DROUGHT-INDUCED PROBLEMS AND RESPONSES OF SMALL TOWNS AND RURAL WATER ENTITIES IN COLORADO: THE 1976-1978 DROUGHT

by

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Colorado Water
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Abstract

"Drought Induced Problems and Responses of Small Towns and Rural Water Entities in Colorado: the 1976-1978 Drought"

The climatological and hydrologic conditions across the State of Colorado during the 1976-1978 drought showed great diversity, adjacent drainage basins often experiencing quite different conditions. This emphasizes the importance of providing climatological information and assistance programs that are tailored to local areas (e.g. the Water Districts in Colorado).

Small towns experienced the intensifying of problems that, for the most part, had existed for a long time: lack of adequate raw water; poor system performance and high loss of produced water from lack of maintenance; inadequate financing and the use of water revenues for general purposes; and, at times, inadequate management. The latter is often caused by high turnover as personnel are attracted to the larger towns.

Town responses included emergency repairs, drilling wells, buying additional water rights and renting water from farmers, restrictions on water use, installation of meters, and increasing water charges (both price and flat rates).

The town experience indicated that many effective counter-drought actions depend upon local knowledge and initiative. State and federal programs cannot substitute for this, so these higher level programs must be designed to stimulate local initiative and not to be "a reward for 50 years of bad management."

Rural water entities providing mostly irrigation water experienced problems stemming in part from over-irrigation in the early season, over-expansion of acreage relative to reliable water supply, and inflexible reservoir management. Cooperative sharing of water and water rentals among farmers frequently helped avoid the economic inefficiencies that would occur under strict application of priority rights. This emphasizes the importance of facilitating both the short and long-term transferability of water among uses.

Major opportunities exist for conjunctive management of surface and tributary groundwaters. The State priority rights system currently prevents rational conjunctive management.

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The success of a study like this is totally dependent on the cooperation of many people. Our research team was very fortunate in finding talented, devoted people who were deeply concerned about drought issues and who were willing to take time from already too busy schedules to talk with us, to look up information for questionnaires, and to write us letters. Many were participants in successful drought assistance programs for which they received little recognition. Much of the information and many insights reported here could not have been gained from statistical analysis of cold figures: they had to come from individuals who had played active roles during the drought. Others provided a valuable review of drafts of the report. We want to acknowledge their vital assistance.*

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I.

THE COLORADO DROUGHT OF 1976-1977

A. The Geography of Colorado

The State of Colorado is divided into three major regions with the Rocky Mountains dividing the plains to the east and the plateau region to the west. The plains climb from an elevation of 3,400 feet at the Kansas border to about one mile at the foot of the mountains 150 miles to the west. The mountains themselves run roughly north-south and rise over 14,000 feet. Within the mountain region are four major valleys: North Park, Middle Park, South Park, and the San Luis Valley. To the west of the mountains and extending into Utah is a region of relatively flatter country with several broad plateaus.

Most of the major rivers of the state begin in the central mountains. Three principal rivers start on the east of the continental divide and eventually flow into the Gulf of Mexico: the South Platte and the Arkansas cut roughly west to east across the plains into Nebraska and Kansas respectively, while the Rio Grande River flows south through the San Luis Valley in the south central portion of the State, eventually flowing through New Mexico, and along the international border between Texas and Mexico.

Several important rivers originate on the western side of the continental divide and flow into the Colorado River drainage. The Yampa and the White flow westward through the northern part of the plateau country, while the Dolores drains much of the southwest. The Uncompahgre, Gunnison, and Colorado Rivers have their origins in the mountains and flow through the central portion of the plateau region.

The Division of Water Resources of the State of Colorado has formed seven management divisions, generally following the major drainages described above. Divisions 1 and 2 correspond to the areas drained by the South Platte and the Arkansas. The Rio Grande drains Division 3. Division 4 includes the Uncompahgre and the Gunnison, Division 5, the Colorado, Division 6, the Yampa and the White, and Division 7, the Dolores and the San Juan. Each Division is divided into Districts that correspond to the sub-drainages of the Division. State water administration is under the direction of the State Engineer, assisted within each division by a Division Engineer who is, in turn, assisted by a Water Administrator in each District. The Divisions and Districts are shown in Fig. 1.

There are several thousand man-made reservoirs throughout the State, both public and private and ranging in size from less than 100 acre-feet to more than 700,000 acre-feet.

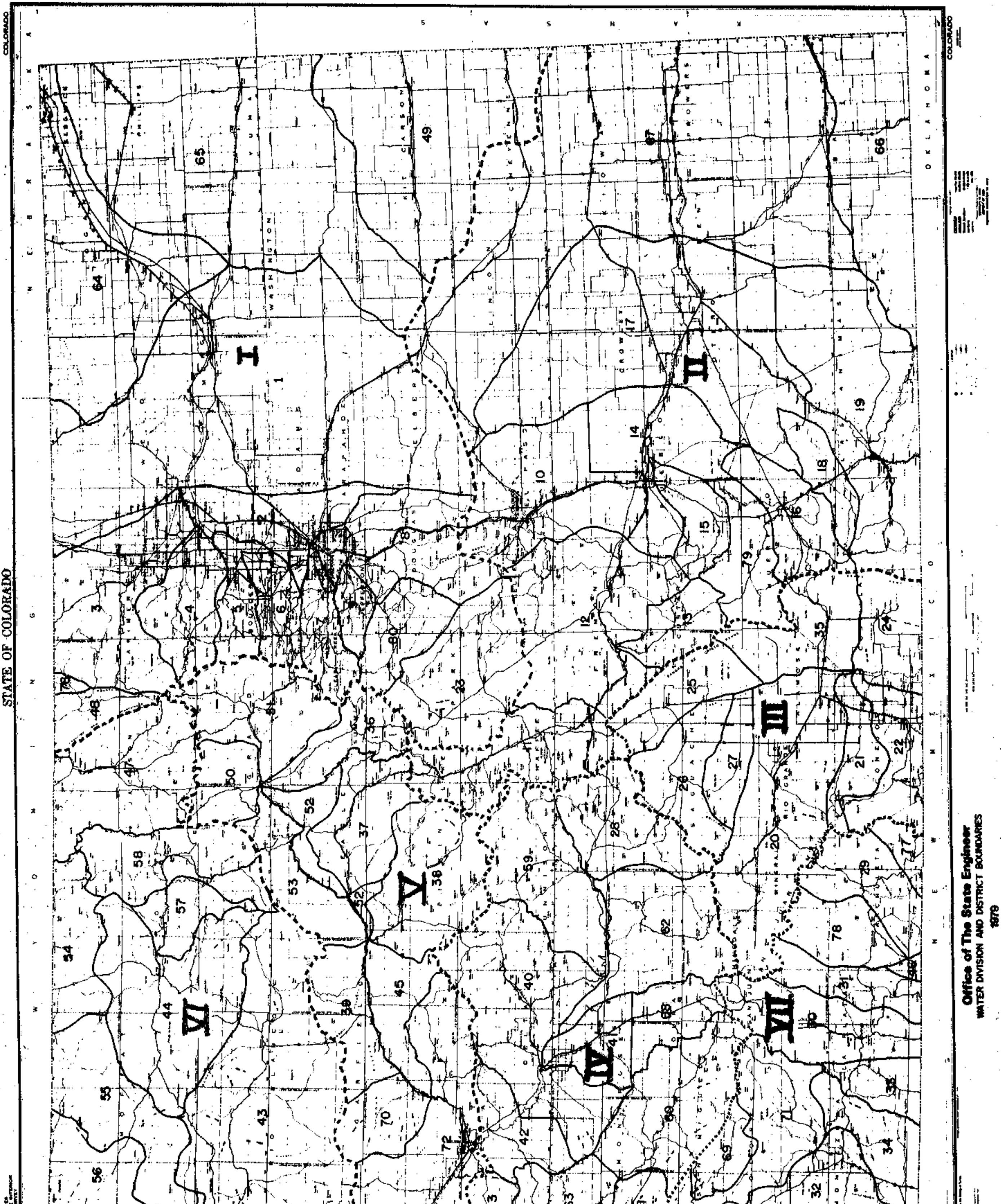
B. The Definition of Drought

There is no doubt that the western United States experienced an unusual period of dryness from the winter of 1975 - 76 to the winter of 1977 - 78. California was perhaps the hardest hit state, with Marin County receiving National and even international attention in its attempts to cope with an extreme shortfall of water supply. However, the Northwest was hard hit, too, with the Columbia River reaching the lowest flow of record with resultant electric power shortages and major fish kills.

The "drought" hit Colorado in the winter of 1976 - 1977 when mountain snowfall was extremely low. Ski resorts had great difficulty opening even at Christmas, and the outlook for the coming summer's water supply was grim.

Figure 1.

STATE OF COLORADO



Office of The State Engineer
WATER DIVISION AND DISTRICT BOUNDARIES
1979

While these climatic events were easily recognized as unusual and labelled as drought, what working definition can we give to "drought"? When the eastern Colorado water manager describes the conditions in the summer of 1976 as a "near normal drought" or when the western slope rancher condemns the "damned unpredictable weather", what do they have in mind? Do the Mohave and Sonoran Deserts experience drought?

For practical policy-making purposes, drought is a combination of climatic and socio-economic conditions that can be summarized as follows:

> Drought is the existence of a persistent shortfall in water supply relative to the "expected" supply; stemming from a shortfall in precipitation either locally or in hydrologically connected regions that provide the water supply.

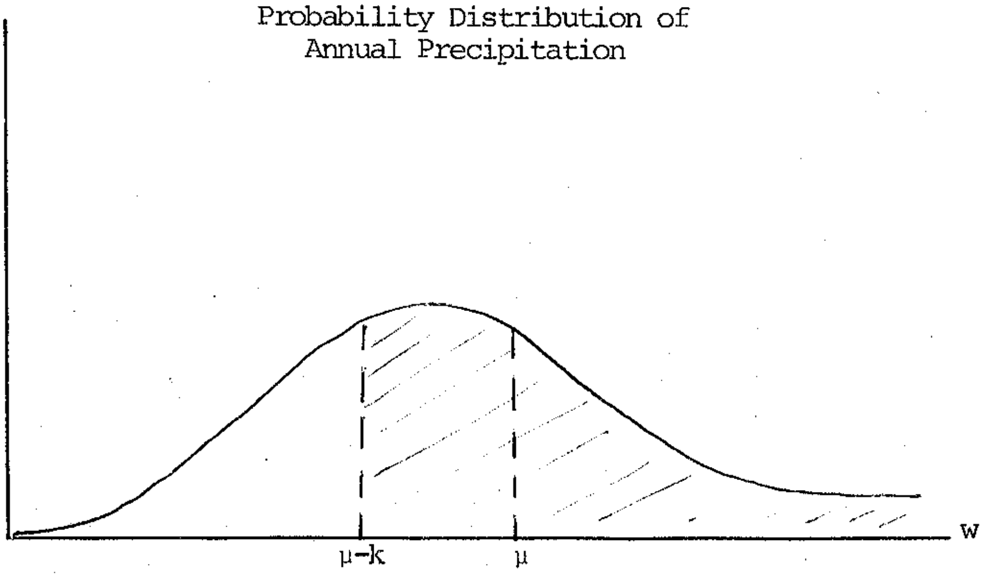
The expectations referred to are in the minds of water users and are important because economic and social decisions are based on these expectations, e.g. cropping patterns, recreational plans, and urban investment decisions. True deserts do not experience drought in this sense because anyone contemplating economic or social activity there expects no rainfall and bases plans on that expectation.

The definition also covers the case of a region that has not experienced direct climatic change but in which streamflows and groundwater recharge have been diminished because of precipitation deficiencies in upstream regions. The full meteorological or climatic conditions must be included in the analysis of drought.

Drought could be defined in purely physical terms, based on annual precipitation or some cumulative measure of precipitation over several years. Figure 2 shows a hypothetical probability destribution of annual precipitation, indicating the long-term annual mean μ, and a value $(\mu - k)$

that might be referred to as the "reliable rainfall level", i.e. a level of rainfall for which the probability of getting that level or more is sufficiently high to "bet on" or to use as the basis for decision-making. The shaded area shows the probability of (μ - k) or more precipitation.

Figure 2
Probability Distribution of
Annual Precipitation



What we find, however, is that the level of k that people use to specify the "safe" yield depends upon the uses to which the water is being put. For municipal or industrial uses, k is likely to be chosen large relative to u, so that the ratio $(\mu - k)/\mu$ is small. For most irrigation applications, k is likely to be given a small value, so that $(\mu - \mu k)/\mu$ is closer to 1. This suggests that the level of precipitation or water supply considered "safe" depends on the severity of the losses that occur when actual precipitation or yields fall before that level and on the additional values that may be gained if yields should be above that level. Thus economic consequences are implicity introduced along with climate information in the definition of reliable or safe levels of precipitation or other water supplies.

This suggests that one role of studying drought is to quantify the severity of impacts of water shortage so that we can more rationally plan ways of dealing with drought. If impacts are slight, then we can stand to put up with shortages fairly frequently, while severe impacts imply that we should invest in new water supplies or consider steps to modify current water uses.

For policy purposes, we are interested in the gains or losses accruing to all of society from surpluses or shortfalls of water relative to expected supplies. Different water user groups or water managers may, however, have a viewpoint different from that of all society. The manager of an urban system may perceive the losses from water shortage to be much greater than they really are because he is likely to be personally criticized when customers are asked to curtail use. Well-meaning officials may be tempted to exaggerate the severity of drought to stimulate cooperation in water conservation or to make a case for drought-related aid. The aggregate agricultural and broader economic and employment effects in Colorado appear to have been substantially exaggerated in the press and through agency announcements during the drought.[1]

The problem of measuring losses due to drought is even more subtle than questions of human perception and motivation. Many costs incurred during drought that at first appear to be drought-induced losses turn out, upon closer inspection, not to be. As will be noted later in this study, much of the monetary aid provided by federal and state agencies to towns and rural water agencies was used

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[1] See "Colorado Manpower Review", Nov. 1977, monthly newsletter of the Colorado Department of Labor and Employment and Herbert H. Fullerton, "Drought Lessons from Agriculture," paper given at the Engineering Research Foundation Water Conservation Conference, Rindge, NY, July, 1979.

to repair or improve water system components the conditions of which had nothing to do with the drought. Russell *et*. *al*. also found that much of the "cost of the drought" to Massachusetts industry consisted of investments in water systems that would have been profitable to undertake for years but to which attention was first called by the drought.[1]

Severe drought usually builds up over more than one year, depleating reservoir and groundwater storage, reducing soil moisture and the waste-assimilative capacities of streams, and placing perennial plants under increasing stress. A measure frequently used to measure drought physically is

$$D(T) = \sum_{t=T-j}^{T} (T_t - \bar{R})$$

where R_t is annual precipitation in year t, R is the long-term mean annual annual precipitation, and j is the number of years over which these differences are cumulated.[2] The patterns of this measure for four towns in Massachusetts from 1870 to 1970 are shown in Figure 3. One will note the "drought of record" of 1908 - 11 and the 1963 - 67 drought.

(Figure 3 here)

Another widely used physical measure of drought is the Palmer Index that measures the moisture stress placed on plants. The manager or public's *perception* of drought may, of course, lag behind any of these physical indexes. Russell *et al*.

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[1] See Russell *et.al*., pp. 206-208.

[2] *ibid*. pp. 44-47.

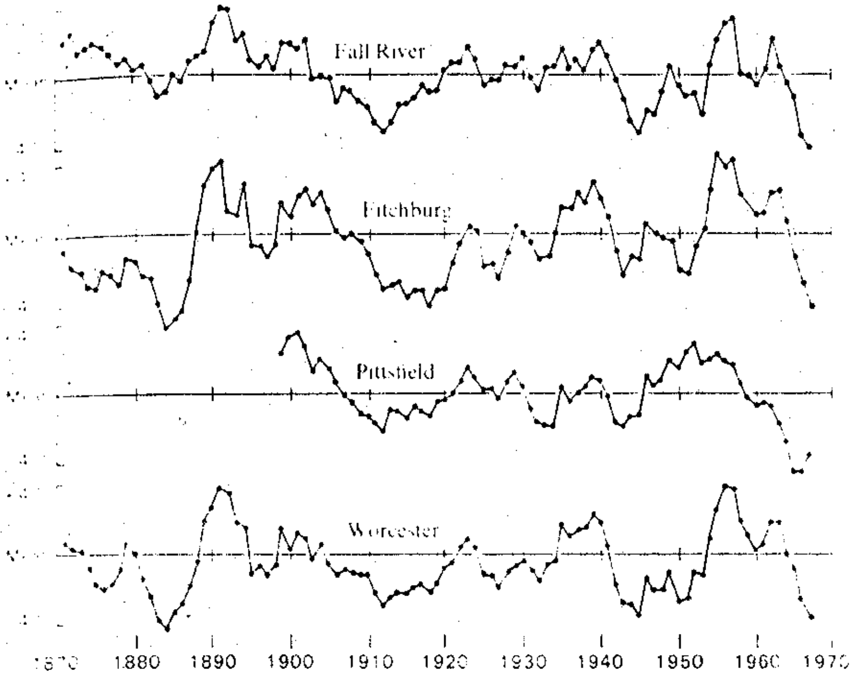

Figure 3.
Four-year Cumulative Deviations of Annual Rainfall from the Long-term Mean Annual Rainfall in Four Massachusetts Towns.

Source: Russell, et al., Fig. 11, p. 45

have shown the pattern of lags between town water manager's perception of the beginning of drought and the beginning as measured by the Palmer Index.

Table 1

Region of Massachusetts	Beginning of Drought: Palmer Index	No. Cases Where Manager Perceived Drought Beginning:			
		Same Year	1 Yr. Later	2 Yr. Later	3 Yr. Later
Western	1961	0	0	0	2
Central	1962	4	5	4	2
Coastal	1963	4	3	3	0
Percentage of total responses:		30%	30%	26%	15%

Source: Russell et al., Table 9, p. 50

These lags in the perception of drought emphasize the importance of keeping water users and water managers informed about climatic conditions. The onset of drought can be quite subtle and, under ordinary climatic regimes, there is very little year-to-year correlation between annual rainfall totals.

C. The Colorado Drought of 1976 - 1977

1. Overview. Precipitation, streamflow and reservoir levels in the State of Colorado for 1976 and the first half of 1977 were all well below normal. Not since the first half of the 1930's had there been such an extremely dry period. Of the two years, 1977 had a higher level of precipitation, primarily due to the heavy rains that came during the summer of 1977. In several instances, these arrived at propitious times for the agricultural community. Streamflow levels, on the other hand, which normally lag behind the recorded precipitation levels, tended to decline from 1976 to 1977. Many smaller streams dried up completely.

The South Platte drainage basin showed great variability in precipitation levels both between recording stations and between the years 1976 and 1977, as did most of the eastern half of the state. The full degree of this variability can be clearly seen in part 2 of this Section. For example, stations in Julesberg and Sterling improved substantially from 1976 to 1977, going from 54% of average in 1976 to a level 118% above normal in 1977. Overall, the basin recorded a level 90% of normal for both years. Streamflow in this region at various gauging stations varied from between slightly above normal (Cache La Poudre) to 84% of normal (upper South Platte) in 1976 and from slightly below normal to 36% of normal respectively in 1977. Overall, reservoir storage levels were only slightly below average for this period.

Precipitation in the Arkansas drainage basin showed a pattern similar to that of the South Platte with levels of 90% of normal in 1976 and 92% in 1977. Streamflow levels were slightly below that of the South Platte division. Levels ranged in 1976 from slightly above average (Cucharas River gauging point) to 50% and 60% (on the Arkansas), dropping in 1977 to 36% and between 18% and 30% respectively. Reservoir levels were considerably lower in this region than in the South Platte. While the westernmost part of this division had levels only slightly below average, the reservoirs of the central and eastern sectors showed levels that were below 10% of normal.

Table 2 - Streamflow*

	% of 50 Year Average	
	1976	1977
Cache La Poudre	NN	NN
Upper South Platte	84%	36%
Cucharas River	NN	36%
Arkansas	50%-60%	18%-30%
Rio Grande	NN	20%
Colorado	60%	16%
White	90%	8%
Yampa	50%-60%	16%

NN = near normal

* from selected gauging stations on the river

The drainage basin of the Rio Grande was the only division in which precipitation levels dropped from 1976 (88% of normal) to 1977 (81% of normal). Similarly, while streamflow was near normal in 1976, it dropped to 20% of normal in 1977. Reservoir levels also fell from slightly below normal to 30% to 45% of normal in 1977.

Overall precipitation on the western slope rose from 50% of normal in 1976 to 85% in 1977. The southwestern section of the state was the hardest hit area in the state. In 1976, this section received 75% of its usual level of precipitation, improving to 86% in 1977. River gauging stations registered a drop from 70% of normal to between 10% and 20% of normal. Reservoir levels were recorded at below 25% of normal.

The west-central section of the state, including the drainage basins of the Gunnison and the Colorado, recorded an overall level of precipitation of 79% of normal in 1976 and 84% in 1977. Streamflow levels dropped from around 60% of normal to below 16% in 1977. Reservoir levels ranged from near normal to 20% of normal.

In the northwest corner of the state (Yampa and White drainage basins), precipitation levels rose from a low of 73% of normal in 1976 to 86% in 1977. The White River exhibited a drop from 90% of normal to 8% of normal, while the Yampa fell from between 50 and 60% of normal to around 16% of normal. Fish and game reservoirs in this division were constantly full. Other reservoirs however, showed a broad range of levels.

In terms of the overall impact of the drought then, Water Resource Division 7 experienced the largest deficit in water availability relative to historical norms, while Region 1 experienced the least. Nevertheless, pockets of extreme shortage existed in every part of the state.

2. Precipitation.[1] Precipitation on the average improved substantially between 1976 and 1977. The northeastern part of the state progressed from extreme

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[1] Precipitation data were acquired from the Office of the State Climatologist, Department of Atmospheric Sciences, Colorado State University.

deficiency in 1976 to only small deficiencies in 1977. The southeastern part of the state clearly got worse from 1976 to 1977, while conditions went from an extreme 1976 deficit to near normal in the northwest.

The drainage basin of the South Platte exhibited great diversity as shown in Figure 4 in which the dotted partial columns show the extent of improvement from 1976 to 1977, while the black partial columns show the extent of deterioration in 1977. Julesburg and Sterling showed great improvement while stations like Denver and Lakewood deteriorated significantly. Overall, the basin remained at about 88% of normal.

(Figure 4 here)

The Kansas drainage basin in the east-central part of the state exhibited uniform improvement as shown in Figure 5, progressing from 67% of normal in 1976 to 90% in 1977.

(Figure 5 here)

The Arkansas basin in the southeastern corner of the state exhibited some diversity as shown in Figure 6. The Rio Grande basin similarly showed diversity among sub-areas, but was the only major basin for which overall precipitation actually declined between 1976 and 1977 (See Figure 7).

(Figure 6 here)

(Figure 7 here)

Finally, the Colorado Basin (defined here to cover the entire western slope), exhibited general improvement, but with some dramatic exceptions. Durango fell from 77 to 60%, while other southwestern stations recorded decreases. (See Figure 8.)

(Figure 8 here)

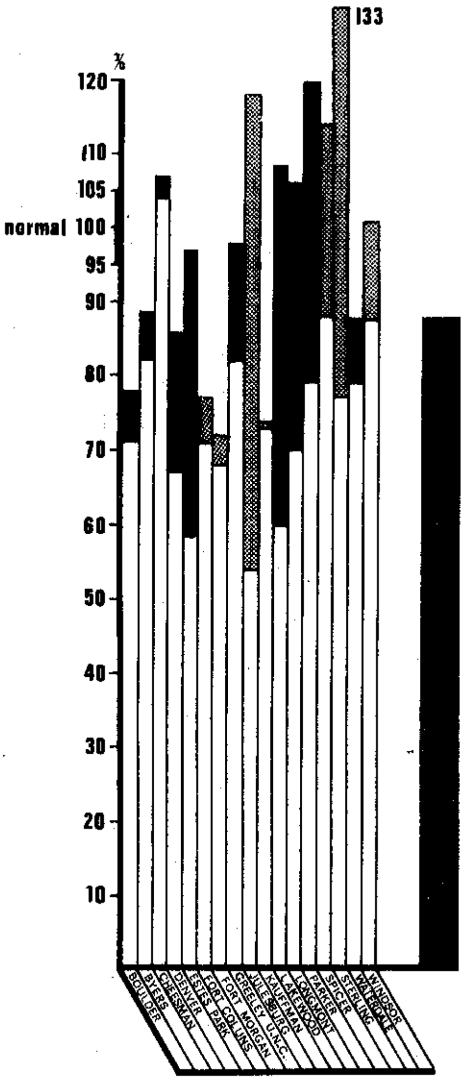

Figure 4.

SO. PLATTE DRAINAGE BASIN; 1976-77 precipitation as % of normal - 1)

1) Figs. 6-10 are read as follows; for dot columns, the height of the white gives the 1976 percentage, while the height of the white plus dot gives the 1977 percentage. For the black columns, white plus black height gives the 1976 percentage, while the white alone gives the 1977 percentage.

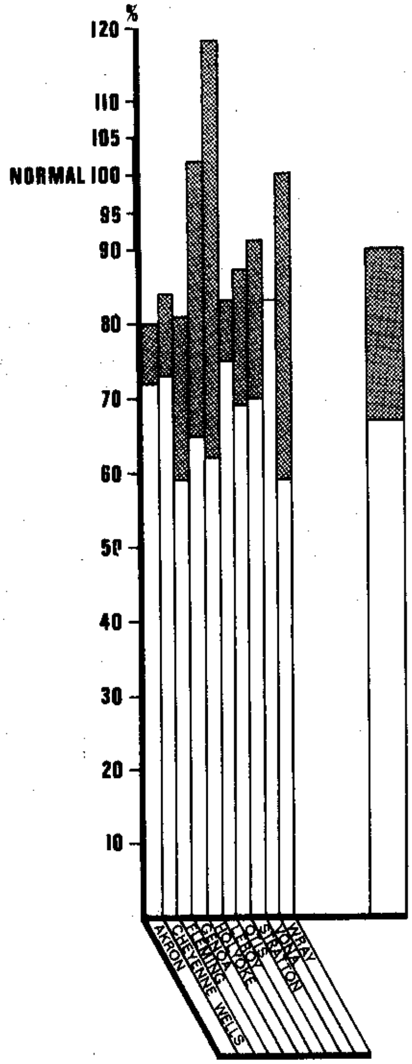

Figure 5.

KANSAS DRAINAGE BASIN; 1976-77 precipitation as % of normal

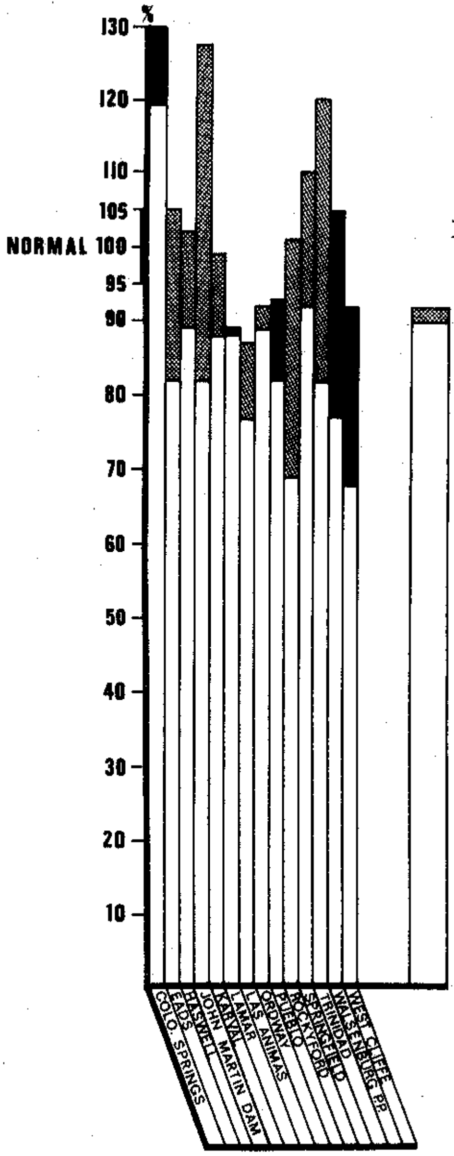

Figure 6.

ARKANSAS DRAINAGE BASIN; 1976-77 precipitation as % of normal

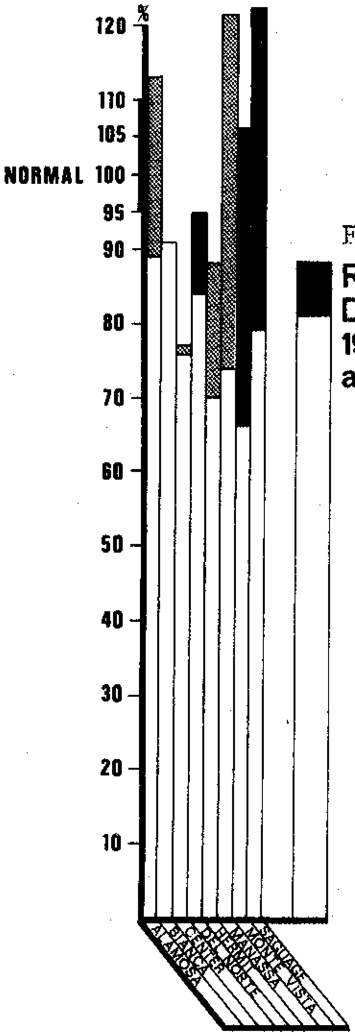

Figure 7.
RIO GRANDE DRAINAGE BASIN; 1976-77 precipitation as % of normal

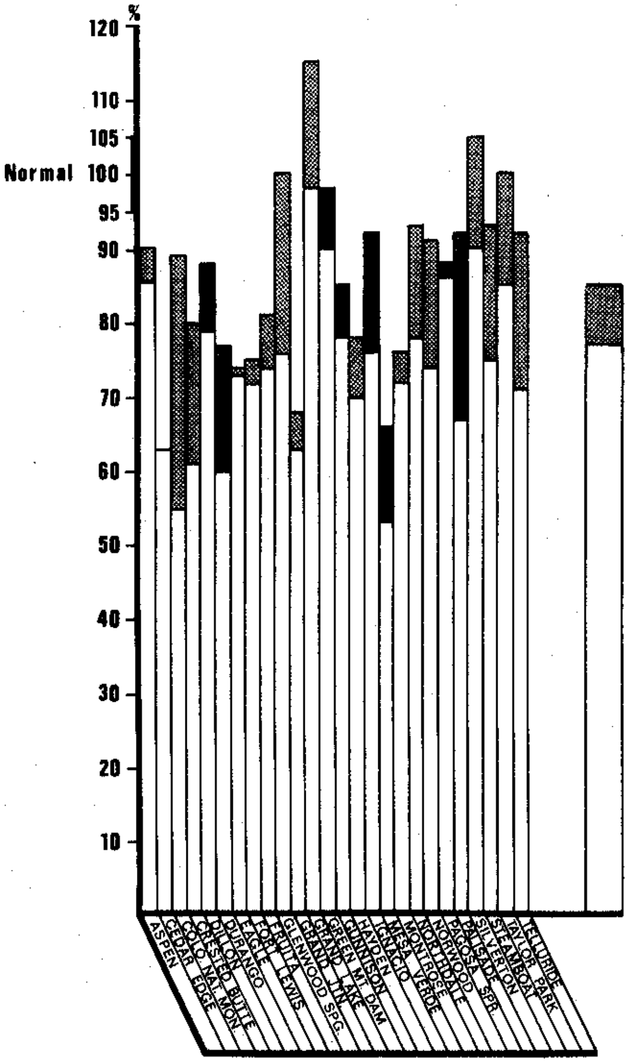

Figure 8.

COLORADO DRAINAGE BASIN; 1976-77 precipitation as % of normal

3. Streamflows. Streamflows for 1976 and 1977 have been expressed here as percentiles of the 1938 - 1978 distribution of flows. That is, the percentile value gives the percent of historical annual flows equal to or less than that particular flow. For example, the South Platte (station 06707500) flow in 1976 equalled the 82nd percentile flow: 82% of the 1938 - 1978 historical flows have the same or lower values. The median flow is that value for which half the annual historical flows were higher and half lower.

The general picture of streamflows in 1976 and 1977 contrasts sharply with the widespread improvement in precipitation noted in the preceding section: in all parts of the state, streamflows fell significantly from 1976 to 1977. Naturally, after more than a year of subnormal precipitation, soil moisture was seriously depleted, aquifers that had supported streamflow were being depleted, as were the aquifers from which irrigation pumping was taking place. As will be seen in the next section, reservoir levels had been drawn down to very low levels in the preceding year - to zero in the case of many small reservoirs. Thus, irrigation applications and releases for streamflow maintenance were down sharply in 1977.

In the northeast, the South Platte and Cache la Poudre flows were falling. The Platte fell to near-historical lows at the Balzac, from the 42nd percentile in 1976 to 18th percentile flow in 1977.

The Arkansas River dominates the southeast, and it fell from about the 30th percentile to below the 15th percentile. The Rio Grande, in the south-central part of the state, fell from about 65th percentile in 1976 to the 8th percentile value in 1977.

These streamflow data bring out a very important point for drought management in streamflow-dependent regions: <u>the drought is not over just because precipitation has improved</u>. Streamflows can continue to fall sharply long after precipitation appears to have recovered. The most severe water shortage may occur long after the "meteorological drought" has ended.

4. <u>Reservoir storage</u>. Partial data on the volumes of reservoir storage were available for 1976-1978. For individual reservoirs, it was possible to compare the level of each month of the years 1976, 1977, and 1978 with that month's average level over the preceding 10 year period. The problem was our inability to get access to the data on many of the state's reservoirs.

Reservoir storage is important to any region with highly variable river flows, for through this storage a reliable water supply can be produced. If reservoirs are not typically emptied annually and are big enough to carry some water over from one year to the next or to more distant future years, they can provide some protection against droughts that last more than one year. This over-year storage is generally quite costly, however, since reservoir size must be extended, the storage is occupied for a long period before the water is beneficially used, and evaporative or seepage losses can be high.

Reservoirs in Colorado range from the very large federal Blue Mesa and Navajo Reservoirs to hundreds of very small reservoirs used by ditch companies for storage and flow regulation. The interests of this study have centered on the small reservoirs since they are devoted to local water supply, in contrast to the federal multiple-purpose reservoirs that are operated as part of a huge western U.S. system.

The ways in which small reservoirs are managed can be very important during drought. Most of these reservoirs are typically managed on an annual fill-and-empty cycle that captures snowmelt in the spring and holds the water until it is needed for irrigation in mid-to-late summer. During the 1976-77 drought, this pattern of management was generally continued. However, the beneficial results that actually were experienced by some irrigation companies from changing their release patterns and the large potential for the reduction of drought losses if similar changes are used by other irrigation companies imply that further studies of small reservoir management policies during drought are warranged. Some preliminary results are given in Chapter III.

In Water Resources Division 1 (see Fig. 1, p. 3), the general impression is that reservoir storage levels were not far below normal during 1976 and 1977. Adjoining Districts 8 and 80 had levels of 60% and 70% of historical monthly levels in July 1976 and June 1977, but other Districts (such as 2 and 9) had above normal storage levels. Inability to gain access to the data for the eastern plains Districts 49 and 65 has prevented reporting in that area, although similar Districts in the southeast (Division 2) experienced very low storage levels.

Division 2 had quite varied experience in terms of reservoir levels. Districts 11, 13, 15, and 19 appear to have been close to their historical pattern on a month-by-month basis. Adjacent Districts 12 and 16 were down to about 50% of normal storage. Districts 10, 17, and 67 (i.e. north of the Arkansas) fell to around 10% of normal levels during the years in question. This does not imply that large damages occurred from water shortage, but it does indicate a seriously increased vulnerability to continuation of the drought.

Analysis of Division 3 was very limited. Storage levels appear to have dropped slightly below average in later 1976 and to have fallen further to about 40% of normal throughout 1977. Division 4's limited data indicated that storage levels in the North Fork Valley dropped very low in late 1977 (20% of monthly normals) with rapid recovery in 1978. Taylor Park Reservoir in District 59 fell steadily to 40% in June 1978.

Division 5 is dominated by large federal and municipal (Lake Dillon - Denver) reservoirs: Shadow Mountain, Grand Lake, Lake Granby, Williams Fork, Green Mountain, and Ruedi. For the most part, these reservoirs are managed for non-local interests, including west-wide power and irrigation. Further, the basin is the origin of most of the Colorado's flow, so there are always flows in excess of locally held rights. Thus, the reservoir data have little to do with the availability of water for local purposes.

Division 6 has little reservoir storage, and much of what exists consists of state fish and game reservoirs. The few active reservoirs in District 58 were below normal, and those in District 47 (the North Platte drainage) appear to have been significantly below normal.

The picture in Division 7 was serious, as previously indicated by precipitation and streamflow data. Several small reservoirs were dry all during 1976 - 1977. Lemon and Vallecito, the largest reservoirs in the Division were carefully managed on an annual basis with some attention to the possible continuation of drought. Vallecito held back early releases, saving for late season needs with careful division among the various ditch companies served. In District 30 containing the Animas and Florida Rivers and Lemon Reservoir, the greatest protective actions observed in this study were undertaken: (1) cooperation was worked out by the Water Commissioner so that senior rights did not call their water, making it possible to share available water more in keeping with the economic allocations; (2) reservoir water was held back to bring to harvest row crops with large late season demands.

In summary, the southeastern and southwestern parts of the state generally had low reservoir levels in 1976 and 1977, increasing their vulnerability to continued drought. Reservoirs that normally fluctuate widely during the year generally had more severe drawdowns during the drought, experiencing greater difficulty in refilling to normal levels.

5. General summary. The drought of 1976-1977 was clearly etched in the records of precipitation, 1976 being a very low year with substantial meteorological recovery through heavy rains in the early summer of 1977. Streamflows behaved in quite the opposite way, with the most severe drops occurring in 1977. The effects of drought continued long after precipitation recovery, in the form of low streamflows and lower than normal reservoir levels. Part of the low flow condition was due to the emptying of small reservoirs in 1976 and attempts to refill them in 1977. The low streamflow conditions and exhausted reservoirs imply that continuation of meteorological drought into 1977-78 would have induced much more severe impacts than those that occurred in 1976 and 1977.

Another important point requires emphasis: there was great variation in the meteorological and hydrologic conditions found in the state in 1976 and 1977. Adjacent Districts often experienced very different conditions. An example would be District 30 (Animas and Florida Rivers, plus Lemon Reservoir) that had a near-normal supply, partly because of careful reservoir management, and adjacent District 33 that faced such critical conditions that <u>all</u> water had to be devoted to domestic and stock uses. <u>This diversity has implications for drought policy</u>.

II.

IMPACTS OF DROUGHT ON SMALL TOWNS IN COLORADO

This study investigates drought-related problems in both rural areas and small towns. The reasons for distinguishing the two types of areas are obvious: (a) in rural areas, the principal water use is irrigation supplemented by stock watering and minor domestic supplies, while the smaller towns use water primarily for residential purposes, supplemented by commercial and public sector uses; (b) the physical systems for the provision of water are much different, sometimes beginning with quite different sources and certainly in terms of different distribution systems; (c) the institutions that have been developed to administer the water systems, both legal and organizational, are quite different and have quite different implications for water policies and strategies during drought.

We have also chosen to confine the study of towns to the smaller towns of Colorado since they appear to have rather unique water-related problems. The smaller towns lack the specialized resources, human and physical, that can be afforded by cities. Because of limited water use, the scale economies of larger water systems are not available to them. The financial base is often too weak to fund emergencies. Thus it appeared that the greatest benefits would come from studying the drought-related problems of these smaller towns. While no fixed limit on town size was established, the average population of the 62 towns studied in detail was 3,264 with a range from 32 to 40,460.

A. The Survey of Towns.

To identify the problems faced by the town water agencies during the drought and to develop a picture of the agencies themselves, a questionnaire (see Appendix to this report) was sent out to 126 different towns across the state. The names of the towns that were chosen for the survey came from lists provided by several government agencies: The Division of Local Affairs, The U.S. Bureau of Reclamation[1]; The Farmers' Home Administration; and the 13 State Planning and Management Regions. These lists included the names of towns that the government agencies felt had experienced some difficulties during the drought.

Initially only 45 questionnaires were returned, even after a second follow-up letter had been sent. To explore the differences between the respondents and non-respondents, 15 of the non-respondents were randomly selected from each Planning District and contacted directly by telephone. In every case, the person contacted agreed either to return the questionnaire immediately or answered over the telephone. The comparison between the initial respondents and those contacted by phone indicated very little difference between the two groups. The low response rate appears to have been due to the limited staff available in the small towns. 62 towns finally responded.

In addition to the mail survey, many personal and phone interviews were held with people directly involved with the town water agencies. Several of the persons on the staffs of the State Planning and Management Regions who had been designated Regional Drought Coordinators as well as members of various town staffs were personally interviewed.

The list of towns that responded and information regarding the mail survey coverage of the various Planning Regions are given in Table 3. Town locations can be checked on a State map.

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[1] Now the Water and Power Resources Service.

Table 3

Respondents To Town Mail Survey

Planning Region I (12 sent, 7 received): Akron, Brush, Fort Morgan, Merino, Ovid, Sedgewick, Yuma

Planning Region II (10 sent, 7 received): Berthod, Erie, Firestone, Gilcrest, Grover, Loveland, Nunn

Planning Region III (13 sent, 9 received): Bennett, Black Hawk, Brighton, Central City, Idaho Springs, Lafayette, Longmont, Nederland, Silver Plume

Planning Region IV (4 sent, 1 received) : Fairplay

Planning Region V (2 sent, 0 received)

Planning Region VI (11 sent, 3 received): Holly, Lamar, Wiley

Planning Region VII (4 sent, 2 received) : Aguilar, Model

Planning Region VIII (8 sent, 2 received): Center, Del Norte

Planning Region IX (8 sent, 5 received): Bayfield, Dove Creek, Man, Pagosa Springs, Rice

Planning Region X (19 sent, 10 received): Cedaridge, Crawford, Crested Butte, Gunnison, Olathe, Ophir, Orchard City, Ouray, Ridgeway, Telluride

Planning Region XI (10 sent, 5 received): Collbran, Craig, Grand Valley, New Castle, Rifle

Planning Region XII (19 sent, 8 received): Aspen, Fraser, Grand Lake, Gypsum, Hayden, Snowmass, Walden, Yampa

Planning Region XIII (5 sent, 3 received): Buena Vista, Coal Creek, Salida

Total Sent: 126

Total Received: 62

Of the 62 responding towns, the average population was 3,264. Of the water agencies that supplied these towns, 60% used a flat rate billing system with a fixed charge per billing period while 38% had some type of block rate structure. Slightly over half had a regular maintenance program for their water system. While 90% did own surface water rights, only 69% felt these were adequate to meet peak demand. 38% indicated that renting water from other water users was possible to increase the available water supply. During the drought, 48% of the towns actually applied for assistance, 64% of these to the FmHA, 29% to the State Division of Local Affairs. 44% of the respondents had applied for assistance before. Table 4 presents some of the interesting characteristics of the sample.

Table 4

Charactersitics of the Sample Towns

Average population	3,264
Average water revenue	$100,000
Flat rate structure (fixed charge per billing period)	60%
Block rate structure (price/thous. gals. varies)	38%
Sewage system managed by same agency	54%
Water funds merged with general fund	19%
Sewage system funds separated from water funds	94%
Average hours/week of town water manager	26 hours
Length of time water manager has been at job	2.5 years
Full-time personnel*	3.9 people
Part time personnel	1.1 people
Average number of hours per week for part time personnel	4.3
Have regular maintenance & replacement program	50%
Agencies with sinking funds for maintenance and replacement	60%
Water right ownership	90%
Able to meet peak demands	69%
Renting of water from other users possible	38%
Charter restrictions on debt or use of funds	6%
Applied for assistance before drought	44%
Heard about assistance programs during drought	65%
Applied for assistance	48%
FmHA assistance	31%
Division of Local Affairs Assistance	14%
Funds applied toward new problem	10%
Funds applied toward old problem	27%
Problems not related to drought	12%

* Probably high due to one or two towns with large number of personnel

B. Problems Encountered by Towns During the Drought.

The drought not only created new water shortage problems, but, as was more often the case, magnified older, more persistent problems with the physical structure of the system and the management techniques being used.

Several problems came about directly as a result of lower water supplies. The first and most obvious was the increasing gap between supply and demand, caused by lowered stream levels, precipitation, and water tables, plus increased use of water to keep lawns, gardens, and fields sufficiently irrigated.

To lessen this gap, conservation was encouraged both locally and regionally. While this alleviated the intensity of the supply problem, it often generated another equally troublesome problem of falling water revenues. After a very successful program initiated by the Colorado Water Congress to get people to cut back on their water usage, the water agency of one town started a campaign to get people to use more water. The lack of adequate water revenues was felt by the water board to put that town's system in jeopardy as it reduced the funds that were necessary for a proper maintenance program. The town based its "counter conservation" approach on the fact that the town actually had an over-abundance of water and that if the conservation practices continued, this would require the town to raise the water rates to keep sufficient funds available for the maintenance program. The same problem in San Francisco had earlier received widespread publicity.

To make matters worse, maintenance costs frequently rose substantially during the drought as a result of the low water levels. Among other things, water lines tended to freeze more often as a result of insufficient snow cover to act as insulation, and low levels in storage reservoirs resulted in greater algae growth, pushing the system beyond the prescribed health and/

or aesthetic standards. With decreased storage, there was also concern that there would be an inadequate reserve and pressure in the water system for proper fire protection.

Towns dependent on surface water supplies often were in fear of having more senior rights holders call their rights with the possibility of leaving the town with an even lower or no supply of water. As far as is known, this did not happen, although there were disputes over town water withdrawals. Another problem arose in connection with water rights that towns had acquired as provision for growth and drought protection: several towns found they had no means to divert the water to their systems.

In several instances, adjacent towns found themselves faced with shortages and surpluses simultaneously. Provision for interconnection of towns when distances are short could be the best way of responding to drought risk. The same situation was often found in New England during the 1961 - 1967 drought.

On the whole, the problems that the drought brought to the surface were the result of larger, much longer processes. The first would be simply the age of many of the town water systems. In many instances, they were installed over sixty years ago by the railroad or mining company that built the town, the ownership and responsibility gradually changing over the years. For many of the older systems, there has never been any kind of regular maintenance program. The towns tend to deal with major difficulties as they arise. As long as the system works well enough to supply current demands of the community, upkeep has a very low priority. The water revenues are frequently insufficient to provide for basic upkeep or a sinking fund for emergencies even if these were considered.

Unfortunately, there appears to be little incentive for the towns not to promote a system of "crisis management". Towns have come to realize they can count on various state and federal agencies to bail them out when a major problem arises, especially when the town is in a poorer part of the state. State and federal programs are often structured in such a way that the more poorly managed systems are the ones that can most easily obtain funds to help alleviate their problems. One town, for example, that was supplied principally by a surface decree tried to get funds to supplement their groundwater back-up supply that was inadequate to supply the needs of the community. Because the town had managed to stay out of debt and could, therefore, technically still borrow from other institutions,they were ineligible for most of the available aid programs. In contrast, a nearby town of the same size that was heavily indebted was awarded over $150,000 to deal with a problem resulting primarily from poor water conservation efforts.

Similar problems exist with newly built systems and ones upon which major improvements are made. Once the system is constructed (be it mains, meters, treatment facilities, etc.), they are usually not well maintained thereafter. As noted before, part of this is due to inadequate generation of local water revenue funds, while additional monies are rarely included in the original grant to maintain the system. Failure to maintain and manage systems properly is also partly due to the fact that the agencies that give the funds fail to follow through with continuing checks on the local program, even though they are usually required to do so by legislation, and/or their own rules and regulations. In addition, smaller towns frequently simply do not have operations and maintenance personnel with enough training and experience to maintain and manage the systems as they were designed to be. Towns are continually plagued by the exodus of personnel just when they have acquired the needed experience, as they move to larger towns with better pay.

Many towns felt heavily burdened, financially and managerically, by the imposition of new types of waste treatment methods and various other new programs and regulations by the state and federal governments. Several towns noted a lack of consistency in what was required of the towns by various regulatory programs. Requirements often differed substantially from one year to the next as well as from town to town. Towns frequently expressed the opinion that they would be more likely to give a system the care it needed if they felt it would not be shortly outdated by new regulations. Credibility of the need for new methods or systems and a belief in the stability of requirements would have a positive effect on the care of the systems.

Some town problems simply relate to the inefficient use of the water that is available. As noted before, there are the basic physical problems of obtaining water from closer or higher points of diversion and keeping leakage in the mains to a minimum. Other needless losses come about as the result of excessive use of the existing water, partly encouraged by the prevalent rate structures.

Table 5 below lists the immediate, apparently drought-related problems encountered, followed by a list of the more fundamental, long-term underlying problems of the small towns.

(Table 5 here)

C. Solutions Used by Towns to Alleviate Problems.

A variety of responses was directed towards these problems, both immediate, short-term measures and longer-term measures. Immediate physical solutions were based mainly on an intensified program of maintenance: water lines were cleaned out, patched and sealed when necessary to stop leaking, and wells were

Table 5

Drought-Related Town Problems: Immediate and Long-Term

<u>Immediate, Drought-Triggered:</u>

1. inability to meet water demands
2. no reserve for fire protection
3. water supply system losses high
4. deterioration of water quality, both surface and groundwater
5. inadequate ownership of sufficiently senior water rights to guarantee supplies during drought
6. revenues from water sales fall just when they are most needed for dealing with drought problems
7. payment of legal fees for assistance in locating aid, in dealing with water rights, and in contacts with agencies so high that no funds available for engineering and management assistance

<u>Longer-Term, Underlying Problems:</u>

1. inadequate level of management, with a nearly complete absence of long-term planning and reliance on "crisis management" strategy
2. local citizen apathy except at times of crisis, because of lack of local leadership and education on water affairs
3. no consistency in state and federal programs over time, including absence of audits and follow-up to determine whether or not funds and new systems being used as planned
4. charges for water inadequate to cover maintenance and replacement and, where metering used, inadequate to stimulate careful use
5. water financial accounts merged into town general accounts, with water revenues being used for general town purposes
6. federal and state "bail-outs" reward poor management and remove incentives for good, imaginative local planning and problem-solving.

sunk deeper to make up for the lowered water table. On the demand side, there were local and state efforts to educate the public to various conservation practices through the use of the media, while many towns wrote ordinances that required better conservation, including various types of restrictions on water use and, in some cases, actual rationing. Some increased their water rates to discourage excessive use of water and to help cover the higher costs often incurred. In a few instances where increased conservation was not sufficient or when there simply was not enough water for even basic needs, towns obtained water from nearby game and fish reservoirs through state cooperation and from farmers who volunteered to share or "rent" their water. Four towns experienced complete failure of their traditional water supplies and had water trucked in.

The effects of the longer-term solutions were not, on the whole, felt substantially during the 1976 - 77 drought. This was partly due to the fact that state and federal aid programs were begun beyond the mid-point of the drought. These solutions for the most part were aimed at increasing the availability of water as well as encouraging conservation. In the latter case, many towns began programs to install water meters. In the former, towns began the process to obtain more water rights or rearrange the structure of their existing rights. There were several instances where capacity of the towns' treatment facilities was the limiting factor, so steps were undertaken to expand treatment capacity. In some cases, additional wells were drilled.

The drought made it clear to several towns that their prevailing rate levels were inadequate and the rate structures inappropriate to deal with the pressures placed on them by the drought. Some rates were found to be far too low to encourage conservation. As a result, at least one town raised its rates three times during the two years of drought. One rural domestic water company added a penalty rate of $3.00 per thousand gallons. Rates historically had been set to meet basic expenditures but not high enough to provide for capital improvements or major repair work. One town, in the face of this problem, added a $5.00 surcharge to all town water bills -- a measure that increased revenue but which would not motivate consumers to conserve water. Another small town that needed extra revenue during the drought felt it unfair to raise rates when people were getting far less water than before, so they enacted a 1% sales tax.

Lower income communities felt it difficult to increase rates to cover the increased operating and maintenance costs without putting an "unbearable" financial burden on the residents of that community. They found it hard to forge a comfortable balance between financial needs of the water utility and equity to the customers. However, most of the towns' revenues barely covered operating costs, several flat rate towns charging only $2.00 per month for residential water service.

Table 6 lists the various steps taken to alleviate the drought-related problems.

Table 6

Solutions Used by Towns

Steps with Immediate Impacts:

1. Obtained surface water on short-term exchange or cooperative basis from farmers and State Fish and Game Commission.
2. Trucked in water.

Table 6 (continued):

3. Obtained permission to change points of diversion in order to use more of existing rights.

4. Cleaned out and repaired water mains.

5. Undertook restrictions in forms of alternate day sprinkling uses, sprinkler bans, and prohibition of outdoor uses.

6. Undertook rationing in the forms of requested percentage reduction from previous year billing period or limitation to a fixed quantity per billing period.

7. Raised water rates in one of the following ways:
   a. monthly flat rates raised (e.g. $5 per month);
   b. sharp increase in rate per 1000 gallons in metered towns;
   c. started use of increasing block rate structure in metered towns.

Steps with Longer-Term Effects:

1. Used increased revenues for system repairs and expansion.

2. Obtained state and federal aid for system repairs and expansion.

3. Applied for or purchased additional water rights.

4. Installed water meters.

5. Supplemented surface supplies with stand-by wells.

6. Imposed local sales tax to help fund water system.

It is clear that town water managers dislike turning to restrictions or rationing[1] and perceive these steps to be costly in terms of their own professional standing in the community. Yet these steps may be the most economical, rational way of dealing with the infrequent, severe drought. Carrying excess system capacities and distribution systems sufficient to meet all extreme, infrequent events can be very costly to a town. Occasional "belt-tightening" can save a lot of money in the long-run. This is another case where federal or state pro-

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[1] For the distinction between restrictions and rationing, see the next paragraph. The importance of this distinction was brought to our attention by Anne U. White.

grams that provide financing only for supply development may discourage local initiatives that represent the best solution.

The distinction between restrictions and rationing should be kept clear. The former limits time and type of use but does not necessarily affect the quantity of water withdrawn. The latter requires meters and limits quantity but leaves the user the choice of time and type of use. Which is to be used depends on which component of the water supply system is actually limiting or threatening to limit service. If treatment and/or delivery capacity is limiting the ability to meet peak demands without unacceptable loss of pressure, then timing restrictions are in order. If raw water shortage is the main problem, then type of use restrictions or rationing are called for.

It is interesting to note the types of rationing programs and restrictions used in the northern San Francisco Bay area where metropolitan[1] drought conditions were the most severe:

a. percentage reduction from previous year's billing period;
b. limitation to a seasonal allotment, i.e. a fixed amount per house or commercial establishment per billing period that varies with the reason;
c. limitation to a fixed allotment for billing period;
d. partial or total bans on outdoor uses.

Enforcement of the first 3 types requires metering, while the last does not.

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[1] John Olaf Nelson, "Northern California Rationing Lessons," paper presented at the Engineering Foundation Water Conservation Conference, Rindge, New Hampshire, July 1979.

John Nelson, General Manager of the North Marin County Water District, emphasizes that [1]

> "...(effective) rationing can only be achieved through the voluntary commitment of the consumer, and to earn that commitment, the utility must communicate the shortage problem and required rationing solution to the consumer via the media in a lucid and truthful fashion."

Regarding water rate increases as a demand-managing measure during drought, three observations are in order: (1) small short-term increases are unlikely to be effective; (2) large short-term penalty rates can be effective (one system imposed a $3 per thousand gallon penalty rate and demand fell 50%) but meet with public resentment; (3) rate increases have their greatest impacts in the longer term as habit patterns and the stock of water-using appliances and garden areas are changed.

D. The Role of Water Metering.

Metering of residential and commercial water use was infrequent in the smaller towns before the 1976-77 drought. Many metering programs were initiated during and after the drought. One metered Colorado town noted that it was financially better off during the drought than before because it pumped more water and collected more revenue. Another metered town in which conservation education had been successful ran into financial problems because it sold much less water and its revenues fell while costs were high because of emergency measures and increased operating costs.

Non-metered flat-rate towns, by definition, had constant revenues. In some cases, where demand increased because of the drought, operating costs

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[1] ibid.

went up, causing severe financial problems. In other cases, where demand went down because of public conservation education, there were no financial problems.

The well-known Johns Hopkins University study of residential water use[1] leaves no doubt that metering reduces water demands, not only on an annual basis but the maximum day and peak hour demands are reduced. Table 7 shows the results of that study, using data from both eastern U.S. and western U.S. residential areas.

Table 7
Residential Water Use in Metered and Flat-Rate
Areas: October 1963 - September 1965

	metered areas	flat-rate areas
	(gallons per day	per dwelling)
Annual averages:		
leakage	25	36
in-house use	247	236
Outside uses	186	420
total	458	692
Maximum day	979	2354
Peak hour*	2481	5170

* Peak hour rates expressed in gallons per day

Further analysis of the Johns Hopkins data by Howe and LInaweaver (1967)[2] indicates that water demands exhibit a responsiveness to increased prices, once metering is established. That study indicated that the price elasticity[3] of in-house uses was about -0.23, while western U.S. areas exhibited an outside use price elasticity of about -0.70.

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[1] See Linaweaver, F. P., Jr., John C. Geyer, and Jerome B. Wolff, Final and Summary Report on Phase Two, Residential Water Use Research Project, Johns Hopkins University, Department of Environmental Engineering Science, Baltimore, June 1966.

[2] Howe, Charles W. and F. P. Linaweaver, Jr., "The Impact of Price on Residential Water Demand and Its Relation to System Design and Price Structure," Water Resources Research, Vol. 3, No. 1, First Quarter, 1967.

[3] The price elasticity is the ratio of the percentage change in quantity demanded to the percentage change in price. Thus, a 10% price hike would induce a 2.3% reduction in in-house uses and a 7% reduction in outside uses.

Rough data bear out a similar relationship for towns in Colorado. According to Anderson [1], in 1978 per capita delivery in metered Boulder was 170 gallons per day, while in the unmetered towns of Fort Collins, Longmont, and Greeley, deliveries were 198 gpd, 243 gpd, and 220 gpd. These figures are not corrected for other differences.

The studies just mentioned plus many others leave little doubt that substantial long-term conservation can be achieved through metering. Whether the installation of meters is justified for a particular town in the long term depends upon the conditions of raw water availability and the frequency and sharpness of peak demands and low water supplies. The 3 major advantages of metering are: (1) the saving of raw water; (2) the reduction in maximum day and peak hour demands; (3) the reductions in treatment capacity and distribution system capacity that are possible because of (2).

It is less clear that metering is a good way to deal with infrequent drought events. That is, if metering is not justified in terms of the long-run savings noted above, it seems unlikely that it could be justified in terms of its usefulness during drought. One reason is that the price elasticity values mentioned above are long-run elasticities, reflecting full adjustment to the existing water price. For in-house uses, the number and types of water-using appliances have been adjusted to the price of water, while outside garden, lawn, and pool areas have been similarly adjusted. When an infrequent drought occurs, these water-using systems are already installed and their owners will be reluctant not to use them. Short-term price elasticities are likely to be

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[1] Personal correspondence from Raymond L. Anderson dated March 14, 1980.

lower than the values given above. It should be remembered, however, that actual rationing requires meters.

In those cases where the costs of metering are not warranted by the savings in raw water development costs and distribution capacity costs, the use of restrictions may still be effective. Little is actually known about the effectiveness of restrictions. Anderson (1980, forthcoming) has carried out one of the few quantitative studies that analyzed water use in Fort Collins during 1977. During the six-week period of July 15 to August 23, several types of restrictions were alternately used: no watering allowed; some watering allowed; 1/3 of the city allowed to water; 1/2 of the city allowed to water. After correcting for changes in weather conditions that had served to reduce potential evapotranspiration considerably, Anderson found that these restrictions could be expected to reduce Fort Collins municipal water withdrawals by approximately 20%.

Metering can be and should be subjected to benefit-cost analysis before being undertaken. Jong (1968) carried out such a study for Boulder, Colorado. The costs per meter per year were calculated to be $12.50 (at that time), while the saving in water withdrawals was estimated to be 83 gallons per capita per day. At a water cost of 18 cents per thousand gallons, a dwelling with four persons would reduce withdrawals by about 121,000 gallons per year, for a savings of $21.75 per year. The benefit-cost ratio was 1.74.

The Jong study omitted the cost savings for sewage treatment that would follow metering (between 60% and 75% of withdrawals are returned through the sanitary sewer system) and probably did not attribute enough cost saving in terms of possible long-run reductions in treatment and distribution capacity.

Several towns mentioned difficulties that they perceived to be associated with meters: (a) the expense of installation; (b) the costs of reading meters[1]; (c) maintenance costs; (d) the freezing of meters in the winter. In addition, equity and "externality" objections to metering are frequently voiced. Metering <u>might</u> increase the water bills of the poor and interfere with the gardening activities of retired persons. These equity objections can, however, be overcome through increasing-block rate structures that permit adequate water use at a low initial rate or (in the age of computerized billing) using special rates for senior citizens.

The "externalities" argument is that unmetered water results in a greener environment to everyone's advantage and that metering is likely to damage the aesthetic appearance of towns. Casual comparisons of unmetered Fort Collins and Greeley with metered Boulder indicate no obvious differences. Further, judging a green (transplanted midwestern or eastern) environment to be superior to ecosystems native to the region is a value judgment on which there is considerable disagreement.[2]

In summary, it appears that most of the value of metering is related to long-term savings of water and water system investment and not primarily to its value during drought. Each town should undertake a careful assessment of the benefits or costs that might accrue during drought.

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[1] Towns elsewhere that have tried voluntary meter reading by users have experienced substantial, systematic under-reporting of water used.

[2] Raymond L. Anderson has frequently raised the equity and externality objections to metering as a panacea to water management problems. See Anderson (1980).

III.

THE IMPACTS OF DROUGHT ON RURAL WATER ENTITIES PROVIDING WATER FOR IRRIGATION AND OTHER RURAL USES.

It should again be emphasized that the rural experience during the 1976-77 drought was quite diverse. Some water Districts faced extreme meteorological and hydrologic conditions and were significantly damaged economically, while close-by Districts managed their water carefully, in some cases even experiencing increased crop yields as a result. Any program aimed at drought mitigation must be keyed to this diversity.

On the average, the economic impacts of the drought on agriculture were exaggerated in terms of the descriptions given of current conditions and in terms of forecasts. This is not to deny some locally severe conditions (e.g. in District 33), but the drought did exhibit the wide range that exists for improving irrigation water management.

Rural water supply organizations tend to treat drought years much the same as other years. Drought is understood as a temporary event and, during the first recognized year of drought, farmers tend to act as if soil moisture levels will be sufficient for regular plantings. The presence of reservoirs helped many Districts during the first year, enough water being carried over from the previous winter to alleviate the precipitation shortage. Beyond the first year, farmers and ranchers (often third or fourth generation and having been through drought before) fall back on helpful remedies of the past: reduction of acreages planted, trucking in water for stock and domestic purposes, getting stock feed assistance from government agencies, etc. Unfortunately for stockmen, the poor growing and pasture conditions are usually accompanied by low beef prices because of general thinning of herds.

Drought induces various forms of highly generous and efficient cooperation in the sharing of water: senior rights holders agree not to call their water so that others can share; towns and farmers share water in both directions; water users collaborate in the storage and more careful application of water. However, as the drought extends, the extent and enthusiasm for such cooperation diminishes.

The main source of information concerning conditions, problems, and procedures followed in the rural areas was the Division Engineers (State Division of Water Resources) of the seven state Water Divisions and members of their staffs, plus information provided by the State Engineer's office. In addition, managers of several irrigation districts were interviewed and,again, the Regional Drought Coordinators provided additional information.

A. Agricultural Drought Experiences in the Seven State Water Resource Divisions.

Division 1 exhibited the smallest percentage deviation of precipitation from the long-term average and also had several other factors that helped them through the dry years. First, groundwater irrigation made possible by the very large size of the alluvial aquifers in the valleys of the South Platte and its tributaries accounts for over 40% of total irrigation, and that figure is increasing. Many irrigation companies had wells drilled before the drought and used them as backup. Secondly, the Big Thompson Project that supplies much of the western part of the Division is organized in such a way that shares of water can readily change hands on both temporary and permanent bases. There is also a substantial degree of sharing between towns such as Greeley that might have excess water and the agricultural sector that might have need of that water. Finally, there was good carryover in the reservoirs for the first year of the drought, although the second year there was virtually no carryover. Only the rains that started in May, 1978, prevented very severe consequences.

Division 2 had a relatively poor year in terms of precipitation in 1977. Since about 90% of the irrigated land in the Arkansas Basin is fed by ditchwater with only limited use of groundwater, the decrease in surface water availability proved to be a larger problem. During the drought, a new system of storage cooperation was set up in the western portion of the Division. While the water users had normally irrigated throughout the winter, they unanimously agreed to store the water that was due them from November to March in a common large reservoir. This reduced evaporation and stored water for a more critical time.

The ditch systems in use in Division 2 have been pretty much the same since 1900. Even the data system that lets users know how much water there is and when it will pass their ditches has been in operation since 1926.

District 11 holds fairly junior water rights and suffered heavily from lack of precipitation. Pastures were severely damaged. District 12 generally holds senior rights and, therefore, was not as severely impacted. District 13 has mostly alfalfa and native grasses, irrigated from small streams, many of which are ephemeral. Conditions there were not too far from normal. District 14 holds senior rights and experienced very few problems except in areas immediately around Pueblo where, as noted earlier, some areas were short of ditch water while the city itself had large reserves of water. Districts 17 and 67 hold fairly senior surface rights, supplemented by wells. These Districts were not severely impacted.

In summary, there was some fairly general damage to pastures and fairly severe soil losses that will take several years of good conditions to undo. It is clear that much more serious damage would have resulted in 1978 had not rains returns to normal in the early summer.

Division 3 normally has less annual precipitation than most of the other Divisions and over 60% of all irrigation is from sprinklers. This percentage is increasing. In addition to the usual problems related to groundwater irrigation such as a falling water table and attempts to limit pumping, this Division has constant concern over satisfying the Rio Grande Compact. So much of the Valley's water has been appropriated that it is sometimes difficult to meet the obligation. A great deal of uncertainty surrounds the effects the increasing use of groundwater may have on the area's ability to fulfill their compact requirements. During the drought there was very little Compact administration at all. Again the experiences of the several Districts were quite different. One District within this Division is well known for the high level of continued cooperation among the water users that makes it possible to meet its share of the necessary deliveries regardless of the amount of precipitation. However, in some instances there was a distinct lack of cooperation and great short-sightedness, including apathy towards new techniques for more efficient water use and soil conservation.

There were problems of enforcing water rights and, as noted in Division 1, it was strongly felt that such enforcement had been made much more difficult by new state laws passed in 1969. Previously, it had been possible for a water master to padlock a headgate and fine a misuser immediately. Now a time-consuming process is required that takes much of the "sting" out of enforcement.

In this Division, the effects of drought continued to be felt through the severe drawdown of groundwater that occurred. Several years will be required to recharge most areas -- if, indeed, the increasing pumping even permits old levels to be attained.

Division 4 contains large acreages of orchards, large hay and livestock operations, and a small amount of irrigated cropland. The orchards survived through an ability to "rent" water from other rights owners, paying as much as $200 for a 1 c.f.s. flow for 24 hours (approximately 2 acre-feet). Livestock and hay operations suffered the most, since much of the hay crop failed and herds had to be sold off at low prices. As noted in other areas, drought and low prices occurring separately can be handled rather well, but they are terribly difficult to withstand together. Crop production was generally 50-75% of normal, with the impacts on yields continuing into 1978 because of depleated soil moisture.

Nearly all irrigation is from surface sources, groundwater being used only for domestic and stock purposes. In 1976-77, many farmers had to truck water for domestic and stock purposes. Reservoir carry-over in that year greatly helped, but there would have been no carry-over in 1977-78 if it had not been for the rains in the summer of 1978. Effective use of small reservoirs was facilitated by senior rights owners allowing the reservoirs to store until later in the season when water was critical to crop and orchard survival, rather than calling for all of their allotted water earlier in the season. Reservoir carry-over was reduced in some cases by the attitudes of field-crop growers that they preferred to get the best crop possible one year, rather than risking two years' crops by attempting to stretch water in storage over two years. More will be said about this in Section C of this chapter.

Division 5 is dominated by the main stem of the Colorado River and its main tributaries: the Blue, the Eagle, the Roaring Fork, and Plateau Creek. The valleys are steep and narrow with most irrigated acreage occurring in the Grand Valley above Grand Junction. Grand Valley users cut back water use substantially, while many ranchers sold off their cattle and let their water stay in the stream.

Generally, there was good reservoir carry-over in 1976-77 and 1977-78, but this would not have been the case if the drought had continued a third year. District 45 along Divide Creek appeared to be the hardest hit area, while District 39 fared well because of substantial reservoir capacity.

Division 6 contains the White and Yampa Rivers. The flows of the mainstem rivers were generally good during the drought, but it was with the smaller tributary streams that the major problems arose. Many of these streams were completely dry in the summer of 1976, leaving ranches without ditch water. As a result, the grass and hay crops failed and large amounts of stock were sold off. Summer rains in 1977 saved the area from much more severe agricultural consequences.

Steamboat Springs had adequate water because of large storage capacity and the ownership of senior surface rights on Fish Creek. Rangeley and Craig had acute water shortages. Water held in Fish and Game reservoirs was frequently made available by the state to various towns. Senior rights owners generally called their rights and left junior rights holders "high and dry." The basin has no trouble fulfilling its compact obligation of 500,000 acre-feet per year because of the heavy mainstem river flows.

Division 7 in the southwestern part of the state was the hardest hit. At the same time, it best exhibits the tremendous diversity that can exist within relatively small areas. 1977 was the critical year. While some irrigation companies and conservancy districts took account of available information on existing and likely future drought conditions and cut back deliveries to save water for use late in the 1977 growing season, others used all their water in 1976. Some of these received no inflow in the 1976-77 winter and could deliver no water during 1977.

District 77, using water primarily for meadow and native grasses, had sufficient water supplies even though streamflows were low by historical standards. In adjacent District 29 (San Juan River and tributaries) where the water uses are the same, the tributary streams are always "under call" (i.e. seniors call for their water and diversions have to be administered by the Water Commissioner. The mainstem San Juan was not under call and many water swaps were worked out so that administration was not necessary.

District 78 (the Piedra and tributaries) diverts water mostly for meadow and native grasses. On the sharper slopes, it is estimated that applications run from 10 to 15 acre-feet per acre per year. These amounts were cut back during the drought and problems of shortage were avoided. It was generally felt that pasture productivity increased as a resuot.

District 31 (Vallecito Creek, Los Pinos River, Vallecito Reservoir) has extensive irrigated cropland. The irrigation district controlling the reservoir saved water until needed in 1977, even though they typically use an annual strategy of refill and use. It again was generally acknowledged that the more careful application of water led to increases in yields. However, if the reservoir had not refilled in the winter of 1977-78, there would have been severe consequences.

District 30 (Animas and Florida Rivers, Lemon Reservoir) provides the Durango municipal supply. The Animas River had a very adequate supply with no calls being made. The Florida River has very extensive farming acreage and is typically on call, although there was adequate supply during 1977 because of the management of Lemon Reservoir. This District took strong protective actions: (1) through the Water Commissioner's strong efforts, the senior rights agreed to cooperate and not call; (2) reservoir releases were held back to provide for the extensive row crops having a late season water demand. Again, however, another year of drought would have been bad.

District 33 (La Plata River and tributaries) had a very bad situation. Half the flow is committed to New Mexico by compact and there are large transport losses. Irrigated acreage is extensive, but all water had to be devoted to domestic and stock purposes. There were no crops in 1977, not even hay. Through the cooperative efforts induced by the Water Commissioner, available water was pooled and stretched to meet domestic and stock demands.

Adjacent District 34 usually has a tight water supply, with the Mancos River and its tributaries typically under administration. The Water Commissioner developed a pattern of cooperation among the water users in 1977, acreages were reduced, lower yields accepted in most cases, and the water was allocated equitably among all users.

District 32 is served by two private ditch companies, one of which is to be incorporated into the Water and Power Resources Service (formerly the Bureau of Reclamation) Dolores River Project. One of the companies was able to provide 50% of the normal water supply in 1977 while the other, having no inflow in 1977, provided no releases.

District 71 (Dolores River) has little irrigation in its upper reaches. During the drought, the lower river was dry, the town of Dove Creek and Slick Rock being totally without water from their traditional source. While those towns own only junior rights on the Dolores, they would have received no water even with the most senior rights because of the large transport losses en route to their downstream location. This would have been a situation where the Water Commissioner or Division Engineer would have entered a "futile" ruling that attempts at downstream delivery would not have been warranted. Various emergency measures including wells and mesa-top water impoundments were undertaken for these towns.

Thus we see the great diversity of conditions within one Division, adjacent Districts frequently facing quite different water supply conditions.

B. Summary of Problems Faced by Rural Water Supply Entities.

The foregoing description of the drought experiences in the seven Water Divisions mentioned the various types of problems encountered in the rural areas. The problems were generally more basic and simpler to describe than the problems faced by towns but nonetheless important. Table 8 summarizes these problems.

(Table 8 here)

C. Steps Actually Taken to Mitigate the Negative Impacts of Drought in Rural Areas.

Table 9 summarizes the major steps actually undertaken in rural areas during the 1976-77 drought. Many of these steps were described previously in Section A of this chapter.

(Table 9 here)

Table 8

Problems Faced by Rural Water Supply Entities

1. Surface water supplies, both run-of-the-river and from storage, significantly below average availability.

2. Erosion of dry soils, resulting in long-term loss of agricultural productivity and in the siltation of streams, reservoirs, canals, and laterals.

3. Reservoir management often appears to be too inflexible, e.g. conservation pools being maintained for one purpose when other purposes badly need the water.

4. Reservoirs often have very junior rights, making it impossible to store water when it would be most valuable.

5. Rural water supply entities tend to follow an annual cycle of operations regardless of the likelihood of drought, especially with respect to reservoir management.

6. In presence of recognized drought, farmers tend to overirrigate in the spring in anticipation of later shortage, sometimes to such an extent that crop growth is impaired.

7. Crop growers appear to prefer getting one good crop with an increased likelihood of no crop in the second year, rather than spreading available water over two years with the associated risks of significant yield reductions. This <u>may</u> represent excessive avoidance of risk.

8. Groundwater initially developed as a drought back-up tends to become part of base supply, resulting in greater acreage and making drought back-up supplies harder to develop.

9. Rural water supply agencies feel obligated to spend large sums of money on legal and engineering consultants in protecting their water rights and in keeping up with new regulations and legislation. The issue is whether or not more economical ways of providing these services may exist.

Table 9

Steps Actually Taken to Mitigate the Negative Impacts of Drought in Rural Areas

1. Cooperation among water rights owners, taking the forms of:
    a. pooling run-of-the-river flows and sharing available water regardless of seniority of decree;
    b. senior rights owners permitting water to be stored for later use by all users.

2. Water "rentals" among rights holders on the same stream or on the same ditch system, whereby water is temporarily sold. Some rental systems are permanently established (e.g. the Northern Colorado Water Conservancy District) while others grow in an ad-hoc manner when the need arises. Prices ran to more than $100 per acre-foot during the drought, but valuable crops and orchards were saved.

3. Payments made to senior rights holders to pool their water, funds being provided either by:
    a. individual contributions by other water users, or
    b. federal programs (Water and Power Resources Service)

4. "Futile declarations" by the Water Commissioner of the District or the Division Engineer, so that water could be used by more junior rights rather than being lost during long runs downriver.

5. Groundwater back-up, through wells previously installed or installed during the drought.

6. Reducing or eliminating winter applications that were intended to raise soil moisture prior to the planting season.

7. Consolidation of storage in larger, more efficient reservoirs.

8. Canal lining and use of gated pipe in place of laterals.

9. More frequent, more carefully monitored irrigation applications, frequently leading to substantially reduced water use and increased yields.

10. Trucking water for rural domestic and livestock purposes.

11. Trucking in supplemental livestock feed to preserve herds in spite of pasture and range impairment.

12. Towns permitting agricultural use of excess water supplies controlled by the towns.

13. Weather modification. This took the form of seeding orographic clouds (those rising over the mountains) to increase snowpack. These operations were undertaken by the State of Colorado and by the Northern Colorado Water Conservancy District, the latter in the Leadwaters areas of the Colorado-Big Thompson Project.

Special mention must be made of the highly constructive roles frequently played by the Division Engineers and the District Water Commissioners. These people first acted as educators and sources of vital climatological and hydrological information. Secondly, they helped conservancy districts manage their reservoirs in ways more appropriate to drought conditions, especially holding water for late season use and for carry-over to the following water year. Third, they very successfully induced water rights owners in the same drainages to cooperate and share water, rather than having the seniors take all the water. Experience showed that this more even allocation of water greatly mitigated the economic impacts of the drought on agriculture.

IV.

ECONOMICALLY EFFICIENT WATER MANAGEMENT DURING DROUGHT: EFFECTS OF WESTERN WATER LAW; RESERVOIR MANAGEMENT; AND GENERAL WATER PLANNING PRINCIPLES

The most important institutional arrangement in the western United States affecting the use of water is the system of prior appropriations. This "first in time, first in right" system is embedded in the water law of nearly all western states, including Colorado. The history of western water law and water rights has been documented in several places (e.g. see Radosevich et al. 1976 and Dewsnup, Jensen, and Swenson, 1973). The system evolved to establish a set of reliable water claims against the varying quantities of streamflow available over time. By establishing property rights in water, appropriations doctrine has made it possible to establish markets for water that, while having some shortcomings, have worked fairly well over long periods of time to allocate water to its highest-value uses. But how does the water rights system work during short-term droughts? This issue is discussed in Section A below.

Another important issue arising from the observations of Chapter III is that of optimum or at least good reservoir management during drought. We have seen that most irrigation reservoirs are simply operated on an annual fill-release cycle that remains the same during drought as in normal times. While this may be the only option for small reservoirs (say 2500 acre-feet and below) because of large storage losses and evaporation, the operating rules for larger reservoirs should be given careful thought, to determine what can be done to adapt them better to drought conditions. This issue is discussed in Section B.

Section C discussed combining climatological data with socio-economic data to determine an appropriate "target" value of available water supply for planning purposes.

A. The Efficiency of Water Rights During Drought.

We first want to establish a benchmark for the economically efficient allocation of a limited water supply among a group of users. Economic efficiency means getting the greatest net benefits (benefits minus costs) from the water, and our benchmark will be that particular allocation of water (i.e. assignment of a definite quantity of water to each user) that maximizes net benefits.

Suppose we have n irrigators, each generating net benefits as a function of the amount of water they are assigned. These net benefits are assumed to be in monetary form and can be represented by the functions $B_1(w_1)$, $B_2(w_2)$, ..., $B_n(w_n)$. The amount of water known to be available to this group for the growing season is some volume W [1]. How should we spread this water among the various users? By definition, the economically efficient way is to choose values for $w_1, w_2, \ldots, w_n$ so as to

$$\text{(1)} \qquad \text{maximize} \left[B_1(w_1) + B_2(w_2) + \ldots + B_n(w_n) \right]$$
$$\text{subject to } w_1 + w_2 + \ldots + w_n \leq W$$

The constraint simply says we cannot assign more water than is available. One can use common sense or minor mathematics to solve this problem (i.e. to describe or characterize the optimum values). The solution would be as

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[1] Assuming the season's water supply to be known at the beginning of the season is not unreasonable in areas fed primarily by snowmelt.

follows:[1]

1) If W is so large that every user can have all the water they can beneficially use, then each user gets the amount at which their <u>incremental net benefits</u> just fall to zero. Note that incremental net benefits in this case are equal across all users at the common value of zero.
2) If W is not large enough to allow every user the amount they would get in (1), then the water should be divided so that the <u>incremental net benefits are equal</u> (at some positive value) across all users receiving water. It may be that the <u>highest</u> incremental net benefits of some users will be less than this common value, and such users will receive no water.

Roughly summarized, the net benefits from the last acre-foot of water used by each active user should be the same. If this does not hold, total net benefits could be increased by shifting some water from users with lower incremental benefits to users with higher incremental benefits.

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[1] Mathematically, one writes the Lagrangean function and necessary conditions for the constrained maximum:

$$L(w_1, \ldots, w_n, \lambda) = B_1(w_1) + \ldots + B_n(w_n) + \lambda(W - w_1 - \ldots - w_n)$$

$$\frac{\partial L}{\partial w_i} = \frac{dB_i(w_i^*)}{dw_i} - \lambda \leq 0 \text{ and } \left(\frac{dB_i}{dw_i} - \lambda\right) w_i^* = 0$$

$$\frac{\partial L}{\partial \lambda} = W - w_1^* - \ldots - w_n^* \geq 0 \text{ and } (W - w_1 - \ldots - w_n)\ \lambda^* = 0.$$

Condition (1) in the text occurs when the second inequality holds strictly, with $\lambda^* = 0$. Condition (2) occurs when $\lambda^* \neq 0$, with the possibility of some $w_i^* = 0$.

Now suppose the annual amount of water available fluctuates from year to year. For simplicity, assume there are just two values, W_1 and W_2, that occur with relative frequencies p_1 and p_2 ($p_1 + p_2 = 1$), i.e. 100 p_1 % of the years will have W_1 available and 100 p_2% will have W_2. Let $W_1 > W_2$.

Suppose further that a system of rights (claims) on the available water has been established over time, the priorities and amounts of these rights being designated $\bar{w}_1, \bar{w}_2, \ldots, \bar{w}_n$, such that

$$\bar{w}_1 + \bar{w}_2 + \ldots + \bar{w}_n = W_1. \tag{2}$$

This means the high flow of the river has been fully appropriated. Note that the numbering of the rights is by priority, not by user number. Since the amount of each right was determined by historical occurrences, it is almost certain that the set of rights $(\bar{w}_1, \ldots, \bar{w}_n)$ does not correspond to the optimal quantities derived earlier $(w_1^*, w_2^*, \ldots, w_n^*)$. If each user is restricted to holding just one water right, it appears that the allocation of water among users must be economically inefficient, even in high flow years. In low flow years when some junior rights cannot be served at all, some high value (net benefit) users might be prevented from receiving any water.

But the rights system need not be economically inefficient if its flexibility can be increased through exchanges and rentals in the short-run, and through sales of rights in the long-run. When the distribution of the rights $(\bar{w}_1, \ldots, \bar{w}_n)$ does not correspond to $(w_1^*, \ldots, w_n^*)$, any rights-holder having less than their optimum quantity w_i^* will find it worthwhile to rent water from some rights-holder that has a call on more water than their w_j^*. An unimpeded rental market would move the short-term allocation toward the efficient one, except that the effects on return flows might be ignored by the buyer and seller. If the return flow *effects are not too important, market processes would lead to a fairly efficient pattern of water use, and the distribution of rights* $(\bar{w}_1, \ldots, \bar{w}_n)$ *would simply determine who pays whom for additional water.*

However, there are problems with keeping a rental market operating for more than a short period (e.g. a few weeks during drought) under appropriations doctrine. If any downstream junior rights-holder is injured through changes in return flows caused by the rentals, court action could stop them. In fact, any appropriator junior to the party renting out the water could object to its being rented to someone junior to themselves. Thus, in the absence of special arrangements, rental markets are likely to be short-lived.

Different institutional arrangements can permit the organization of permanent rental markets. In the Northern Colorado Water Conservancy District distributing Colorado-Big Thompson water, the needed water rights are held by the Water and Power Resources Service, while the water users own shares in the District that entitle them to water. The users are free to transfer the water temporarily or to sell their shares in the District. These arrangements deserve to be copied much more widely.

In the long-run, a question is whether or not the high-value users will tend to buy up the senior rights, leaving the more junior rights to lower-valued users. The evidence on this is mixed, for while it has become very clear that energy-related activities can buy out almost any agricultural water right, many towns (in which water is presumably of very high value) dependent on surface water hold either junior rights or, in a few cases, no rights at all.

The preceding observations suggest the following hypotheses regarding the distribution of water rights and the resultant performance of a water rights system during drought. While the hypotheses are consistent with the evidence gathered in this study, they warrant further theoretical and empirical investigation.

Hypothesis 1: In drainage basins experiencing infrequent drought (1 year in 10 or less), the distribution of water rights by seniority is not likely to correspond to the average values-in-use of water.[1]

Hypothesis 2: During short drought events (1 year or less) in such basins, cooperation in sharing water among rights-holders is likely.

Hypothesis 3: During extended drought events in any basin, cooperation in sharing water is likely to break down.

Hypothesis 4: To the extent the above conditions hold, the more infrequent the drought event, the more severe the impacts are likely to be.

B. The Efficiency of Reservoir Management During Drought.

Chapters I and III indicated that nearly all small irrigation reservoirs are operated on an annual fill-release cycle, even during years when drought is anticipated or already acknowledged to exist. In this Section, we want to expand on the argument that at least the larger, more efficient of these irrigation storage reservoirs should shift into a drought-hedging mode of operation that involves conserving water for carrying into the following year whenever climate data indicate a significant probability of drought for the following water year.

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[1] Although one would expect approximately equal marginal (incremental) values in non-drought years.

We have already seen that it is rational for water users in basins having plenty of water to divert and consume water up to quantities where incremental net benefits drop to zero. Now suppose that it becomes known with certainty that, while year 1 will have normal water supply, year 2 will have only the water carried over in storage from year 1. What pattern of water use and reservoir carryover should be established?

Common sense tells us that 3 major factors should affect our behavior in such a situation:

1. the way in which annual benefits will vary with the amount of water applied in that year;
2. the amount of water kept in storage that will be lost through seepage and evaporation;
3. the importance of time in valuing benefits, usually represented by an interest rate or discount factor on future benefits.

Once again, common sense or a little elementary math tells us that water should be used in each year in amounts that will make the present value of the incremental benefits of water use in year 2 equal to the incremental benefits of water use in year 1. We can state this as a simple problem in the following form:

$$\text{(1)} \qquad \text{to maximize} \left\{ B(w_1) + \frac{1}{1+r} \; B(w_2) \right\}$$

$$\text{subject to } w_1 + e(W - w_1) + w_2 \leq W$$

where r is the discount rate and e is the fraction of stored water lost through seepage and evaporation.

This simply says we want to use the available water W in a way that will maximize the present value of benefits (where r is the discount rate), subject to the obvious constraint that water consumed in the first year plus losses from storage plus water consumed in the second year not exceed the water available. A necessary condition that follows from this maximization is: [1]

$$B'\ (w_1) = \left(\frac{1-e}{1+r}\right) B'\ (w_2) \tag{2}$$

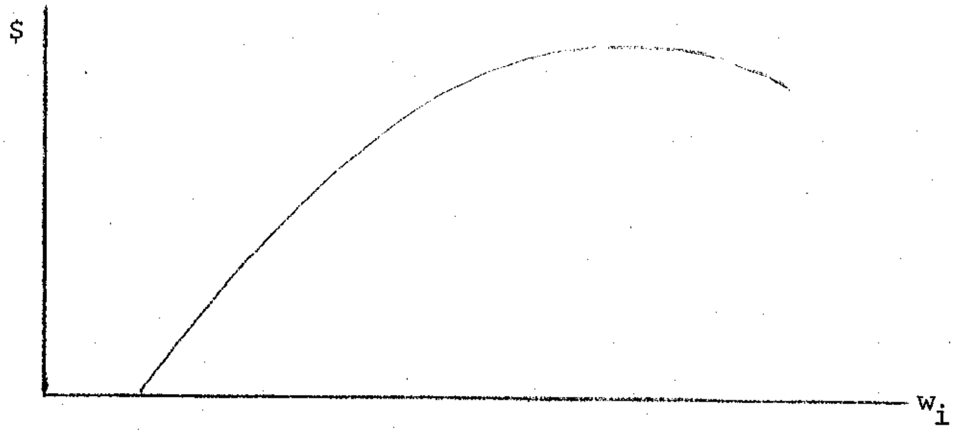
That is, the best way to use the water over the two years must be one that equates incremental benefits this year to discounted incremental benefits in year 2, allowance being made for the losses of any water stored. Since the benefit function for each year is likely to appear as in Figure 9 , one can readily see that (2) implies:

a. the more heavily we discount future benefits, the more water we will use in year 1 (the less we will carry over);

b. the larger the fraction of stored water lost, e, the less we will carry over.

Figure 9

A Typical Annual Agricultural Benefit Function for Water Consumed



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[1] The Lagrangean for the problem is

$$L = B(w_1) + \left(\frac{1}{1+r}\right) B(w_2) + \lambda \left[(1-e)(W-w_1) - w_2\right] .$$

The maximization of L with respect to w_1, w_2, and λ implies (2).

Now let's drop the assumption that year 2 is known with certainty. Suppose at the beginning of year 1 we have a normal supply of water, W, in storage. In year 2, there will either be a normal supply or zero water (except for carry-over from year 1), but we do not know which will occur. However, experience has shown that the <u>probability</u> of normal water supply, W, is p_1 while the probability of zero supply is p_2, such that $p_1 + p_2 = 1$ (i.e. one or the other must happen).

It may be reasonable under such conditions for the agricultural water planner to base decisions on maximizing <u>expected discounted benefits</u>, which would be defined as:

$$(3) \qquad B_1(w_1) + \left(\frac{1}{1+r}\right)\left[p_1 \cdot B(W) + p_2 \cdot B(w_2)\right]$$

where, again

$$(4) \qquad w_1 + e(W - w_1) + w_2 \leq W$$

In this kind of decision situation, one would like to carry some water over to year 2 for protection against drought in year 2, but there is a chance (p_1) that year 2 will turn out to have a normal water supply, implying that the carryover turns out to be useless while lower yields in year 1 have already been incurred.

The solution to this somewhat more realistic problem is characterized by water quantities w_1 and w_2 that would make the following condition hold:[1]

$$(5) \qquad B'(w_1) = \left(\frac{1-e}{1+r}\right) p_2 \cdot B'(w_2)$$

This condition is almost the same as (2) above for the case where we knew drought would occur in year 2. In (5), however, we observe the <u>probability</u>

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[1] The Lagrangean is $L = B(w_1) + \left(\frac{1}{1+r}\right)\left[p_1 B(w_1) + p_2 B(w_2)\right]$ and is maximized subject to (4) above.

of drought on the right-hand side, p_2. If we know drought will occur, $p_2 = 1$. If p_2 is less than 1, then we should adjust w_1 and w_2 so that 5 holds. (5) implies that the higher the probability of drought in year 2, the more water we should save from year 1 and carry over to year 2.

We need to make the situation a little more realistic before trying to draw policy conclusions. In each crop year, some minimum amount of water is necessary to produce any crop at all. If we combine this fact with relatively high storage losses in (5), we can see that for low values of p_2, it may not pay to carry water over, i.e. the one-year fill-release cycle may be quite sensible. When meteorological evidence mounts that there will be drought in year 2, equation (5) tells us that, with this significantly increased value of p_2, we should make plans to carry water over from year 1 to year 2.

Under existing practice, it may be difficult for irrigation officials to hold back water for the following year. First, the reservoir size must exceed the minimum crop needs for the current year. But assuming sufficient capacity for significant carry-over, allocations to the company or district stockholders are typically announced in March or April and cropping plans are based on these allocations. It is then difficult to modify these allocations on the basis of later climate data.

Trying to quantify these relationships and making the appropriate climate data available to water managers promise a sufficient reduction in agricultural drought losses that a cooperative program of continuing agronomic-meteorological-economic research appears warranted.

C. General Water Planning Principles.

We know that water availability for the coming year is uncertain and can most adequately be described by a probability distribution like those shown in Figure 10 below.

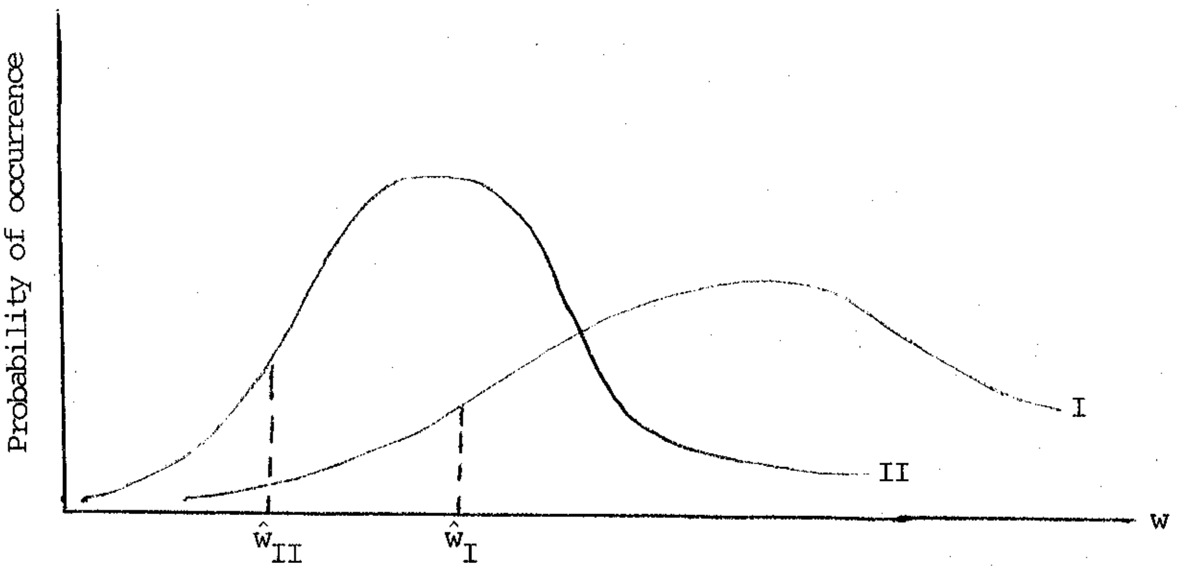

Figure 10

Probability Distributions of Next Year's
Availability of Water for A Drainage Basin

Curve I represents the probability distribution of water availability in a "normal" year, while II might represent the relevant probabilities when it appears that drought conditions will occur.

While good planning requires that explicit recognition be given to the uncertain nature of the coming year's water supply, it is generally difficult to plan acreages, cropping patterns, herd size, new water permits, etc., on the basis of a probability distribution. Usually, some "most likely" or "conservative planning value" is taken as the basis for planning. Such a value might be $\hat{w}_I$ for a normal year or $\hat{w}_{II}$ for a drought year. On what should this value depend?

The planning value, $\hat{w}$, first depends on the shape and location of the probability distribution, information that might come from the State Climatologist or other weather science sources. It will also depend on the social payoffs or penalties that are associated with different water availabilities that actually occur, once plans for water use have already been made. The payoffs from water use in a particular basin might look like Figure 11.[1]

Figure 11

Payoffs from Anticipated and Unanticipated Water Supplies

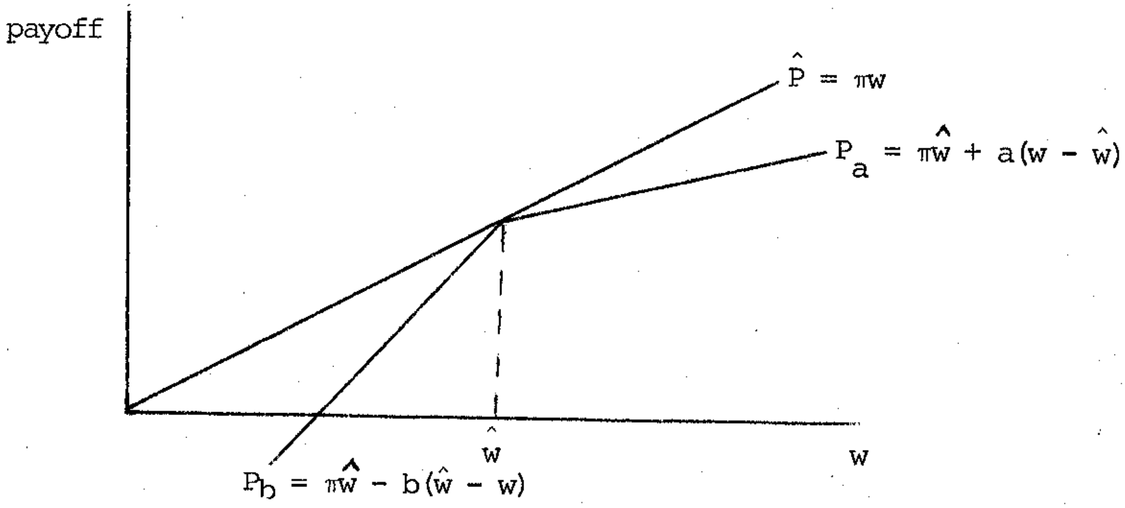

Figure 11 is based on the assumption that, if the actual water supply was always correctly anticipated, we could get a payoff of $\$\pi$ per unit of water used. If we lay plans on the basis of a water supply of $\hat{w}$, it is nonetheless unlikely

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[1] This Figure and the following explanation are also found in very similar form in Anderson and Maass (Technical Bulletin No. 1431) and Hufschmidt and Fiering (1966).

that exactly $\hat{w}$ will occur. If it turns out that more water is available, it will probably have some additional value, but not as much as if its use had been planned for, perhaps following the line P_a. If less water than $\hat{w}$ is available, benefits may drop rather sharply along the line P_b.

In a decision situation like this, it can easily be shown (see the Appendix to this Chapter) that the choice of an appropriate planning value $\hat{w}$ depends on the values π, a, and b as well as on the probability distribution of w. The relationship turns out to be such that the appropriate value of $\hat{w}$ is characterized by the condition that

(1) $$\text{the probability that } w \leq \hat{w} = \frac{\pi - a}{b - a}$$

where this probability is represented by the area under the probability curves in Figure 10.

As an example, if π = \$30 per acre-foot, a = \$10 per acre-foot, and b = \$40 per acre-foot, this probability would equal (30-10)/(40-10) = 20/30 = 0.67. On the other hand, if the penalties from shortfalls of water were much higher, say b = \$80 per acre-foot, then the probability would be (30-10)/(80-10) = 20/70 = 0.28.

The moral of the story is that efficient planning in the face of meteorological uncertainty requires combining climatological information and forecasts with knowledge of the socio-economic payoffs and penalties associated with the various possible anticipated and unanticipated quantities of water that may be available.

Appendix

The mathematical statement of the type of planning problem related in the preceding Section would be as follows: let

$$(1) \qquad \phi(w,\hat{w}) \equiv \begin{cases} \pi \cdot \hat{w} \text{ if } w = \hat{w} \\ \pi \cdot \hat{w} + a(w - \hat{w}) \text{ if } w > \hat{w} \\ \pi \cdot \hat{w} - b(\hat{w} - w) \text{ if } w < \hat{w} \end{cases}$$

be the payoff function. If $f(w)$ is the probability (density) function, then the expected payoff is given by

$$(2) \qquad E\left[\phi(w,\hat{w})\right] = \int_{0}^{\infty} \phi(w,\hat{w})\, f(w)\, dw$$

Expanding this expression by substituting from (1) and taking integrals on the appropriate intervals of w, it is possible to differentiate E with respect to $\hat{w}$, the "target" or planned value of water availability. Setting this derivative equal to zero will characterize the appropriate value of $\hat{w}$ as long as $b > \pi > a$, conditions that seem reasonable. The resulting characterization is

$$(3) \qquad F(\hat{w}) = \frac{\pi - a}{b - a}$$

where F is the cumulative distribution function of w.

V.

STATE AND FEDERAL DROUGHT PROGRAMS

This section will provide a brief summary of state and federal programs that were initiated as a result of the drought. Several existing reports detail the specific programs (WESTPO 1977, 1978 and 1979, Colorado Drought Coordination Project, 1979).

A. Major Federal and State Programs.

Nine federal drought programs were included in President Carter's drought package. All of these were acted upon in April or May of 1977, except the amendment to the Small Business Administration Act that was passed in August of 1977. Four of these programs were directed principally toward helping municipalities and irrigators increase or better manage their water supplies.

The most widespread throughout the State was the program of grants and loans administered by the Farmers Home Administration (FmHA). The Emergency Loans Program provided for $100 million in 5% loans to help farmers and ranchers improve their irrigation and aid with various soil conservation measures. A second program administered by the FmHA included $225 million appropriated for "drought-related" loans ($150 million in 5% loans) and grants ($75 million) to communities that had fewer than 10,000 people. The program run by the Economic Development Administration (U.S. Department of Commerce) on the other hand, appropriated $175 million for loans and grants for the improvement, expansion, or construction of water supply systems in communities over 10,000.

The other major program directed primarily at improving water supplies was the Drought Emergency Program of the Bureau of Reclamation (now the Water and

Power Resources Service) ($100 million). Its purposes were to establish a "water bank" to help water users buy water from parties willing to sell, to issue loans and grants to help organizations augment their water supplies, to "provide nonreimbursable funds to state water resources agencies for drought-related projects, and to aid in the protection of fish and wildlife threatened by the decrease in water supplies."

The State drought program in Colorado was mainly one of increasing public awareness of things that could be done to help alleviate problems caused by the drought. Managed by the Office of the State Drought Coordinator that the Governor established in March of 1977, the program was to help local communities establish their own drought programs, to provide technical help to those areas applying for federal funds, to coordinate and keep open channels of communication between the various drought-related efforts throughout the State, and to analyze the extent of the effects of the drought. The State program was headed by the State Drought Council composed of the Governor and thirteen members, seven appointed by the Governor, three by the Speaker of the House, and three by the Speaker of the Senate. In addition, there were five associate members appointed by the Governor. While the Council oversaw the overall State program, local activities were managed through the State's thirteen Planning Regions. In each Region, a Drought Coordinator was appointed and a technical advisory committee was set up.

B. Some Problems with the Federal and State Programs.

Several major criticisms of the above programs were brought out in the reports referenced earlier, as well as in a recent U. S. General Accounting

Office publication entitled Federal Response to the 1976-77 Drought: What Should Be Done Next? The criticisms noted in these reports were supported by the responses to the survey taken in this study. Only a few will be discussed here.

The first major complaint was simply that the programs went into effect too late to be able to accomplish all that they could have had they been started sooner. The federal program did not get started until April of 1977, while the drought was generally acknowledged to be serious by January of that year. By the time many of the programs got underway, crops had already been planted and irrigation ditches were operating as usual. Not much could be done until the fall. Action by the State, although originally initiated by the Governor as early as the end of January, 1977, was not really in full effect until June 10, 1977, when the Governor signed the weather modification bill and the bill to establish the Office of State Drought Coordinator. Only in the middle of July, 1977, after a grant from the EDA funding the regional drought offices, could the local work begin.

The second major criticism was that the major part of the funds provided did not go toward alleviating the immediate effects of the drought. The majority of applicants saw it as an opportunity for getting funds to deal with problems that already existed independent of the drought. Most of the problems, as noted earlier, were more a function of long-term management practices and neglect of maintenance. The State energies also seemed directed in many instances toward development of management tools such as hydrologic modeling, groundwater studies, and economic modeling of drought impacts. While these efforts may have a long-term payoff if the tools are kept activated, they did not contribute to the direct attack on the immediate problems.

Many of the participants felt the drought programs, in addition to getting started late, were cut off before the drought was over. As a result, many felt they were not able to accomplish the necessary changes that would make their water systems "drought-proof." The lowest yields from a drought situation may come the year after precipitation levels have returned to normal state, and groundwater levels and soils often require several years of good conditions to recover from severe drought.

Finally, several towns complained that they often gave up on attempts to obtain grant money because the process was too complex and the mandated requirements and follow-through were too demanding.

VI.

RECOMMENDATIONS

The observations made in the course of the study, including both data gathered and analyzed plus the insights shared by the many people interviewed in the course of the study, lead to a number of recommendations directed toward government agencies at the federal, state, and local levels and toward private water suppliers and users. These recommendations have appeared (at least implicitly) in the earlier parts of this study but are summarized here.

A. Recommendations Relating to Towns.

The main guiding principle for the evolution of town drought policies at the federal, state, and local levels should be to stimulate local initiative. This follows from numerous observations made during this study. Its pervasive relevance follows from the great diversity of conditions (climatic, hydrologic, and socio-economic) faced by towns and from the large number of mitigating steps that can be taken at low cost at the town level.

Programs of assistance to towns should be predicated upon evidence of local initiatives and good management and should not be "rewards for 50 years of mismanagement" (a phrase heard frequently in the course of this study).

We first list six recommendations that we feel are both quite important and of general applicability. The second group contains recommendations that are, in our opinion, either of a lesser degree of importance or a lesser degree of generality. For a specific town, however, it could well be that one of the latter recommendations would be of greater importance.

Group 1:

1. All towns should have the capability for undertaking long-term planning of raw water, water treatment, and sewage treatment needs. Resources should be devoted to maintaining an up-dated plan covering these aspects of the water-sanitation system.
2. Towns dependent on surface water should study the adequacy of the water rights they own in terms of their seniority and its implications for town water availability, given the hydrology of the streams involved. Adequacy <u>need not</u> mean ability always to meet all water demands, but quite a few towns appear to own inadequate rights, while a few own none.
3. Towns should investigate making arrangements with ditch companies on their streams to use ditch company water during periods of drought, by paying an amount equal to the estimated losses of income from crops.
4. Customer charges, whether collected through metering or through a fixed charge per billing period, should be sufficient to cover operating, maintenance, and system replacement costs.
5. The financial accounts of the water and sewerage systems should be kept separate from town general accounts and, in addition to maintaining an adequate cash working balance for the water system, a sinking fund for major maintenance and replacement expenditures should be maintained.
6. The possibility of greatly expanding the use of "circuit riders" in the areas of general town management, financial management, and water management, engineering, and law should be considered by the appropriate state agencies (e.g. Division of Local Government or Regional Planning and Management Agencies) and by groups of towns themselves. Such arrangements, in which one person provides expert service to several towns on a continuing basis, have proved very effective in several cases and can help retain qualified people to serve the smaller towns.

7. Local programs of consumer education regarding drought problems, the frequency of drought, and the usefulness of following "mixed strategies" (e.g. some supply supplementation, some improvements in water-use efficiency, some rationing, etc.) will help prepare the public for drought and to avoid public apathy when drought occurs.

Group 2:

8. Town distribution systems and storage reservoirs for both raw and treated water should be checked for leaks. Some towns lose more than 50% of the water they produce.
9. Larger towns should undertake a benefit-cost assessment of metering all customers. This may be an effective long-term measure for better controlling water use. To a lesser extent, it can reduce demands during drought by permitting use comparisons, rationing, and through the imposition of surcharges relating to the volume used.
10. The use of wells for backing-up systems dependent on surface water can be a cost-effective strategy where non-tributary groundwater is available.
11. In cases of towns in close proximity to each other and having independent water supplies, town interconnections should be considered.

B. Recommendations Relating to Rural Water Supplies.

As with towns, a major principle in rural areas should be to <u>stimulate local initiative</u>. In a number of cases cited earlier, state and federal programs simply took over the financing of activities already taking place. In other cases, local initiatives were inhibited by the expectation that outside programs would eventually become available. Examples would include water exchanges, water rental arrangements, well-drilling, canal lining, and improved on-farm efficiencies.

Group 1:

1. The Cooperative Extension Service, the Office of the State Climatologist, the Division Engineering, and the District Water Commissioner should collaborate in developing a strategy for irrigation water use during drought for each state Water District. This strategy would include:
    a. suggestions for cropped acreages and cropping patterns, including substitution of more drought-resistant varieties;
    b. methods for greater on-farm efficiencies, such as closer supervision, more frequent applications, reduced early-season applications, etc.;
    c. proposed cooperative arrangements for sharing water, including compensation to seniors who share water.
2. Any steps -- legislative, administrative, or institutional -- that have the effect of facilitating the transfer of available water from one use (or user) to another should be investigated and encouraged. This promotes easier adaptation to changing climatic and economic circumstances, and will stimulate efficient water use by establishing a market price for water. The practices of the Northern Colorado Water Conservancy District (Loveland) and the terms of the contract between that District and the Bureau of Reclamation should be studied carefully.

3. Management strategies for irrigation reservoirs should be studied further, with the particular objectives of:
    a. increasing the flexibility of management of the various types of reservoirs (ditch company, town, industrial, fish and game) during droughts;
    b. developing a rational basis for keying water carry-over decisions to general climatological conditions and District soil and agronomic conditions.
4. The State Engineer, the Division Engineers, and the Water Commissioners should investigate further opportunities for the conjunctive management of ground and surface waters, both as drought protection and for regular seasonal water management. Where aquifer capacity is large and where natural recharge from streams and canal seepage is large, substantial opportunities appear to exist for expanding effective water supplies by pumping in dry years and recharging in wet years. There appear to be opportunities for increasing recharge by keeping canals full.
5. The current State water law relating to tributary ground waters (passed in 1969, placing wells in order of priority) should be re-studied to facilitate conjunctive management.

Group 2:

6. The Office of the State Engineer should consider the criteria that should be used by Division Engineers and/or District Water Commissioners in making "futile declarations," i.e. in declaring that the rights next in line to receive water from a stream cannot be served because of excessive losses in transit. A set of well conceived criteria based on

economic and equity considerations would relieve officials in the Divisions and Districts of having to make decisions under pressure, based upon their own hurried judgment. More carefully planned, futile declarations would become a more valuable aid in dealing with water supply during drought.

7. Consolidation of storage in larger reservoirs that are subject to less evaporation and seepage losses during drought should be urged for any Districts where this is physically possible.
8. Where towns hold rights to excess water in anticipation of future growth, cooperative agreements for the agricultural use of that water during drought should be worked out now.

C. General Recommendations Relating to State and Federal Policies and Programs.

The following recommendations are of a more general nature. It seems warranted to emphasize once again that drought conditions and mitigating options vary tremendously from area to area, from town to town within the state. Thus, <u>local steps based on detailed knowledge of local conditions will always constitute at least a part of the best overall drought mitigation strategy</u>. State and federal programs should stimulate imaginative local initiatives and not simply substitute for them.

1. <u>Definition of Drought</u>. For operational purposes, it is recommended that the relevant state officials and agencies, (e.g. state climatologist, the Division of Water Resources, etc.) define sets of conditions that would constitute a state of "drought warning" and a "policy triggering level" at which the various assistance

programs would go into effect.

Since drought represents the interaction of socio-economic demands for water and the physical climatological-hydrologic conditions, one definition of the warning and triggering levels for the entire State will not suffice. Rather, decisions should be made regarding:

a. the division of the state into areas that share similar climatological and socio-economic conditions;

b. defining for each such area the climatological-hydrologic-soil conditions that should constitute warning and triggering levels.

2. Dissemination of drought information. While some excellent sources on regional climatological conditions exist[1], and while the State Climatologist provided detailed in-state data during the later parts of the 1976-78 drought, a review should be made of the actual channels through which climatological information should be transmitted to residents of the areas defined in (1a) above. These channels should be capable of quick, pervasive transmission of the occurrence of the "warning" and "triggering" levels, plus more general information (see fn.).

3. It is recommended that the federal agencies having drought assistance programs coordinate the timing and coverage of their programs, as well as dissemination of information regarding these programs through the channels identified in (2) above.

4. All state and federal agencies having drought assistance programs should develop monitoring programs for use during and after drought to see that the

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[1] "Water Supply Outlook for the Upper Colorado Basin," NOAA-NWS River Forecast Center, Salt Lake City; "Water Supply Outlook for the Western United States" (map), NOAA-NWS, Silver Springs, Md.; "Water Supply Outlook for Colorado and New Mexico and Federal-State-Private Cooperative Snow Surveys as of (date, monthly)," Soil Conservation Service, USDA; computer data bank of the Water Resources Division, Department of Natural Resources.

objectives of their programs are being achieved and that the resources provided are being effectively applied.

5. The State of Colorado should urge Congress and the National Climate Program Office to strenghten the Intergovernmental Climate Program called for in the National Climate Program Act of 1978, so that the data sources of NOAA and the other federal agencies can more effectively be channelled to the states and to promote decentralized state and regional climate impact studies.

ATTENTION: Please Return To:

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WATER AGENCY QUESTIONNAIRE

Name of Water Agency:

Area Served:

Total Population Served:

1. Please describe the nature of problems encountered during the 1975-1977 drought: (Please indicate whether problems were actually caused by the drought or merely intensified due to the severity of the drought.)

   a. Physical supply

   b. Financial

   c. Other

2. Steps taken to deal with these problems: (How effective were they?)

   a. Physical supply:

   b. Financial:

   c. Other

3. Relation of water supply agency to municipal government:

   a. Department

   b. Private company

   c. Special district

   d. Other. Specify:

4. Is the sewage system managed by the same agency?

5. What is the nature of the financial accounting system for water revenues and expenses?

   a. Are they merged with municipal general fund accounts or are they in a separate system?

   b. Are sewage and water accounts kept separate?

6. Is the office of the water agency manager a:

   a. Full time job?   b. Part time job?

   c. If a part time job, fraction of time spent at job:

   d. Length of time of current manager at job:

7. How many people does the water/sewage agency employ?

   a. Full time:

   b. Part time:

   c. Average fraction of time spent on job for part time employees:

8. Does the agency have a regular maintenance and replacement program for:

   a. Raw water storage facilities?

   b. Wells and pumps?

   c. Treatment plant?

   d. Local storage?

   e. Mains?

   f. Other?

9. Are funds regularly set aside for replacement and expansion of the system? If so, please explain:

10. Please describe the water rate structure (flat rate, block structure, other bases for charging, etc.):

11. Describe the nature of the sewer rate structures:

12. Basic principle behind rate structure:

    a. Full cost coverage?

    b. Operation and maintenance coverage?

    c. Full cost plus systems expansion?

    d. Other? Specify:

13. Best estimate of delivered cost per 1000 gallons:

14. Total water distributed:

    1974

    1975

    1976

    1977

    1978

15. Total water revenues:

    1974

    1975

    1976

    1977

    1978

16. Does the water agency or town own any water rights?

17. Are these adequate to meet peak demand?

18. Can additional water be temporarily "rented" (purchased) from other parties? Please explain:

19. Are there any legal or charter restrictions on water pricing, borrowing money or other financial constraints that were bothersome during the drought?

20. Did you hear about emergency assistance programs during the drought?

    Through what channels did you learn of these?

21. Did your agency apply for external assistance?

    a. If yes, was the funding directed toward new drought-induced problems, old problems aggravated by the drought, or problems not directly related to the drought?

    b. Through what programs did your agency apply?

22. Did you find the assistance programs sufficient to meet your needs?

23. Were there occasions before this drought that you sought outside technical or financial aid? Explain:

24. General comments:

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