Historical Dry and Wet Periods In Colorado
(Part A: Technical Report)

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Climatology Report No. 99-1 A

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July 1999

funded by:
Office of Emergency Management
15075 South Golden Road
Golden, CO 80401

under P.O. #PD97SEM000015

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Table of Contents

List of Tables

List of Figures

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1.0 Introduction

Colorado is a dry state with a large spatial variation in precipitation. The annual average precipitation shown in Figure 1 reveals a maximum of over 50 inches in small areas of the higher mountains in the southern and northern parts of the state. The lowest precipitation near 7 inches is in the San Luis Valley in south central Colorado while much of the western part of the state at lower elevation from southwest to northwest has below 10 inches. The eastern plains vary from near 12 inches to more than 16 inches. The statewide average is near 17 inches as described by Cowie and McKee (1986). Adequate water is one of the most critical issues which the citizens of Colorado must constantly address. There are only two sources of water in Colorado. One source is water located in underground aquifers which was stored long ago and today is being mined. The second source is precipitation in the form of rain, hail and snow. Other forms of water from the atmosphere such as dew are not considered for the present discussion. Precipitation is the source of water but it is not the form of water used in Colorado. Precipitation falls and then in some scale of time it becomes one of five sources of usable water – snowpack (SN), streamflow (ST), reservoir water (RW), soil moisture (SM) or ground water (GW). In reality, time is an important factor because precipitation occurs irregularly in time and then it immediately adds to snowpack (SN) and soil moisture (SM) but in a variety of time delays it becomes streamflow (ST), reservoir water (RW), or ground water (GW).

Colorado has a complex and sophisticated system of water distribution within and outside the state. However, there are two dominant pathways of water use that are pertinent to the discussion presented here. The first pathway is that precipitation falls on ground and becomes soil moisture (SM) and ground water (GW) to support vegetation and other uses locally where it occurs. A portion may also become streamflow (ST) and reservoir water (RW). This is the dominant pathway for all lower elevations of the state and for the higher elevations in the summer season. The second pathway is that precipitation falls on the ground at higher elevations in the winter season, snowpack (SN), and becomes available as streamflow (ST), reservoir water (RW), soil moisture (SM) and ground water (GW) during the following spring and summer and beyond in time depending on many factors.

These two pathways of water supplied by precipitation lead to a very natural question. How variable in time and space is the supply of precipitation in Colorado? This is the question that this report will address. Climate is known to vary on all time scales from years to decades to centuries to millennia. Locally, at a specific location a general guideline would be that annual precipitation varies from one-half the average to twice the average in a period of a few decades. This variation by a factor of two from the average is large and can be critical for a relatively dry state like Colorado. If the variation were plus or minus 10%, concerns and impacts would be much smaller. Other questions about variation is whether dry and wet periods occur one year at a time or in groups of years and are they predictable? This report will seek to explain how precipitation has varied for nearly the past 100 years (snow is less) and where we are now. The question of predictability will not be addressed.

There are many studies of the variation of precipitation by itself. Dry periods identified as drought have been of concern for a long time. Tannehill (1947) recognized that all geographic areas have periods of drought and that the 1930s were really unusually dry in the central U.S. In the later 1970s a workshop summarized by Rosenberg (1978) recognized the 1930s, 1950s and a portion of the 1970s have all led to drought problems. In a summary of streamflow (ST) the USGS (1989) has identified periods of drought as 1930-42, 1949-57, 1958-70 and 1976-82. Research based on tree rings by Meko et al. (1995) has indicated several periods since the mid 1500s in the western U.S. have been drier than the present 30-year average. Tarboton (1995) has identified drought periods for the Colorado River. He reports droughts with duration longer than 10 years are to be expected with return periods on the order of 100 years. A study by Edwards and McKee (1997) of drought in the United States in the 20th century indicates that much of the U.S. has had fewer drought events in the past 25 years. A summary of drought globally in the period 1900-1995 has been given by Dai et al. (1998).

In this report the analysis tool used by Edwards and McKee (1997) will be introduced to describe both drought and wet events for periods in Colorado. Information is included here related to precipitation, snowpack and streamflow which give a broader view of drought and wet periods. A set of appendices is contained in a separate report identified as Part B.

2.0 Precipitation and Snowpack Data

The two data sources used for this study are stations with long-term records in precipitation operated by the National Weather Service (NWS) and in snowpack operated by the Natural Resource Conservation Service (NRCS). National archives are held in Asheville, NC, and Portland, OR, respectively. For the precipitation data, we have applied further quality control procedures which has resulted in some modified values so the archive now maintained at Colorado State University in the Colorado Climate Center is not identical to the national archive. Table 1 shows the stations with precipitation data along with the geographic location, elevation, and starting year of the observation period. The snow sites are given in Table 2 with similar information. A map of all the precipitation and snow sites is shown in Figure 2. The snow sites are restricted to the higher elevations of the mountainous portion of the state while the precipitation sites are located throughout the State at lower elevations. The highest elevation of a precipitation site is 8,900 feet (Dillon). There are 24 sites included with records longer than 100 years. The intent is to have enough long-term sites to be able to characterize drought back to the beginning of the twentieth century for precipitation. Notice the snow measurements are not as long. Most of the early observations were in the 1940s and 1950s. Climate average for this study is the period 1941-1980 or the period available.

Snow observations have not been quality controlled to the same extent as the precipitation observations. Liquid-water content of the snowpack increases through the winter and almost always past April 1. During April, the snow can continue to accumulate or it can start to melt. While the April 1 snowpack is not the maximum, it is the last monthly observation which can be used uniformly in the mountains. Consequently, only the April 1 observations will be used in this study of dry and wet conditions. A subset of total snow sites are used in this report. The sites chosen include many that are used by the NRCS in streamflow estimates (Perkins, 1999).

Data for individual stations are used in this report and in addition the state has been subdivided into river basins for the analyses. The boundaries of the river basins are shown in Figure 2. The basins include the Yampa-White (YW), Colorado (CO), Gunnison (GU), San Juan, Animas and Dolores (SA), Rio Grande (RG), North Platte (NP), South Platte (SP), and Arkansas (AR). The South Platte (SP) and Arkansas (AR) have been further divided into the Upper (U) and Lower (L) to separate the Front Range and Plains portions of these river basins. No long-term precipitation station exists for the North Platte but snow observations do relate to the North Platte.

3.0 Precipitation and Seasonality in Colorado

The distribution of precipitation in space and time in Colorado is strongly related to how dry and wet periods occur. Three topics are interrelated to obtain a physical grasp of how precipitation is controlled. These include seasonality, elevation and large events. Each of these are discussed as they affect Colorado. A few comments about water in the atmosphere will help to guide the discussion of precipitation. The amount of water vapor contained in a parcel of air at a fixed relative humidity increases as the temperature increases. At 100% relative humidity the mass of water per unit mass of air approximately doubles for each 10°C (18°F) increase in air temperature. Another feature of the atmosphere is that as air moves upward or downward without condensation or evaporation, temperature decreases (up motion) or increases (down motion) at a fixed rate which is about 10°C per 1,000 meters (6°F per 1,000 feet) as the pressure changes. Consequently, precipitation occurs when air moves vertically upward, cools by expansion until near saturation, forms droplets or ice crystals which grow with continued rising motion, and the particles then fall as they get large enough. The upward motion is provided in the atmosphere or when air is forced to rise up by the topography.

3.1 Seasons

The primary factors that control the precipitation climate pertain to the mid-latitude, high elevation, interior continental location of Colorado (37°N to 41°N). Figure 3 shows a depiction of the seasonal cycle in Colorado. The annual cycle and associated types of storms control where and in which season different parts of Colorado receive maximum precipitation. During the winter months, the winds in the mid-troposphere (approximately 500 mb in pressure or 5,600 m or 17,100 feet) in this latitude zone are relatively strong and blow primarily from west to east with considerable variation from south of west to north of west. As a result most synoptic scale storms reach Colorado from the west during winter and deposit precipitation (primarily snow) along and west of the mountain ranges of Colorado. Some of the mountain areas have their wettest season in winter. As the air crosses the higher elevations and starts to move downward, the precipitation weakens and typically ends by 2,800 m (9,186 feet) to 2,400 m (7,874 feet) elevations. Winter is the driest season on the plains with cold air and small amounts of water in the atmosphere. Occasionally, large storms do occur on the plains and eastern slopes of the mountains when storms have the right timing to bring water westward over the plains to Colorado.

During the spring months, the temperature warms, water content of the air increases, west winds weaken, and the storm track begins to move northward. Storms are fewer in number and slower moving but they occasionally bring abundant moisture from the Gulf of Mexico and the central U.S. into eastern Colorado and can produce more precipitation in eastern Colorado and the Front Range. A single spring storm can deposit as much precipitation in eastern Colorado as most winter storms combined. Spring becomes the wettest period for the Front Range. This period typically lasts from March into early June. At the same time, storms for the west become less frequent especially over southwestern Colorado. June is often the driest month of the year for western Colorado.

The last half of June is often a dry period in much of Colorado. In mid summer, winds aloft are normally quite weak and solar heating of the ground leads to convection which becomes the dominant element in daily weather. The storm track moves north of Colorado most of the time but does occasionally dip southward to strengthen convective storms in Colorado in July and August. This leads to a maximum of precipitation over the eastern plains in summer. As a region of weak low pressure forms over the desert southwest and Colorado plateau areas, low-level subtropical moisture usually drifts northward over Mexico. This wind circulation is sometimes called the "Southwest Monsoon" and often brings moist air northward into southern and western Colorado during July, August and early September. Late summer into fall is the wettest period for much of the southwest Colorado. In some years the moist air extends northward and eastward to encompass the entire state. Localized afternoon and evening thunderstorms develop nearly every day in the mountains if the air is moist enough. Humid air can also periodically drift into eastern Colorado from the central and southern plains providing fuel for summer thunderstorms from the Front Range eastward.

As the summer comes to an end, the westerly winds aloft increase again, the low-level moisture from the south retreats and drier air often dominates Colorado. However, occasional storms, with significant moisture reach Colorado and can bring very heavy and widespread rains and early snows. As fall progresses, the synoptic storms of the winter season return as temperatures cool.

The resulting interplay between the Rocky Mountain topography, Colorado's high elevations, and these seasonally-varying moisture sources and storm tracks creates a remarkably diverse climate unique for North America in which different portions of Colorado see markedly different seasonal precipitation patterns than others.

For Colorado's highest mountains, mid winter is typically the wettest time of year while early summer is the driest. For Colorado's Front Range, spring is typically the wettest time of year, while mid winter is the driest. Mid summer is the wettest time on the plains with winter the driest time of year. Summer, and particularly July and August, contributes the greatest amounts of precipitation over most of southern Colorado. For a small region of the State on the Colorado Plateau near the Utah border, autumn is the wettest time of year while late spring and early summer is the driest. A few areas in between see precipitation that averages nearly the same amount in each month of the year. Seasonal precipitation distributions not only vary from region to region across the state but may also vary locally from one side of a mountain to the other or as a function of elevation within a drainage basin. Some of the high mountains have a mid winter precipitation maximum and some are wetter in mid summer. Most precipitation in summer in the higher mountains produce little streamflow (ST) as most of the water is returned to the atmosphere by evapotranspiration.

3.2 Elevation

Elevation has a large effect in the total annual precipitation as is shown in Figure 1. In this study a major limitation is that very few year round precipitation measurements are made at higher elevations. The seasonal distribution of precipitation varies rapidly with elevation. Denver has a spring maximum but just 30 miles to the west Berthoud Pass has a mid winter maximum. In western Colorado a similar shift occurs from a late summer maximum in many valley locations to winter at higher elevations. This reality means that combining data from different locations in one river basin has the problem of combining data from different seasonal distributions which can be misleading since the various precipitation systems operating throughout the year are not well correlated.

In the winter west of the Continental Divide the higher elevations receive more precipitation in individual storms and receive a larger number of days with precipitation. Along the Front Range, the higher elevations receive a larger number of days with precipitation (due to snow coming over the top from the west) but do not necessarily receive higher amounts from individual storms. Most Front Range snow storms have maximum precipitation at mid elevations. In summer the large convective rain storms decrease in precipitation at higher elevations. But the higher elevations can receive more total precipitation due to a larger number of days with precipitation.

3.3 Large Daily Precipitation

The other characteristic of precipitation important to any discussion of variability is the role of larger amounts of daily precipitation. Figure 4 shows the percent of annual precipitation as a function of the percent of daily events of precipitation for the Northern Front Range of Colorado and for the State as a whole from Cowie et al. (1986). The graph shows that 50% of the annual precipitation comes from about 18% of the days with largest amounts of precipitation. About 50% of the days contribute nearly 80% of the precipitation. Since most of the precipitation come from a relatively small number of days with larger amounts of precipitation, it would follow that the large daily events would dominate the variation of precipitation from year to year. The study of daily precipitation in Colorado by Cowie et al. (1986) for the period 1951-1980 showed that the larger daily events which produced just 24% of the annual precipitation produced 59% of the change in annual precipitation from the 10 driest years to the 10 wettest years. This leads to the conclusion that the addition or subtraction of just a few large storms is the primary difference between dry and wet years. The change in the total number of days with precipitation is a secondary contributor. The study reported here used monthly data, so no information is given about the cause of year-to-year variations.

4.0 Definition of Dry (Drought) and Wet Periods

Drought is fundamentally a deficit of water in the sense that demand for water is greater than the supply of water. This can apply to any source of water so there is not a single definition that meets all information needs. As a result several definitions could be constructed which each apply to a specific aspect of water supply. Most of the effort to define drought has been concerned with the supply of water. The demand for water is not as well defined. One definition proposed by Palmer (1965) has been used extensively in the United States for the past 40 years. The Palmer Drought Severity Index (PDSI) has been used to monitor agricultural drought and also as a general measure of drought. Unfortunately, the PDSI does not answer most of the questions asked about drought in Colorado or other places. These questions include: What is the water deficit in terms of probability, percent of average, or precipitation deficit? How bad is it now? When did it start? How does it compare with past droughts? When did it end? Other questions relate to the impact of drought on natural ecosystems or on the economy and society. The word drought and dry are used interchangeably in this study. The opposite of dry is wet and the definition of dry has an exact opposite which is used for wet periods.

There is no single definition of drought that satisfies most needs. Wilhite and Glantz (1985) discuss definitions but don't conclude there is any universal definition. However, for a quantitative description of drought or wet periods a definition is required. The definition of drought used here is one that will answer most of the questions about water supply in terms of precipitation and snowpack. It will allow a determination of beginning and ending along with intensity. It can be applied to streamflow, reservoirs, soil moisture and ground water but the first two of these are affected greatly by the management of them and the last two are not observed extensively to allow a similar analysis. The variable used to define dry and wet conditions is the Standardized Precipitation Index (SPI) which was used in Edwards and McKee (1997). Precipitation and snow have two qualities that influence how the SPI is calculated. The first is that it is highly variable in time so that many years are needed to obtain useful estimates of its probability distribution. The second is that precipitation and snow are not normally distributed statistically which means that the distribution is skewed and the mean and median are not the same. Assume as an example that precipitation is observed monthly for many years. All of the monthly values are used to fit a Gamma frequency distribution which is given by:

$$g(x) = \frac{1}{\beta \gamma \, \Gamma(\gamma)} x^{\gamma - 1} e^{\frac{-x}{\beta}}; \; \beta > 0, \; \gamma > 0 \tag{1}$$

Thom (1966) has shown the Gamma distribution fits precipitation quite well. The frequency density $g(x)$ for the Gamma is a two parameter function with β and γ being the fitted parameters. The variable x is precipitation. The mean or average value of x is $\beta\gamma$. The cumulative probability is given by:

$$G(x) = \int_{o}^{x} g(x)dx \tag{2}$$

where $G(x)$ is the probability that x is equal to or less than x.

In the application to drought, precipitation is fitted to the Gamma distribution. Then at a particular time, precipitation is observed. The observed value (x_i) is used with the Gamma to determine the cumulative probability at that time, $G(x_i)$. Next an equiprobability transformation is made from the Gamma function to the normally distributed function with a mean of zero and a standard deviation of one with a cumulative probability defined as $N(z)$ or a particular $G(x_i)$ as $N(z_i)$. Both $G(x_i)$ and $N(z_i)$ have the same probability. The advantage of the transformation is that N is normally distributed so it can be used to define wet periods as well as dry periods and the values of z are in units of standard deviations. Thus the values of z are the values of the SPI. An example is given for Fort Collins, CO, in Figure 5 for its period of precipitation observation. The SPI values on the ordinate are uniquely connected to cumulative probability as given in Table 3 so -1, 0, 1 are associated with cumulative probability of 16%, 50% and 84%. Values of SPI are linear with precipitation difference from the mean and they do have a unique relationship to probability. Since the mean value of precipitation from the Gamma is $\beta\gamma$, the fraction of average precipitation is just $x_i / \beta\gamma$. This can also be normalized as the precipitation deficit as a fraction of average values as $(\gamma_i - \beta\gamma) / \beta\gamma$. The actual annual water-year precipitation (October through September) for Fort Collins, CO, is shown in Figure 6. Figure 6 has one point per year and Figure 5 has one point per month but Figure 6 and Figure 5 (12 month) are both 12 month values. Water year 1961 ended in September 1961 in Figure 6 for the single wettest year in the graph. In Figure 5 (12 month) the monthly data points reach a peak in later 1961 and continue into 1962. The SPI values in Figure 5 give a better picture of the duration of a wet or dry period. Some of the advantages of the SPI as a monitoring tool are that it has a straightforward interpretation as probability, percent of average, precipitation deficit and it show duration clearly.

Another useful application of the SPI is that any accumulation period of a number of months can be used. Figure 5 shows the history of Fort Collins precipitation for periods of accumulation (defined here as time scale) of 3 months, 6 months, 12 months, 24 months, and 48 months. The dramatic character of climate is that as the time scale is increased the dry periods with SPI below zero becomes less frequent but they last longer and the wet periods behave in the same manner. At the 3 month time scale, there are approximately 90 droughts per 100 years and the number decreases to about 10 between 24 months and 48 months. Time scale becomes an important part of any discussion of drought. Notice for Fort Collins at 48 month, there has been no drought since 1980. The real problem of drought in Colorado is that the accumulation period of precipitation (time scale) for water in the form of soil moisture, snowpack, streamflow, reservoir storage, and ground water are all different.

The definition of drought used in this analysis is based on the SPI and a time scale must be identified. Dry or drought is defined as a period in which the SPI equals or is below -1.0. The drought is defined as starting when the SPI first becomes less than zero and it ends when the SPI again becomes greater than zero but it must get below -1 at some time. This definition is arbitrary and better ones may evolve with experience. Thus, each drought has a beginning date and an ending date which defines a duration. Wet periods have similar definition with positive values of SPI. A current intensity of the dry and wet is also defined in terms of the SPI in Table 3. Three measures of drought are the time scale, intensity and duration. The notion of time scale also makes it possible to be in or out of a short-term drought when in or out of a long-term drought. In Figure 5 for Fort Collins all of the periods below an SPI of -1 or above 1 are shaded to allow a visual identification of drought periods and wet periods. The 3 month droughts come and go quickly as any one or two month period can start or end a drought. Short-term droughts can be very significant for dryland agriculture and forest fires. Longer-term drought are more significant for domestic and urban water supply and multiple year concerns for agriculture and natural ecosystems. The fourth measure of drought is magnitude. Magnitude is defined as the ratio of the largest accumulated precipitation deficit to the annual mean precipitation. For example, the worst drought in Fort Collins at the 12 month time scale started in October 1952, ended in May 1956, had a duration of 43 months, and had a magnitude of 0.95 of annual precipitation.

5.0 Drought and Wet Periods Occurrence and Description

Drought is such a complex phenomena that different aspects must be viewed somewhat differently. The definition of drought given above for a single location is quantitative and clear for a monthly continuous series of observations. The analysis of snowpack based on April 1 values will provide another view of drought using one data point each year. A similar thing occurs when the interest is in just the summer or spring or any fixed interval of time. This section includes discussions of drought and wet periods from several different points of view.

5.1 Precipitation

Dry and wet conditions can be characterized for Colorado by examining the fraction of stations in the state which are dry or wet at the same time. The spatial extent of dry or wet conditions is shown in Figure 7 for the period of the early 1890s through 1996 for averaging time scales of 3, 6, 12, 24 and 48 months. Fewer stations were reporting observations in the 1890s so the results during this period are indicative but not as definitive as in the period after the very early 1900s. Notice in Figure 7a for the 3 month time scale that the fraction changes rapidly in time and peak values exceed 0.80 on 4 occasions for dry conditions with SPI < -1 (1890, 1893, 1939, 1981) and on 7 occasions for wet conditions with SPI > 1 (1891, 1905, 1906, 1914, 1941, 1957, 1995). As the averaging periods or time scales become larger, graphs show less rapid changes, the dry or wet periods last longer, and the maximum fraction is reduced. The 24 month graph in Figure 7d has been used to characterize dry and wet periods that affect approximately 40% of the state during the episodes. These are given in Table 4. The periods are not uniformly dry or wet and often have a portion of the period in which the opposite condition increases a bit and then decreases. A sum of the durations of each type show that wet existed for 64 years and dry for 33 years. The 48 month graph (Figure 7e) shows the clearest view of longer time-scale precipitation. The top with SPI > -1 shows the two long periods 1905-1931 and 1980-1996 were wet with only small drought occurrence. Colorado is clearly now in an extended period with less drought impacts. The top of Figure 7e indicates the current wet period is similar to the one beginning in 1905 but the 1983-1988 period had a larger fraction of stations above 0.4 for a longer time period than the earlier wet period. The depiction of dry and wet periods in Table 4 provides a broad overview of drought periods in Colorado that have affected large areas of the state. Wet periods tend to last longer than dry periods and no dry periods longer than 5 years have occurred since the 1950s.

The beginning period of 1893-1905 was dry but the number of observing sites was smaller and changing. A rather long wet period followed from 1905-1931 with brief moderately dry periods in the early teens and again in the early to mid 1920s. Much of the 1940s were wet. The 1950s and 1960s had shorter periods of dry and wet conditions with 1951-1957 dry, 1958-1962 wet, and 1963-1966 dry again. A longer period for 1967-1975 was wetter but not to the extent and duration of earlier periods. A brief dry period followed in 1975-1978 and then a change occurred to start the wet period from 1980 to 1996 with one lull in the late 1980s to early 1990s.

From the state as a whole the next view of dry or wet periods is seen on a regional level within the state. The SPI for each region is shown in Figure 8 and the SPI in each graph is the average of the SPIs of all stations in the region. This was done so that wetter or drier locations would not dominate the combined indicator for the region. All of the periods in which SPI is greater than 1 or less than -1 are shaded to clearly indicate when drought or wet conditions were present in the region. In these graphs the averaged SPIs are not uniquely connected to probability as they are for individual sites. Notice again how rapidly drought and wet conditions appear and disappear at the 3 month time scale. In the Yampa-White (YW) (Figure 8a) there are about 65 drought periods and 69 wet periods. At the 48 month time scale, there were 8 or 9 drought periods and 11 wet periods. It is also quite clear the duration of dry or wet periods is greater at the longer time scales.

Table 5 contains a summary of dry and wet period from each of the regions arranged in the time periods defined in Table 4. The years that are dry or wet consistent with Table 4 are listed in the columns. If the region was mixed in dry and wet or didn't move far from the average then an "M" appears in the table. Most of the river basins did experience dry and wet conditions near the same time periods. The major wet period 1905-1931 was widespread. The drought of the 1930s was not nearly as pronounced in western Colorado. The wet period 1965-75 was not at all uniform. The recent wet period 1979-96 had a significant break in northwest Colorado which is most evident in the Yampa-White (YW).

Each of the regions have some unique characteristics with drought and wet periods. These will be discussed in order of the graphs in Figure 8. The Yampa-White (YW) is represented by only 3 stations of which 2 are in the Yampa drainage. The data prior to 1900 is just from one site – Meeker. It does show a major dry period in the first 5 years of this century. The three stations do not have the same seasonal variation. Steamboat Springs has a mid-winter precipitation maximum but Hayden has a maximum in August. This indicates a substantial variation with elevation in the Yampa-White (YW) drainage. For the 3 month time scale the recent droughts of 1994, 1981, 1976-1977, 1971 and 1966 are as intense as any this century. The period 1981-1994 was remarkably free from drought. The 12, 24 and 48 month graphs all show the 1980s as the wettest period in the past 100 years. The 24 and 48 month portion shows the 1976-1980 drought period was the worst extended drought period this century.

Most of the stations in the Colorado (CO) drainage have a mid to late summer maximum in precipitation which is not usually the same for the higher elevations. A total of 8 sites are included for the Colorado (CO) and 4 of them are below Glenwood Springs. Only 3 of these 8 sites had data prior to 1905. The 3 month SPI shows recent short droughts in 1994, 1990, 1981, 1979, 1978 and 1976-1977. The late 1970s were the driest few years in the record. Again, the period since 1980 has been the wettest period and is not very different for the period in the 1920s.

In the Gunnison (GU) drainage 3 of the 5 sites have data prior to 1900 so the drought period 1900-1905 is very evident and well defined. Recent droughts for the 3 month SPI include 1990, 1978, 1976-1977, and 1972. For the Gunnison (GU) the three drought periods of the 1900-1905, 1950s, and later 1970s are the three for this century. The period since 1982 is the wettest of this century but has not lasted as long as the wet period for 1906-1931. The figures show the Gunnison (GU), Colorado (CO) and Yampa-White (YW) have much in common for drought and wet periods.

The San Juan, Animas and Dolores (SA) drainage has only 1 site with data prior to 1906 so the very dry conditions are from Durango data. The 3 month data shows recent droughts involve mostly two years in 1995-1996, 1989-1990, 1980-1981, and 1976-1977. At the 24 month SPI, it is clear the 1989-1990 and 1976-1977 droughts were worse and very much like the droughts in the 1950s and 1930s. The San Juan, Animas and Dolores (SA) definitely experienced the drought of the 1930s considerably more than the Yampa-White (YW), Colorado (CO) and

Gunnison (GU). Also, in the San Juan, Animas and Dolores (SA) the recent wet period after 1980 has not been as wet as the 1906-1930 period.

The Rio Grande (RG) has a history quite different from the previous ones. Most of the area at the lower elevations have a precipitation maximum in July and August. The 3 month SPI shows several droughts in recent years including 1995-1996, 1980-1981, 1974, and 1972. At 12 month the 1995-1996 drought was the most significant since 1950-1952. Years in the late 1970s and the 1930s were not really dry. At longer time scales the most significant droughts were in the 1940s and 1950s as well as near the turn of the century. The recent wet period has not been as wet as the 1905-1925 period.

The South Platte drainage (Upper and Lower) is characterized with drought in the 1890s, 1930s, 1950s and 1970s. Since the 1970s, the Upper South Platte (USP) has had no significant drought and the Lower South Platte (LSP) has had only short term drought at 3 month and 6 month SPI in 1994 and 1989. Longer time scales have not shown drought. While the recent history has been wet at longer time scales, it has not been as wet as the 1905-1930 period. The droughts in the 1970s were stronger in the Lower South Platte (LSP) and there were several short episodes in 1974, 1976 and 1978.

The Arkansas drainage (Upper and Lower) have good long term data sites prior to 1900 but does not have the strong drought conditions prior to 1905 in the longer time scales. They do show significant drought up to the 12 month time scale. The short time scales do show recent drought in 1996, 1991, 1982 and 1981. At the 12 month time scale, the last serious drought was in the 1960s. The 1930s were the worst decade for the Lower Arkansas (LAR) but not the Upper Arkansas (UAR). The Upper Arkansas (UAR) had more drought problems in the 1950s and

1960s while the Lower Arkansas (LAR) shared the 1950s but not the 1960s. The wet period since 1980 is not as wet as the period for 1905-1930.

The correlation of the precipitation for the water year (October through September) and the 12 month SPI between the regions is shown in Table 6 and Table 7. These show clearly that the precipitation is more highly correlated with neighboring regions in western and eastern Colorado and not well correlated from west to east. The Rio Grande region is better correlated with the San Juan, Animas and Dolores (SA) and Gunnison (GU) but not as well correlated as the western or eastern regions are with each other. These correlations also indicate that wet and dry periods will have a spatial variation in Colorado so the periods identified in the previous tables are generally applicable but individual years will have differences.

The regional history of summer (April-September) and winter (October-March) precipitation is given in Figure 9 and 10. One of the obvious features is that seasonal precipitation can be quite stable for a period of years and vary much more from year to year for a period of years. Correlation of summer and winter precipitation among the regions is presented in Tables 8 and 9. These graphs and tables show similar patterns to the water year and 12 month SPI ones before. Regions are correlated best with those nearby much less with those on the opposite side of the mountain ranges. In a similar way the occurrence of dry and wet periods is related but not exactly the same.

The worst dry and wet periods for each location are given in Appendix E. These tables contain the dry and wet periods for all time scales for the largest and next to largest magnitude of drought with the associated start and end dates and the duration of the event. Magnitudes of dry or wet events have been averaged over the stations in each drainage basin for each time scale and are presented in Table 10. In Table 10 the magnitudes are the largest accumulated precipitation deficit (dry) or surplus (wet) in fraction of the annual precipitation averaged over the drainage basin. Magnitudes start at the 3 month time scale at 0.5 (0.6) for the Yampa-White (YW) up to 0.9 (1.0) for the Lower Arkansas (LAR) with the dry magnitudes slightly less than the wet magnitudes in parentheses. As the time scale increases from 3 months to 24 months nearly all of the magnitudes have increased to greater than 1.0 which is the average annual precipitation. From 24 months to 48 months time scale only small changes occur and in some basins the values actually decrease. The conclusion is that the worst droughts or wet periods in Colorado are usually associated with precipitation deficits or surpluses that equal or exceed the annual average precipitation locally. Examination of Appendix E shows that the actual ranges are quite larger at individual locations. Appendix E also reveals that the dates of the worst dry and wet periods have a wide range and do not group easily into the broad time periods identified in Table 4. This is simply the reality of how variable precipitation is especially where convective rainfall in the summer is important. An examination of Appendix E for duration of dry and wet events shows that these major dry or wet events last longer than one year and the duration increases with increasing time scale.

Examples of the extent and severity of drought and wet events are shown on the maps of Figure 11a-d . Two of the worst droughts this century were present in March 1935 (Figure 11a) and September 1956 (Figure 11b). Both show more than 40% of the state in drought. Note the maps do not have areas blocked off but most higher elevations are not represented by observations. There has not been such a widespread drought in Colorado at the 12 month time scale since the 1950s. There is no known reason why droughts of this nature should not return again. Two exceptionally wet periods are shown in October 1957 (Figure 11c) and June 1995

(Figure 11d) for the 12 month time scale. These also have more than 40% of the state in wet conditions. Each of these dry or wet periods are more extreme in a sub-portion of the state. The first and second most severe droughts in Appendix E are often related to the 1930s and 1950s. Wet periods are not quite as uniform in time.

5.2 Snowpack and Streamflow

The dominant source of water for streamflow and reservoir storage is the winter snowpack. However, the snowpack has a limited number of observation sites and the spatial variation of snowpack (SN) in elevation and horizontally is often large in Colorado. The streamflow is also a complex variable to relate to snowpack. The streamflow (ST) can vary significantly with the weather which controls melting and with precipitation which occurs after April 1 which is the date of the snowpack (SN) used in this study. The streamflow (ST) is further complicated by both water stored in reservoirs to be released later, by transmountain diversions which move water from one drainage to another and by water used for irrigation in the basin. The analyses discussed below will however allow dry and wet years to be identified.

The April 1 SPI for snowpack (SN) (called SSI to distinguish it from SPI) is given for 56 locations in Appendix B in which the observing sites have been grouped by river basins. The sites in Appendix B have been selected as representative of the basins. More sites are available to establish a climatology of snowpack (SN) but the relationship to streamflow (ST) was a factor in the selection of sites for this report. The average SSI for each basin is given in Figure 12. Historic observed streamflow (ST) for selected locations in each basin are given in Appendix C and the reconstructed streamflow (ST) for a more limited time period are given in Appendix D. The streamflow (ST) show that the winter of 1977 was uniformly a dry year and it is the driest year since 1960 to use as a reference. The other really widespread dry events were in 1966 and 1981. Other low streamflows (ST) were more localized. The SSI in Figure 12 also indicates the dry conditions in 1966, 1977 and 1981. Years with large streamflow (ST) are not necessarily associated with large snowpack (SN) since wet springs after April 1 can lead to large streamflow (ST). The very high streamflow (ST) of 1984 was associated with such a wet spring. The regional SSI have been used to depict the timing of wet and dry periods similar to precipitation in Table 5 but for snow in Table 11. Table 11 indicates the snow wet and dry periods do occur in the same basic time periods of the precipitation but they are often of different durations and have more variation within the periods. The "M"s indicate a mixed response during the period and the "--" indicate a different response. The correlation of the snowpack for all basins is given in Table 12. These values remain above 0.50 with the primary exception the southwest areas (San Juan, Animas and Dolores, SA; and Rio Grande, RG) to the northeast (Cache La Poudre, CLP; Big Thompson, BT; and North Platte, NP). The high correlations here is a result of the snow at the higher elevations comes from storms with westerly wind components. The correlation of winter precipitation to snowpack is given in Table 13. The numbers shaded are the comparison of precipitation with snowpack in the same basins. The higher correlation of the top portions of the table across to the eastern drainages is same as in the previous table. This shows also that the high elevation snowpack has only small correlation to the winter precipitation on the eastern plains as seen in the bottom four rows of Table 13 with correlation coefficients of both positive and negative signs and values usually less than 0.20. Maximum correlations are found in Western Colorado with values from 0.64 to 0.83.

Although the winter precipitation and April 1 snowpack (SN) have reasonable correlations (Table 13), the time series of SSI do not translate very well into the same dry and wet periods as precipitation (Table 12). The reason for this lies in two aspects of precipitation. The first reason is that the SSI is only winter while the 12 month to 24 month SPI is dominated by warm season precipitation. The second reason is that in winter the snow is a combination of active storms that have well defined upward vertical motion fields and thus snowfall in areas affected by the topography and periods of snowfall due only to the upward vertical motion forced as air moves over the topography. These two sets of conditions can produce complex patterns of snow on the ground which are then followed by the conditions which lead to snowmelt and runoff.

One question often asked is how is the winter snow correlates to the following summer precipitation. Table 14 provides the answer to this question. These correlations show very little relationship between the winter snow and following summer precipitation. Again the numbers shaded are for the same basins.

Appendix C and Figure 13 give observed streamflow and Appendix D gives reconstructed streamflow for a more limited time period. The correlations of April 1 SSI to streamflow and 12 month SPI on September 30 to streamflow average given in Tables 15 and 16. Correlations for the Yampa (YW), Colorado (CO), and Gunnison (GU) are mostly in the range of 0.60 to 0.80 which means 35% to 65% of the variance between the variables is explained by the relationship. On the east side of the mountain ranges for the Cache La Poudre (CLP), South Platte (SP) and Arkansas (AR) the correlations are lower and the SPI correlations lower yet. The lower correlations are due primarily to the fact that the Cache La Poudre (CLP), South Platte (SP) and Arkansas (AR) have areas with a spring maximum in precipitation so April, May and early June often contribute significant water to the drainage basins for precipitation, snowpack and streamflow.

One of the most interesting periods in history is the recent period from the late 1980s to 1996 which is the last data for streamflow (ST). Most of the rivers had a significant reduction in streamflow sometime during this period. The snowpack (SN) shows a reduction but it is not strong in several areas. The SPI shows very little at the 12 month and longer time scales; however, the shorter time scales at 3 and 6 months clearly show the reduction in precipitation. The period had several dry winters but wet summers and for the SPI the wet summers dominate the longer time scales.

The observed streamflow (ST) in Figure 13 and Appendix C can be compared to Tables 4, 5 and 11. The Yampa and White are quite similar to each other. They show the wet periods and dry periods similar to the tables. The highest streamflow was in the mid 1980s which was immediately followed by the lowest period of streamflow in the late 1980s and early 1900s. The Colorado streamflow shows the higher flow in the 1940s followed by a low flow period with a few exceptions through the later 1960s. The mid 1980s had very high streamflow and the late 1980s to early 1990 had lower streamflow. Observations for the Gunnison (GU) and San Juan, Animas and Dolores (SA) are quite similar to the Colorado (CO). Higher streamflow in the 1920s was followed by lower streamflow in the 1930s. Again the period for the early 1950s through the late 1960s had lower streamflow with a few years with large streamflow. The mid 1980s were notable for large streamflow and the later 1980s to early 1990s was less dry in the San Juan, Animas and Dolores (SA). The Rio Grande near Del Norte shows a dramatic shift to lower streamflow in the 1940s. The streamflow for the basins on the east side of the mountains have poor correlations with snowpack (SN) and the SPI in Table 15 and 16. The Cache La Poudre, Big Thompson, South Platte and Arkansas had a large streamflow from a portion of the 1950s through the 1960s and a short higher streamflow in the mid 1980s. Individual years of largest or two-year periods are common along with several years below average. The four-year running mean values show a consistent character of the climate in Colorado.

6.0 Summary and Conclusions

A study to document the drought (dry) and wet periods in Colorado during this century has been conducted using precipitation, snowpack and streamflow observations. Drought and wet periods have been defined using the Standardized Precipitation Index (SPI) for a variety of time scales including 3, 6, 12, 24 and 48 months. A range of time scales are used since the time for precipitation to be transformed to water sources of soil moisture, snowpack, streamflow, reservoir water, and ground water vary. The 3-6 month periods are more related to snowpack and soil moisture. Time scale of 6-12 months have more relationship to streamflow and reservoir water while the 24-48 month time scale is related to reservoir water, streamflow and groundwater. A fundamental character of precipitation is that the longer the averaging period the less impact a short time period has on accumulated precipitation. Consequently, the longer time scales (averaging periods) have fewer dry and wet periods but the periods last longer. In the U.S. the 3 month time scale leads to approximately 65 drought periods in 100 years with an average duration of 6 months. A time scale of 24 months is needed to reduce the number of droughts to about 10 per 100 years with a duration of nearly 13 months. Thus the frequency of drought (wet) periods, the duration, and the magnitude of precipitation deficit are all a function of the time scale. Severity of drought and wet periods is not affected by time scale.

An analysis of the fraction of precipitation observing sites in dry or wet conditions indicates that approximately 60% of the state can be dry or wet at the 24 month time scale. Using the percentage of sites being dry or wet, the dry and wet periods this century are:

- WET: 1905-1931, 1941-1951, 1957-1959, 1965-1975, 1979-1996
- DRY: 1893-1905, 1931-1941, 1951-1957, 1963-1965, 1975-1978

These periods indicate several aspects of climate during nearly a century. Two long wet periods (1905-1931 and 1979-1996 and continuing) are longer than any dry periods. Two dry periods of 1931-1941 and 1951-1957 had severe short term (3 month) and long term (48 month) drought. No long-term drought has occurred since the 1950s but short term drought has been as severe in the recent years as during the major dry periods.

When the state is divided into river basins, the dry and wet mostly agree with the analysis from the percentage of sites. Major exceptions were that the Yampa-White basin was mixed in the 1940s and 1950s, the western slope had a dry period in the later 1980s into 1990s and plains portions of the South Platte and Arkansas were mixed in the period 1965-1975.

The worst dry and wet periods at individual locations have a wide variety of years of occurrence and magnitudes. Regionally the magnitude (accumulated precipitation deficit) of the worst periods increase with increasing time scale to 24 months and at 24 months lead to deficits (surpluses) of 1 to 2 times the annual precipitation. Periods during the 1930s and 1950s were common for drought.

Correlation coefficients of water year precipitation (October through September) between river basins is above 0.50 for basins on the same side of the Continental Divide and much lower for basins on opposite sides. Precipitation in the Rio Grande basin does not correlate well with other basins. Correlation relationships of 12 month precipitation and the 12 month SPI are similar. A comparison of summer precipitation on the plains to the previous winter April 1 snowpack shows a very small correlation.

Snowpack and streamflow do not group into periods of dry and wet years to the extent of precipitation. They are often best described as dry or wet individual years. Winter of 1977 and 1981 are the driest since many of the snow measurements were started. The relationship of April 1 snowpack to streamflow has correlation near 0.7 - 0.8 west of the Continental Divide. The South Platte and Arkansas streamflow do not correlate well to April 1 snowpack because these two rivers respond to spring rain since spring is the wet season near the Front Range.

The analysis of this study did not identify significant trends in precipitation or streamflow over a period of the past century.

7.0 References

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Table 1.

List of precipitation stations by Drainage basins through 1996.

Station	Name	Latitude	Longitude	Elevation	Start	Ave Precip 1961-1990
Yampa-White (YW)						
55484	Meeker	40 02	107 54	6240	1892	14.20
53867	Hayden	40 30	107 15	6340	1914	16.84
57936	Steamboat Springs	40 30	106 50	6770	1909	23.38
Colorado (CO)						
50370	Aspen	39 11	106 50	7910	1936	
51741	Collbran	39 14	107 58	6140	1893	14.48
52281	Dillon	39 36	106 03	8900	1912	13.81
52454	Eagle	39 38	106 55	6500	1937	10.65
53146	Fruita	39 09	108 44	4520	1904	8.76
53488	Grand Junction	39 07	108 32	4850	1893	8.64
57031	Rifle	39 31	107 47	5300	1913	12.54
57618	Shoshone	39 34	107 14	5933	1911	21.07
Gunnison (GU)						
51440	Cedaredge	38 54	107 56	6180	1912	12.83
52192	Delta	38 45	108 04	5120	1889	8.93
53662	Gunnison	38 33	106 55	7630	1894	10.20
55722	Montrose	38 29	107 53	5830	1886	9.68
56306	Paonia	38 52	107 35	5690	1906	15.17
San Juan, Animas and Dolores (SA)						
52432	Durango	37 17	107 53	6550	1896	19.29
54250	Ignacio	37 08	107 38	6420	1916	14.38
55531	Mesa Verde National Park	37 12	108 30	6960	1924	18.07
55970	Northdale	37 49	109 02	6480	1931	12.40
57656	Silverton	37 48	107 40	9420	1906	25.15
58204	Telluride	37 57	107 49	8750	1914	23.61
Rio Grande (RG)						
51458	Center	37 42	106 08	7673	1893	7.03
52184	Del Norte	37 40	106 21	7880	1920	10.45
55322	Manassa	37 11	105 57	7700	1907	7.84
57337	Saguache	38 05	106 09	7700	1895	8.37
Upper South Platte (USP)						
50848	Boulder	40 01	105 16	5400	1894	18.58
51179	Byers	39 42	104 13	5200	1933	15.45
52220	Denver WSFO	39 46	104 53	5290	1880	15.40
53005	Fort Collins	40 35	105 05	5000	1891	15.07
53553	Greeley	40 25	104 42	4650	1888	13.97
54762	Lakewood	39 45	105 08	5640	1909	15.86
55116	Longmont	40 10	105 04	4950	1911	13.60

Table 1.

List of precipitation stations by Drainage basins through 1996.

Station	Name	Latitude	Longitude	Elevation	Start	Ave Precip 1961-1990
55116	Longmont	40 10	105 04	4950	1911	13.60
Lower South Platte (LSP)						
50109	Akron 4E	40 09	103 09	4540	1905	16.24
51121	Burlington	39 18	102 16	4170	1893	15.29
54082	Holyoke	40 35	102 18	3730	1889	17.84
54945	Leroy	40 29	103 01	4390	1891	17.45
57950	Sterling	40 37	103 12	3940	1912	16.16
59243	Wray	40 04	102 13	3510	1891	17.53
59295	Yuma	40 07	102 44	4130	1891	16.39
Upper Arkansas (UAR)						
51071	Buena Vista	38 51	106 08	7930	1907	10.64
51294	Canon City	38 26	105 16	5340	1889	12.96
51528*	Cheesman	39 13	105 17	6890	1904	17.10
51778	Colorado Springs	38 49	104 42	6170	1886	16.24
54452*	Kassler	39 30	105 06	5500	1901	17.85
56740	Pueblo	38 17	104 31	4640	1881	11.19
58429	Trinidad	37 10	104 30	6300	1889	15.31
* = Sites placed in UAR based on correlation analysis.						
Lower Arkansas (LAR)						
51564	Cheyenne Wells	38 49	102 21	4250	1897	15.45
52446	Eads	38 29	102 46	4260	1926	14.69
54076	Holly	38 03	102 07	3390	1896	15.54
54770	Lamar	38 04	102 37	3640	1891	14.62
54834	Las Animas	38 05	103 13	3890	1897	12.12
55018	Limon	39 11	103 42	5560	1908	13.88
57167	Rocky Ford	38 02	103 42	4170	1889	10.87
North Platte (NP)						
	(No stations exist)					

Table 2.

List of snow course and snowtel sites by river basin.

Site Id.	Snow Course Site Name	Est	No. of Years	Begin Year	Latitude	Longitude	Elevation	Apr 1 SWE 61-90
Yampa River (Y)								
07J03	Bear River		30	1956	40 04	107 01	9100	10.9
06J29S	Tower Pillow	est	32	1965	40 32	106 41	10500	45.4
06J10	Yampa View		45	1951	40 22	106 46	8200	15.5
White River (W)								
07K02S	Burro Mountain Pillow	est	60	1936	39 53	107 36	9400	18.8
Colorado River (CO)								
05K14S	Berthoud Summit Pillow	est	46	1951	39 48	105 47	11300	17.7
06K21	Blue River		40	1957	39 23	106 03	10500	8.3
06K08S	Fremont Pass Pillow	est	58	1939	39 23	106 12	11400	15.6
06J11	Gore Pass		42	1951	40 05	106 33	9400	10.4
06K04S	Independence Pass Pillow	est	61	1936	39 05	106 37	10600	16.9
05K21	Jones Pass		39	1957	39 46	105 54	10400	16.2
05J10S	Lake Irene Pillow	est	59	1938	40 25	105 49	10700	25.4
06K28	McKenzie Gulch		32	1962	39 30	106 45	8040	5.9
06K12	Middle Fork Campground		61	1936	39 47	106 01	9000	10.1
05J24	Milner Pass		45	1952	40 24	105 50	10100	13.3
05J09	North Inlet Grand Lake		58	1938	40 17	105 46	9000	8.6
07K01S	North Lost Trail Pillow	est	61	1936	39 05	107 09	9200	18.4
06J02	Park View		60	1936	40 22	106 06	9200	9.5
06K09	Shrine Pass		55	1942	39 32	106 13	10700	18.0
05K16	Snake River		46	1951	39 38	105 54	9700	7.7
06K39S	Vail Mountain Pillow		18	1979	39 37	106 23	10300	21.6
05K19	Vazquez		40	1957	39 51	105 49	9600	13.4
05J05	Wild Basin		61	1936	40 12	105 36	9600	10.7
06J05S	Willow Creek Pass Pillow		18	1979	40 21	106 06	9540	12.0
06J10	Yampa View		45	1951	40 22	106 46	8200	15.5
Gunnison (GU)								
06L11S	Butte Pillow	est	32	1965	38 54	106 57	10160	15.6
06L06	Cochetopa Pass		47	1949	38 10	106 36	10000	6.0
06K04S	Independence Pass Pillow	est	61	1936	39 05	106 37	10600	16.9
07M06	Ironton Park		59	1937	37 58	107 40	9600	14.2
07M08	Lake City		47	1948	37 59	107 15	10160	7.3
07K09S	McClure Pass Pillow	est	47	1950	39 08	107 17	9500	18.3
07M14S	Mineral Creek Pillow	est	46	1951	37 51	107 44	10040	15.2
07K01S	North Lost Trail Pillow	est	61	1936	39 05	107 09	9200	18.4
06L02S	Park Cone Pillow	est	60	1936	38 49	106 35	9600	10.2
07K06S	Park Reservoir Pillow	est	57	1940	39 03	107 52	9960	26.6

Table 2.

List of snow course and snowtel sites by river basin.

Site Id.	Snow Course Site Name	Est	No. of Years	Begin Year	Latitude	Longitude	Elevation	Apr 1 SWE 61-90
06L03S	Porphyry Creek Pillow	est	56	1940	38 29	106 20	10760	15.2
07M33S	Red Mountain Pass Pillow	est	46	1951	37 54	107 43	11200	25.8
06L05	Saint Elmo		30	1949	38 42	106 22	10400	12.7
07M02	Telluride		61	1936	37 56	107 48	8800	8.0
San Juan, Animas and Dolores (SA)								
08M04	LaPlata		30	1950	37 25	108 03	9340	18.6
07M23	Lemon Reservoir		28	1968	37 27	104 40	8700	9.3
07M14S	Mineral Creek Pillow	est	46	1951	37 51	107 44	10040	15.2
07M33S	Red Mountain Pass Pillow	est	46	1951	37 54	107 43	11200	25.8
07M11S	Spud Mountain Pillow	est	46	1951	37 42	107 47	10660	26.6
Rio Grande (RG)								
06M21	Grayback		29	1967	37 28	106 32	11600	16.0
07M10	Love Lake		32	1962	37 40	107 02	10000	10.3
06M14	Pool Table Mountain		47	1949	37 48	106 48	9840	5.8
07M20	Porcupine		45	1951	37 51	107 10	10280	9.9
06M17S	Wolf Creek Summit Pillow	est	46	1951	37 29	106 48	11000	33.8
North Platte River (NP)								
05J03	Big South		61	1936	40 37	105 49	8707	2.3
05J10S	Lake Irene Pillow	est	59	1938	40 25	105 49	10700	21.0
06J02	Park View		60	1936	40 22	106 06	9200	9.5
South Platte River (SP)								
05K25	Como		30	1967	39 21	105 55	10370	6.5
05K11	Geneva Park		48	1949	39 31	105 43	9750	3.8
06K35	Horseshoe Mountain		30	1967	39 12	106 08	11400	10.6
06K34	Mosquito Creek		30	1967	39 17	106 08	11200	9.3
St. Vrain Creek (SV)								
	(None)							
Big Thompson River (BT)								
05J17	Deer Ridge		48	1949	40 24	105 38	9050	4.9
05J13	Hidden Valley		56	1941	40 24	105 39	9480	9.9
05J22	Longs Peak		46	1951	40 16	105 35	10500	11.0
05J09	North Inlet Grand Lake		58	1938	40 17	105 46	9000	8.6
Cache La Poudre (CLP)								
05J33	Bennett Creek		31	1966	40 40	105 37	9300	7.3
05J01	Cameron Pass		61	1936	40 31	105 53	10300	28.2
05J02	Chambers Lake		60	1936	40 36	105 50	9000	8.9

Table 2.

List of snow course and snowtel sites by river basin.

Site Id.	Snow Course Site Name	Est	No. of Years	Begin Year	Latitude	Longitude	Elevation	Apr 1 SWE 61-90
05J06S	Deadman Hill Pillow	est	59	1937	40 48	105 46	10200	16.6
05J37S	Joe Wright Pillow	est	30	1967	40 32	105 53	10120	22.1
05J10S	Lake Irene Pillow	est	59	1938	40 25	105 49	10700	25.4
05J24	Milner Pass		45	1952	40 24	105 50	10100	13.3
Arkansas (AR)								
06L02S	Park Cone Pillow	est	60	1936	38 49	106 35	9600	10.2
06L03S	Porphyry Creek Pillow	est	56	1940	38 29	106 20	10760	15.2
06L05	Saint Elmo		30	1949	38 42	106 22	10400	12.7

Table 3.

SPI and corresponding cumulative probability in relation to the base period.

SPI	Cumulative Probability	Intensity
+ 2.5	0.9938	
		} Extreme Wet
+ 2.0	0.9772	
		} Severe Wet
+ 1.5	0.9332	
		} Moderate Wet
+ 1.0	0.8413	
+ 0.5	0.6915	
0.0	0.5000	
- 0.5	0.3085	
- 1.0	0.1587	
		} Moderate Drought
- 1.5	0.0668	
		} Severe Drought
- 2.0	0.0228	
		} Extreme Drought
- 2.5	0.0062	

Table 4.

Summary of Dry and Wet Periods for Colorado from the Fraction of Observing Sites. Precipitation for 24 month SPI.

Date	Dry	Duration	Date	Wet	Duration
1893-1905	X	12	1905-1931	X	26
1931-1941	X	10	1941-1951	X	10
1951-1957	X	6	1957-1959	X	2
1963-1965	X	2	1965-1975	X	10
1975-1978	X	3	1979-1996	X	17

Table 5.

Regional Periods of Dry and Wet Conditions from 24 month SPI compared with fraction of the State from Table 4.

Dry or Wet Period from Table 4.	**Dry** **1893-1905**	**Wet** **1905-1931**	**Dry** **1931-1941**	**Wet** **1941-1951**	**Dry** **1951-1957**	**Wet** **1957-1959**	**Dry** **1963-1965**	**Wet** **1965-1975**	**Dry** **1975-1978**	**Wet** **1979-1996**
River Basin										
Yampa-White (YW)	1901-1905	1906-1933	1934-1937	M	M	1957-1959	1963-1965	1965-1971	1976-1978	1979-1988
Colorado (CO)	1889-1905	1905-1931	M	1941-1951	1951-1957	1957-1959	1960-1965	1965-1971	1976-1978	1979-1989, 1991-1996
Gunnison (GU)	1889-1905	1906-1931	1931-1938	1941-1949	1951-1957	1957-1959	1960-1964	1965-1971	1975-1978	1979-1989, 1991-1996
San Juan, Animas and Dolores (SA)	1899-1905	1906-1930	1931-1936	1941-1945	1951-1957	1957-1959	1960-1964	1965-1971	1976-1978	1979-1989, 1991-1995
Rio Grande (RG)	1897-1906	1906-1925	1926-1935	1941-1943, 1947-1949	1950-1952	1957-1959	1963-1965	1965-1971	1971-1978	1982-1995
Upper South Platte (USP)	1893-1896	1905-1931	1931-1941	1941-1949	1953-1957	1957-1960	1963-1965	1967-1975	1977-1979	1979-1996
Lower South Platte (LSP)	1889-1905	1905-1931	1931-1941	1941-1950	1953-1957	1958-1960	1964-1965	M	1976-1979	1980-1996
Upper Arkansas (UAR)	1888-1895	1905-1931	1931-1941	1941-1950	1950-1957	1957-1959	1963-1965	1965-1975	1975-1979	1980-1996
Lower Arkansas LAR)	1893-1898	1905-1931	1931-1941	1941-1950	1953-1957	1958-1960	1963-1956	M	1975-1978	1980-1996

Table 6.

Correlation of Water Year precipitation between basins.

	Yampa-White YW	Colorado CO	Gunnison GU	San Juan, Animas, Dolores SA	Rio Grande RG	Upper South Platte USP	Lower South Platte LSP	Upper Arkansas UAR	Lower Arkansas LAR
YW	1								
CO	0.79	1							
GU	0.66	0.85	1						
SA	0.54	0.75	0.82	1					
RG	0.31	0.39	0.55	0.55	1				
USP	0.44	0.51	0.49	0.40	0.36	1			
LSP	0.16	0.28	0.33	0.23	0.24	0.66	1		
UAR	0.34	0.47	0.50	0.41	0.44	0.68	0.51	1	
LAR	0.18	0.24	0.36	0.27	0.33	0.66	0.70	0.68	1

Table 7.

Correlation of 12 month SPI between basins.

	Yampa-White YW	Colorado CO	Gunnison GU	San Juan, Animas, Dolores SA	Rio Grande RG	Upper South Platte USP	Lower South Platte LSP	Upper Arkansas UAR	Lower Arkansas LAR
YW	1								
CO	0.79	1							
GU	0.66	0.82	1						
SA	0.53	0.71	0.80	1					
RG	0.28	0.36	0.55	0.55	1				
USP	0.42	0.45	0.45	0.39	0.39	1			
LSP	0.19	0.26	0.31	0.21	0.19	0.65	1		
UAR	0.32	0.44	0.49	0.43	0.50	0.70	0.50	1	
LAR	0.16	0.22	0.38	0.26	0.37	0.66	0.67	0.70	1

Table 8.

Correlation of 6 month SPI (April - September) between basins.

	Yampa-White YW	Colorado CO	Gunnison GU	San Juan, Animas, Dolores SA	Rio Grande RG	Upper South Platte USP	Lower South Platte LSP	Upper Arkansas UAR	Lower Arkansas LAR
YW	1								
CO	0.75	1							
GU	0.66	0.75	1						
SA	0.56	0.66	0.77	1					
RG	0.46	0.42	0.62	0.59	1				
USP	0.42	0.42	0.31	0.25	0.40	1			
LSP	0.14	0.23	0.22	0.09	0.22	0.63	1		
UAR	0.42	0.46	0.42	0.48	0.60	0.70	0.47	1	
LAR	0.21	0.21	0.30	0.26	0.39	0.66	0.68	0.68	1

Table 9.

Correlation of 6 month SPI (October - March) winter precipitation between basins.

	Yampa-White YW	Colorado CO	Gunnison GU	San Juan, Animas, Dolores SA	Rio Grande RG	Upper South Platte USP	Lower South Platte LSP	Upper Arkansas UAR	Lower Arkansas LAR
YW	1								
CO	0.77	1							
GU	0.61	0.82	1						
SA	0.47	0.71	0.82	1					
RG	0.15	0.35	0.52	0.59	1				
USP	0.29	0.35	0.39	0.34	0.31	1			
LSP	0.09	0.23	0.33	0.30	0.39	0.68	1		
UAR	0.14	0.27	0.47	0.32	0.53	0.71	0.51	1	
LAR	0.00	0.12	0.33	0.29	0.45	0.60	0.72	0.71	1

Table 10.

Average Dry (Wet) magnitude for most extreme Dry (Wet) period as ratio of maximum accumulated precipitation deficit (surplus) to annual average precipitation.

	Time Scale				
Basin	**3 month**	**6 month**	**12 month**	**24 month**	**48 month**
Yampa-White (YW)	0.5 (0.6)	0.5 (0.9)	0.6 (1.2)	0.7 (1.2)	0.8 (1.3)
Colorado (CO)	0.6 (1.0)	0.6 (1.5)	0.9 (1.7)	1.2 (2.0)	1.2 (1.8)
Gunnison (GU)	0.7 (0.8)	1.0 (1.4)	1.2 (1.8)	1.4 (1.8)	1.2 (1.6)
San Juan, Animas and Dolores (SA)	0.7 (1.0)	0.9 (1.1)	1.0 (1.3)	1.0 (1.4)	1.3 (1.6)
Rio Grande (RG)	0.9 (0.9)	1.1 (1.1)	1.1 (1.4)	1.0 (1.5)	1.2 (1.8)
Upper South Platte (USP)	0.8 (0.9)	1.0 (1.0)	1.2 (1.3)	1.2 (1.3)	1.3 (1.5)
Lower South Platte (LSP)	0.6 (0.8)	0.8 (1.2)	1.2 (1.0)	1.3 (1.2)	1.4 (1.3)
Upper Arkansas (UAR)	0.7 (0.8)	0.8 (1.0)	1.1 (1.2)	1.3 (1.4)	1.6 (1.7)
Lower Arkansas (LAR)	0.9 (1.0)	1.3 (1.2)	1.7 (1.3)	2.2 (1.7)	2.0 (2.2)

Table 11.

Regional periods of wet and dry from regional snow SSI.

Dry or Wet Period from Table 4		**Wet** **1941-51**	**Dry** **1951-57**	**Wet** **1957-59**	**Dry** **1963-65**	**Wet** **1965-75**	**Dry** **1975-78**	**Wet** **1979-96**
Yampa	Y	N/A	M	1957-59	M	1969-75	1976-77	1978-86
White	W	M	1953-57	1957-59	1963-64	1968-75	1977	1980-88
Colorado	CO	1947-51	1953-55	1957-59	1963-64	M	1976-77	1980-86
Gunnison	GU	M	1953-56	1957-58	1963-64	M	1976-77	1978-82
San Juan-Animas-Dolores	SA	N/A	1951-55	1957-58	1963-64	M	1977	1979-87
Rio Grande	RG	N/A	1951-56	1957-58	1963-64	M	1977	1979-87
North Platte	NP	1947-51	1953-55	1957-59	1963-64	M	1976-77	1979-88
Big Thompson	BT	1947-51	1954-56	M	1963-64	M	1976-77	--
Cache La Poudre	CLP	M	1954-56	1957-59	1963-64	M	1977	M
South Platte	SP	N/A	M	1957-59	1963	1970-75	1977	1979-89
Arkansas	AR	M	1953-56	1957-58	1963-64	M	1977	M

N/A = Not applicable.

M = Mixed response.

-- = Different response.

Table 12.

Correlation of winter snow (April 1 SSI) among regions.

	Yampa Y	White W	Colorado CO	Gunnison GU	San Juan Animas Dolores SA	Rio Grande RG	North Platte NP	Cache La Poudre CLP	Big Thompson BT	South Platte SP	Arkansas AR
Y	1										
W	0.79	1									
CO	0.92	0.74	1								
GU	0.76	0.79	0.75	1							
SA	0.55	0.74	0.57	0.92	1						
RG	0.44	0.64	0.46	0.81	0.87	1					
NP	0.85	0.70	0.86	0.67	0.52	0.49	1				
CLP	0.89	0.62	0.87	0.60	0.46	0.40	0.86	1			
BT	0.72	0.50	0.82	0.50	0.34	0.35	0.74	0.79	1		
SP	0.71	0.59	0.73	0.74	0.56	0.51	0.63	0.62	0.58	1	
AR	0.67	0.65	0.72	0.88	0.77	0.73	0.59	0.58	0.60	0.72	1

Table 13.

Correlation of winter precipitation to April 1 snowpack (October - March SPI to April 1 SSI).

	Yampa Y	White W	Colorado CO	Gunnison GU	San Juan Animas Dolores SA	Rio Grande RG	North Platte NP	Cache La Poudre CLP	Big Thompson BT	South Platte SP	Arkansas AR
YW	0.81	0.73	0.73	0.72	0.62	0.56	0.69	0.70	0.54	0.58	0.58
CO	0.73	0.74	0.64	0.80	0.77	0.68	0.62	0.54	0.36	0.60	0.61
GU	0.42	0.47	0.28	0.65	0.74	0.66	0.33	0.22	0.09	0.45	0.46
SA	0.29	0.46	0.22	0.65	0.83	0.78	0.24	0.10	0.13	0.32	0.51
RG	0.12	0.24	-0.02	0.32	0.47	0.65	0.06	-0.04	0.00	0.15	0.25
USP	0.16	0.17	0.15	0.31	0.28	0.30	0.33	0.23	0.17	0.29	0.20
LSP	-0.07	0.05	-0.12	0.10	0.14	0.17	0.03	-0.09	-0.14	-0.04	-0.03
UAR	0.08	0.15	0.04	0.26	0.36	0.27	0.13	0.06	0.04	0.22	0.12
LAR	-0.15	0.00	-0.13	0.11	0.29	0.28	-0.05	-0.18	-0.07	-0.06	-0.01

Table 14.

Correlation of summer precipitation to (April - September SPI) with previous winter snow (April 1 SSI).

	Yampa Y	White W	Colorado CO	Gunnison GU	San Juan Animas Dolores SA	Rio Grande RG	North Platte NP	Cache La Poudre CLP	Big Thompson BT	South Platte SP	Arkansas AR
YW	-0.05	0.05	-0.06	0.14	0.09	0.09	0.00	-0.11	-0.12	0.14	0.09
CO	0.03	0.09	-0.01	0.17	0.09	0.11	0.08	-0.02	-0.08	0.15	0.10
GU	0.09	0.14	0.01	0.10	0.05	0.08	0.09	0.03	-0.02	0.07	0.06
SA	0.12	0.09	-0.09	-0.03	-0.14	-0.05	0.04	-0.09	-0.08	0.01	-0.06
RG	-0.02	0.14	-0.06	0.04	0.00	-0.01	0.01	-0.05	-0.16	-0.07	0.03
USP	0.17	0.21	0.13	0.34	0.36	0.26	0.14	0.11	-0.03	0.30	0.29
LSP	-0.03	0.09	-0.05	0.12	0.14	0.21	0.03	-0.05	-0.08	0.06	0.09
UAR	0.02	0.15	-0.01	0.12	0.07	0.02	0.02	-0.08	-0.13	0.13	0.00
LAR	0.11	0.20	-0.01	0.17	0.20	0.18	0.06	0.00	-0.09	0.12	0.11

Table 15.

Correlation of April 1 SSI to water year streamflow (ST) (October - September).

	Yampa Y	White W	Colorado CO	Gunnison GU	San Juan Animas Dolores SA	Rio Grande RG	North Platte NP	Cache La Poudre CLP	Big Thompson BT	South Platte SP	Arkansas AR
Y	0.79	0.69	0.69	0.58	0.43	0.37	0.77	0.50	0.57	0.34	0.43
W	0.73	0.71	0.66	0.65	0.62	0.56	0.65	0.42	0.52	0.44	0.59
CO	0.75	0.67	0.66	0.57	0.41	0.34	0.73	0.55	0.60	0.35	0.46
GU	0.75	0.77	0.70	0.80	0.79	0.71	0.71	0.51	0.63	0.56	0.67
SA	0.58	0.64	0.54	0.69	0.83	0.74	0.57	0.46	0.58	0.47	0.60
RG	0.43	0.52	0.46	0.56	0.75	0.81	0.49	0.24	0.42	0.41	0.57
NP	0.62	0.59	0.63	0.53	0.43	0.38	0.74	0.58	0.61	0.40	0.52
CLP	0.67	0.58	0.59	0.45	0.31	0.26	0.76	0.54	0.55	0.30	0.42
BT	0.48	0.48	0.39	0.26	0.19	0.19	0.57	0.44	0.44	0.14	0.32
SP	0.62	0.65	0.59	0.65	0.62	0.60	0.63	0.39	0.55	0.45	0.51

Table 16.

Correlation of 12 month SPI to water year streamflow (ST) (October - September).

	Yampa Y	White W	Colorado CO	Gunnison GU	San Juan Animas Dolores A	Rio Grande RG	North Platte NP	Cache La Poudre CLP	South Platte SP	Arkansas AR
YW	0.62	0.62	0.60	0.63	0.53	0.45	0.63	0.38	0.51	0.57
CO	0.67	0.71	0.72	0.79	0.69	0.59	0.62	0.51	0.71	0.79
GU	0.56	0.63	0.64	0.77	0.71	0.63	0.51	0.38	0.72	0.78
SA	0.46	0.56	0.53	0.59	0.84	0.75	0.39	0.35	0.65	0.72
RG	-0.11	-0.05	-0.02	0.06	0.29	0.34	0.13	-0.12	0.16	0.42
USP	0.24	0.33	0.35	0.44	0.51	0.43	0.43	0.39	0.60	0.56
LSP	0.02	0.10	0.12	0.23	0.41	0.40	0.27	0.13	0.31	0.35
UAR	0.18	0.22	0.29	0.40	0.44	0.40	0.25	0.29	0.58	0.64
LAR	0.03	0.10	0.16	0.32	0.51	0.46	0.16	0.13	0.38	0.51

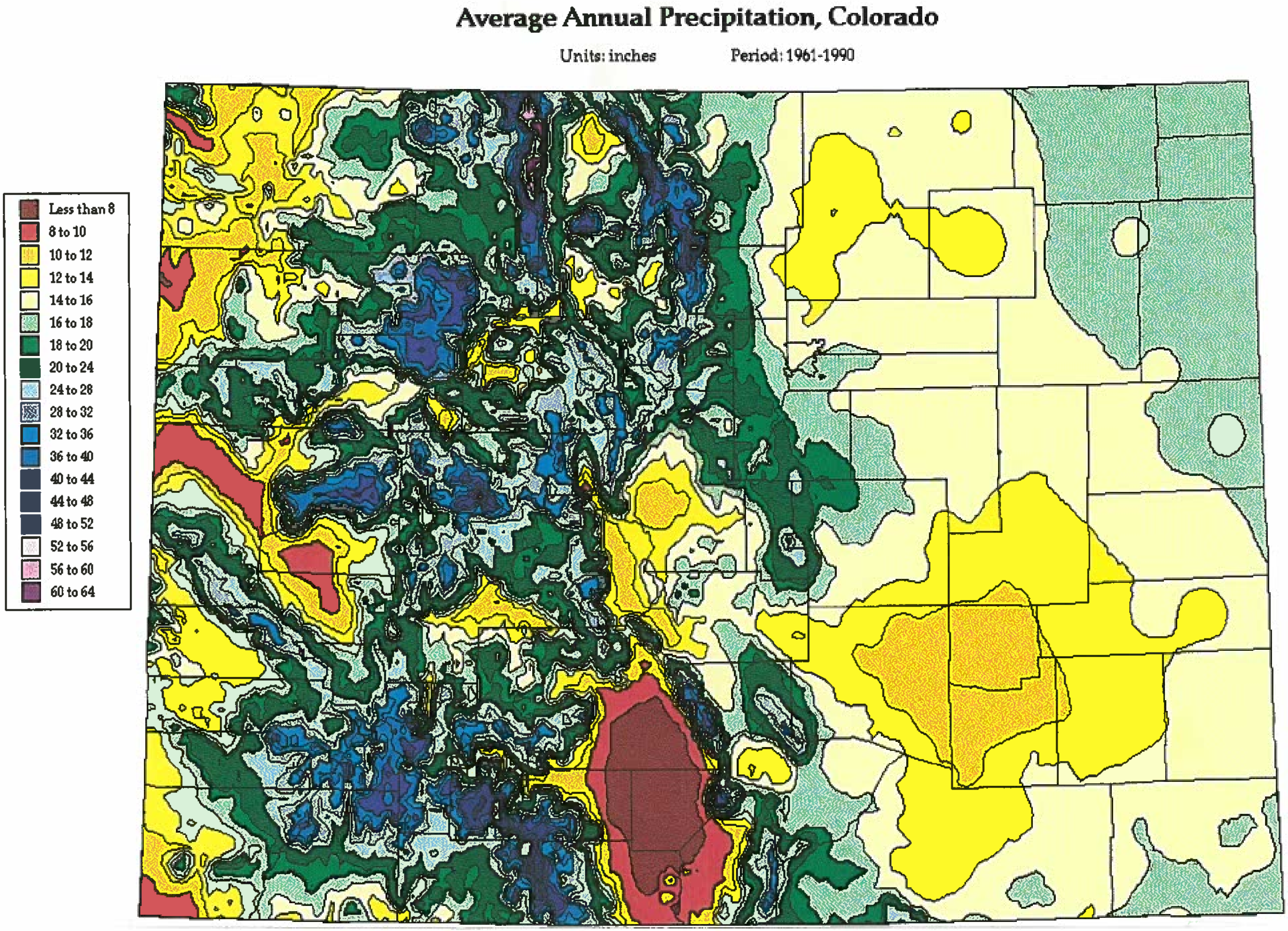


Figure 1. Colorado average annual precipitation map for period 1961-1990 (from Oregon Climate Service).

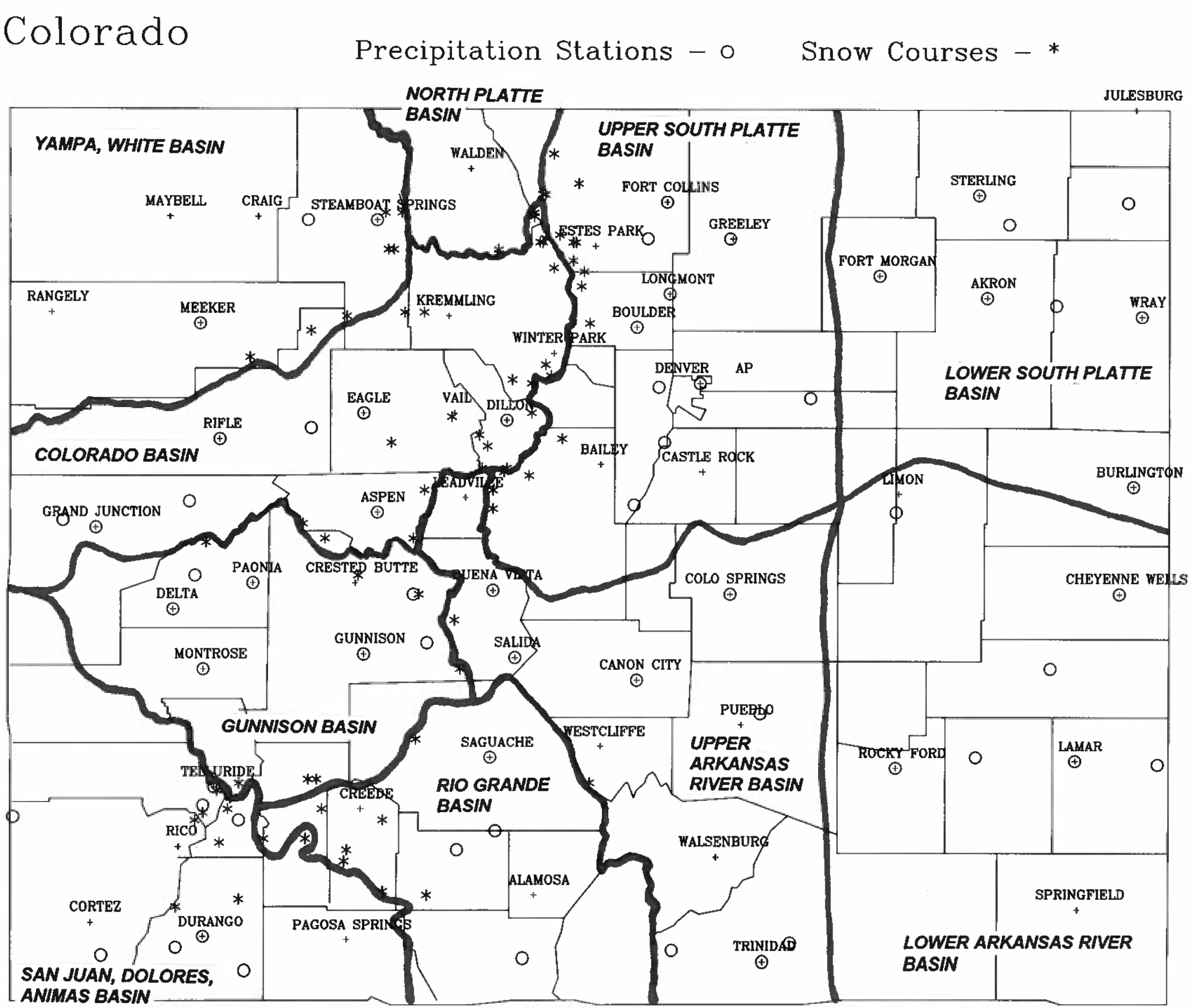


Figure 2. Map of Colorado precipitation stations (circles) and snow courses (stars) included in this study and their corresponding river basins.

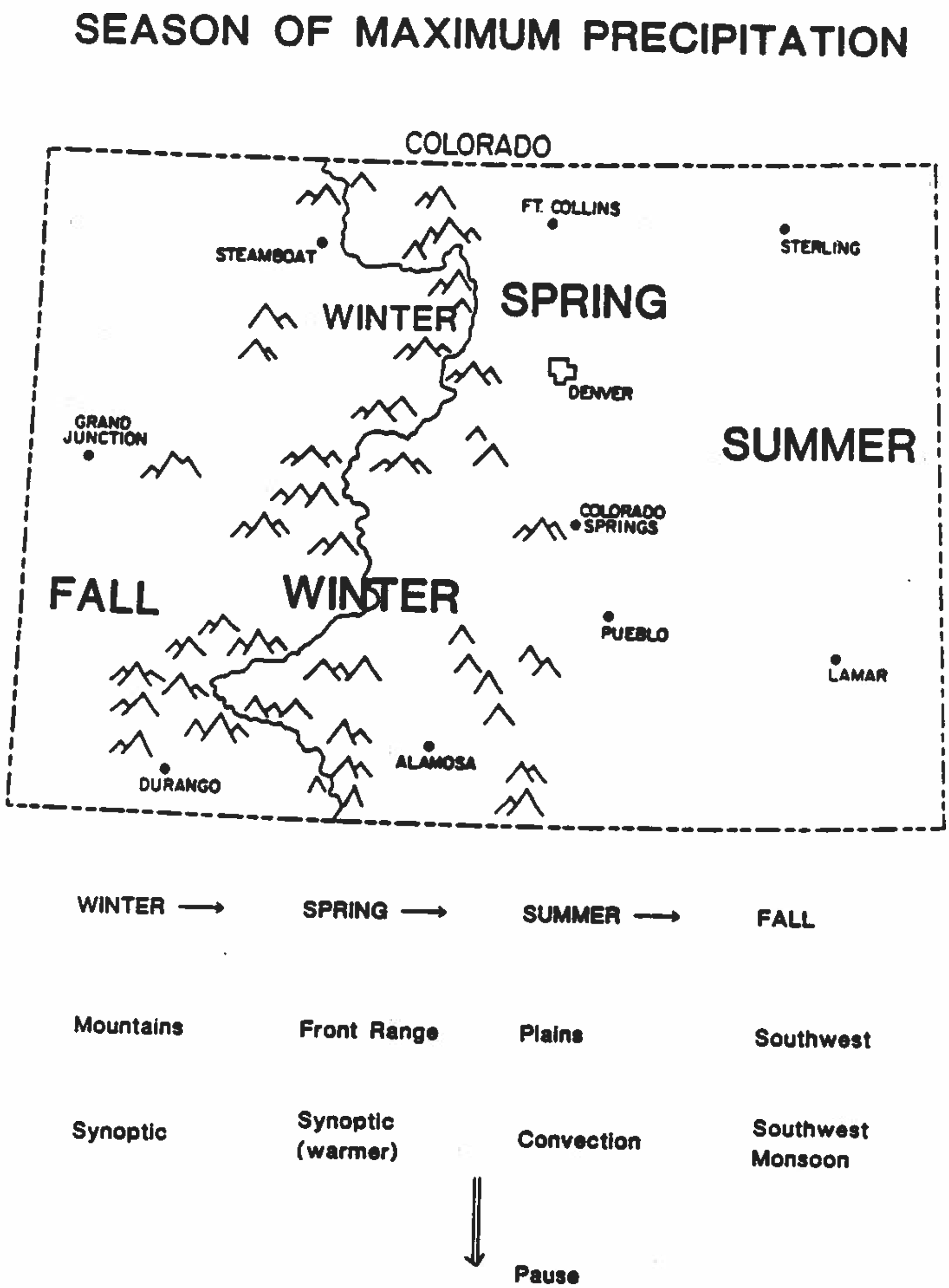


Figure 3. Seasonal distribution of precipitation in Colorado.

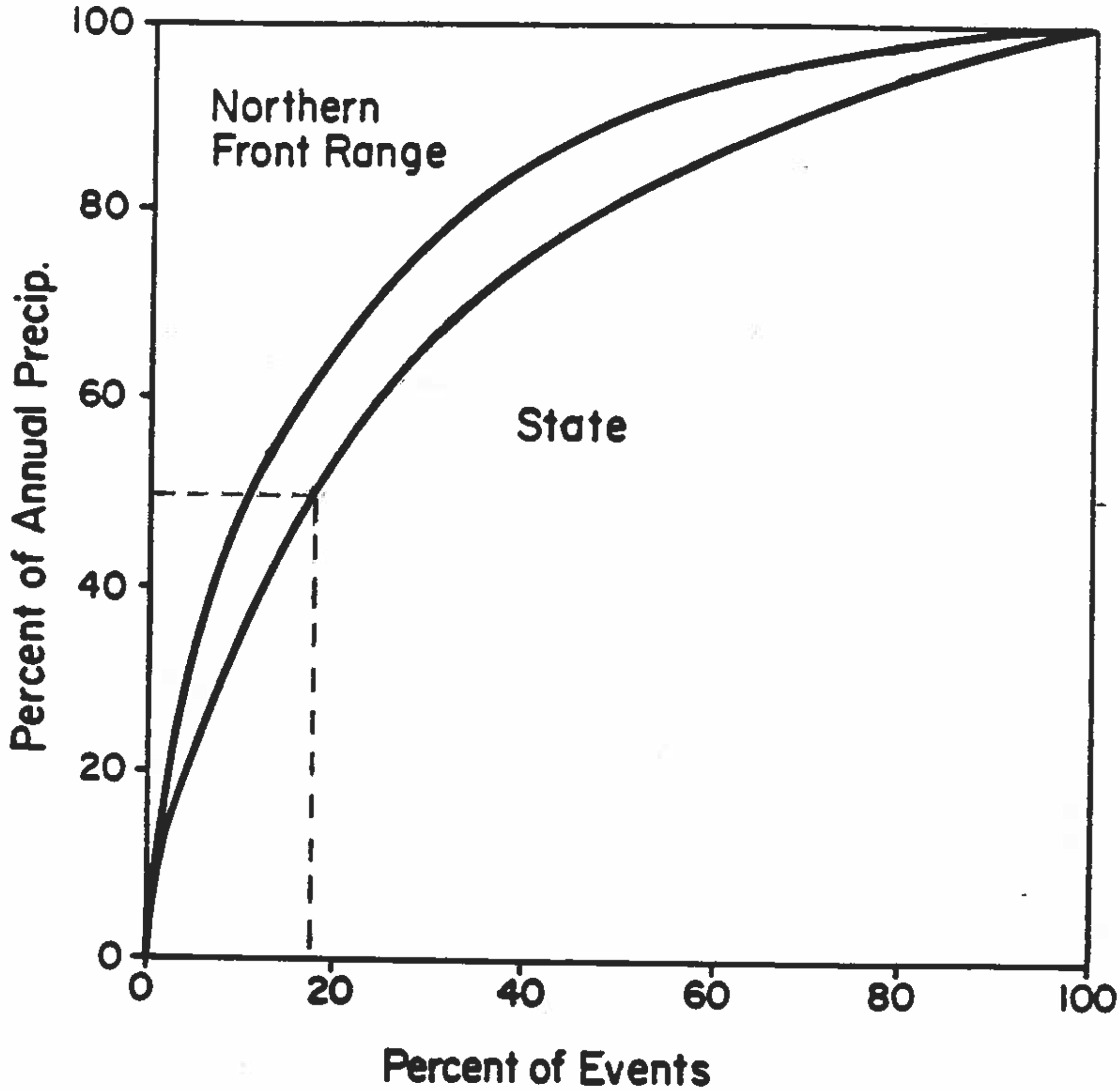


Figure 4. Fraction of precipitation for daily events (from Cowie and McKee, 1986). Percent of annual precipitation versus percent of events for the sum of the largest to smallest events for the State and the Northern Front Range region.

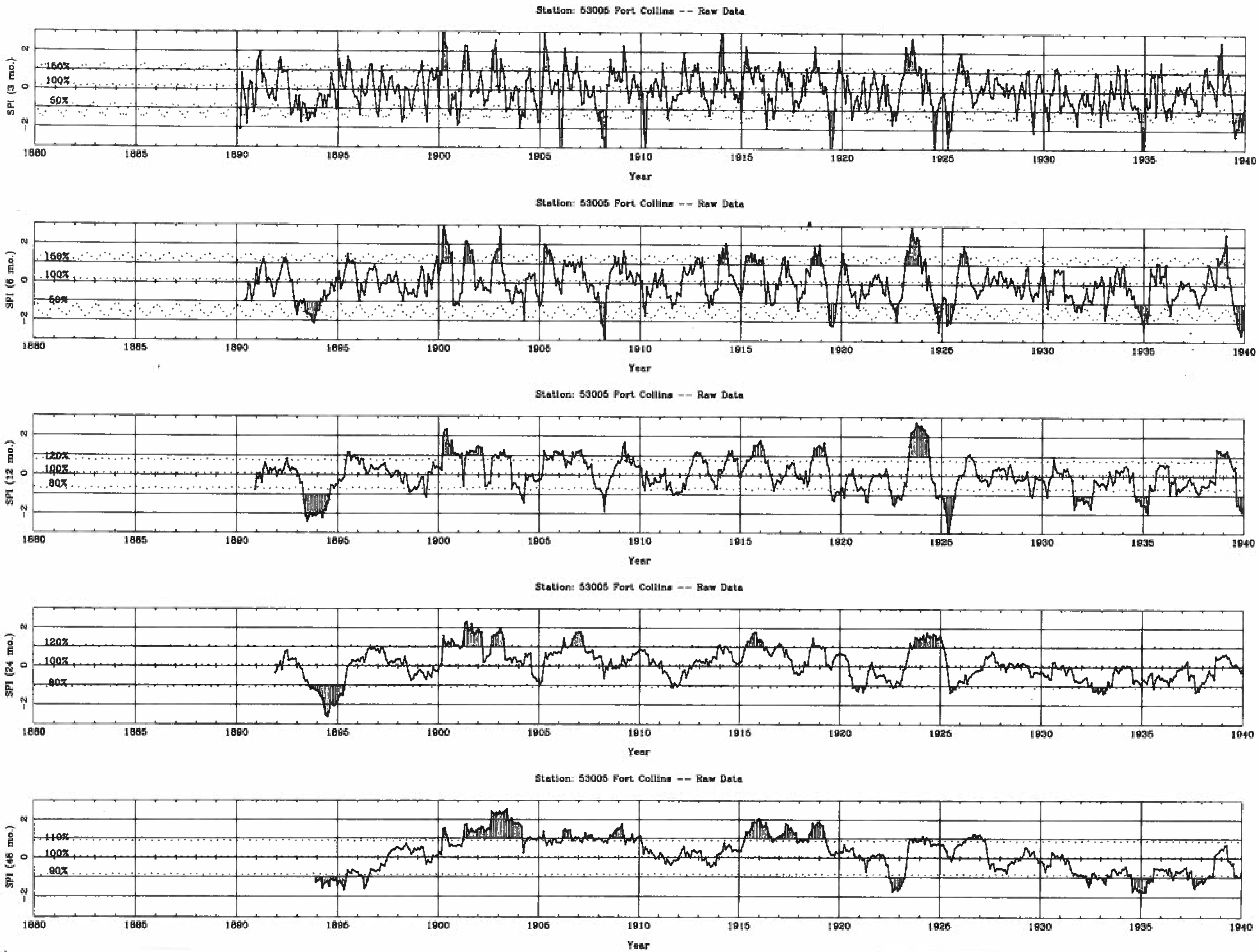


Figure 5a. Fort Collins standardized precipitation index (SPI) for 3, 6, 12, 24, and 48 months for years 1890 - 1940.

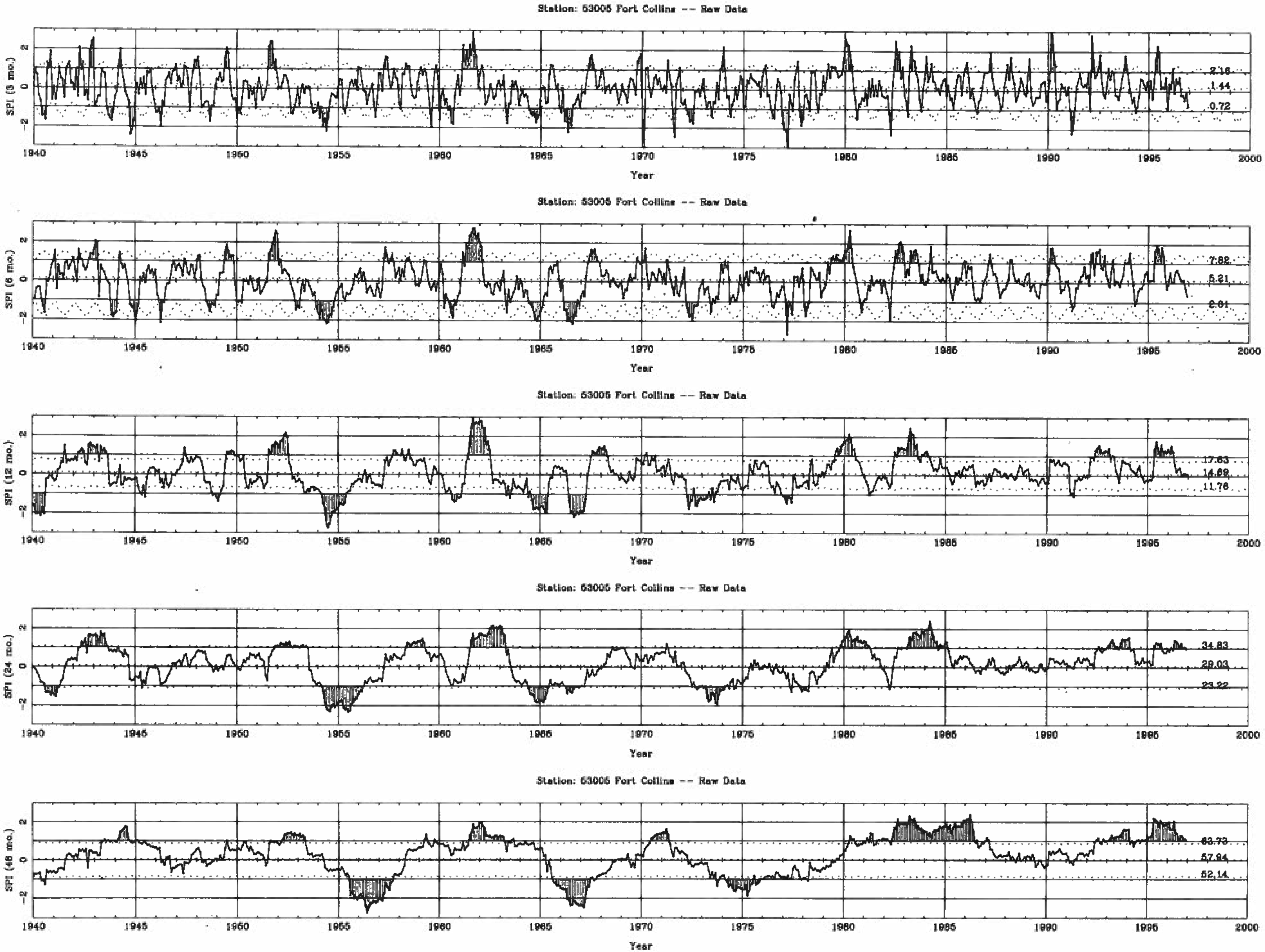


Figure 5b. Fort Collins standardized precipitation index (SPI) for 3, 6, 12, 24, and 48 months for years 1940 - 1997.

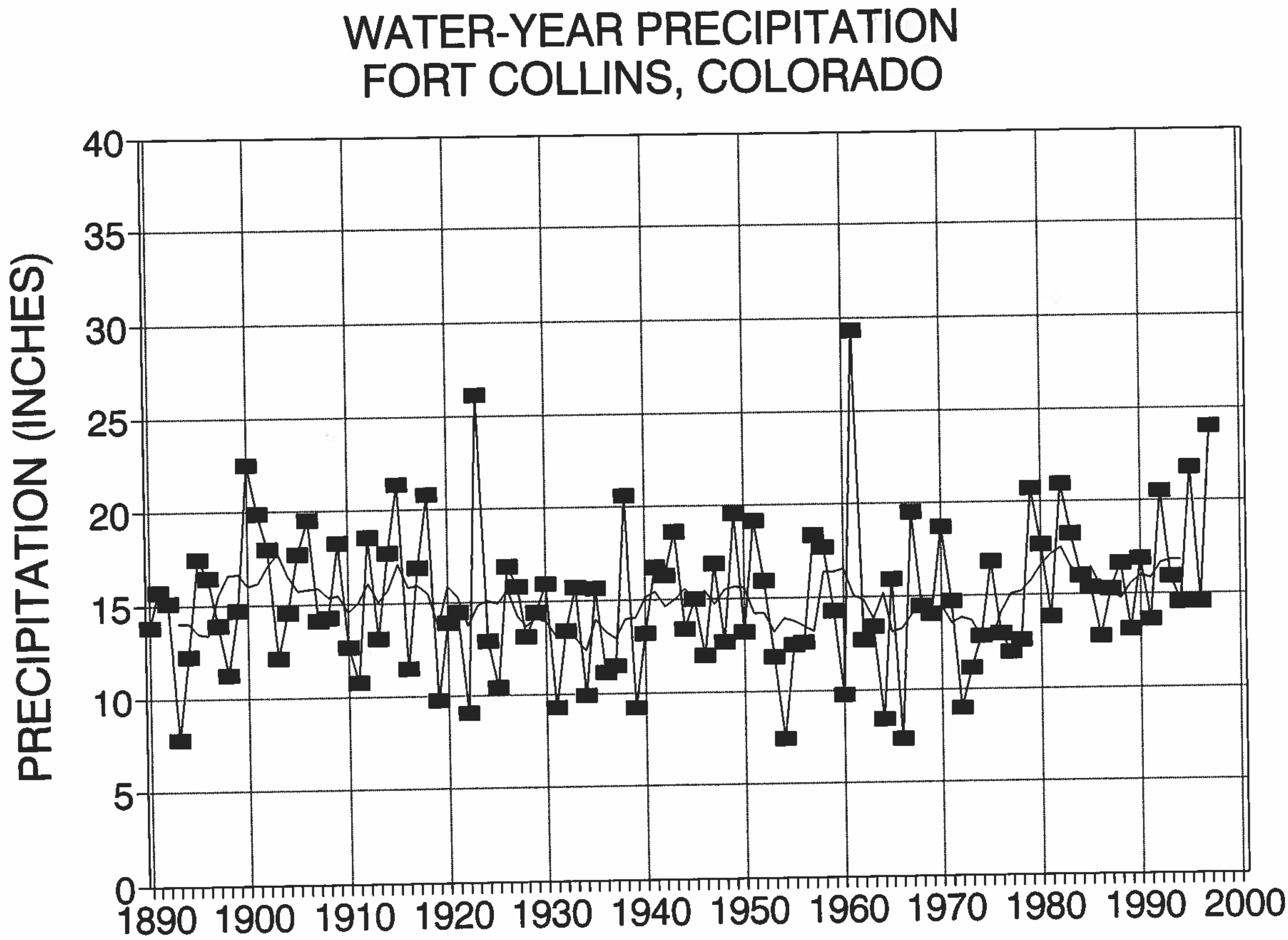


Figure 6. Water year (October - September) precipitation for Fort Collins, Colorado from 1890-1997.

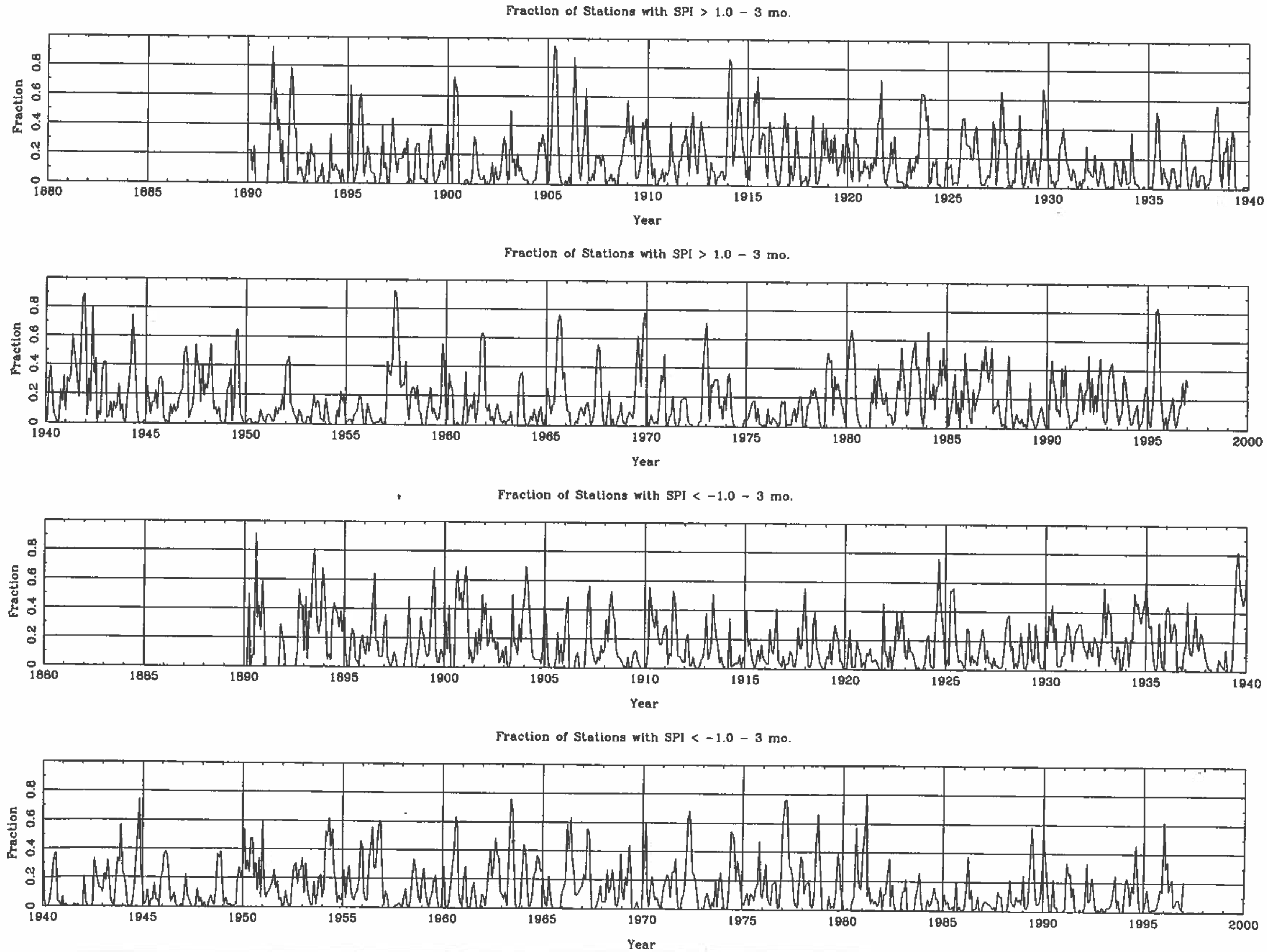


Figure 7a. Fractions of stations in Colorado with SPI greater than 1.0 (wet) and less than -1.0 (dry) for 3 months.

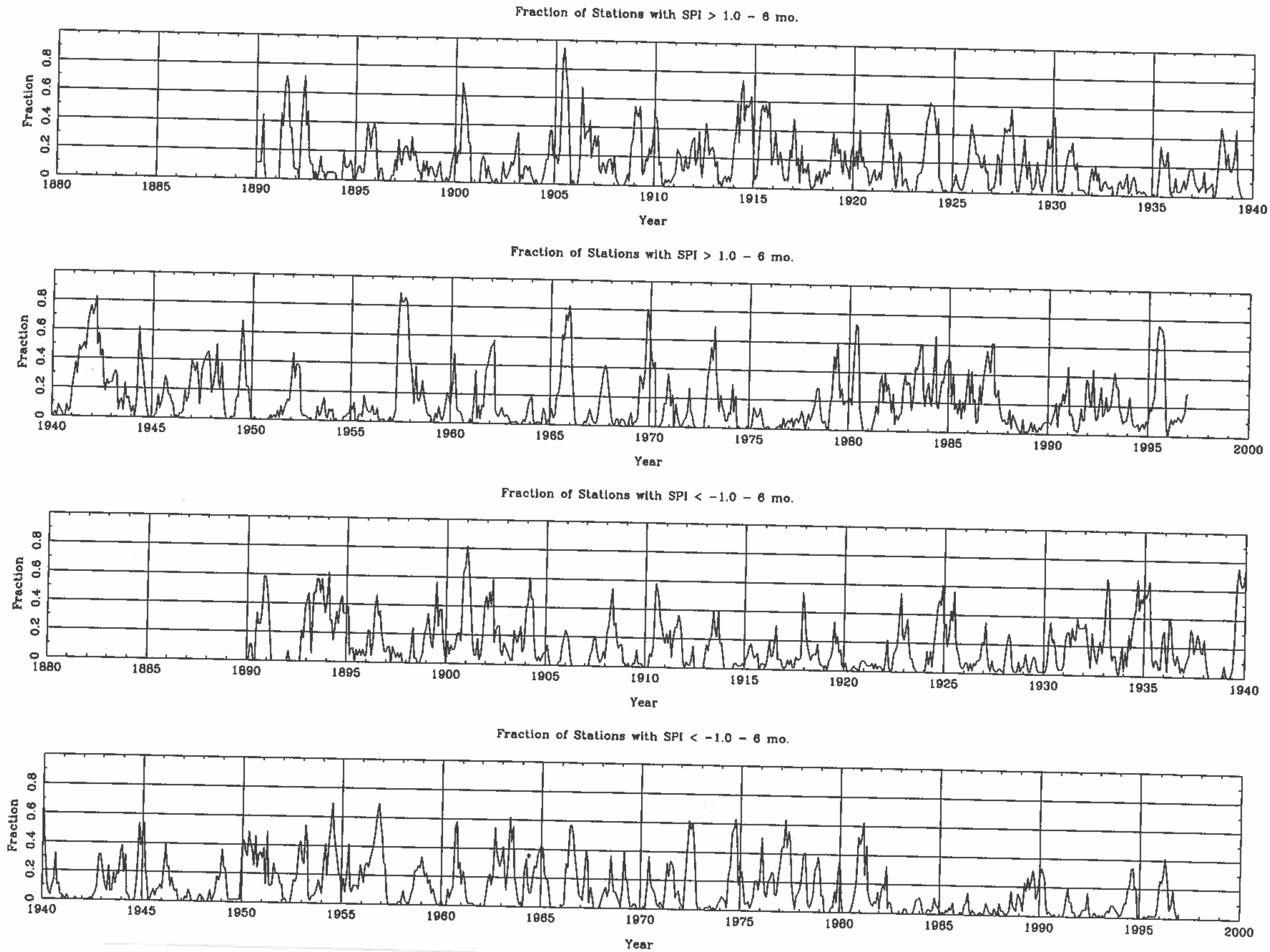


Figure 7b. Fractions of stations in Colorado with SPI greater than 1.0 (wet) and less than -1.0 (dry) for 6 months.

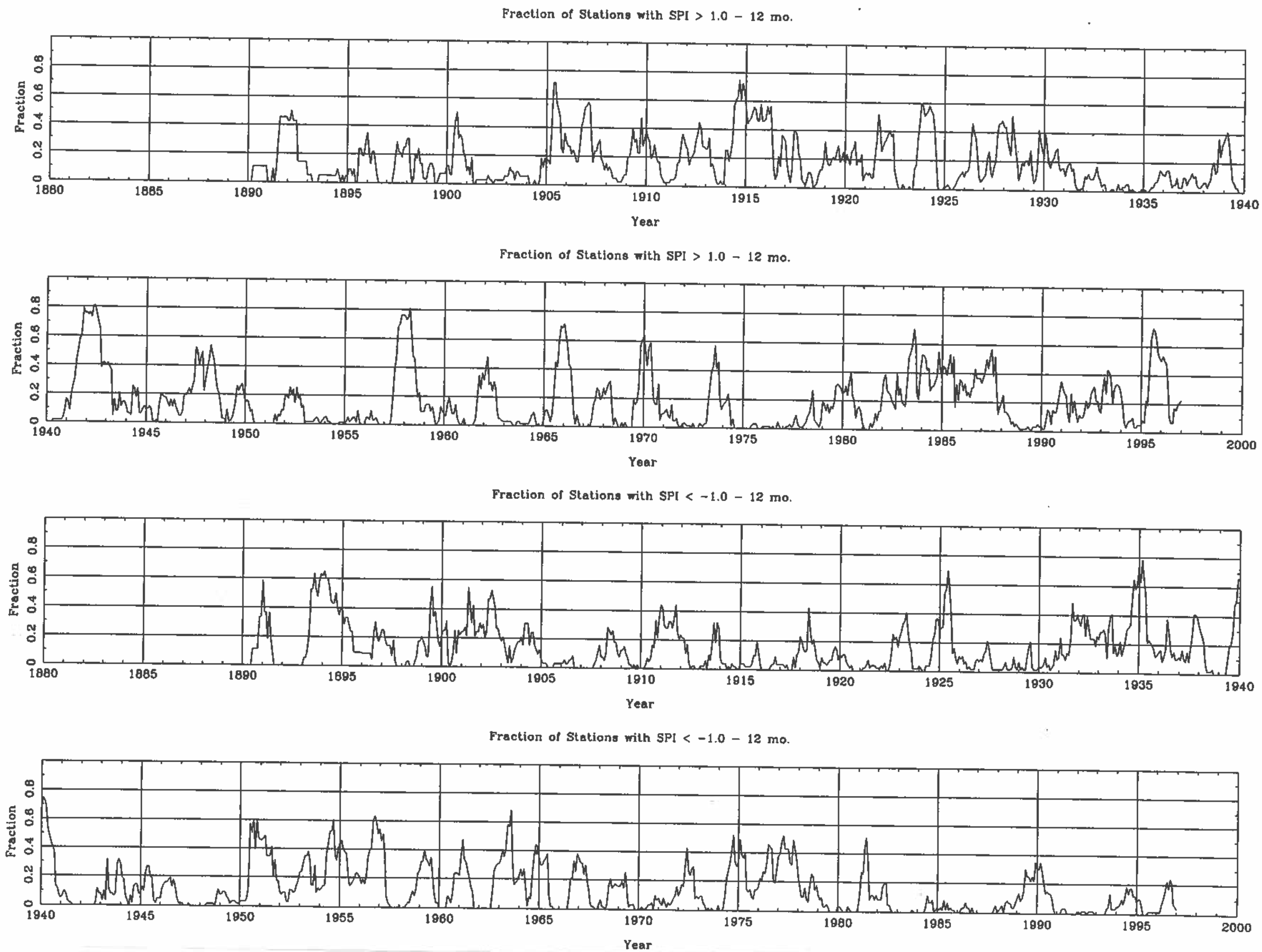


Figure 7c. Fractions of stations in Colorado with SPI greater than 1.0 (wet) and less than -1.0 (dry) for 12 months.

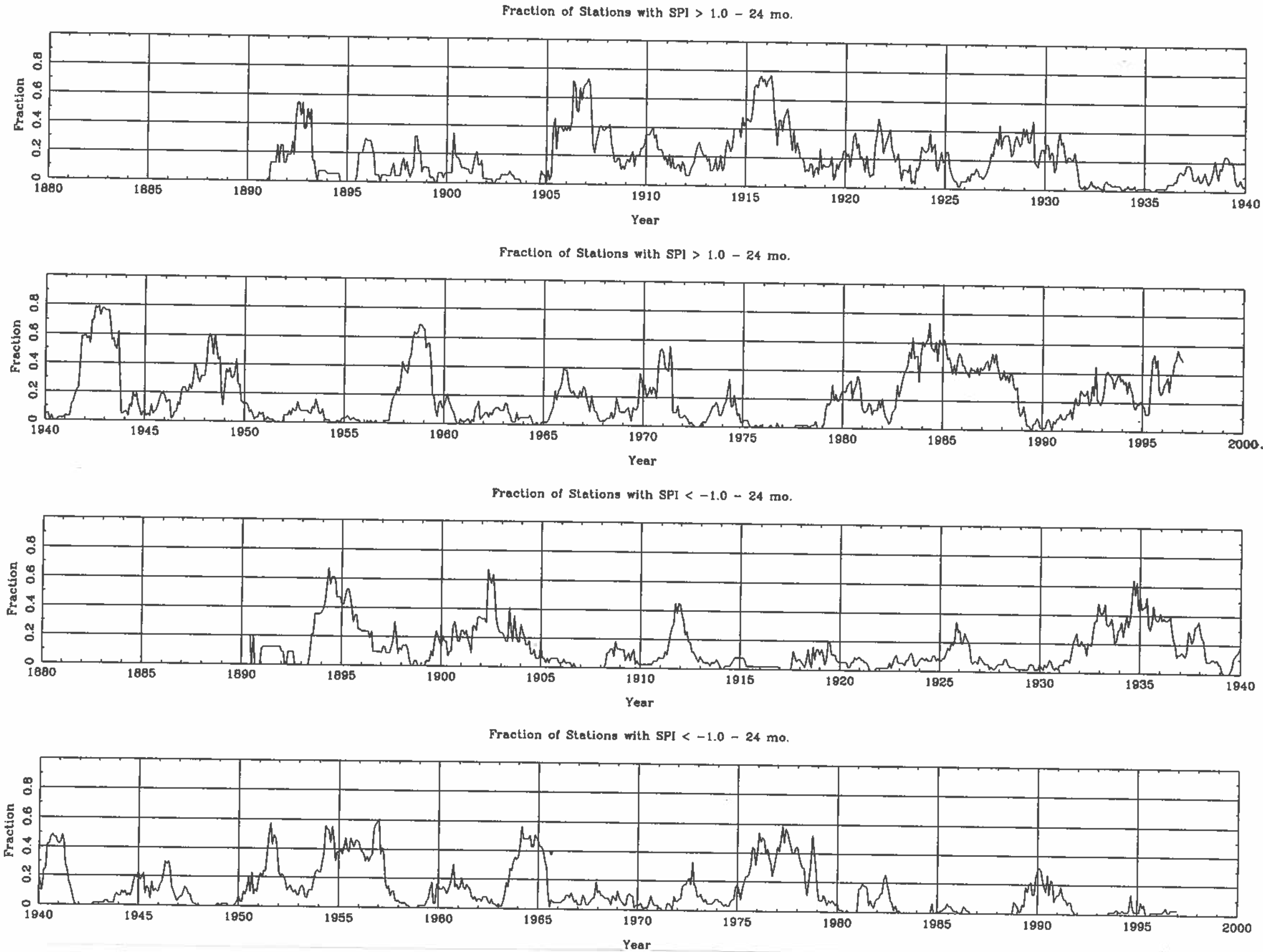


Figure 7d. Fractions of stations in Colorado with SPI greater than 1.0 (wet) and less than -1.0 (dry) for 24 months.

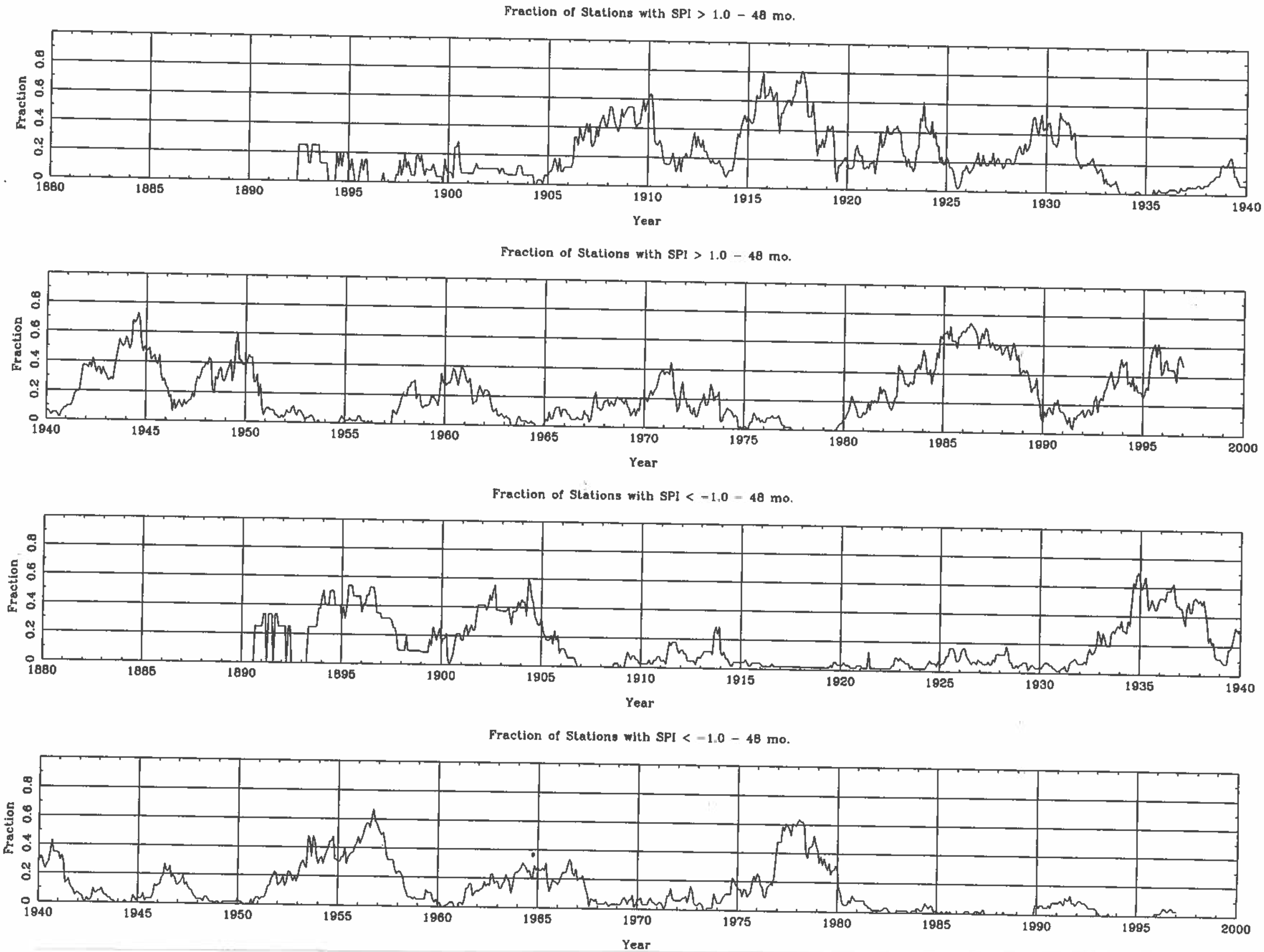


Figure 7e. Fractions of stations in Colorado with SPI greater than 1.0 (wet) and less than -1.0 (dry) for 48 months.

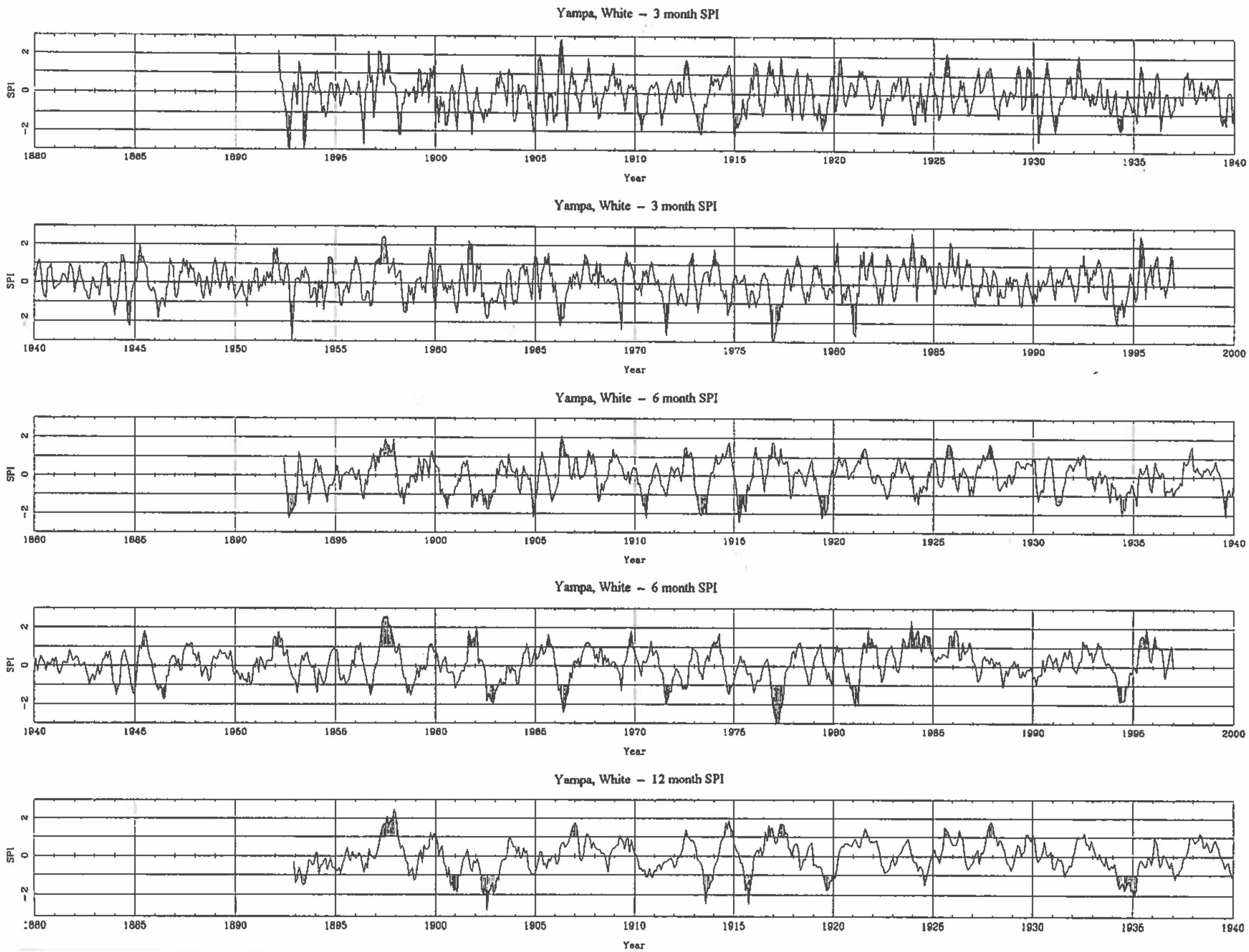


Figure 8a. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Yampa, White (YW) river basin.

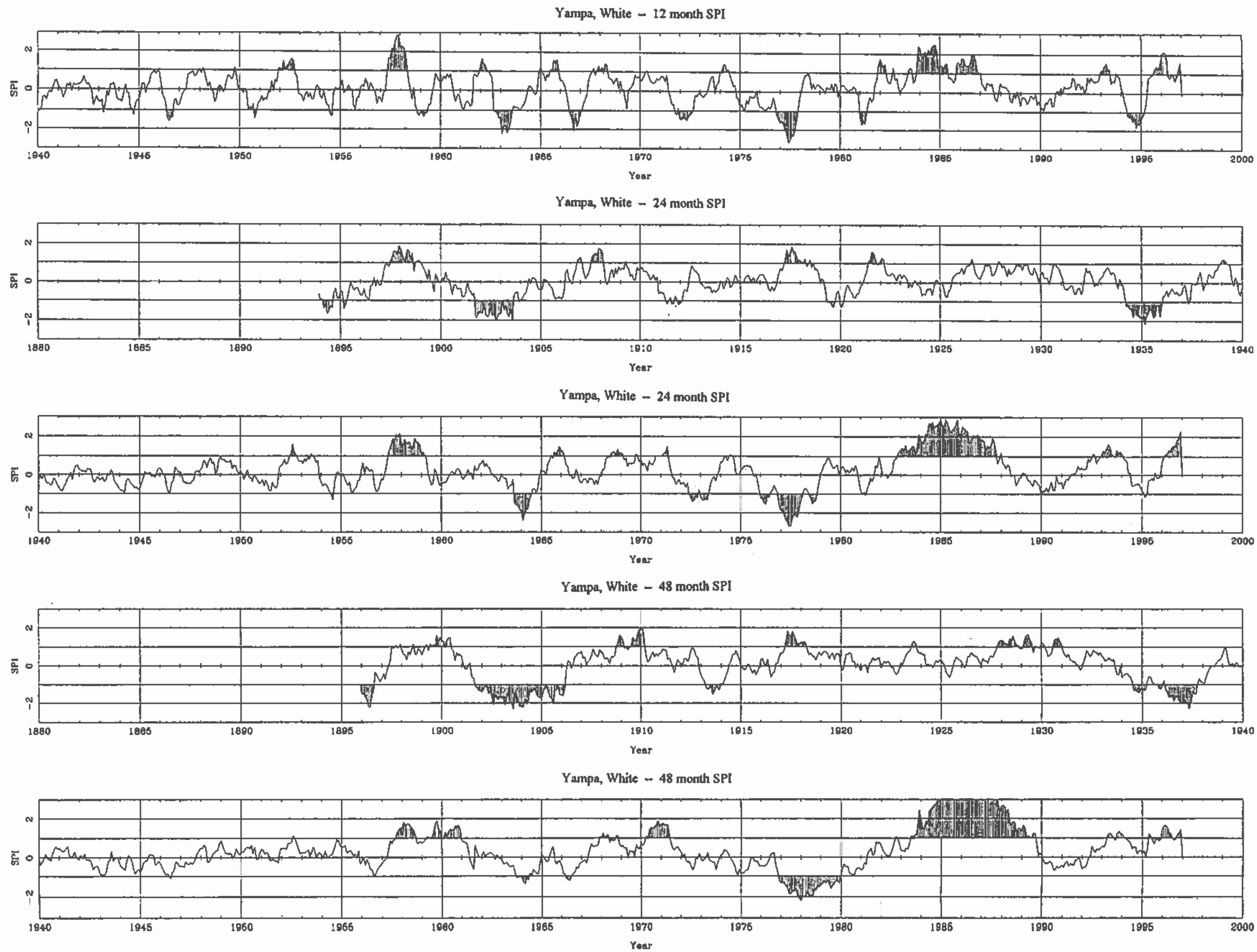


Figure 8a. Continued for Yampa, White river basin.

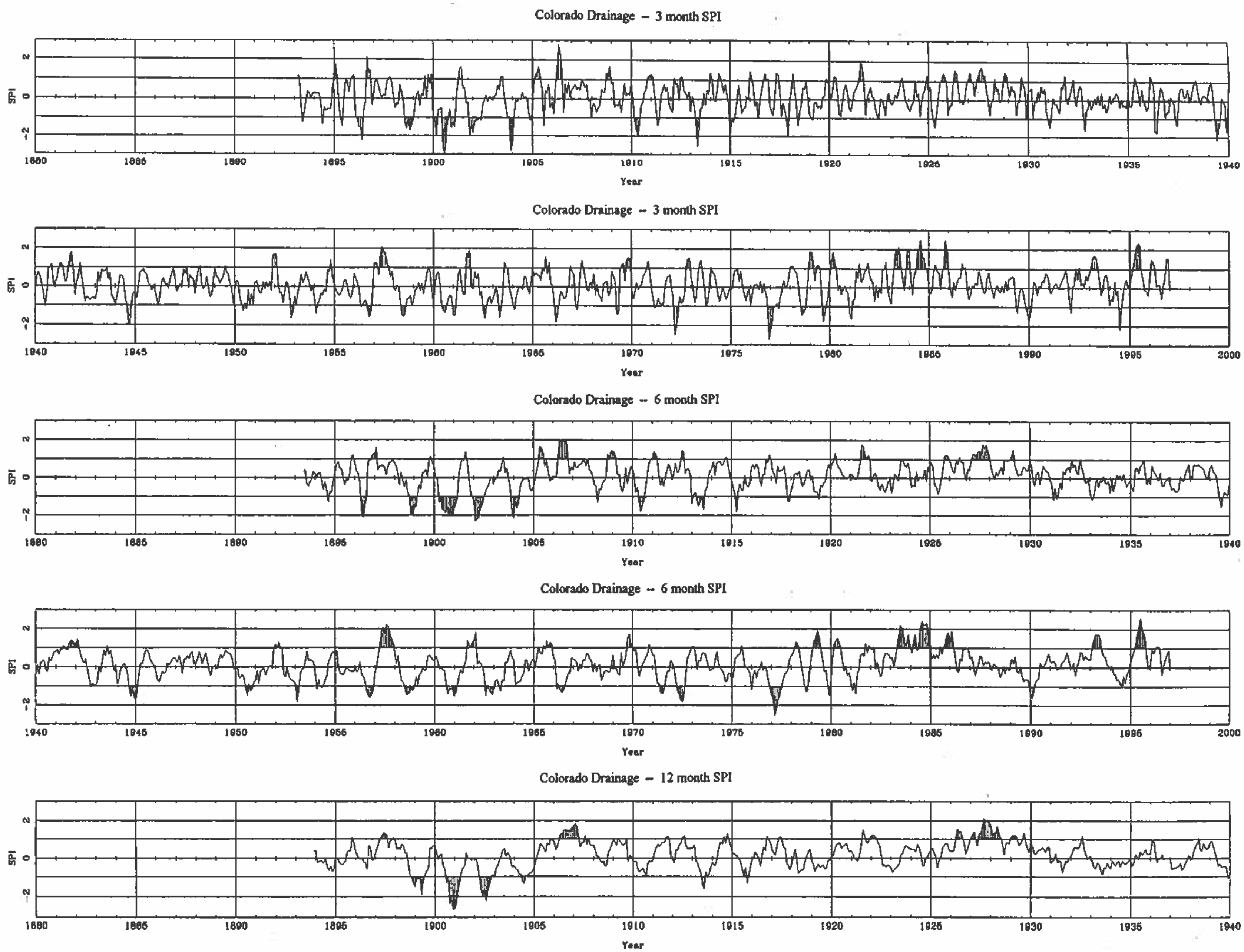


Figure 8b. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Colorado (CO) river basin.

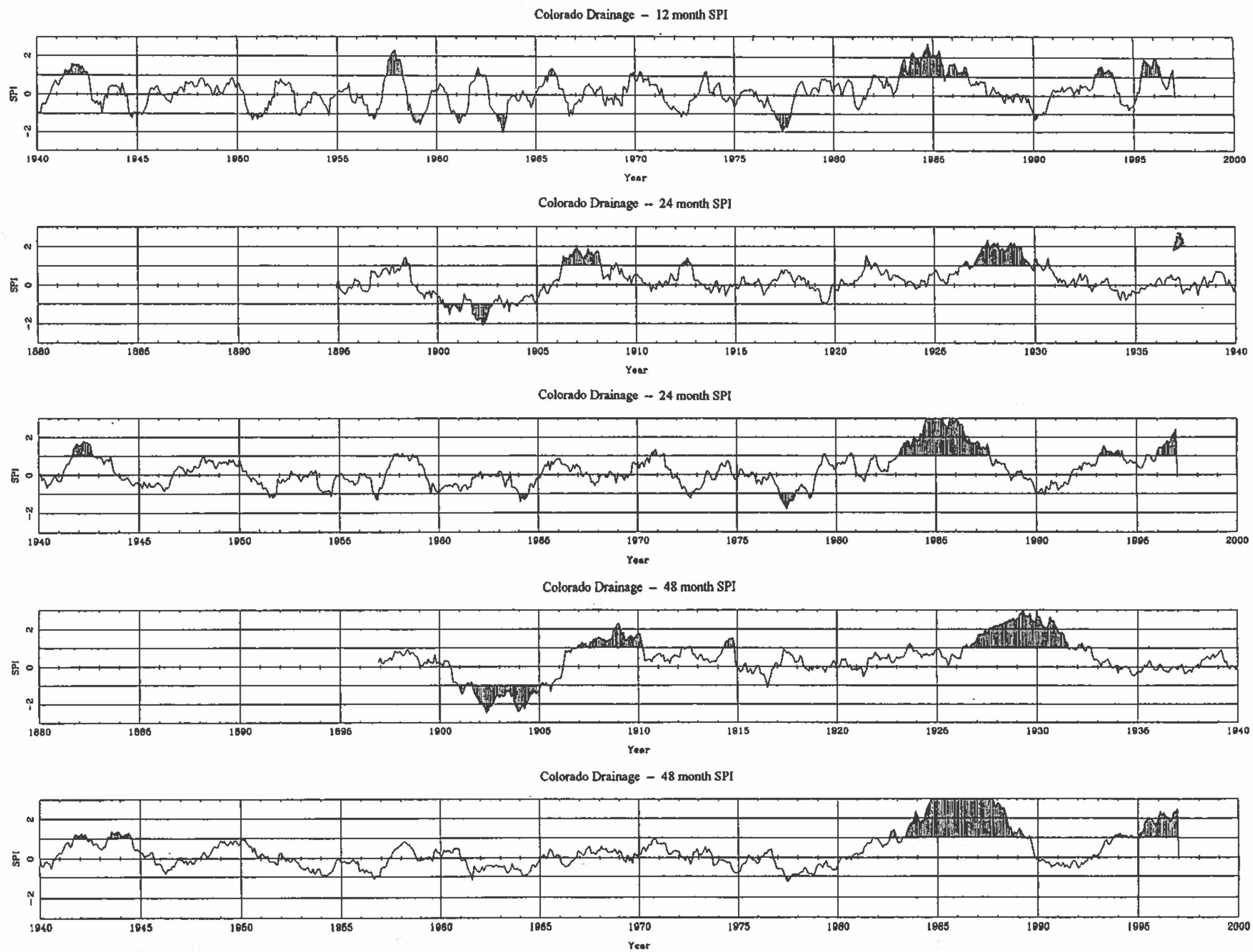


Figure 8b. Continued for Colorado river basin.

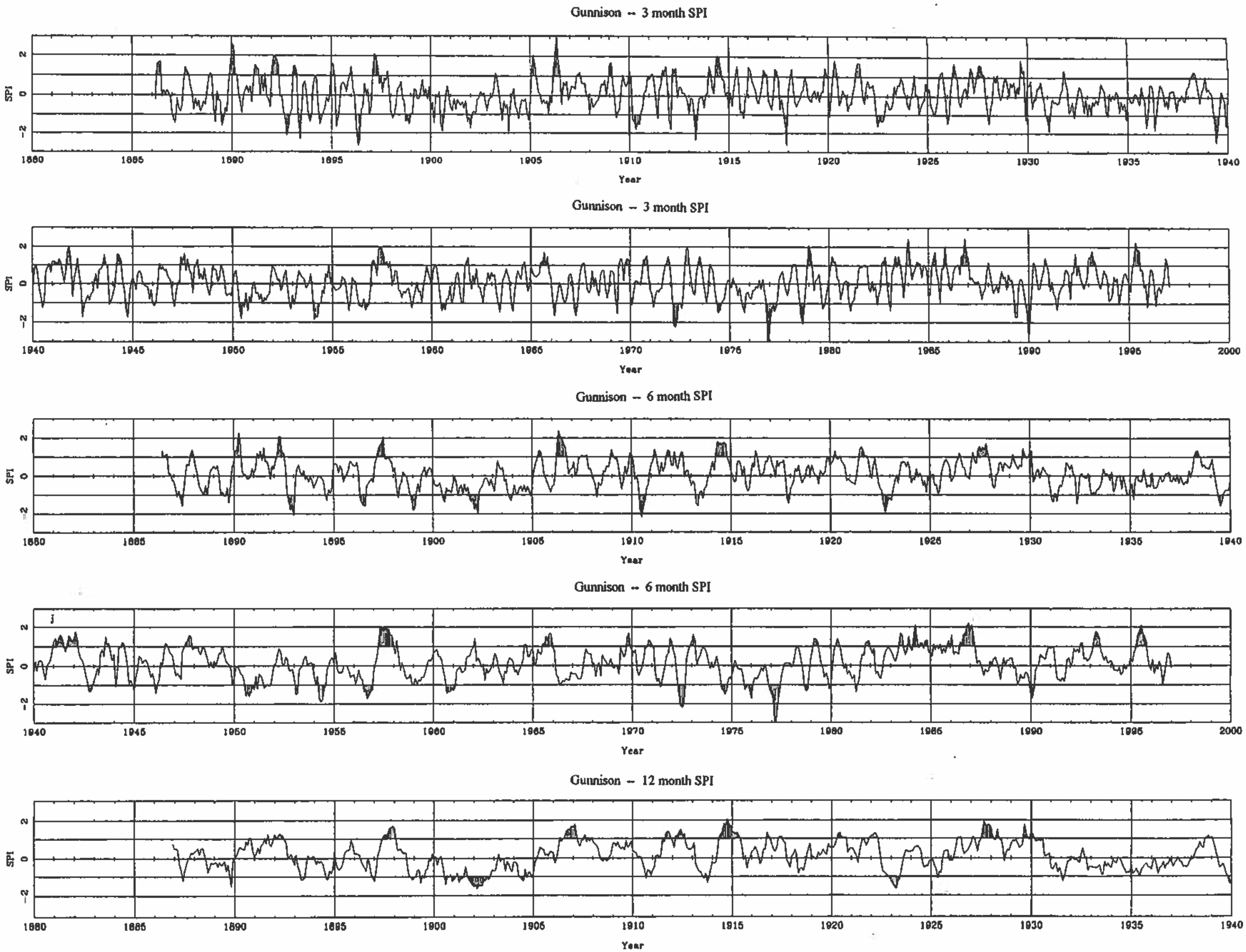


Figure 8c. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Gunnison (GU) river basin.

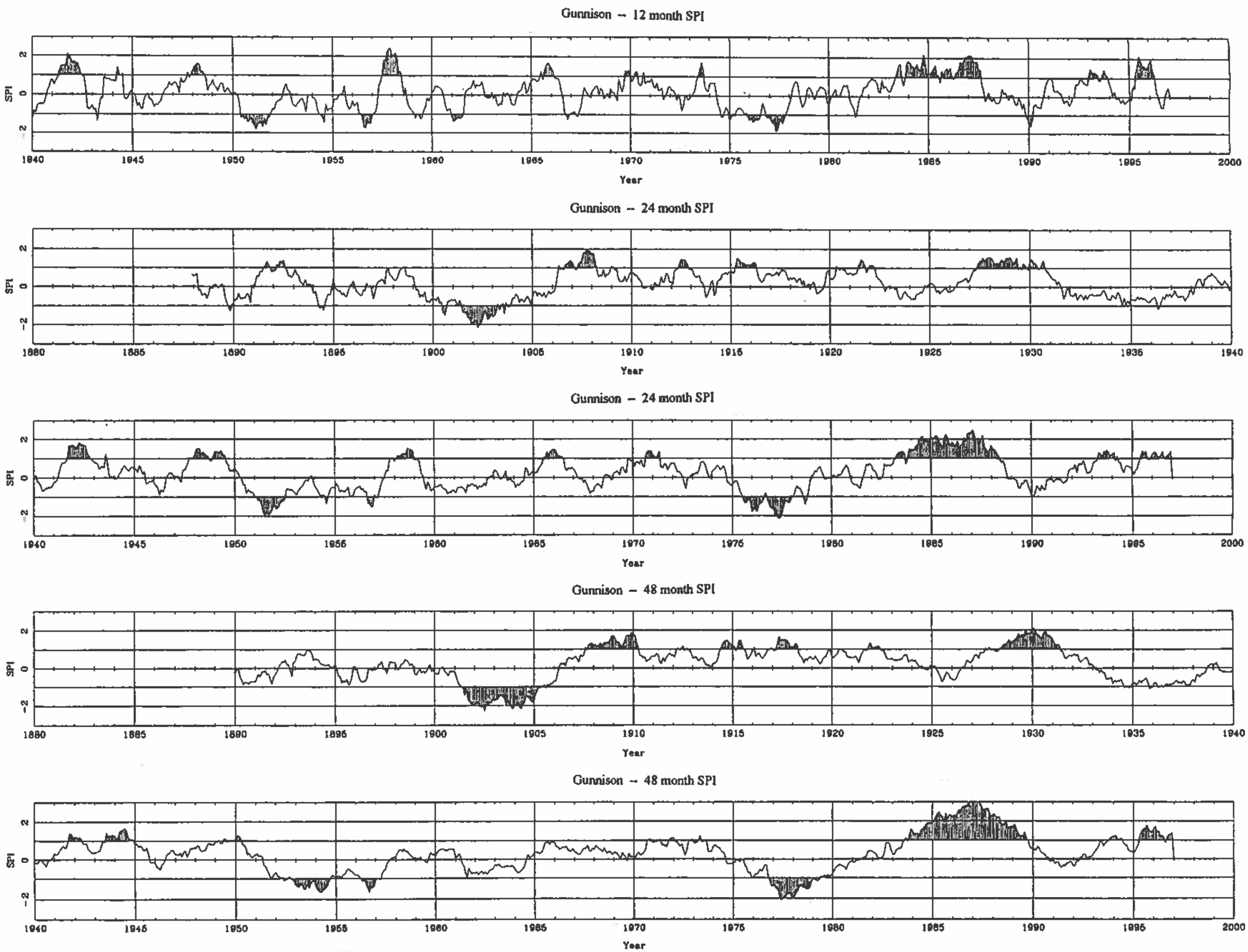


Figure 8c. Continued for Gunnison river basin.

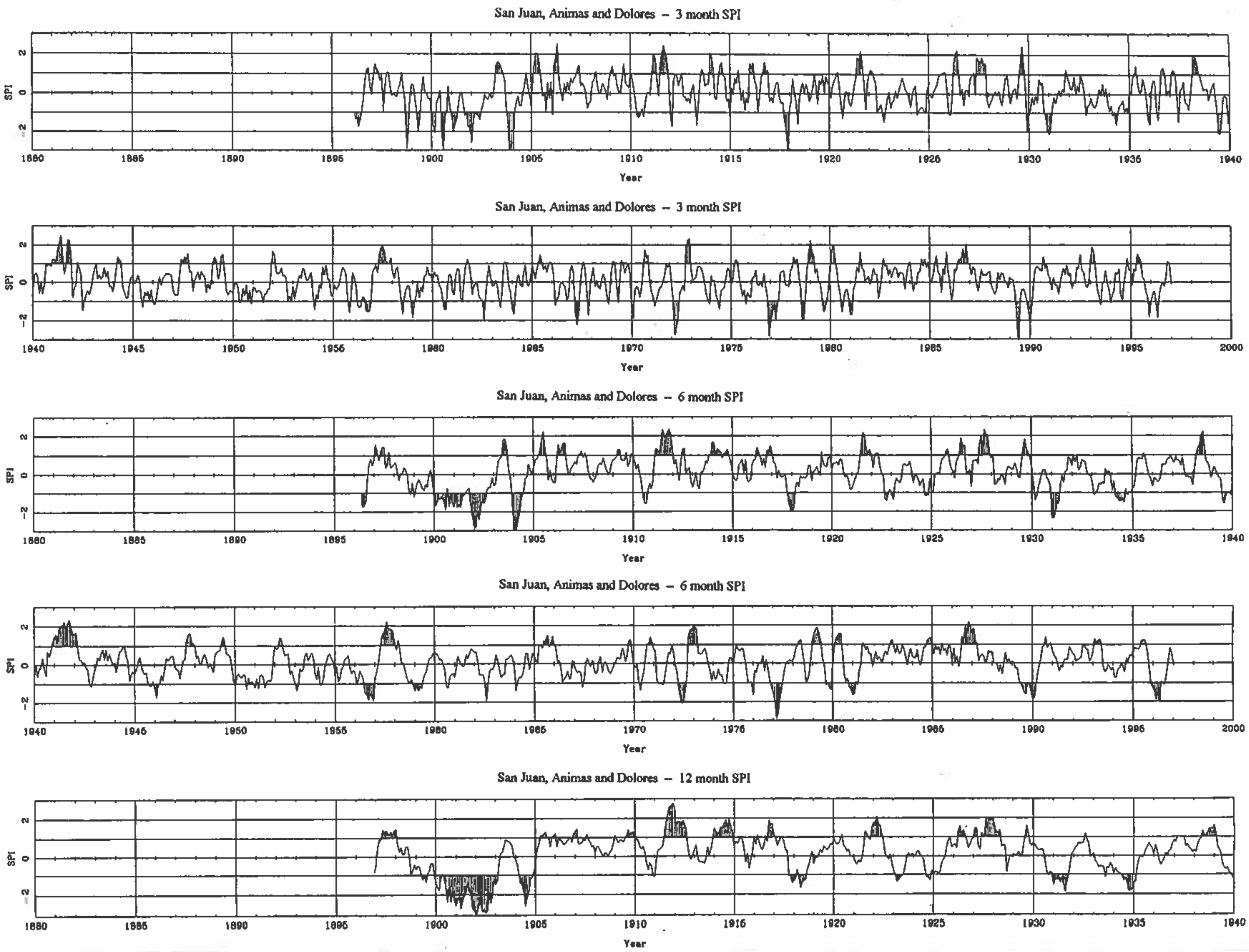


Figure 8d. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the San Juan, Animas, Dolores (SA) river basin.

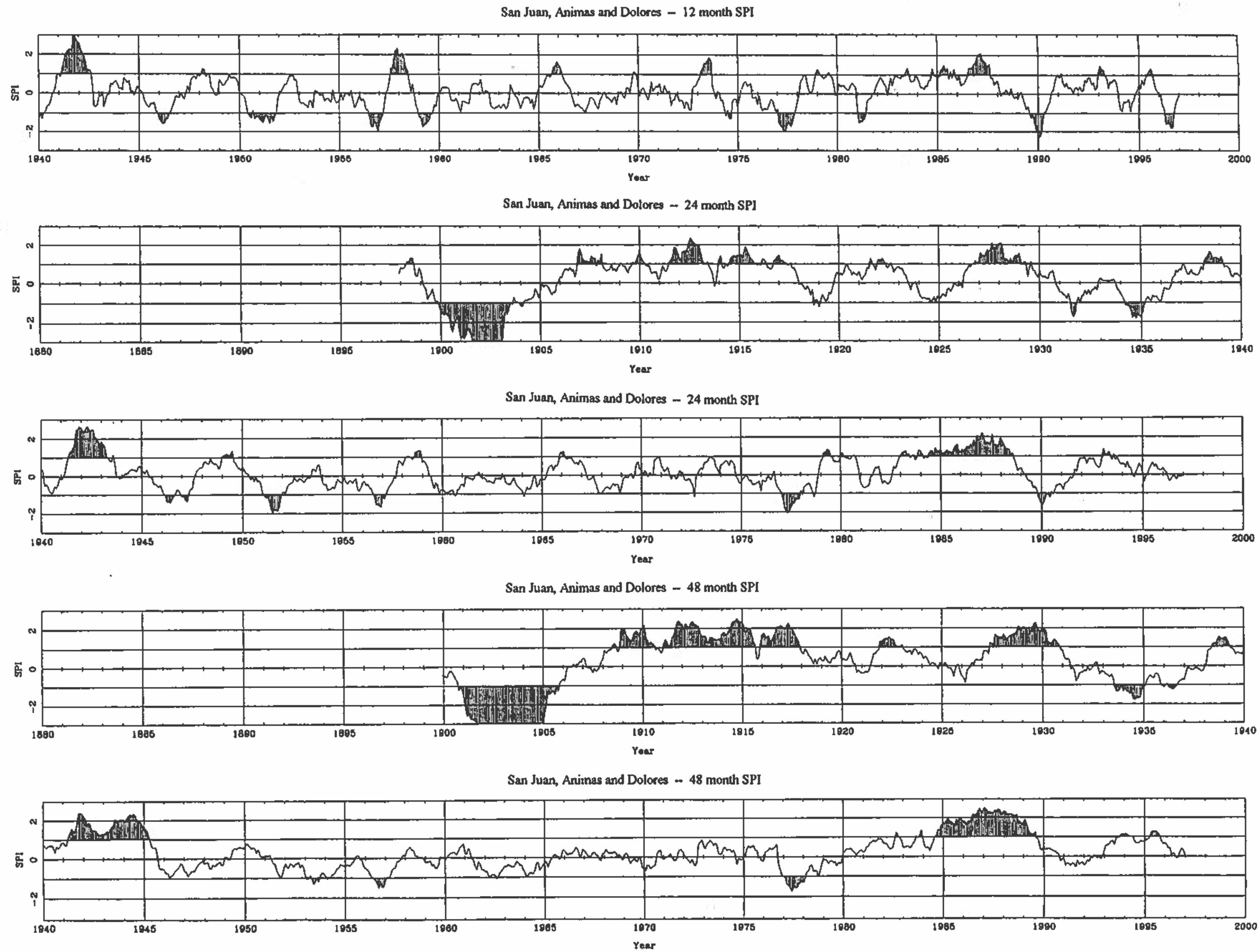


Figure 8d. Continued for San Juan, Animas, Dolores river basin.

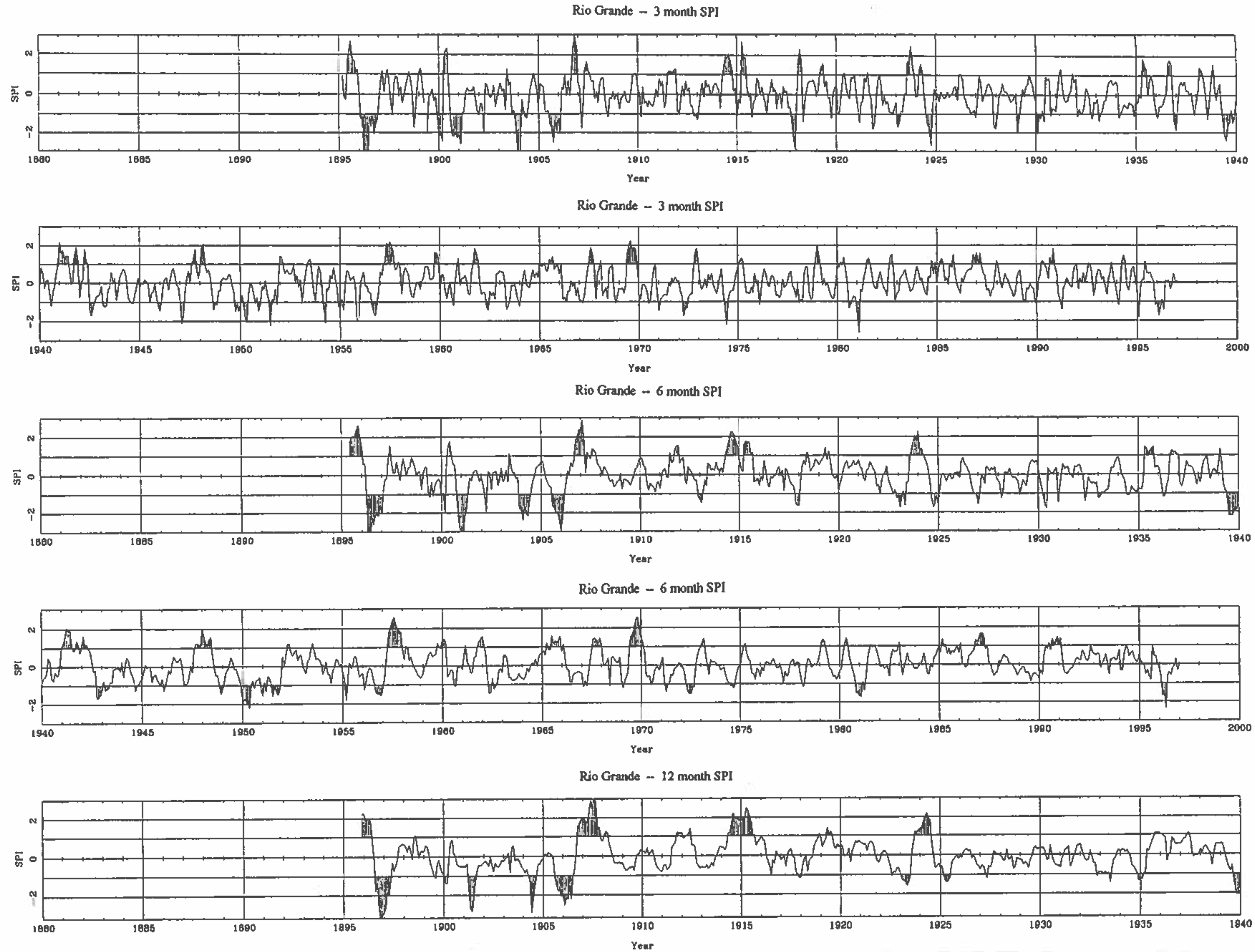


Figure 8e. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Rio Grande (RG) river basin.

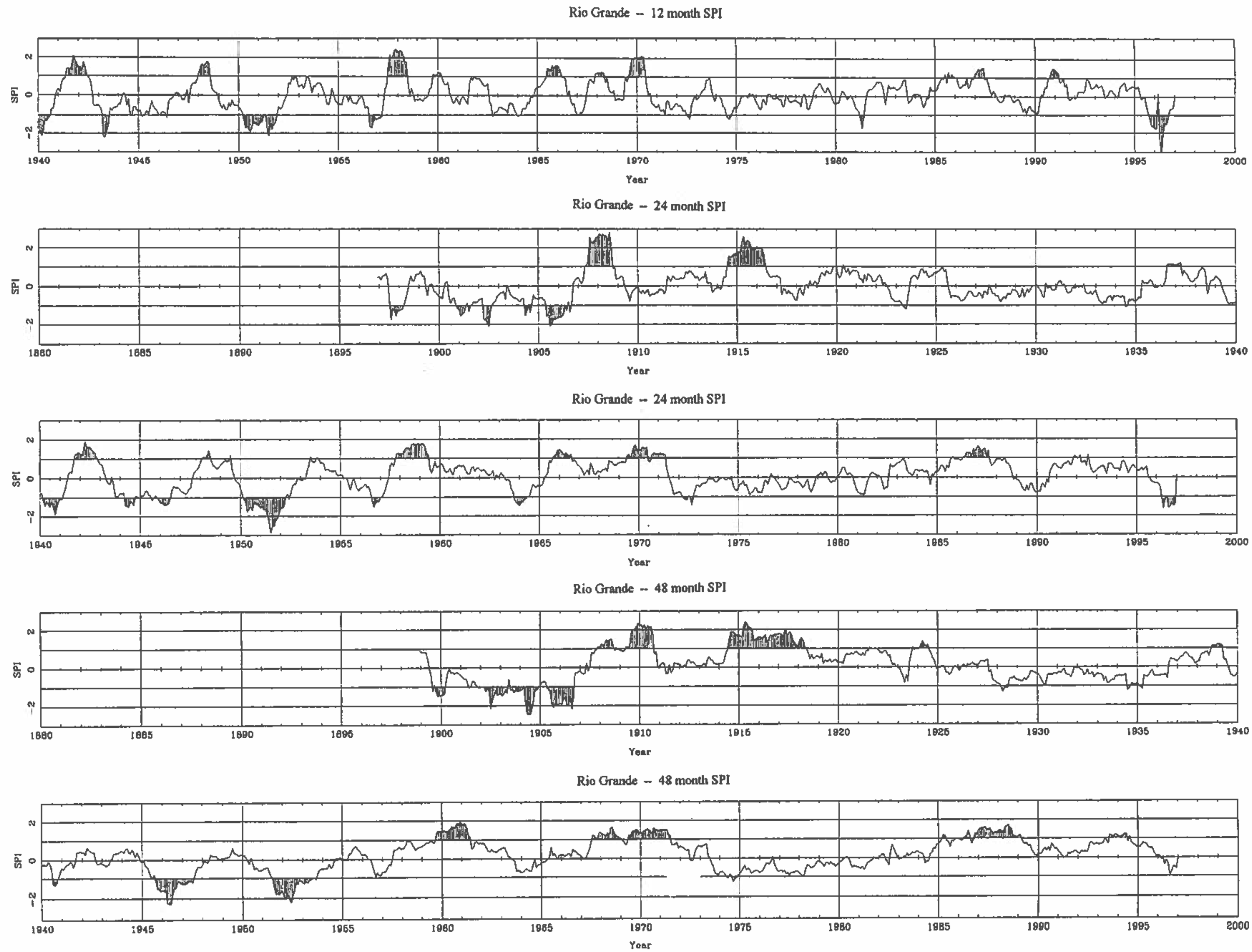


Figure 8e. Continued for Rio Grande river basin.

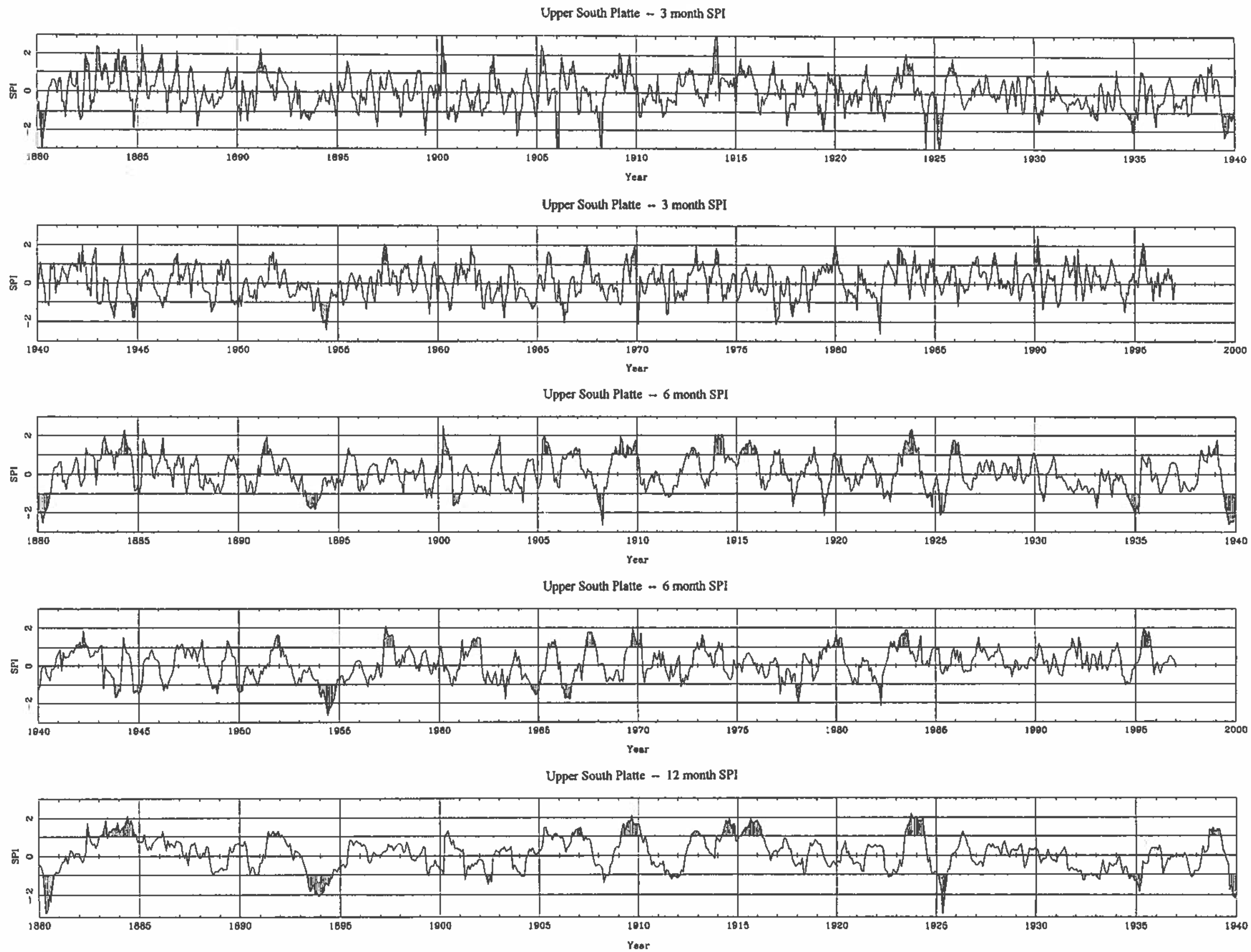


Figure 8f. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Upper South Platte (USP) river basin.

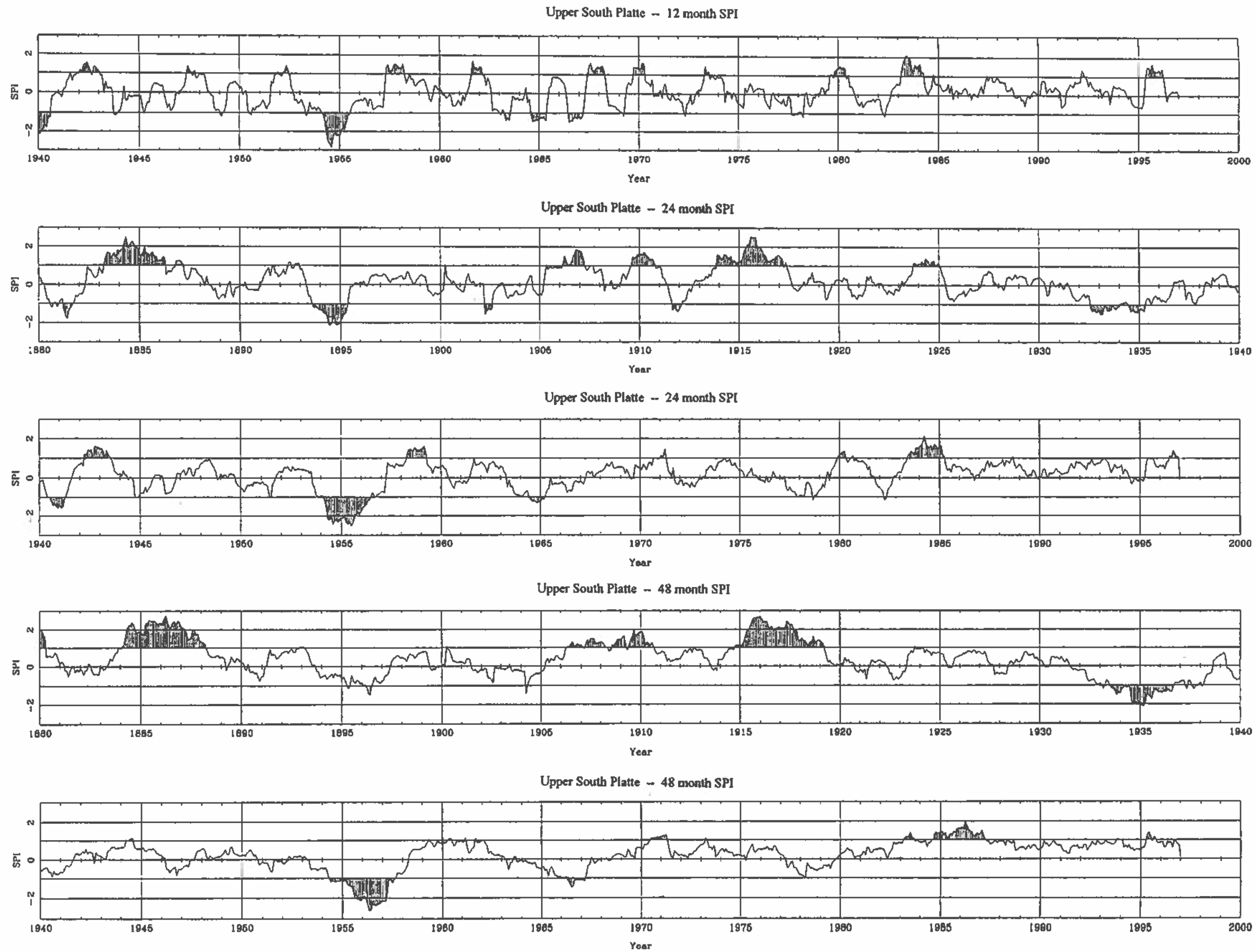


Figure 8f. Continued for Upper South Platte river basin.

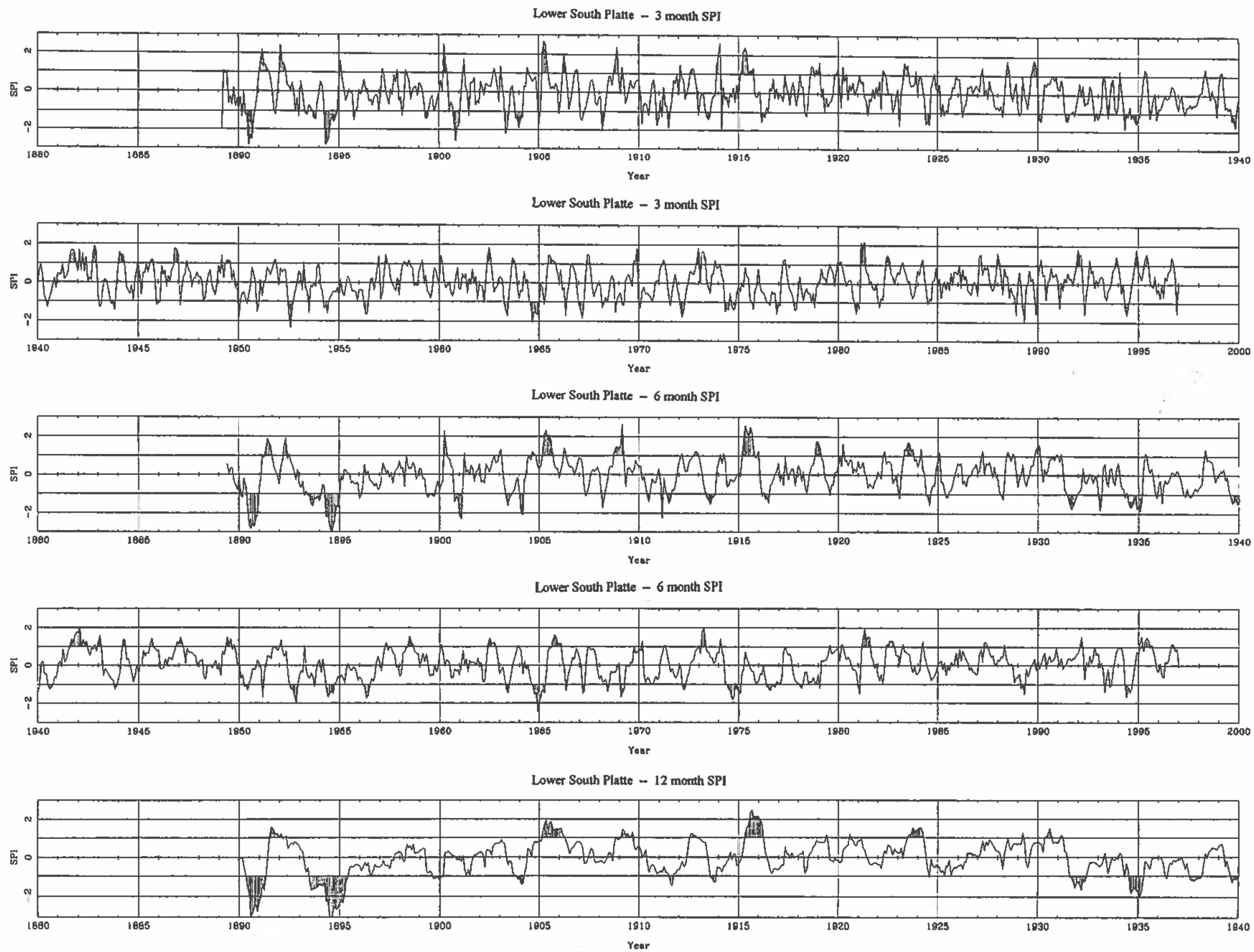


Figure 8g. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Lower South Platte (LSP) river basin.

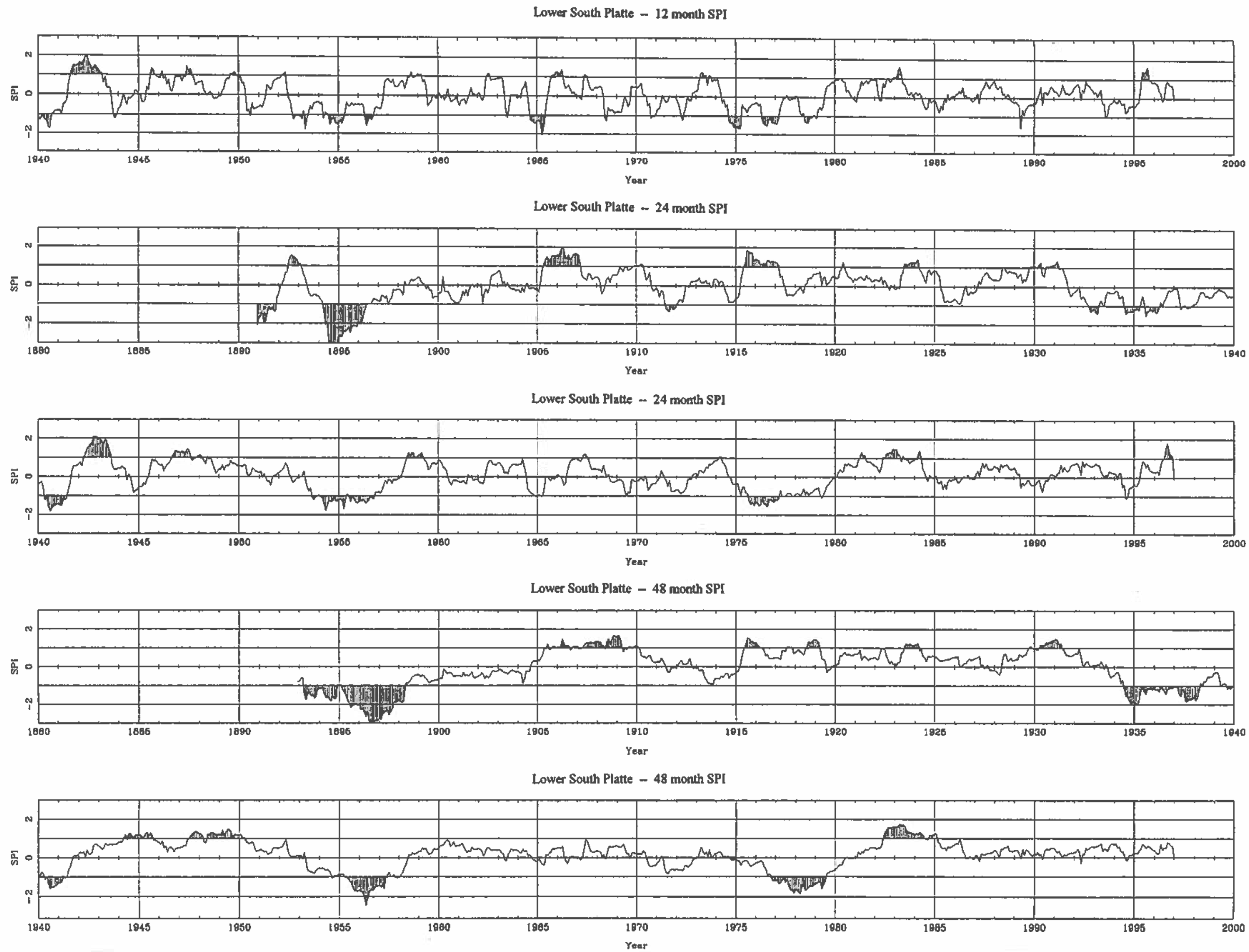


Figure 8g. Continued for Lower South Platte river basin.

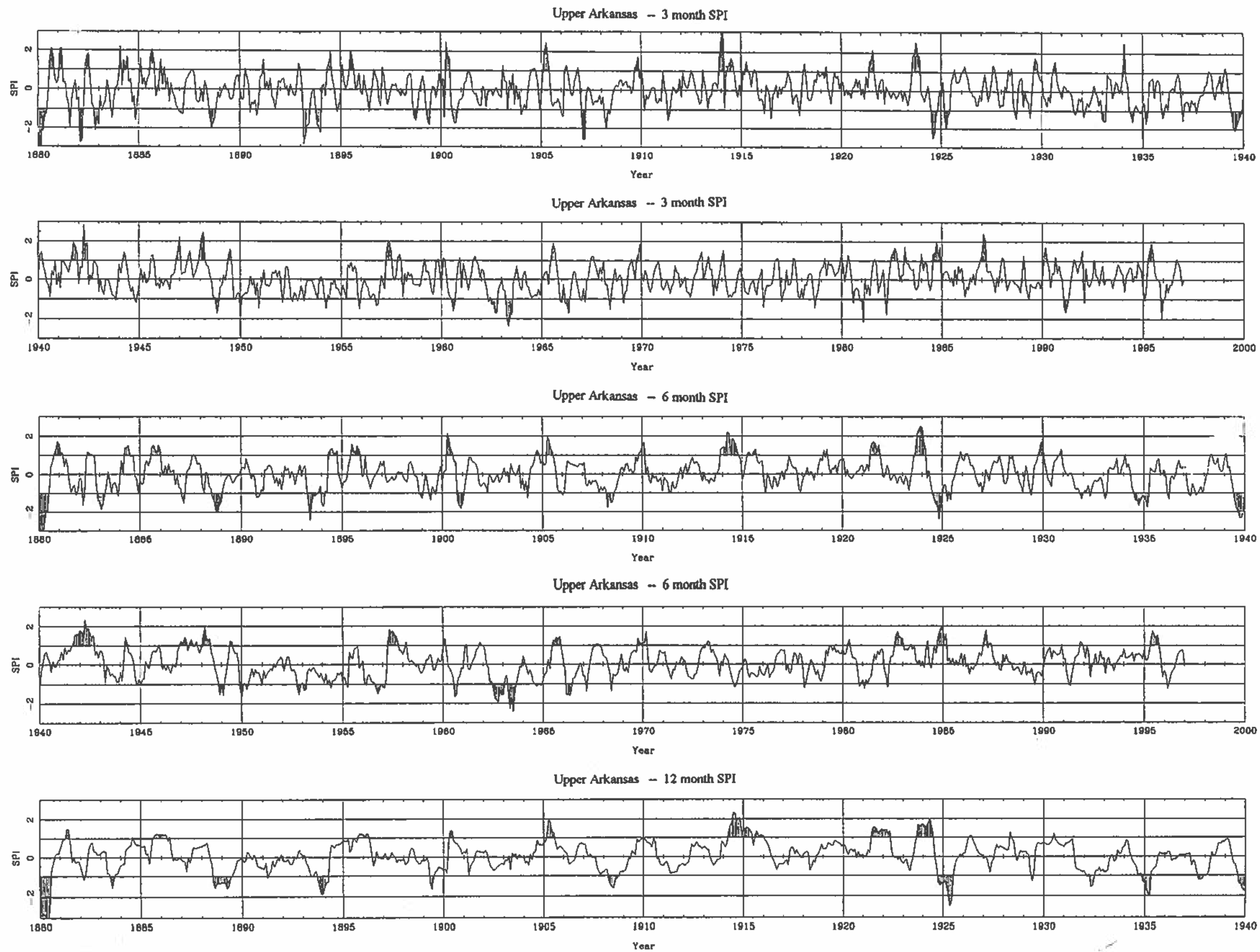


Figure 8h. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Upper Arkansas (UAR) river basin.

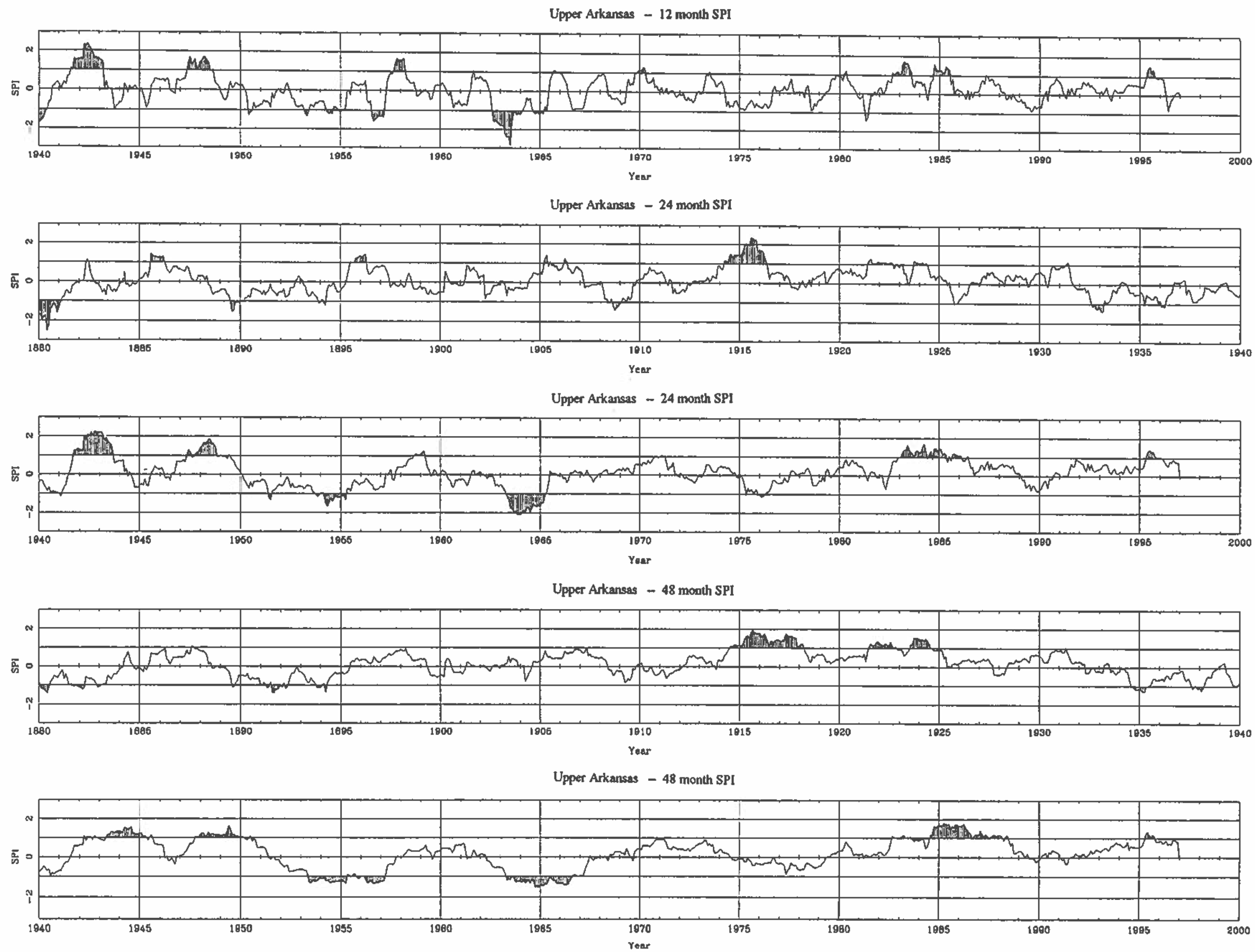


Figure 8h. Continued for Upper Arkansas river basin.

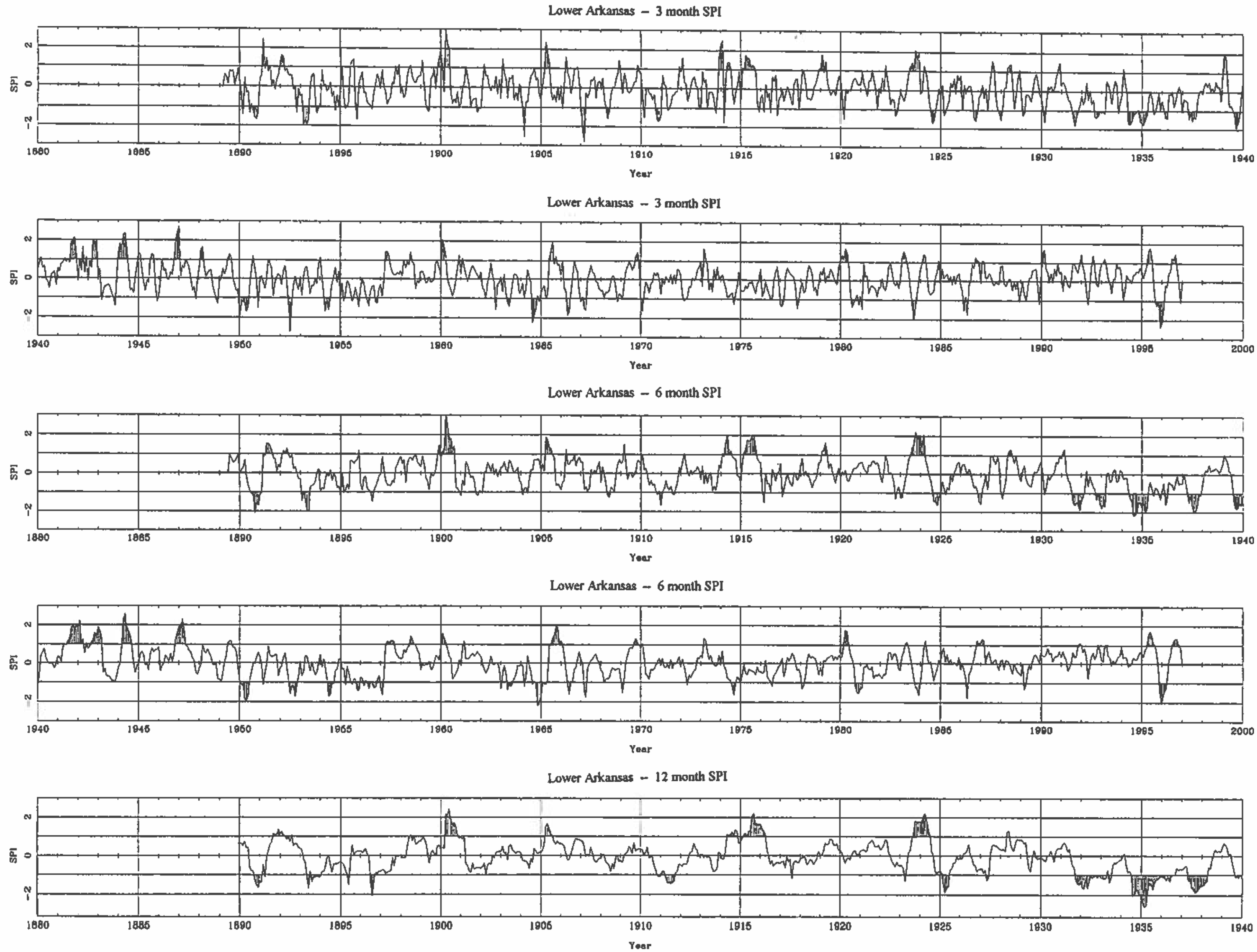


Figure 8i. Standardized precipitation index (SPI) for 3, 6, 12, 24 and 48 months for the Lower Arkansas (LAR) river basin.

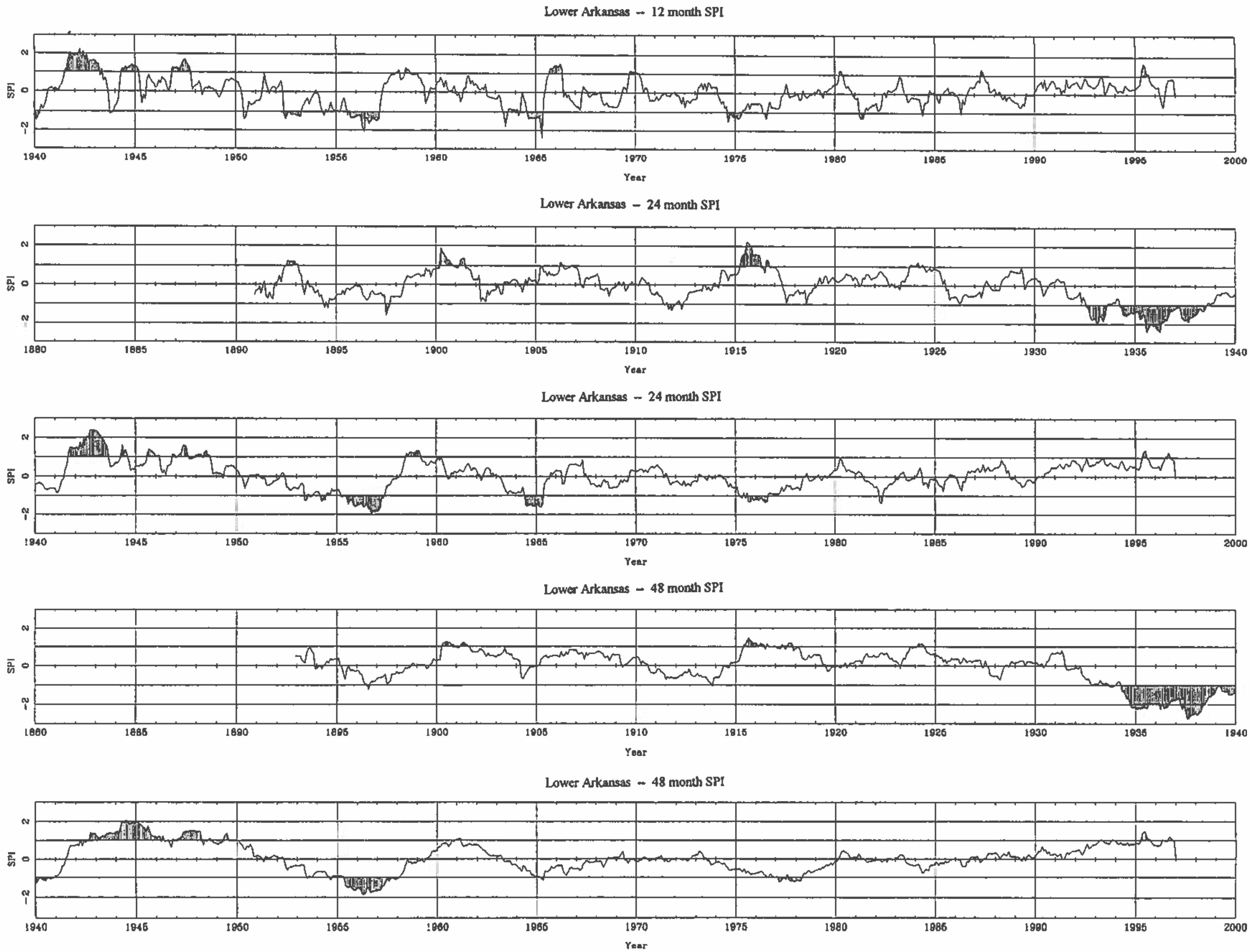


Figure 8i. Continued for Lower Arkansas river basin.

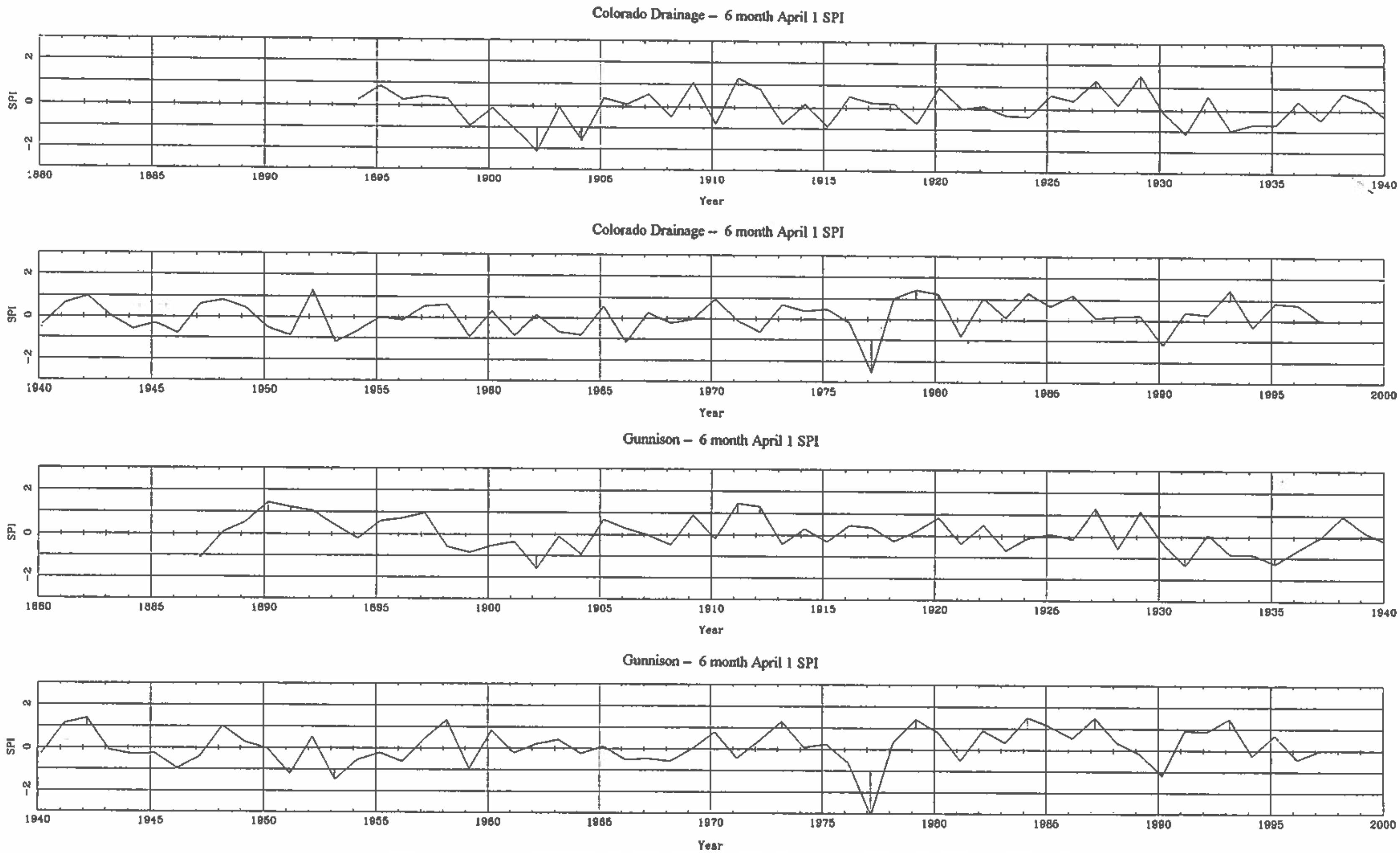


Figure 9a. Regional SPI for the winter season (October-March) for Colorado and Gunnison river basins.

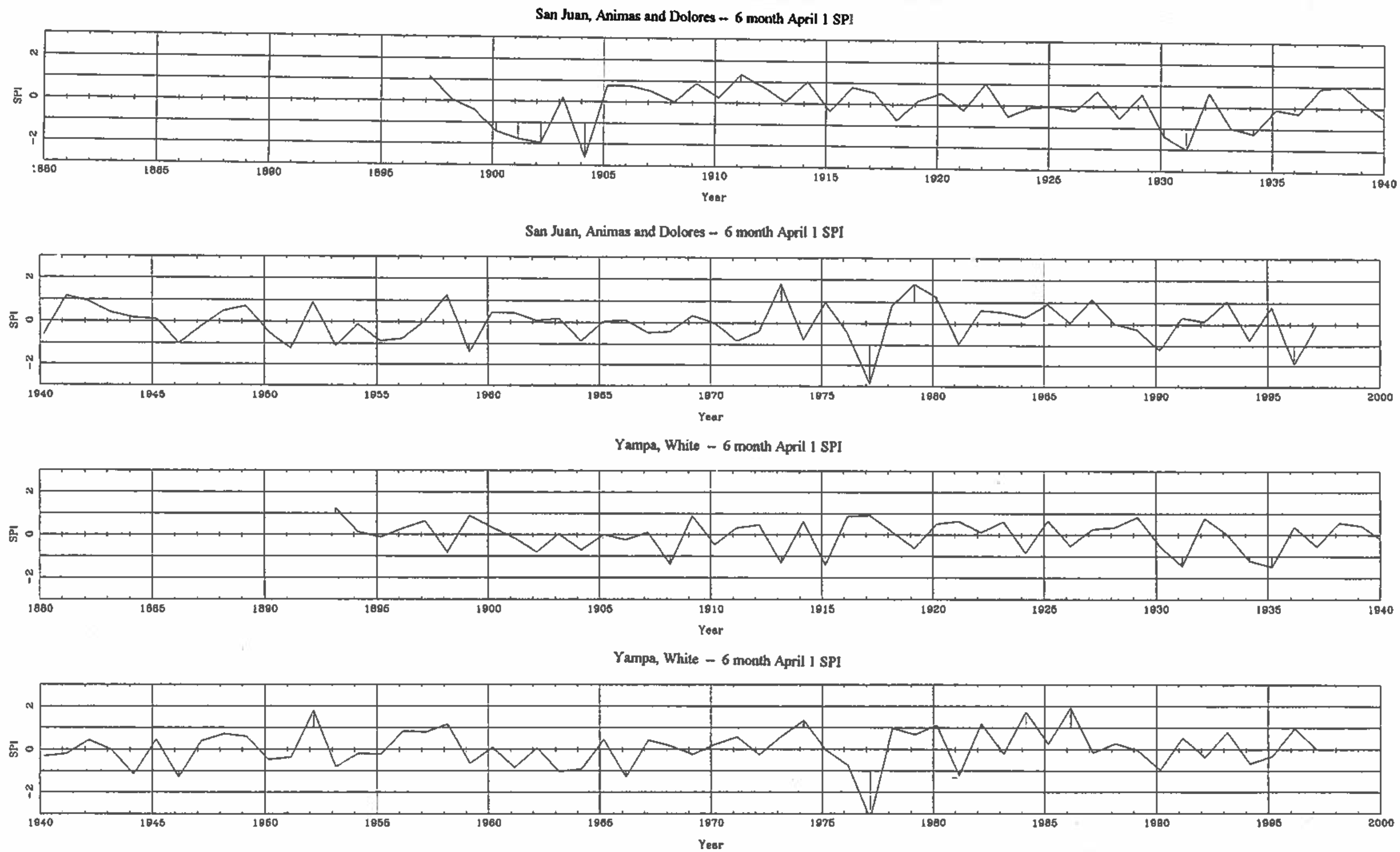


Figure 9b. Regional SPI for the winter season (October-March) for San Juan, Animas and Dolores and Yampa, White river basins.

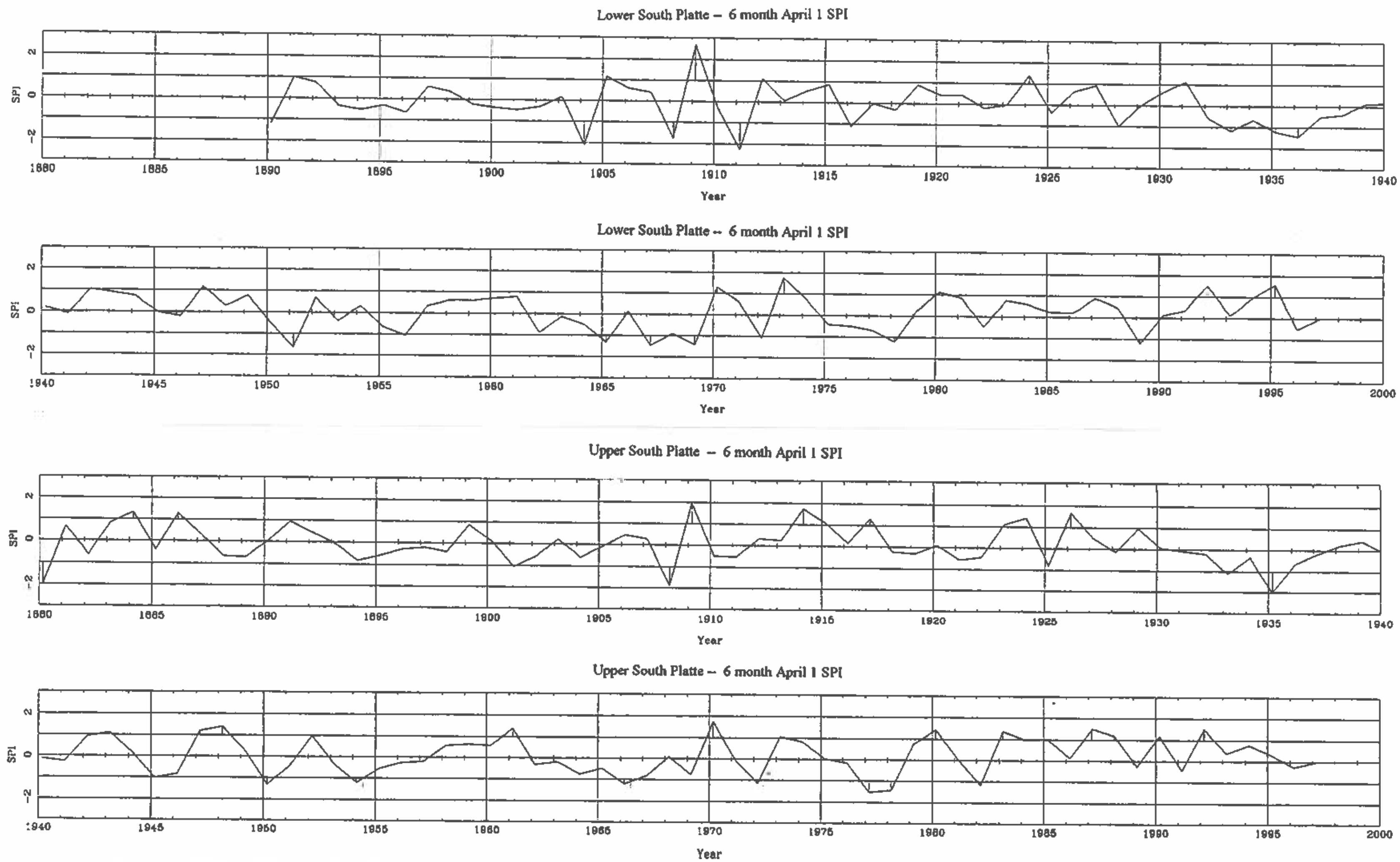


Figure 9c. Regional SPI for the winter season (October-March) for Lower South Platte and Upper South Platte river basins.

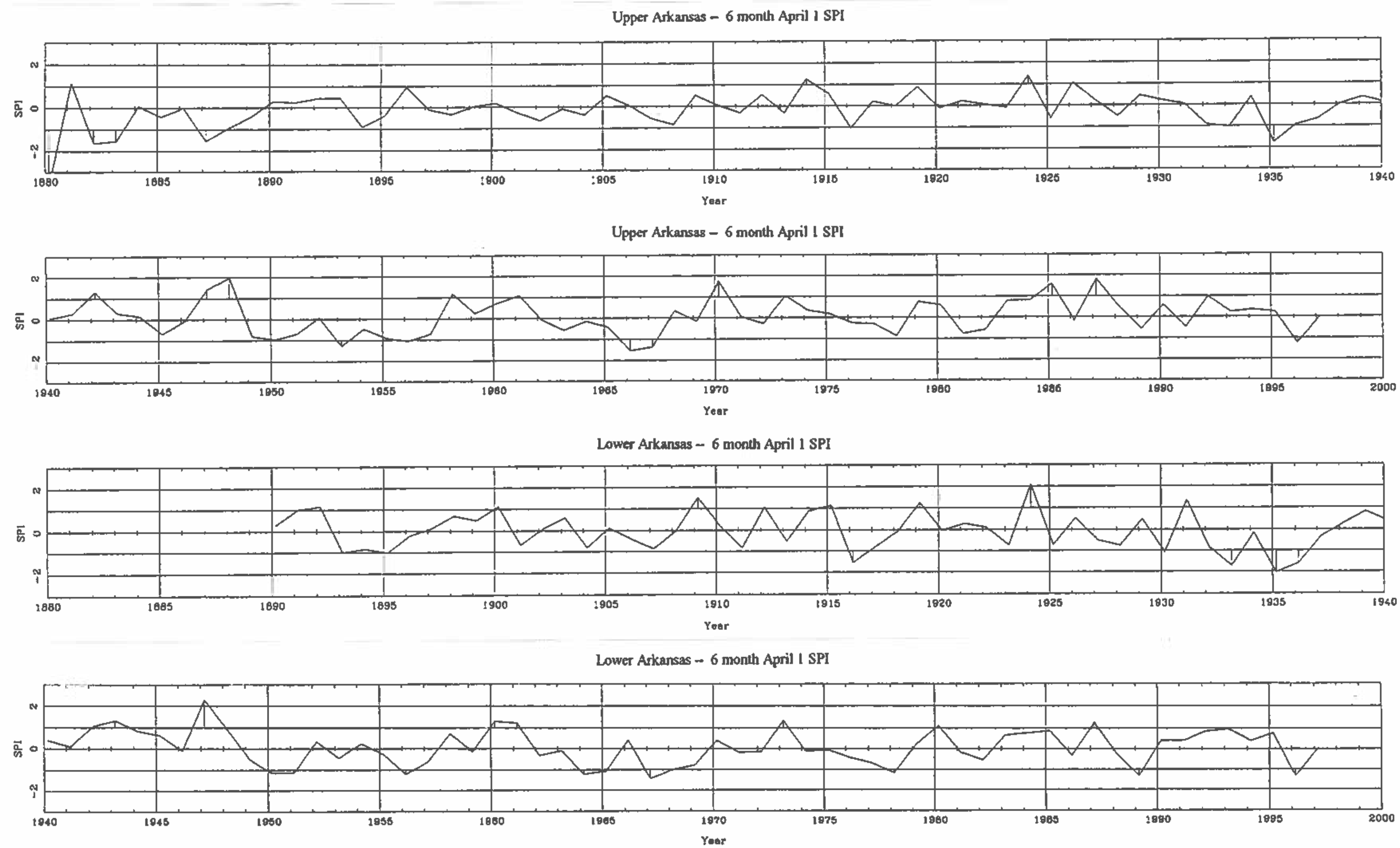


Figure 9d. Regional SPI for the winter season (October-March) for Upper Arkansas and Lower Arkansas river basins.

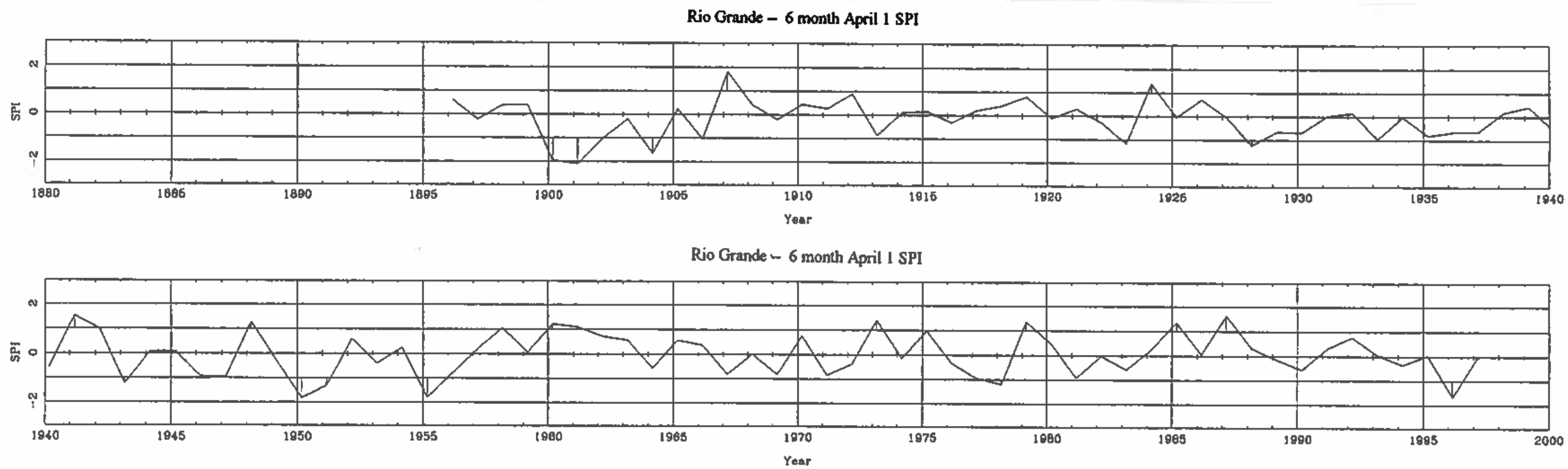


Figure 9e. Regional SPI for the winter season (October-March) for Rio Grande river basin.

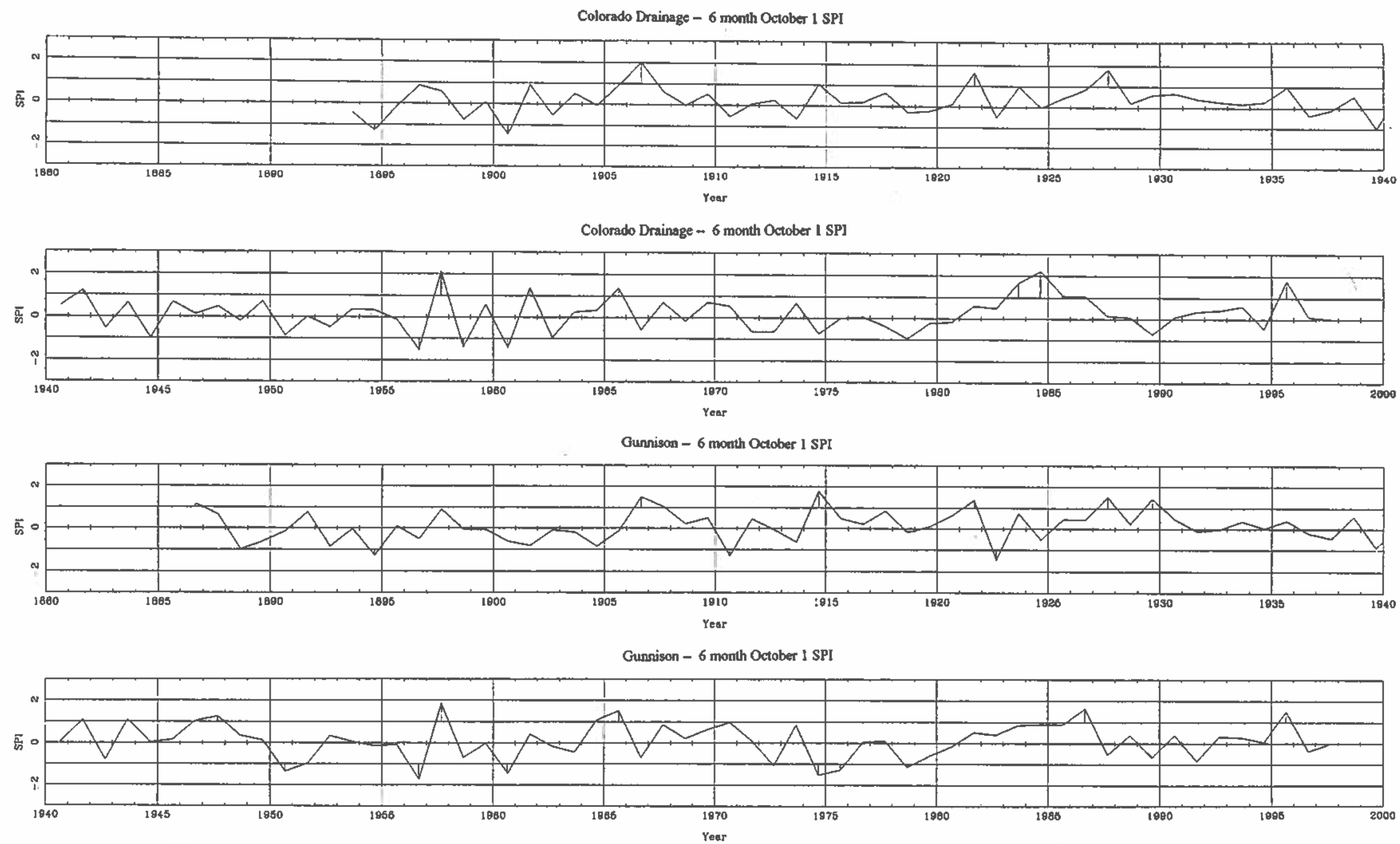


Figure 10a. Regional SPI for the summer season (April-September) for Colorado and Gunnison river basins.

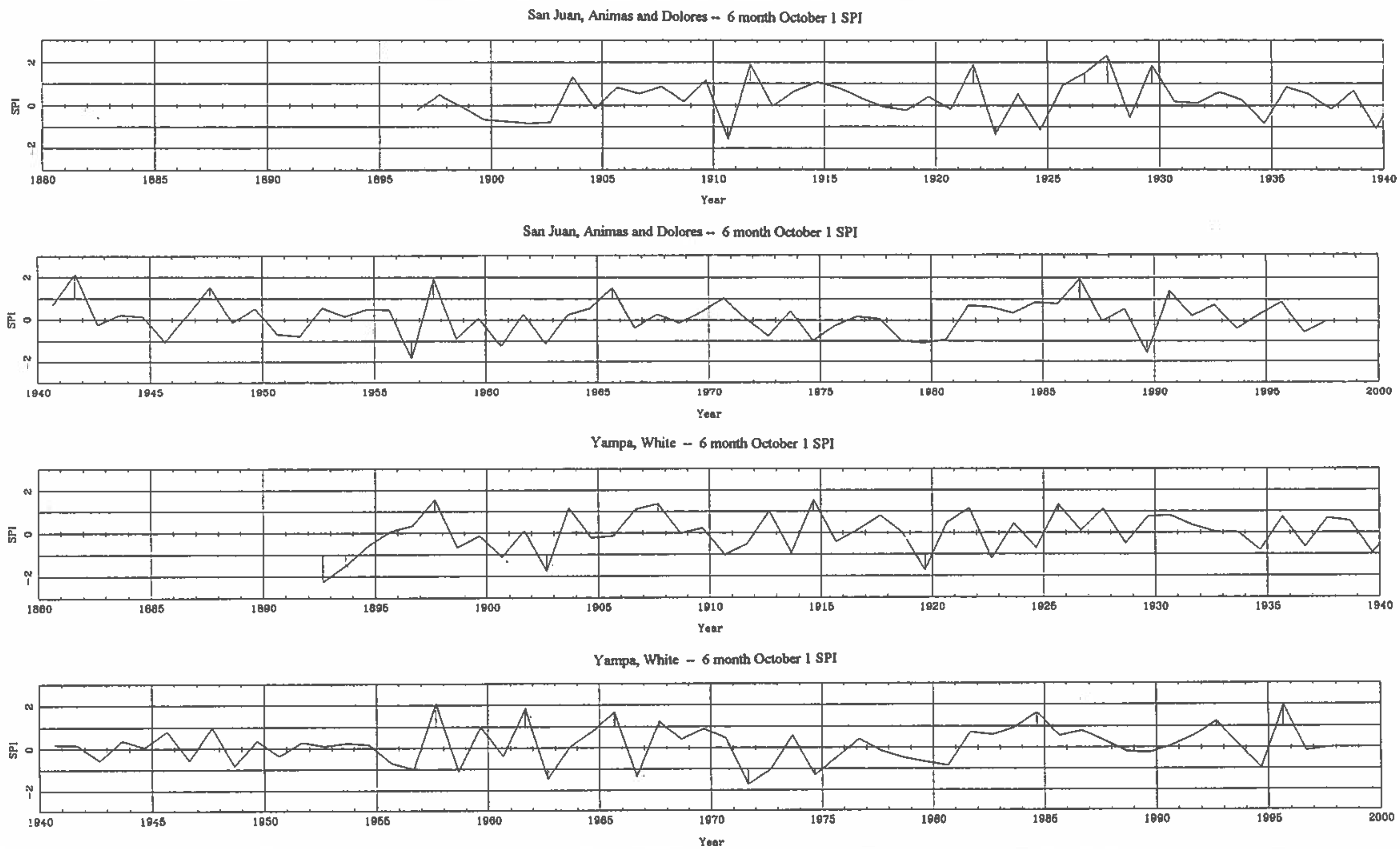


Figure 10b. Regional SPI for the summer season (April-September) for San Juan, Animas and Dolores and Yampa, White river basins.

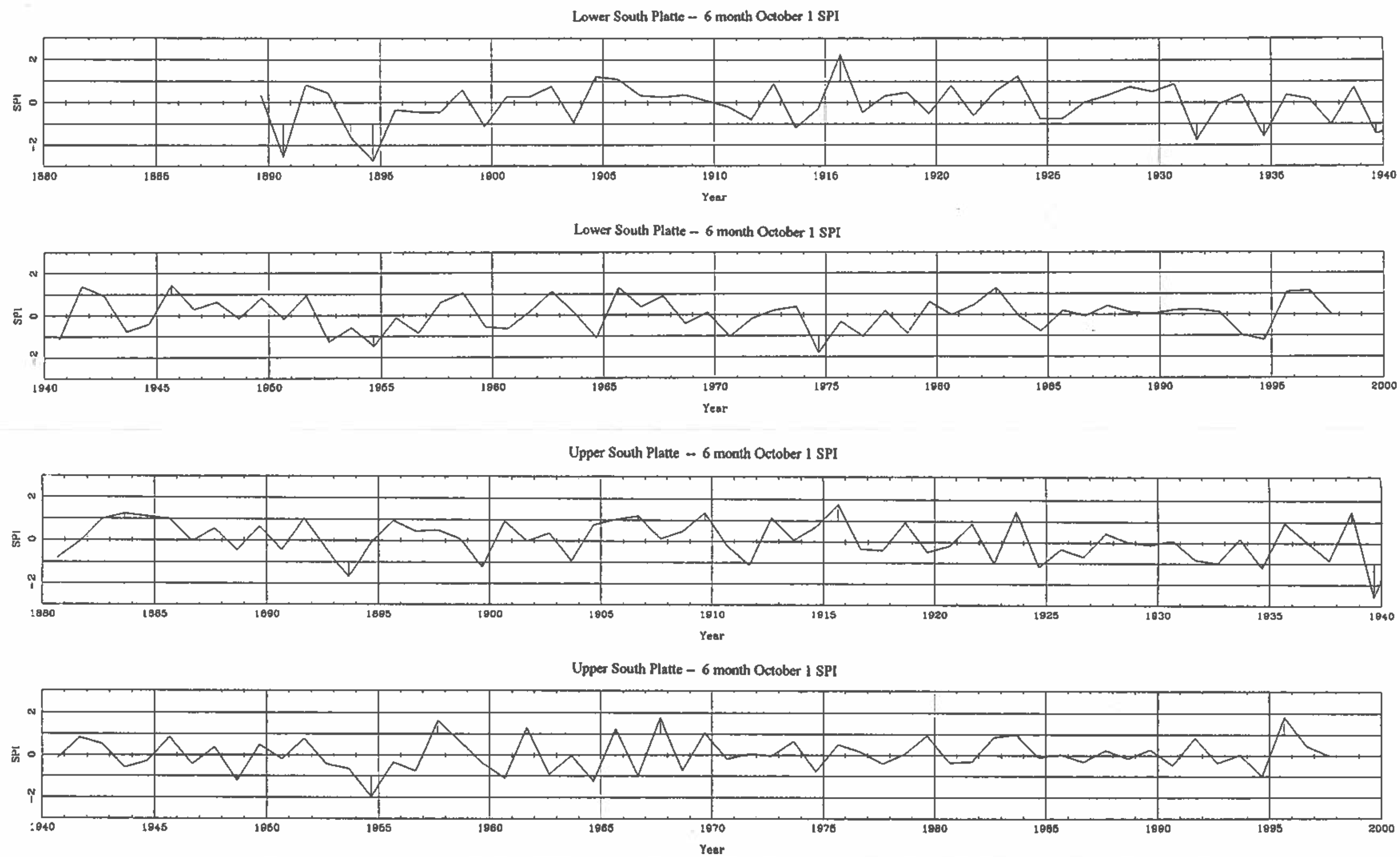


Figure 10c. Regional SPI for the summer season (April-September) for Lower South Platte and Upper South Platte river basins.

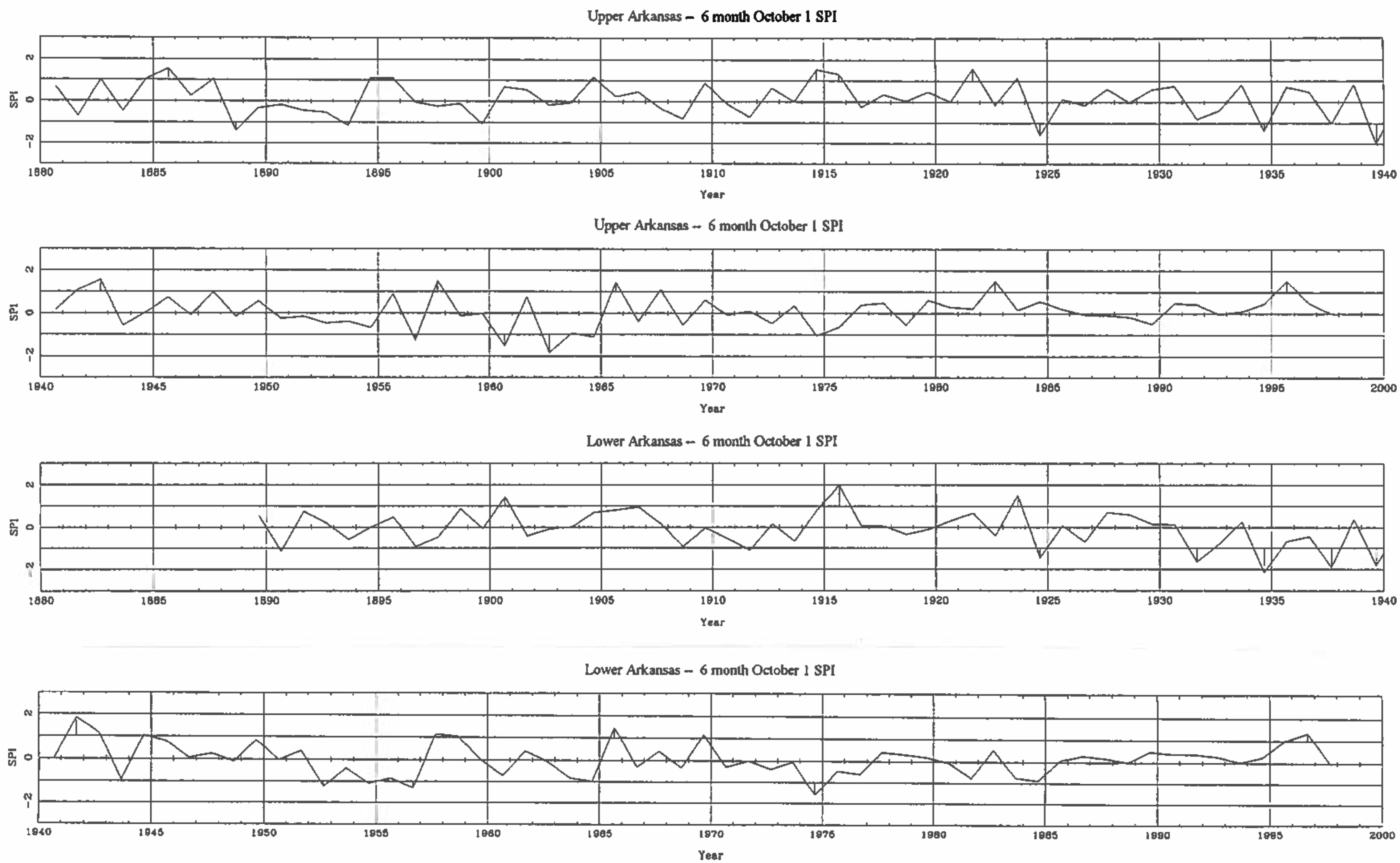


Figure 10d. Regional SPI for the summer season (April-September) for Upper Arkansas and Lower Arkansas river basins.

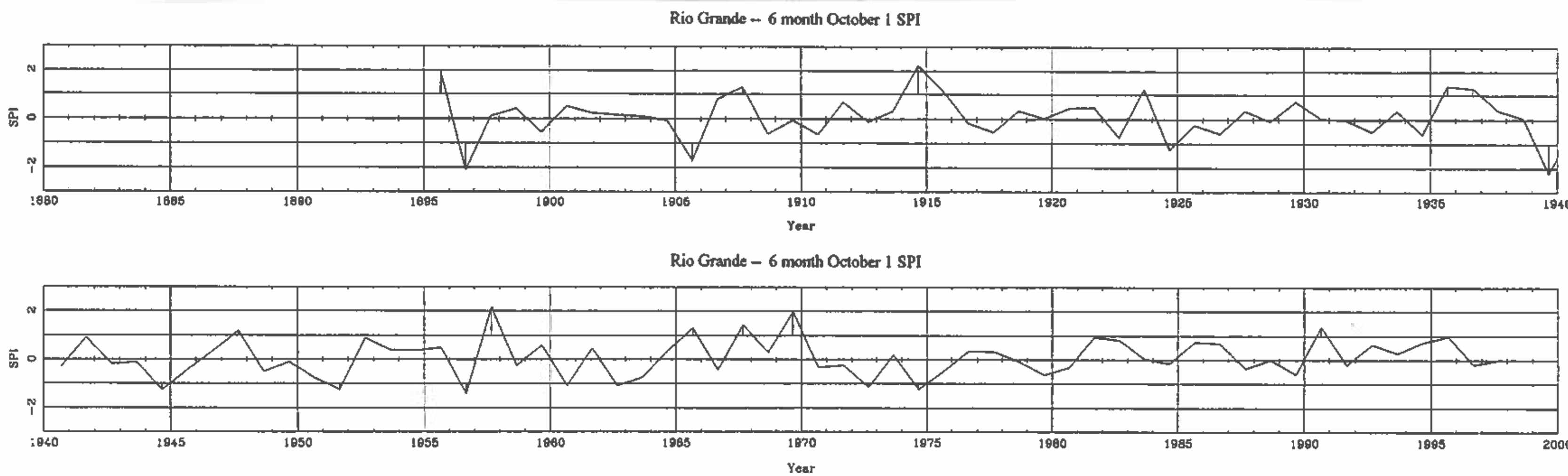


Figure 10e. Regional SPI for the summer season (April-September) for Rio Grande river basin.

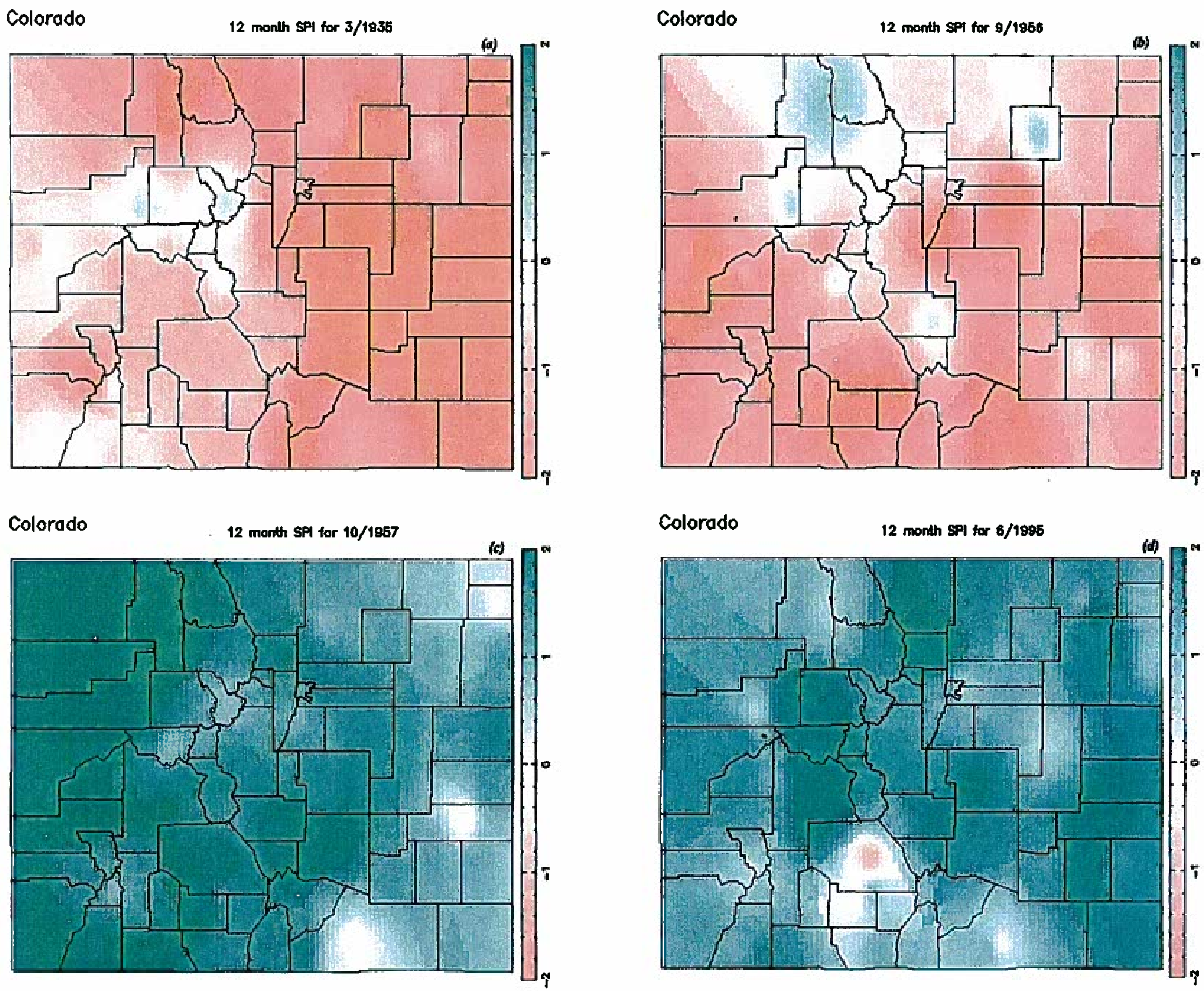


Figure 11. Examples of the extent and severity of Colorado drought events for (a) March 1935 and (b) September 1956 and wet events for (c) October 1957 and (d) June 1995.

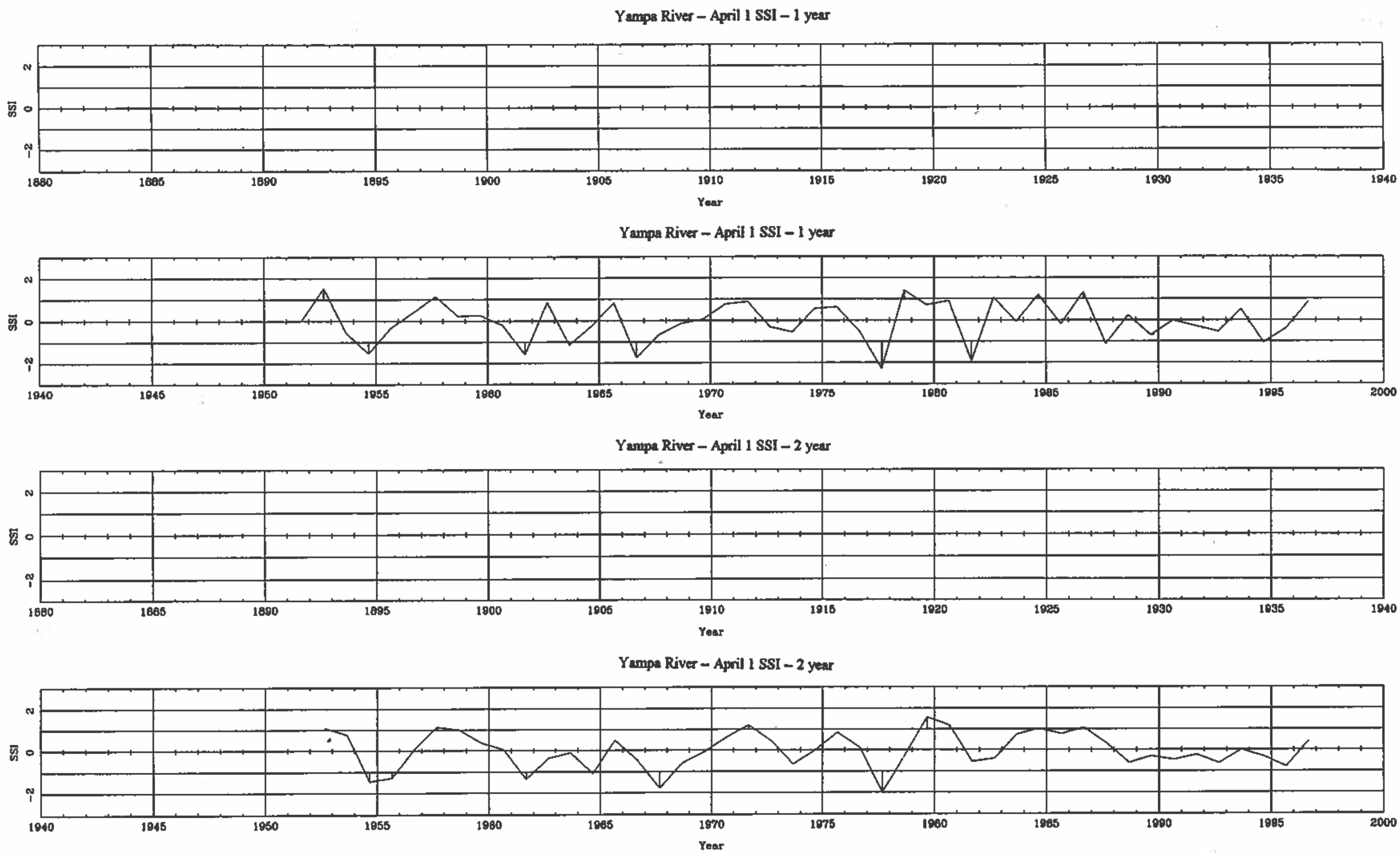


Figure 12a. SSI winter season (October - March) for 1, 2, 4, and 8 years for Yampa river basin.

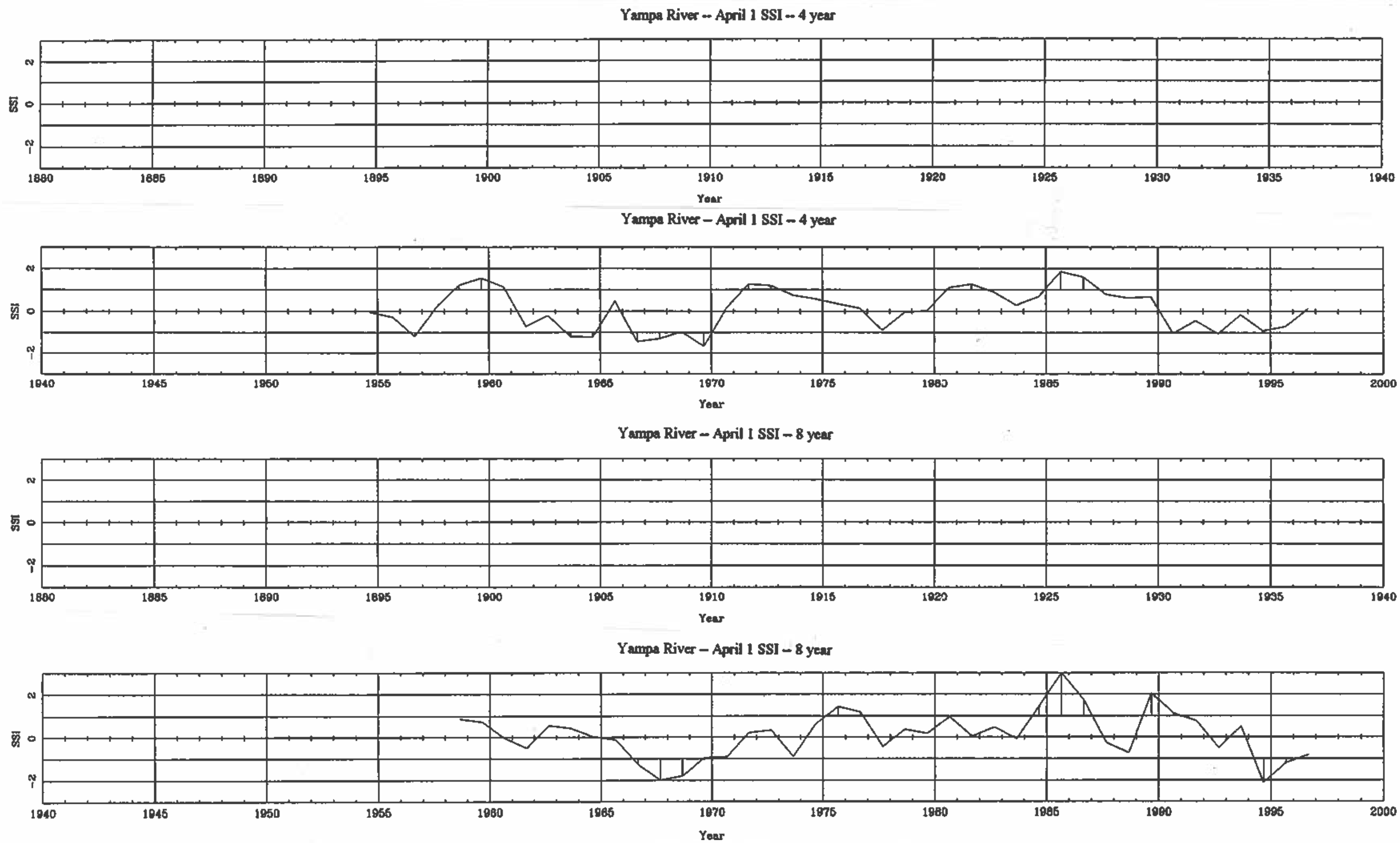


Figure 12a. Continued for Yampa river basin

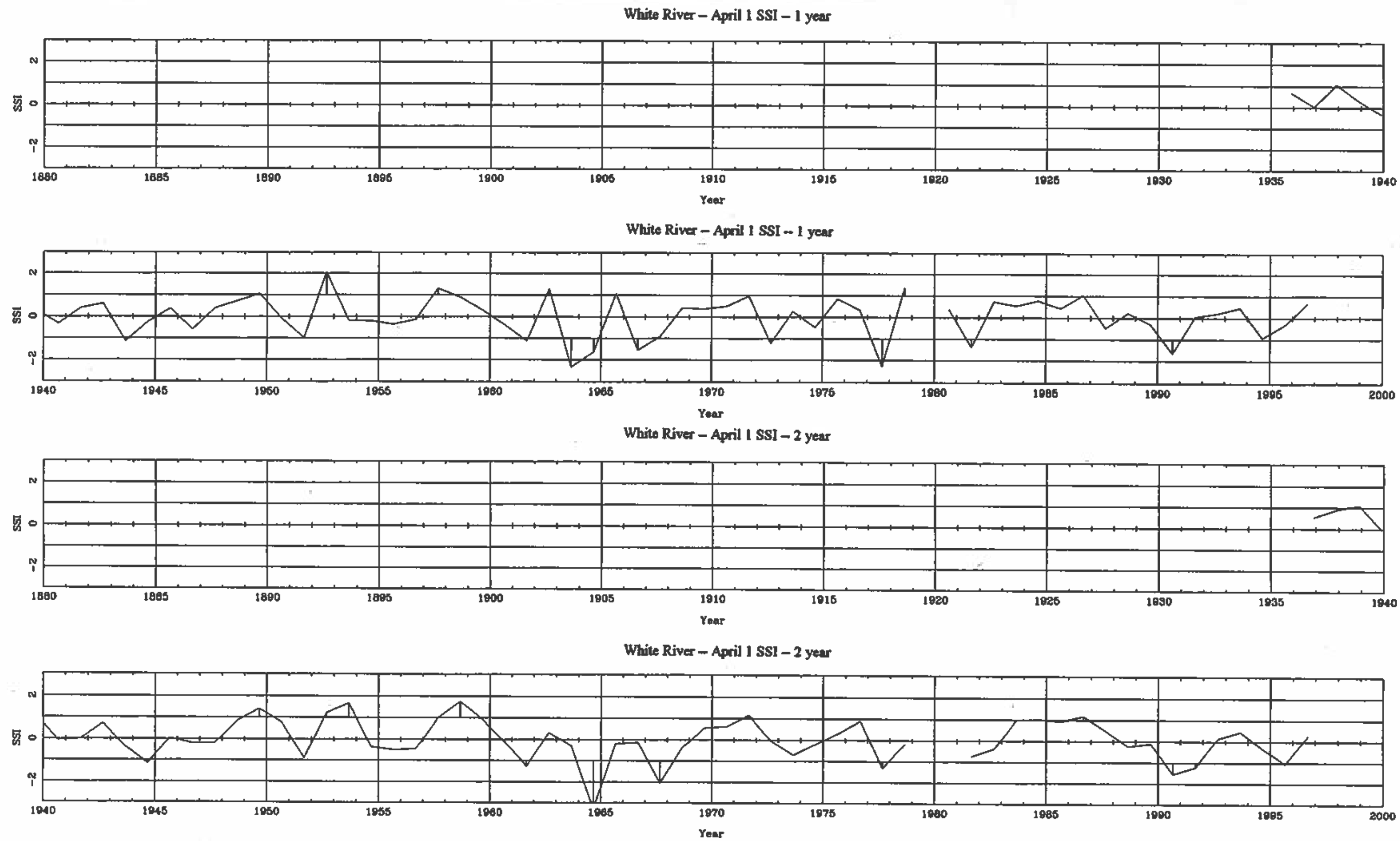


Figure 12b. SSI winter season (October - March) for 1, 2, 4, and 8 years for White river basin.

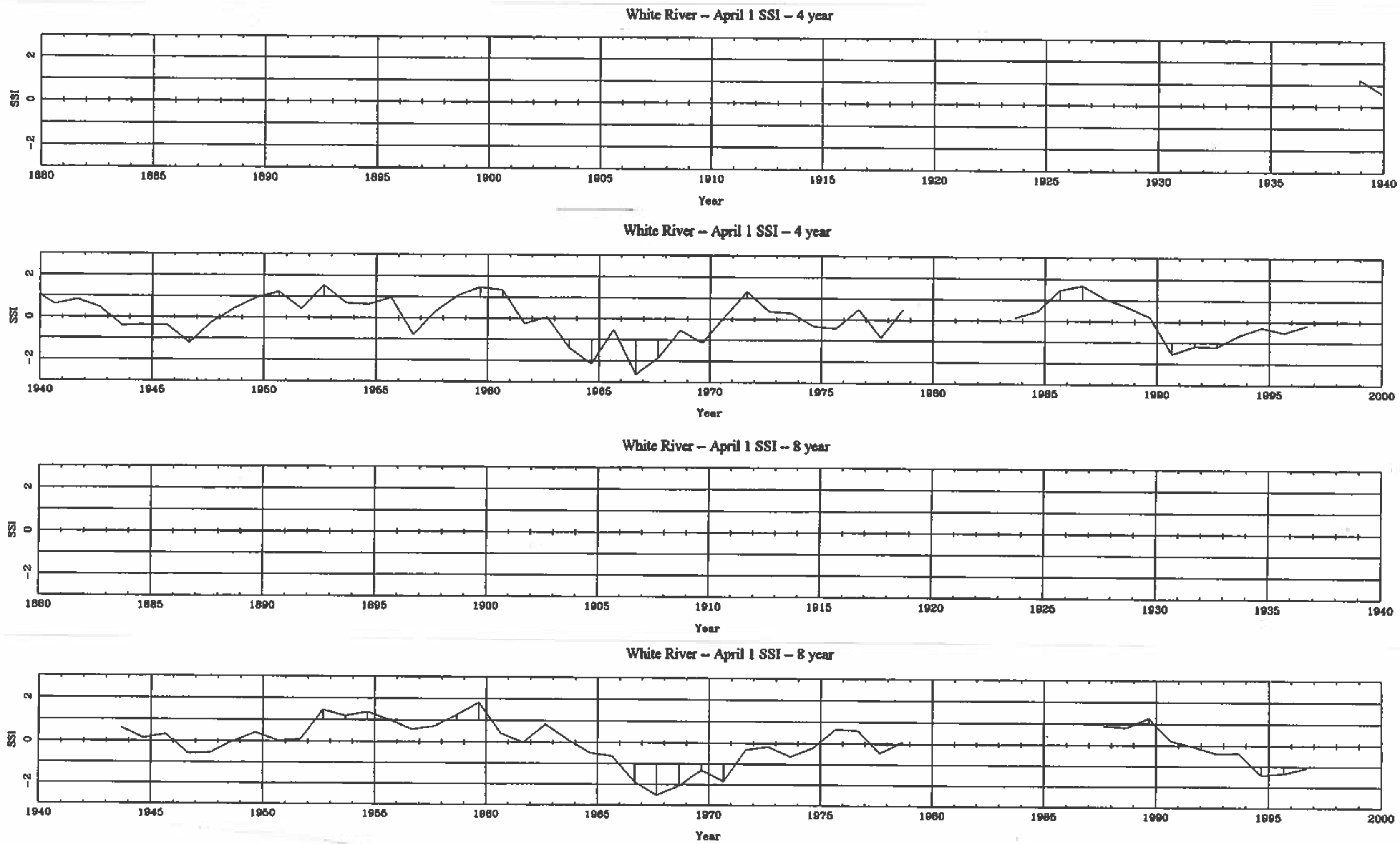


Figure 12b. Continued for White river basin.

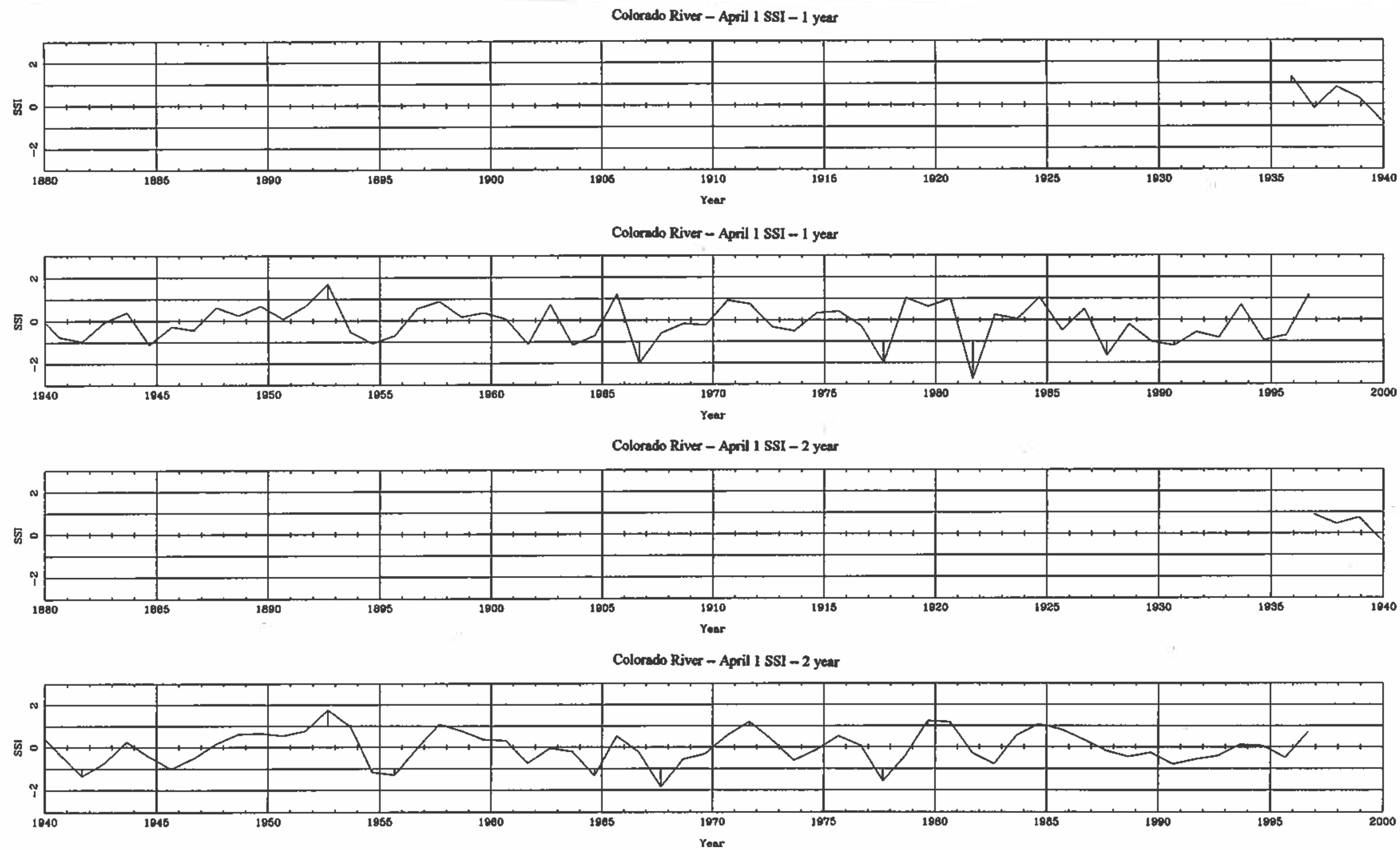


Figure 12c. SSI winter season (October - March) for 1, 2, 4, and 8 years for Colorado river basin.

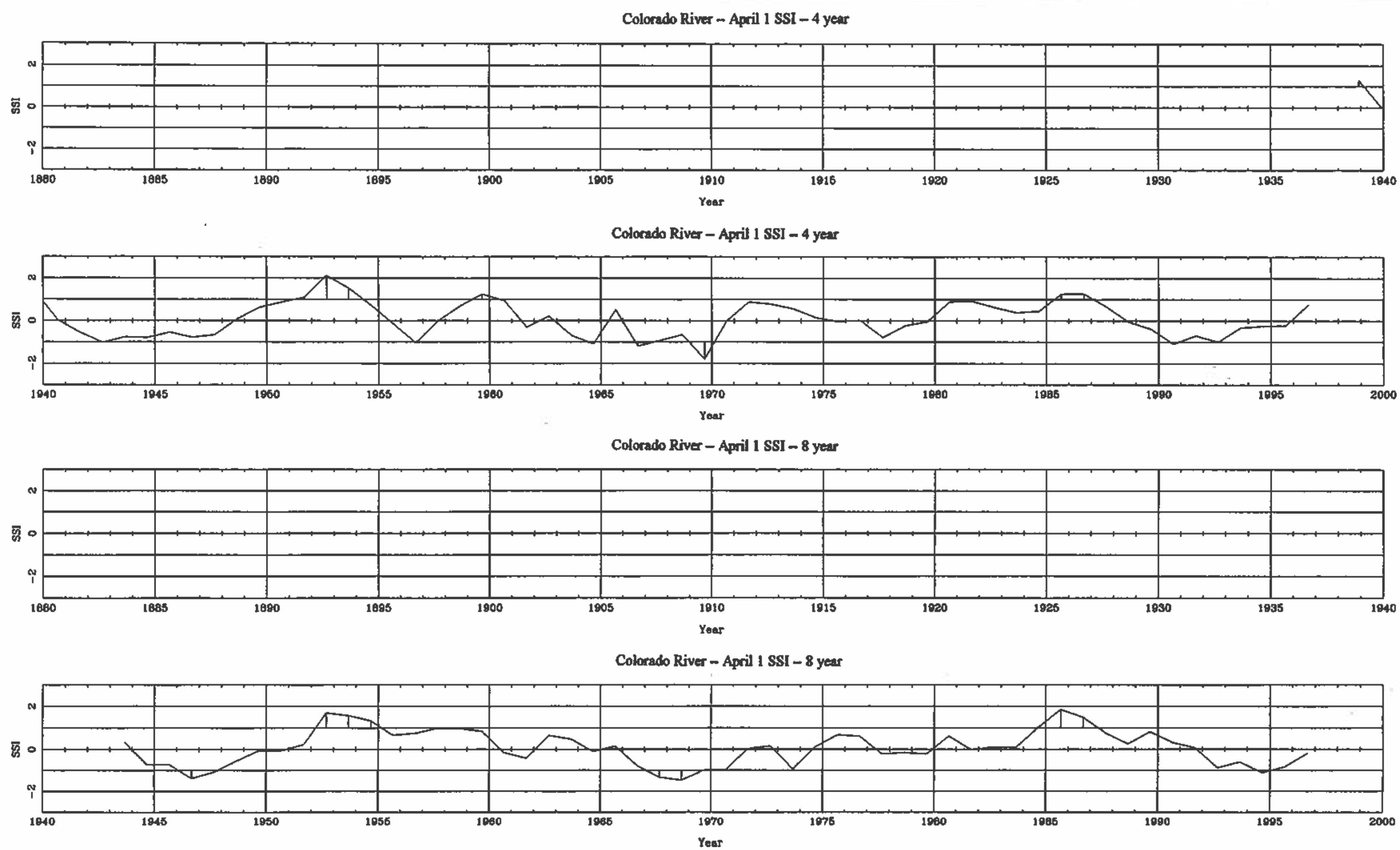


Figure 12c. Continued for Colorado river basin.

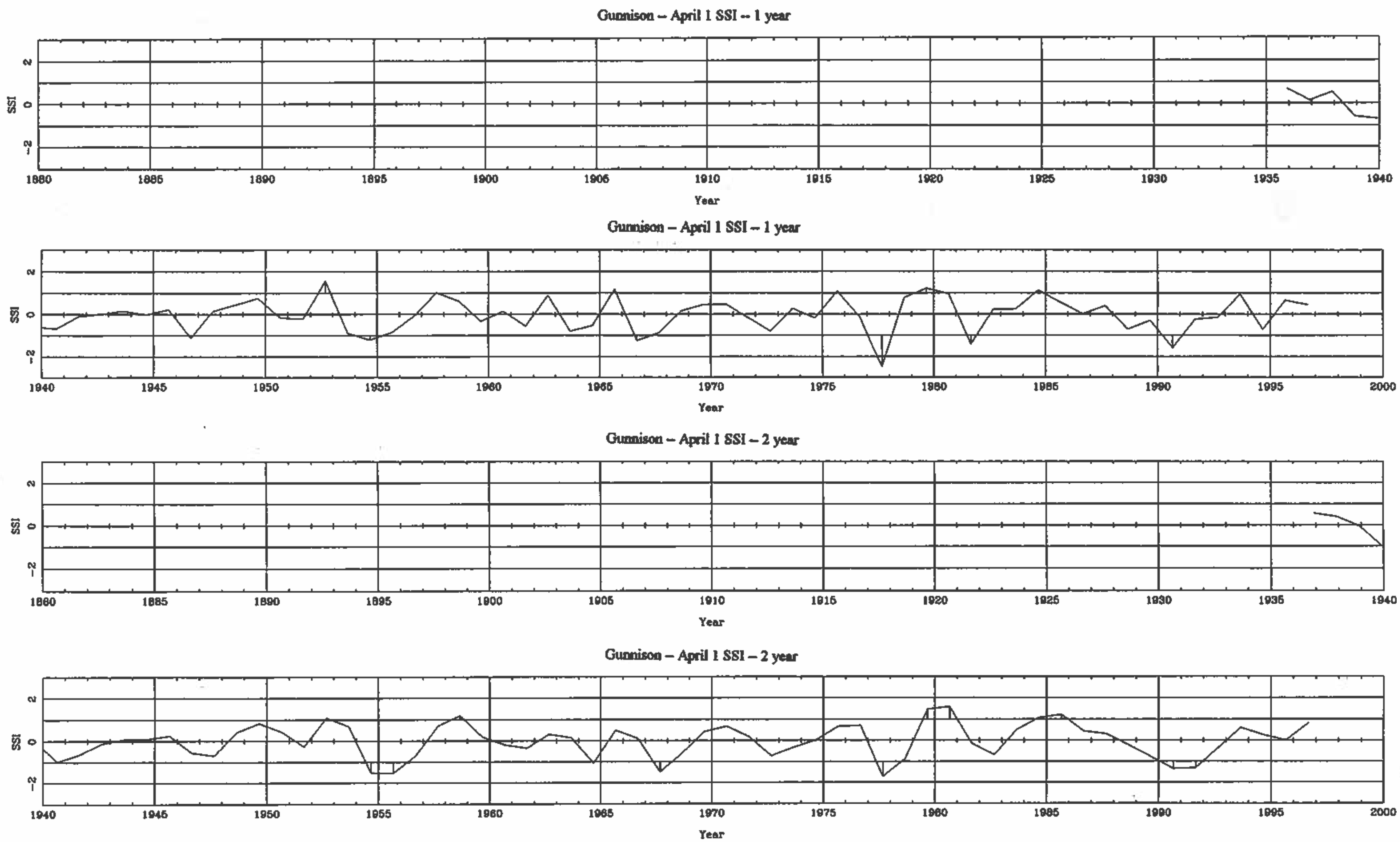


Figure 12d. SSI winter season (October - March) for 1, 2, 4, and 8 years for Gunnison river basin.

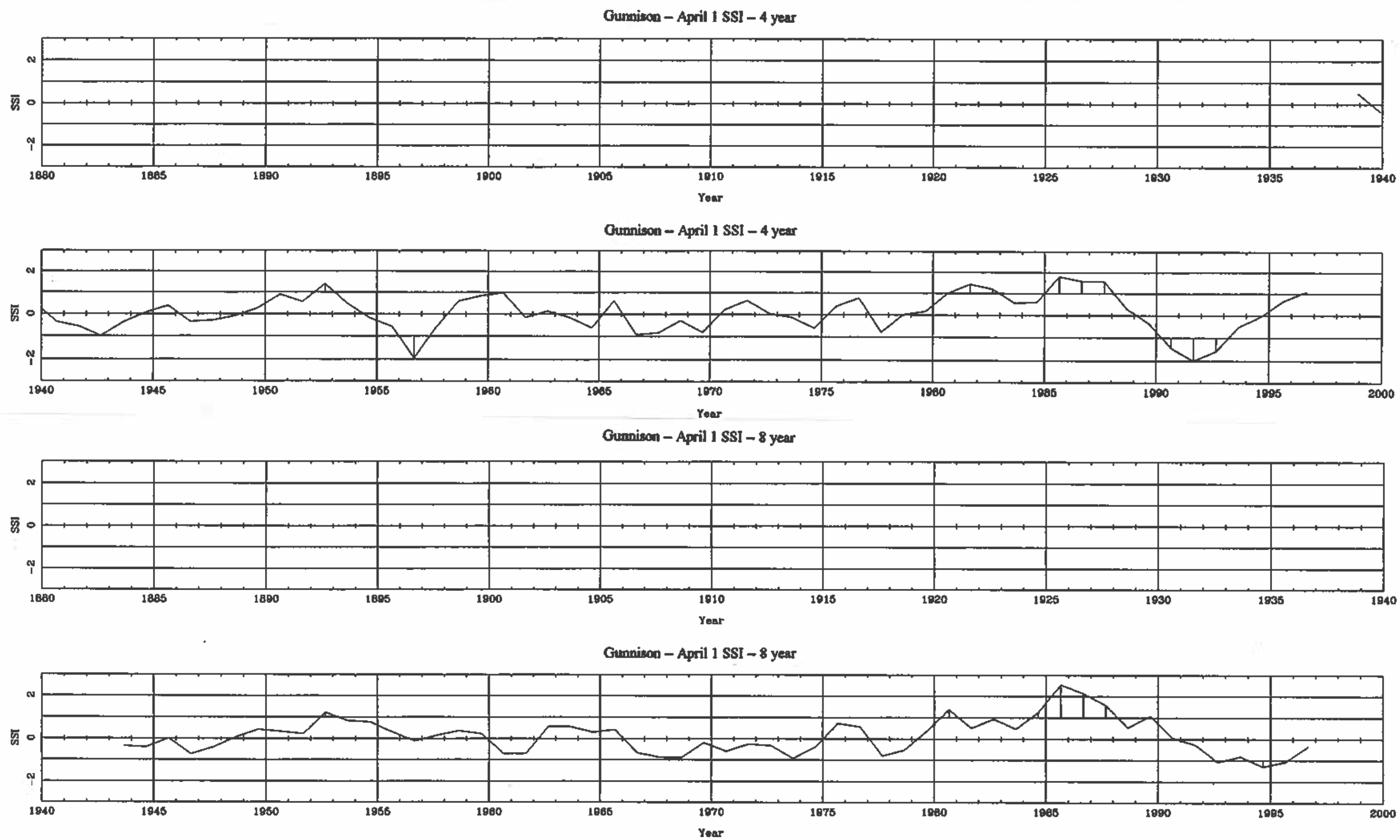


Figure 12d. Continued for Gunnison river basin.

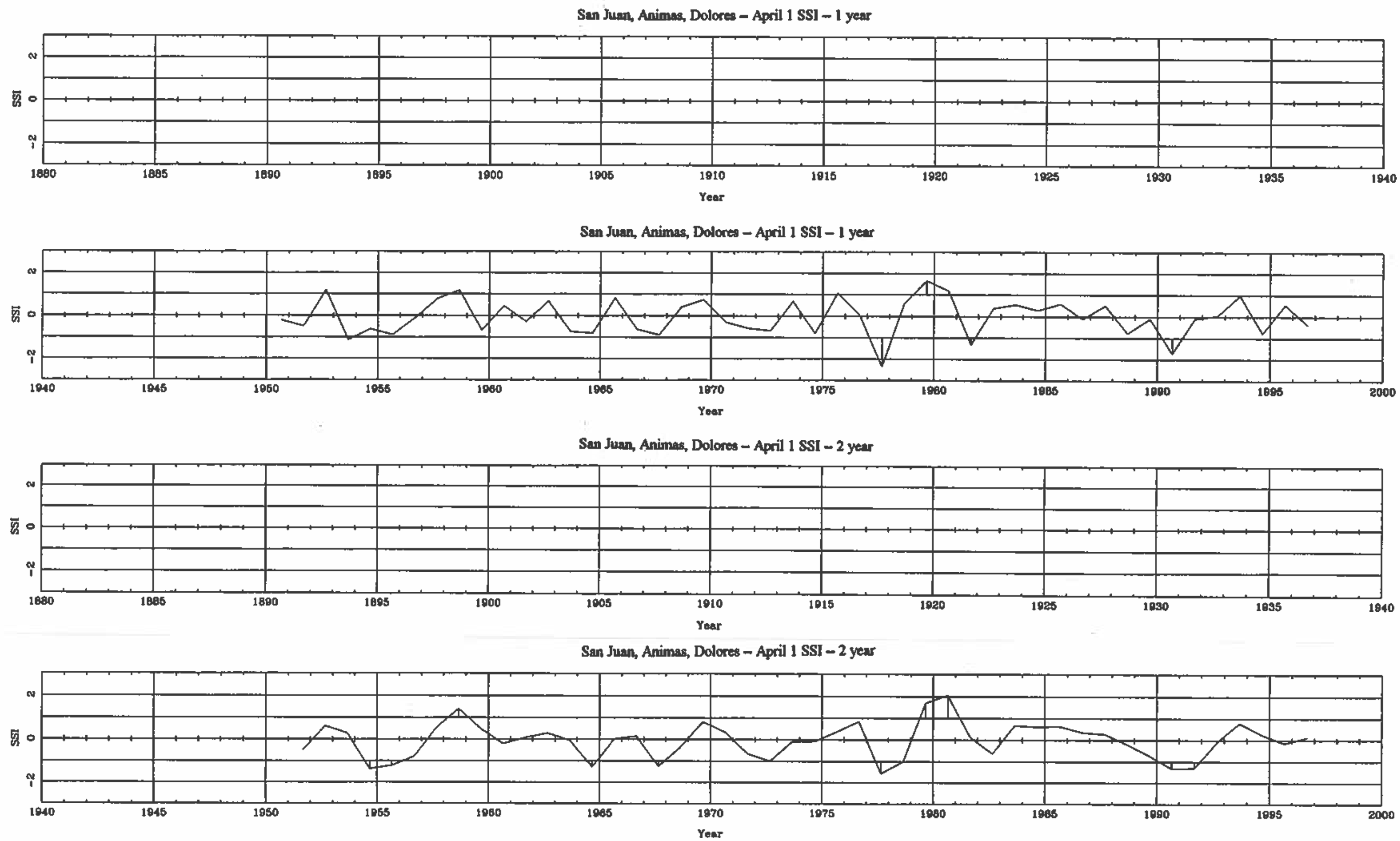


Figure 12e. SSI winter season (October - March) for 1, 2, 4, and 8 years for San Juan, Animas and Dolores river basins.

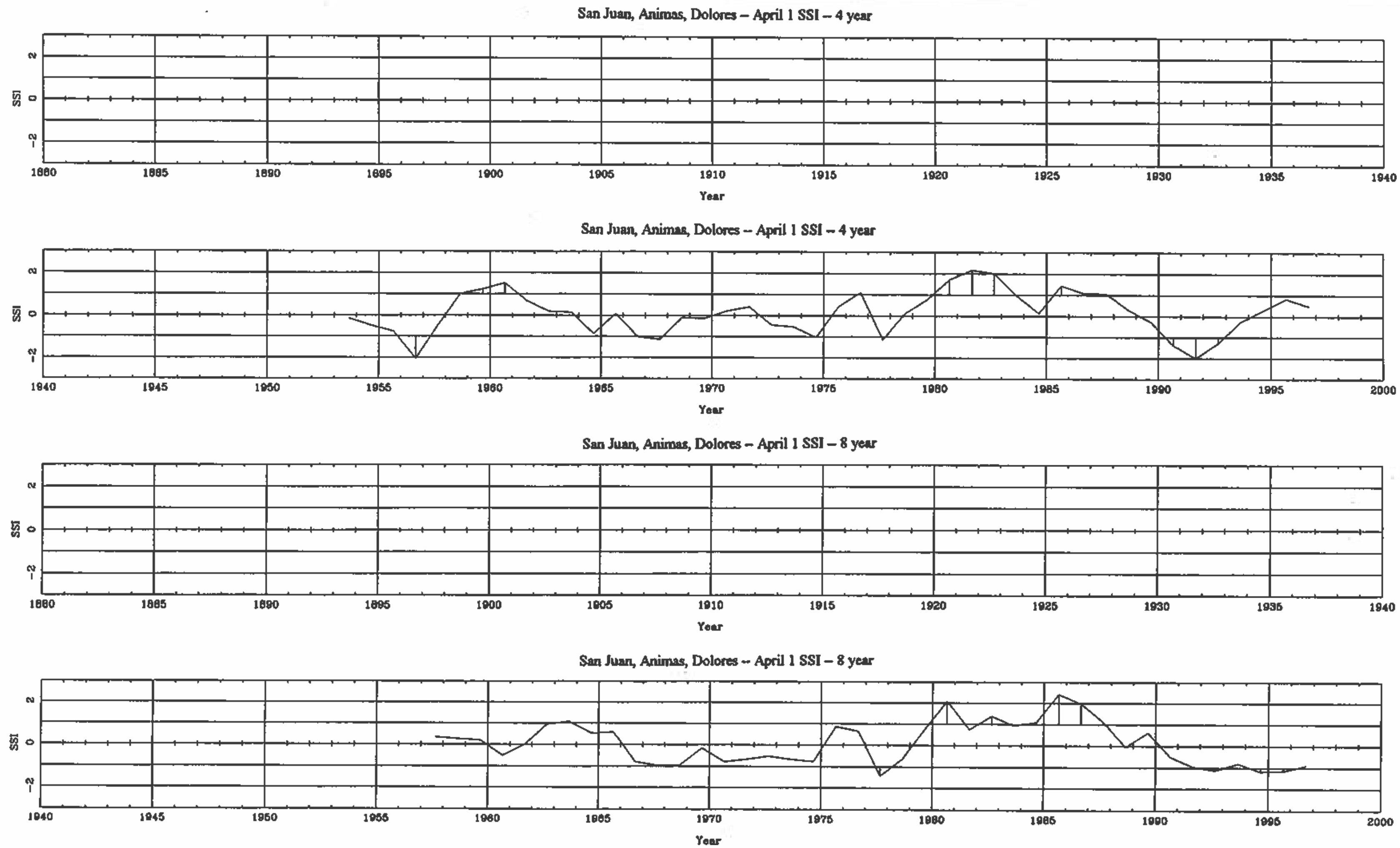


Figure 12e. Continued for San Juan, Animas and Dolores river basins.

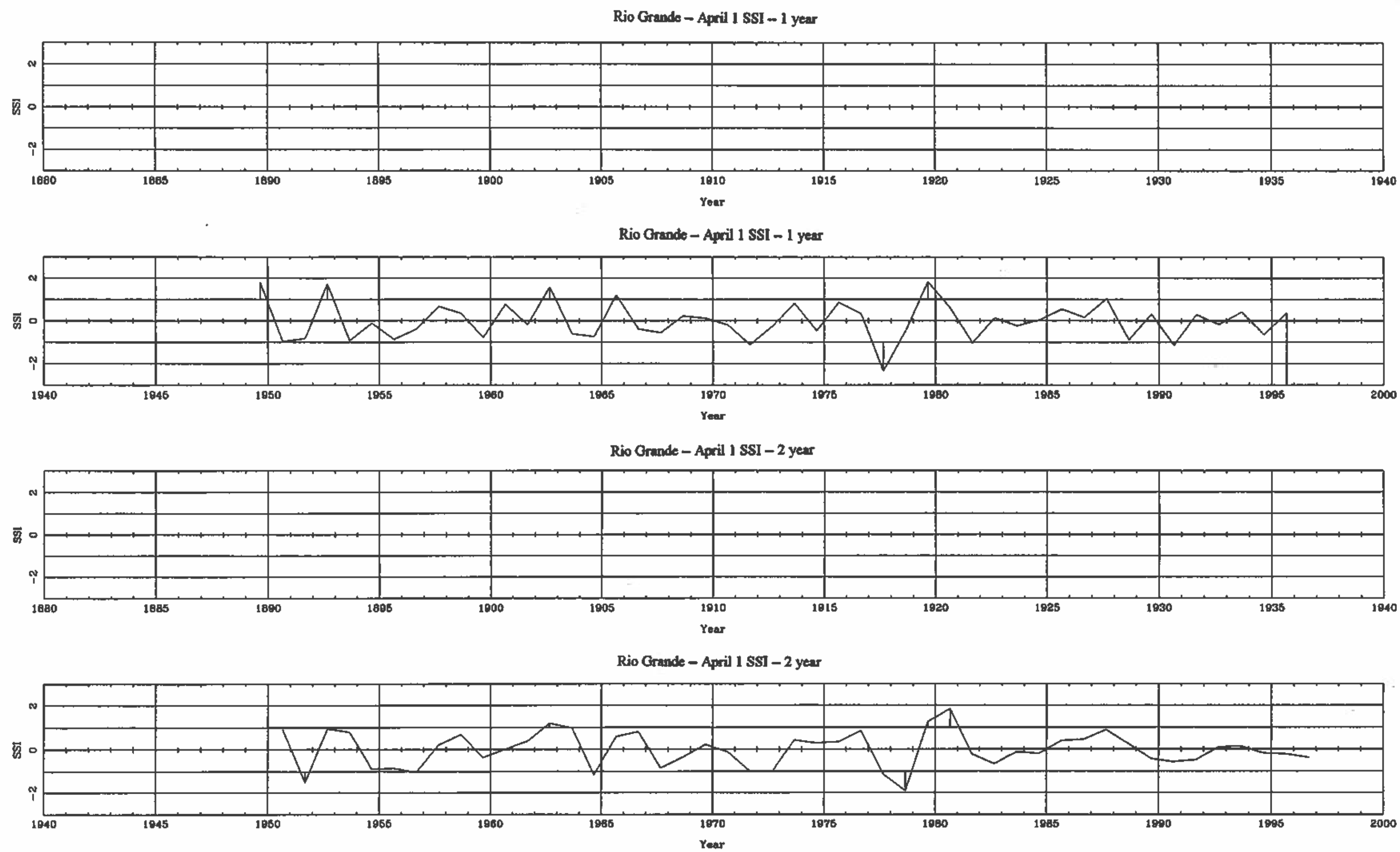


Figure 12f. SSI winter season (October - March) for 1, 2, 4, and 8 years for Rio Grande river basin.

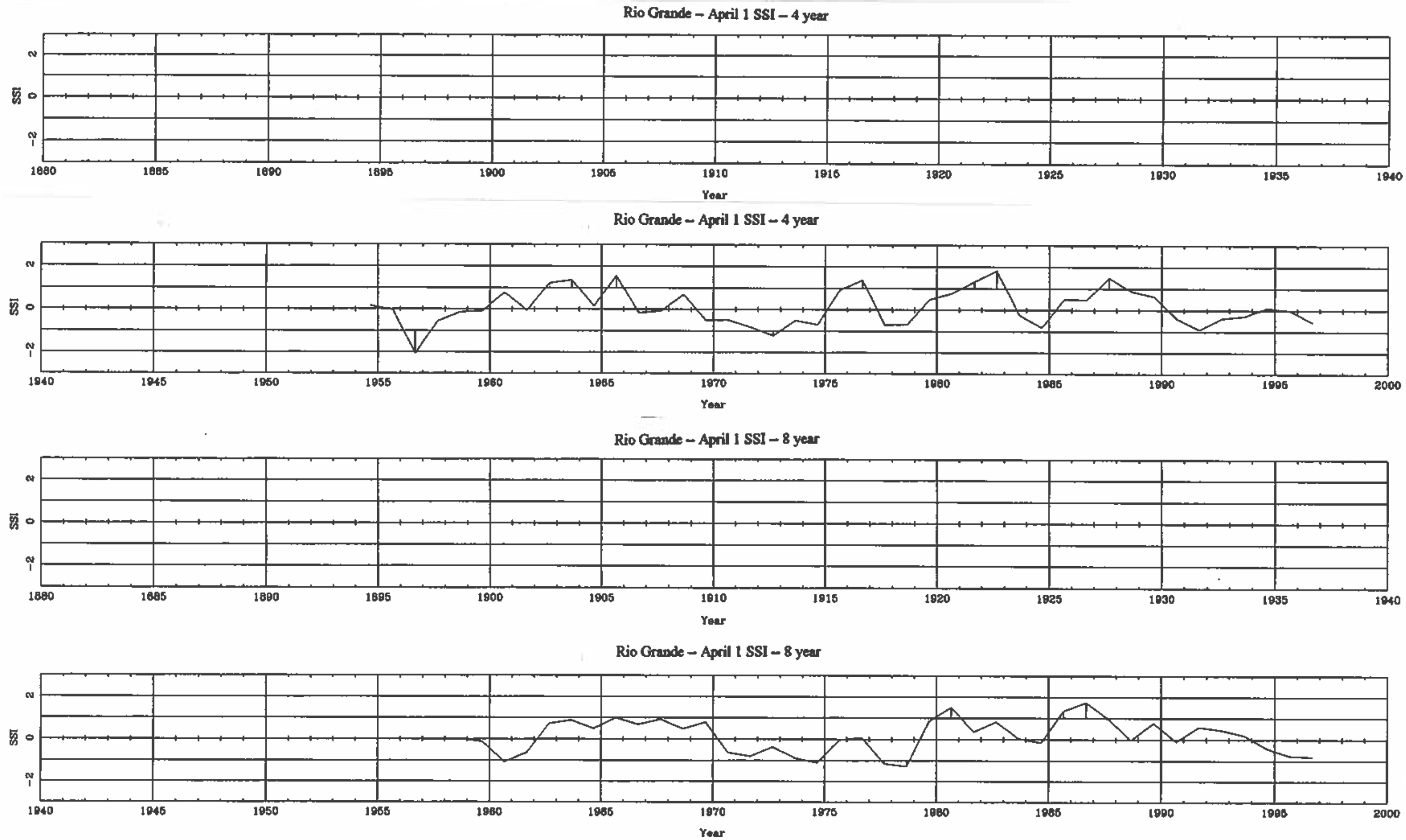


Figure 12f. Continued for Rio Grande river basin.

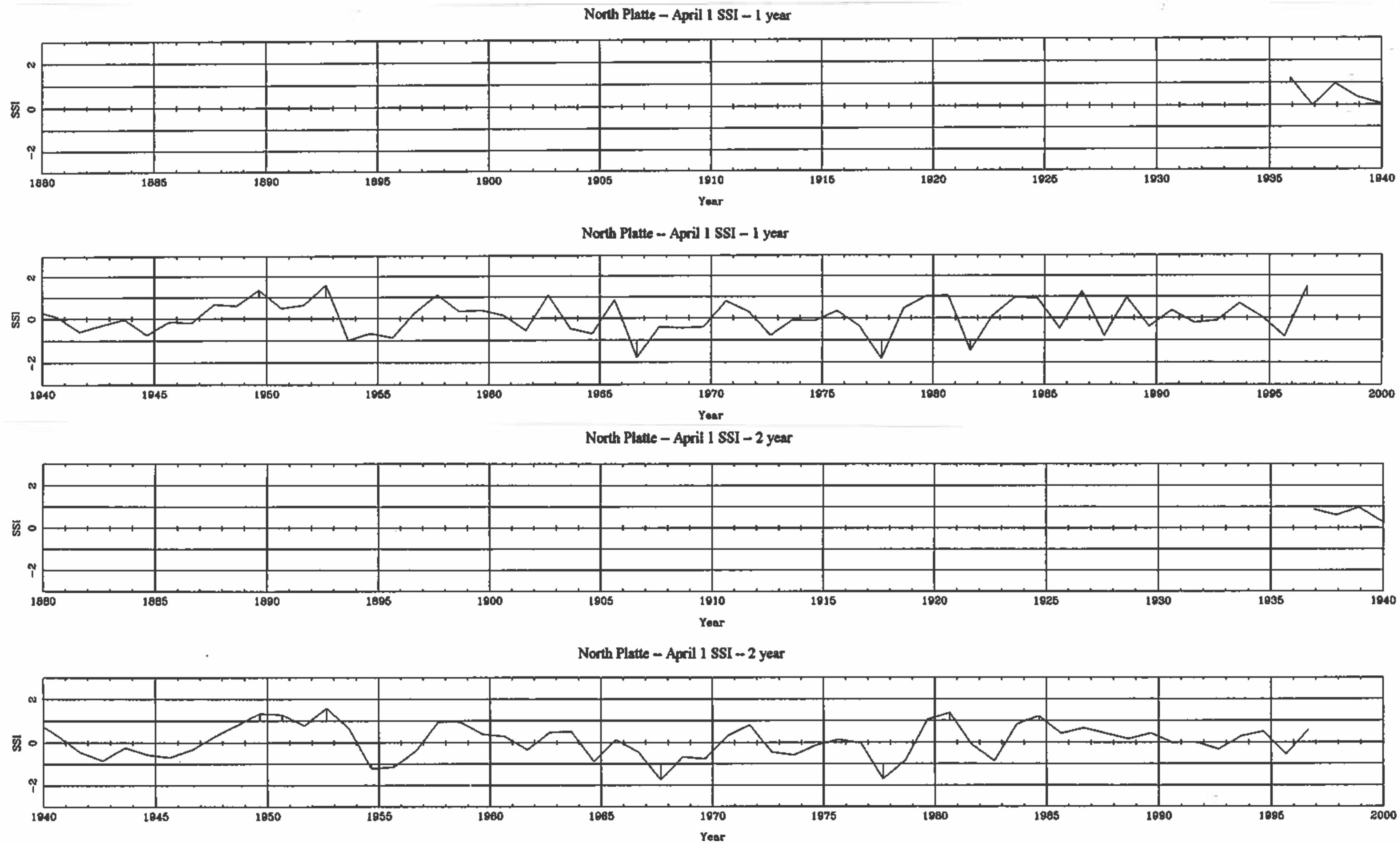


Figure 12g. SSI winter season (October - March) for 1, 2, 4, and 8 years for North Platte river basin.

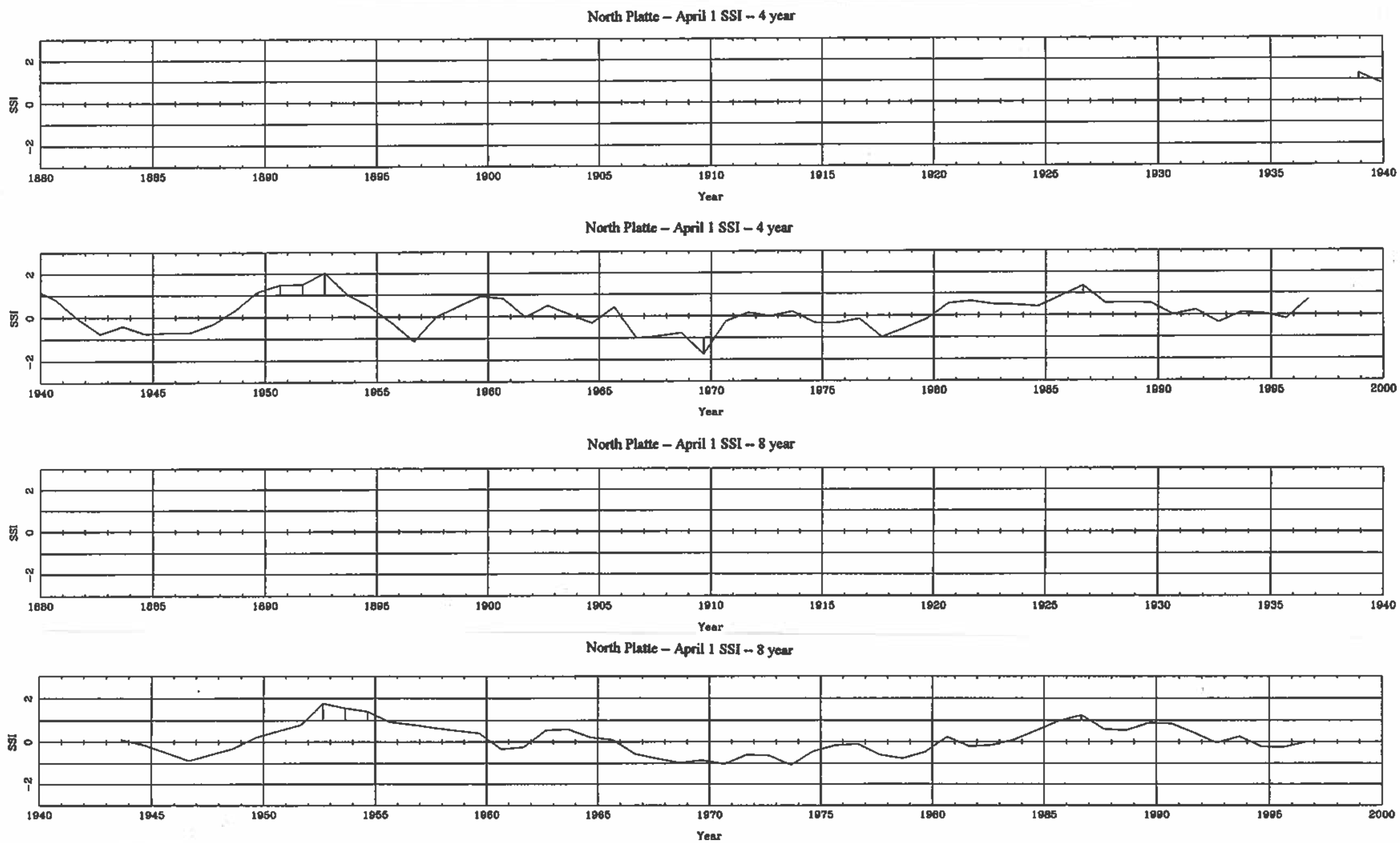


Figure 12g. Continued for North Platte river basin.

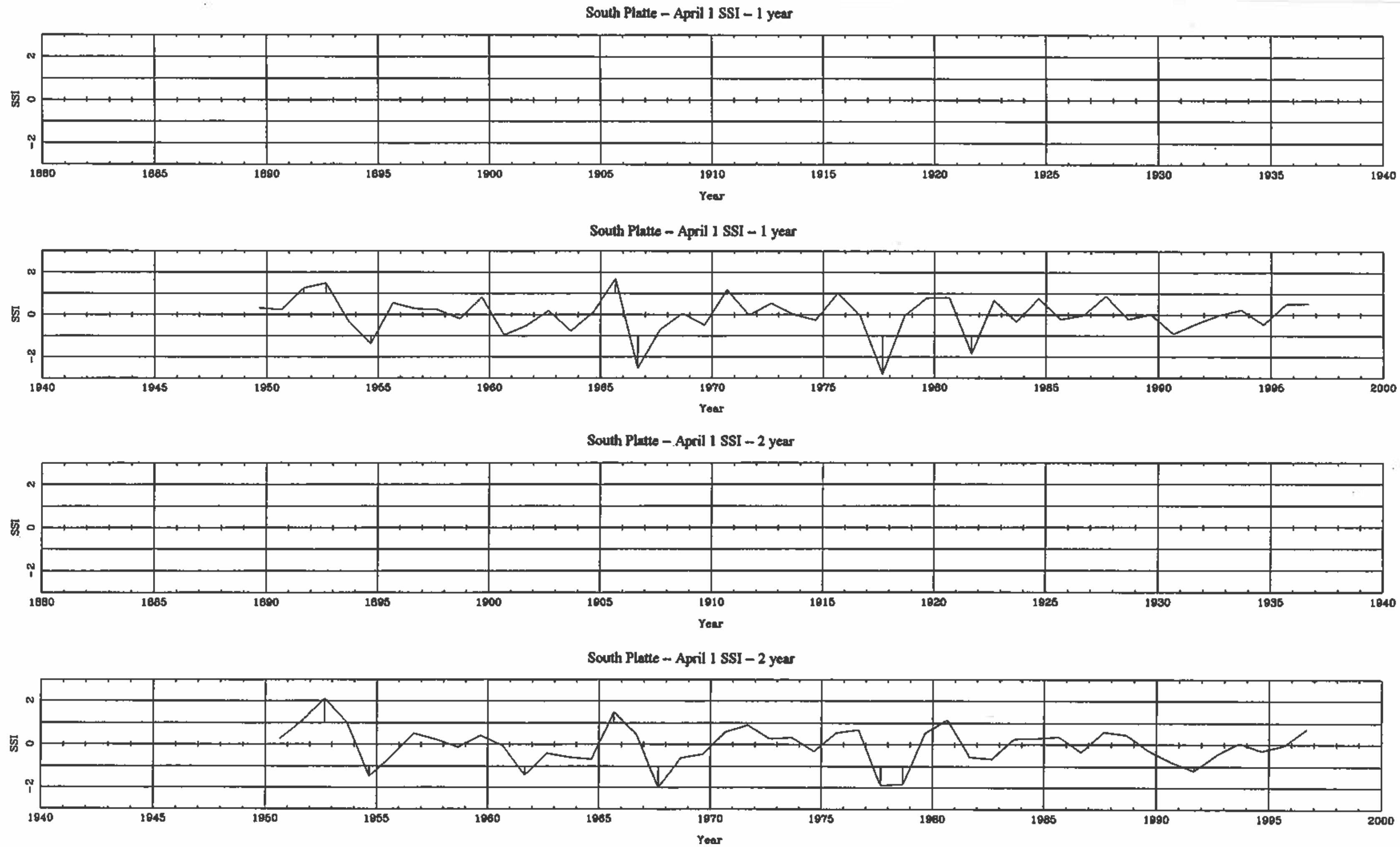


Figure 12h. SSI winter season (October - March) for 1, 2, 4, and 8 years for South Platte river basin.

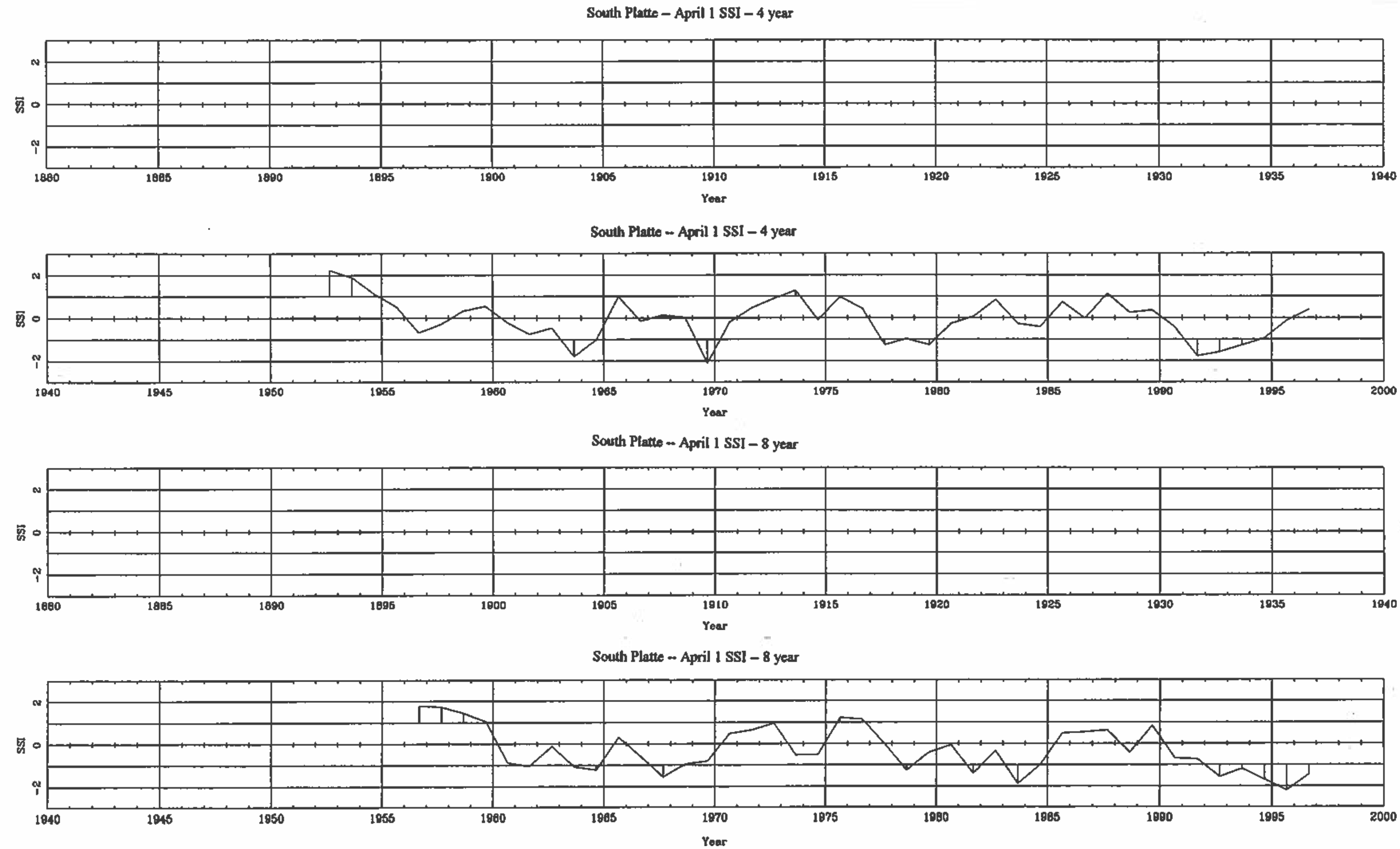


Figure 12h. Continued for South Platte river basin.

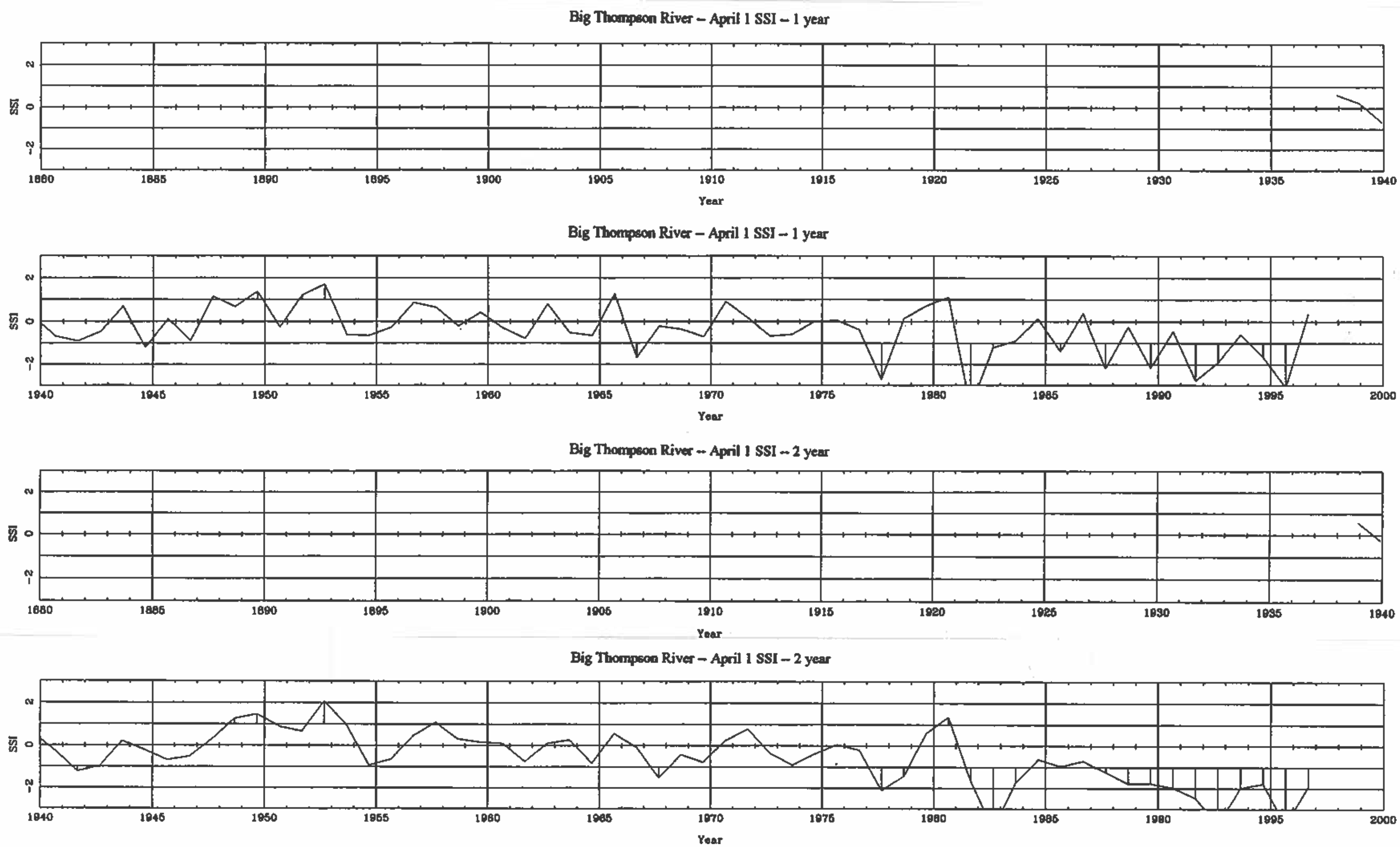


Figure 12i. SSI winter season (October - March) for 1, 2, 4, and 8 years for Big Thompson river basin.

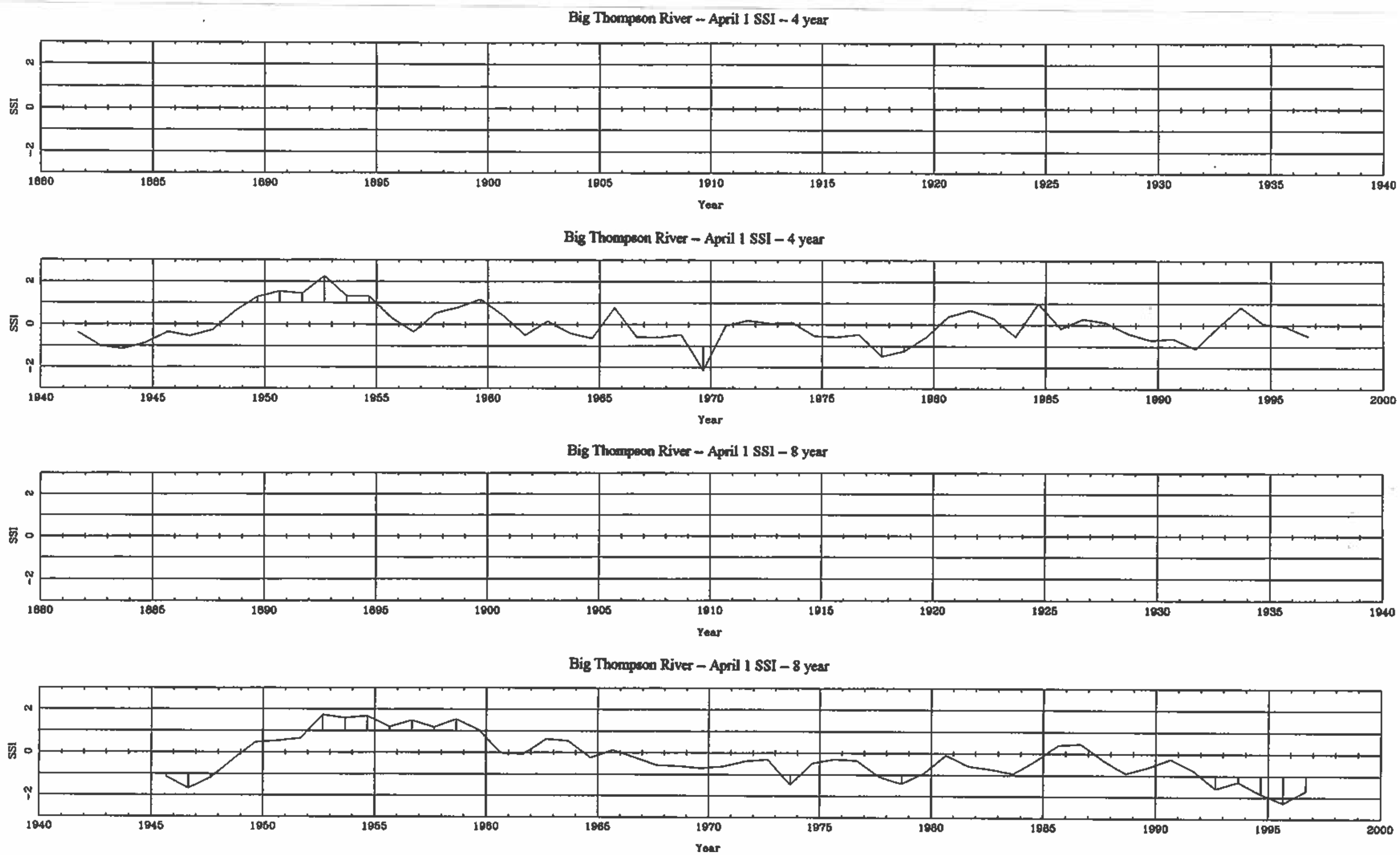


Figure 12i. Continued for Big Thompson river basin.

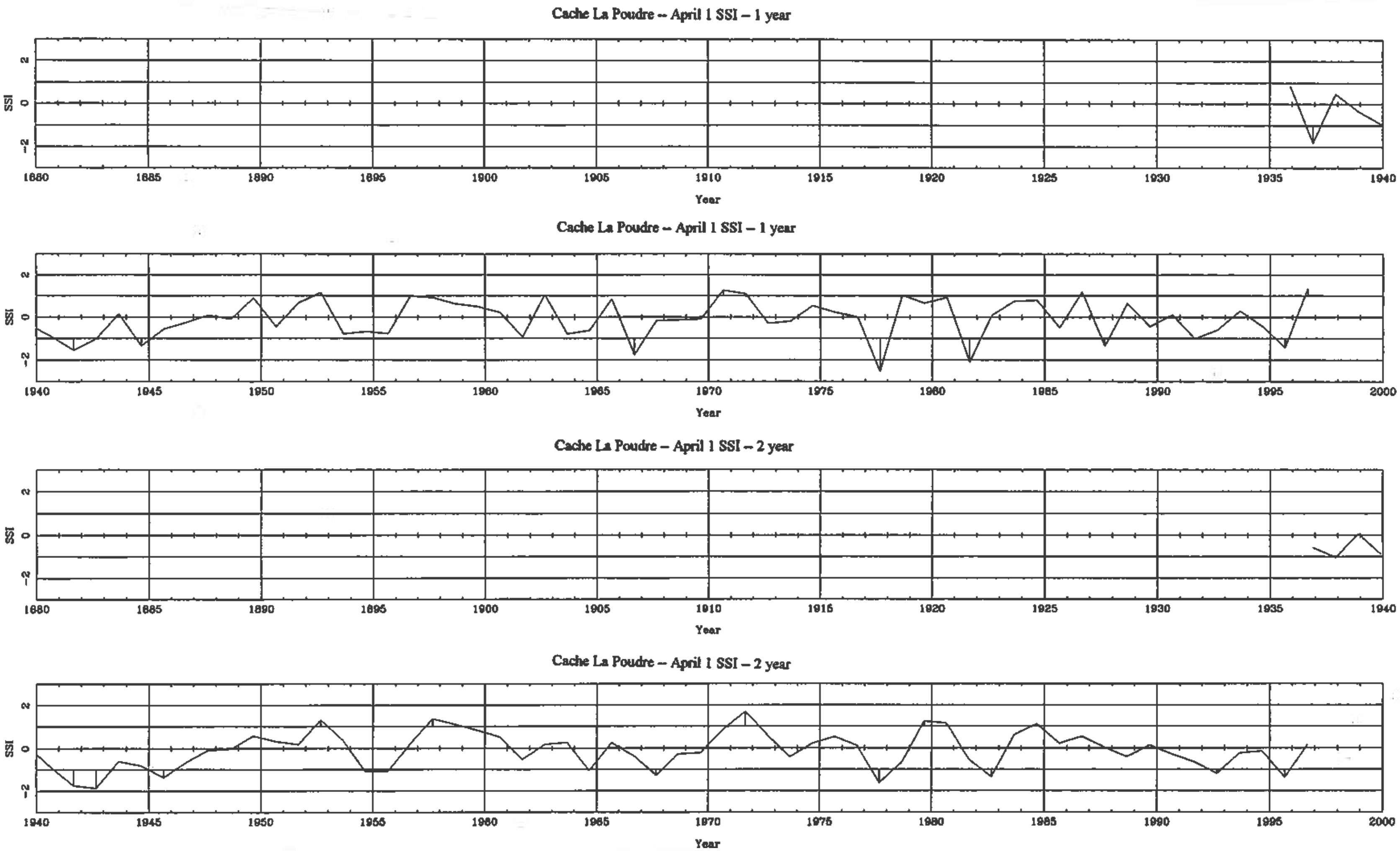


Figure 12j. SSI winter season (October - March) for 1, 2, 4, and 8 years for Cache La Poudre river basin.

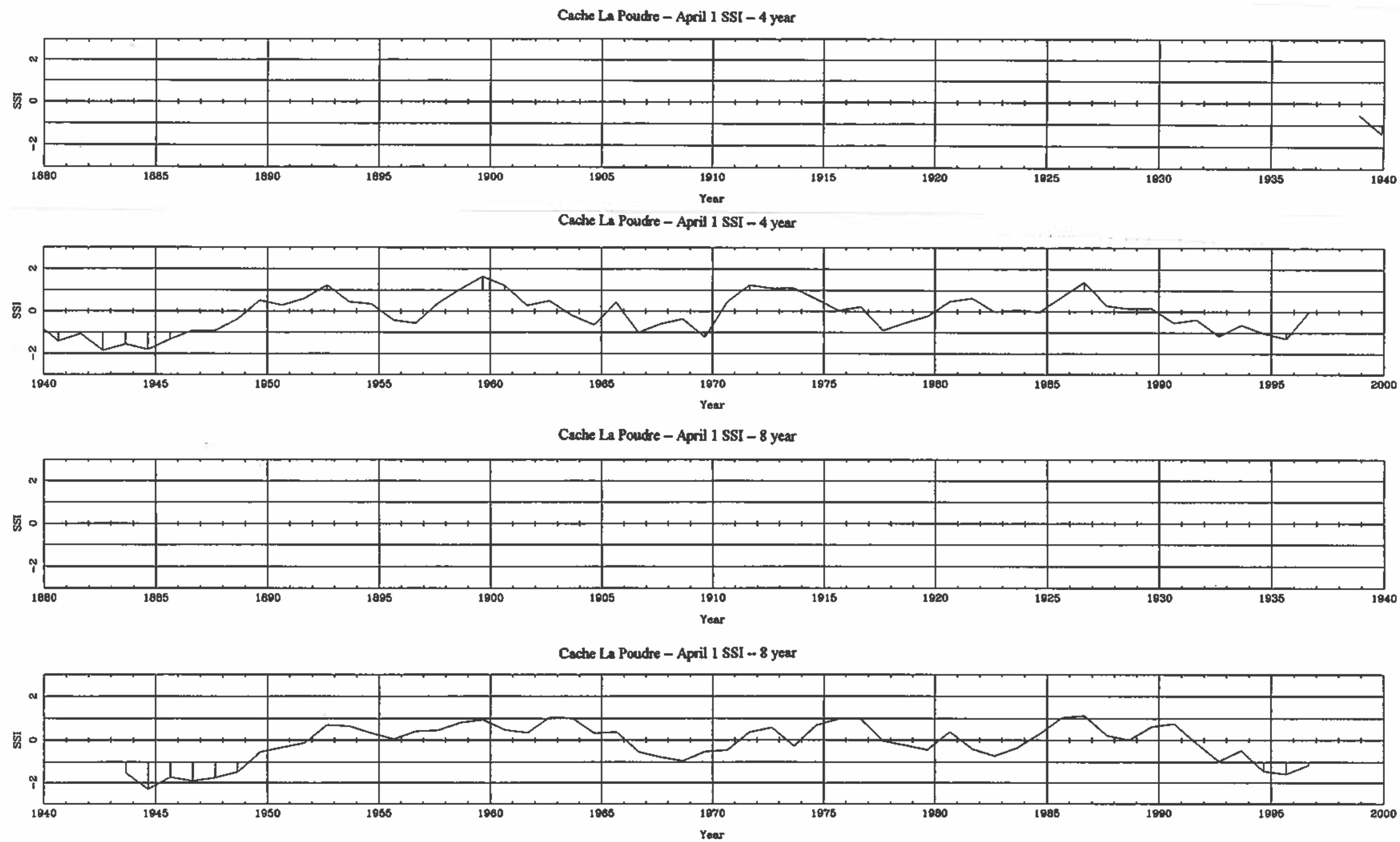


Figure 12j. Continued for Cache La Poudre river basin.

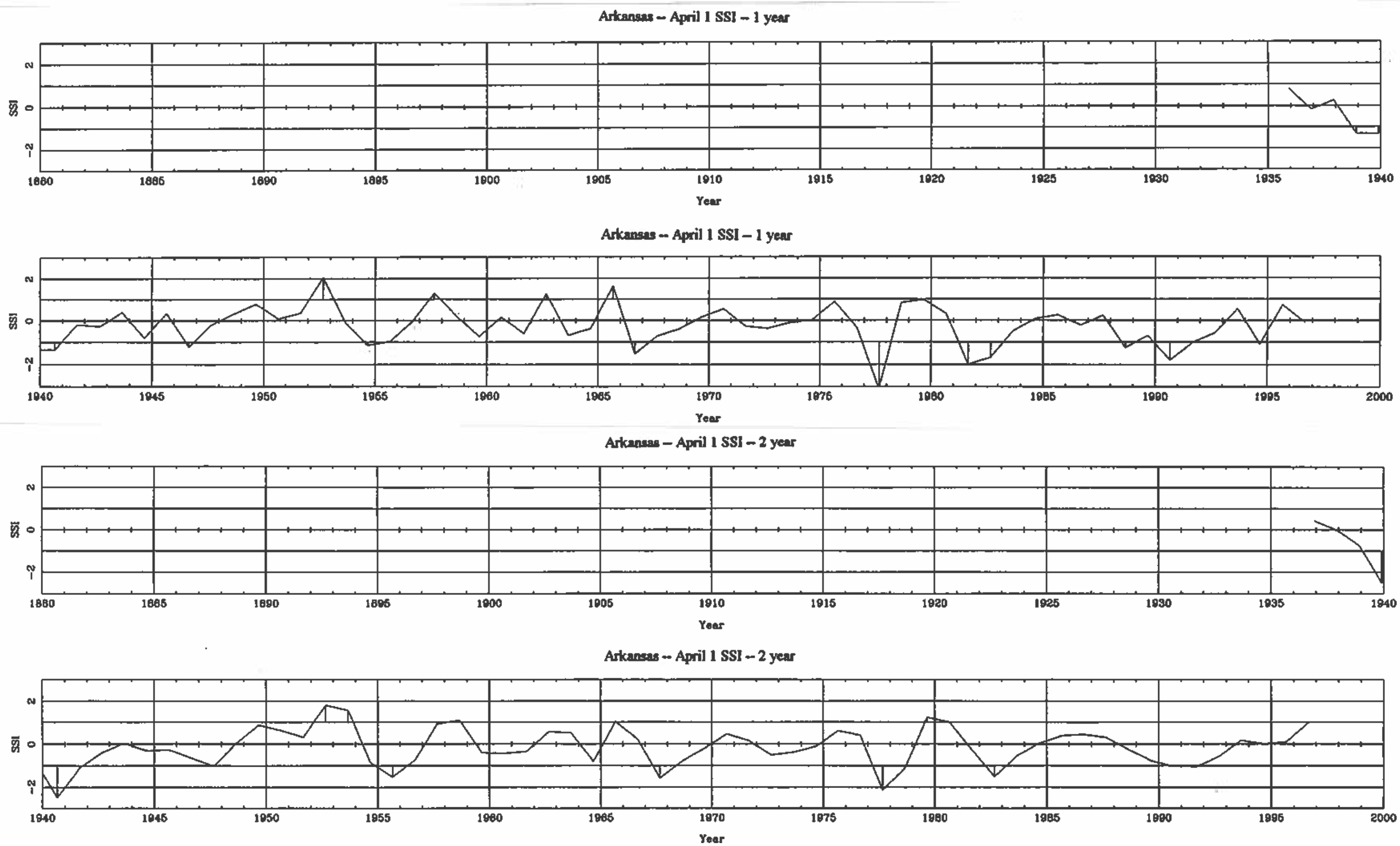


Figure 12k. SSI winter season (October - March) for 1, 2, 4, and 8 years for Arkansas river basin.

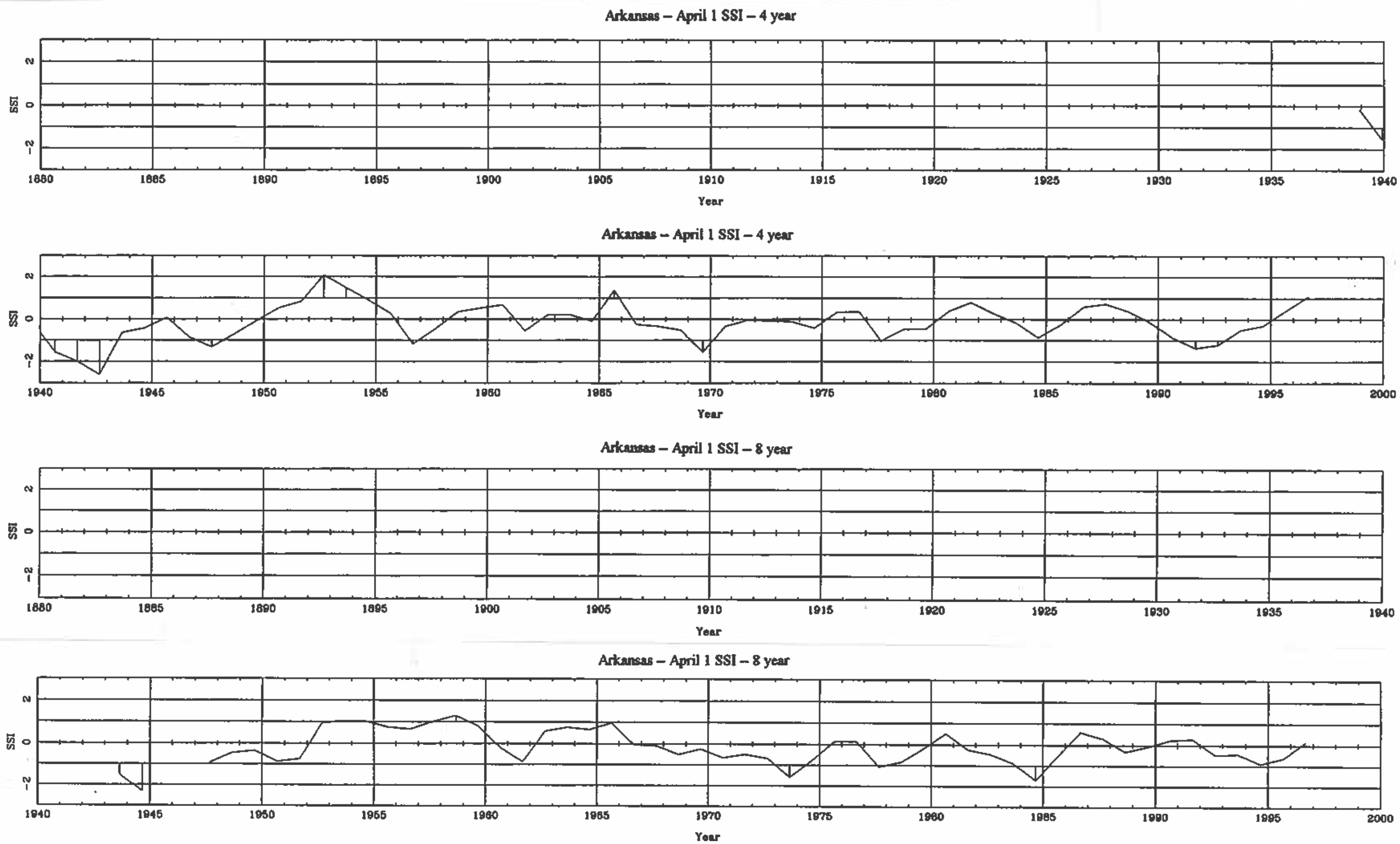
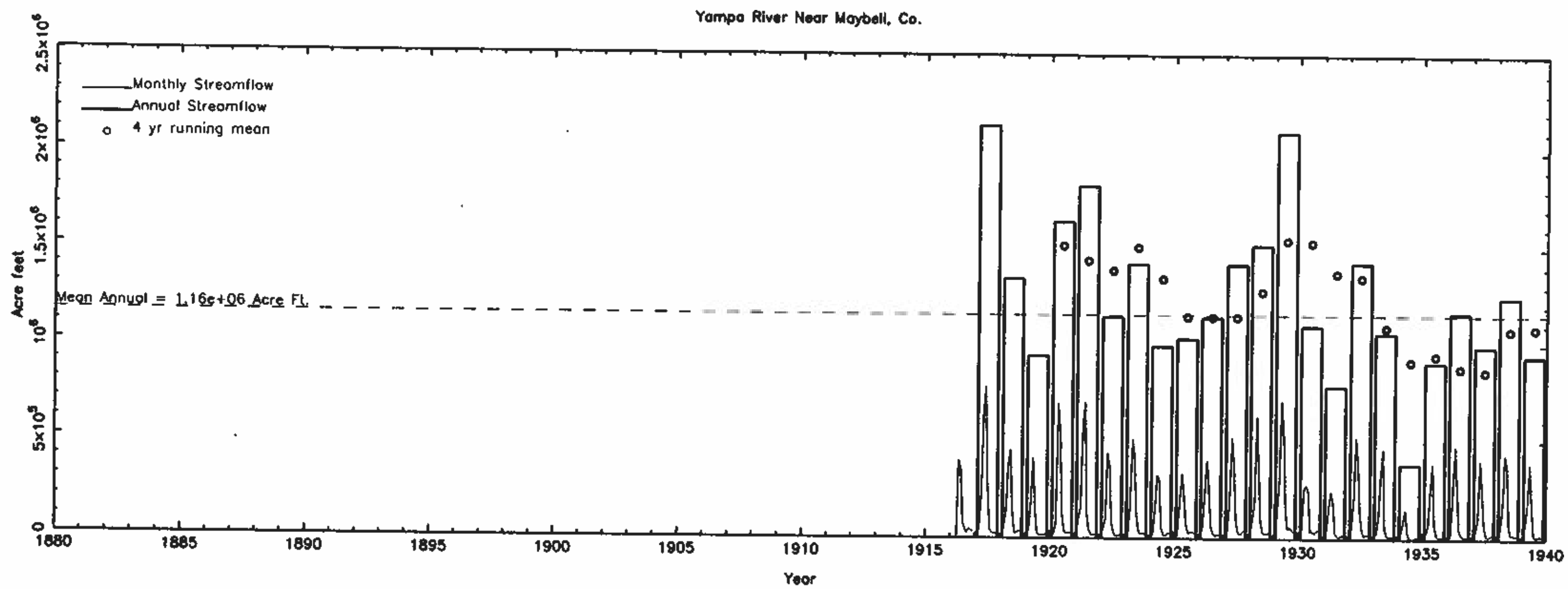


Figure 12k. Continued for Arkansas river basin.



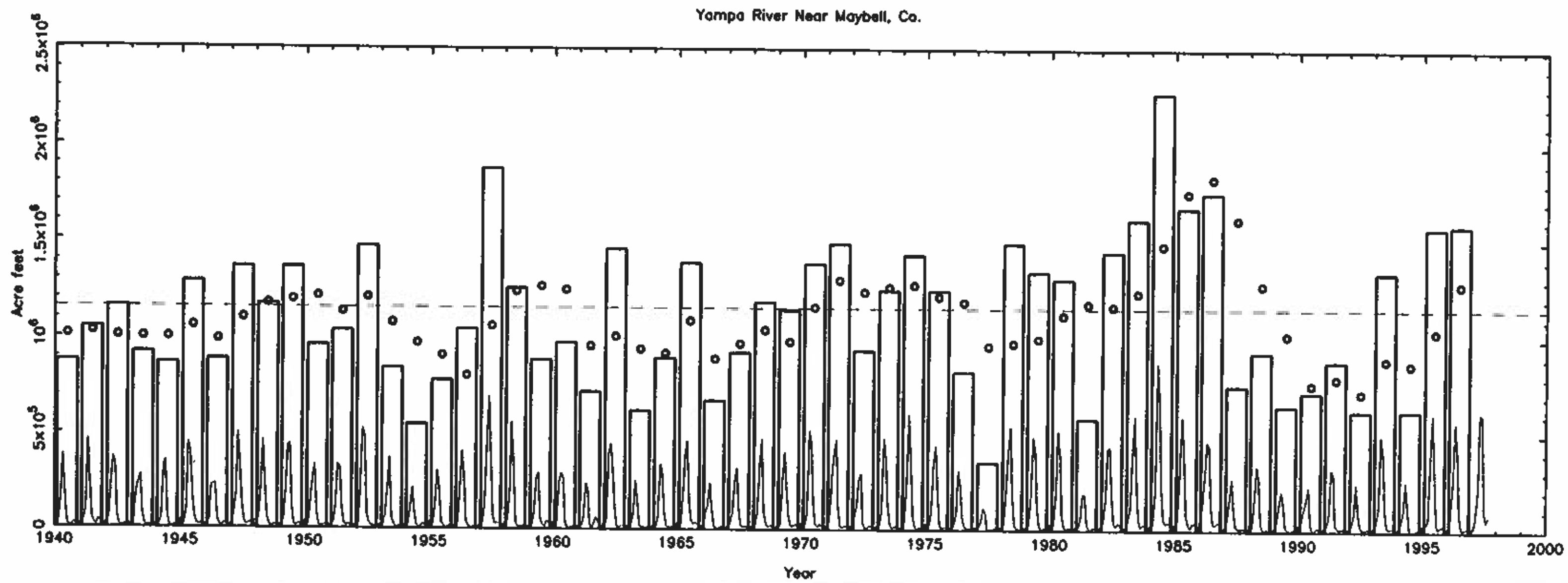


Figure 13a. Observed streamflow for Yampa river near Maybell, Colorado.

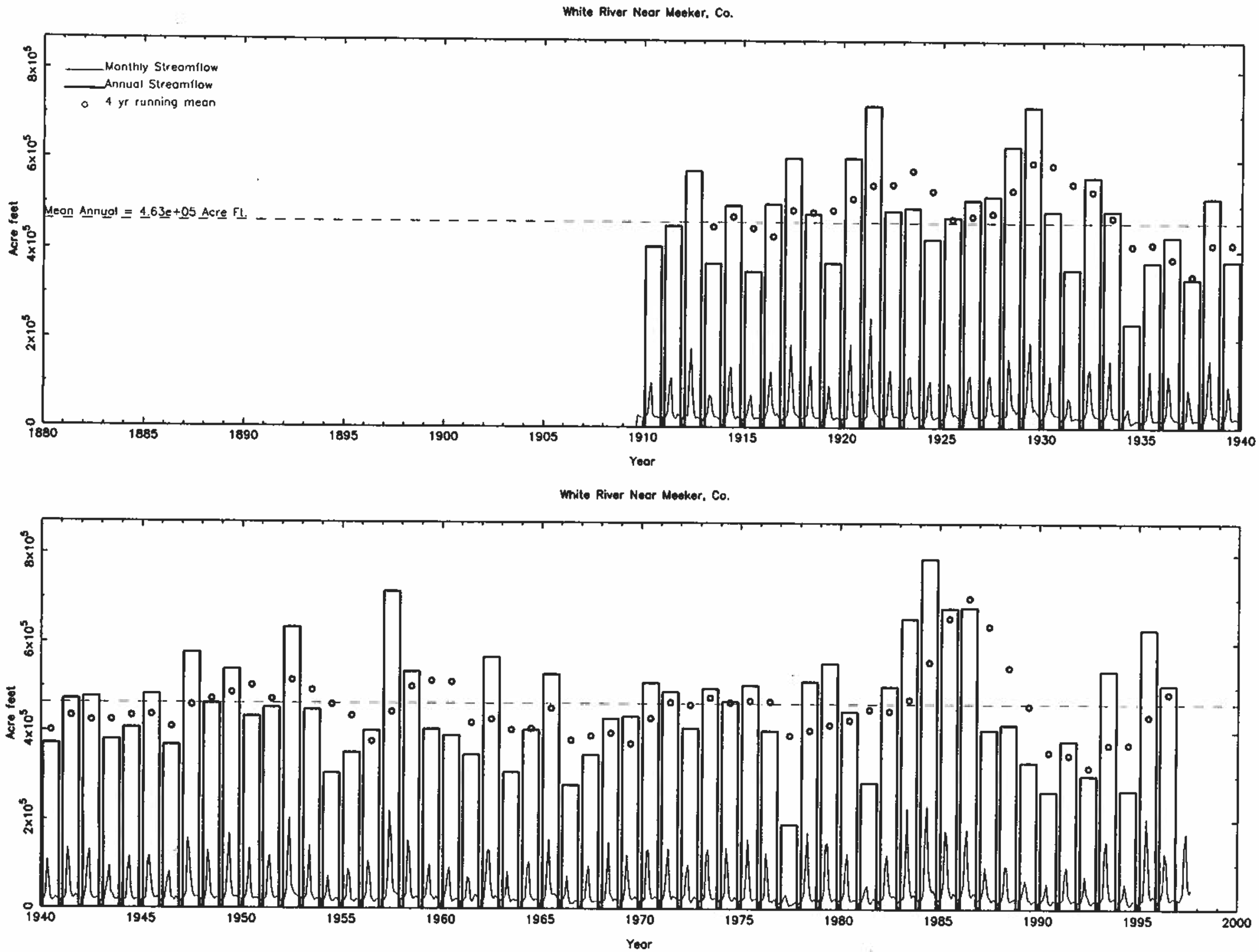


Figure 13b. Observed streamflow for White river near Meeker, Colorado.

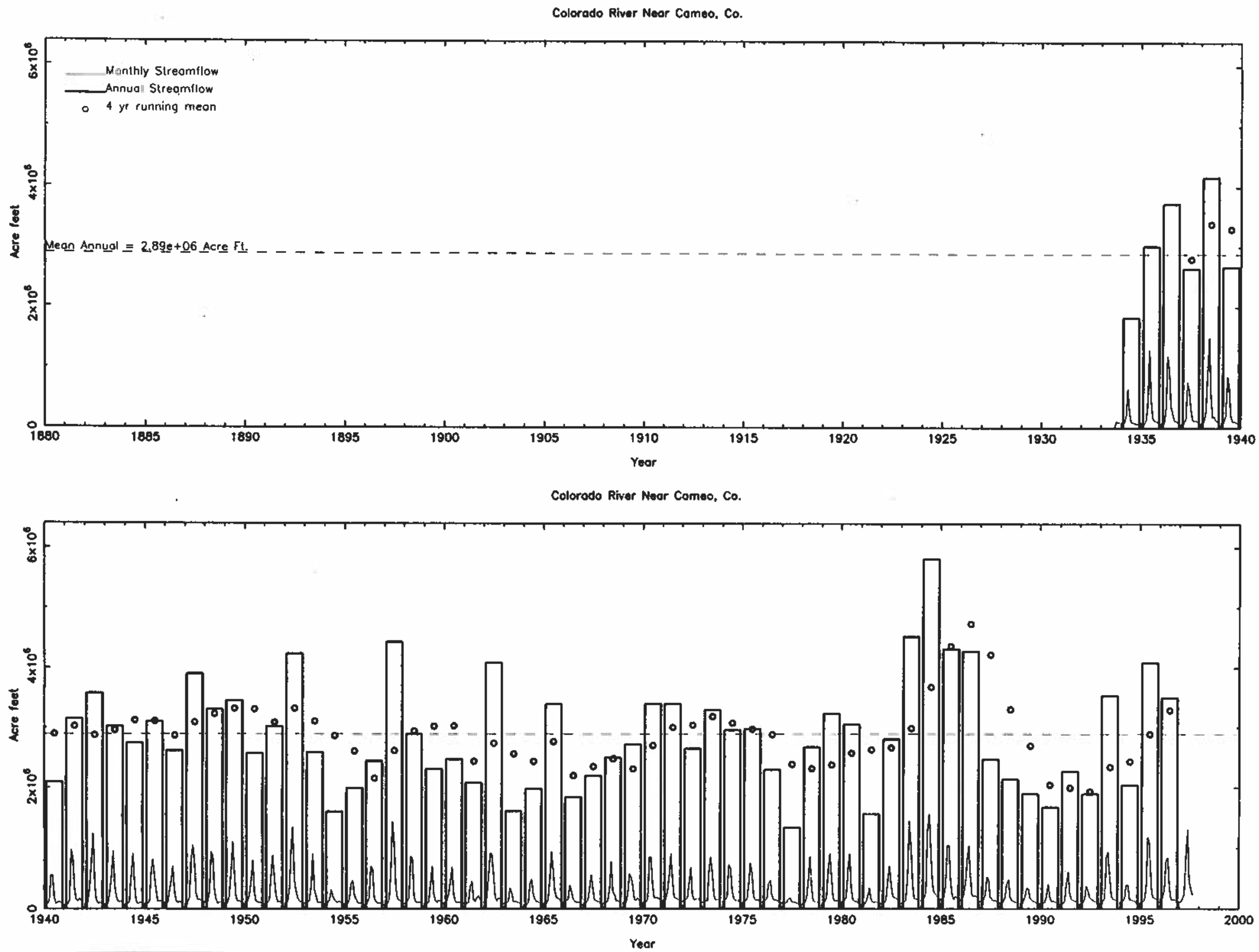


Figure 13c. Observed streamflow for Colorado river near Cameo, Colorado.

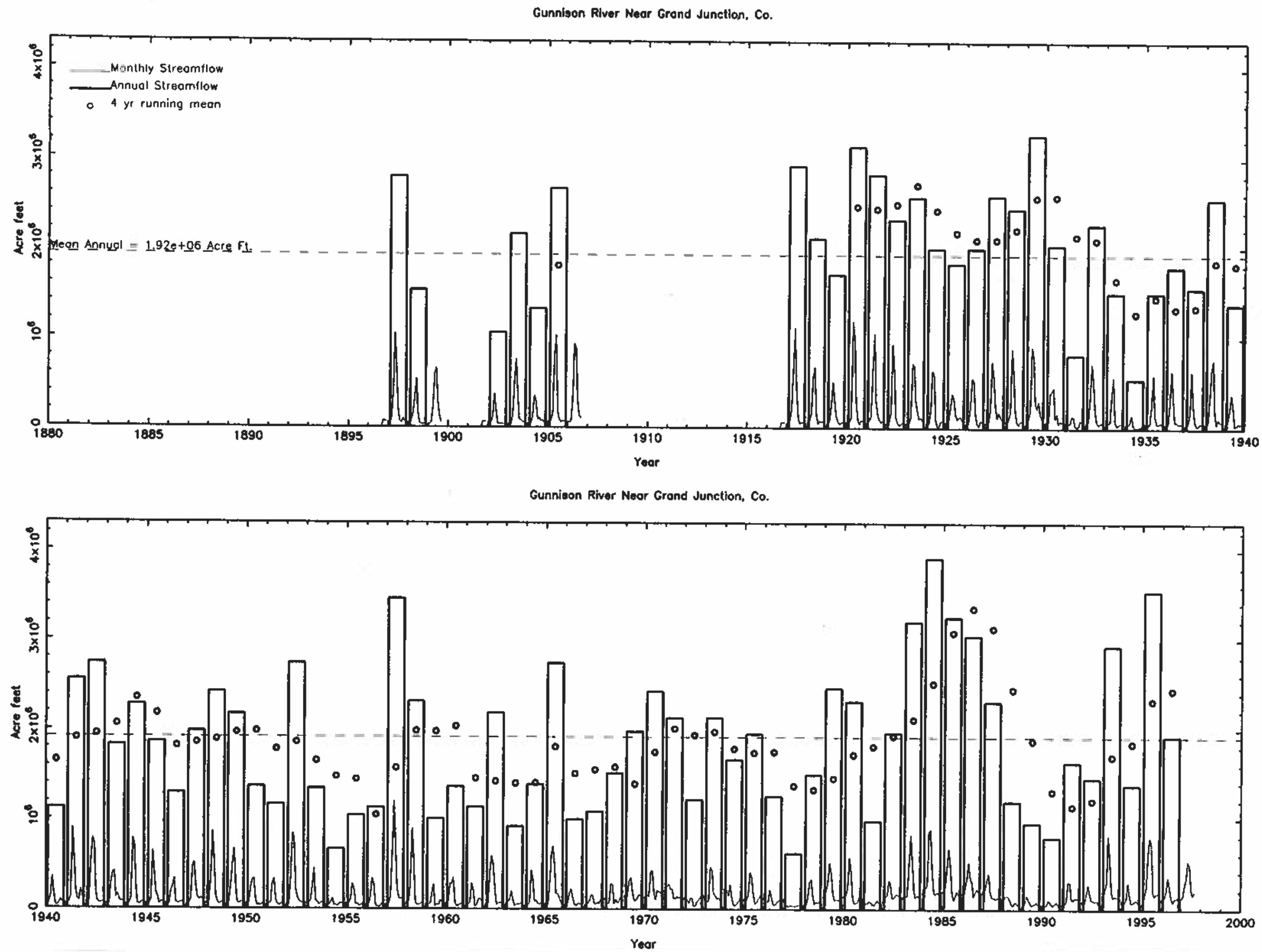


Figure 13d. Observed streamflow for Gunnison river near Grand Junction, Colorado.

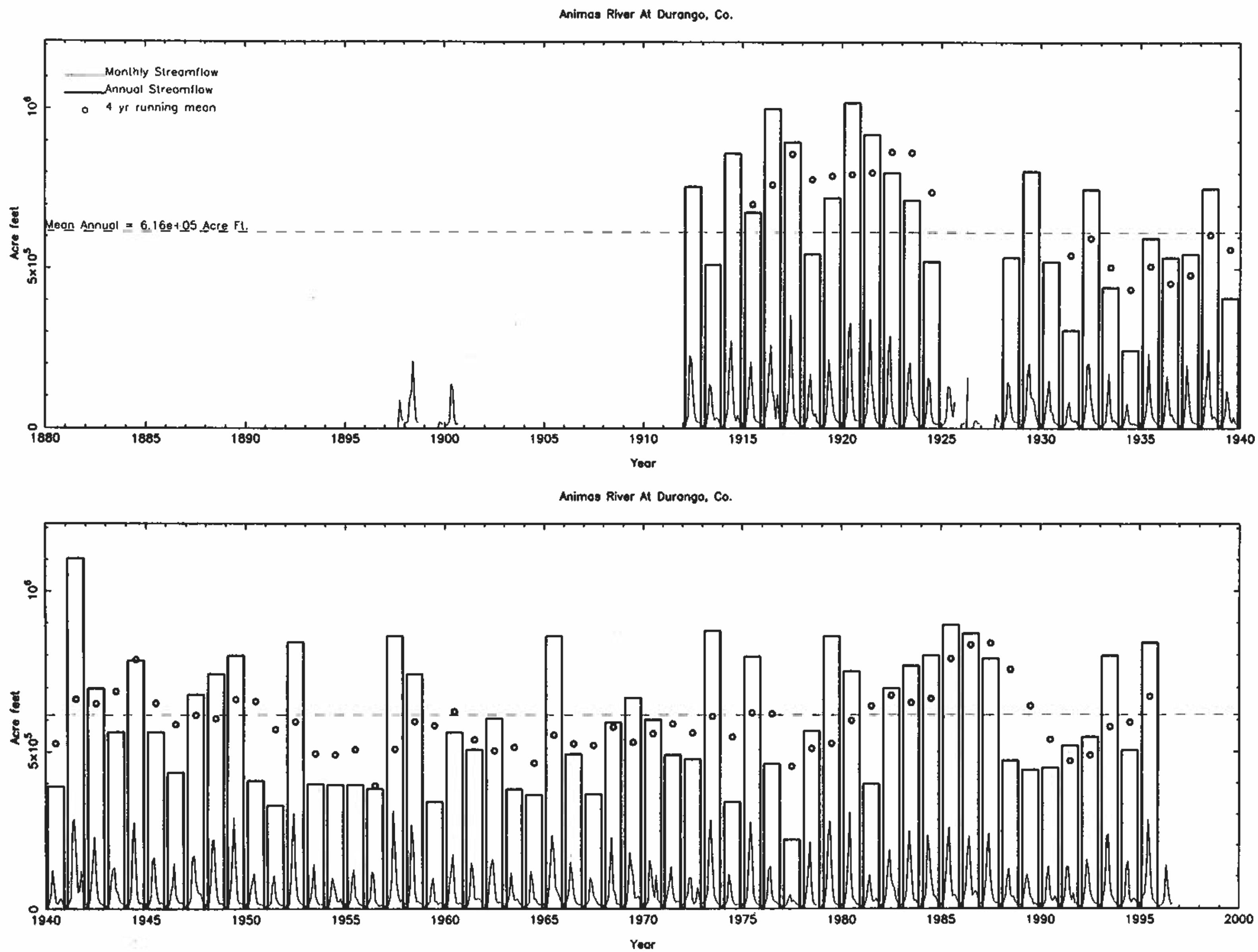


Figure 13e. Observed streamflow for San Juan, Animas and Dolores river at Durango, Colorado.

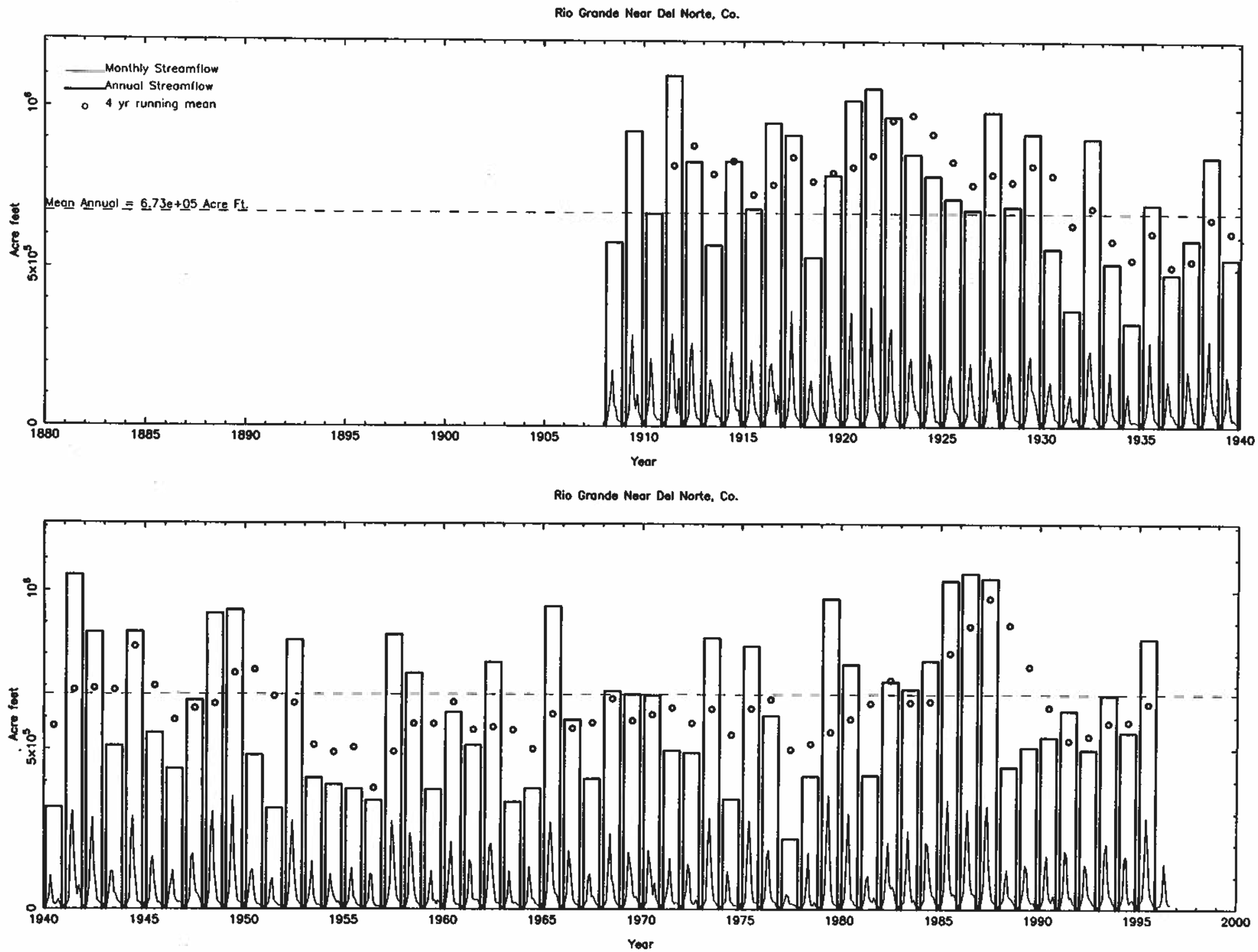


Figure 13f. Observed streamflow for Rio Grande river near Del Norte, Colorado.

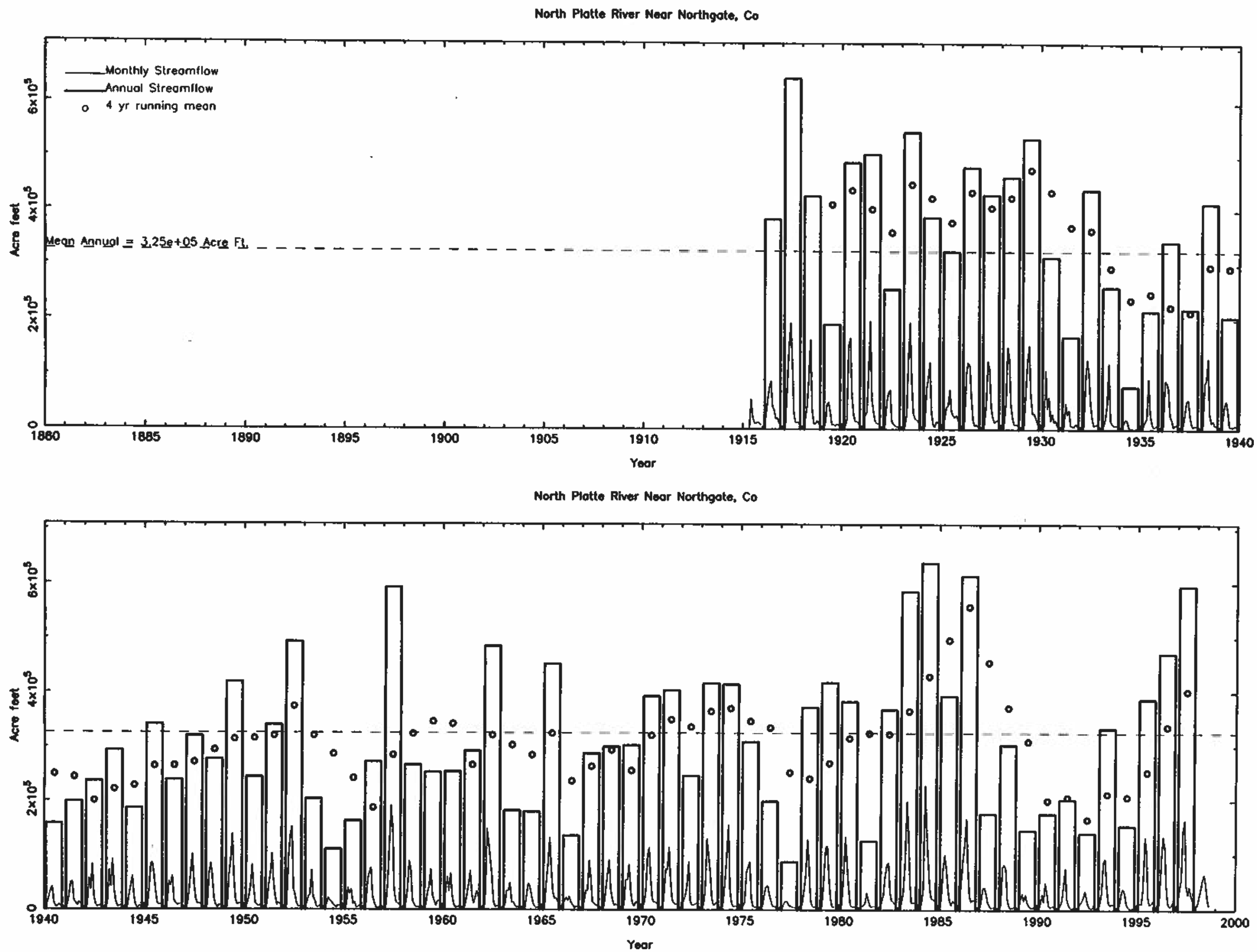


Figure 13g. Observed streamflow for North Platte river near Northgate, Colorado.

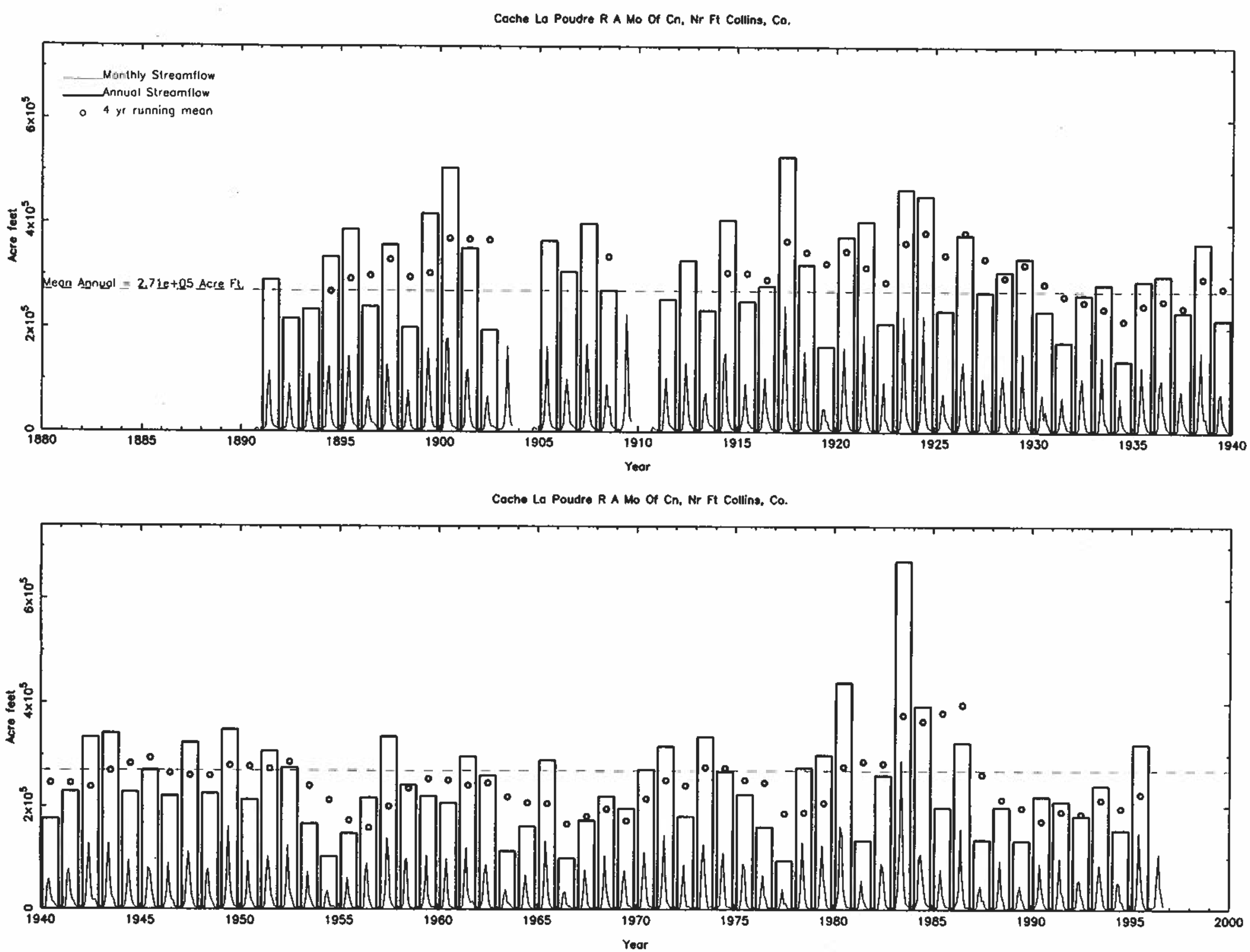


Figure 13h. Observed streamflow for Cache La Poudre river at the mouth of the canyon.

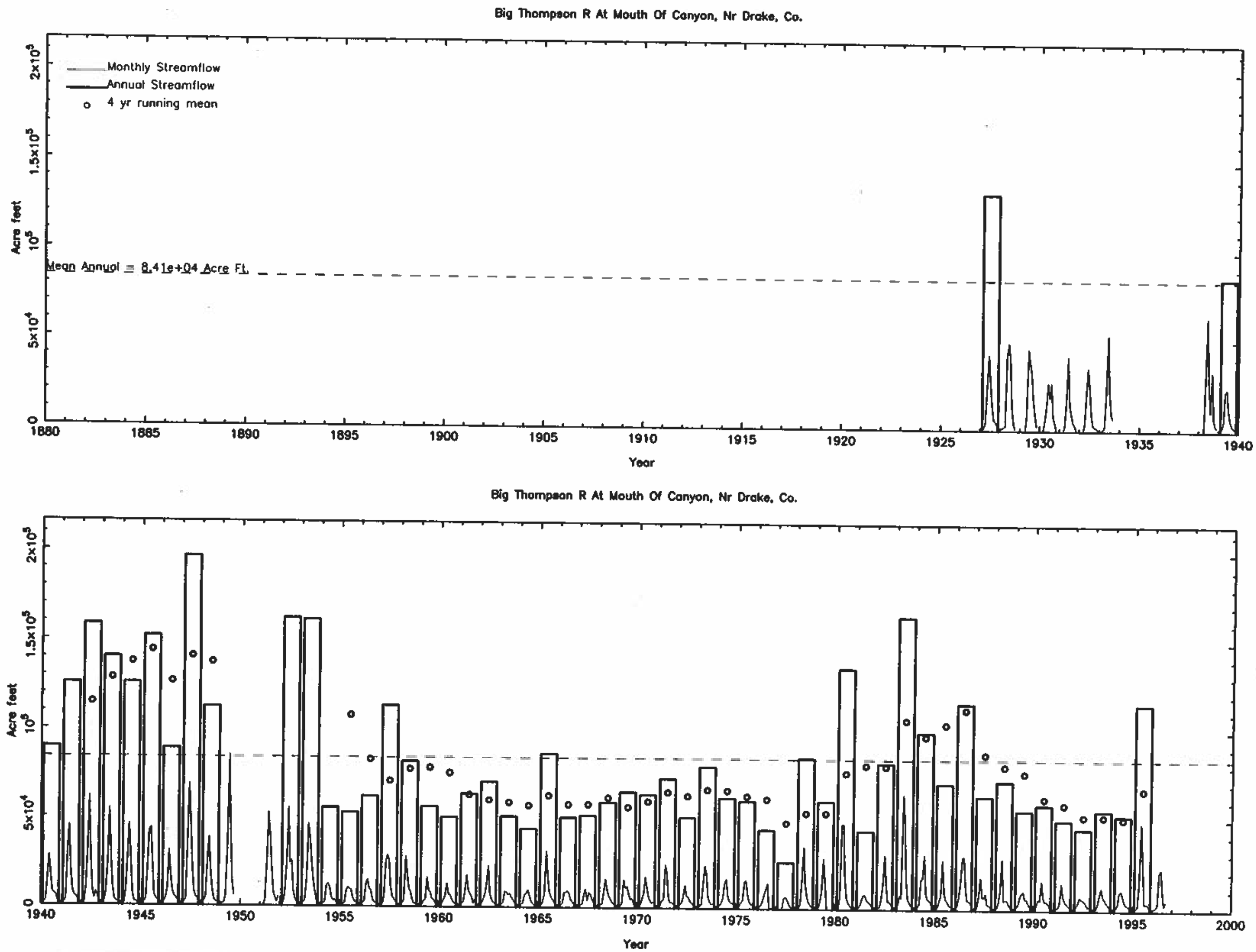


Figure 13i. Observed streamflow for Big Thompson river at the mouth of the canyon.

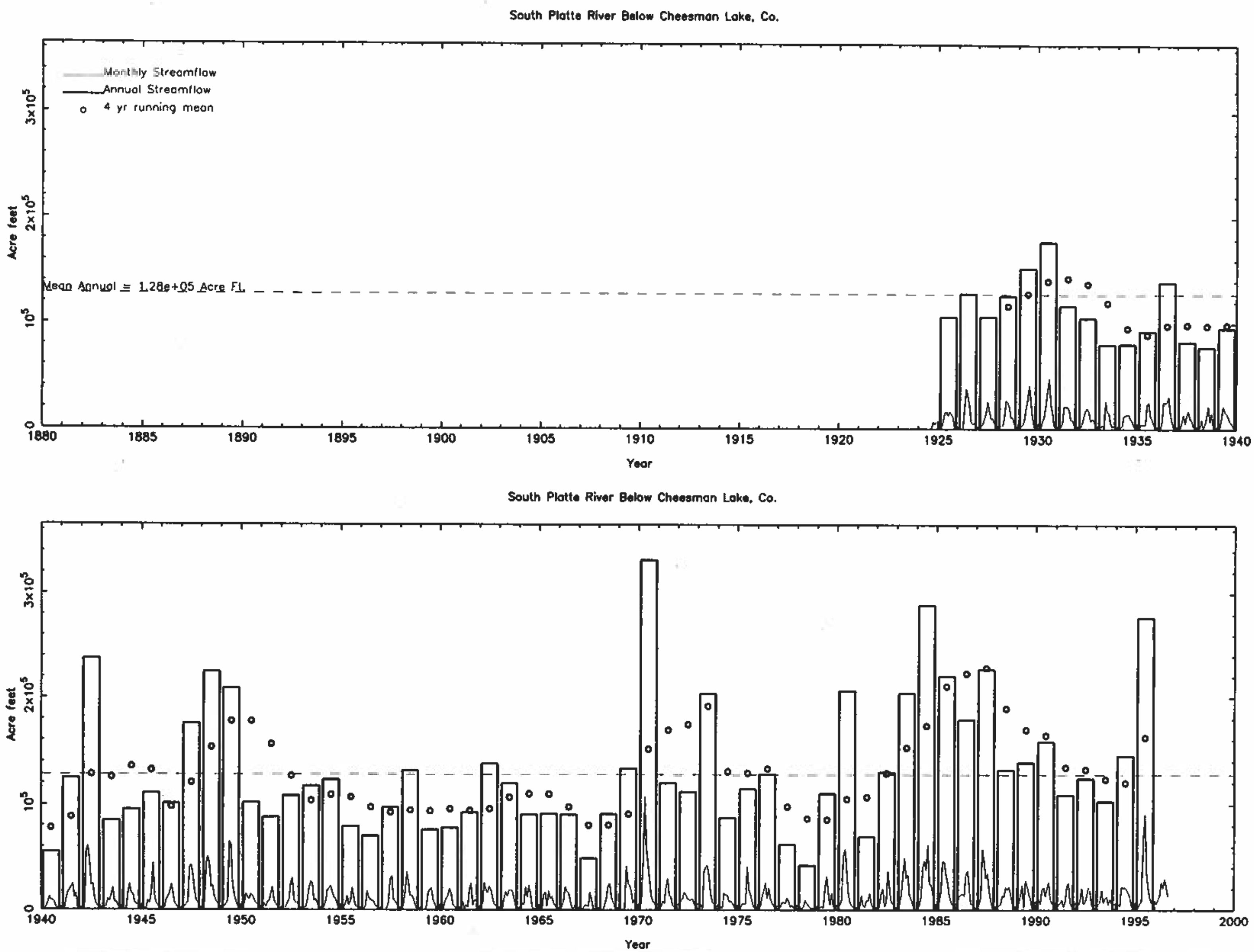


Figure 13j. Observed streamflow for South Platte river below Cheesman, Colorado.

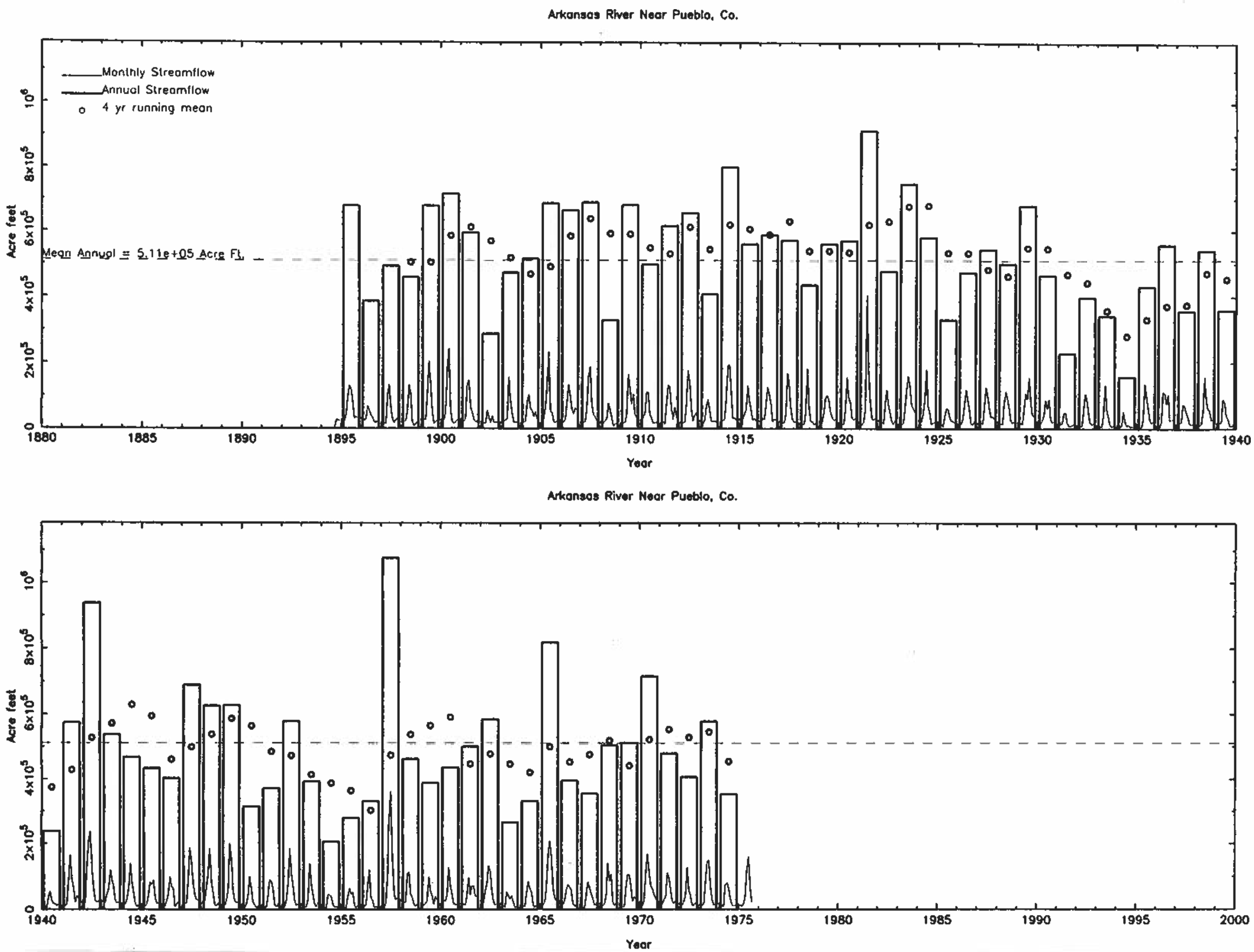


Figure 13k. Observed streamflow for Arkansas river near Pueblo, Colorado.

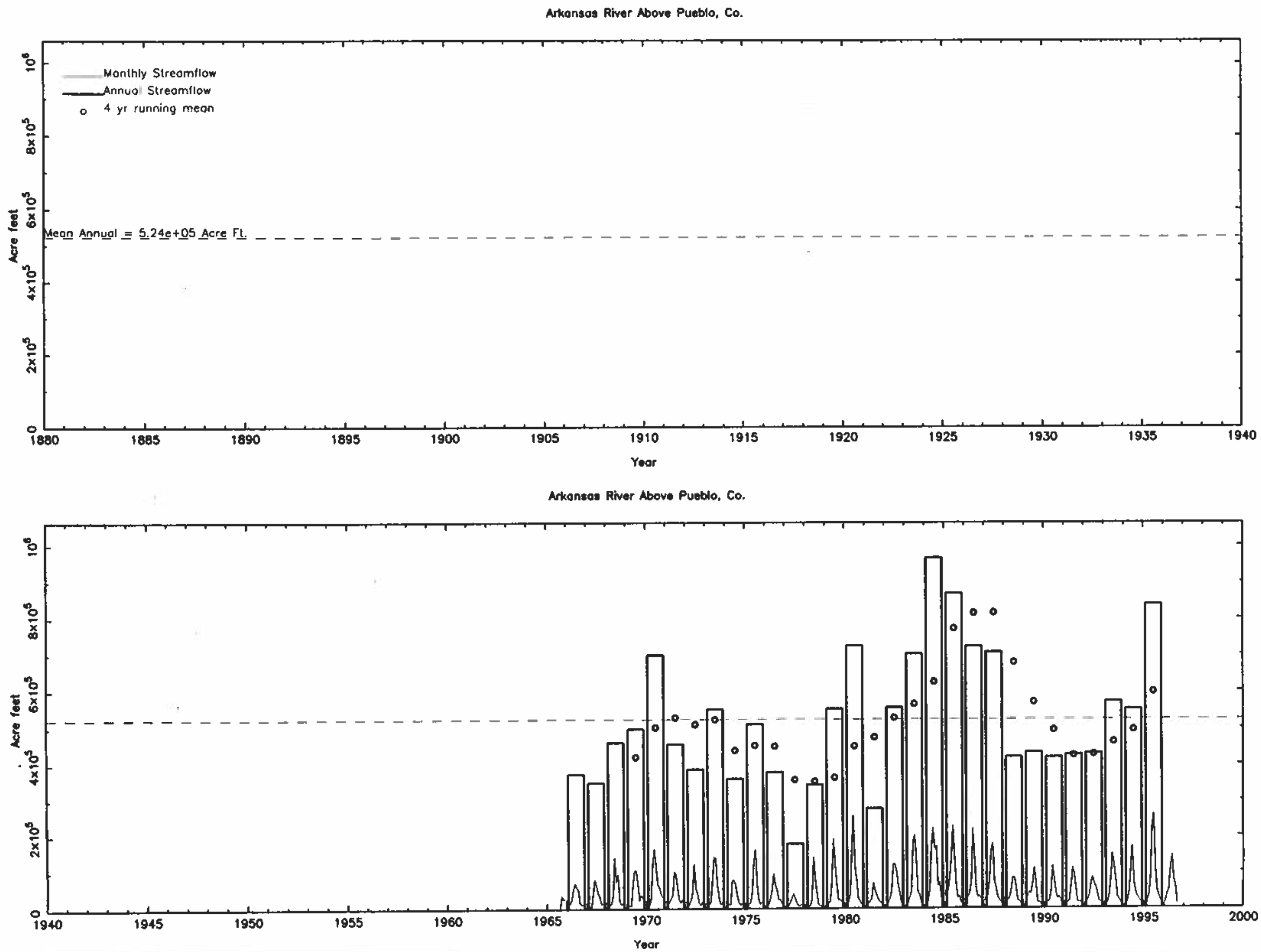


Figure 13ℓ. Observed streamflow for Arkansas river above Pueblo, Colorado.