Long-term variation in Rainfall and its effect on Peace River Flow in West-Central Florida

Hydrologic Evaluation Section
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Contents

Figures

Tables

Long-term variation in rainfall and its effect on Peace River Flow in West-Central Florida

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1.0 INTRODUCTION

Hammett (1990) determined a statistically significant decline in annual mean discharge for the Peace River at Bartow, Zolfo Springs, and the Arcadia gaging stations from the 1930s to 1984. Lewelling and others (1998) updated this work by including the subsequent 10-year period and found the same declining trend from the 1930s to 1994. Previous studies attribute this flow decline primarily to anthropogenic factors, mainly loss of baseflow contribution due to ground-water withdrawals or stormwater capture resulting from land-use alterations (Hammett,1990;Lewelling and others,1998). While there is little doubt that anthropogenic factors have contributed to flow reductions, the role of long-term, multi-decadal variation in rainfall toward stream flow changes has received little attention until very recently.

A new study by scientists from the National Oceanic and Atmospheric Administration (NOAA) the University of Miami, and the South Florida Water Management District found statistically significant differences in rainfall between the pre-1970 period versus the last 30 years which produced a 40 percent change in inflow to Lake Okeechobee (Enfield and others, 2001). These rainfall changes were identified in National Weather Service Region 4, which includes the Peace River basin (see Figure 2 for location). Their research attributed this shift in the rainfall regime to the Atlantic Multidecadal Oscillation (AMO), a naturally occurring variation in North Atlantic Ocean temperatures that occurs every 20 to 50 years.

Enfield and others (2001) indicate that warmer than average sea surface temperature periods of the AMO lead to increased wet season rainfall while cooler than average ocean temperatures decrease summer rainfall on the Florida peninsula. During warmer ocean temperature periods, global atmospheric circulation patterns shift to a more predominant southeasterly flow across the Florida peninsula, which leads to increased afternoon convective-activity and higher wet season rainfall. During cooler ocean temperature intervals, the upper atmospheric pattern is interrupted more frequently by mid-latitude disturbances, which generally results in less wet season rainfall.

Higher sea surface temperatures also lead to atmospheric circulation patterns that tend to increase rainfall in the Sahel region of west Africa and decrease upper-level wind shear in the tropical Atlantic Ocean. As a result, a higher frequency of major tropical cyclones along with a longer duration of hurricane days (cumulative time of all activity) occurs in the Atlantic and Caribbean Basins (Gray and others, 1997; Landsea and others, 1999). Throughout Florida's history, tropical systems have produced extremely high rainfall, with a single storm event producing as much as one-third of annual wet season rainfall.

Alternating cycles of warmer and cooler sea surface temperatures have been identified over the last 150 years starting with warm phases during the years 1869-1893, 1926-1969, and post-1995. Cooler phases correspond to the periods 1894-1925 and 1970-94 (Landsea and others, 1999). This section examines in detail long-term changes in rainfall, focusing on decadal variations and its impact on streamflow. The hydrologic significance of these changes is demonstrated through analytical methods and surface-water modeling. Much of the analysis includes data from the 1930s through 2000 since it coincides with the initial period-of-record for the stream gaging stations on the Peace River.

1.1 Background

Peninsula Florida's precipitation regime is largely dominated by a summer wet season (June through September) when more than 60 percent of annual precipitation occurs due to local convective-type thunderstorm activity. During this period, tropical cyclones may also affect the region with extremely heavy rain and wind. The remainder of the year, weather patterns are controlled by mid-latitude frontal systems. Typically, November is the driest month with July and August the wettest months. Hydrologically, the surface-water system is lowest during May just prior to initiation of the summer rainy season when antecedent moisture conditions are dry, precipitation is low, temperatures are high, and evapotranspiration is high. The months of September-October, at the end of the summer rainy season, are generally when the hydrologic system reaches its annual peak.

Two major criteria in quantifying the impact on the hydrologic system due to rainfall variation is the time of year when it occurs and the role of antecedent moisture conditions. The majority of annual rainfall occurs in central Florida during the months of June through September. The month of October is generally considered a transition month into the fall dry season. Rainfall becomes most important in the runoff process during the months of June through October because of its magnitude, intensity, and the generally wet antecedent conditions. During the summer rainy season, soil moisture content is highest, ground-water levels rise closer to land surface, and surface storage decreases which results in higher percentages of rainfall contributing to runoff. Based on the results of a 10-year surface-water simulation within west-central Florida, the percentage of monthly rainfall that contributes to stormwater runoff is highest during the months of June through October, when 62 percent of annual runoff occurs (Ross and others, 2001). The lowest runoff months were April, May, and November.

In determining rainfall changes, the issue of time scale is an important one. Droughts are frequent events in Florida. They can occur for durations that span several months to several years. Likewise, heavy rainfall periods associated with El Nino events are typically seasonal in duration. Superimposed over these relatively short-term extremes are cyclic periods that cover several decades. It becomes essential to differentiate between short-term events and longer-term changes when determining effects on the hydrologic system over the period-of-record. These longer-term cycles ultimately influence the hydrologic system when viewed over the 60 to 70 year streamflow record of the Peace River.

In most of this analysis, the long-term record was divided into two 30-year periods, 1941-1970 and 1971-2000 or 1936-1965 and 1966-1995. The justification for this division was based on a substantial change in rainfall and stream discharge that occurs in the mid-to-late 1960s. This point also coincides with a change in the AMO from a warmer to cooler phase. While the periods do not exactly match the duration of each AMO phase, it is important that equal time segments are used for contrast and comparison purposes. While it can be argued, depending on the type of analysis and the location of the rainfall station, that the change occurred a few years before or after this point, it seems reasonable to use these periods to divide the 60-year record into two equal time segments.

2.0 RAINFALL ANALYSIS

Since rainfall events are highly variable, several techniques were employed that smooth or attenuate the data to demonstrate periods of higher or lower precipitation regimes. Multi-year moving averages, cumulative departures from average, single mass analysis, linear regression, and time series plots were utilized and applied to six stations within or immediately adjacent to the Peace River basin. Data from 27 long-term rainfall stations (greater than 40 years of record) were first evaluated to view regional changes in the rainfall regime (Figure 1). Later, more detailed analysis is included for those stations within the Peace River basin where changes in rainfall have been correlated with river flow using empirical analysis and results from a 10-year surface-water model using the Hydrologic Simulation Program Fortran (HSPF) code.

2.1 Regional View

The National Weather Service has divided central Florida in Regions 3 and 4 (Figure 2). The distribution of monthly rainfall based on the period 1895-2000 for both regions is shown in Figure 3. Based on simple linear regression of annual rainfall data from stations with over 100 years of record, average annual rainfall has not changed significantly over the last century (Figure 4). If the record is divided into shorter intervals, however, a pattern of above-or-below average rainfall is evident. A close inspection of 5-year running mean rainfall generally shows below average periods from 1901-20 and 1970-1994 and an above average period from 1921-70 which corresponds closely to the AMO cycles (Figure 5). Median rainfall by decade from the 27 stations also follows these below-or-above average periods (Figure 6). From the previous information, multi-decadal cycles of above-or-below average rainfall appear to closely follow the AMO.

2.2 Peace River Basin

In the Peace River basin, rainfall was analyzed from the Lakeland, Bartow, Haynesworth, Wauchula, Avon Park, and Arcadia stations (Figure 7). Annual rainfall was examined along with dividing the data into wet and dry seasons. The wet season period was classified as the June through October period, with the months of January through May making up the dry season. The inclusion of October into the wet season period could be debated since June through September is traditionally considered the summer “rainy season”. However, based on the fact that a high percentage of October rainfall contributes to runoff due to wet antecedent conditions, and the month is an active part of hurricane season, there is compelling evidence that it should be included in the wet season analysis. Regardless of which way one views the issue, the month only contributes about 10 percent of annual wet season rainfall so its inclusion should not have a significant effect on the results.

Differences in annual rainfall over 30-year periods are shown in Table 1 for the six rainfall stations. It’s interesting to note that regardless of when the 30-year periods were partitioned, either at 1965 or 1970, the differences in mean or median rainfall were not substantially different. Averaged from all six stations, the change in rainfall was about five inches per year between the three decade periods. The 5-year running mean plot of annual rainfall (averaged from the six stations) is very similar to the 27-station average shown in the regional analysis (Figure 8).

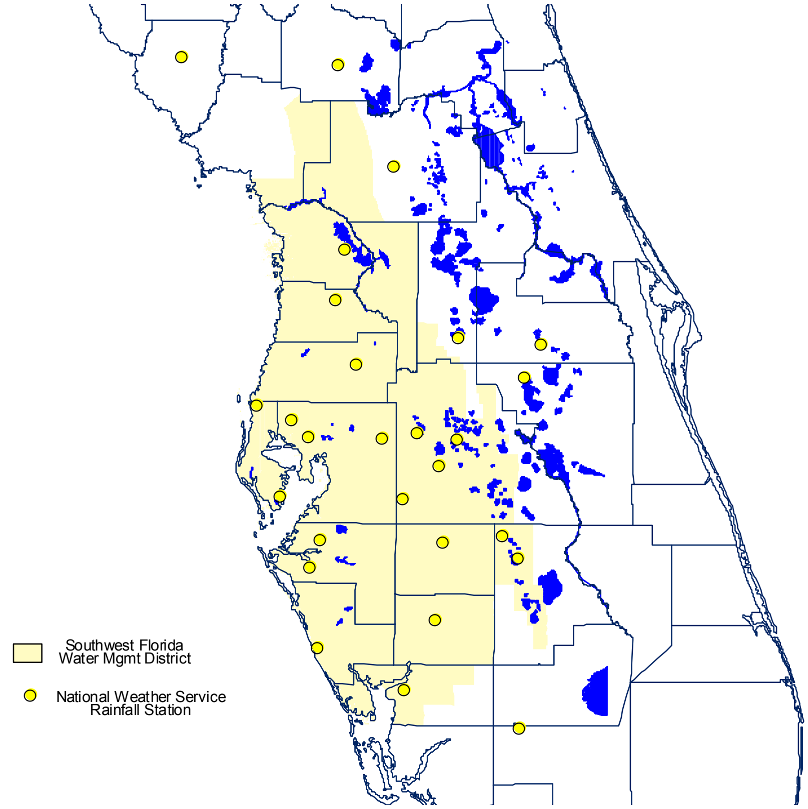

Figure 1. Location of 27 long-term rainfall stations.

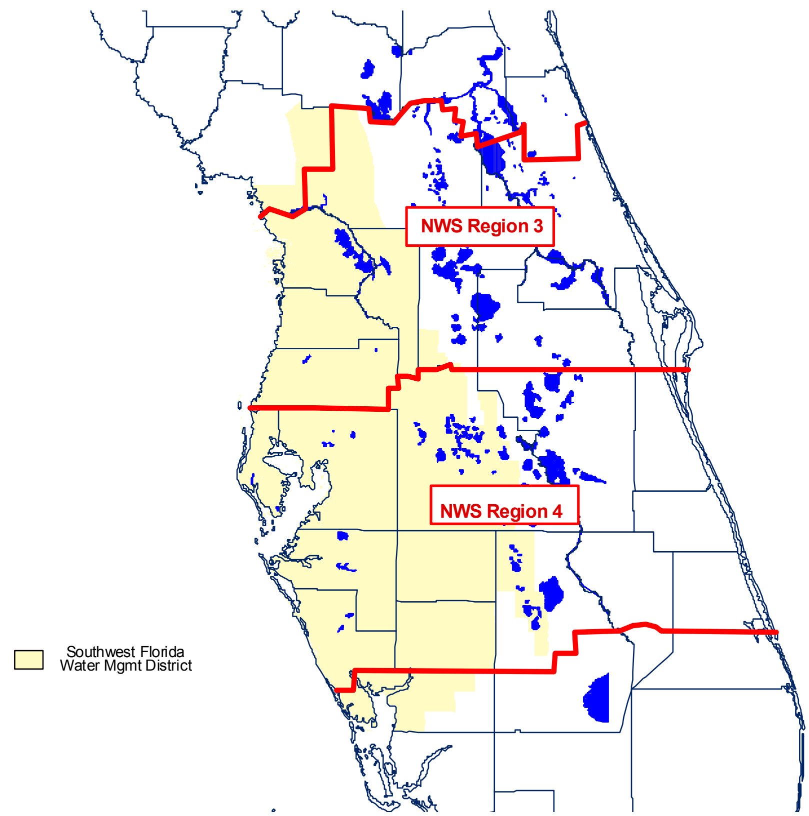

Figure 2. Location of National Weather Service's North-Central (Region 3) and South-Central (Region 4) rainfall zones.

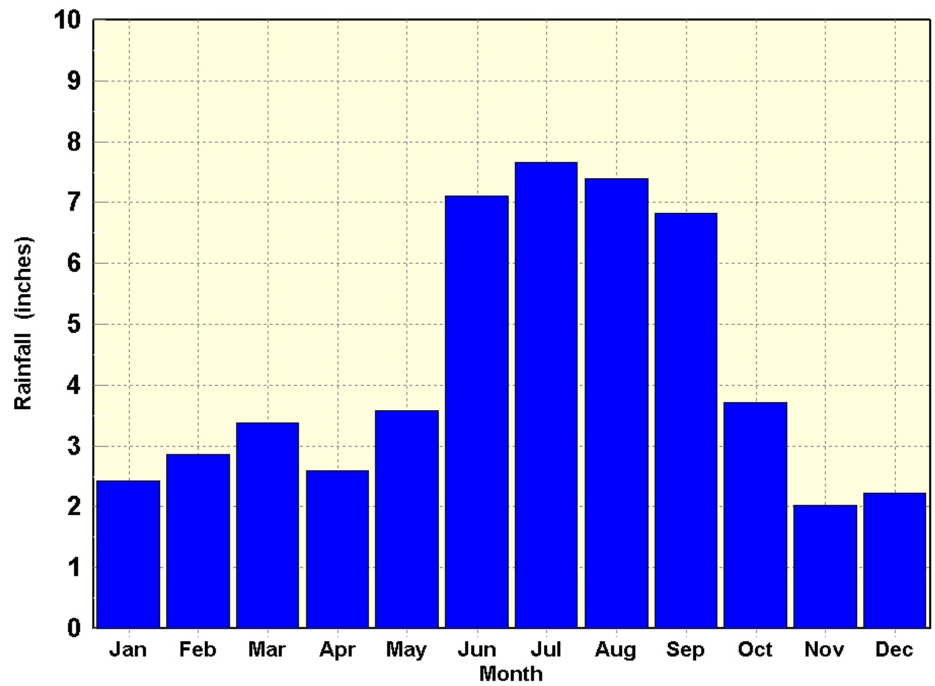

Figure 3. Average monthly rainfall from NWS Regions 3 and 4 (period-of-record 1895-2000).

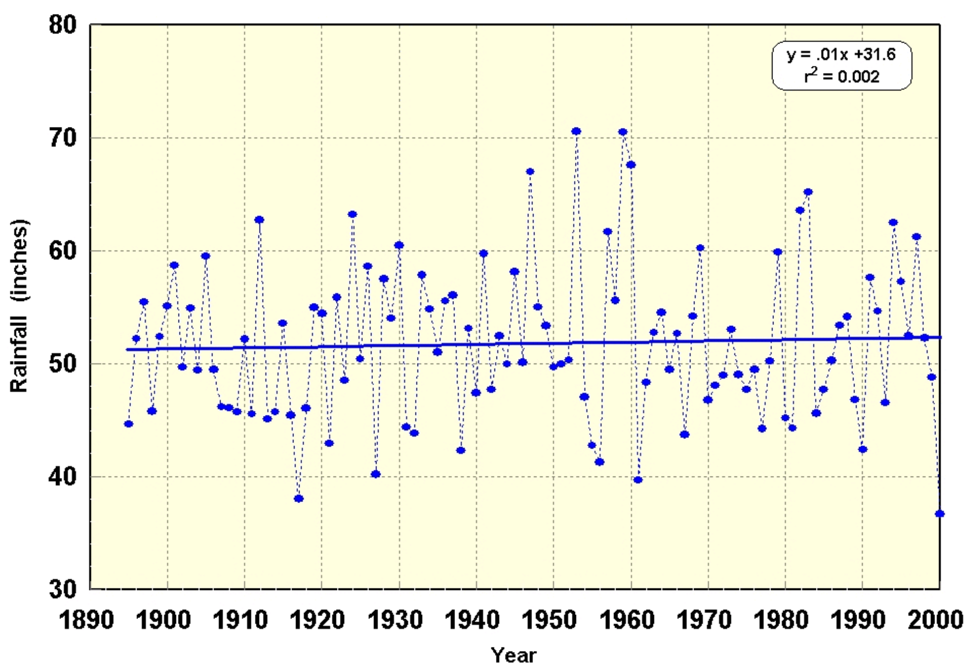

Figure 4. Linear regression of 105 years of annual rainfall from National Weather Service Regions 3 and 4 (see Figure 2 for location).

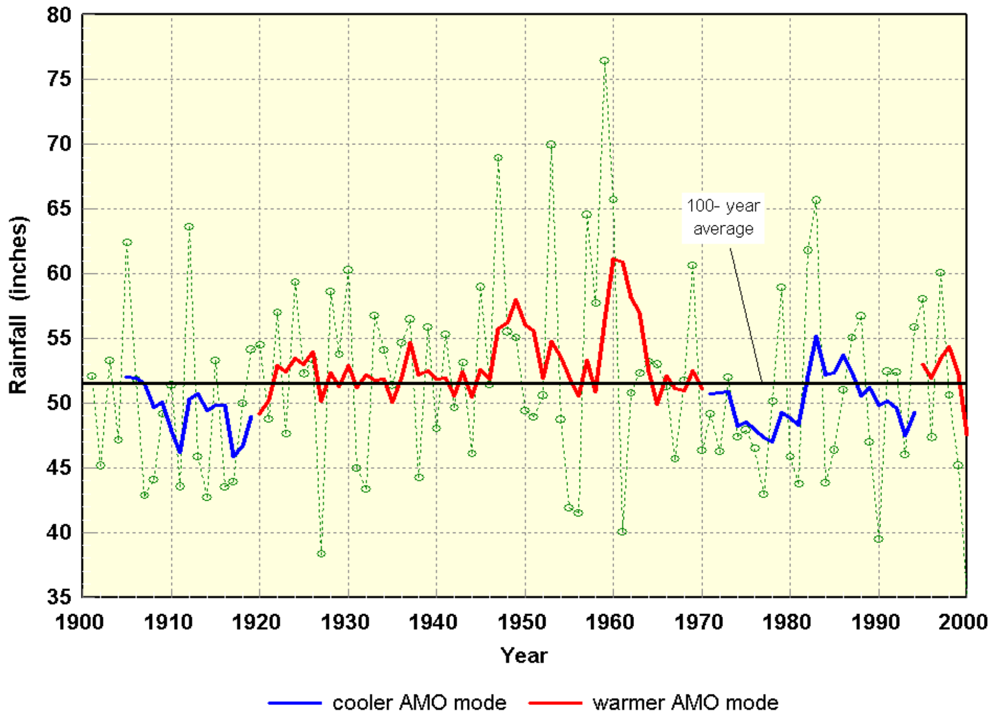

Figure 5. Annual and 5-year running mean rainfall averaged from 27 long-term stations.

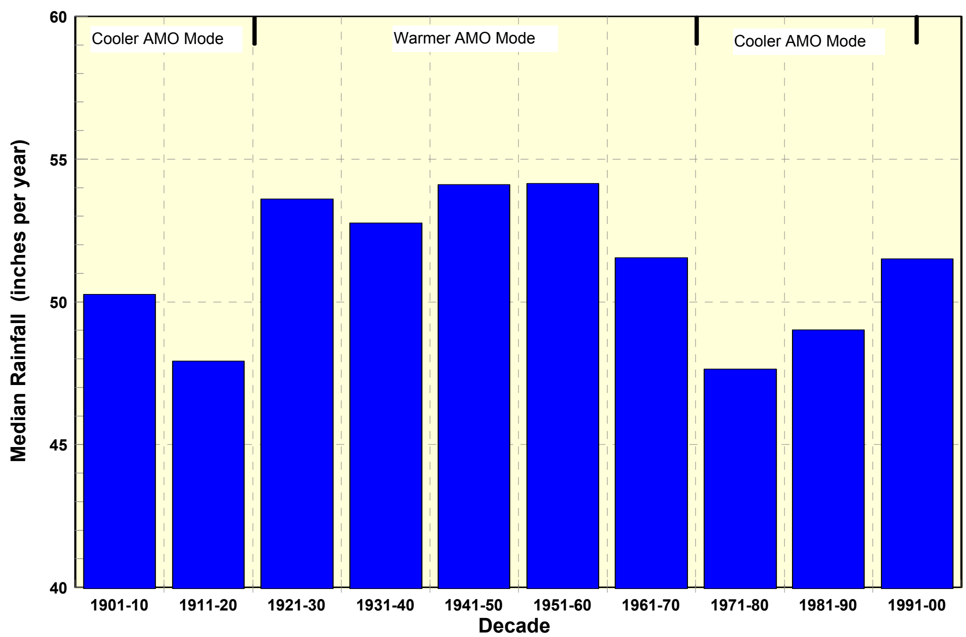

Figure 6. Median rainfall by decade averaged from 27 long-term stations.

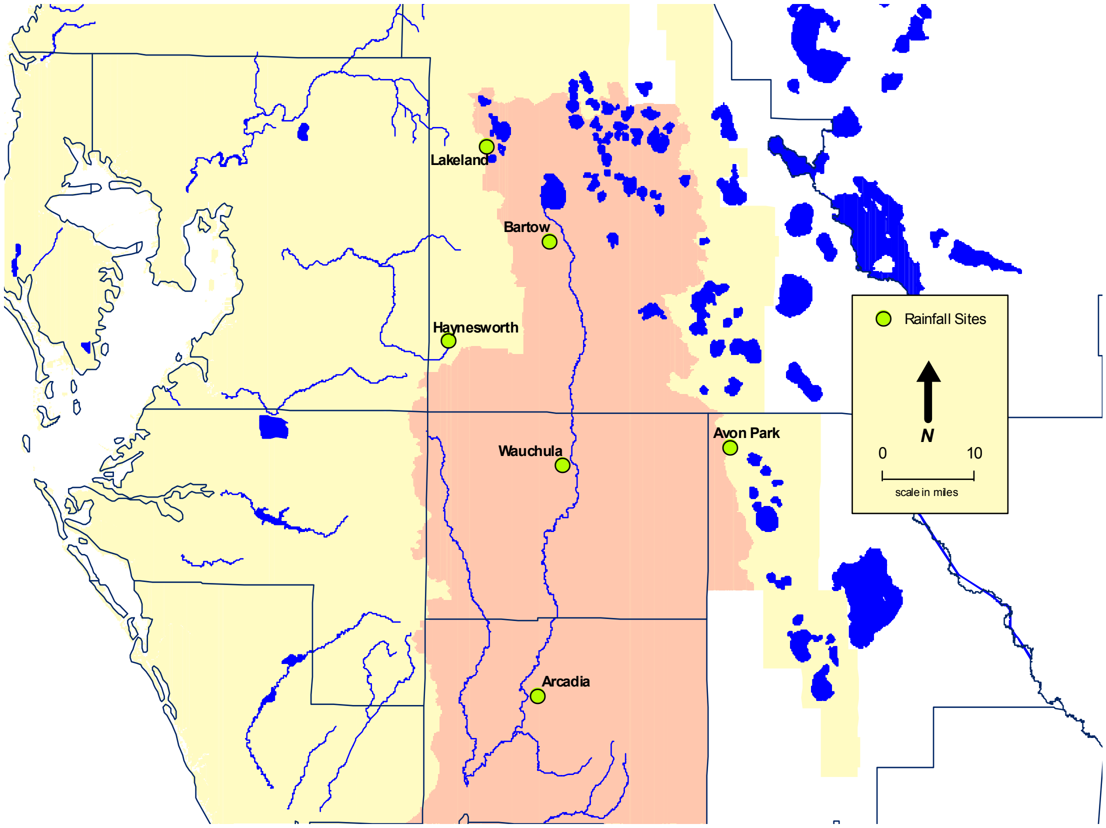

Figure 7. Location of long-term rainfall stations within or adjacent to the Peace River basin.

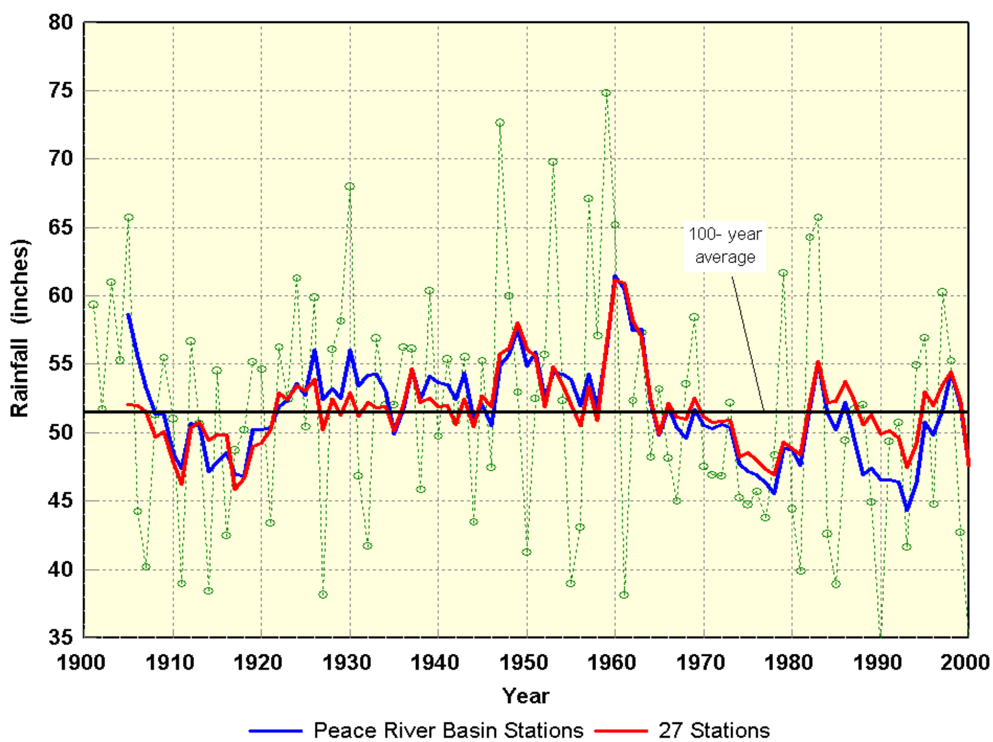

Figure 8. Annual and 5-year running mean rainfall averaged from Peace River basin stations compared with 5-year running mean from 27 long-term stations.

Table 1. Historical comparison of mean and median annual rainfall from 6 stations within or near the Peace River basin using two different 60-year periods.

Station	**Mean**		**Difference (inches/yr)**	**Median**		**Difference (inches/yr)**
	1936-65	**1966-95**		**1936-65**	**1966-95**	
Lakeland	49.7	49.8	+0.1	47.9	48.4	+0.5
Bartow	55.4	50.6	-4.8	53.9	50.0	-3.9
Avon Park[1]	55.6	50.1	-5.5	54.7	47.7	-7.0
Haynesworth	54.1	47.2	-6.9	55.5	46.2	-9.3
Wauchula	56.0	49.6	-6.4	54.7	49.2	-5.5
Arcadia[2]	55.1	51.6	-3.5	56.7	50.9	-5.8
6 station avg:	54.3	49.8	**-4.5**	53.9	48.7	**-5.2**

Station	**Mean**		**Difference (inches/yr)**	**Median**		**Difference (inches/yr)**
	1941-70	**1971-00**		**1941-70**	**1971-00**	
Lakeland	49.4	50.2	+0.8	47.3	50.2	+2.9
Bartow	55.3	50.4	-4.9	53.3	50.0	-3.3
Avon Park[1]	55.4	48.9	-6.5	54.7	47.0	-7.7
Haynesworth[3]	52.9	46.8	-6.1	54.2	43.9	-10.3
Wauchula	54.6	49.5	-5.1	54.0	48.3	-5.7
Arcadia[2]	55.1	50.2	-4.9	55.0	46.4	-8.6
6 station avg:	53.8	49.3	**-4.5**	53.1	47.6	**-5.5**

1 Excludes 1937, 1987-1989 due to missing data
2 Excludes 1990 and 1993 due to missing data
3 Excludes 2000 due to station termination

In addition to moving averages, long-term changes in rainfall over the last 60 to 70 years were analyzed by accumulating the departure from average for distinct time periods. Figures 9 and 10 are the cumulative departure totals from 27 rainfall stations for the periods 1936-1965 and 1966-1995. In the procedure, mean annual rainfall was determined from the period-of-record for each station, with most stations having more than 80 years of record. The difference in each year's rainfall (either positive or negative) from the period-of-record mean rainfall was cumulatively totaled for the two periods. In the earlier 30-year period, departures were above average for most of the basin and varied from +47 inches at Bartow to +122 inches at Arcadia. From 1966-1995, departures were below average ranging from -17 inches at Lakeland to -101 inches at Haynesworth in southwest Polk County. Total departure change between the two 30-year periods ranged from +1 inch at Lakeland to -207 inches at Haynesworth with the entire drainage basin from Bartow south to Arcadia exhibiting a total decline of 150 inches or greater (Figure 11). It appears that the Lakeland-Clermont area and the southwest Gulf Coast areas were the only regions that did not show a appreciable decline in rainfall between the two 30-year periods.

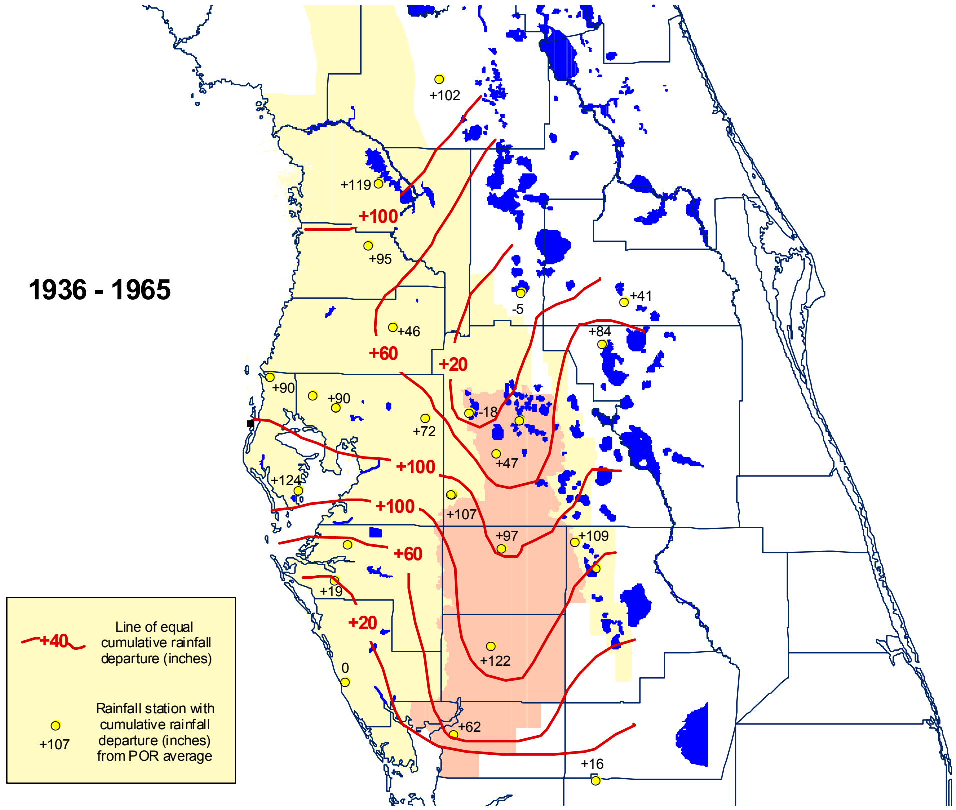

Figure 9. Cumulative rainfall departure for the 30-year period 1936-1965.

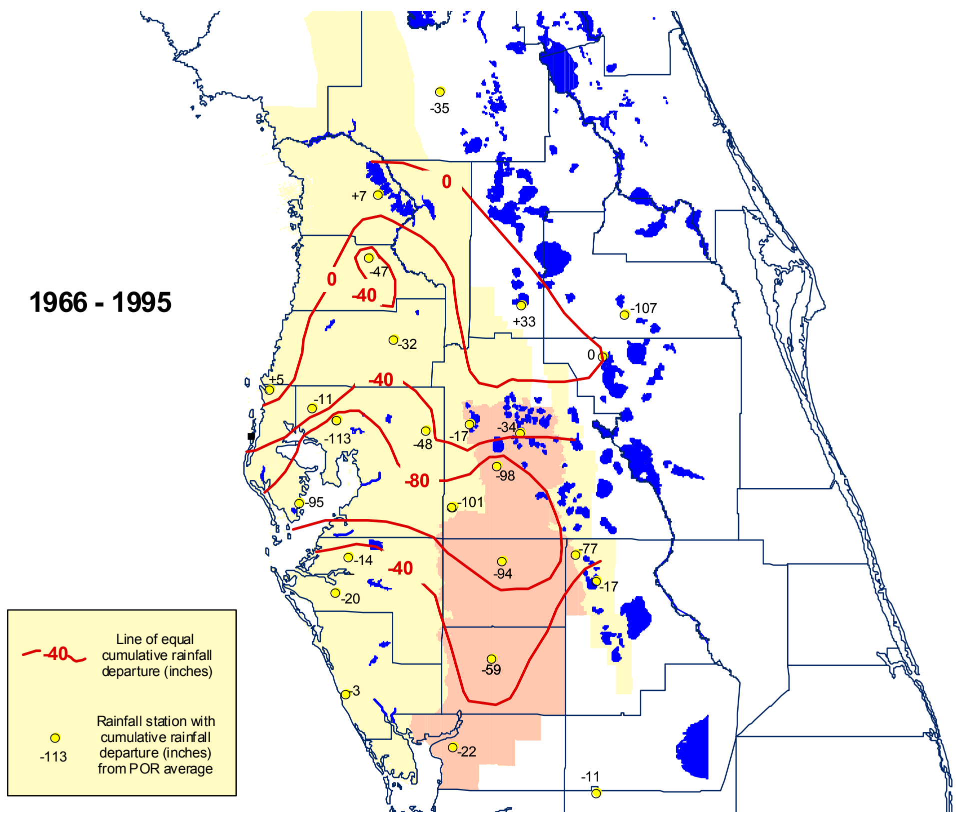

Figure 10. Cumulative rainfall departure for the 30-year period 1966-1995.

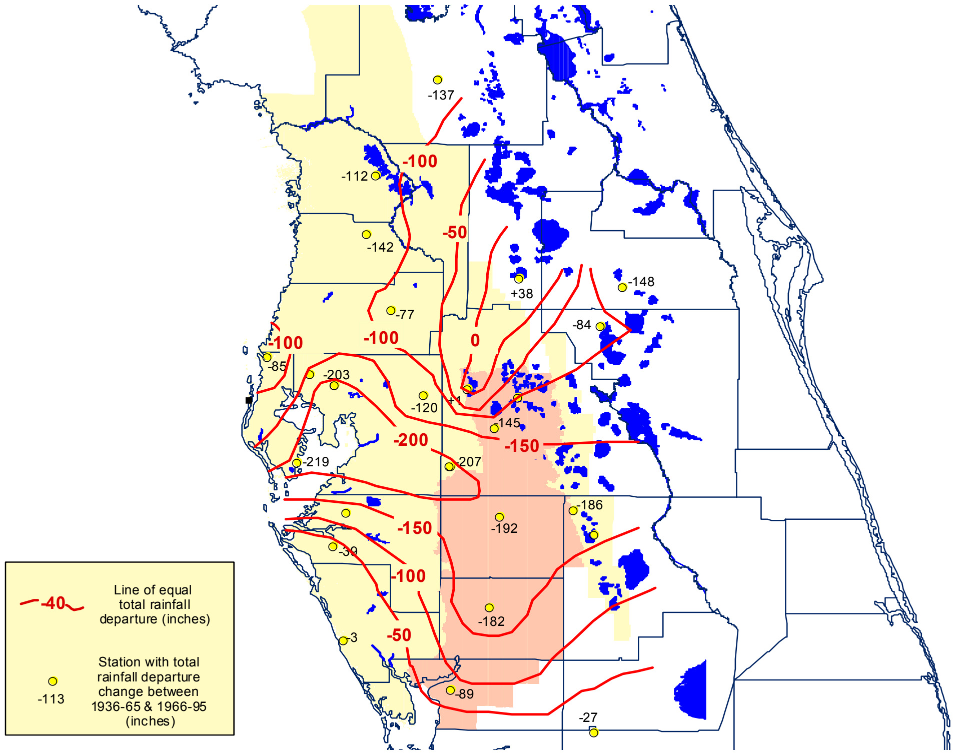

Figure 11. Total change in rainfall departure between two 30-year periods (1966-1995 minus 1936-1965).

2.3 Wet Season Analysis

Since more than 60 percent of west-central Florida's annual rainfall falls in a four-to-five month summer rainy season, changes in wet season precipitation can have a profound effect on the hydrologic system. The majority of surface-water runoff and recharge to the ground-water system occurs during the wet season when antecedent soil moisture conditions are high, surficial aquifer water levels rise, and surface storage becomes minimal. In an effort to distinguish when rainfall changes have occurred, monthly precipitation from the six stations within the Peace River basin was averaged for the period-of-record. As in the previous section, two different 60-year periods were compared to note monthly change in the rainfall regime (Figures 12 and 13).

Annual rainfall has decreased about 5 inches/year between 1940s-60s and the last 30 years (see Table 1). Based on the monthly distribution, about 80 percent of this change was due to a decline in wet season rainfall during the months of June through October. Depending upon which 30-year period is compared, the largest monthly declines have taken place in June, July, September, and October. This decline in wet season rainfall is consistent with Enfield and others (2001) who found a statistically significant change in wet season rainfall pre-1970 versus post-1970 for NWS Region 4, which includes the Peace River basin.

Single mass plots of wet season rainfall from 1930 to 2000, where each annual value is cumulatively totaled, show that the change in wet season rainfall emanated around 1970 (Figures 14 and 15). Two single mass analyses of wet season rainfall, one using June through September and the other June through October are both consistent in displaying this change. A running 5-year mean of wet season rainfall also confirms the reduction in wet season rainfall around 1970 (Figures 16 and 17).

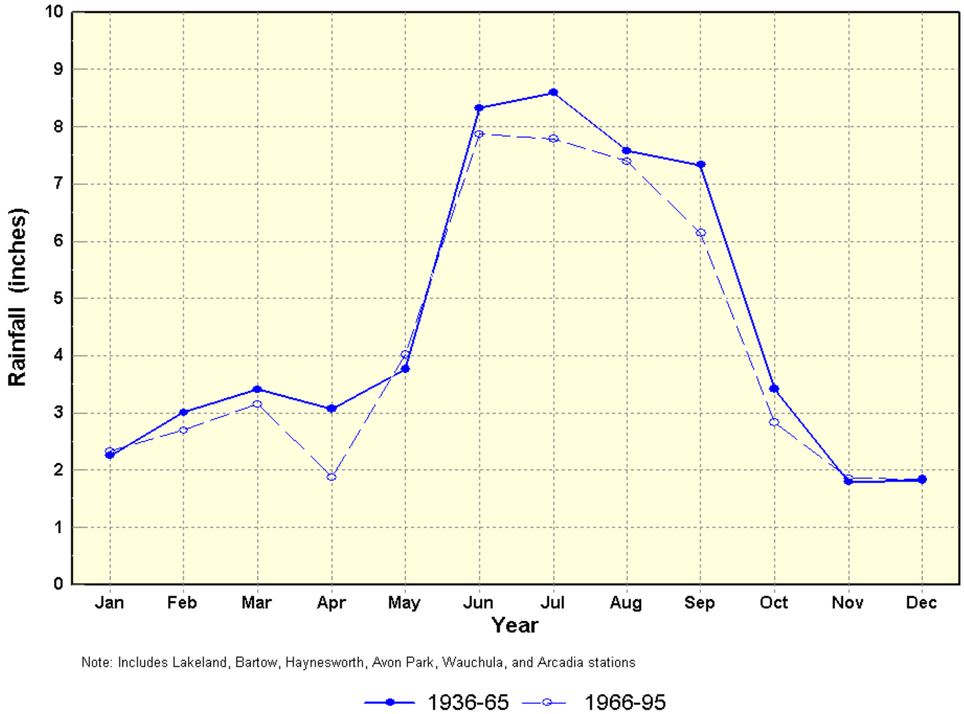

Figure 12. Comparison of monthly rainfall between two 30-year periods (1936-1965 and 1966-1995).

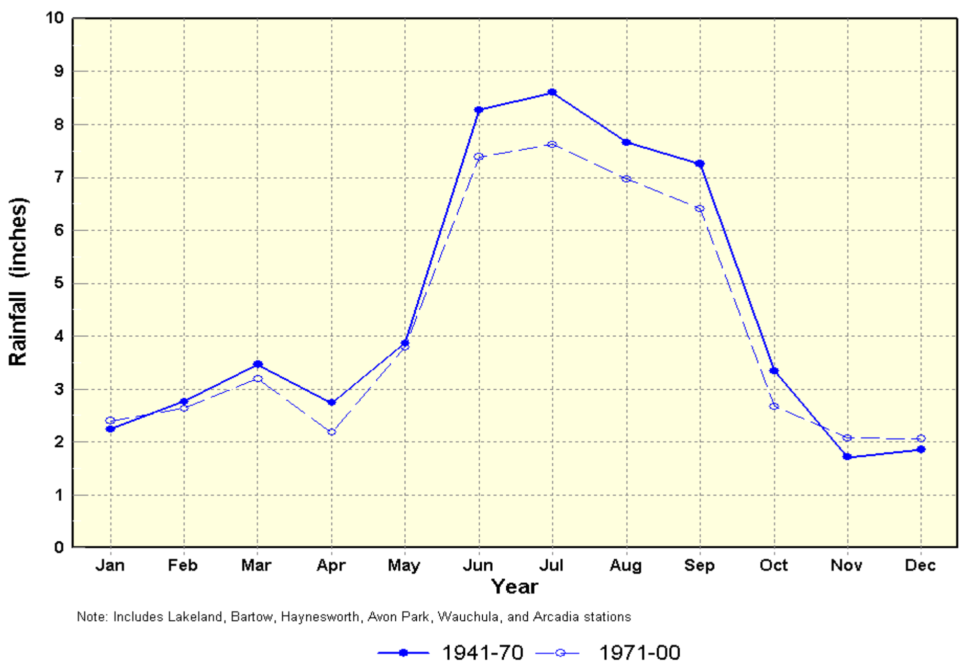

Figure 13. Comparison of monthly rainfall between two 30-year periods (1941-1970 and 1971-2000).

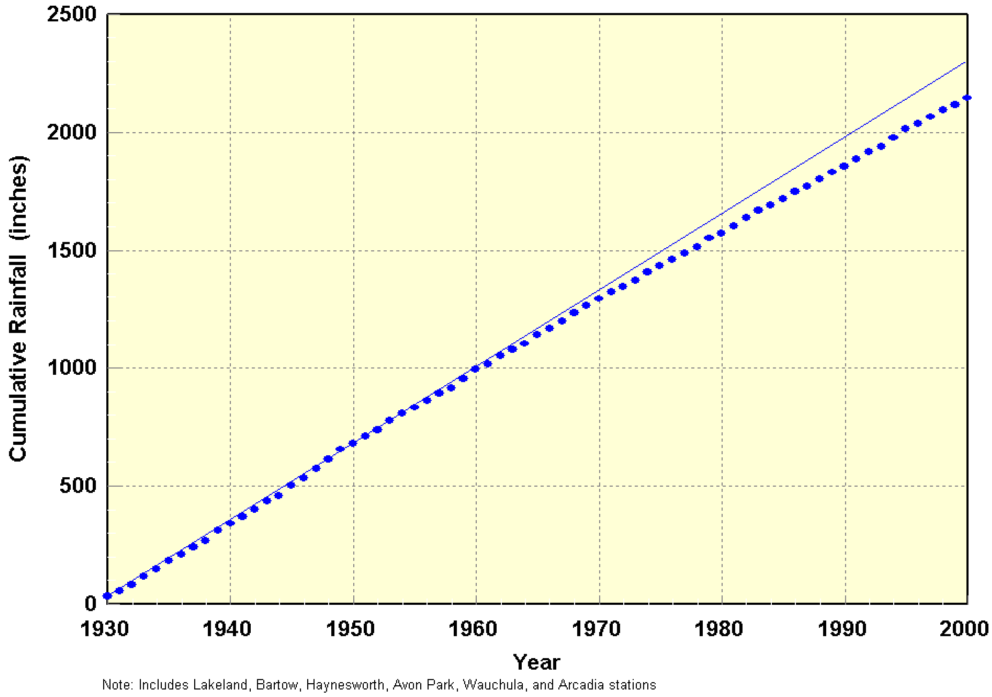

Figure 14. Single mass plot of wet season rainfall (June through September).

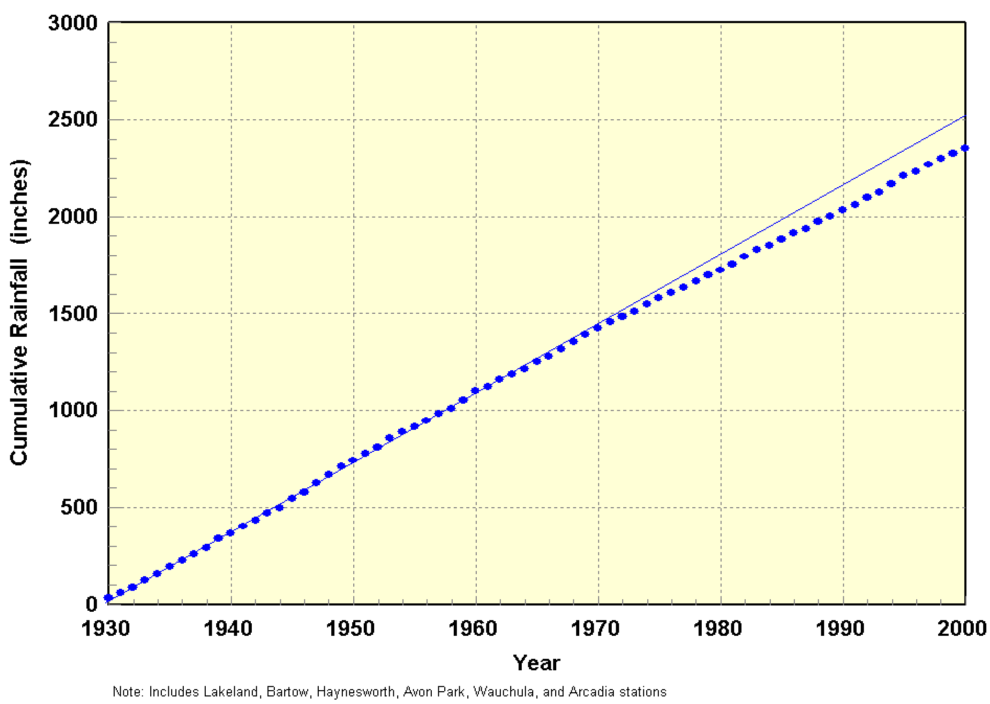

Figure 15. Single mass plot of wet season rainfall (June through October).

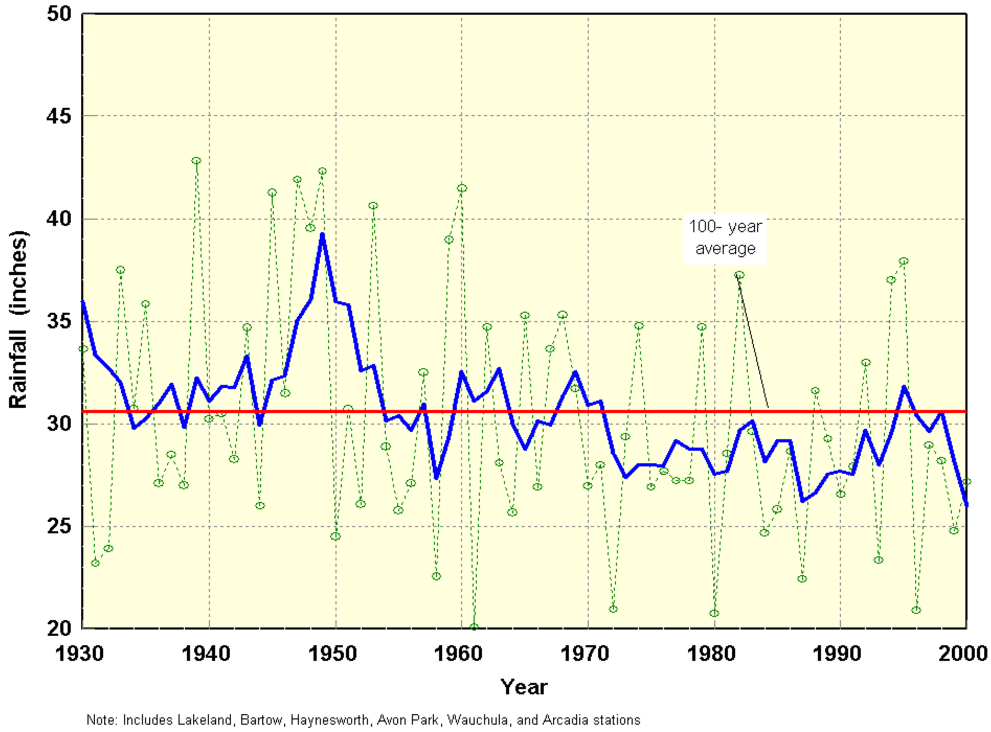

Figure 16. Annual and 5-year running mean of wet season rainfall (June through September).

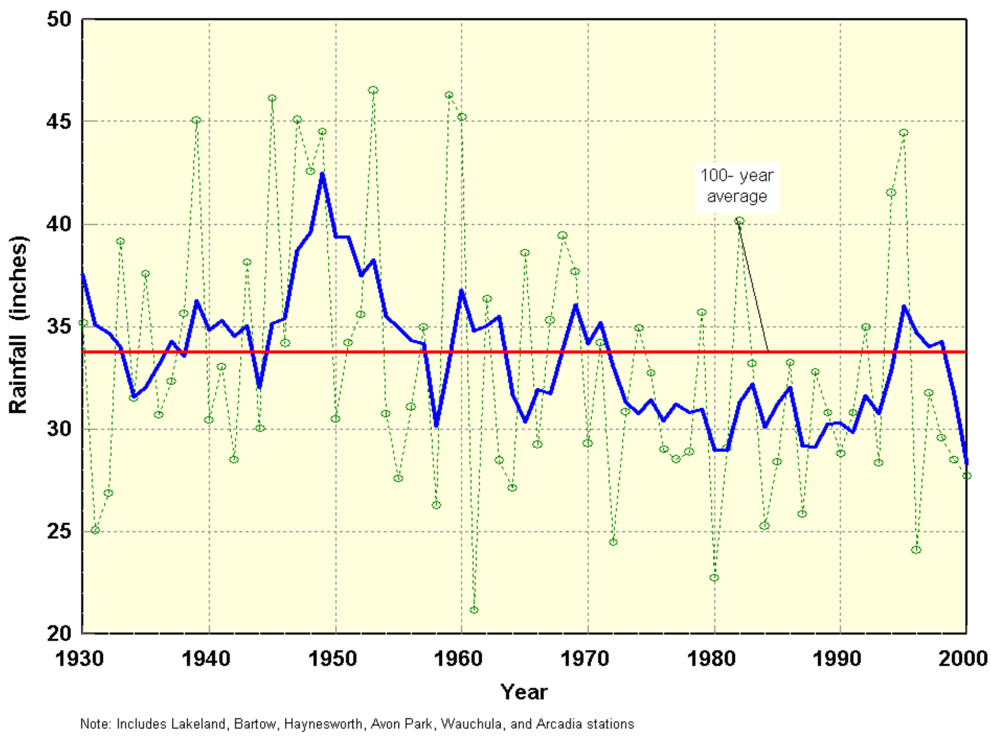

Figure 17. Annual and 5-year running mean of wet season rainfall (June through October).

2.4 Dry Season Analysis

Review of monthly rainfall changes between the two 30-year periods indicated a small decline during February, March, and April. January and May rainfall remained largely unchanged. A single mass analysis of dry season rainfall shows a slight decline starting in the mid-to-late 1960s which corresponds with the departure in wet season rainfall (Figure 18). The 5-year running mean of dry season rainfall is consistent with a slight decline appearing after 1965 (Figure 19). Currently, there is little evidence in the literature to suggest that this change is associated with the AMO. Rather, there may be other factors that are related to this slight decline such as the relative intensity and frequency of the El Nino-Southern Oscillation (ENSO), which is linked to above-average winter-early spring season rainfall.

2.5 The Impact of Tropical Cyclone Frequency on Rainfall Changes

Numerous studies, Gray and others, (1997), Landsea and others, (1999), and Goldenberg and others (2001), have documented the causal link between the Atlantic Multidecadal Oscillation and the frequency of tropical cyclones in the Atlantic Basin which includes the Gulf of Mexico, southern Atlantic Ocean and Caribbean Sea. Natural shifts in salinity in the Atlantic Ocean cause cycles of warmer or cooler than average North Atlantic sea surface temperatures that alternate every two-to-five decades. These changes lead to global atmospheric conditions that not only influence summer rainfall on the Florida peninsula but also the frequency of tropical cyclone formation. Warmer AMO modes tend to have more tropical cyclones, more major hurricanes, and a longer duration of hurricane days while cooler AMO periods generally show a reduction or lull in tropical activity. Of course, there are many factors that enhance or inhibit tropical cyclone activity on an annual basis such as the strength of ENSO, west African rainfall, Caribbean sea surface pressure, and high-altitude winds. Over the longer-term time scale of decades, however, the AMO is strongly associated with variation in tropical cyclone activity.

Hickey (1998) examined rainfall and stream flow in west-central Florida and found a reduction in rainfall and stream flow starting around 1970. He attributed this decline to a reduction in the frequency of tropical storms and hurricanes from the period pre-1970 versus the last 30 years. Goldenberg and others (2001) have documented that the AMO cooler mode from 1970 to 1994 led to a lull in tropical cyclone activity in the Atlantic Basin compared with the previous 45 years (1926-1969). The question remains....did this account for all of the four-to-five inch/year decline in annual rainfall between the two periods? In order to answer this question, a historical review of tropical cyclone generated rainfall for the Peace River basin was undertaken since 1930.

A tropical cyclone is defined as any non-frontal low pressure system (closed-circulation) that develops over tropical or sub-tropical waters with a surface wind speed of 35 miles-per-hour or greater (Landsea, 2000). The National Hurricane Center archives contain information on past tropical cyclone tracks dating back to 1921. Tracks were reviewed over the last 70 years to note the dates when a tropical cyclone passed over or near the Peace River basin. A total of 47 tropical cyclones (includes sub-tropical systems, depressions, tropical storms, and hurricanes) impacted the Peace River basin from 1930 to 2001. Decadal totals are shown in Figure 20. During the warmer AMO phase (1930-1969), 33 tropical cyclones affected the basin with an average occurrence ratio (total years /number of cyclones) of 1.2 years per cyclone (four cyclones every five years). During the cooler AMO phase (1970-1994), only 10 tropical systems impacted the region yielding an occurrence ratio of 2.5 years per cyclone (two cyclones every five years).

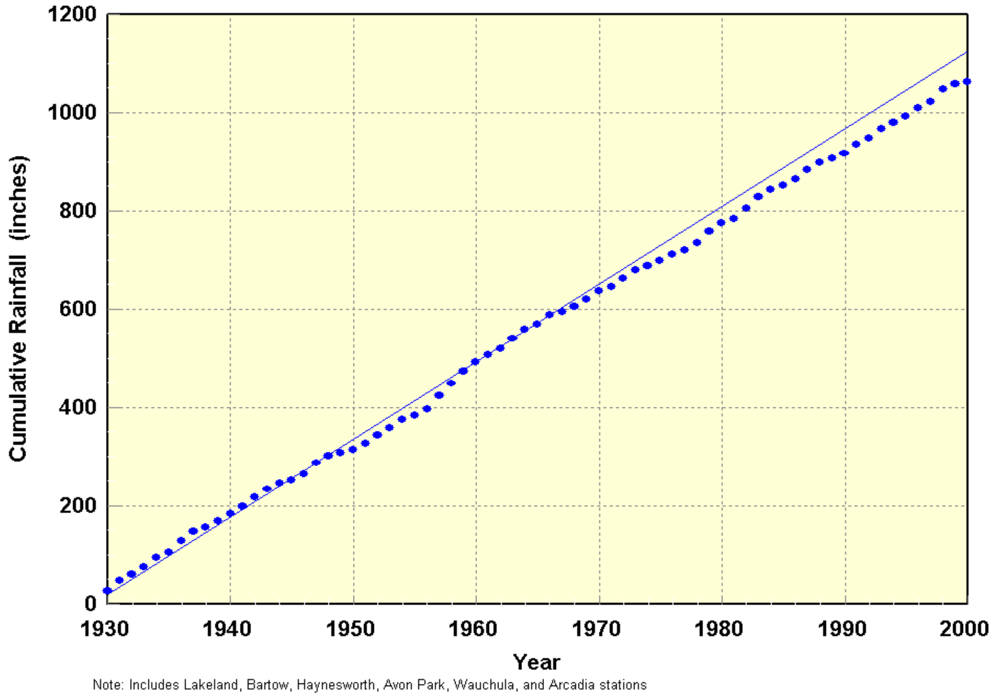

Figure 18. Single mass plot of dry season rainfall (January through May).

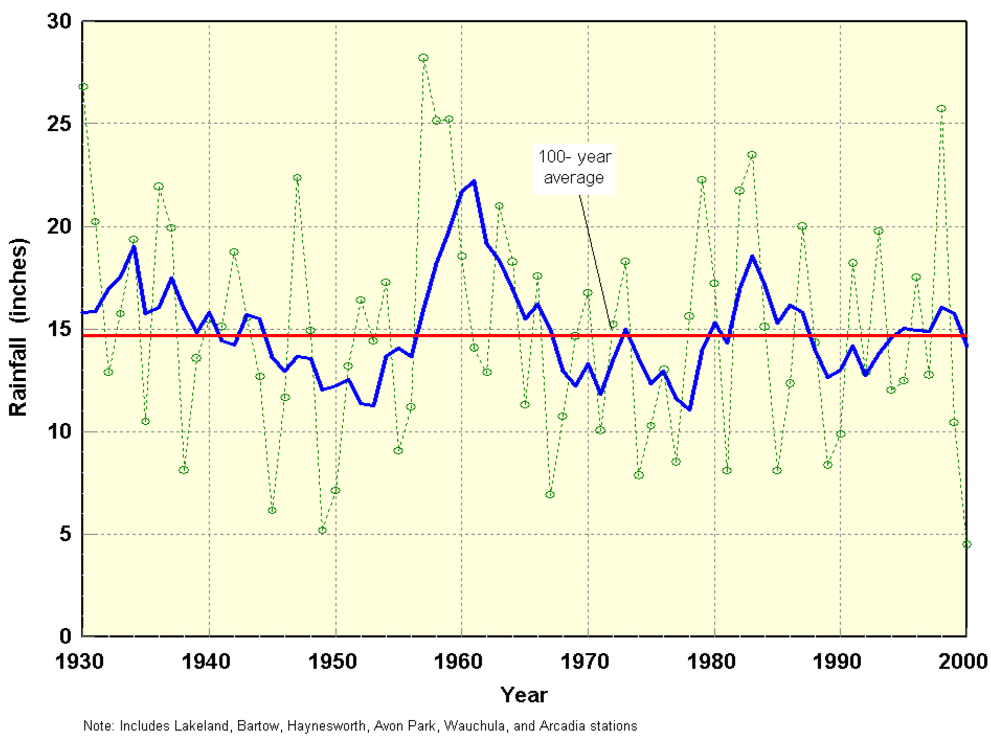

Figure 19. Annual and 5-year running mean of dry season rainfall (January through May).

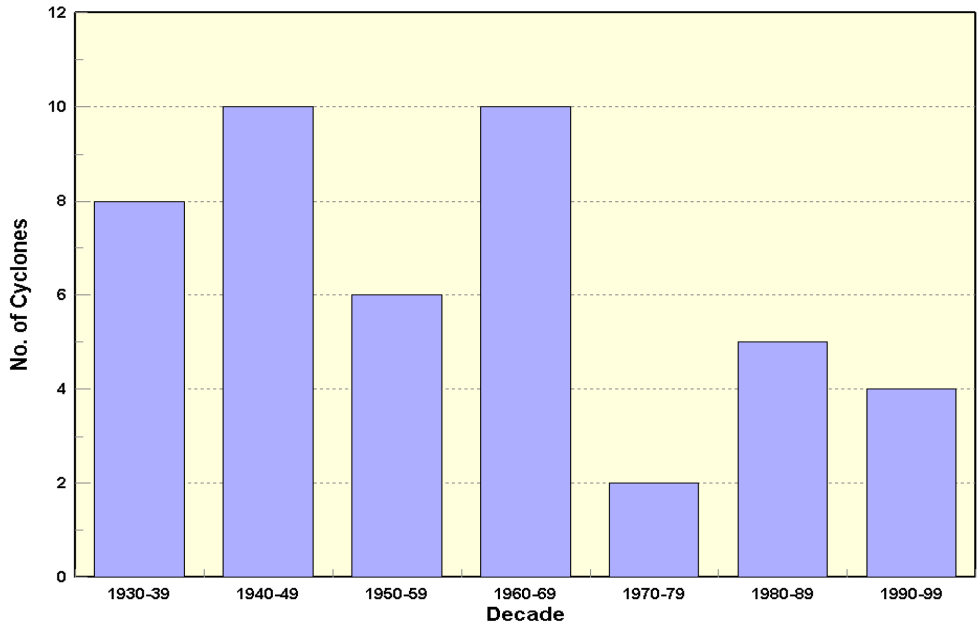

Figure 20. Number of tropical cyclones affecting the Peace River basin (1930-1999).

Individual rainfall amounts associated with each tropical cyclone are often highly variable due to several factors. Along the track of a storm, the wettest quadrant usually occurs on the north and east side of the storm center. If the storm tracks east of your location, rainfall is generally light. The forward speed of each storm can highly influence storm rainfall totals since system speeds can range from less than five miles per hour (mph) to more than 20 mph. Finally, the overall size of the storm determines the area coverage of rainfall. A histogram of storm totals averaged from the six Peace River basin rainfall stations along with the highest 24-hour total recorded at any one station are shown in Figures 21 and 22. Based on 47 cyclones, median storm and median maximum 24-hour totals for the basin were 2.2 inches/event and 2.3 inches/day, respectively.

Tropical cyclone mean rainfall, declined from 2.3 inches/yr for the 1936-1965 period to 1.2 inches/yr for the 1966-1995 period with a net cumulative rainfall difference of 33 inches. Since there is a cumulative departure of -141 inches between the two 30-year periods (averaged from six stations), the change in tropical cyclone frequency accounts for approximately 23 percent of the decline in rainfall. Or another way to view it is that 1.1 out of the 5-inch difference in annual rainfall between the two 30-year periods is due to the lull in tropical cyclone activity experienced during the cooler AMO mode. Using the later 30-year periods, mean tropical cyclone rainfall declined from 2.6 inches/yr for the 1941-1970 period to 0.9 inches/yr for the 1971-2000 period, indicating that tropical cyclone frequency accounted for about one-third of the 5 inch/yr decline in rainfall.

Mean wet season rainfall (June through October) for the period-of-record from six stations in the Peace River basin is 33.8 inches. Rainfall contribution by tropical cyclones was highest during the 1940s with over four inches/yr added by these systems (Figure 23). From 1944-1951, 8 consecutive years of impacting storms contributed an average of 5.3 inches/yr to wet season rainfall (Figure 24). With the exception of the 1940s, the role of tropical systems on changes in wet season rainfall appears modest. The effect of these systems on stormwater runoff, however, can be more significant.

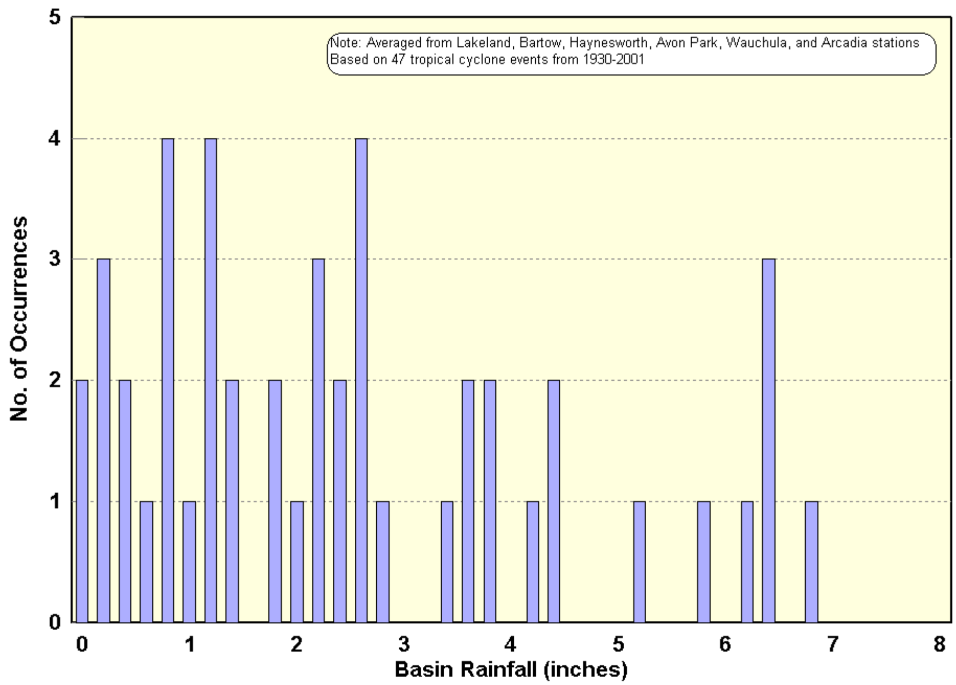

Figure 21. Histogram of tropical cyclone precipitation totals affecting the Peace River basin (1930-2001).

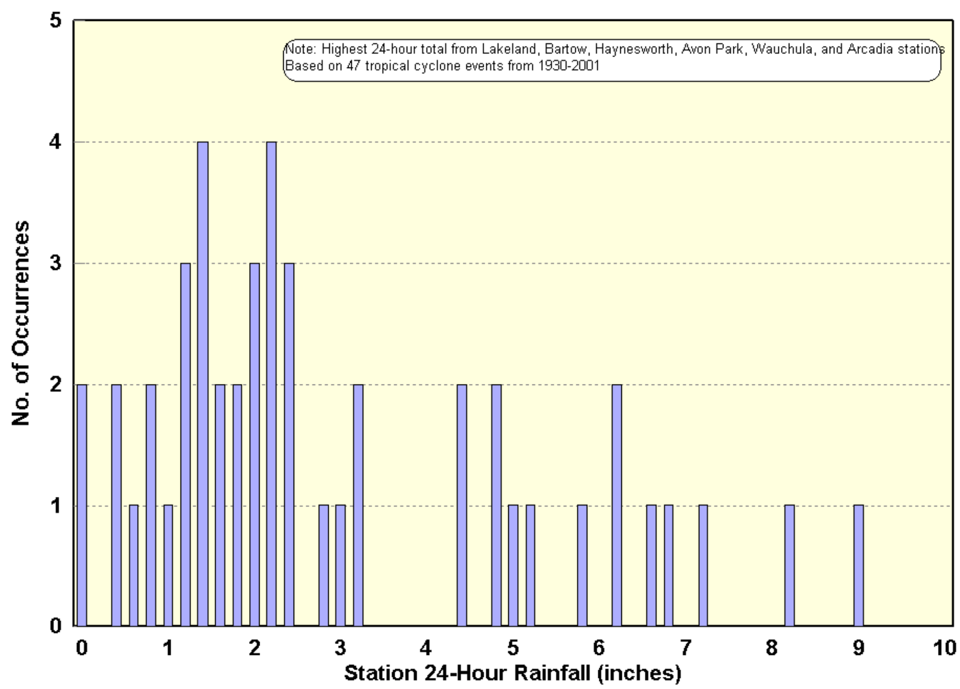

Figure 22. Histogram of tropical cyclone maximum 24-hour precipitation affecting the Peace River basin (1930-2001).

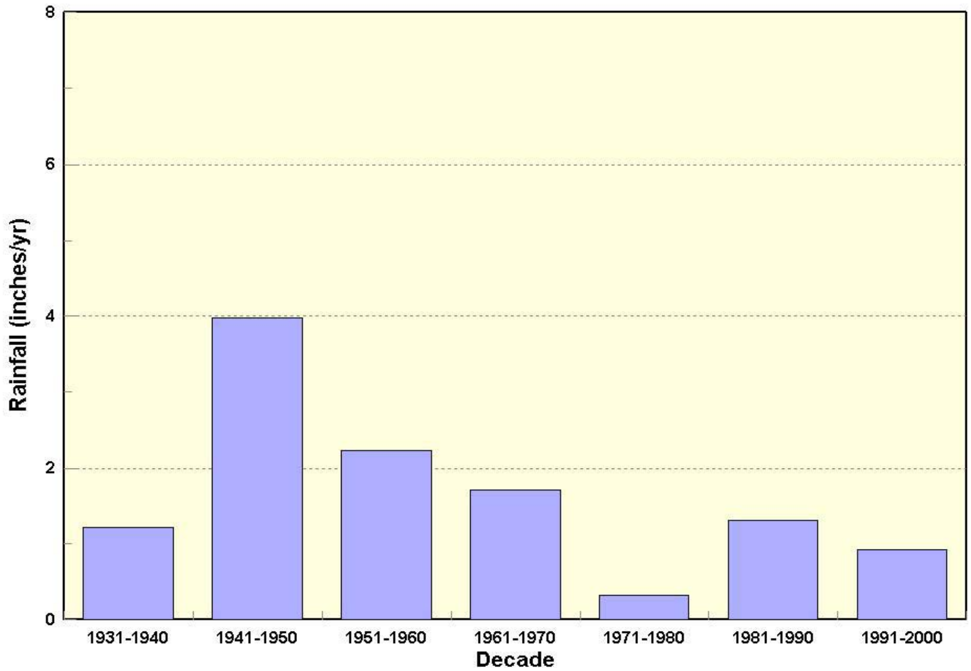

Figure 23. Tropical cyclone rainfall contribution by decade in the Peace River basin (1931-2000).

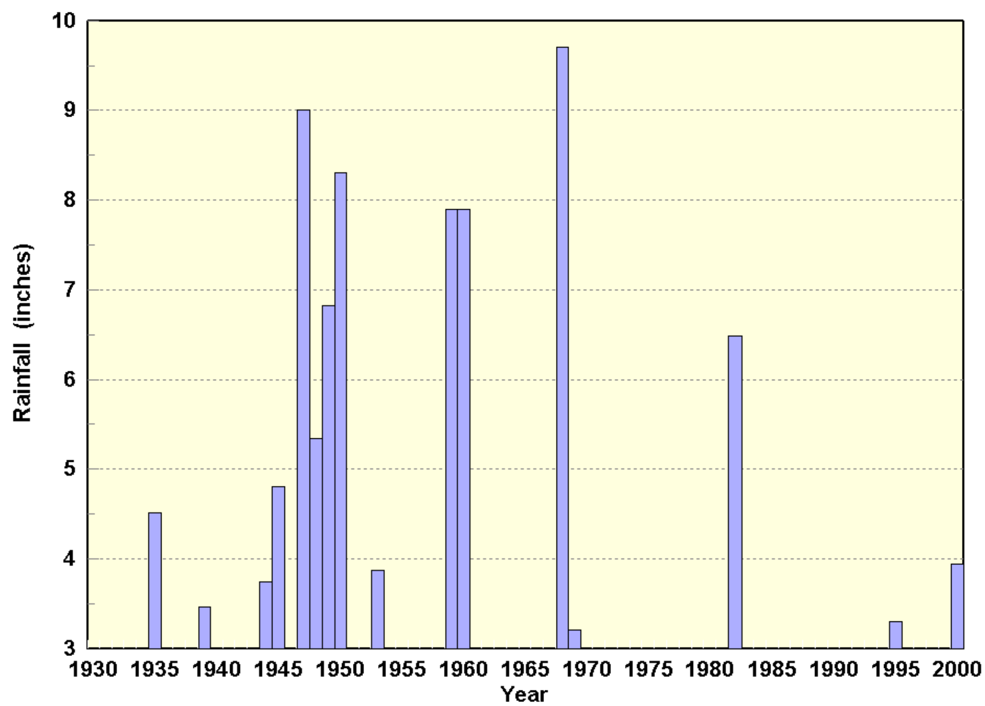

Figure 24. Tropical cyclone contribution (>3 inches) to wet season rainfall in the Peace River basin (1930-2000).

Hurricane Donna moved over the Peace River basin on September 10 and 11, 1960. Average basin rainfall from this event was 6.6 inches over a two-day period. The total runoff volume at the Bartow stream gaging station was calculated during a 37-day period from September 10 to October 16, 1960 - based on the difference in flow between September 9, 1960 and each days difference until streamflow fell at or below the recorded value prior to the hurricane (Figure 25). Total runoff at the Bartow gage was 3.5 inches (normalized for the contributing area of 390 square miles). Average annual streamflow at Bartow from 1940-2000 is 7.8 inches. Therefore, this single storm event represented over 40 percent of the long-term average annual flow recorded at Bartow. While this analysis represents one of the highest rainfall events associated with a tropical cyclone (95 percent of storms had lower rainfall totals), it still points out the impact these storms can have on streamflow volumes.

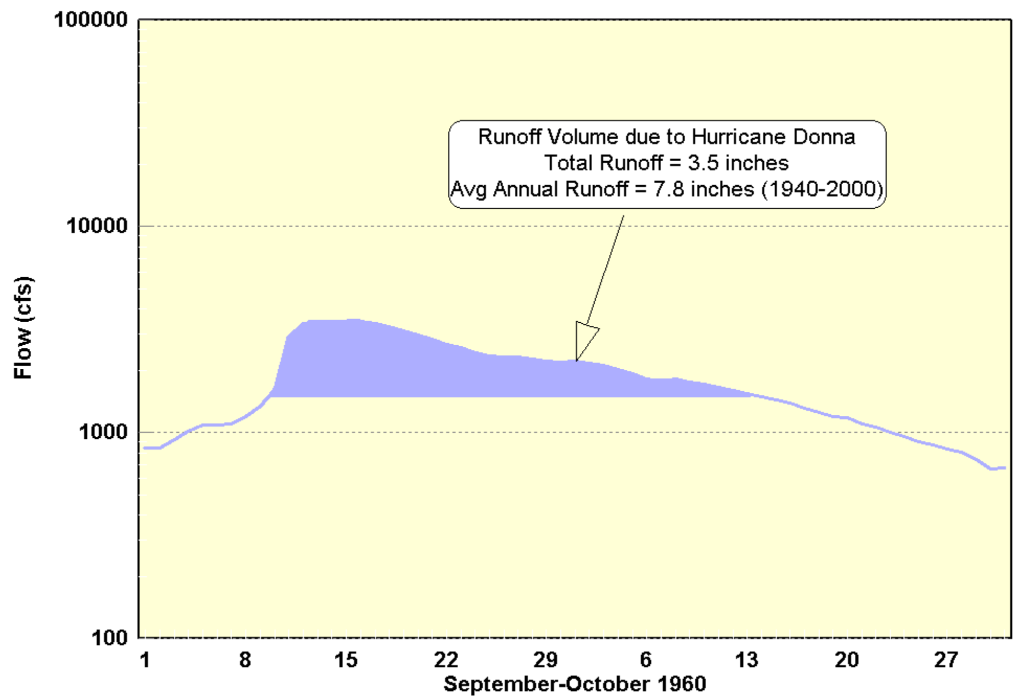

Figure 25. Runoff contribution at Bartow from Hurricane Donna.

2.6 Statistical Significance

According to the AMO theory, precipitation totals for the period of 1966 - 1995 should be less than those of the preceding 30 year period, 1936 - 1965. Review of mean and median differences in rainfall between the two periods support that assertion. However, precipitation is naturally variable and it is possible that some of those differences can be accounted for simply by chance. In order to investigate this possibility, annual rainfall data from 21 stations was examined for the two thirty-year periods. Six other rain stations mentioned earlier in this report were not included because their periods-of-record were less than 60 years.

The annual rainfall totals for all 21 stations were examined; and all annual totals were deleted with less than 12 months of data. This was done to prevent an artificial low bias in the means or medians. After arranging the data in this manner, the means and medians were calculated for each thirty-year period. In 19 of the 21 rain stations, the most recent thirty-year period was drier than the preceding thirty-year period. Only two stations did not show a decline. The Lakeland station indicated a 0.04-inch increase in the mean rainfall in the most recent period and the Clermont station showed a 1.28-inch increase for the recent period over the prior thirty-year period.

In order to determine if the observed differences can be attributed to chance, an analysis was performed to determine if the difference is statistically significant. If the data follow a normal probability distribution a two-sample t-test is appropriate. However, if the assumption of normality is rejected, a non-parametric test is applied such as the Wilcoxon Rank Sum test. Using *NCSS2000* statistical processing software, data from all 21 rain stations were examined for normality and applied the appropriate significance test. Of the 21 stations examined all but 4 could not reject the assumption of normality and thus the two-sample t-test was used for 17 rain stations and the Wilcoxon Rank Sum test was used at the remaining 4 stations.

In a test for statistical significance one is testing a null hypothesis, that the means or medians are equal, against an alternate hypothesis. In this case the alternate hypothesis is that mean or median of the most recent thirty-year period is not just different but less than the preceding thirty-year period. Therefore, a one-tailed test is used for significance.

Discussions of whether or not some phenomenon is “statistically significant” are fairly common. In many instances a test of statistical significance is used to make a “yes/ no” decision. For example, is a change in water quality enough to justify remedial actions or the cost of cleanup. The answer, of course, comes back to how certain it is that water quality is actually different. In such cases, the investigator establishes *a priori* an acceptable risk factor or error rate, known as alpha. For example, in a contamination study, if an alpha of 0.05 is selected then the probability of stating that there is no contamination, when in fact there is, is only 5 percent. Conversely, there is a 95 percent (1 - 0.05) probability that the contamination actually exists. There is no rule for choosing a value for alpha. The choice is determined by the comfort level of the investigator. If people’s lives are at stake it may be reasonable to choose alpha equal to 0.01 (99 percent confidence level), while for simply determining a hierarchy of investigation an alpha of 0.2 (80 percent confidence level) may be appropriate. A 95 percent confidence level is often cited but this is based upon tradition rather than rule (Helsel and Hirsch, 1992).

In the case of rainfall there is no reason to choose a particular alpha. Instead the goal is to understand the natural system and determine if our assumptions of a drier period following a wetter period are reasonable. Because of this the results of statistical significance analysis have been presented in terms of the probability or confidence level that the most recent thirty-year period is drier than the prior thirty years. Figure 26 shows the location of the 21 rain stations as well as the probability that the period of 1966-1995 is drier than the period of 1936-1965. The four stations whose data were treated using non-parametric methods are identified on the figure.

It is interesting to note that 17 of the 21 rain stations examined have probabilities of drier recent conditions in excess of 80 percent. Also of interest is that there appears to be an east-west trending band of very high probability (> 95 percent) of drier recent conditions. It is not surprising that these same stations have the largest difference in means and medians of the two time periods.

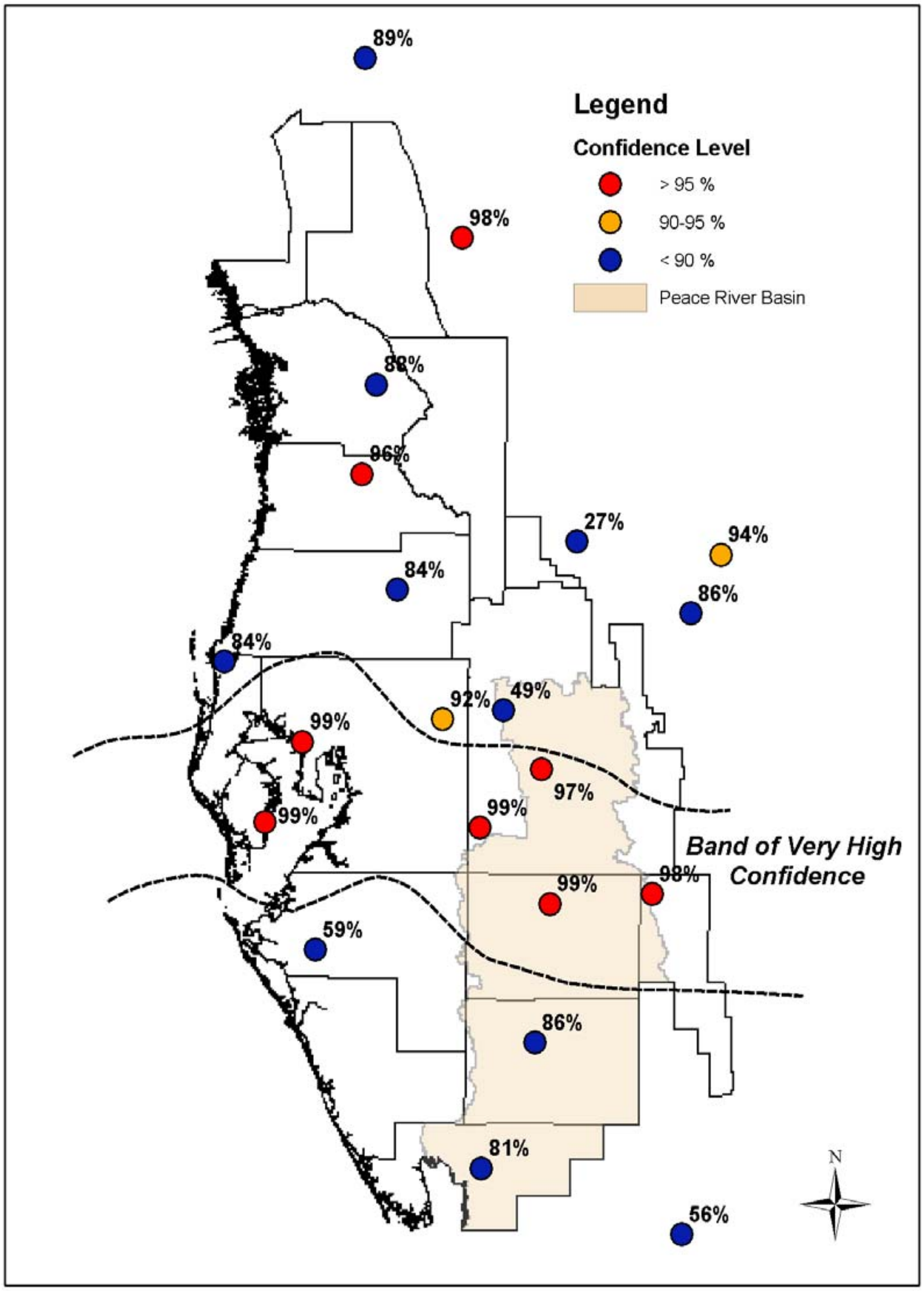

Figure 26. Probability that Post–1965 Precipitation is Less Than Pre-1965 Precipitation.

As was previously noted, the Lakeland rain station had virtually equal average rainfall for both time periods. In order to gain some insight into the sensitivity of the statistical significance calculation, this data was used for a test. With approximately equal rainfall in both periods the test found that there was only a 49 percent probability that the recent period was drier. Using the actual data for the period of 1966 - 1995 and incrementally adding 0.5 inches to the mean rainfall for the period of 1936 - 1965, it was possible to recalculate the probability that the recent period was drier for each increment (Figure 27). The results are non-linear with most of the increase in probability occurring in the first inch or two and succeeding increments having lesser effects. Nonetheless, a two-inch increase in the annual average rainfall of the first period raises the probability of a drier second period to 80 percent. By the time the annual average increase has reached 4 inches the probability has increased to 96 percent.

The importance of this is realized when one examines all the rain stations with significance levels at the 80 percent level. It would not take a very large increase in the difference of the two means of pre- and post-1965 to raise their statistical significance levels into the 90 percent or better range. Another point to bear in mind is that statistical significance is not the same as physical significance. If by choosing some arbitrary risk level, the difference between the two averages is found to be "not significantly different from zero" does not mean that zero should be assumed for some physical analysis (Haan, 2002). For example, a four-inch difference in average rainfall between the two periods may not be "statistically significant" but might very well be "physically significant" in terms of aquifer recharge or streamflow.

Overall, the significance levels observed throughout the study area support the hypothesis that the post-1965 period is drier than the pre-1965 period. What remains to be seen is the impact of the difference on the hydrology, in other words the physical significance.

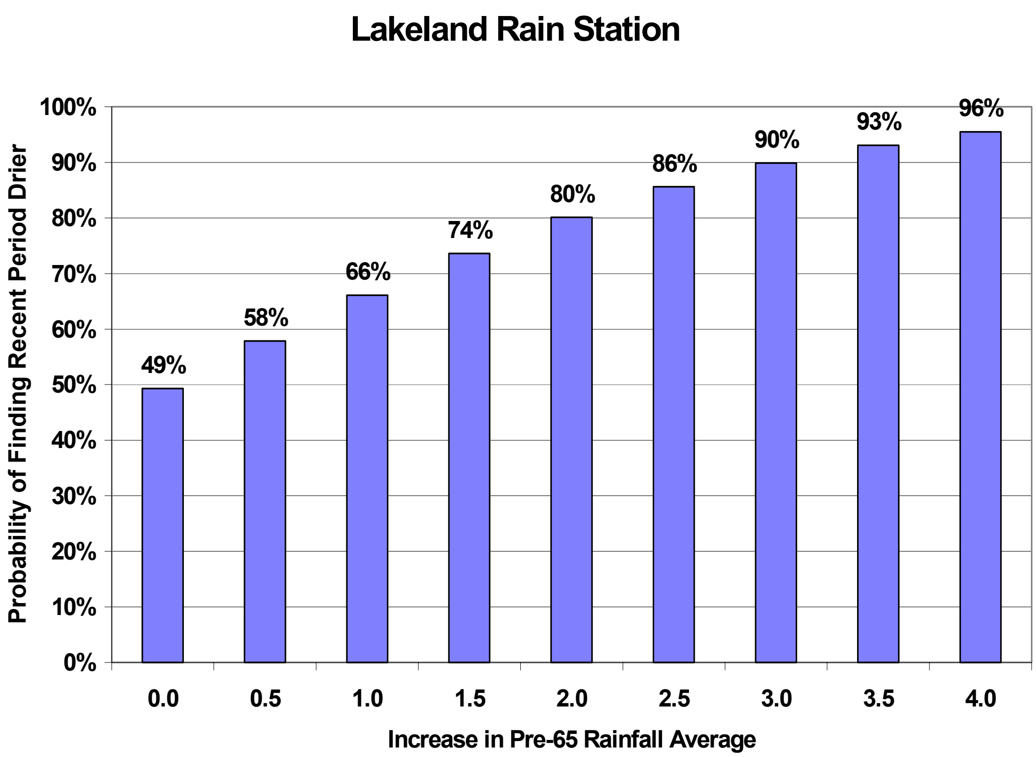

Figure 27. Change in probability of finding recent 30-year period drier by increasing pre-1965 mean rainfall.

3.0 CHANGES IN STREAMFLOW DUE TO RAINFALL DECLINE

Mean rainfall declined about 5 inches/yr between two 30-year periods over the Peace River basin. Hammett (1990) and Lewelling and others (1998) found a declining trend in streamflow at Bartow, Zolfo Springs, and Arcadia stations from the 1930s to 1994. If rainfall has declined by 5 inches/yr with about 80 percent of this decline occurring during the wet season, how much could the change in rainfall affect streamflow volumes? In this section, estimates of streamflow decline due to rainfall changes have been calculated through empirical and surface-water model results. While it is recognized that sophisticated surface-water/ground-water models may provide more detailed information on the role of rainfall and runoff in the basin, the use of less rigorous methods may still provide some measure of the impact of rainfall changes on the flow regime.

Streamflow at Bartow, Zolfo Springs, and Arcadia was graphed against rainfall (averaged from six stations) on an annual basis for the period-of-record for each station (Figures 26-28). Simple linear regression was applied to each station to develop an equation that relates annual rainfall to flow volumes. Based on the slope of each regression, a correlation can be developed between flow and rainfall. R-squared values (coefficient of determination) were greater than 0.7 other than Bartow. Table 2 summarizes the results.

Table 2. Streamflow volume associated with changes in annual rainfall based on regression results at the Bartow, Zolfo Springs, and Arcadia gaging stations.

Flow Station	Flow (cfs) per 1 inch of rainfall	Flow (cfs) per 5 inch Decline in Rainfall	Period-of-Record Mean Flow (cfs)	Percent of Mean Flow related to Rainfall Decline
Bartow	15.7	78.5	224	35
Zolfo Springs	34.4	172	621	28
Arcadia	61.0	305	1,066	29

The regression analysis assumes that the relationship between rainfall and streamflow can be approximated through a linear function. The physical relationship between rainfall and runoff is inherently non-linear, particularly on the time scale of minutes to days. By annualizing the data and determining the results over a relatively small change in rainfall (compared to the entire range), any errors introduced through the linear approximation should be small.

It is interesting to note that the y-intercept values were 36.9, 33.7, and 34 inches of annual rainfall for the Bartow, Zolfo Springs, and Arcadia gaging stations. This suggests that minimum annual rainfall values need to be on the order of about 34 inches/yr for the Peace River to remain a perennial system.

One of the possible limitations in utilizing the aforementioned approach may be that the rainfall-flow relationship is influenced by other factors such as drainage changes or baseflow loss through ground-water withdrawals. Ross and others (2001) completed a surface-water model of west-central Florida that included the Peace River basin. The 10-year HSPF simulation, from 1989-1998, discretized 20 drainage sub-basins with the entire Peace River basin. A linear

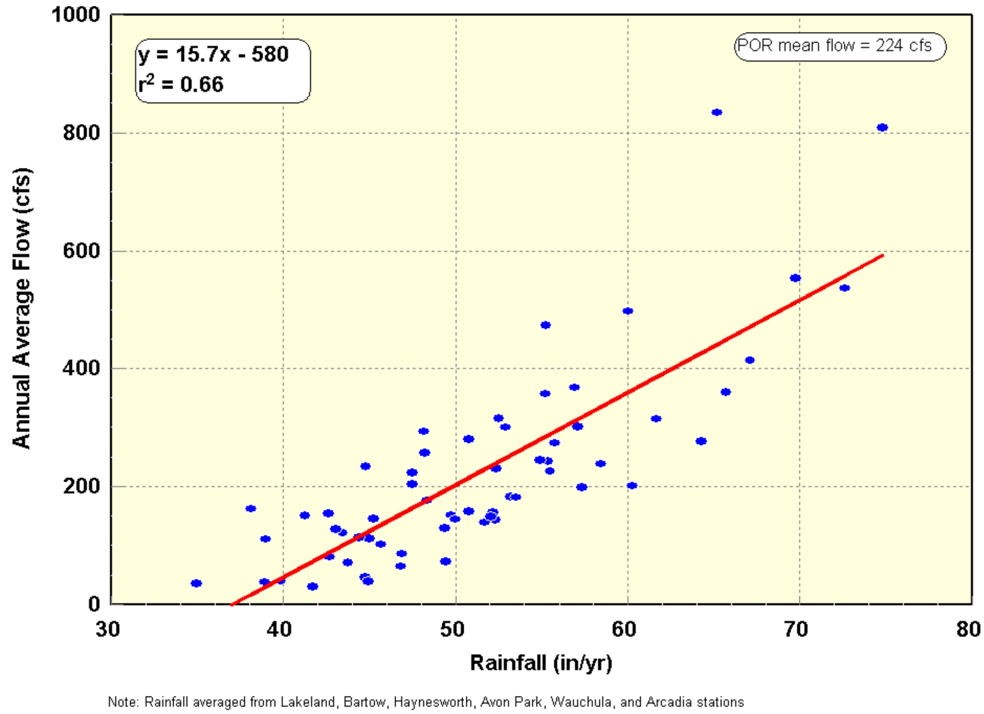

Figure 28. Regression of annual rainfall versus flow at the Bartow gaging station.

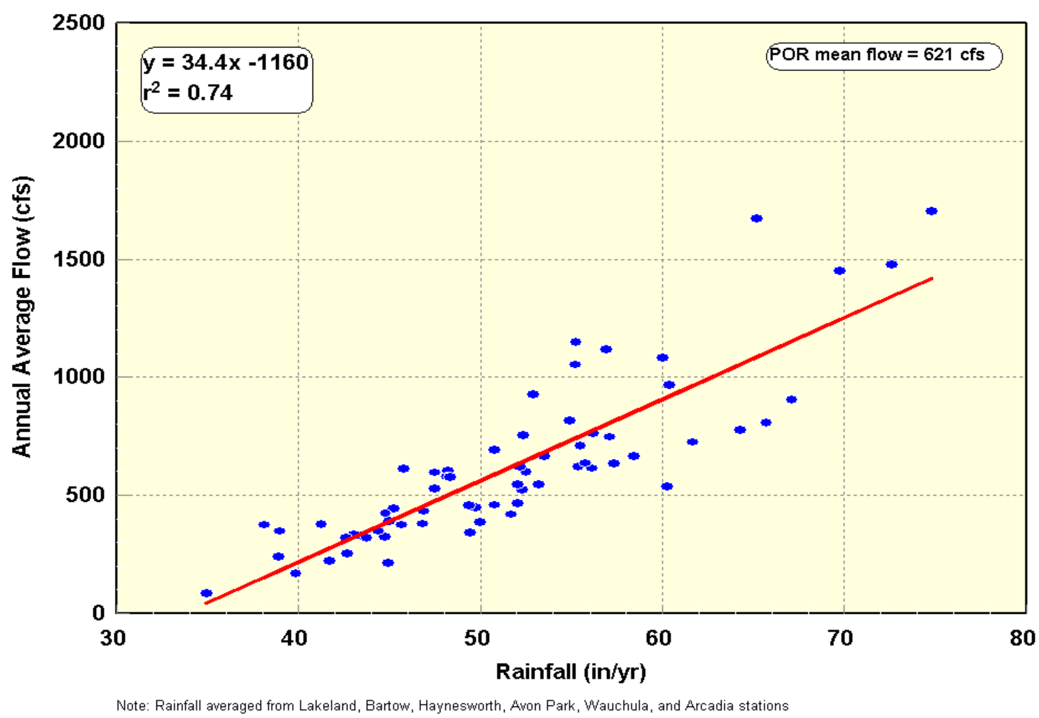

Figure 29. Regression of annual rainfall versus flow at the Zolfo Springs gaging station.

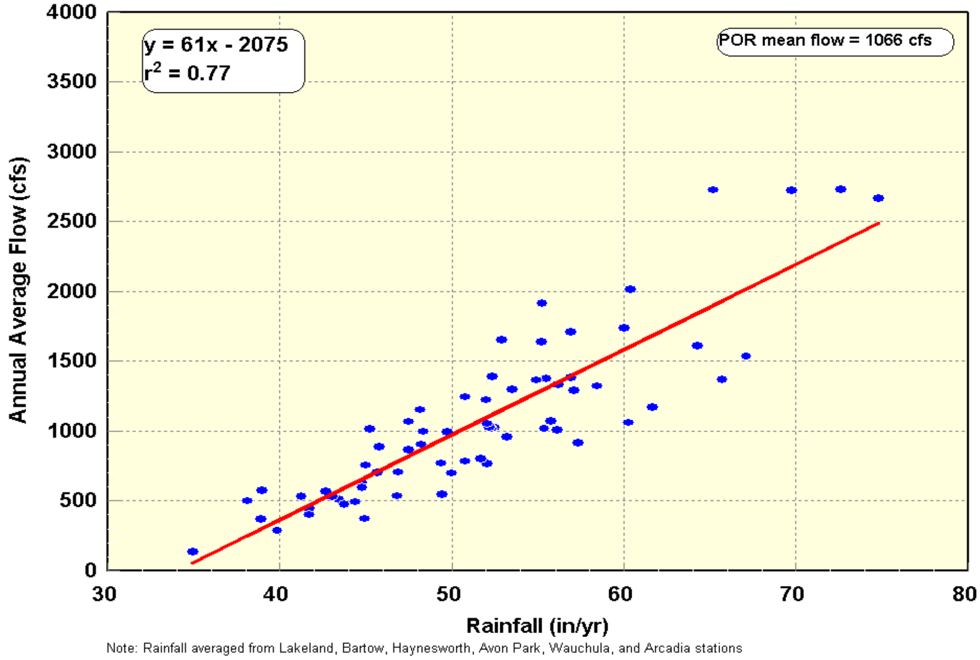

Figure 30. Regression of annual rainfall versus flow at the Arcadia gaging station.

regression of annual rainfall versus streamflow was completed at the Bartow, Zolfo Springs, and Arcadia gaging stations for the 10-year period (Figures 29-31). Similar to the previous procedure, the slope of the regression was used to calculate the change in flow per change in rainfall. R-squared values were again greater than 0.7 except for Bartow. Table 3 summarizes the results.

Table 3. Streamflow volume associated with changes in annual rainfall based on results of a HSPF surface-water model for the Bartow, Zolfo Springs, and Arcadia gaging stations.

Flow Station	Flow (inches)* per 1 inch of rainfall	Flow (cfs) per 1 inch of rainfall	Flow (cfs) per 5 inch Decline in Rainfall	1989-1998 Mean Flow (cfs)	Percent of Mean Flow related to Rainfall Decline
Bartow	0.34	9.8	49	198	25
Zolfo Springs	0.45	27.4	137	621	22
Arcadia	0.49	49.3	246	1,108	22

* = inches of runoff over drainage basin

The y-intercept values ranged between 29 and 33 inches/yr of rainfall, which were slightly lower than the previous regression analysis. The streamflow versus rainfall correlations (which were lower than the empirical approach) may be due to variations in the time periods used in each analysis (period-of-record compared with a 10-year simulation period) or other factors. In any case, the magnitude of flow decline associated with a 5-inch per year rainfall change varies from 25 to 35 percent at Bartow, 22 to 28 percent at Zolfo Springs, and 22 to 29 percent at Arcadia, expressed as a percentage of mean flow.

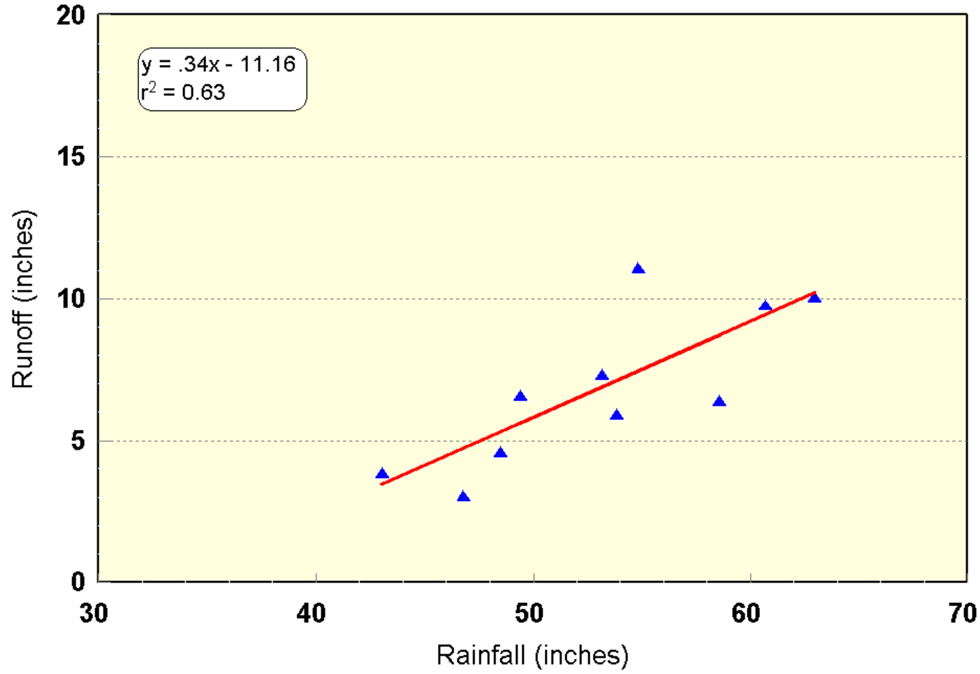

Figure 31. Regression of annual rainfall versus flow at the Bartow gaging station based on a 10-year HSPF simulation.

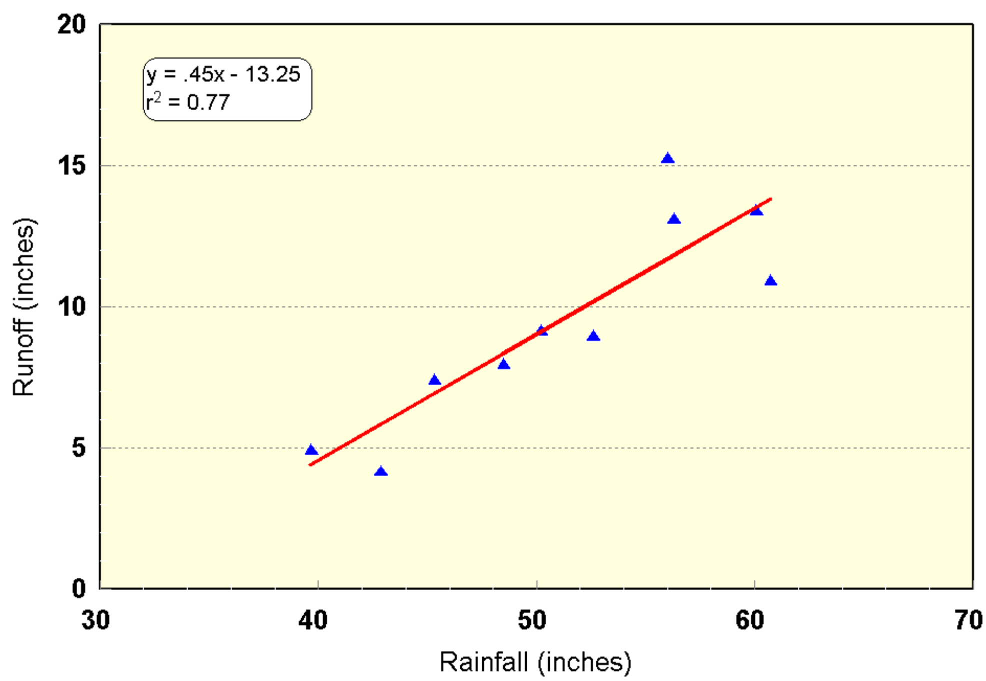

Figure 32. Regression of annual rainfall versus flow at the Zolfo Springs gaging station based on a 10-year HSPF simulation.

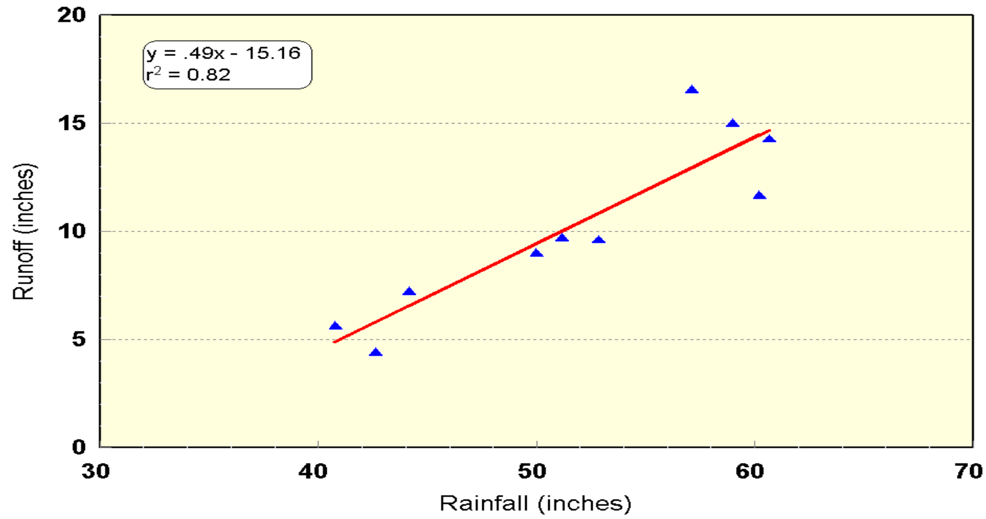

Figure 33. Regression of annual rainfall versus flow at the Arcadia gaging station based on a 10-year HSPF simulation.

As a cautionary note, the previous analyses should be considered approximations until a more refined approach such as long-term surface-water/ground-water modeling can be completed. The rainfall-runoff process is strongly influenced by changes in land use/cover , rainfall intensity, water table depth, and antecedent soil moisture conditions. Much of the Peace River basin has experienced changes in land use due to phosphate mining, agriculture, and urbanization. The rainfall-runoff process is non-linear given that the same amount and intensity of rainfall will lead to higher runoff volumes if antecedent conditions are wetter (higher soil moisture and water table closer to land surface). Therefore, if the earlier 30-year period was wetter than the last 30 years, the rainfall-runoff relation might vary considerably between the two periods. The simple regression models can not account for this situation. Given this knowledge, the regression models would tend to underestimate streamflow volume changes associated with changes in rainfall.

To further estimate the role of long-term rainfall changes on total streamflow, single-mass plots were constructed of annual average river flow at the Bartow, Zolfo Springs, and Arcadia gaging stations (Figures 34-36). The abrupt break in slope around 1970 illustrates the decline in flow at all three stations. Based on the linear regressions of annual flow versus rainfall, the amount of streamflow volume lost due to a 5.7-inch/year rainfall decline was added to the actual data starting in 1970. The 5.7 inches/yr difference in mean rainfall was calculated between the 1941-70 and the 1971-2000 periods using the Bartow, Haynesworth, Wauchula, Avon Park, and Arcadia stations. The anomalous Lakeland station was excluded from the data set.

Review of the single mass plots show that not all of the streamflow decline can be attributed to a difference in rainfall. However, when Kissengen Spring discharge (30 cfs), which ceased flow in 1960, is added to the Zolfo Springs and Arcadia stations, the estimated flow closely approximates the pre-1970 streamflow after adjusting for rainfall effects. Even without Kissengen Spring discharge, over 90 percent of the river flow decline observed at the Zolfo Springs and Arcadia stations after 1970 can be accounted for by long-term changes in rainfall. At the Bartow station, about three-quarters of the observed streamflow decline can be attributed to long-term changes in rainfall.

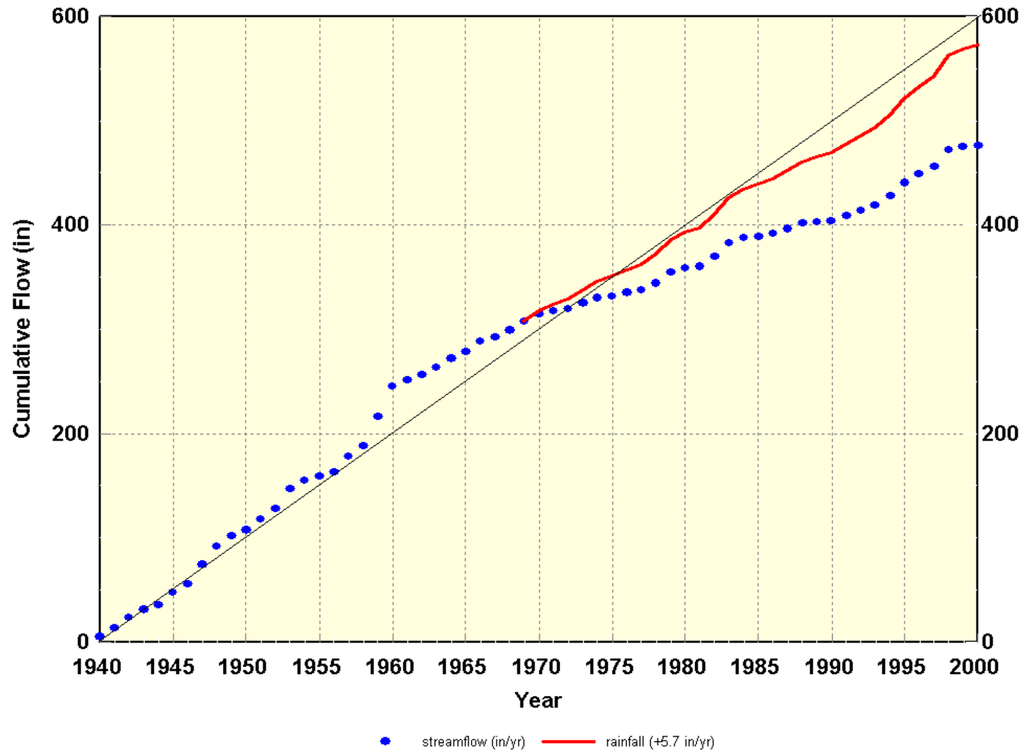

Figure 34. Single mass plot of Peace River flow at Bartow with streamflow adjusted to account for rainfall decline.

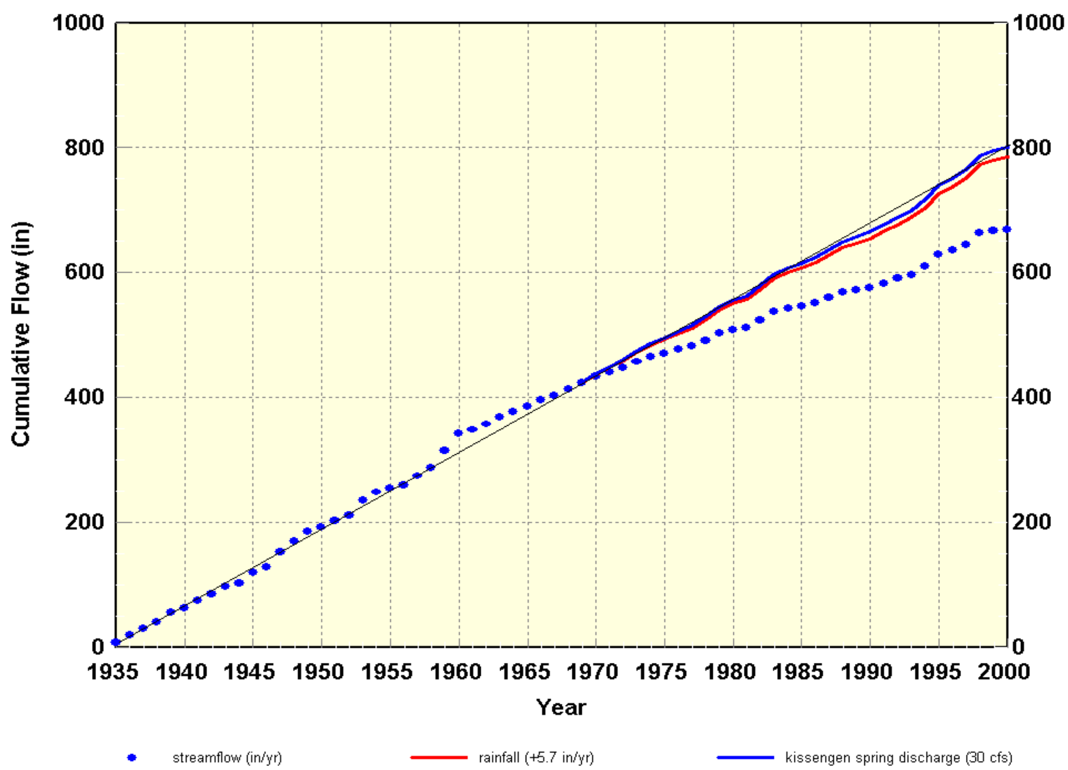

Figure 35. Single mass plot of Peace River flow at Zolfo Springs with streamflow adjusted to account for rainfall decline and Kissengen Spring discharge.

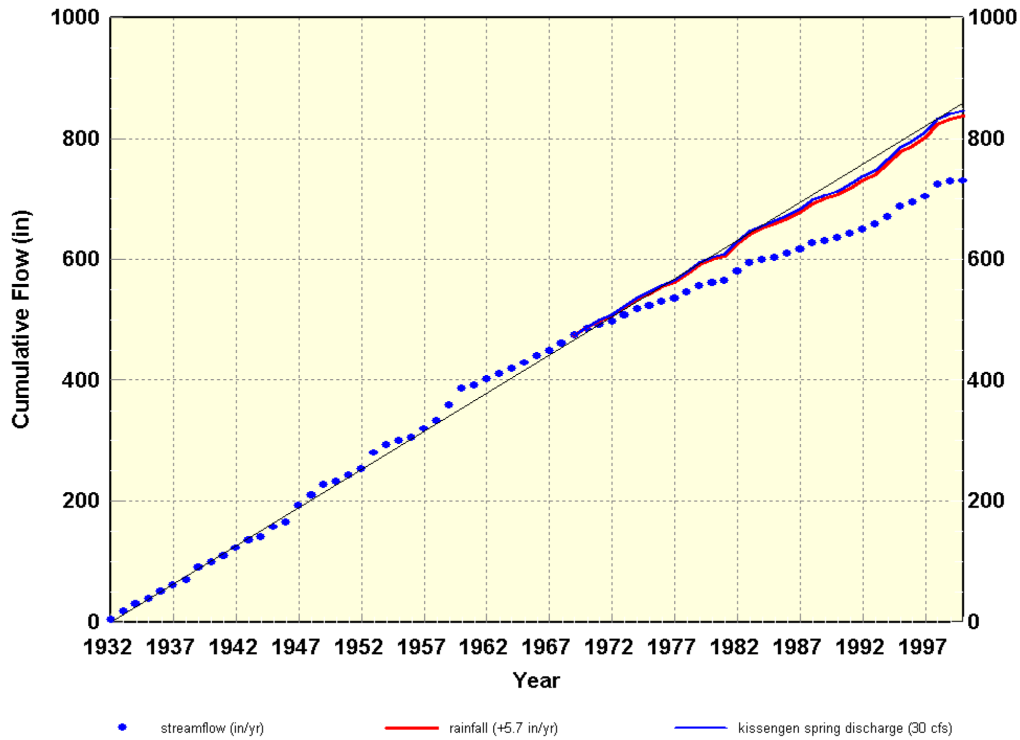

Figure 36. Single mass plot of Peace River flow at Arcadia with streamflow adjusted for rainfall decline and Kissengen Spring discharge.

4.0 SUMMARY

Over the last century, there has been no significant change in annual rainfall. If the record is partitioned into shorter intervals, however, several decade cycles of above-or-below average rainfall are evident. These cycles have been closely linked with the Atlantic Multidecadal Oscillation (AMO), a naturally occurring variation in North Atlantic Ocean temperatures that occurs every 20 to 50 years. Enfield and others (2001) indicate that warmer than average sea surface temperature periods of the AMO lead to increased wet season rainfall while cooler than average ocean temperatures decrease summer rainfall on the Florida peninsula. Higher sea surface temperatures also lead to atmospheric circulation patterns that tend to increase the frequency of major tropical cyclones in the Atlantic and Caribbean Basins. Throughout Florida's history, tropical systems have produced extremely high rainfall, with a single storm event producing as much as one-third of annual wet season rainfall.

Based on the 5-year moving average, mean and median statistics, cumulative departure analysis, single mass techniques, and time series plots, it is apparent that the decades of the 1930s, 1940s, 1950s, and 1960s were wetter than the most recent three decades. Averaged from six stations within or adjacent to the Peace River basin, mean and median decline in rainfall between two 30-year periods ranged between 4.5 and 5.5 inches/yr. Changes in wet season rainfall, primarily linked to the AMO, accounted for about 80 percent of the rainfall difference. An analysis of rainfall associated with tropical systems found that the lull in tropical cyclone activity experienced from 1970-1994 contributed up to one-third of the observed decline in wet season rainfall. Dry season rainfall, using the January through May periods, has also declined slightly between the two 30-year periods, perhaps reflecting changes in the frequency and strength of ENSO events, which influences winter-early spring season rainfall.

The issue of statistical significance regarding changes in the rainfall regime was addressed by examining annual data from 21 stations throughout west-central Florida. The hypothesis that the most recent 30-year period (1966-1995) was drier than the previous 30-year period (1936-1965) was tested using a two-sample t-test and the non-parametric Wilcoxon Rank Sum method to test for differences in mean and median rainfall, respectively, between the two periods. Prior to the test, 19 of the 21 stations had lower mean and median rainfall for the most recent 30-year period compared to the previous one. After testing for significance, 17 of the 21 rain stations examined had probabilities of drier recent conditions in excess of 80 percent. There also appears to be an east-to-west trending band from Avon Park in Highlands County to the Tampa Bay region of very high probability (> 95 percent) of drier recent conditions. It is not surprising that these same stations exhibited the largest decline in mean and median rainfall between the two time periods.

The Lakeland and Clermont stations were the only two rainfall sites that did not reflect drier conditions during the most recent 30-year period. Mean difference in rainfall between the two 30-year periods at Lakeland was essentially zero. In order to gain some insight into the sensitivity of the statistical significance calculation, mean rainfall amounts were incrementally increased by 0.5 inches for the period of 1936-1965 to investigate the effect of increasing differences on the confidence level. The results demonstrate that a two-inch increase in the mean annual rainfall for the first period increases the confidence level of a drier second period to 80 percent. By the time the mean annual increase has reached 4 inches the confidence level has increased to 96 percent.

To maintain the Peace River as a perennial flow system would require annual rainfall of 30 to 35 inches per year based on regression analysis. Estimates of Peace River flow through regression of empirical data and surface-water model results indicated that a 5-inch per year decline in rainfall could result in streamflow volume changes ranging from 22 to 35 percent, expressed as a percentage of mean flow. Using single mass analysis and results from the regression of empirical data, about 90 percent of observed streamflow decline at the Zolfo Springs and the Arcadia stations can be attributed to a post-1970 rainfall departure of 5.7 inches/yr. At the Bartow station, about 75 percent of the observed streamflow decline can be related to long-term changes in rainfall.

5.0 FUTURE OUTLOOK

A warmer ocean phase of the AMO mode began in 1995 with North Atlantic Ocean temperatures running 0.4 to 0.6 degrees C above average (Gray and others, 2002). This wetter cycle should last another 20 to 50 years. In fact, rainfall was above-average for the 1994-1998 period for the six rainfall stations of the Peace River basin. Unusually strong La Nina conditions experienced after an intense 1997-1998 El Nino episode and the general lack of major land falling hurricanes on the U.S. coastline have contributed to a recent 3-year drought (1999-2001), which has masked the wetter regime. Gray and others (2002) indicated that the last seven years (1995-2001) constituted the most active tropical cyclone period on record. However, of the 27 major hurricanes formed during this period, only three made landfalls on the U.S. coast. During this seven-year period, the Florida peninsula and U.S. east coast experienced only 22 percent as many major hurricane landfall events as during the average of the previous 95 years. This fortuitous landfall downturn is unlikely to persist.

As a result of these conclusions, the South Florida Water Management District is now considering adjusting their operation and management of Lake Okeechobee water levels to account for the AMO 20 to 50 year cycles. Of more immediate significance, however, is that this recent warmer phase of sea surface temperatures could lead to increased tropical cyclone activity and summer rainfall over the Florida peninsula that hasn't been experienced in over 30 years.

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