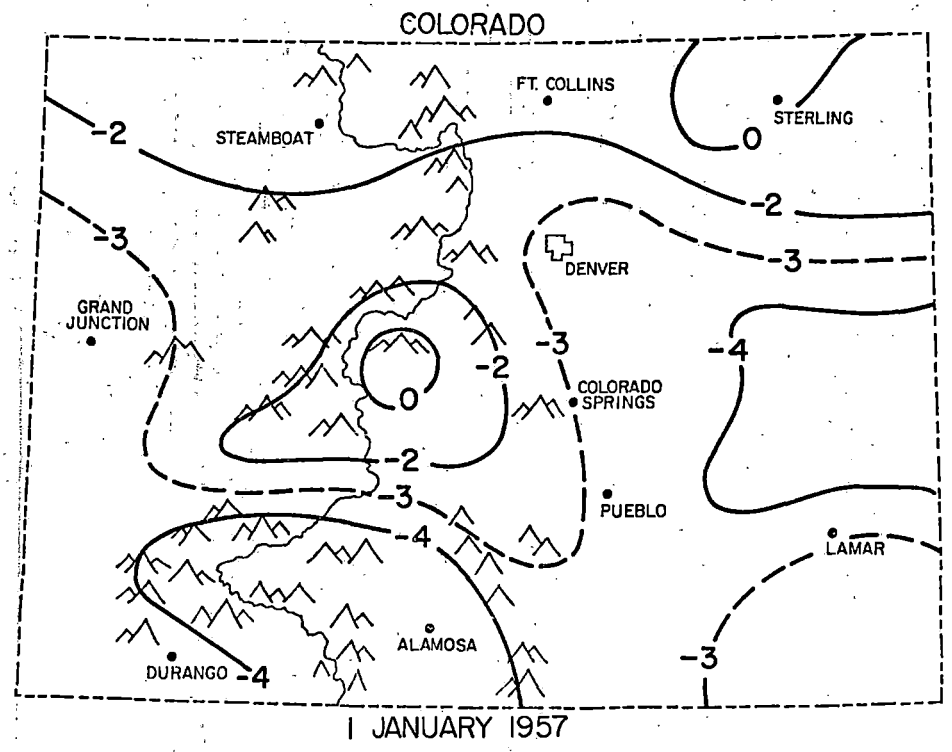


Figure 10c. Palmer Index pattern for Colorado based on the 25 new regions (top) and Palmer Index values for the 5 original divisions (bottom) for 1 October 1956.



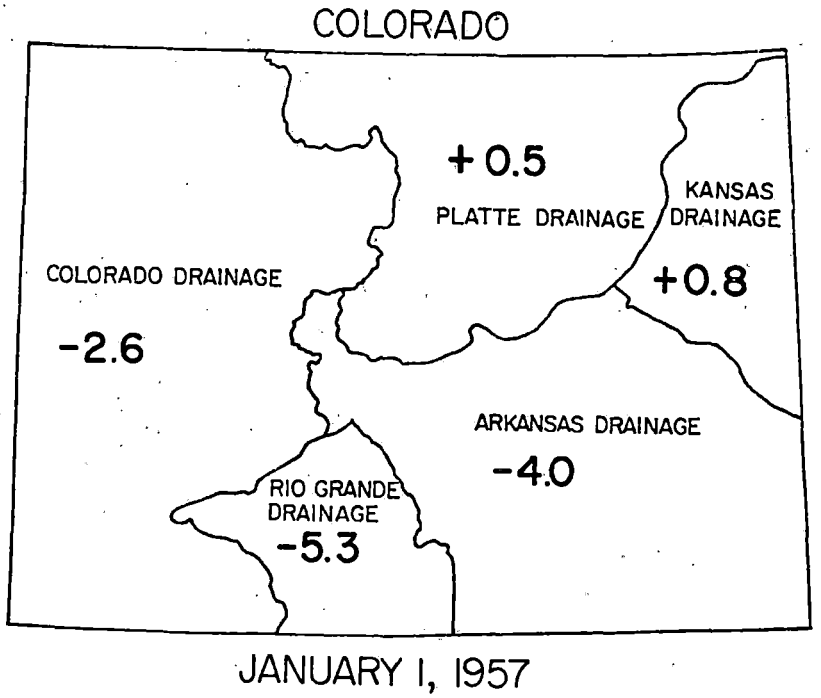
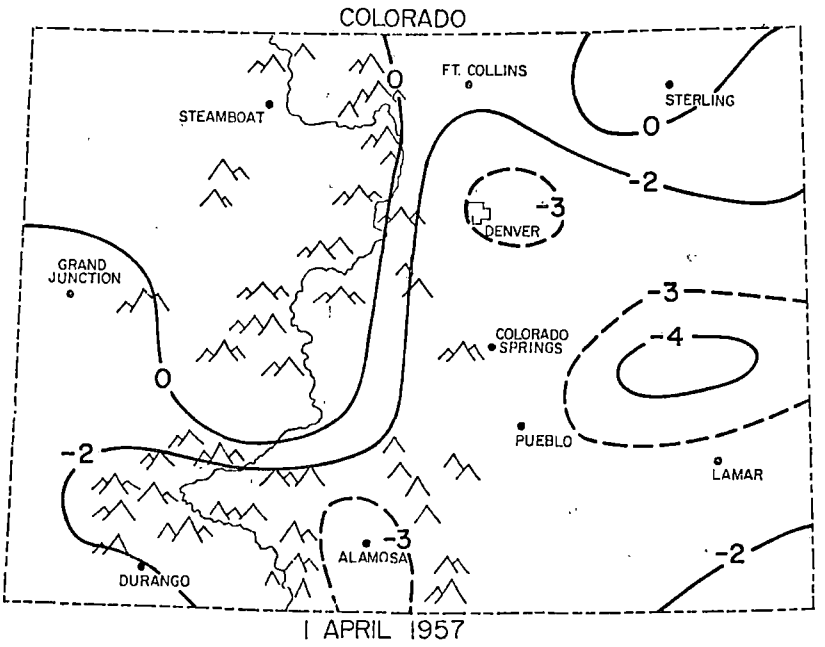


Figure 10d. Palmer Index pattern for Colorado based on the 25 new regions (top) and Palmer Index values for the 5 original divisions (bottom) for 1 January 1957.



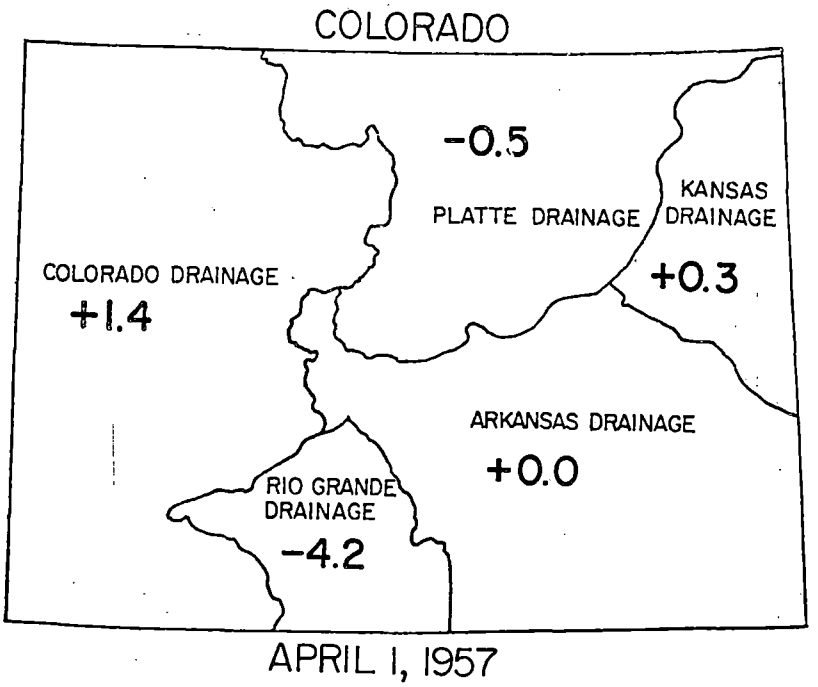
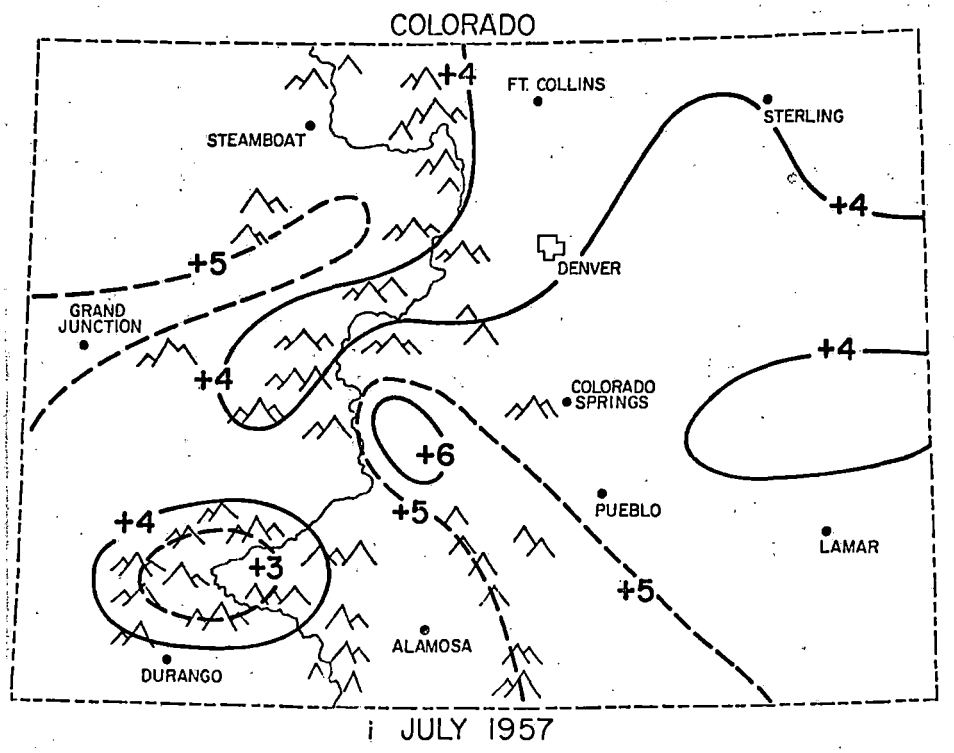


Figure 10e. Palmer Index pattern for Colorado based on the 25 new regions (top) and Palmer Index values for the 5 original divisions (bottom) for 1 April 1957.



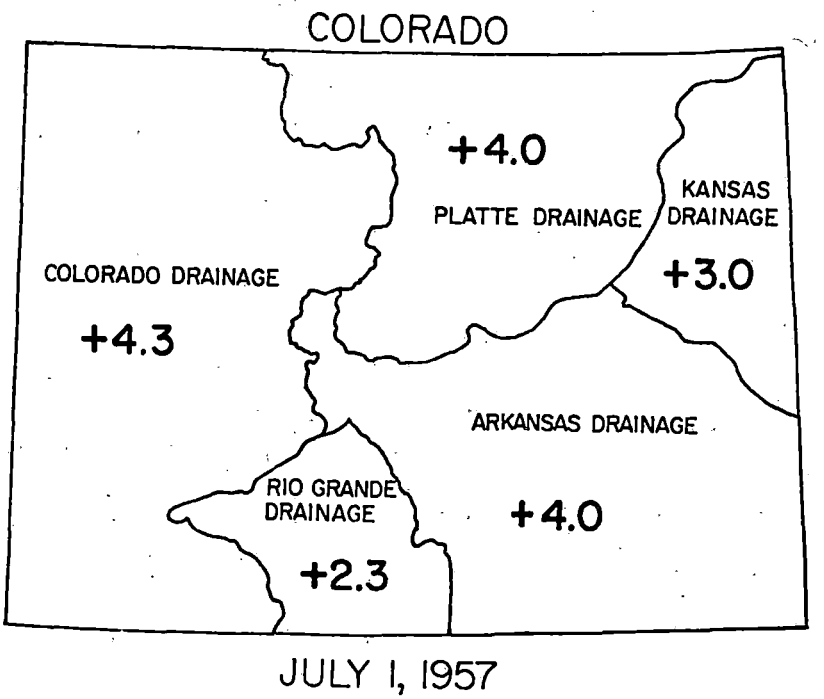


Figure 10f. Palmer Index pattern for Colorado based on the 25 new regions (top) and Palmer Index values for the 5 original divisions (bottom) for 1 July 1957.

V. APPLICATION OF THE PALMER INDEX IN COLORADO TO WINTER WHEAT PRODUCTION

A. Wheat Yield Information

The examples presented in the previous sections have indicated that the Palmer Index, calculated for relatively small geographical areas, yields realistic estimates of overall soil moisture conditions compared to the climatic normal. This does make it useful as a general tool for drought monitoring. The value and usefulness would be even greater, however, if it could be applied to the impact side of drought. Drought is not really drought unless there is some hardship caused by the lack of normal moisture. For this reason, a specific application area was selected to study how the Palmer Index could be used as an indicator of economic impact.

Winter wheat is the dominant cultivated crop in Colorado's agricultural economy. More than 3.5 million acres have been planted each year since 1980 accounting for nearly half of all the cultivated land in Colorado. Only about 4 percent of all winter wheat grown in Colorado is irrigated, so the bulk of Colorado's wheat relies solely on precipitation and stored moisture in the soil. As such, it is an appropriate element of Colorado's economy to study. While drought-hardy varieties are being and have been developed, winter wheat continues to be very climate sensitive. The Palmer Index, being essentially an indicator of deep soil moisture, is ideally suited for comparison with wheat production.

In this study a very simple approach was taken. Wheat yields in the various subregions of the state were compared to Palmer Index values for the past several years using simple statistical correlation techniques.

Several assumptions and approximations were required to facilitate this comparison.

1) Wheat yield information for each year 1941-1981 was obtained from the Colorado Department of Agriculture, "Colorado Agricultural Statistics" annual reports.

2) Yield statistics were based on average yield (bushels) per non-irrigated acre harvested for each county.

3) The subregions used for Palmer Index calculations did not correspond to county areas. Yield information was determined for each subregion by selecting the major wheat producing county within the subregion. In large subregions yield information from 2 or 3 counties were combined, weighted proportionally according to the total production in each county.

4) Yield information was assembled for only 10 of the 25 subregions. These 10 areas accounted for 90% of the total 1981 production. No wheat is grown in 9 of the 25 subregions.

5) Wheat yields have improved due to changes in farming practices, technology, and wheat varieties. This improvement, while almost certainly nonlinear with time, constitutes a trend which is unrelated to climate. Simple linear regression was used to remove this trend from the data.

Average yield for each year from 1941 to 1981 is plotted for two major wheat growing areas of Colorado in Figure 11. The trend line obtained by linear regression is also shown. This trend line will be considered as the "average" yield for a particular area for a particular year. Later analyses will refer to annual departures from "average" yields. Significant year to year differences can be seen in this figure along with large differences between subregions. For example, the effects of the mid-1950's drought appears to have been much greater in region 8 (Kit Carson county and surroundings) compared to region 10 (Weld, Morgan, and Logan counties). Yields in general have been more consistent in region 10 then in region 8.

Table 4 summarizes the regional winter wheat yield information used in this study. The highest, average yields occur in northeastern

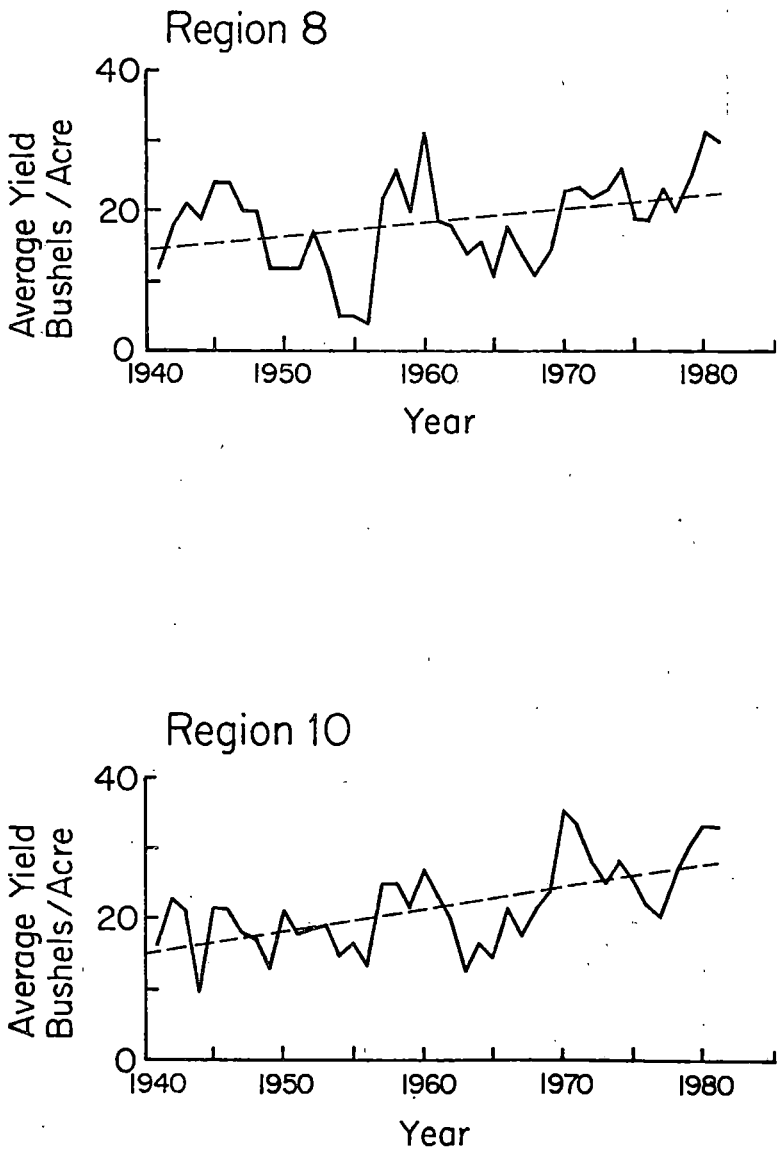


Figure 11. Time series, 1941-1981, of annual average wheat yield in Region 8 (southern half of Kansas drainage) and in region 10 (Platte drainage -- Colorado northeastern plains). Dashed lines are the "average" yield defined by the trend line obtained using linear regression.

TABLE 4.

Regional Statistics on Colorado
Winter Wheat Production, 1941-1981

Region	Annual Avg. Temp. (F)	Average* Wheat Yield (bu/acre)	Estimated** normal yield as of 1941 (bu/acre)	Estimated** normal yield as of 1981 (bu/acre)	Estimated** annual rate of improvement (bu/acre)/yr
1	53.2	14.7	12.5	16.8	+.11
2	53.3	15.3	13.1	17.6	+.11
3	50.7	16.6	13.0	20.2	+.18
4	51.8	13.9	12.0	15.9	+.10
5	43.9	13.9		not calculated	
6	44.9			Insufficient wheat grown	
7	34.5			Insufficient wheat grown	
8	50.8	18.3	14.6	22.5	+.20
9	50.4	23.7	17.4	30.2	+.32
10	48.7	21.8	15.5	28.0	+.31
11	48.8	22.4	18.2	26.6	+.21
12	49.9	23.9		not calculated	
13	46.4	17.8		not calculated	
14	40.9			Insufficient wheat grown	
15	36.8			Insufficient wheat grown	
16	36.1			Insufficient wheat grown	
17	41.9			Insufficient wheat grown	
18	50.0	16.6		not calculated	
19	46.1	15.7	14.8	16.6	+.04
20	44.0	20.2	19.4	20.9	+.04
21	38.0			Insufficient wheat grown	
22	39.1	17.9		not calculated	
23	38.3			Insufficient wheat grown	
24	36.2			Insufficient wheat grown	
25	35.8	23.5		not calculated	

* Yield statistics are based on acres harvested. Regional statistics obtained by selecting representative counties in each region. Data obtained from "Colorado Agricultural Statistics". Annual Publications, 1941-1982. State Department of Agriculture.

** Linear regression analysis used to determine estimates of annual normals and trends.

Colorado. Regions 9 and 10 have experienced the greatest improvement in yields over the past 40 years and also the most consistent yields on a year to year basis. Yields are much more variable and have improved at a much slower rate in southeastern Colorao. Yields on the Western Slope have shown little improvement in the past 40 years.

B. Correlations of Palmer Index Values with Wheat Yields

Using the winter wheat yield data, a number of comparisons with Palmer Index values were performed using the monthly PI values for each subregion. The first analysis was a comparison of annual wheat yields with the PI value for each month beginning 6 months before the typical planting data, continuing throughout the entire growth cycle of the crop, and terminating 6 months after harvest. The results of this correlation for region 8 is shown in Figure 12. Correlations were performed using both the actual yield data and also the yield residual (the difference between the actual yield and the "average" yield for that year as defined by the trend line shown in Figure 11). Correlations were significantly improved when the "average" yield (trend line) was removed. During the months prior to planting, the correlation coefficient improved steadily from 0.2 on March 1 to 0.5 on September 1. Improvement continued during the fall growth period but leveled off during the months of winter dormancy. Beginning March 1 of the harvest year the correlation began a steady improvement which peaked with a correlation coefficient in excess of 0.8 on July 1 near the time of harvest. Correlations, following harvest, degraded rapidly but remained above 0.6 at the end of December.

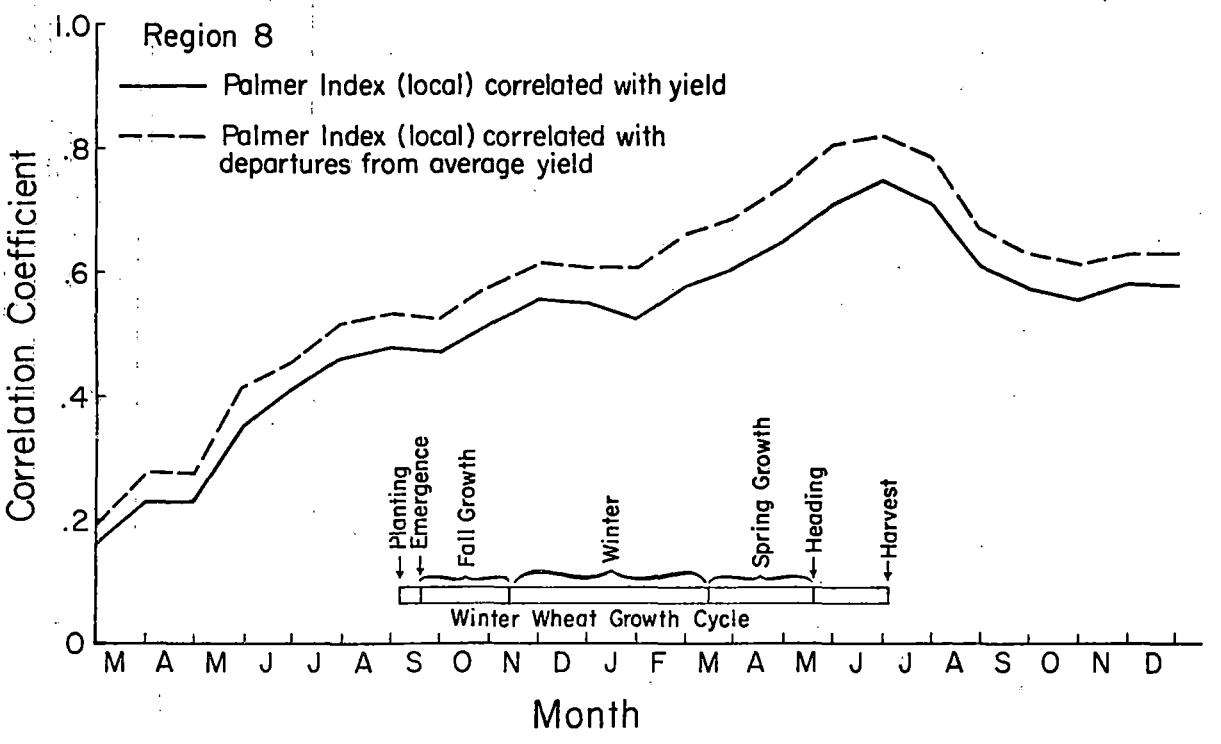


Figure 12. Correlation coefficients of the Region 8 monthly Palmer Indexes correlated with wheat yield (solid line) and with departures from "average" trend values of yield (dashed line) for the period 1952-1980.

In other regions of the state a similar pattern was observed. Peak correlation coefficients varied from as low as 0.6 in Region 2 to 0.85 in Region 10. The best correlations with wheat yield usually occurred with the June 1 Palmer Index in the southeastern regions and with the July 1 PI in northeastern and western Colorado, but this was not constant.

The correlation coefficients, while reasonably high, are not high enough to indicate a high predictive value of the PI several months in advance. The correlation coefficients during the previous autumn were rarely much above 0.6 meaning that only 36% of the possible variations in yield could be explained by the PI. Correlation coefficients exceeding 0.7 or 0.8 (explaining more than half of the variation) typically occurred only during May, June, and July.

C. Comparison of New Index Values with the Original Palmer Index Calculations

The question basic to this research project is, "Can it be shown quantitatively that Palmer Indexes calculated for new and smaller areas of Colorado are significantly better than the values already being calculated for the 5 large drainage areas of the state?" An attempt is made here to answer this question using winter wheat yield as the indicator.

A time series of June 1 PI values for Region 10 and for the entire Platte drainage area[1] is shown in Figure 13. Also plotted are the annual wheat yields in that region and the difference between the actual yield and the estimated average yield for each year.

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[1]At the time this report was written a complete time series of PI values for the original Platte Drainage had not yet been obtained.

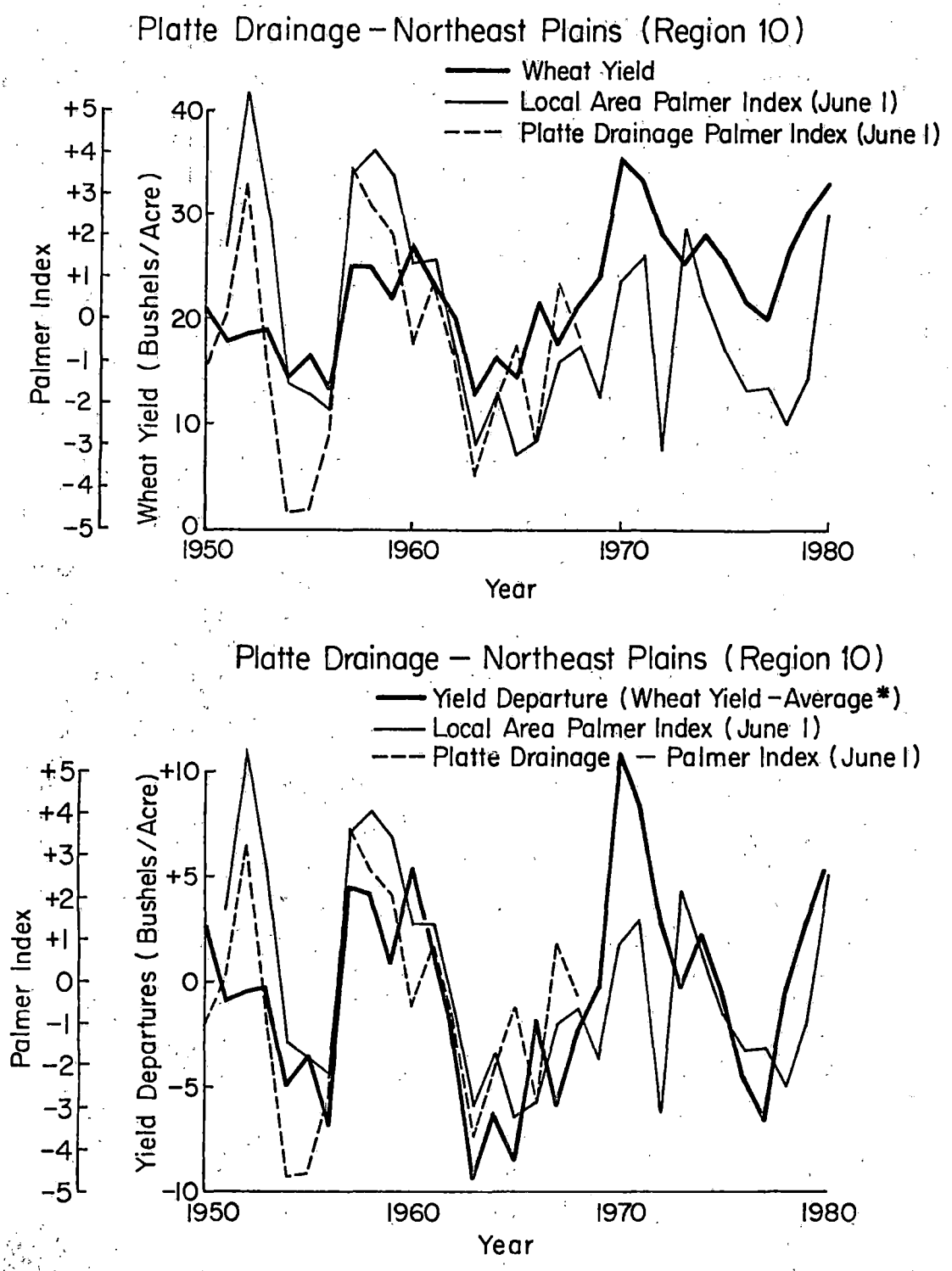


Figure 13. Coincident time series, 1950-1980, of Region 10 wheat yields, Region 10 June 1 Palmer Index values, and Platte drainage June 1 Palmer Index values (top graph). The bottom graph shows the same Palmer Index information plotted with yield departures from the average "trend" values.

This figure clearly shows that both indexes generally traced the ups and downs of the wheat yield. The local area index picked up some of the smaller details better than the overall index and tended to follow the graphs of wheat yield more closely, especially during the 1960's. Some obvious discrepancies were present, however. In 1952, both of the June PI values were very high. There was no corresponding peak in the yield data. Possible reasons for such discrepancies will be discussed in Section V.D.

Figure 14 shows more quantitatively the improvement that can be obtained by using the PI calculated for smaller areas. In Region 10, correlation coefficients were consistently at least 0.1 higher for the local area index correlated with yield residual as opposed to the results obtained using the Palmer Index for the entire Platte drainage.

This analysis did not offer results which conclusively showed the local area PI to be far superior to the PI for the entire drainage area. In several of the regions, the original PI's showed better correlation with yield data than the local area PI's several months prior to harvest. As harvest approached, the local area indexes nearly always correlated best with the yield. We are not prepared to offer a thorough explanation for this response. With only 17 years of overlapping data to work with, the statistical significance of this analysis is questionable.

Another way was chosen to address this question. Figure 15 a-c shows local area and original drainage area Palmer Index values along with yield data as a percent of average for 3 years during the 1970's. While absolute numbers did not always correlate well, local differences in wheat yields between adjacent regions were reliably consistent with

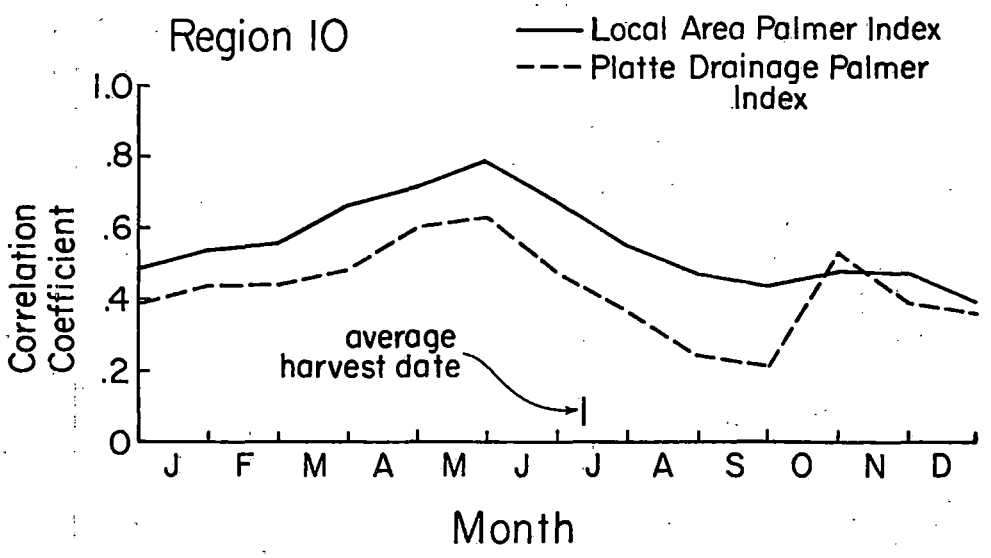
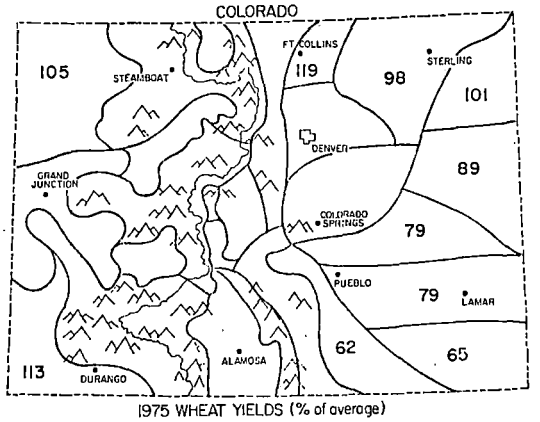
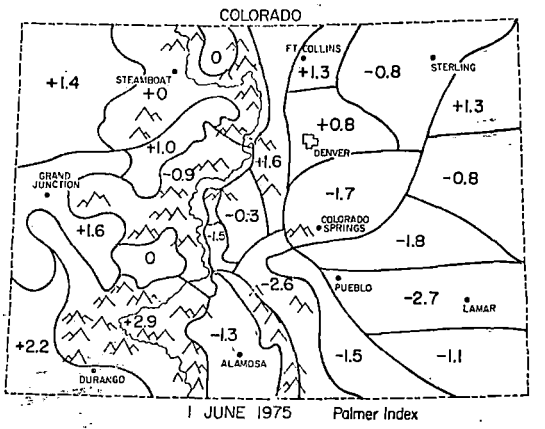


Figure 14. Correlation of 1952-1968 monthly Palmer Index values for Region 10 with departures of the annual wheat yields from the "average" trend value (solid line). The dashed line is the same correlation using original monthly Palmer Index values from the entire Platte drainage.





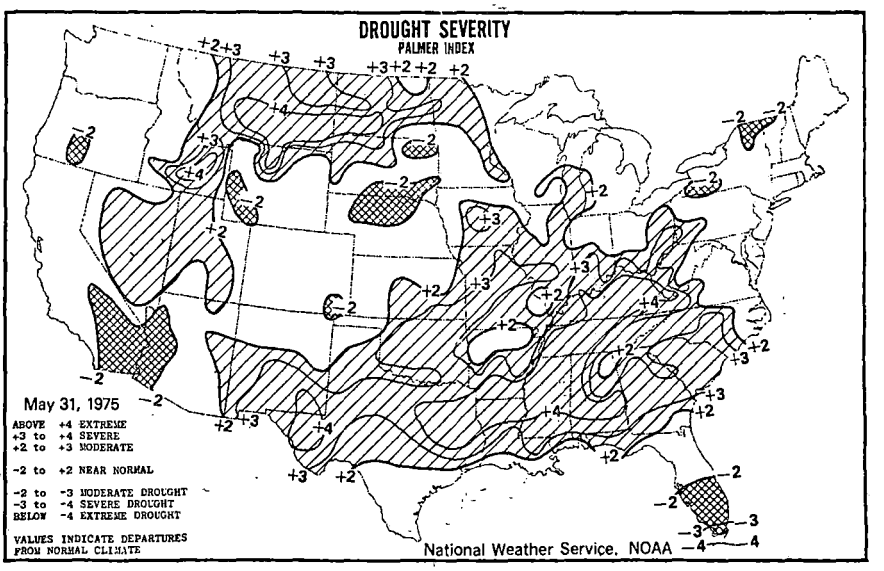


Figure 15a. 1975 percent of average wheat yield (top left), 1 June 1975 Colorado Palmer Index values (top right), and 31 May 1975 U.S. Palmer Index pattern (bottom).

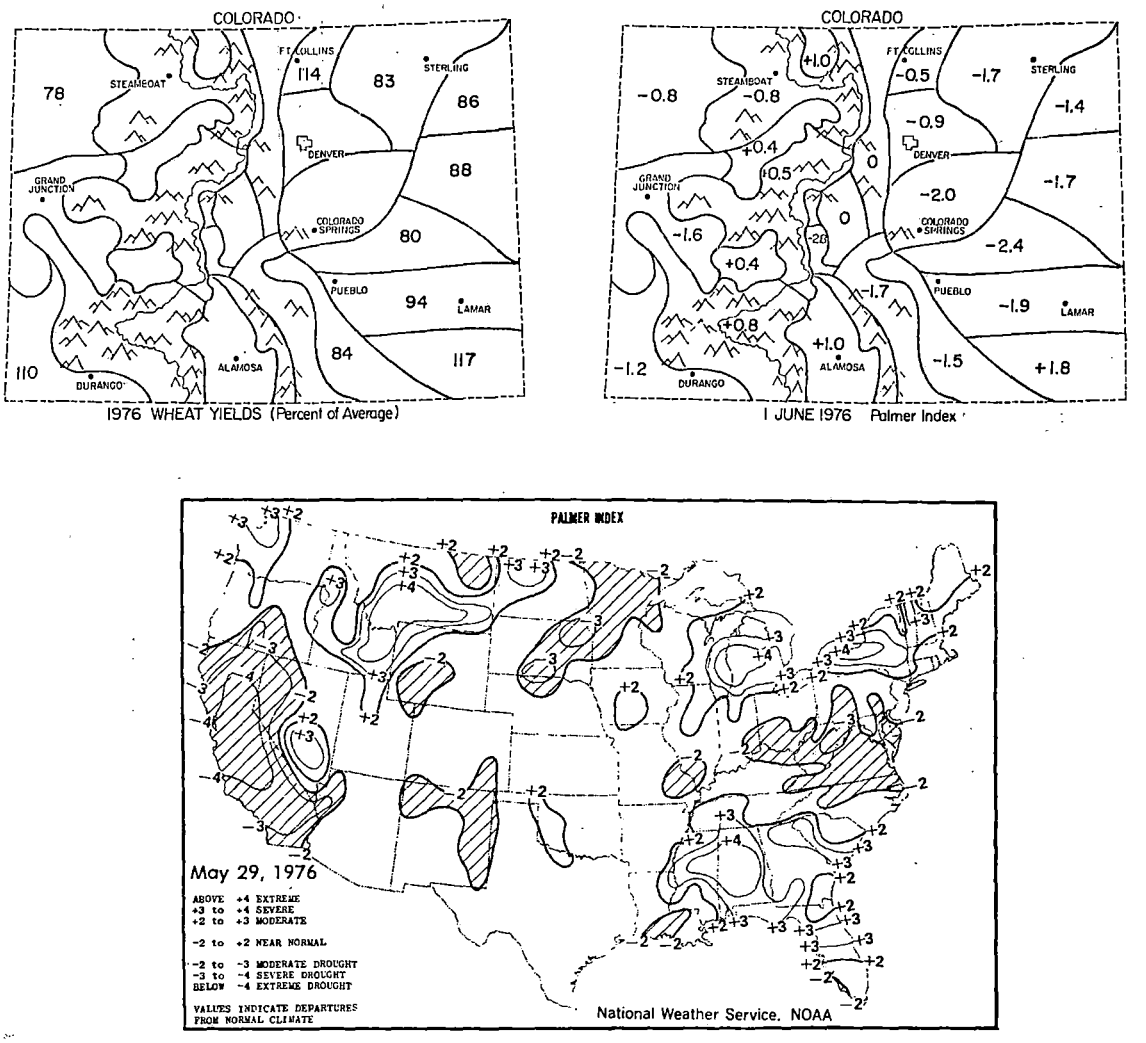


Figure 15b. 1976 percent of average wheat yield (top left), 1 June 1976 Colorado Palmer Index values (top right), and 29 May 1976 U.S. Palmer Index pattern (bottom).

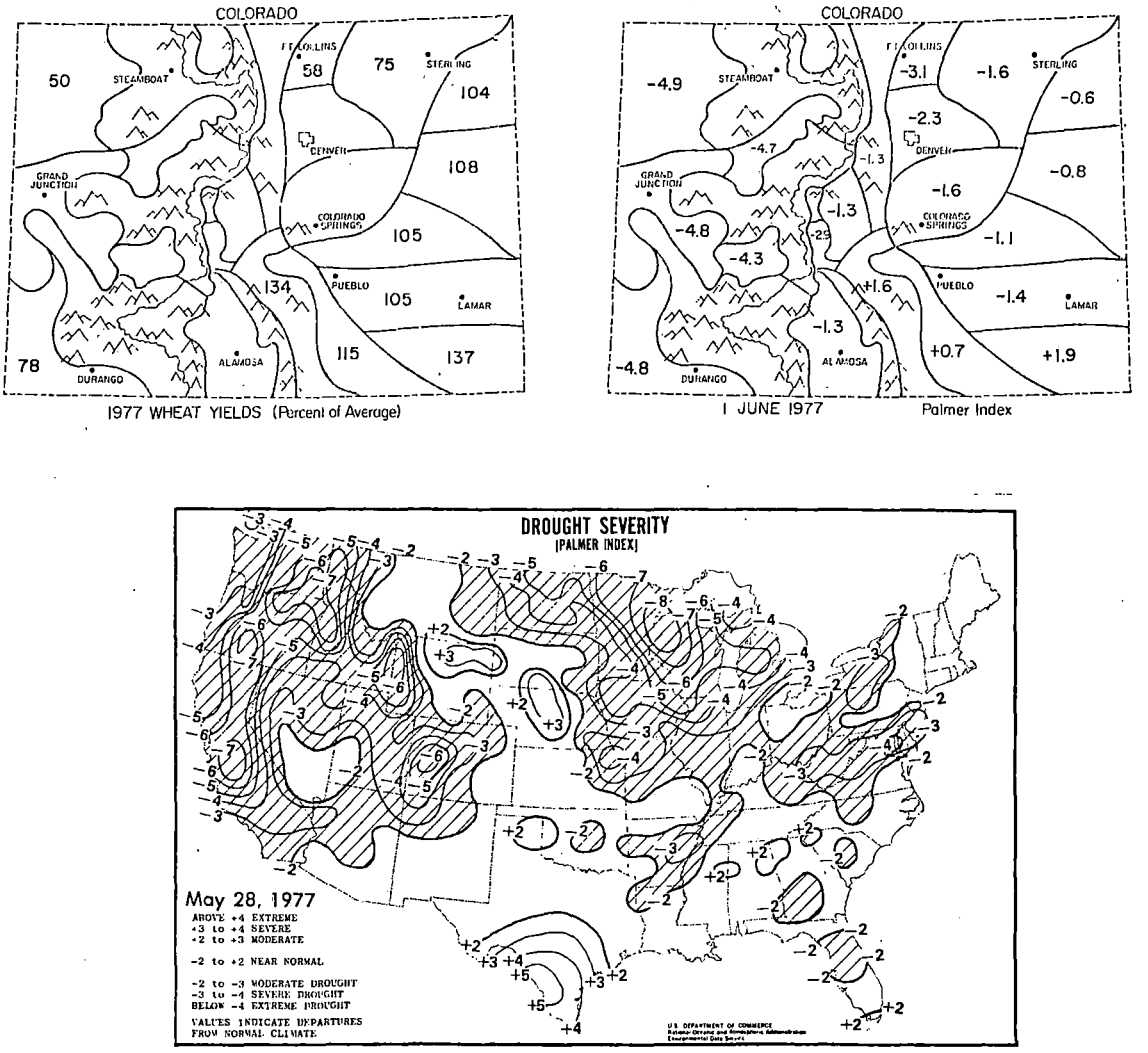


Figure 15c. 1977 percent of average wheat yield (top left), 1 June 1977 Colorado Palmer Index values (top right), and 28 May 1977 U.S. Palmer Index pattern (bottom).

differences in the local PI's. The national analyses were much too coarse to resolve these smaller scale variations.

One additional test was performed to verify whether or not it was necessary to "normalize" the temperature and precipitation data used as input for the Palmer model. "Normalizing" in this case refers to the adjustments made in the data to minimize the effects of moves and changes of the reporting station.

In Region 11 Palmer Indexes were calculated first using the raw data for the region. This means that monthly temperature and precipitation data from all stations in the area collecting data at any time during the 1951-1980 period were simply averaged together each month to obtain the regional inputs for the model. Indexes were then calculated a second time using input data which were adjusted based on the regional 1961-1980 averages of only the current weather stations. Each set of PI values were then correlated with Larimer County wheat yield data. Figure 16 shows the results. The adjustments seldom changed the regional input climate data by more than 0.5^{o} Fahrenheit and/or 0.10 inches of precipitation per month, and the effects on the PI values seemed small (usually less than ± 0.5). However, when correlated with wheat yield (Figure 16), PI's calculated with the adjusted input data had a significantly higher correlation coefficient, particularly during the months just prior to harvest. The statistical sample was quite small and this test was performed on only one region. Still, these results show dramatically that better PI values could be obtained using consistent input data.

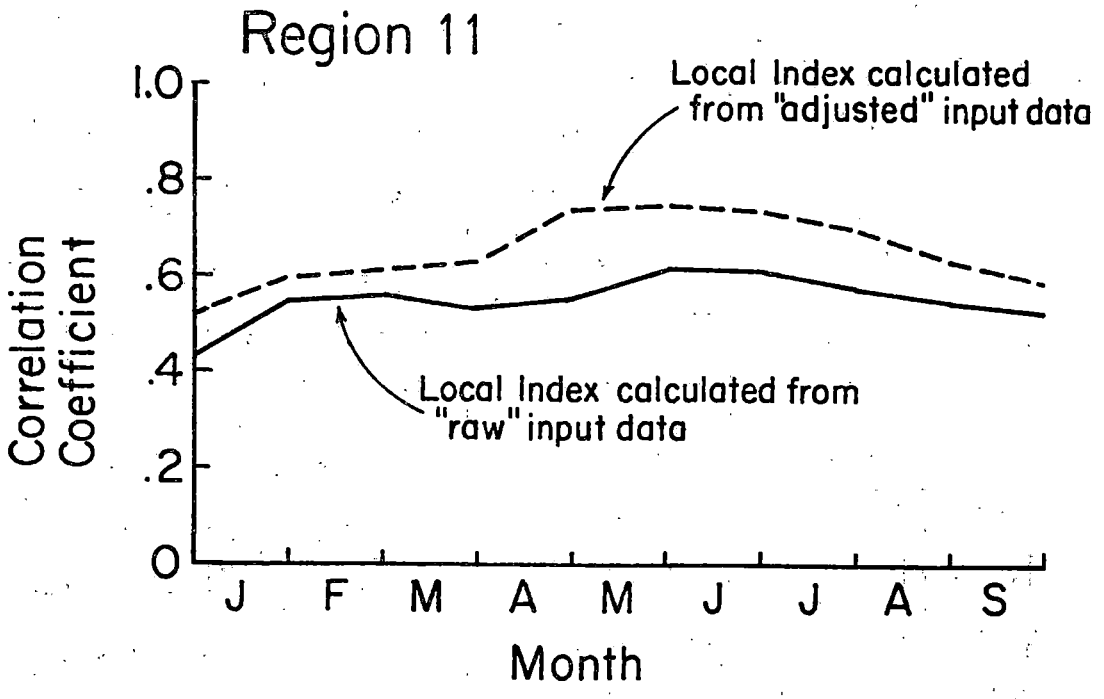


Figure 16. Correlation of Region 11 monthly Palmer Index values with annual wheat yield using unadjusted input temperature and precipitation data (solid line) and adjusted input data (dashed line).

D. Other Factors Affecting Wheat Yield

Soil moisture conditions as indicated by the Palmer Index show good correlation with non-irrigated winter wheat yields in Colorado. Correlation coefficients of 0.8 and higher denote that nearly two-thirds of the variance in year to year yields (with trends removed) can be explained using the PI. That seems to be about the upper limit, however. Many other independent factors influence yield which the Palmer Index modelling simply cannot account for.

Timing of precipitation events can be as important to wheat growth as the total amount of precipitation. Land use practices and weed control, also have very significant effects on soil moisture (Echols, 1983). Early summer hail storms or strong winds just before harvest time can significantly reduce yields even on a county-wide basis. Winter kill can affect wheat nearly independent of soil moisture. Finally, manipulation to achieve maximum advantage from government programs is certainly not unheard of, particularly in some of the marginal wheat growing areas of the state.

Knowing that each of these factors (and this is only a partial list) may play a significant role, and that each factor is probably independent of other factors, makes a clear point that there is no such thing as a simple model to predict wheat yields on a regional basis. It is far beyond the scope of ths project to address the specifics of wheat growth and yield modelling. Realizing these many variables makes the current success of the Palmer Index seem all the more impressive.

VI. SUMMARY

A. Review and Recommendations of the Water Availability Task Force

The Water Availability Task Force (WATF) functioned as a peer review group throughout the one-year Palmer Index project. During each monthly meeting of the WATF, a brief project status report was given, problems were discussed, and work priorities were set. The review was completed in February 1983 when a complete oral presentation on the PI project was given to the Task Force. A written summary of work progress and WATF recommendations was prepared by the task force chairperson following that meeting. The following comments and recommendations of the Task Force were the consensus of the members present at the February 16, 1983 meeting.

Comments

1. The project was a worthwhile activity and achieved the results set out for it.
    a. Transferred the capability to produce the Palmer Index to Colorado.
    b. Investigated the need for designating more homogeneous reporting areas for PI values in Colorado.
    c. Put in place the mechanism for operational production of Palmer Indexes for drought monitoring.
2. The project identified several areas that need to be considered to assure reliability and availability of locally calculated PI values in times of serious drought.
    a. Further study of the model is advisable since some questionable assumptions and techniques are employed.
    b. More refinement of the state regions may be desirable.
    c. Index results should ideally be validated directly with actual soil moisture measurements in addition to the indirect validation done using wheat yields.
    d. Production of the PI needs to be incorporated into an ongoing system within state government. Otherwise the capability acquired during this project will be lost by the time a serious drought impacts the state.

Recommendations

1. The State should pursue additional research in refining the Palmer Index capability. The Colorado Climate Center should be the lead agency for securing funding for such work, assisted by the Colorado Department of Agriculture, the Colorado Commission on Higher Education, and by Colorado State University as well as any interested state and federal agencies.

2. The State should fund the routine monthly production of PI values for the purpose of drought monitoring. The Climate Center and Colorado Department of Agriculture should coordinate the dissemination of this product.

3. In the case that funding cannot be secured for routine production, the Colorado Climate Center (Office of the State Climatologist) should receive, at the minimum, sufficient funding to maintain the program and input data in a standby mode. The State Climatologist should develop a budget proposal for this activity and solicit funding support through the Department of Disaster Emergency Services and the Office of the Governor.

The complete written summary prepared by the WATF chairperson is included in Appendix C. In addition to the written comments, Task Force members offered further suggestions. Great interest was shown in the wheat yield comparison and it was suggested that this work be completed and published, hopefully incorporating expertise from the agricultural community. The Crop Moisture Index data, which were generated along with the PI's but were not included in the statistical comparison with wheat yield, should be included in additional studies. Many ideas were presented as possible applications of the Colorado Palmer Index.

The unanimous decision of the WATF was that the PI calculated for smaller, climatically homogeneous areas of Colorado was definitely a better drought index than has previously been available. The WATF members believed that the PI would nicely complement the Surface Water Supply Index (Shafer and Dezman, 1982) recently developed to monitor that portion of Colorado's water resources.

B. Time, Effort, and Cost of Producing the Palmer Index for Operational Use by the Water Availability Task Force

Running the Palmer Index program is not a difficult process. With all coefficients already generated for each area, the additional work to calculate monthly index values consists mostly of preparing monthly temperature and precipitation input data. Actual computer time and programmer time is small.

The following is a time estimate for producing the PI monthly:

Activity	Time/month	Staff
Calculation of monthly mean temperature and precipitation for 25 areas of Colorado and entry into computer.	16 hrs	Climatologist & Technicians
Computation of PI values and storage of results	8 hrs	Programmer
Preparation of monthly summary	6 hrs	Climatologist
Dissemination (depends on method and volume)	6 hrs	Secretary

Approximate costs based on 1983 dollars would be:

Salaries		
Technician	$100/month	
Computer Programmer	$100/month	
Secretary	$ 60/month	
Climatologist	$150/month	
Total Personnel Cost		$410/month
Computer Costs		$100/month
Mail/Telephone/ Supplies/Printing		$150/month
Total Cost		$660/month (7,920/year)

These estimates do not specifically include overhead costs charged by Colorado State University.

To simply maintain the program and input data up to date but on a standby basis would cost approximately $2,000/year. Practically all of this cost would be for preparing and storing the input data in the format required for the program.

These costs are only approximate. Initial programming costs would be considerably higher, but long-term expenses could be reduced by adapting the Palmer Index program to a smaller in-house computer. Currently the program and data files reside on the large main computer at Colorado State University. The means and extent of dissemination of PI results also would have significant effect on costs. Most likely the PI values would be combined with other index information and made a part of the "Monthly Water Availability Status Report" which is currently being developed by the Colorado Climate Center on an experimental basis for the WATF. Again, initial costs would be higher but long-term costs could be trimmed by piggy-backing this project onto existing data processing and report preparation responsibilities of the Colorado Climate Center.

C. Conclusions

The capacity to calculate the Palmer Index in Colorado has been sucessfully transferred to Colorado. Program results have been verified by comparing monthly index values calculated for the Kansas drainage area with original values calculated by the National Climatic Data Center.

The state has been divided into 25 areas which are climatically similar and which complemented the larger drainage basins used the USDA Soil Conservation Service. Consistent temperature and precipitation

data have been assembled for these 25 areas. Palmer Index coefficients have been generated and monthly Palmer Index values for the period 1951-1980 have been calculated for each region.

Progress and results have been shared with the Colorado Water Availability Task Force. These interactions prompted a more indepth study of Palmer Index values. Case studies of two major drought events showed that the locally calculated Palmer Index described Colorado drought patterns with considerably greater resolution than had originally been possible. Correlations with winter wheat yields in unirrigated agricultural areas were performed. Results showed that the Palmer Index could explain a considerable portion of the annual variations in wheat yield as well as regional differences in yield in a particular year.

Considerable data and information have been generated during this project. More ideas for additional research have appeared and many more analyses can be done applying and testing the Palmer Index. This research effort has accomplished the goal of enhancing Colorado's drought monitoring capabilities while spurring on more research.

VII. APPENDICES

Appendix A

Water Availability Task Force Member Agencies

Colorado Division of Disaster Emergency Services
(Agency providing chairperson)

Colorado Department of Natural Resources
Weather Modification Office

Colorado Department of Natural Resources
Division of Water Resources

Colorado State University
Department of Atmospheric Science
Colorado Climate Center
(State Climatologist)

U.S. Department of Commerce
National Weather Service

U.S. Department of Agriculture
Soil Conservation Service

U.S. Department of Interior
Bureau of Land Management

U.S. Department of Interior
Geological Survey

APPENDIX B

Colorado Water Availability Status Report

January 1, 1983

State Assessment

Mountain precipitation was mostly near or below average during December. While the Northern Mountains from Steamboat Springs to Berthoud Pass received slightly above average snowfall for the month, the San Juans were slightly below average, and the Central Mountain areas were quite dry. The western valleys were very dry (Gunnison and Delta each received only a trace for the month) except for extreme southwestern Colorado.

Two major snowstorms, the Christmas Eve blizzard and a second storm a few days later, blanketed most of eastern Colorado with much above average snowfall. Two to five times the normal December precipitation was common over most of the plains. The only dry areas east of the Continental Divide, compared to average, were the upper Arkansas Valley above Pueblo, portions of the San Luis Valley, a tiny area north of La Junta, and the northern halves of Weld and Larimer counties in northcentral Colorado.

Despite below average snowfall in many of the high precipitation areas of the state, water supplies remain in good shape. Snowpack continues above average and reservoir storage is excellent for this time of year in most of the major basins. Surface Water Supply Index values, which are used to monitor surface water resources, remain positive except in the Arkansas drainage. Values continue to fall off, however, from their late summer peaks.

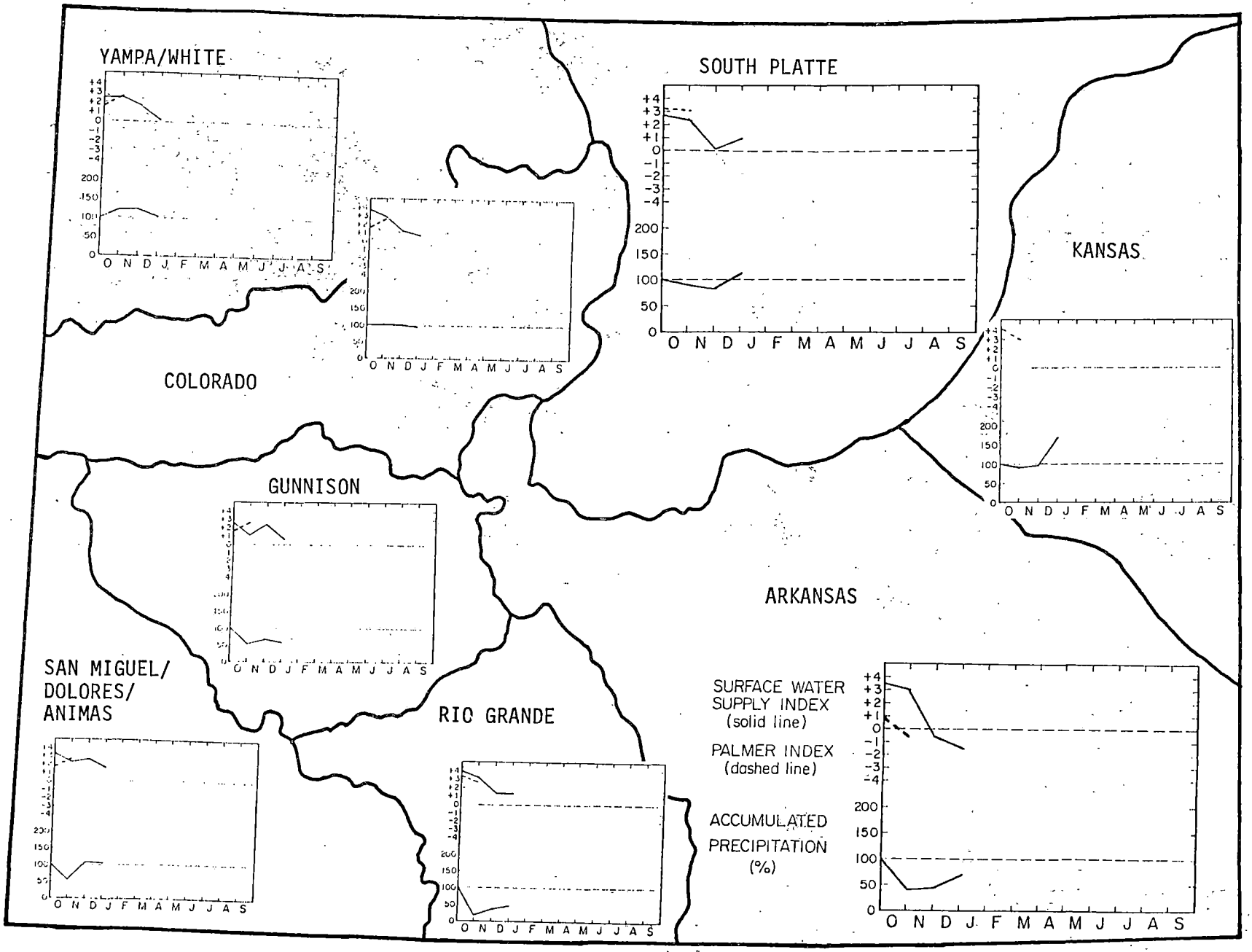
Palmer Index values are not being calculated during the winter months. Subjective measurements suggest fair to good soil moisture in agricultural areas of the state. Melting snows on the Plains should contribute more valuable moisture, but many areas were blown clear.

Outlook

Near normal precipitation and below normal temperatures are anticipated by the National Weather Service for January. Water supplies should continue to be adequate to ample in the months to come.

More detailed basin descriptions and specific snowpack data are contained in the USDA -- Soil Conservation Service "Water Supply Outlook for Colorado and New Mexico -- January 1, 1983."

COLORADO WATER AVAILABILITY STATUS REPORT



JANUARY 1 1993

DESCRIPTION OF INFORMATION PRESENTED ON MAP

The map showing Colorado water availability was designed to give a quick general view of current status and trends in available water. Graphs of two indexes and the accumulated precipitation are shown for the current water year. The water year in Colorado is defined as the 12-month period beginning October 1.

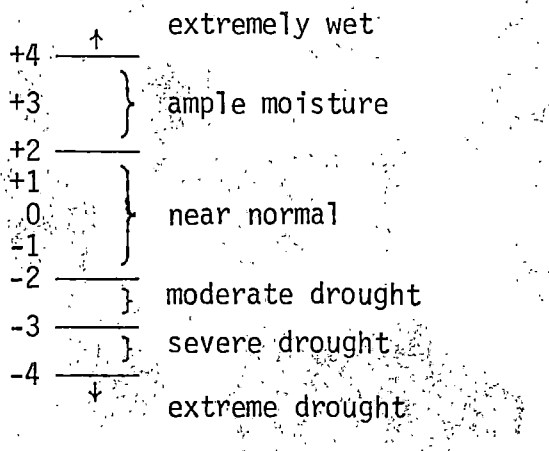
Surface Water Supply Index:

This index has been especially developed for Colorado by the Colorado State Engineer's Office and the Soil Conservation Service. It is based on snowpack, reservoir storage, streamflow, and precipitation and is a general indicator of surface water supply conditions. It is best suited for areas which rely on river or reservoir water. It may not accurately reflect conditions on individual tributaries.

Palmer Index:

The Palmer index is a relative indicator of soil moisture. It uses regional temperature and precipitation data as inputs to a soil moisture budget. It is best suited for unirrigated non-mountainous locations.

Interpretation on Indexes:



Accumulated Precipitation:

The percent of average water-year precipitation for each basin is calculated based on several representative weather stations in each region. The accumulation period begins October 1. Numbers less than 100% denote below average precipitation.

Special Notes:

1) Currently only one Palmer Index is calculated for all of western Colorado.

2) Palmer Index values not available during mid winter.

MEMORANDUM

Department of Military Affairs
DIVISION OF DISASTER EMERGENCY SERVICES

Richard D. Lamm
Governor

Brig. Gen. John L. Fran
The Adjutant General

John P. Byrne
Director

TO: Members of the Drought Water Availability and Chairpersons of the Review and Reporting Task Forces.

FROM: FOR Ken Beales. John P. Byrne, Task Force Chairman

SUBJECT: Minutes of the Water Availability Task Force Meeting (16 Feb. 1983)

DATE: 9 March 1983

Meeting was called to order at 0845 hrs. at the State Emergency Operations Center Camp George West, Golden, Colorado. Present were representatives of DODES, SCS, Office of the State Climatologist and Weather Modification Department of Natural Resources. Absent were representatives of NWS, USGS, and BLM.

DODES representative made introductory remarks to start the meeting off noting the items in the handout packet. Items of special note were articles on a new self reporting weather station, and notice of a conference on Flood Warning and Water Management to be held Sept. 19-23, 1983 in Sacramento, California. Conference will emphasize the use of sophisticated new computer data-gathering and analysis systems to solve water related problems including drought.

Old Business

(1) Water Availability Status Report - Representative of the Office of the State Climatologist reported no special action has been taken on this item as of yet due to the reorganization (change over by key personnel) at the Univeristy. Report will continue to be produced in house until a formalized decision is reached.

(2) Drought Plan Revision - DODES representative reported no additional progress made on this item due to other committments within DODES. No action input has been received from the Impact Task Forces. Concentration at this point will be on updating of the WATF annex and the management decision making diagram of the basic plan.

Special Consideration

Palmer Index Research Project - this item was given special consideration at the meeting to provide a detail review of the project and allow the Task Force to consider its recommendations concerning the Project so that they could be incorporated into the final project report of the State Climatologist. Some of the goals and accomplishments of the project were.

1. Obtain the program, bring it to Colorado and get it running. This has been accomplished with no modifications in the program itself although there is some potential for change in the program.

2. Verify the Program - A test was conducted on the Kansas Drainage in Colorado. Were not able to copy exact results but could track throughout the index except in the +1 to -1 category.

3. Investigate the potential for reorganizing the State into more homogeneous reporting areas, than those designated by NWS. Started off considering eleven or twelve areas and ended up with twenty-five. Of these twenty-five sub regions, sixteen are continental divide east and nine are continental divide west. Main emphasis was on low elevation areas. Climatic homogeniality was sought for each sub region.

4. Normalized monthly data to drive model and co-effecients. 1951-1981 data normalized to current stations for all sub regions. This was the most time consuming task of all those undertaken. No station weighting was done. Co-efficients were calculated for all twenty-five sub regions.

5. Comparisons of Index values from sub regions to major regions to see if there were significant differences. If there were this would validate the need for these sub regions. Results of this comparison reflected significant differences in many cases between the sub regions and the major region.

   There was some discussion on how difficult the index was to produce and how frequently it should be run based on present data availability and reporting systems. Calculations are easy and straight forward and can be run on a small computer. The 14th of the month appears to be the best time frame to get the index out by based on current input mechanism; and monthly appears to be the most useful frequency of producing indexes.

The discussion then turned to the need for validating the results of the index and methods to do this. Ideas consisted of making a comparison of the Index to Precipitation (Stream Flow Data). Perhaps using Dry Land Wheat Production. There appears to be a fairly decent correlation between wheat yields for unirrigated farm land and the index, but there are a lot of other variables that need to be factored into such comparisons to get a true picture. There appears to be some interest within the agricultural elements of the University in this particular activity. The State of Kansas has done the most work in this area making use of the comparison of wheat production and the Palmer Index. The discussion identified the need for more validation of index results as well as more investigation into the use of the Index to assist the Agricultural Community in forecasting crop production.

State Climatologist representative asked the Task Force members provide him with written comments/recommendations they might have on the project not later than the end of the month so they could be included in the final report.

The following comments/recommendations summarize the general concensus of the Task Force members present at the meeting.

1. The Project was a worthwhile activity and has achieved the results set out for it, namely to

   A. Transfer the capability to produce the Palmer Index to Colorado.

   B. Investigate the need for designating more homogeneous reporting areas for Palmer Index values in Colorado.

   C. Have an operational capability in place to produce Palmer Index values.

2. The Project has identified several areas which need to be addressed before the system can be considered to be fully reliable and available for use in a serious drought. These are.

   A. Consideration of modifications to the program to increase its reliability. Present program has several questionable assumptions built into it as well as a significant degree of subjectivity.

   B. More work needs to be done on refinement of the sub regions to insure their value and validity.

   C. Index results need to be validated against actual conditions.

   D. Index production needs to be incorporated into an on-going system within State Government or the present knowledge and capability acquired through this project will rapidly diminish and be non existant when a serious Drought impacts the State.

   With these considerations in mind, Task Force recommendations were -

1. The State should pursue additional research effort in refining the Palmer Index capability it has acquired through this project, with areas of concentrations in Program Modification; Refinement of Sub Regions; validation of Index results. The office of the State Climatologist should be the lead agency in securing funding for this activity assisted by the Colorado Department of Agriculture (who should have a direct interest in this activity) and by the Commission on Higher Education,

the Department of Higher Education and Colorado State University, as well as other State and Federal Agencies who have an interest in the Program. The research effort main focus would be to develop a fully reliable program/ system to produce Palmer Index Values on a monthly basis.

2. The State should fund the routine production of Palmer Index values on a monthly basis year around within the system of State Government. The Task Force felt that both the office of the State Climatologist and the Colorado Department of Agriculture had an interest and a role in this activity and perhaps the production - dissemenation functions could be shared by the two agenices.

3. In consideration of the funding restrictions the State is presently experiencing and the possibility that neither item 1 and 2 above are funded, the Task Force felt that at a minimum sufficient funding should be provided to the Office of the State Climatologist to provide for program maintenance in a dormant phase; The system could then be rapidly activated under potential serious drought conditions within a reasonable time frame. This effort would require imputing data into the system periodically to keep it current through the present time frame for each of the sub regions and conducting periodic familiarization of the State Climatologists' staff in the program to insure trained personnel are available to bring the program on line when needed. State Climatologist should develop a budget proposal for this activity and solicit funding support through DODES and the Office of the Governor.

New Business

Current Water Availability Conditions

(1) SCS reported that the snow pack as of the 1st of February was 70% of last year at this time. The snow pack statewide had dropped from 121% of normal on the 1st of January to 90% of normal on the 1st February. We are 60% through the winter with January and February being the normal high precipitation months. It will take several large storms to bring the snow pack up to normal. Reservoir Storage remains excellent for the State at 40% above average. The South Platte snow pack is 30% below average and the reservoir storage in this area is down from what it was last year at this time. This is an area that will need close monitoring. Soil moisture conditions are good across the State and the wind erosion problem has simmered down. The SWSI reflects considerably reduced index values for all river basins with the lowest being a -2.1 in the Arkansas Basin and negative indexes in the Yampa - White, N. Platte; Colorado; Gunnison; and Rio Grande River Basins. The S. Platte and San Juan - Dolores are barely in the positive category.

(2) National Weather Service Forecast indicated above normal temperatures and above normal precipitation through the end of February.

(3) State Climatologist reported that precipitation had really dropped off in January with the North East corner of the State being super dry. Temperatures for the most part were above normal across the State for the month of February.

(4) State Climatologist reported that the Water Availability Status Report graphic portrayal of data indicated the downward trend of the indexes and precipitation in the various river basins, as covered in the other reports. Note during this time frame time when the Water Supply Outlook Publication is being produced, no narrative is being produced, strictly the graphic data. If it is decided at some future date to go with 25 sub regions for Palmer Index values the graphic portrayl of this report may need to be modified. (See attachment #1).

In summary January weather conditions indicate a considerable downward trend in the availability of water in Colorado and has given raise to concern over potential drought conditions. February and March will be the critical months in determining just what the status will be going into the spring runoff period. The South East Corner of the State is still in a condition of moderate drought. The South Platte is also an area of concern and will need to be monitored closely.

Other

It was decided that the next meeting should be scheduled for Friday, 18 March 1983, at 0845 hrs. at the State EOC. (Some consideration was given to holding this meeting at NWS, but a conflict of schedule arose). See agenda attached. There being no further business the meeting was adjourned at 12:15 hrs.

VIII. REFERENCES

Brown, Merle J., 1979a: A FORTRAN Program for Obtaining Monthly Palmer Index Values. Departmental Report 679. Department of Physics, Kansas State University, Manhattan, Kansas. June 1979.

Brown, Merle J., 1979b: A FORTRAN Program for Obtaining Weekly Crop Moisture Index--Palmer Index Values. Departmental Report 779. Department of Physics. Kansas State University, Manhattan, Kansas. July 1979.

Colorado Department of Agriculture, 1982 (and previous years): 1982 Colorado Agricultural Statistics. Colorado Crop and Livestock Reporting Service, Bulletin 1-82, State of Colorado. Denver, Colorado. July 1982.

Doesken, N. J. and T. B. McKee, 1978: Colorado Climate Summary Water-Year Series (January 1977-September 1977, October 1977-September 1978). Climatology Report No. 78-3. Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado. December 1978.

Echols, James W., 1983: Personal communication. Colorado State University Extension Service, Fort Collins, Colorado.

Lamm, Richard D., 1981: The Colorado Drought Response Plan. Executive Chambers, State of Colorado. May 1981.

Lewis, Irma, 1982: Personal communication. National Climatic Data Center, Asheville, North Carolina.

Main, William, 1982: Personal communication. U.S.D.A. Forest Service, North Central Forest Experiment Station, East Lansing, Michigan.

National Climatic Data Center, 1982: Unpublished tabulation of monthly Palmer Index coefficients for the 5 climatic divisions in Colorado. Asheville, North Carolina.

Palmer, W. C. and A. V. Havens, 1958: A Graphical Technique for Determining Evapotranspiration by the Thornthwaite Method. Monthly Weather Review, vol. 86, No. 4. April 1958, pp. 123-128.

Palmer, W. C., 1965: Meteorological Drought. U.S. Department of Commerce, Office of Climatology, U.S. Weather Bureau. Research Paper No. 45. Washington, D.C. February 1965.

Shafer, B.A., and L.E. Dezman, 1982: Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. Proceedings of the 1982 Western Snow Conference, Reno, Nevada, April 1982.

U.S. Department of Commerce, U.S. Department of Agriculture, 1981: Weekly Weather and Crop Bulletin, Volume 69, No. 31. NOAA/USDA Joint Weekly Agricultural Weather Facility. Washington, D.C. October 1981.