Edwards Aquifer Authority
San Antonio, Texas

Analysis of Recharge and Recirculation
Edwards Aquifer
Phase 2

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Todd Engineers
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Executive Summary

Background

In April 2004, Edwards Aquifer Authority (EAA) contracted with Todd Engineers to conduct a multi-phase study on enhanced recharge and recirculation (R&R) strategies. Phase 1 of that work was completed in September 2004 (Todd Engineers, 2004). The Phase 1 report included a review of existing studies, an analysis of Edwards Aquifer hydraulics, installation and operation of the 2004 U.S. Geological Survey (USGS) MODFLOW model of the Edwards Aquifer, and application of the model for test runs at two hypothetical recharge sites. Test runs indicated that long-term benefits measured in years can be achieved for Comal Springs flow by increasing aquifer recharge. Further, the magnitude and duration of increased springflow was found to vary significantly from site to site.

Phase 2 Scope of Work

Phase 2 of the R&R study analyzed the magnitude and duration of increased springflow from enhanced recharge at eight sites considered for development by the South Central Texas Regional Water Planning Group (SCTRWPG, 2001). Objectives for Phase 2 included a comparison of impacts on a site-to-site basis for both a single recharge event and yearly enhanced recharge events over time. To achieve these objectives, the approved scope of work for Phase 2 was designed with the following tasks:

1. Conduct individual single-year model recharge applications at Type 1 and Type 2 recharge sites as defined by SCTRWPG (2001) as shown in Figure 6 of the Phase 1 report.
2. Conduct model recharge applications as in Task 1 above assuming one or more sites have a constant annual recharge from 1946 to 2000.
3. Conduct model recharge applications as in Task 2 above assuming continuous annual recharge proportional to annual natural recharge from 1946 to 2000.
4. Determine for representative recharge sites how much recharge water emerges at the five major springs.
5. Study flow paths of recharge water in the vicinity of the Balcones Fault Zone and Knippa Gap.
6. Evaluate the effect of recharge when annual pumpage is reduced to selected upper limits.
7. Analyze results of the above model investigations and determine sites and amounts of recharge that appear to be most promising in sustaining Well J-17 levels and Comal Springs flows.
8. Prepare a report summarizing the above tasks and serving as a proposal to the Edwards Aquifer Authority for work to be performed in Phase 3.

Application of the USGS Model

These analyses were conducted with the application of the recently-available USGS MODFLOW model of the Edwards Aquifer (Lindgren, 2004). Although the model represents a much-improved tool with which to analyze R&R scenarios, numerous uncertainties are associated with the model. The model uncertainties and limitations were summarized in the Phase 1 report and are briefly re-stated in this report to highlight model application objectives in Phase 2.

In order to prevent the introduction of more uncertainty in the Phase 2 analyses, all of the model applications began with a baseline run of the unmodified USGS model, using USGS-generated inputs and boundary conditions to define model-generated output of water levels and springflow for various time periods. Phase 2 applications of the model were used to generate similar data sets of water levels and springflow with modified inputs of recharge or pumping as described for each analysis. These outputs were then compared back to baseline conditions. Most of the results presented in this study are the difference between baseline and Phase 2 applications rather than a prediction of actual flows or levels.

Enhanced Recharge Model Runs

Given the uncertainties associated with the model and the approved scope of work, a series of model runs were devised to analyze the response of the aquifer and springflows to various scenarios of enhanced recharge. Preliminary model runs examined the impacts of adding 25,000 AF/yr of water, individually and cumulatively for each of the eight recharge sites previously analyzed by SCTRWPG (2001). The amount of 25,000 AF/yr was selected for the initial model runs because it was within the range of average recharge amounts estimated for the eight recharge sites and was determined in Phase 1 to have a measurable impact on water levels and springflow. Applying the same amount of recharge to each site allowed a comparison of the benefits at one site to the others.

Subsequent model runs used actual estimates for maximum recharge enhancement water under average and drought conditions for the eight recharge sites as summarized by Turner Collie & Braden and LBG Guyton in their 1999 work for EAA (Table 5). Enhanced recharge volumes were applied both during certain months and continuously throughout the year. Although the recharge associated with Type 2 projects may not be available year round, Type 1 projects could hold water for recharge when needed. Therefore, continuous recharge scenarios were a way of analyzing impacts from Type 1 projects in addition to Type 2 projects. The effects of adding recharge enhancement available during average conditions continuously were analyzed as well as varying the amount of enhanced recharge during drought conditions.

The relationship of timing of recharge to response of springflow was analyzed by adding recharge at the eight sites for one year, five years and 27 years, covering various hydrologic time periods. Since the aquifer response to recharge was determined to behave uniformly after a certain period of time, the entire time period of 1946-2000 did not have to be run continuously to analyze the response for a given duration of recharge. As a result, the two halves of the model (1946-1973 and 1974-2000) or portions of these model halves were employed as appropriate for various analyses.

Impacts of Enhanced Recharge On Springflow

Enhanced recharge at each of the eight sites resulted in some increase in springflow at each of the five major springs, although impacts were related to distance to the spring and impacts on some springs were very small (Table 1 and Figure 2). As anticipated, recharge sites closer to Comal Springs, including Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, and Cibolo, produced the greatest increase in springflow there, equivalent to about one-half of the total recharged amount. Remaining amounts were either discharged through other springs, contributed to aquifer storage, or were discharged out of the aquifer at unmonitored locations in the model. The eastern-most site, Lower Blanco, was not effective at contributing to springflow at any location except at nearby San Marcos Springs. Other springs were not affected due to the Lower Blanco's downgradient location and proximity to San Marcos Springs.

The two western sites, Indian Creek and Lower Frio produced the largest benefit to Leona Springs in an amount equivalent to about 45 percent of the total volume of enhanced recharge (Table 1). Recharge at these two sites was less effective at impacting Comal Springs, but did contribute an average of about 25 percent of the equivalent volume recharged under various recharge scenarios. Volumes equivalent to 70 percent or more of the recharge volumes could be accounted for in springflow discharge for all except one (Indian Creek) of the recharge sites. For Indian Creek, an equivalent volume of only about one-half of the recharge, continuously applied, had been discharged at any of the springs even after a 27 year model run. These remaining volumes may be contributing to aquifer storage or, less likely, have been discharged at an unmonitored location.

Two smaller springs, San Antonio Springs and San Pedro Springs, appear to receive little benefit from the modeled enhanced recharge (Table 1 and Figure 2). San Antonio Springs benefits somewhat from recharge at centrally-located sites from Lower Sabinal to San Geronimo, but other sites are located either too far west or downgradient to the east. San Pedro Springs, a low yielding and intermittent spring, gains little or no benefit from any of the recharge sites (Table 1 and Figure 2).

Increases in springflow occur quickly in response to recharge because of the rapid transmission of the pressure wave in the aquifer. However, in most cases the actual water molecules that are recharged remain in the aquifer for a long time.

Volumetric increases in springflow were very similar for model runs that added water to only one recharge site at a time and model runs that added the same corresponding amounts of water cumulative in one run (Table 2). However, continuous recharge results in more uniform springflow (Figures 8 through 12). Although variations in natural recharge are reflected somewhat in the variability of response to recharge at the springs, the effect is attenuated. Increases in springflow are more closely related to the amount of enhanced recharge than to the variability of natural recharge.

Although volumes equivalent to large percentages of recharged water were discharged to springs, the enhanced recharge did not appear to result in large flow rates. For the one-year, five-year, and 27-year model runs with 25,000 AF/yr enhanced recharge, flow rates at Comal Springs were increased a maximum yearly average of about 14 cfs, 23 cfs, and 27 cfs, respectively (San Geronimo site). On a continuing recharge basis, Comal Springs flow increased by 0.9 to 1.1 cfs for each 1,000 AF/yr of enhanced recharge into each of the Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, or Cibolo sites (see Table 3).

Model runs that applied the previously-determined recharge amounts for average and drought conditions at each Type 2 site (Table 5) showed similar relationships of recharge to springflow as seen in the runs with 25,000 AF/yr constant rates. This indicates that the gain in flow is proportional to the magnitude of the recharge.

Water Levels and Flowpaths

Enhanced recharge at seven of the eight sites results in raising the water level in Well J-17. Recharge at Lower Blanco does not appear to impact the well due to the site's downgradient location. The well-established correlation between water levels in Well J-17 and Comal Springs flow is also seen in the model runs for enhanced recharge. A one-foot rise in water levels at J-17 is equivalent to an increase in Comal Springs flow of about 5 cfs.

The USGS model was used to map the directions of water movement on a grid over the entire aquifer. Velocity vectors were created using a square grid of five cells (1.25 miles on a side). Excluding inactive cells, this totals 3,395 vectors to analyze model-simulated groundwater flow directions. As there is little change in flow direction with time, any instant in the model after several months of recharge will yield a representative picture of two-dimensional flow. Arrows representative of the flow field were placed on a map of the aquifer for review (Figure 16). Flows in the central part of the aquifer change directions sharply in response to flow through and around the Balcones Fault zone as previously shown by Maclay (1995). The convergence of western recharge water toward Leona Springs is clearly demonstrated. In Bexar County, variable flow directions are influenced by concentrated local pumping.

Benefits of Enhanced Recharge on Drought Effects

In order to simulate severe drought conditions that incorporated decreased natural recharge (as occurred in the 1950s drought of record) and increased (current) pumping totals, the USGS model was modified. Natural recharge conditions from the first half of the model (1947-1973) were superimposed on the pumping and other conditions in the second half of the model (1974-2000). Subsequent runs with this modified model, referred to as Recharge Model 1, allowed the analysis of enhanced recharge during these extreme conditions. In the baseline run of Recharge Model 1, the number of days when Comal Springs was not flowing, during the drought of record recharge, totaled more than 1,200 days (more extreme than the actual drought of record when no-flow conditions occurred over approximately 185 days). Enhanced recharge at all of the sites reduced the number of simulated days with no flow, but the reduction was relatively small given the extreme condition of the simulation. Enhanced recharge at San Geronimo produced the greatest benefit, reducing the no-flow conditions by 271 days (20 %) under the 25,000 AF/yr./site recharge simulations. Because San Geronimo contains only a small amount of enhancement recharge under the previously-determined Type 2 analyses (Table 5), the effects were much smaller when those amounts were simulated (reduction of 66 days compared to 271 days). Under these recharge conditions, Indian Creek, with one of the largest amount of previously-determined enhancement recharge, reduced the no-flow days by 113 days, even though the site is far to the west. These runs illustrate that the magnitude of the recharge can overcome the long distances to the springs in terms of benefits.

Well Recirculation Recharge

To analyze a management strategy that involves the recirculation of groundwater from downgradient in the aquifer to enhanced recharge sites, a model simulation was devised involving all model wells within a 50-mile radius of Comal Springs. The total volume pumped from these 87 wells was increased by 50 percent each month if the aquifer was not in critical period. This simulation produced an average recharge amount of 976 AF/month. Although benefits in increased flow were observed at Comal Springs, the increase in flow rate amounted to less than 10 cfs most of the time.

Critical Period Management Rules

It was originally envisioned that model modules being prepared by Hydrogeologic for EAA would be available to facilitate model simulations that incorporated demand management and critical period management (DMCPM) rules. However, the modules were not in the needed format and were of limited use for analysis. An alternative approach was developed using numerous interactive model runs to adjust pumping according to EAA critical period rules. Although the DMCPM rules are independent of enhanced recharge, the two strategies combined were observed to significantly increase springflow and maintain Comal Springs flow longer than under baseline conditions.

Alternative Management Scenarios

With the responses of Comal Springs to various locations and magnitudes of enhanced recharge developed in Phase 2, it is possible to formulate a number of scenarios that potentially could provide sufficient water to meet Comal Springs minimum requirements (depending on how they are defined). The determination of the quantity of water to be recharged depends not only on the hydraulic feasibility of the aquifer, investigated herein, but also on the source of water and cost of recharge. These considerations lead to a large number of possibilities, all of which necessitate evaluation of legal, political, and economic realities. The next phase will examine some of these alternatives and economic considerations to gain insight into how to provide supplemental water to the Edwards Aquifer for the purposes of maintaining Comal Springs. To meet this objective, a proposed scope of work for Phase 3 is presented.

Conclusions

A summary of the preliminary findings of the Phase 2 analyses based on applications of the USGS MODFLOW model are briefly summarized as follows:

1. On a 5-year recharge basis, Comal Springs flow increases by an amount of water equivalent to 45 to 54 percent of water recharged from the Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, or Cibolo sites. The remaining sites, Indian Creek, Lower Frio, and Lower Blanco, are less effective in terms of benefits to Comal Springs (see Figure 2).

2. A flow increase in Comal Springs resulting from enhanced recharge at an individual site is independent of water recharged at any other site (see Table 2).

3. Year-round recharge yields more uniform springflow than does seasonal recharge (see Figure 8).

4. On a continuing recharge basis, Comal Springs flow increases by 0.9 to 1.1 cfs for each 1,000 AF/yr of enhanced recharge into each of the Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, or Cibolo sites (see Table 3).

5. Tributary runoffs reaching Indian Creek and Lower Blanco recharge sites are the largest of the eight sites but contribute least to Comal Springs flow (see Table 5).

6. Well J-17 shows an increase in water level of about 0.2 foot for each 1,000 AF/yr of continuous recharge into the Lower Sabinal, Lower Hondo, Lower Verde, or San Geronimo sites.

7. Model results indicate that the observed Comal Springs drought of less than 185 days in 1956 would increase to 1,264 days of no flow under the hypothetical situation of 1950s recharge and 1980s pumpage (see Table 8). If all annual average available recharge were applied to a single site (Lower Verde), the no flow period would be reduced to 512 days, and if DMCPM rules were also in effect, the period would be further reduced to zero days.

Analysis of Recharge and Recirculation
Phase 2

Introduction

This study focuses on the feasibility of implementing enhanced recharge and recirculation (R&R) for the Edwards Aquifer in order to develop an integrated and coordinated approach to water management that will provide adequate flows in Comal Springs during drought conditions. This report covers Phase 2 of a planned four-part study.

Background

The Edwards Aquifer Authority (EAA) is evaluating management options including enhanced artificial recharge and recirculation of groundwater from one part of the aquifer to another as part of an integrated management approach for the Edwards Aquifer. In April 2004, EAA contracted with Todd Engineers to conduct a multi-phase study on artificial recharge and recirculation strategies.

Phase 1 of that work was completed in September 2004 (Todd Engineers, 2004). The Phase 1 report included a review of existing studies, an analysis of Edwards Aquifer hydraulics, installation and operation of the 2004 U.S. Geological Survey (USGS) MODFLOW model of the Edwards Aquifer, and application of the model for test runs at two hypothetical recharge sites. Test runs examined the response of the aquifer with a particular emphasis on springflow response at Comal Springs to enhanced recharge of 25,000 acre-feet (AF) at a Medina River recharge site and an Elm Creek recharge site. Model outputs of Comal Springs discharge with and without artificial recharge were compared for the analysis.

Phase 1 test runs indicated that artificial recharge at the Medina River site increased discharge at Comal Springs by an equivalent of about two-thirds of the recharge amount over an eight-year model run. At the Elm Creek site, located fifteen miles west of Medina River, increases in discharge were attenuated, perhaps by faults and flow through Knippa Gap. At this site, discharge at Comal Springs increased by slightly more than 50 percent of the total artificial recharge volume during the eight-year model run. These results indicate that long-term benefits measured in years can be achieved for Comal Springs flow by increasing aquifer recharge. Further, the magnitude and duration of increased springflow vary significantly from site to site. These analyses were conducted with the 2004 USGS model, but are generally consistent with previous analyses of artificial recharge with former modeling tools.

Scope of Work

Results of Phase 1 indicate the need to quantify the magnitude and duration of response at Comal Springs to enhanced recharge at selected sites. To address this need, the scope of work for Phase 2 included the following tasks:

1. Conduct individual single-year model recharge applications at Type 1 and Type 2 recharge sites as defined by SCTRWPG (2001) as shown in Figure 6 of the Phase 1 report.
2. Conduct model recharge applications as in Task 1, above assuming one or more sites have a constant annual recharge from 1946 to 2000.
3. Conduct model recharge applications as in Task 2 above assuming continuous annual recharge proportional to annual natural recharge from 1946 to 2000.
4. Determine for representative recharge sites how much recharge water emerges at the five major springs.
5. Study flow paths of recharge water in the vicinity of the Balcones Fault Zone and Knippa Gap.
6. Evaluate the effect of recharge when annual pumpage is reduced to selected upper limits.
7. Analyze results of the above model investigations and determine sites and amounts of recharge that appear to be most promising in sustaining Well J-17 levels and Comal Springs flows.
8. Prepare a report summarizing the above tasks and serving as a proposal to the Edwards Aquifer Authority for work to be performed in Phase 3.

The locations used in this R&R study have been selected for proposed Type 2 retention structures. Type 2 structures are defined as structures located on the recharge zone, consisting of the unconfined portion of the aquifer, and are designed to retain storm runoff allowing for direct infiltration. Similarly, Type 1 structures have been designated upstream of Type 2 structures where they are intended to store tributary runoff; however, Type 1 structures are planned for streams outside of the Edwards Aquifer where water cannot be recharged directly into the aquifer. Therefore, the focus of this study will be limited to Type 2 structures that permit water to be recharged into the aquifer. However, the recharge associated with Type 2 projects may not be available year round while Type 1 projects could hold water for recharge when needed. The continuous recharge scenarios analyzed were a way of analyzing impacts from Type 1 projects in addition to Type 2 projects. Type 2 structures provide for direct recharge and are normally dry, impounding water for only a few days or weeks following storm events. With large recharge rates of 2 to 3 feet per day, the reservoirs minimize evaporation losses and maximize recharge.

The relationship of timing of recharge to response of springflow was analyzed by adding recharge at the eight Type 2 sites for one year, five years and 27 years. Since the aquifer response to recharge was determined to behave uniformly after a certain period of time, the entire time period of 1946-2000 did not have to be run continuously to analyze the response for a given duration of recharge. As a result, the two halves of the model (1946-1973 and 1974-2000) or portions of these model halves were employed as appropriate for various analyses.

Model runs used actual estimates for maximum recharge enhancement water under average and drought conditions as summarized by Turner Collie & Braden and LBG Guyton in their 1999 work for EAA (Table 5). Several runs were made by adding enhanced recharge which was based on the state of water level and springflow in the aquifer, indirectly based on natural recharge. In several model runs, recharge was varied based on the critical period threshold (the criteria defined by EAA as the trigger for Stage I of critical period). During these select runs, if the aquifer was in critical period, either Drought Type 2 enhancement recharge or no enhanced recharge was used.

Background for Model Applications

A series of reports on recharge enhancement of the Edwards Aquifer was prepared by HDR Engineering beginning in 1991 (see references). A recent report (SCTRWPG, 2000) defined recharge sites based on the earlier reports. Most important are sites along the northern boundary of the Edwards Aquifer that show promise for augmenting recharge. The map in Figure 1, based on Figure 2.2-1 in the SCTRWPG report, shows the location of these particular sites. They include stream channels of Indian Creek, Lower Frio, Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, Cibolo, and Lower Blanco.

For modeling purposes, it was assumed that recharge water percolates downward to the aquifer at each Type 2 site, located at the end of a naturally recharging streambed, over a length of ten cells (equivalent to 2.5 miles) and a width of one cell (0.25 mile). Initial model runs were made assuming that 25,000 AF/yr of water were recharged at each individual site. The benefits of each recharge site were evaluated in terms of supplemental water increasing flow at the five major springs (Comal, San Marcos, San Antonio, San Pedro, and Leona Springs). Benefits are first analyzed in terms of volumetric supplements of water to the springs and subsequently in terms of increased flows at the various springs.

Model Summary and Limitations

The Edwards Aquifer model, used to run these R&R scenarios, was created by USGS and is documented in a Scientific Investigation Report (Lindgren et al. 2004). The simulation is a finite difference model created using MODFLOW 2000. The model represents the latest information and conceptualization of the Edwards Aquifer. The conceptual model was developed by a panel of advisors, the Ground-Water Model Advisory Panel (GWMAP). Members of the GWMAP consisted of staff from various local organizations and recognized Karst experts. The main purpose of the model was to develop an improved understanding of the aquifer as well as to evaluate the hydrologic responses to various alternative proposals.

The model is a regional model designed to evaluate variations in spring flow, regional water level changes, and relative comparison of water management scenarios. The model’s calibration and testing confirm that it is a reasonable representation of the regional ground-water flow system. The model, however, cannot be used for local analysis, for example the drawdown effects of a pumping well. The simulation of the conduits as one cell wide also has considerable local scale effects. Because the locations of the conduits are uncertain, the local effects of the conduits in the model may not simulate the actual response in the natural system. The conduits simulated in the model as one cell wide (1,320 ft) are up to 50 times larger than the estimated width of natural conduits occurring in the aquifer.

The Edwards Aquifer model is a porous media model used to simulate a karst system. The model cannot simulate turbulent flow occurring in the conduits and locations of the simulated conduits have a strong impact on the areas surrounding the conduits. The model, however, can predict regional variations in water levels and spring flow, although it probably should not be used to predict the fate and transport of particles of water or contaminants.

The model provided a better simulation of the confined zone than the recharge zone. The model may be limited in predictions of head in the recharge area. The hydrogeology of the recharge zone is not well known and data for model construction were limited. The lack of fit in the recharge zone is not unique to this model; other previous models have seen similar problems. Future versions of the model may need to model the recharge zone with dual-porosity or as more than one layer to better simulate the varying storativity values.

Given these model limitations, the model is a valuable tool to look at volumetric flow responses in the confined zone, particularly the major springs. Although enhanced recharge is added in the recharge zone, the effects are measured in the confined zone through spring discharge and water levels at selected monitoring wells (J-17 and J-27). The observed spring discharge for Comal Springs was well matched by the simulated discharge in the model. Because the simulations undertaken are consistent with the regional design of the model, the simulated volumetric flow rates in the aquifer are consistent and reproducible at the scale of the model.

Springflow Responses to Enhanced Recharge

<u>Volumetric Responses to Individual Recharge Sites</u>

Model calculations were made for enhanced recharge over one year, over five years, and over 27 years. Results for the total volume of recharge at each of the eight recharge sites (Indian Creek, Lower Frio, Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, Cibolo, and Lower Blanco) are listed in Table 1. In Table 1A a one-year enhanced recharge of 25,000 AF is assumed to occur continuously for five months (March-July) in 1974 at a rate of 5,000 AF per month. Tabulated values provide the total volume of increased springflow from the 1974 recharge event over the ensuing 27 years (1974-2000). It should be noted that this does not involve molecules of recharge water flow through the aquifer and appearing as molecules of spring water. Instead the recharge water increases the pressure in the aquifer; the transmission of this pressure in turn causes more groundwater near the springs to be released.

The increase in spring volume is based on calculating in the model the difference in springflow with and without recharge. The second half of the model period (1974-2000) was studied rather than the entire model for convenience in model operation, for pumping conditions that are more representative of the current situation, and because a longer time period would have little effect on volumetric increases to springs. It is further assumed that actual natural recharge and pumping occur throughout the aquifer each year without modification. For illustration, note in Table 1A that recharge of 25,000 AF into Lower Sabinal increased discharge to Comal Springs by 11,225 AF and a total increase of 24,250 AF at the five major springs during the 27 years. The remaining volume of 750 AF most likely remains in aquifer storage as the model provides no other major outlets or changes in pumping.

In Table 1A, the "Remaining Recharge" columns show the volume of water in acre-feet and the percentage of 25,000 AF that has not increased flows to the five major springs during the 27-year. Note that generally an equivalent volume of recharge is discharged at the five springs over the 27 years. At only two sites, Indian Creek (19.6% and Lower Frio (12.1%), does less than 90% of the volume recharged contribute to spring discharge. Because of their distance from major springs, a smaller and more delayed impact is anticipated. Almost all of the equivalent volume of recharge water from San Geronimo influenced the five springs. The negative difference for Cibolo shown in Table 1A, suggesting that increased springflow exceeded the recharge volume, may be an anomaly of the model. San Geronimo and Cibolo, sites closest to Comal Springs, resulted in the largest impact to the major springs over the simulated 27-year period.

A primary focus of this investigation is to determine enhanced recharge impacts to Comal Springs. The Table 1A data in the Comal column indicate that the maximum benefit accrues from the San Geronimo site, 13,212 AF or 52.8% of the equivalent recharge volume. However, contributions from Lower Sabinal to Cibolo fall within a similar narrow range (44.9% to 52.8%). As could be anticipated, the western sites and Lower Blanco result in relatively small impacts to Comal Springs discharge (24.6% of recharge volume for Indian Creek, 29.5% for Lower Frio, and 3.3% for Lower Blanco). Enhanced recharge in the western sites resulted in more springflow for Leona springs, while enhanced recharge at Lower Blanco contributed to the flow at San Marcos Springs. It is apparent that distance from recharge site to spring and the direction of groundwater flow govern the benefits of enhanced recharge on springflow.

Table 1B summarizes results from the second set of model runs, where enhanced recharge of 125,000 AF was added to each site over a five-year period, March 1974 to July 1978 (25,000 AF per year). Data are formatted similar to Table 1A. The difference between the increased discharge at the major springs and the total volume of enhanced recharge is summarized in the "Remaining Recharge" columns. As shown in Table 1B, the equivalent volume of recharge not discharged from the aquifer is relatively small. Enhanced recharge at Cibolo results in the greatest equivalent recharge volume discharged in the springs, with only 0.2% of the recharge volume remaining in the aquifer. The most western site, Indian Creek shows the largest volume (21.9%) of enhanced recharge not flowing for the major springs in the 27-year period.

Increases in springflow at Comal Springs from the five-year recharge period given in Table 1B are proportional to those found in the one-year recharge data of Table 1A. In both cases, the maximum increase in Comal discharge, occurs from enhanced recharge at San Geronimo (67,864 AF or 54.3%). Centrally located recharge sites increase Comal Springs flow from 46.0% up to the 54.3% of the total recharge. Indian Creek and Lower Frio are less efficient (24.6% and 32.4%, respectively) while Lower Blanco has the least impact on Comal, contributing only 3.3% of the equivalent recharge volume. Again, Leona Springs takes a large fraction of western enhanced recharge water. The percentage of equivalent volume each site contributes to each spring is shown in Figure 2.

Results for the third set of model runs are shown in Table 1C. Here recharge was assumed to be 25,000 AF/yr over a five-month period each year for 27 years extending from 1974 to 2000 for each individual recharge site. Thus 675,000 AF were recharged into each site. Similar to other model run results, springflow discharge is increased by a volume equivalent to more than one-half of total recharge. The "Remaining Recharge" columns in Table 1C shows the equivalent volume of recharge not accounted for by spring discharge. Values range from a low of 9.3% at Lower Blanco to 46.0% at Indian Creek. These results show much larger percentages of water not reaching the springs as compared to those previously described for shorter recharge durations. This may be due to recharge and discharge periods (27 years) being identical. Water is continuing to enter the aquifer up to the end of the 27-year period so that the attenuated response to later enhanced recharge has not fully developed throughout the aquifer.

<u>Volumetric Responses to Multiple Recharge Sites</u>

All of the model results presented in Table 1 assume recharge takes place at a single site for a specified period. Clearly the maximum benefit to springs can be achieved with recharge originating simultaneously from multiple recharge sites. To evaluate the impacts from operation of multiple recharge sites, recharge was added simultaneously into each of the eight recharge sites at a rate of 25,000 AF per year per site for five years, totaling one million acre-feet (8 sites x 25,000 AF/yr x 5 years = 1,000,000 AF).

The comparison of recharge sites operating individually and simultaneously is tabulated in Table 2. "Individual Sites", in Table 2, assumes that each recharge site operates independently and sums the volume of increased springflow over the 27-year period (summed from Table 1B). "Multiple Sites", in Table 2, assumes that the eight recharge sites are operating together for the same five-year period (a new model run). The small percentage differences listed on the bottom line of Table 2 indicate that the amount of increased springflow is nearly identical for either recharge scenario. This finding is significant because it suggests that supplemental springflows are additive and independent of the operation of recharge sites.

Interpretation of Recharge Sites

Analysis of the model runs documented in Table 1 leads to the conclusion that from a volumetric standpoint, water recharged into the Lower Sabinal, Lower Verde, Lower Hondo, San Geronimo, and Cibolo will prove to be most efficient in increasing flow at Comal Springs. Figure 2 summarizes the impacts on Comal Springs from each recharge site as well as contributions to other springs. The percentage of equivalent recharge volume (from five years of recharge 1974-1979) that is discharged in Comal Springs during the 27-year period is shown on Figure 2A. Ranking them in relation to Comal Springs, San Geronimo is first, followed by Lower Verde, Lower Hondo, Cibolo, and Lower Sabinal; however, the differences among these are small so that each should be considered as an important recharge site. Figure 2B shows the percentage of equivalent recharge volume (from five years of recharge 1974-1979) that is discharged in each of the major springs during the 27-year period. The western sites, Indian Creek and Lower Frio, have less of an impact on Comal because they are subject to large losses to Leona Springs, while the eastern site, Lower Blanco, is not effective at Comal Springs because of its downgradient location from Comal Springs and its proximity to San Marcos Springs.

Recharge Effects on Springflows

The above analyses demonstrated that enhanced recharge in the Edwards Aquifer can increase the volume of water discharged by Comal Springs and other springs. But equally important are the amount of time it takes each spring to respond and the duration of the response. This question of timing can be expressed as the increase in springs flows as a function of time. The MODFLOW model was used to calculate daily springflow both with and without enhanced recharge. Taking the difference between these two allows the increase in flow to be shown as a time function.

For baseline comparisons, model simulated historic flows of the five springs without enhanced recharge are shown in Figures 3 to 7. The differences between these base flows and calculated springflow from the enhanced model runs provide estimates for the benefits that can be achieved by recharge. It is important to note that differences are those between two sets of model output; therefore, any discrepancies between actual and modeled springflows are eliminated.

Graphs of model outputs for various combinations of recharge sites and springs are presented in the appendix and provide the basis for the results presented in Table 3. In Appendix A graphs are ordered by each spring as follows: Comal (pages A1-A24), San Marcos (pages A25-A48), San Antonio (pages A49-A72), San Pedro (pages A73-A96), and Leona Springs (pages A97-A120). For each spring the recharge sites appear in following the sequence: Indian Creek, Lower Frio, Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, Cibolo, and Lower Blanco. Differences in springflows are plotted from 1974 to 2000 for the three recharge scenarios: 25,000 AFY in 1974, 25,000 AFY for 1974-1978, and 25,000 AFY for 1974-2000. Water is recharged uniformly from March to June in each year of enhanced recharge. All flow increases are plotted in cubic feet/second (cfs).

The flow differences shown graphically in Appendix A, represent increases in flow caused by enhanced recharge. Individual daily dots generated by the model merge to form a solid line. Where a series of dots appears at a given time, these represent rapid changes in springflow that may be anomalies in the model that may have no factual bases. Note that the vertical scale varies from graph to graph in order to facilitate review. The maximum yearly average (highest average of a 365-day period) flow increase for each spring, recharge site, and recharge scenario are shown in Table 3.

<u>Comal Springs</u>

Because of the importance of Comal Springs, both in terms of ecosystem support and as an indicator of aquifer response to recharge, model results for this spring are further analyzed. Springflow at Comal Springs as modeled without enhanced recharge is shown in Figure 3 for 1974-2000. Data indicate an average continuous flow over the 27-year period of about 260 cfs with a range from 40 cfs to 500 cfs. An overall downward trend in flow occurs during this time interval. Enhanced recharge at Indian Creek does not increase these flows significantly, adding 0.6, 3.1 cfs, and 9.7 cfs for the 1, 5, and 27-year recharge periods respectively (Table 3). Recharge at Lower Frio increases Comal Springs flows somewhat with respective increases of 1.4, 6.1, and 13.5 cfs. Moving eastward, recharge at Lower Sabinal continues the trend with respective increases of 8.4, 16.7, and 23.2 cfs. The well-defined saw-tooth flow pattern indicates a rapid response to the seasonal recharge (see graphs in Appendix A, A-7 through A-9). At Lower Hondo flows show gains of 5.7, 15.9, and 23.3 cfs, respectively. Similar results are seen at Lower Verde, with increases of 4.1, 14.1, and 22.9 cfs, respectively. Continuing eastward, San Geronimo recharge increases flow at Comal up to 12.9, 22.6, and 29.6 cfs, respectively. At this site, the maximum benefit to springflow is reached within ten years and is stabilized thereafter (A-18). Comal Spring response to Cibolo is seen immediately, due to the short distance from recharge site to spring (A-19). Springflow is increased up to 12.1, 19.6, 24.5 cfs. Recharge from Lower Blanco does not result in significant flow increases at Comal Springs, less than 2 cfs for all scenarios. This small contribution occurs because the recharge site is downgradient of Comal Springs. San Marcos Springs, being closer, receives the most benefit from recharge at Lower Blanco.

In summary, enhanced recharge at Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, and Cibolo are most beneficial with respect to increasing springflow at Comal Springs. Indian Creek and Lower Frio sites are relatively inefficient at maintaining Comal Springs flow, while Lower Blanco recharge does not significantly impact Comal Springs. However, if a large volume of enhanced recharge were available at the two western sites, these could be as beneficial as those much closer to Comal Springs. The combined 27-year scenario at all eight sites results in a maximum increase in Comal Springs of 148 cfs. This finding does suggest that substantial springflow augmentation at Comal Springs can be generated with Type 2 structures.

Other Springs

Enhanced recharge effects on springflow in the major springs other than Comal are summarized in Table 3. San Marcos Spring, historically a perennial spring (see Figure 4), receives little or no benefit from enhanced recharge at any site except Lower Blanco. Because San Marcos Spring is located east and downgradient of Comal Springs, Comal relieves most of the aquifer pressure created from enhanced recharge. Enhanced recharge at nearby sites is the source of most of the increased San Marcos discharge from enhanced recharge.

San Antonio Springs, an intermittent spring (see Figure 5), has been dry for a most of the time since 1984. It can benefit from centrally located recharge sites from Lower Sabinal to San Geronimo; other sites are located either too far west or downgradient to the east.

San Pedro Springs, a low yielding and frequently intermittent spring (see Figure 6), gains little or no benefit from any of the recharge sites. Much of this can be attributed to the nearby and lower San Antonio Springs, which yields several times as much water.

Leona Springs with an average flow of about 60 cfs and almost always perennial (see Figure 7), is unique because of its location in southern Uvalde County and upgradient of Knippa Gap. Geologic evidence suggests that faults as well as igneous intrusions in northern Uvalde and Medina Counties restrict typical west to east groundwater flow, thereby diverting water southward through Knippa Gap. As a consequence substantial quantities of water are discharged from Leona Springs and are lost in terms of usefulness elsewhere in the aquifer. As indicated in Table 3, enhanced recharge at Indian Creek and Lower Frio have more of an impact on Leona Springs than Comal Springs. Enhanced recharge from San Geronimo eastward does not significantly impact Leona Springs.

Effects of Variations in Recharge Rate

To improve understanding of how recharge rates affect springflow, two additional model runs were conducted. The first of these changed the 25,000 AF/yr recharge from a 5-month intermittent application to a uniform 12-month interval for the Lower Sabinal site. The lines in gray on Figures 8 through 12 show increases in flow for the five major springs with 5-month recharge while the red lines indicate those with uniform recharge and show less annual fluctuation (typically about one-third as much). The overall contribution to each spring remains essentially the same; volumetric differences tabulated in Table 4A amount to 3 percent or less.

The second model run again assumed a uniform annual recharge but reduced the rate to one-half or 12,500 AF/yr at the Lower Sabinal site. Lines in blue on Figures 8 through 12 illustrate the smaller increases in springflow. The reduction in recharge reduces the enhanced springflow by 50 percent, as is numerically verified in Table 4B. Together these two runs indicate that the increase in springflow is proportional to the recharge quantity and to the uniformity of recharge.

The multi-year fluctuations shown on Figures 8 through 12 imply that even with uniform supplemental recharge, there is temporal variability in the amount of water reaching the springs. The variable response is due to variable precipitation and natural recharge. Increases in natural recharge from wet years raise groundwater levels, which affects the discharges at all the springs. The effect of natural recharge variation on the benefit of enhanced recharge at the springs is relatively minor. For Comal Springs (see Figure 8), oscillations are 1.5 to 2.5 cfs about a mean line, amounting to a 10 to 15 percent variation in flow increases. To illustrate the variability in natural recharge, consider conditions for two time periods 1990-1992 and 1993-1995. For these two time periods basin-wide natural recharge, from U. S. Geological Survey data, was 1,706,000 AF and 506,000 AF, respectively. Although this variation in natural recharge was more than a factor of three, the response of continued enhanced recharge on Comal Springs flows caused differences of only 5 cfs.

Increase in Comal Springs with Type 2 Enhancement Recharge

Estimates of the long-term average water volumes that may be available for enhanced recharge at the eight recharge sites were summarized by Turner Collie & Braden with LBG Guyton (1999) and are presented in Table 5. This summary was based on HDR's previous work for the Trans-Texas program (HDR 1998). Recognizing that the gain in flow at Comal Springs is proportional to the magnitude of recharge, it is possible to make an approximate estimate of how much the sites collectively can enhance the flow of Comal Springs. Adjusting the flow increases in Table 4 in relation to the recharge enhancements of Table 5 provides potential increases ranging from 3.5 cfs from San Geronimo recharge to 17 cfs from Lower Sabinal. Accumulating these contributions on the basis of contribution to springflow yields the enhancement graph of Figure 13. This shows that the largest contribution of 17 cfs would come from Lower Sabinal alone, while adding Cibolo would increase the maximum flow by 30 cfs. Adding each succeeding smaller benefit leads to the fact that if all eight recharge sites were in operation, an average ongoing enhancement to Comal Springs would amount to about 71.5 cfs. This analysis is not suggesting a construction sequence of Type 2 projects. However, it illustrates that San Geronimo and Lower Blanco sites have marginal benefit, to Comal Springs, based on the volume of water the Type 2 structure would yield. The economics of each project must be considered as well as the relative benefits of where to add other source waters, such as recirculated spring water and imported water. These possibilities will be investigated in Phase 3 of this study.

Table 5 also lists water volumes that may be available for recharge in drought conditions. These amounts are about one-half of the long-time average enhanced recharge, which would suggest a smaller benefit to Comal Springs. But as indicated above temporal variations in annual rainfall and natural recharge have only a minor influence on continuing recharge from Type 2 sites. If additional water were available to recharge, the enhancement to Comal Springs would be proportional to normal conditions. Thus, the drought only affects the quantity of available for recharge, not the hydraulics of the recharged volume in the system.

Water Levels and Flowpath Analysis

Recharge Effects on Well J-17

Well J-17, a monitoring well in the San Antonio metropolitan area, has served as a useful indicator not only for local water levels but also as a measure of pending drought. There is a good correlation between Well J-17 levels and flows in Comal Springs so that the well is used to predict springflow. The MODFLOW model can generate groundwater levels at any location and therefore can be used to define impacts to Well J-17 under various scenarios of enhanced recharge. Model generated water levels at the well with no added recharge are shown on Figure 14. Water levels average about 670 ft above mean sea level (msl) and range from 620 ft to 700 ft. Using the same recharge scenarios described in previous sections, water levels at Well J-17 were determined for the 27-year period 1974-2000. Differences in water levels, expressed in feet of increased water levels, are presented on graphs in Appendix A (pages A-121 through A-144). Maximum rises of water levels in the well are summarized in Table 6.

As shown on Table 6, enhanced recharge at seven of the eight sites results in higher water levels in Well J-17. Recharge at Lower Blanco does not appear to impact Well J-17 water levels, likely due to its downgradient location. The most significant impact on water levels (5.6 ft) occurs in response to recharge at the San Geronimo site. These results correspond to increases in springflow shown in Table 3, where the greatest flow increase at Comal Springs (29.6 cfs) also originated from San Geronimo. The maximum response of water levels and spring flow to recharge in Tables 3 and 6, show that a one-foot rise in the Well J-17 is equivalent to about a 5 cfs increase in Comal Springs flow. However, this correlation does not apply to recharge at the Cibolo and Lower Blanco sites, located down gradient of Well J-17. Effects on Well J-17 are minimal for recharge at the distant western sites (Indian Creek and Lower Frio) and at the downstream eastern sites (Cibolo and Lower Blanco).

Figure 15 shows the effects of continuous recharge on Well J-17 water levels. Note that the amplitude of annual fluctuations for continuous recharge over 12 months (the red line) is approximately one-third of that for the same amount of recharge applied over 5-months (the gray line), indicating that the more uniform the recharge, the more uniform the response. Also in Figure 15 the black line shows that cutting the annual recharge in half (to 12,500 AF) reduces the well response also by one-half. Thus, as was the case with springflow, water levels at Well J-17 correlate with the magnitude and uniformity of recharge.

Flow Paths from Recharge Sites

Using the MODFLOW model for the Edwards Aquifer, general groundwater flow paths were evaluated. These flow lines are approximate because the model assumes a porous media aquifer with simulated high permeability conduits. To determine flow paths rather than flow times, velocity vectors were used to indicate only the direction of flow. Actual flow velocities are highly variable so that travel times for a given molecule of water from recharge to discharge in the aquifer are the order of days to hundreds of years. To define a flow line from a single point could involve an extended time series of model runs and the result is heavily dependent on locations of conduits in the model. A more practical approach to accomplish the same purpose is to map directions of water movement on a grid over the entire aquifer. Velocity vectors were created using a square grid of five cells (1.25 mi) on a side, amounting to one in every 25 cells. Excluding inactive cells, this totals 3,395 vectors. As there is little change in flow direction with time, any instant in the model after several months of recharge will yield a representative picture of two-dimensional flows.

Based on model velocity vectors, Figure 16 illustrates groundwater flow directions for various locations over the confined portion of the Edwards Aquifer. Recharge sites and springs are also shown so as to indicate the general pattern of water migration relating to these inflow and outflow locations. Flows in the central part of the aquifer change directions sharply in response to flow through and around the Balcones Fault Zone as previously shown by Maclay (Maclay, 1995). The convergence of western recharge water toward Leona Springs is clearly demonstrated. In Bexar County variable flow directions are also influenced by concentrated local pumping.

Management Scenarios for Comal Springs

<u>Drought Effects on Comal Springs</u>

The USGS model was employed to determine what effect current pumping together with a drought comparable to that of 1956 would have on Comal Springs. For this purpose, advantage was taken of the fact that the model was divided for convenience into two sections by the USGS to allow it to be run using the pre-processor Groundwater Vistas. The first section contains the simulation of the aquifer from 1947 through 1973 and the second section contains the simulation from 1974 through 2000.

In order to simulate an intense drought, similar to the drought of record (1950s), actual natural recharge of the first half of the model (1947-1973) was used to replace the actual natural recharge of the second half of the model (1974-2000). Aside from this substitution of recharge, no other modifications were made for this hybrid model; initial head, boundary conditions, aquifer characteristics, and pumping all remained the same in the second half of the model (1974-2000). By changing the recharge amounts in the second half of the model, pumping, boundary conditions and recharge are treated as independent values. In reality the quantity, distribution, and timing of pumping and the boundary conditions are dependent on the fluctuations of recharge. Also, as the resulting model no longer simulates a real period of time, the initial head is an arbitrary starting point for these hypothetical model runs. To overcome these issues in the analysis, all runs are compared with a baseline model run or to each other. Subsequent model runs are used to assess the relative effects of recharge scenarios. This allows an estimate of the relative aquifer response to a drought that caused a more serve impact than the impacts that occurred in the 1950's, due to the increase in pumping in the hypothetical model than originally occurred.

The hybrid model, referred to as Recharge Model 1 in the remainder of this report, indicates Comal Springs would not flow for 1,940 days (during the period reflected by 1947-1973 recharge and 1974-2000 pumping) and with no flow occurring intermittently for 1,264 days in the 1952-1959 period as shown by the green line in Figure 17 and also in Table 7. This compares with a computed model no-flow period of 113 days in 1952-1959 period assuming actual recharge and pumping (actual no-flow in 1956 was observed to around 185 days). It follows that repetition of the earlier drought with recent pumping would have made the springflow more vulnerable in terms of the duration and frequency of no-flow periods. It should be remembered that this model result is based on hypothetical conditions; nevertheless it suggests that the historic increase in pumping (from 320,000 AF/yr in 1956 to 500,000 AF/yr in 1996), and particularly the concentration of urban pumping upstream of Comal Springs, magnifies the potential for springflow depletion.

The blue line in Figure 17 shows the modeled Comal Springs flows for actual recharge and pumping conditions in the 1974-2000 period, referred to as the Unmodified Model for the rest of the report.

Management Scenarios with Recharge for Comal Springs

Various management scenarios were tested to determine the effect of enhanced recharge on Comal Springs during the drought of record using Recharge Model 1. In addition, similar analyses were conducted for the drought of 1996 using unmodified second half of the original USGS model. The scenarios include:

- Adding a fixed volume of water to each recharge site
- Adding amounts of Type 2 enhancement developed for the Trans Texas program
- Recirculation of water pumped from wells in the aquifer

Fixed Volume Recharge Scenarios

As discussed in previous sections, each of the eight main recharge sites affect Comal Springs in different ways. Because Lower Blanco has limited impact to the flow of Comal Springs, it was excluded from further recharge scenarios. To examine the impact of the recharge sites during drought conditions, 25,000 acre-feet per year of enhanced recharge was added to one site for an individual model run. Scenarios using Recharge Model 1, responses can be gauged by the number of days Comal Springs has no flow. The effects of adding recharge are tabulated in the second line of Table 7 and can be compared with the baseline model run results in the first line. It can be seen that all seven of the recharge sites reduce the no-flow days to below the no-recharge base of 1,264 days (days of no flow during recharge simulation of 1952-1959); however, benefits overall are not significant. The San Geronimo site produced the greatest benefit, lowering the no-flow days by 271 days to 993 days. Other sites that showed favorable impacts on Comal Springs include Lower Sabinal, Lower Hondo, and Lower Verde.

Additional model runs were conducted to analyze the effect of recharging 25,000 acre-feet per year (equivalent to 2,033 acre-feet per month) only during non-critical periods. Here a critical period is defined as when well J-17 level is below 650 ft or Comal Springs is flowing less that 220 cfs. The results in terms of days of no flow in Comal Springs are shown on the third line of Table 7. These model runs were designed to look at the residual impact individual sites may have after enhanced recharge has ended. The seven sites showed similar impacts to Comal ranging from 1,235 (Cibolo) to 1,183 (Lower Verde). The delayed response from the western sites offset the initial high volume response from the intermediate sites.

<u>Type 2 Recharge Enhancement Scenarios</u>

In the Trans Texas study, estimates were developed for maximum recharge enhancement from Type 2 structures at each recharge site for both average and drought conditions (HDR, 1998). These quantities (later updated and summarized by Turner, Collie and Brandon and LBG Guyton), shown in Table 5, were used in a series of Recharge Model 1 simulations to determine the effects on Comal Springs both for average and drought conditions.

A set of model runs using the average Type 2 enhancement volumes was performed, one on each Type 2 site during all time (both critical and non-critical periods) using Recharge Model 1. The resulting number of days Comal Springs had no flow during the drought period (1952-1959) appears in line four of Table 7. Those sites with larger enhancement recharge, by volume, had greater impacts on Comal Springs. Thus Indian Creek, with over 34,000 acre-feet of enhancement recharge per year, reduced no flow at Comal to 1,151 days, 113 days below the base of 1,264 days, whereas San Geronimo with 3,000 acre-feet of recharge reduced it only 66 days. Recharge applied at Lower Sabinal resulted in the fewest number of no-flow days in Comal Spring, 1,108 days.

Further scenarios were run using Type 2 recharge enhancement, but the enhanced recharge was varied based on the aquifer response. One set of scenarios evaluated applying average Type 2 recharge enhancement during months when the aquifer was not in critical period and no enhanced recharge during critical period. Applying no enhanced recharge during critical period yields no-flow days listed in line five of Table 7. Indian Creek proved to decrease the number of no flows days in Comal Springs by the most days (63 days). The pressure response from Indian Creek, the most western site, has a delayed response compared to the other sites. This delay combined with the large volume of enhancement recharge available results in the largest benefit to Comal Springs in this scenario. Another set of scenarios was simulated using average Type 2 enhancement conditions when the aquifer was not in critical period and drought Type 2 conditions when the aquifer was in critical period. The results of these scenarios are listed in line six of Table 7. Applying the drought Type 2 enhanced recharge during critical period decreased the number of no-flow days at Comal Springs by 41 days (San Geronimo) to 95 days (Indian Creek). As expected, applying drought Type 2 enhanced recharge showed a greater benefit at Comal Springs than adding no recharge during critical period. The greatest difference is seen in Lower Sabinal, the number of no-flow days at Comal

Springs decreased by an additional 64 days (from the no recharge in critical period scenario) due to the enhanced recharge during critical period.

Another set of model scenarios was performed with Type 2 enhancement recharge applied to each of the seven sites simultaneously (excluding Lower Blanco). Adding average Type 2 recharge enhancement volumes at all times resulted in only 591 days of no-flow at Comal Springs (Table 8, line 2). Figure 18 shows the baseline run of Recharge Model 1 compared with both continuous recharge of 25,000 AF/yr and Average Type 2 enhancement recharge added at each site simultaneously. A simulation was performed where average Type 2 enhancement recharge was applied only when the aquifer was not in critical period. In this scenario no water was added during critical period. The result reduced Comal Springs to 1,152 days without flow (Table 8, line 3). A third scenario (using all seven times simultaneously) was run where average Type 2 enhancement recharge was applied when the aquifer was not in critical period and drought Type 2 enhancement recharge was applied to each site during critical period. The results are summarized in Table 8 (line 4). By adding the relatively small amount of enhanced recharge available during drought conditions, the benefit to Comal (measured by reduction of no-flow days from baseline simulation) was doubled. Comal Springs had 239 less no-flow days than the baseline simulation when drought Type 2 enhancement volumes were applied and only 112 less no-flow days when no enhanced recharge was applied during critical period.

Additional model runs evaluated the benefits to Comal Springs if Type 2 recharge enhancement volumes were transported to one site. Type 2 enhancement recharge for all eight structures (Table 5) was summed and the total was applied to each of the selected seven sites using Recharge Model 1. In the model runs, average condition amounts were added during months when the aquifer was not in critical period and drought condition amounts were added when the aquifer was in critical period. These results appear in the seventh line of Table 7. Note in the table that the minimum no-flow days decrease from the baseline by 752 days to 512 days, during the drought period (1952-1959) with all enhancement water applied to the Lower Verde site.

<u>Well Recirculation Recharge Scenarios</u>

Another management scenario that has been suggested to maintain springflow at Comal is well recirculation. The concept involves pumping wells near the springs during times with ample springflow, transporting that water to a nearby recharge site, and recharging it to provide supplemental water to Comal Springs. A simulation was run using all wells in the model within a 50-mile radius of Comal Springs. The total volume pumped from these 87 wells was increased by 50% each month when not in critical period and the additional volume of water added to the recharge site San Geronimo during the same month. San Geronimo was selected as the recharge site because it is one of the closest sites to Comal Springs and was one of the best sites for flow enhancement at the springs. The recirculation scenario was run in both Recharge Model 1 and Unmodified Model assumptions.

In Recharge Model 1 the increased pumping yielded an average of 537 AF per month when not in critical period. Recirculation showed little impact on Comal springs, decreasing the number of no-flow days by four days (1,264 days in baseline runs to 1,260 days in recirculation run). A similar result was shown in Unmodified Model. The same 87 wells were affected and 976 AF per month, when the aquifer was not in critical period, was available for recharge. A larger volume of water was available to recharge as the pumping was greater during the 1996 drought because the pumping that in the second half of the model that overlaps with the 1950's drought (1979-1986) was lower. Benefits of the well pumping were negligible as shown in Figure 20 with changes in flow amounting to less than 10 cfs for both model conditions.

Critical Period Management Rules

Efforts to conserve Comal Springs and to avoid cessation of its flows as happened in 1956 can be accomplished by enhanced recharge as has been described above and also by reducing pumping. In pursuit of the latter approach the EAA has adopted a comprehensive plan, the Demand Management and Critical Period Management Rules (DMCPM rules), for reductions in well pumpage throughout the aquifer when water levels fall to certain levels. Rules limiting the amount of pumping are intended to increase aquifer levels and thereby maintain minimal flows in Comal Springs. Details of the plan are complex and quite specific, leading to a stepwise series of pumping limitations based primarily on water levels in Well J-17.

In brief, the plan establishes rules for the four stage reductions in pumping as follows:

San Antonio Pool

- Stage I occurs in the San Antonio pool when:
    - J-17 is less than 650 ft msl
    - San Marcos 5-day average discharge is below 110 cfs
    - Comal 5-day average discharge is below 220 cfs
- Stage II occurs in the San Antonio pool when:
    - J-17 is less than 640 ft msl
    - San Marcos 5-day average discharge is below 96 cfs
    - Comal 5-day average discharge is below 154 cfs
- Stage III occurs in the San Antonio pool when:
    - J-17 is less than 630 ft msl
    - San Marcos 5-day average discharge is below 80 cfs
    - Comal 5-day average discharge is below 86 cfs
- Stage IV occurs in the San Antonio pool when:
    - J-17 is less than 630 ft msl for more than 30 days
    - J-17 is less than 627 ft msl

Uvalde Pool

- Stage III occurs in the Uvalde pool when:
  - J-27 is less than 845 ft msl
- Stage IV occurs in the Uvalde pool when:
  - J-27 is less than 845 ft msl for more than 30 days
  - J-27 is less than 842 ft msl

Management modules were developed by Hydrogeologic, a consultant to EAA, to simulate critical period management. Todd Engineers had originally planned to incorporate these modules in the analysis for this report. However, due to the inability of the format to work with preprocessors, their use for these simulated scenarios was limited. Accordingly, an alternative approach was developed to simulate critical period management (DMCPM) rules. This approach was iterative and involved running the model multiple times, determining from model output when a stage of critical period is entered, and then adjusting pumping for the next stage.

This iterative approach to simulate DMCPM rules began with identifying the wells that the rules would affect. Information about the wells such as location, county, and model cell were provided by EAA. Wells were divided into two pools, the San Antonio pool (Bexar, Comal, and Medina Counties) and the Uvalde pool (Uvalde County) and two use categories, irrigation and non-irrigation. Because, pumping is simulated in monthly stress periods in the model modifications were made to pumping on a monthly basis. Pumping was changed on the first day of the month based on the highest DMCPM stage that occurred in the last 15 days of the previous month and the first 15 days of the current month. The affected pumping remained the same for the entire month.

The first run of the iterative approach was a baseline scenario to determine when each critical period stage would be reached if the DMCPM rules were not in effect. The baseline run identified when Stage I is triggered thereby causing the pumping to be decreased in the model based on the DMCPM rules from that point forward until the stage has ended. Additional runs were made with similar methodology by adjusting pumping based on the DMCPM stage until the DMCPM rules were simulated over the course of the drought. Water rights were assumed equal to the amount pumped; consequently, the volume of water pumped in a stress period was decreased based on the particular DMCPM stage. The amount of pumping decrease for each DMCPM stage is detailed on the following page:

- Stage I
    - San Antonio wells decrease non-irrigation 5%
- Stage II
    - San Antonio wells decrease non-irrigation 10%
- Stage III
    - San Antonio wells decrease non-irrigation and irrigation 15%
    - Uvalde wells decrease non-irrigation and irrigation 15%
- Stage IV
    - San Antonio wells decrease non-irrigation and irrigation 23%
    - Uvalde wells decrease non-irrigation and irrigation 23%

The DMCPM rules were applied during the recharge of the drought of record using the eight-year period 1952-1959 in Recharge Model 1 superimposed on current pumpage. As indicated in Figure 21, the rules made a substantial improvement in flow at Comal Springs: the spring remained dry for only 292 days during the drought compared to 1,264 days without DMCPM rules. It should be noted that there were other days when the spring went dry outside of the eight-year period. Tabulation of Recharge Model 1 run results for the four DMCPM stages appear in Table 9A.

The DMCPM rules are independent of enhanced recharge but when combined they can make a significant difference in flow at Comal Springs. It is noteworthy that, in the hypothetical Recharge Model 1, the DMCPM rules, together with recharge of all Type 2 projects at the Lower Verde site (see Figure 22), resulted in zero no-flow days at Comal Springs compared with decreased conditions at Comal Springs from 292 days of no-flow with DMCPM rules with no enhanced recharge (Table 8, lines 6 and 7).

The DMCPM rules were also applied, in the Unmodified Model, to the drought that occurred in 1996. Results are summarized in Table 9B. During the 1996 drought, the baseline run of Unmodified Model resulted in 20 days in Stage III; however, with application of the DMCPM rules, the aquifer did not enter Stage III (Table 9B). However, the implementation of the rules did not show significant improvement over other management scenarios such as using average enhancement from Type 2 structures when not in critical period. In summary, the implementation of the DMCPM rules had a large impact on the severe drought simulated in Recharge Model 1 but had a much smaller impact on the shorter less severe drought of 1996.

Conclusions

Summary of Findings

The numerous model runs conducted in this Phase 2 of the study provide useful information on how the Edwards Aquifer responds to supplemental recharge and modifications in pumpage with particular emphasis on how these inputs and outputs of water impact flow in Comal Springs. For convenience the chief findings based on the USGS MODFLOW model are briefly summarized as follows:

1. On a 5-year recharge basis 45 to 54 percent of water recharged from the Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, or Cibolo sites reaches Comal Springs. The remaining sites Indian Creek, Lower Frio, and Lower Blanco are less effective (see Figure 2).

2. A flow increase in Comal Springs resulting from enhanced recharge at an individual site is independent of water recharged at any other site (see Table 2).

3. Year-round recharge yields more uniform spring flow than does seasonal recharge (see Figure 8).

4. On a continuing recharge basis Comal Springs flow increases by 0.9 to 1.1 cfs for a recharge of each 1000 AF/yr into each of the Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, or Cibolo sites (see Table 3).

5. Tributary runoffs reaching Indian Creek and Lower Blanco recharge sites are the largest volumes of the eight sites (see Table 5) but contribute least to Comal Springs flow.

6. Well J-17 shows an increase in water level of about 0.2 foot for each 1000 AF/yr of continuous recharge into the Lower Sabinal, Lower Hondo, Lower Verde, or San Geronimo sites.

7. Model results indicate that the observed Comal Springs drought of less than 185 days in 1956 would increase to 1,264 days of no flow under the hypothetical situation of 1950s recharge and 1980s pumpage (see Table 8). If all annual average available recharge were applied to a single site (Lower Verde), the no flow period would be reduced to 512 days, and if DMCPM rules were also in effect, the period would be further reduced to zero days.

Alternative Recharge Scenarios

With the responses of Comal Springs to various locations and magnitudes of recharge and pumpage presented in this report, it is possible to formulate a number of scenarios that could provide sufficient water to meet minimum flow requirements, as determined by EAA, for Comal Springs. The determination of the quantity of water to be recharged depends not only on the hydraulic feasibility of the aquifer, investigated herein, but also on the source and cost of recharge. Water from the drainage basins north of the Edwards Aquifer involves costs for Type 2 structures and perhaps in some cases also Type 1 structures. Recirculation of Comal Springs flow and/or imported water from external sources generates costs for diversions, pumps, and pipelines. Excluding legal and political ramifications, which are beyond the scope of this study, a large number of alternative possibilities exist including consideration of economic factors. Phase 3 of this study will consider these in an effort to identify realistic opportunities for protecting Comal Springs.

Phase 3 Scope of Work

To gain an insight as how to provide supplemental water to the Edwards Aquifer for the purpose of maintaining Comal Springs flow under drought conditions, a systematic approach can be taken. Variables include recharge sites, available water, minimum springflow, and costs. A proposed scope of work to provide such an evaluation in Phase 3 includes the following tasks:

Task 1: For the Type 2 recharge sites of Indian Creek, Lower Frio, Lower Sabinal, Lower Hondo, Lower Verde, San Geronimo, Cibolo and Lower Blanco, apply known average recharge rates plus imported or recirculated water that could be made available to determine alternative combinations that could supply Comal Springs on an ongoing basis with minimum flows (to be specified by EAA for this analysis).

Task 2: Apply the findings of Task 1 to external sources of water, either recirculated spring flows or imported from sources identified by SCTRWPG, to estimate costs based on known SCTRWPG costs prepared by HDR Engineering for delivery of water to alternative recharge sites.

Task 3: Estimate the physical and economic feasibility of guaranteeing Comal Springs flow by well injection of imported water directly into the aquifer rather than by use of Type 2 recharge sites.

Task 4: Prepare a report summarizing results of the above tasks and including a proposal to Edwards Aquifer Authority for Phase 4 of this study.

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Table 1. Impacts on Major Springs from Individual Recharge Sites, 1/1/1974 - 12/31/2000

Table 1A. One Year of Recharge (1974)

	Enhanced Recharge			Increased Springflow (AF), 1974-2000						Recharge Remaining	
Recharge Site	**Begins**	**Ends**	**Total (AF)**	**Comal**	**Leona**	**San Marcos**	**San Antonio**	**San Pedro**	**Total**	**AF**	**%**
Indian Creek	Mar-74	Jul-74	25,000	6,144	11,673	378	1,560	345	20,100	**4900**	**19.6%**
Lower Frio	Mar-74	Jul-74	25,000	7,379	11,254	461	2,426	463	21,983	**3017**	**12.1%**
Lower Sabinal	Mar-74	Jul-74	25,000	11,225	6,115	718	5,388	803	24,250	**750**	**3.0%**
Lower Hondo	Mar-74	Jul-74	25,000	11,809	4,970	753	5,615	847	23,994	**1006**	**4.0%**
Lower Verde	Mar-74	Jul-74	25,000	12,455	4,677	793	5,232	881	24,037	**963**	**3.9%**
San Geronimo	Mar-74	Jul-74	25,000	13,212	3,098	870	6,800	963	24,943	**57**	**0.2%**
Cibolo	Mar-74	Jul-74	25,000	12,350	691	9,426	2,616	321	25,405	**-405**	**-1.6%**
Lower Blanco	Mar-74	Jul-74	25,000	831	11	22,285	32	5	23,164	**1836**	**7.3%**

Table 1B. Five Years of Recharge (1974-1978)

	Enhanced Recharge			Increased Springflow (AF), 1974-2000						Recharge Remaining	
Recharge Site	**Begins**	**Ends**	**Total (AF)**	**Comal**	**Leona**	**San Marcos**	**San Antonio**	**San Pedro**	**Total**	**AF**	**%**
Indian Creek	Mar-74	Jul-78	125,000	30,727	57,058	1,875	6,396	1,619	97,675	**27,325**	**21.9%**
Lower Frio	Mar-74	Jul-78	125,000	40,542	59,891	2,514	11,295	2,400	116,643	**8,357**	**6.7%**
Lower Sabinal	Mar-74	Jul-78	125,000	57,519	30,431	3,644	22,349	3,989	117,932	**7,068**	**5.7%**
Lower Hondo	Mar-74	Jul-78	125,000	61,911	25,240	3,921	23,493	4,260	118,825	**6,175**	**4.9%**
Lower Verde	Mar-74	Jul-78	125,000	64,665	23,430	4,084	22,462	4,314	118,955	**6,045**	**4.8%**
San Geronimo	Mar-74	Jul-78	125,000	67,864	15,568	4,436	28,930	4,836	121,635	**3,365**	**2.7%**
Cibolo	Mar-74	Jul-78	125,000	62,310	3,494	47,227	10,143	1,592	124,766	**234**	**0.2%**
Lower Blanco	Mar-74	Jul-78	125,000	4,063	54	108,438	148	25	112,727	**12,273**	**9.8%**

Table 1C. Twenty Seven Years of Recharge (1974-2000)

	Enhanced Recharge			Increased Springflow (AF), 1974-2000						Recharge Remaining	
Recharge Site	**Begins**	**Ends**	**Total (AF)**	**Comal**	**Leona**	**San Marcos**	**San Antonio**	**San Pedro**	**Total**	**AF**	**%**
Indian Creek	Mar-74	Jul-00	675,000	113,464	218,022	6,632	20,602	5,725	364,445	**310,555**	**46.0%**
Lower Frio	Mar-74	Jul-00	675,000	179,787	252,849	10,604	35,558	9,306	488,104	**186,896**	**27.7%**
Lower Sabinal	Mar-74	Jul-00	675,000	313,832	135,936	18,690	65,035	16,630	550,123	**124,877**	**18.5%**
Lower Hondo	Mar-74	Jul-00	675,000	330,952	111,206	19,719	70,793	17,862	550,531	**124,469**	**18.4%**
Lower Verde	Mar-74	Jul-00	675,000	327,259	98,430	19,482	70,066	17,772	533,010	**141,990**	**21.0%**
San Geronimo	Mar-74	Jul-00	675,000	381,373	70,946	23,184	84,157	20,293	579,953	**95,047**	**14.1%**
Cibolo	Mar-74	Jul-00	675,000	327,752	16,397	232,064	27,775	6,534	610,522	**64,478**	**9.6%**
Lower Blanco	Mar-74	Jul-00	675,000	21,956	257	589,225	409	101	611,948	**63,052**	**9.3%**

Table 2. Supplemental Water Volumes to Major Springs from Multiple Recharge Sites, 1/1/1974 - 12/31/2000

	Enhanced Recharge			Increased Springflow (AF), 1974-2000						Recharge Remaining	
Recharge Site	Begins	Ends	Total (AF)	Comal	Leona	San Marcos	San Antonio	San Pedro	Total	AF	%
Individual Sites Total	Mar-74	Jul-78	1,000,000	389,601	215,165	176,141	125,216	23,035	929,158	70,842	7.6%
Multiple Sites Total	Mar-74	Jul-78	1,000,000	378,881	207,155	178,540	126,884	22,563	914,023	85,977	8.6%
Difference from Individual				10,720	8,010	-2,399	-1,668	472	15,135		
Difference %				2.8%	3.7%	-1.4%	-1.3%	2.1%	1.6%		

Table 3. Maximum Spring Flow Increases by Recharge (Values in cubic feet/second)
Recharge 25,000 AF/yr at each site

Recharge Site	Springs and Duration of Recharge														
	Comal			San Marcos			San Antonio			San Pedro			Leona		
	1 yr	5 yr	27 yr	1 yr	5 yr	27 yr	1 yr	5 yr	27 yr	1 yr	5 yr	27 yr	1 yr	5 yr	27 yr
Indian Creek	0.6	3.1	9.7	0.0	0.2	0.6	0.6	1.6	5.9	0.0	0.2	0.7	1.4	6.4	16.9
Lower Frio	1.4	6.1	13.5	0.1	0.3	0.8	0.7	4.6	7.5	0.1	0.5	1.0	2.6	8.9	19.4
Lower Sabinal	8.4	16.7	23.2	0.3	0.8	1.3	6.6	7.8	10.3	0.7	1.3	1.7	2.1	5.4	10.3
Lower Hondo	5.7	15.9	23.3	0.2	0.8	1.4	5.2	8.0	11.0	0.4	1.2	1.7	1.2	4.1	8.6
Lower Verde	4.1	14.1	22.9	0.2	0.8	1.4	2.0	7.9	11.4	0.3	1.1	1.6	0.9	3.5	7.8
San Geronimo	12.9	22.6	29.6	0.5	1.2	1.6	9.2	10.3	13.3	1.0	1.7	2.2	0.9	2.7	5.4
Cibolo	12.1	19.6	24.5	7.8	13.8	16.6	4.3	4.9	5.1	0.3	0.5	0.7	0.1	0.5	1.3
Lower Blanco	1.5	1.8	2.0	48.4	53.1	56.5	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0

* Maximum calculated as highest 365-day average

Table 4. Supplemental Water Volumes to Major Springs from Recharge Sites Under Varied Recharge Regimes, 1/1/1974 - 12/31/2000
(All values in acre-feet)

Table 4A. Comparison of months recharge is applied

*Recharge applied to the Lower Sabinal recharge site only

Months of Applied Recharge	Total Amount (AF)	Comal	Leona	San Marcos	San Antonio	San Pedro	Total	Difference	Difference %
Mar-Jul (5 months)	675,000	313,832	135,936	18,690	65,035	16,630	550,123	124,877	18.5%
Jan - Dec (12 months)	675,000	310,375	134,953	18,492	67,002	16,806	547,628	127,372	18.9%
Difference		3,457	983	198	-1,967	-176	2,496	-2,496	
Difference %		1.1%	0.7%	1.1%	-3.0%	-1.1%	0.5%	-2.0%	

* Both runs applied 25,000 acre-feet of recharge per year

Table 4B. Comparison of amount of recharge applied

*Recharge applied to the Lower Sabinal recharge site only

Amount of Applied Recharge	Total Amount (AF)	Comal	Leona	San Marcos	San Antonio	San Pedro	Total	Difference	Difference %
25,000 af/yr	675,000	310,375	134,953	18,492	67,002	16,806	547,628	127,372	18.9%
12,500 af/yr	337,500	156,153	67,437	9,298	33,355	8,212	274,455	63,045	18.7%
Difference		154,222	67,516	9,194	33,647	8,594	273,173	64,327	
Difference %		49.7%	50.0%	49.7%	50.2%	51.1%	49.9%	50.5%	

*Recharge applied 12 months per year

Table 5. Type 2 Recharge Structures Summary

Water Supply Option Number	Type 2 Recharge Structure	Maximum Pool Capacity (AF)	Average Conditions: Maximum Recharge Enhancement (AF/yr)	Average Conditions: Unit Cost ($/AF Recharge)	Drought Conditions: Maximum Recharge Enhancement (AF/yr)	Drought Conditions: Unit Cost ($/AF Recharge)	Sustained Yield (AF/yr)	Unit Cost ($/AF S. Yield)	% Recovery	Total Project Cost (Million $)
EAA-02 (1)	Cibolo Dam #1	50,000	12,849	138	2,474	719	1,269	1,401	51	26
EAA-02 (2)	Lower Blanco	50,000	49,766	121	22,821	264	2,165	2,786	10	78
EAA-02 (3)	San Geronimo	14,000	3,231	394	1,423	895	552	2,308	39	18
EAA-02 (4)	Lower Sabinal	35,000	18,400	155	4,012	711	4,225	675	105	40
EAA-02 (5)	Lower Hondo	28,000	9,420	262	3,250	761	42,702	915	83	36
EAA-02 (6)	Lowr Verde	24,000	6,220	222	2,190	631	1,986	696	91	19
EAA-02 (7)	Lower Frio	50,000	14,400	285	5,063	810	5,390	761	107	58
EAA-02 (8)	Indian Creek	165,000	34,500	371	19,890	643	7,361	1,737	37	151
8 Projects Combined		416,000	148,786	220	61,123	535	25,650	1,274	42	427

Reference Turner Collie & Braden/LBG Guyton, 2000

Table 6. Maximum Increases by Recharge in Well J-17 Water Levels From Enhanced Recharge

Recharge Site	Water Level Rise for Recharge Scenarios (feet)		
	One Year	Five Years	Twenty Seven Years
Indian Creek	0.1	0.6	1.8
Lower Frio	0.3	1.2	2.6
Lower Sabinal	1.6	3.2	4.4
Lower Hondo	1.1	3.0	4.4
Lower Verde	0.8	2.7	4.3
San Geronimo	2.5	4.3	5.6
Cibolo	0.8	1.5	2.1
Lower Blanco	0.0	0.0	0.0

* Maximum calculated as highest 365-day average

Table 7. Comparison of No-Flow Conditions at Comal Springs for Recharge Scenarios (all units in days)

Drought Period 1952-1959
Pumping Period 1979-1986

Enhanced Recharge Applied in Scenarios	Number of days Comal is Not Flowing for Each Recharge Scenario						
	Indian Creek	Lower Frio	Lower Sabinal	Lower Hondo	Lower Verde	San Geronimo	Cibolo
No Enhanced Recharge (Baseline)	1,264	1,264	1,264	1,264	1,264	1,264	1,264
25,000 Ac-ft per year (all time)	1,177	1,146	1,043	1,035	1,041	993	1,064
25,000 Ac-ft per year (non-CP only)	1,221	1,215	1,223	1,195	1,183	1,213	1,235
Average Type 2 enhancement recharge (all time)	1,151	1,162	1,108	1,153	1,181	1,198	1,150
Average Type 2 enhancement recharge (non-CP only)	1,201	1,237	1,237	1,243	1,244	1,260	1,249
Average Type 2 enhancement recharge (non-CP) and Drought Type 2 enhancement recharge (CP)	1,169	1,202	1,173	1,191	1,221	1,223	1,215
All Type 2 enhancement recharge applied to only single site (Focused Recharge)	1,023	886	675	571	512	532	769

***Values should be used to compare between sites and scenarios not as absolute values**

Note: Each recharge site evaluated separately with a site-specific model run. Model runs conducted on Recharge Model 1.

Table 8. Comparison of Days Comal Springs is Dry in Various Recharge Scenarios on Recharge Model 1 (all units in days)

Enhanced Recharge Applied in Scenarios	Drought (1/52 - 12/59)
Baseline	1,264
Type 2 Enhancement - All Sites (all sites, average volumes all time)	591
Type 2 Enhancement - All Sites (all sites, average volumes non-CP only)	1,152
Type 2 Enhancement - All Sites (Average condition during non-CP and Drought conditions during CP)	1,025
All Type 2 Enhancement applied to only Lower Verde (Focused Recharge)	512
DMCPM Rules Only and Lower Verde Focused Recharge	0
DMCPM Rules Only	292
Recirculation	1,260

***Values should be used to compare between scenarios not as absolute values**

CP=Critical Period DMCPM =Demand Management Critical Period Management

Table 9. Comparison of the Number of Days in Each Stage of Critical Period for Various Recharge Scenarios (all units in days)

Table 9A. Comparison of Various Recharge Scenarios on Recharge Model 1

Stage	Baseline	Average Type 2 Enhancement All Times	Average Type 2 Enhancement Non-Critical Period	Average and Drought Type 2 Enhancement	Recirculation	DMCPM Rules	All Type 2 Enhancement in Lower Verde	DMCPM Rules and Focused Recharge LV
Jan 1952- Dec 1959 San Antonio								
Stage 0	113	258	134	190	111	222	306	658
Stage I	137	408	135	181	140	339	473	523
Stage II	473	767	669	742	471	849	737	772
Stage III	246	183	170	141	251	244	270	672
Stage VI	1924	1277	1785	1640	1920	1239	1105	269
Uvalde								
Stage 0	131	573	192	307	139	153	323	499
Stage I								
Stage II								
Stage III	30	43	46	30	30	30	85	30
Stage VI	2732	2277	2655	2556	2724	2710	2479	2364

Table 9B. Comparison of Various Recharge Scenarios on Unmodified Model

Jan 1996- June 1997

San Antonio

Stage	Baseline	Type 2 Enhancement All Times	Type 2 Enhancement Non-Critical Period		Recirculation	DMCPM Rules
Stage 0	77	205	176		56	99
Stage I	188	263	161		183	183
Stage II	233	53	184		271	236
Stage III	20	0	0		11	0
Stage VI	0	0	0		0	0

***Values should be used to compare between scenarios not as absolute values**

May 2005

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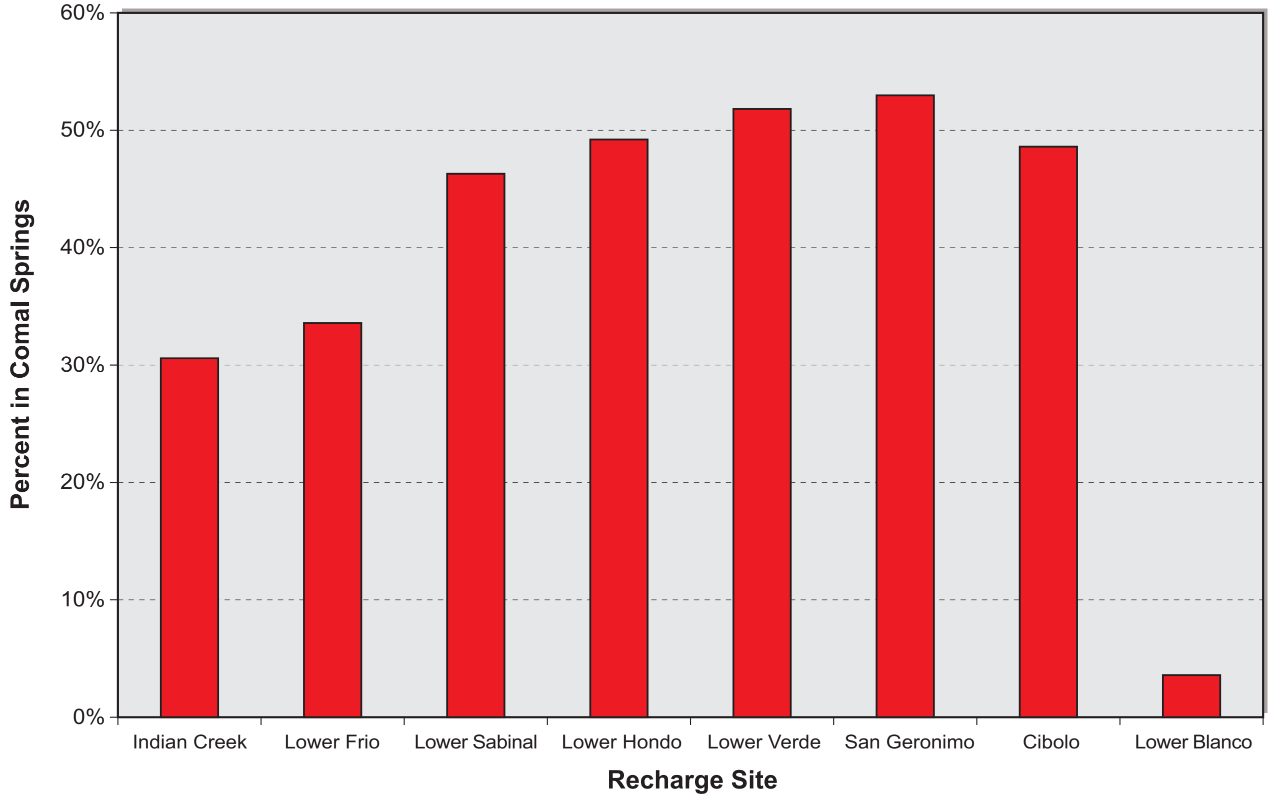
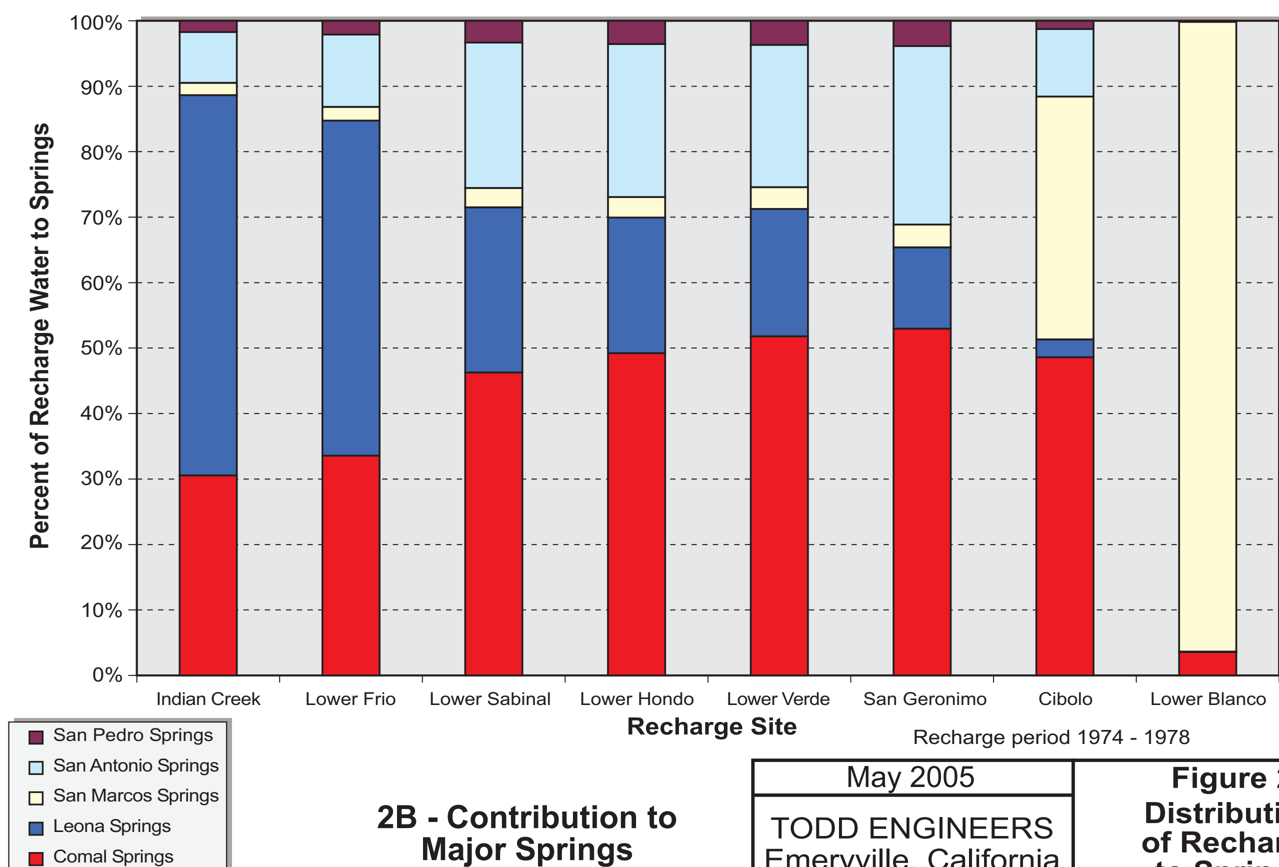
Figure 1
Location of Type 2 Recharge Sites

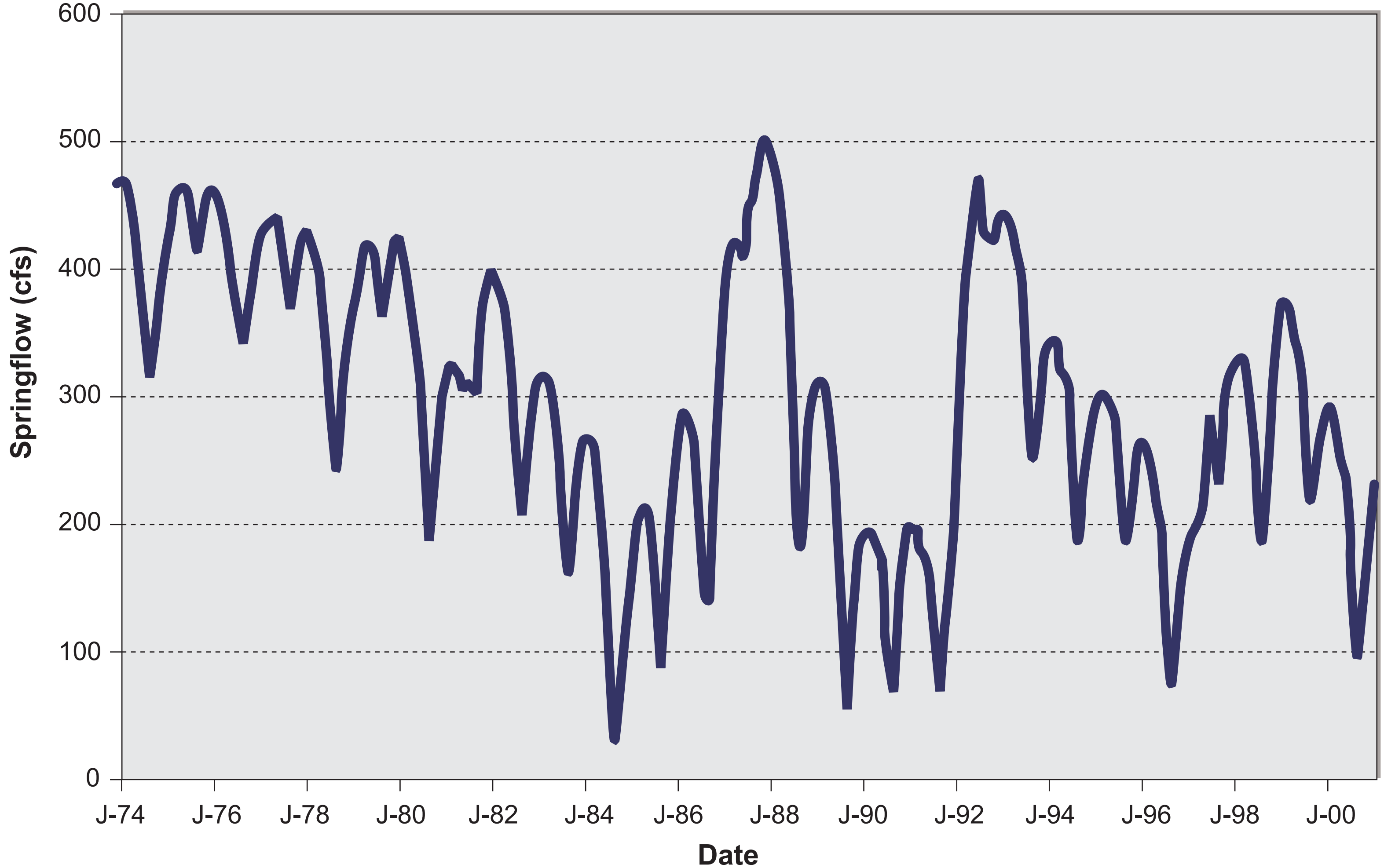


2A - Percent of Recharge Water Contributing to Comal Springs



2B - Contribution to Major Springs

May 2005	**Figure 2**
TODD ENGINEERS Emeryville, California	**Distribution of Recharge to Springs**



May 2005

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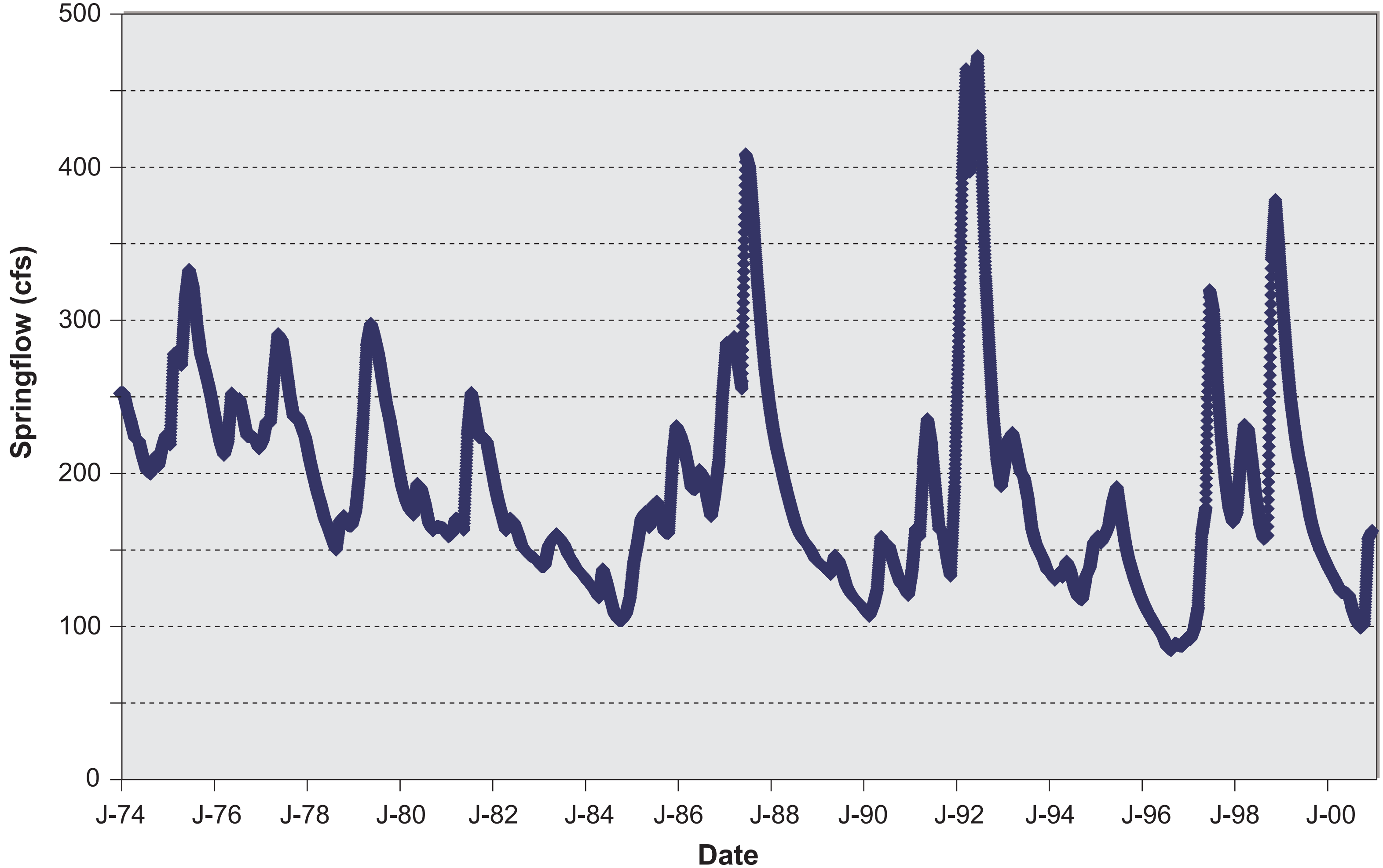
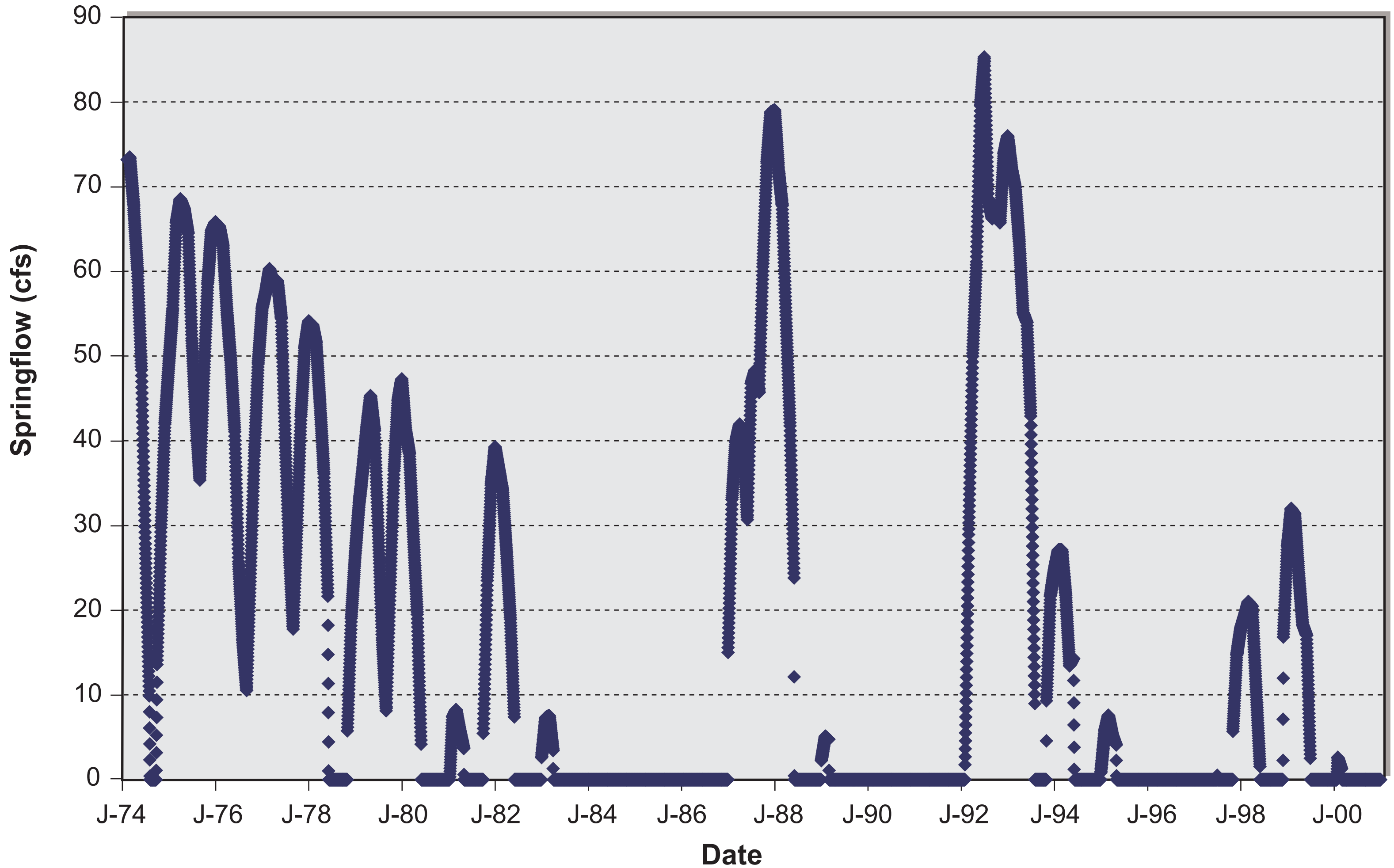
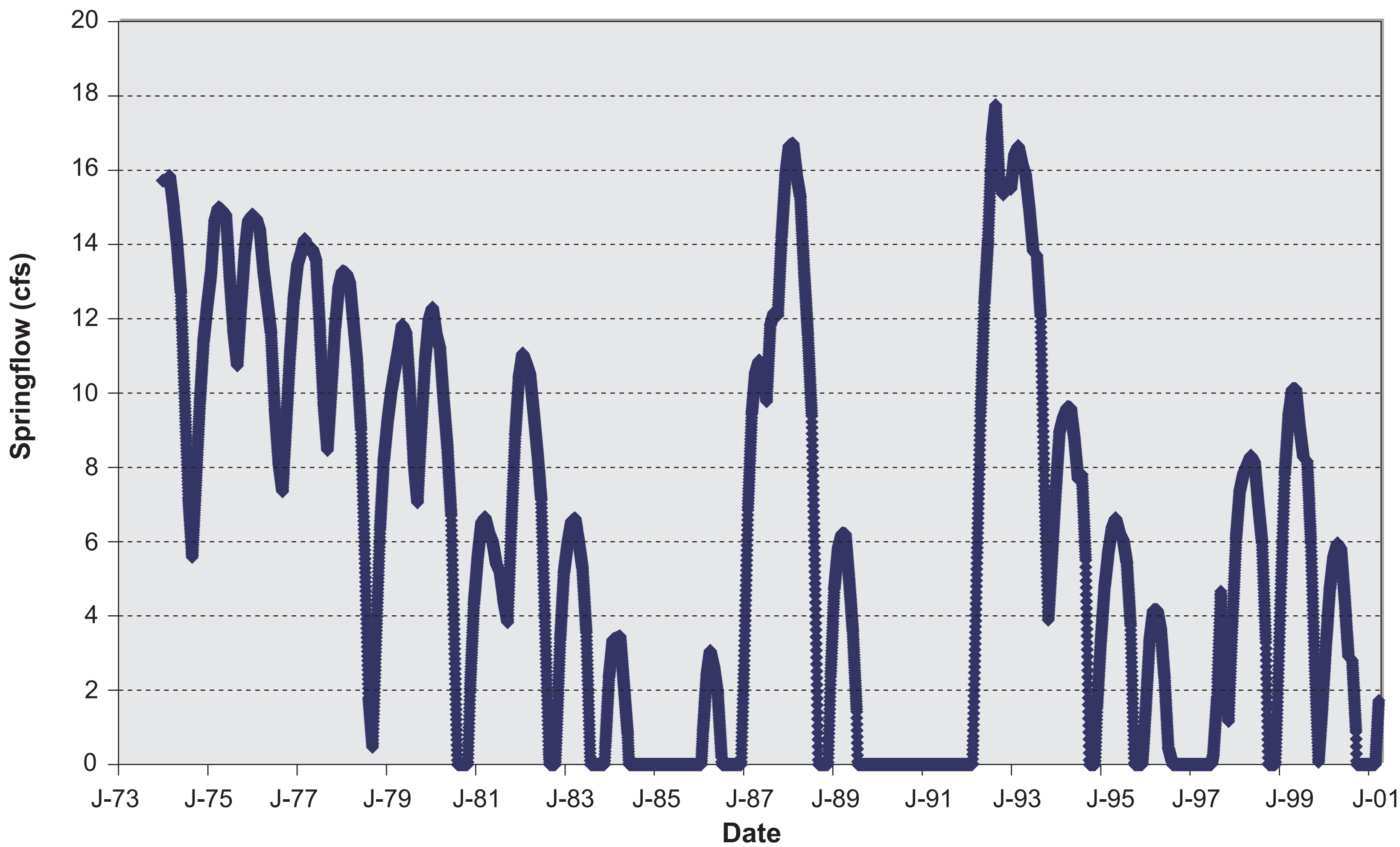
Figure 3
Comal Springs
Baseline



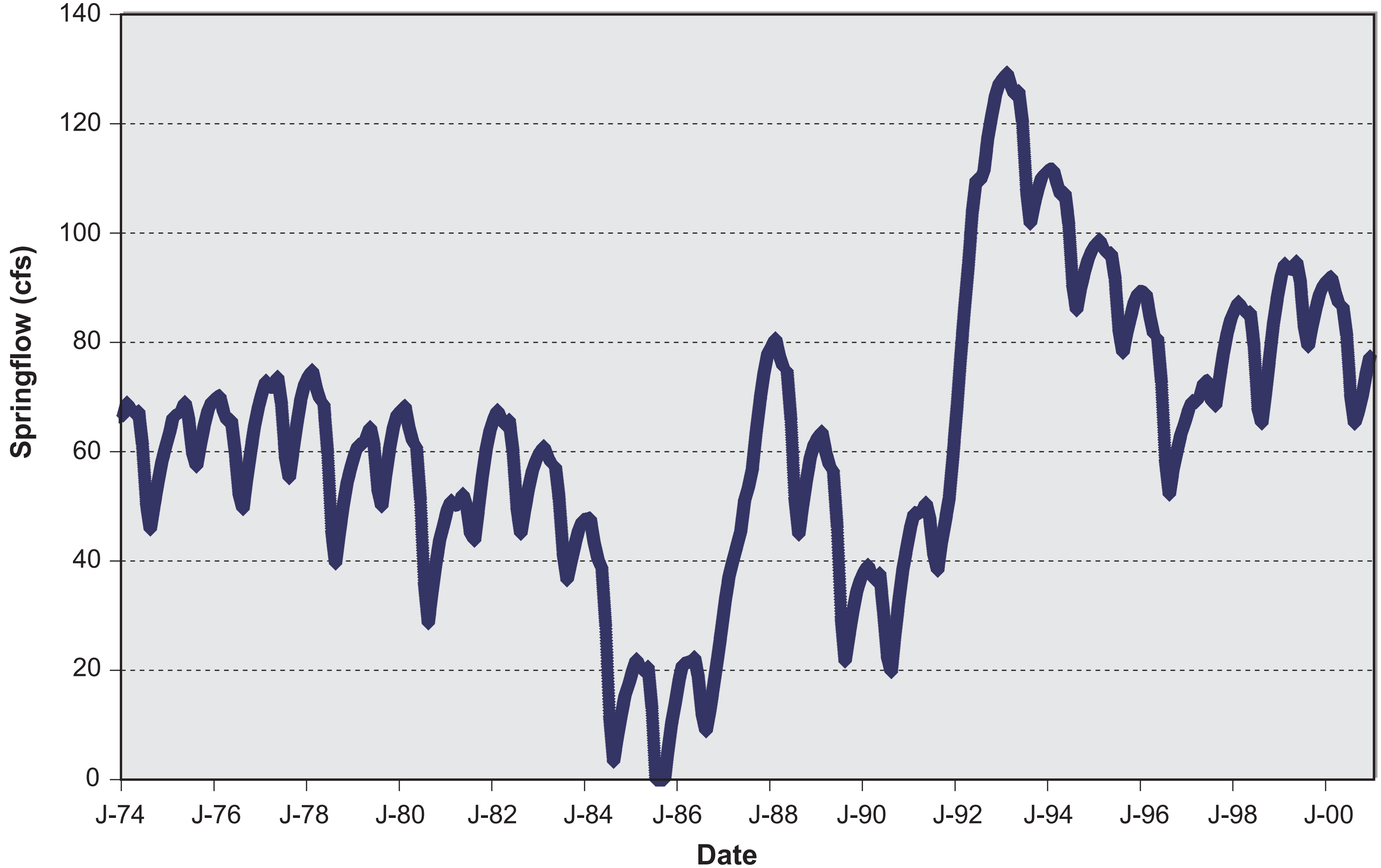
May 2005	**Figure 4** **San Marcos Springs** **Baseline**
TODD ENGINEERS Emeryville, California	



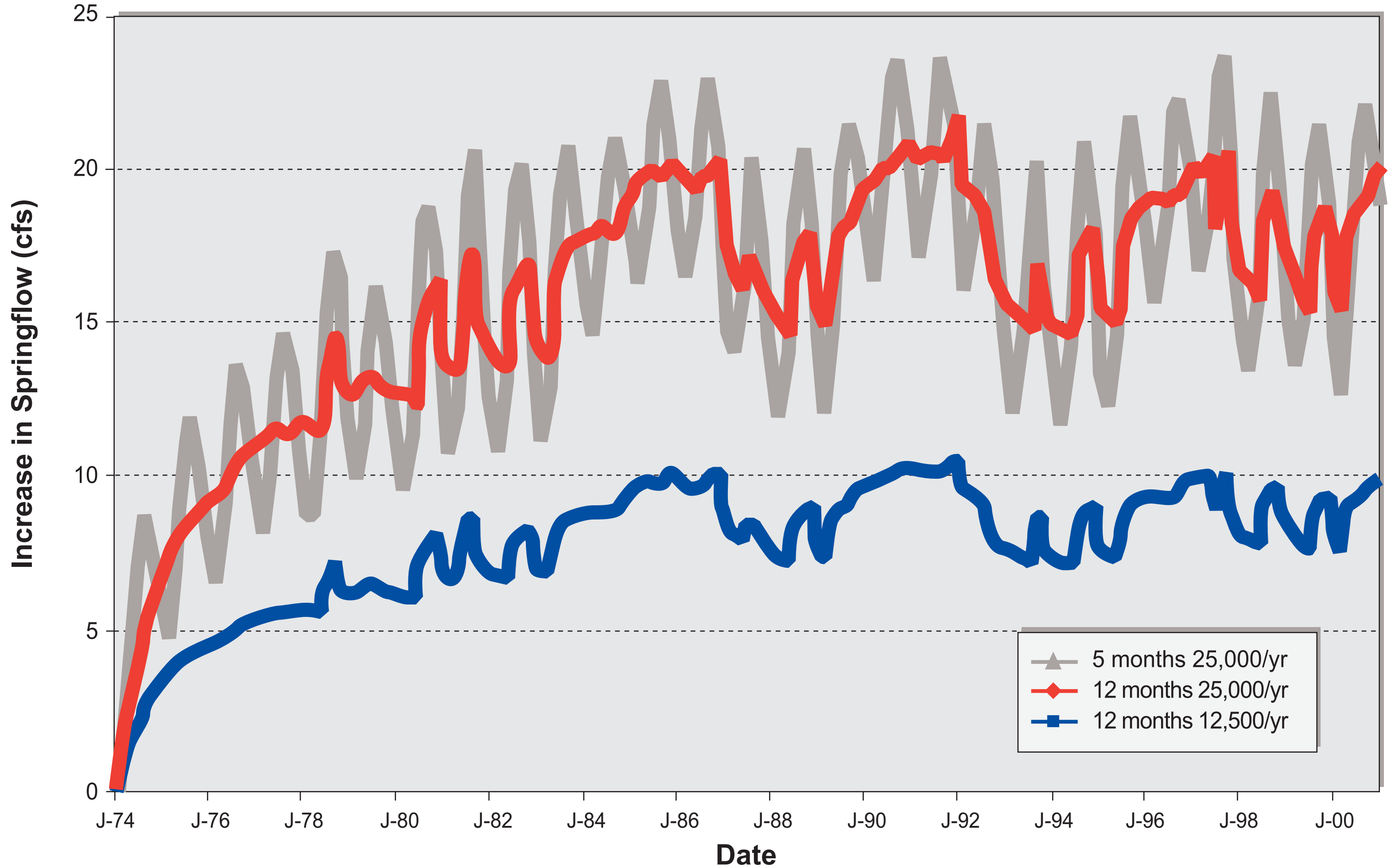
May 2005	**Figure 5**
TODD ENGINEERS Emeryville, California	**San Antonio Springs Baseline**



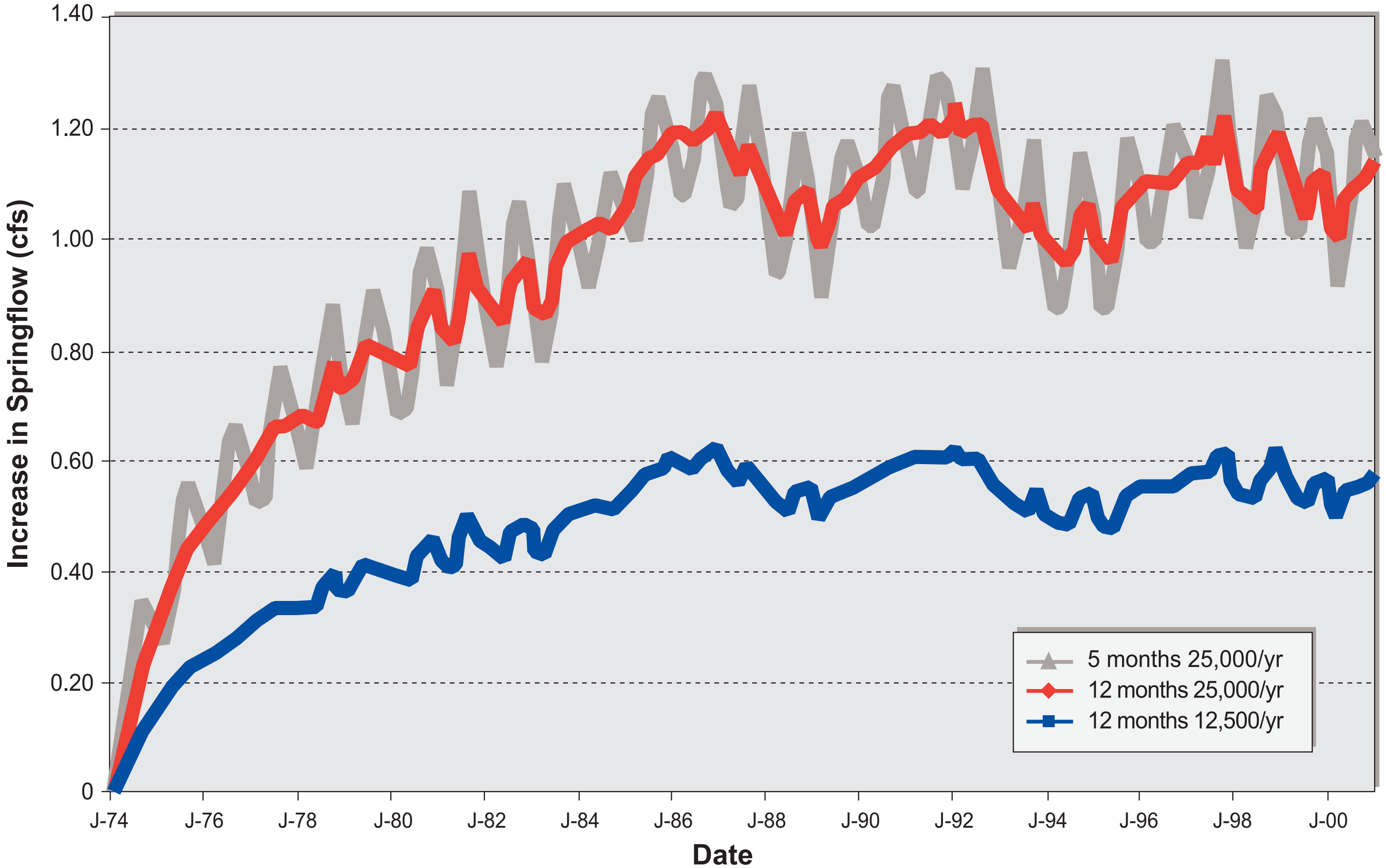
April 2005	**Figure 6**
TODD ENGINEERS Emeryville, California	**San Pedro Springs Flow Base**



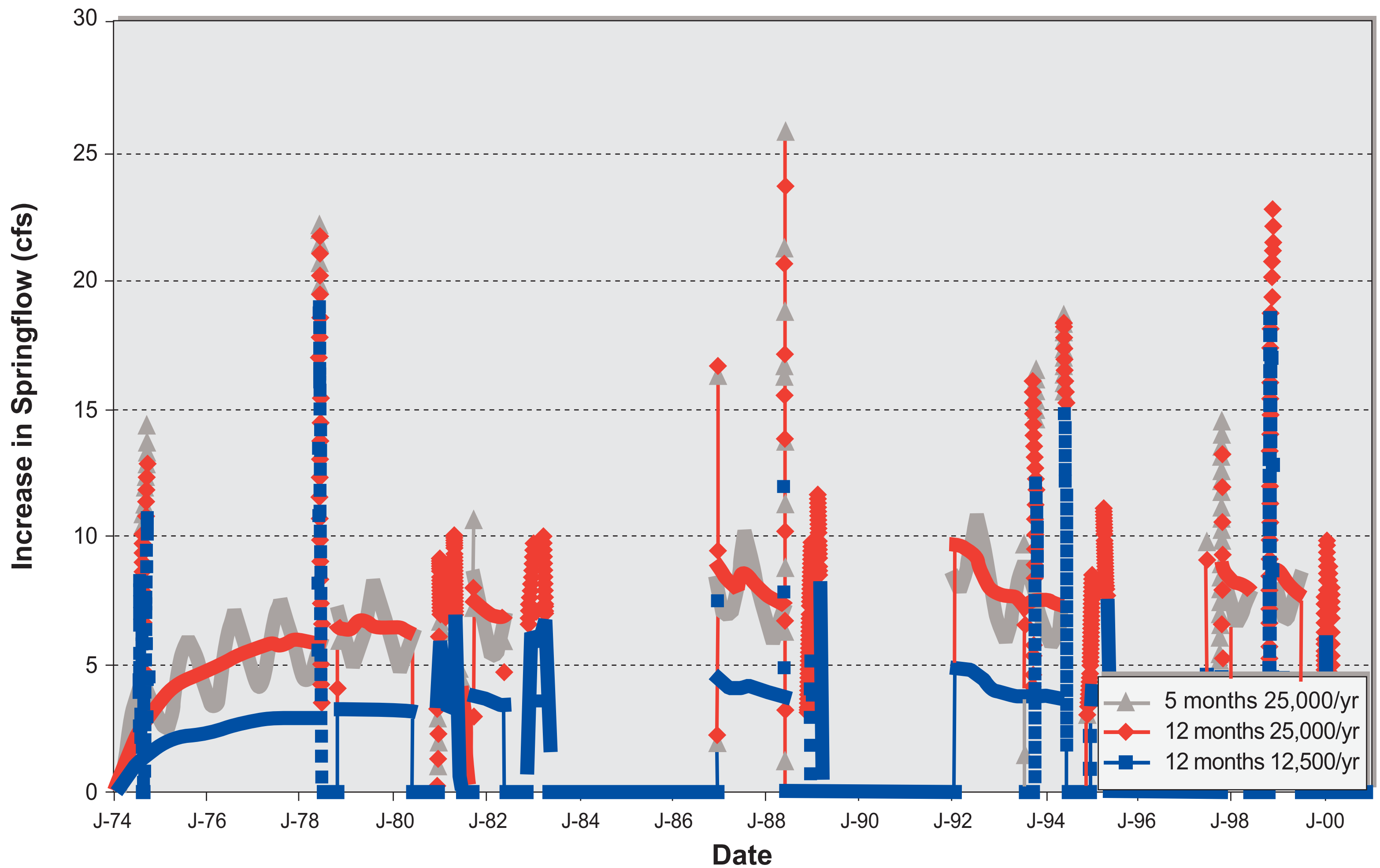
May 2005	**Figure 7**
TODD ENGINEERS Emeryville, California	**Leona Springs Baseline**



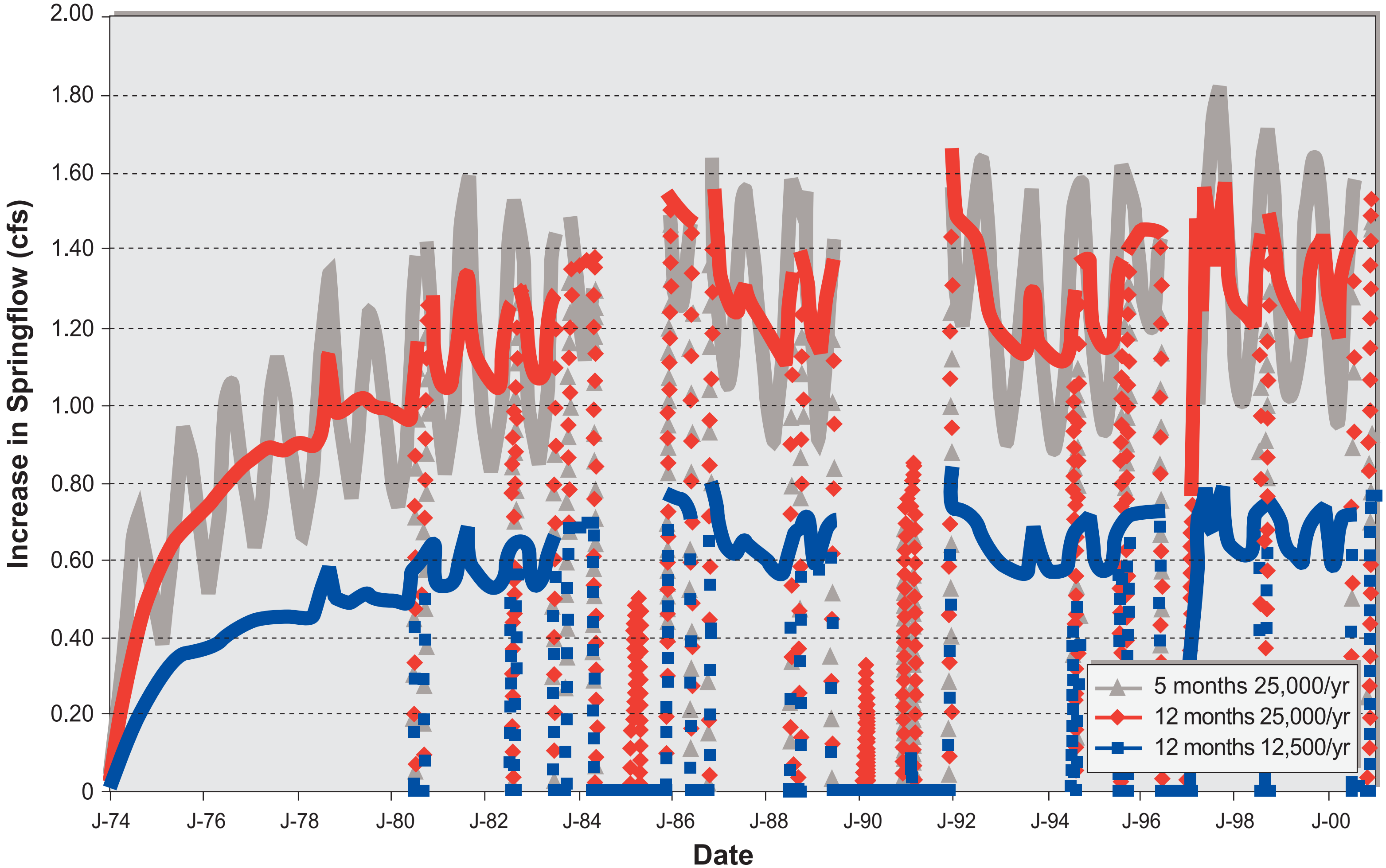
May 2005	**Figure 8** **Impacts to** **Comal Springs** **From Variable Recharge** **at Lower Sabinal**
TODD ENGINEERS Emeryville, California	



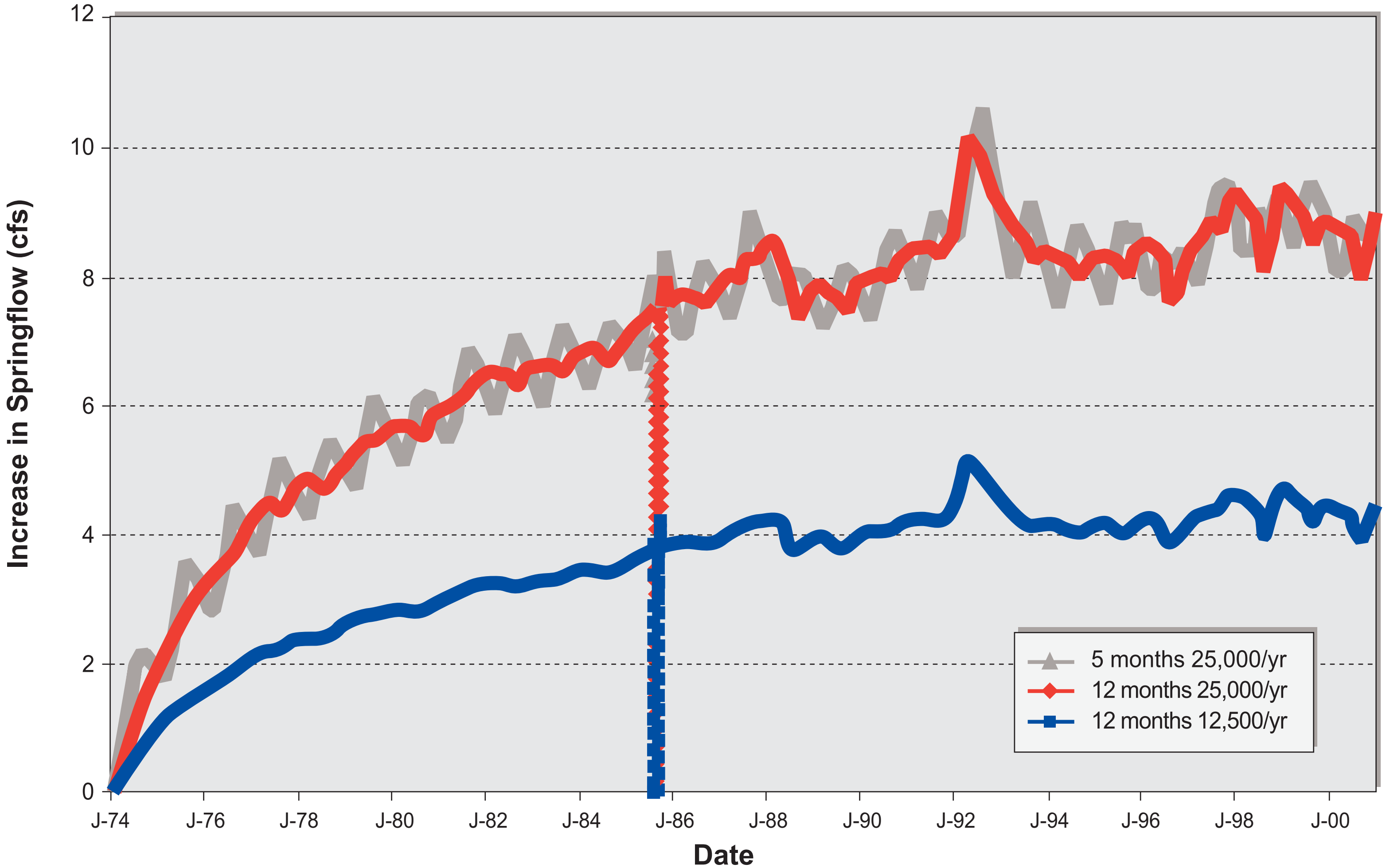
May 2005	**Figure 9**
TODD ENGINEERS Emeryville, California	**Impacts to San Marcos Springs From Variable Recharge to Lower Sabinal**



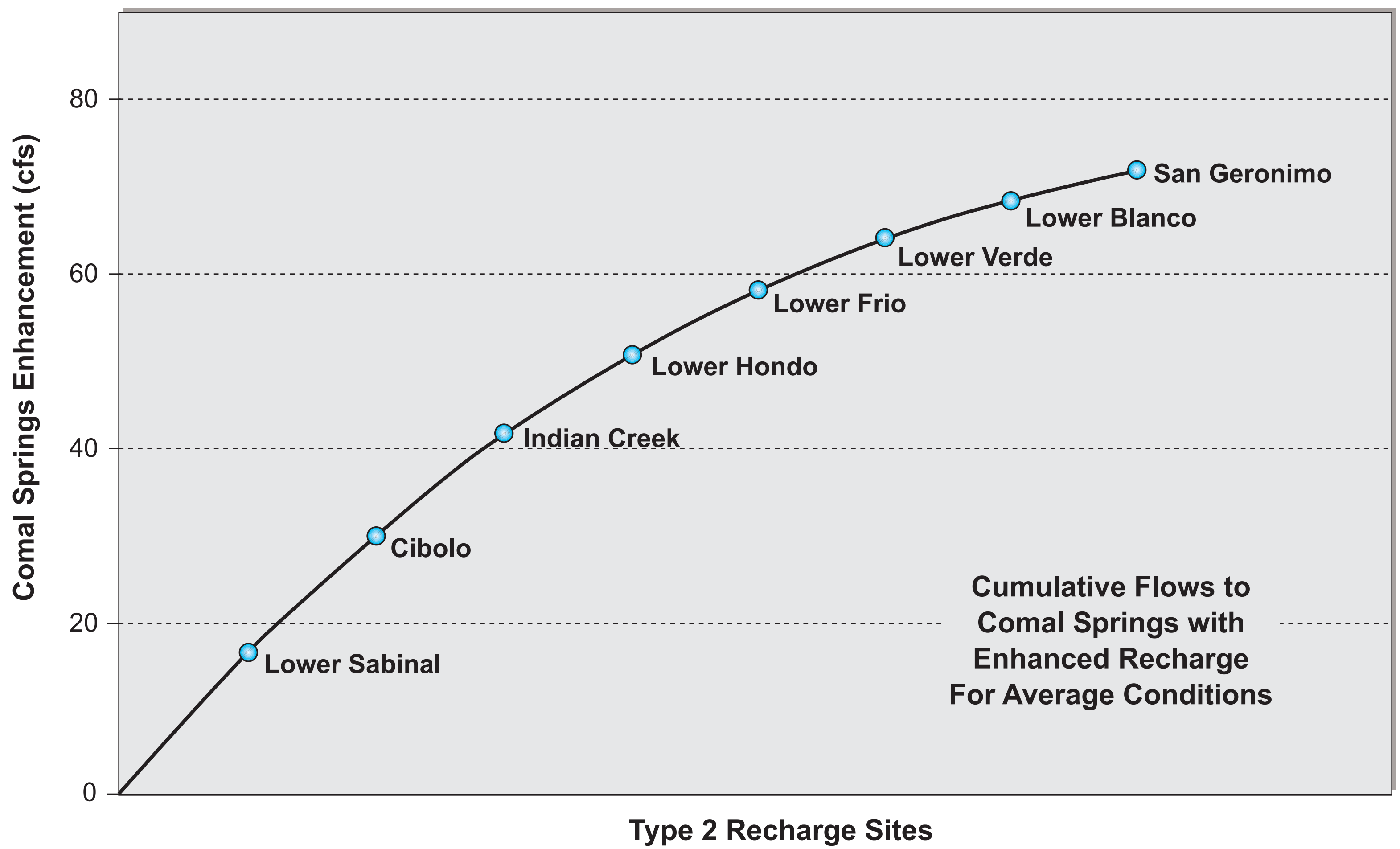
May 2005	**Figure 10** **Impacts to** **San Antonio Springs** **From Variable Recharge** **at Lower Sabinal**
TODD ENGINEERS Emeryville, California	



May 2005	**Figure 11** **Impacts to** **San Pedro Springs** **From Variable Recharge** **at Lower Sabinal**
TODD ENGINEERS Emeryville, California	



May 2005	**Figure 12**
TODD ENGINEERS Emeryville, California	**Impacts to Leona Springs From Variable Recharge at Lower Sabinal**



May 2005

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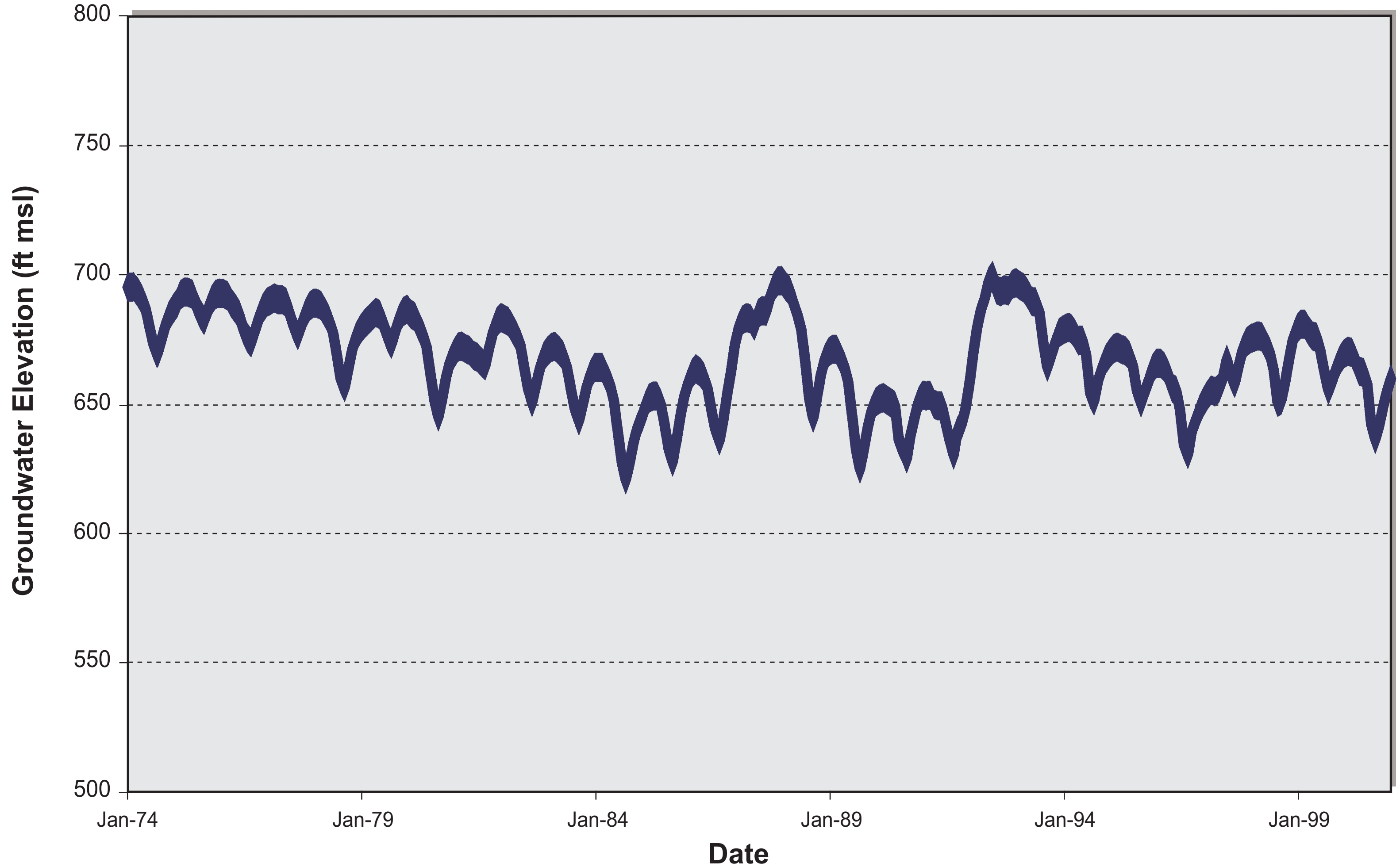
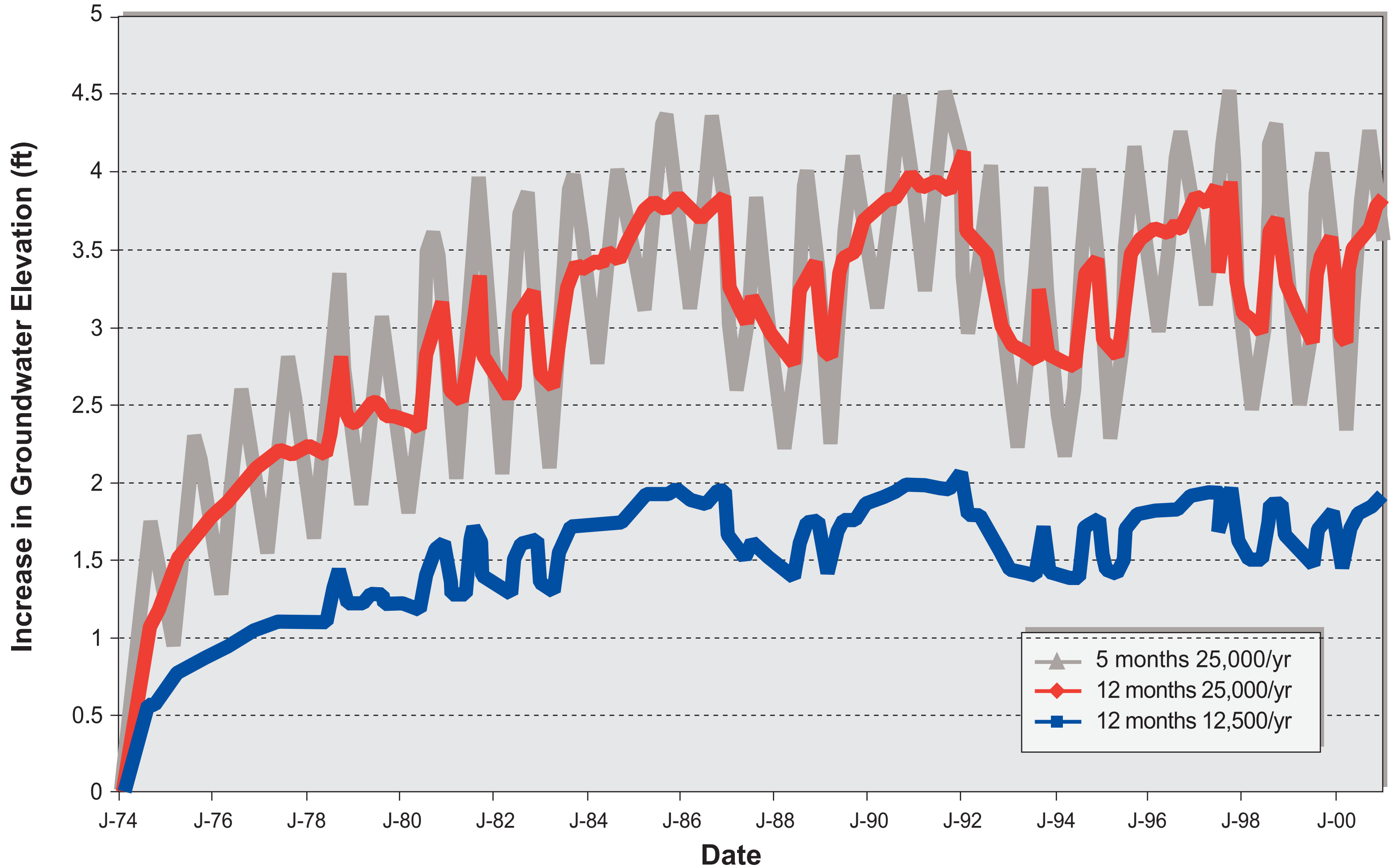
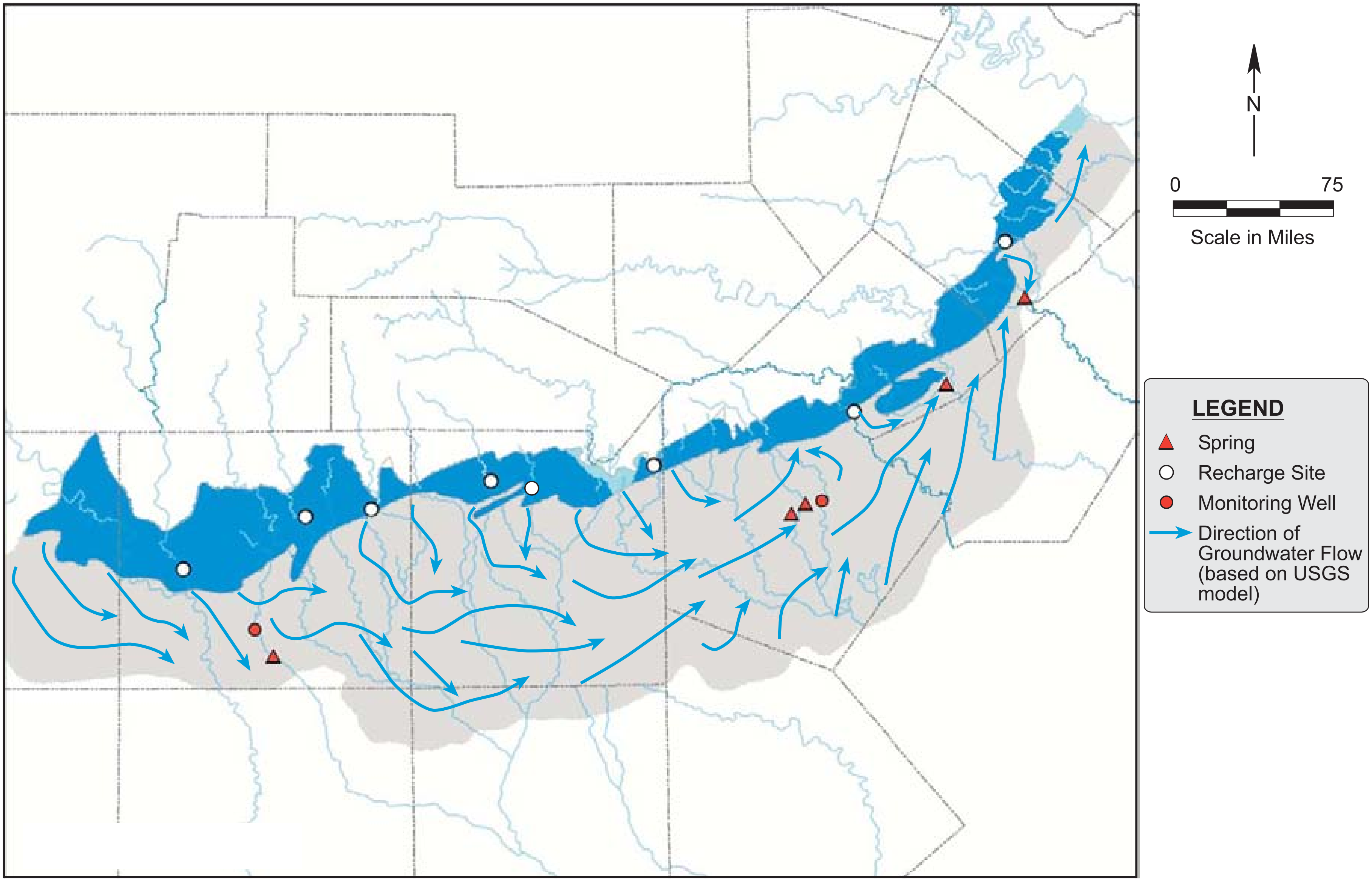
Figure 13
Comal Springs Enhancement From Combined Recharge



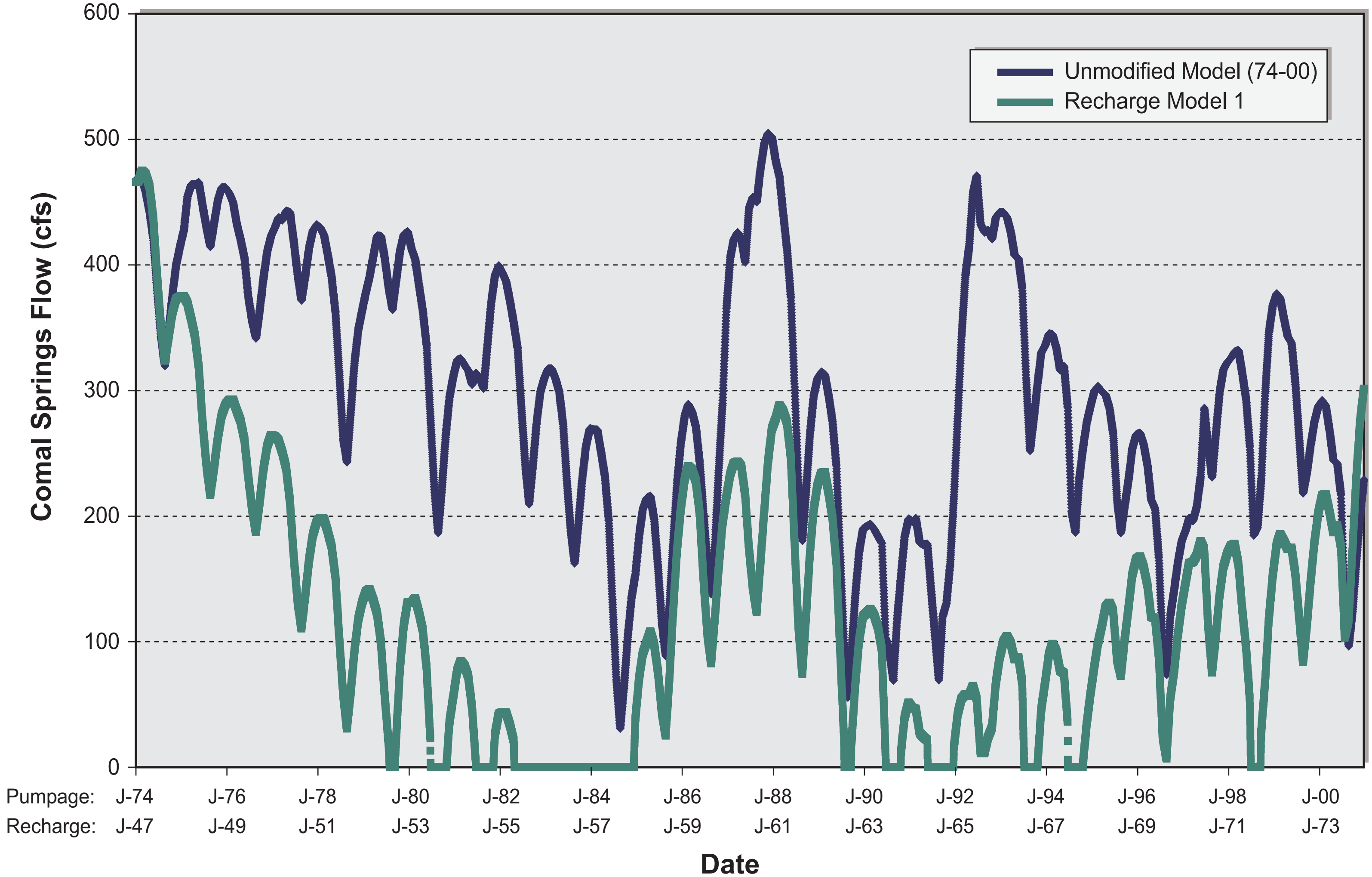
May 2005	**Figure 14** **Groundwater Elevation** **Well J-17**
TODD ENGINEERS Emeryville, California	



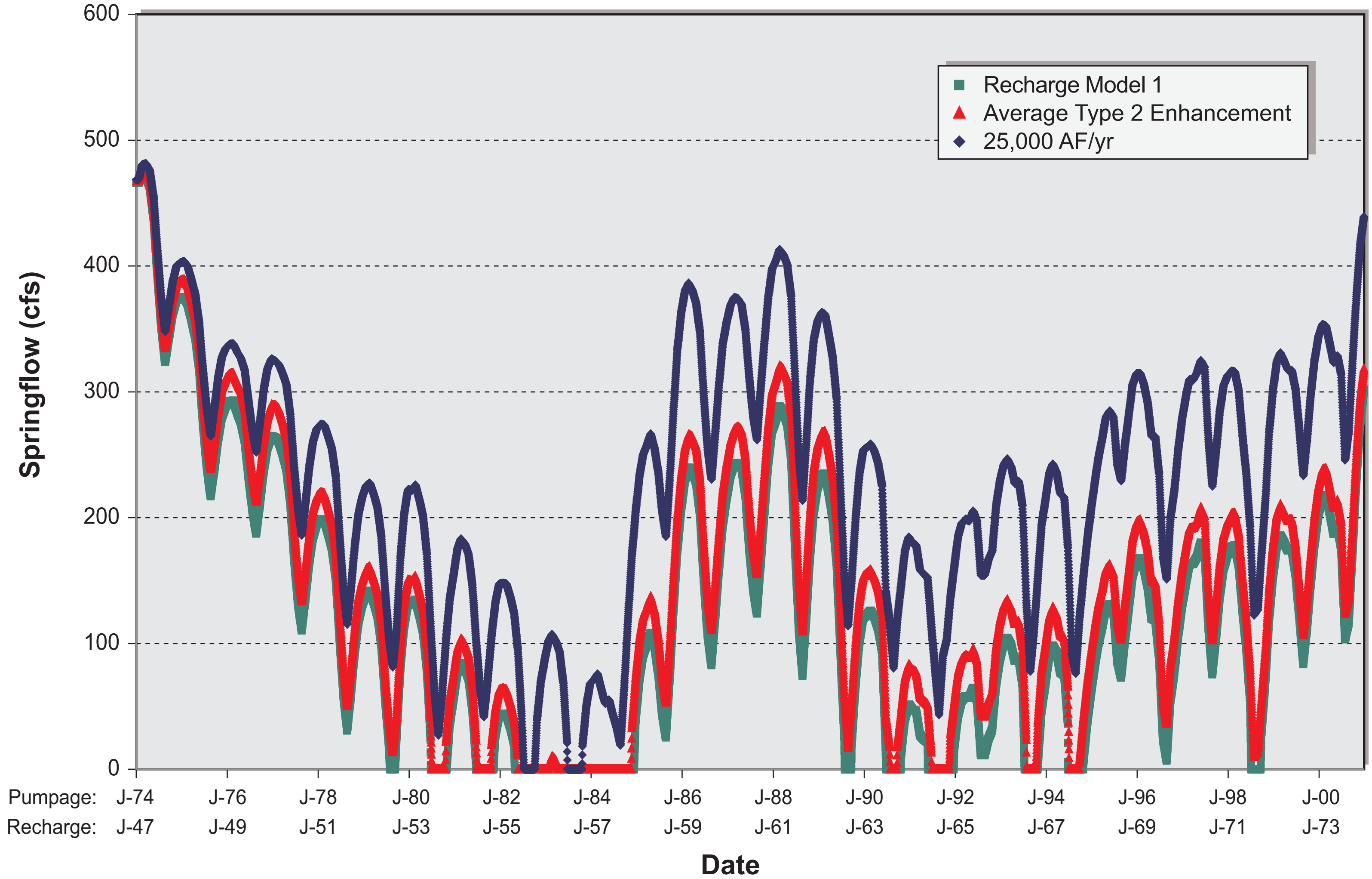
May 2005	**Figure 15** **Impacts to** **J-17** **From Variable Recharge** **at Lower Sabinal**
TODD ENGINEERS Emeryville, California	



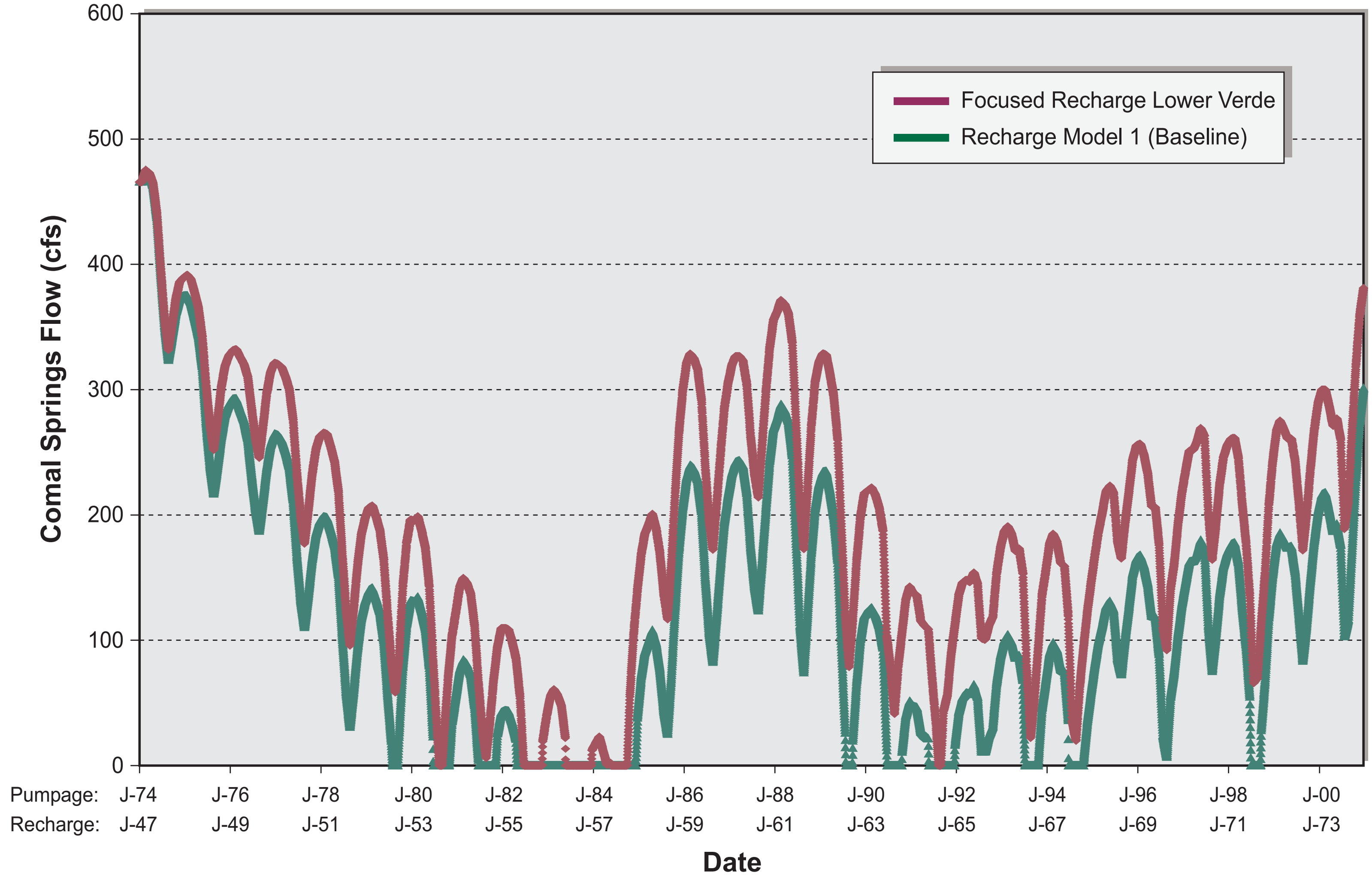
May 2005	**Figure 16 Groundwater Flow Directions**
TODD ENGINEERS Emeryville, California	



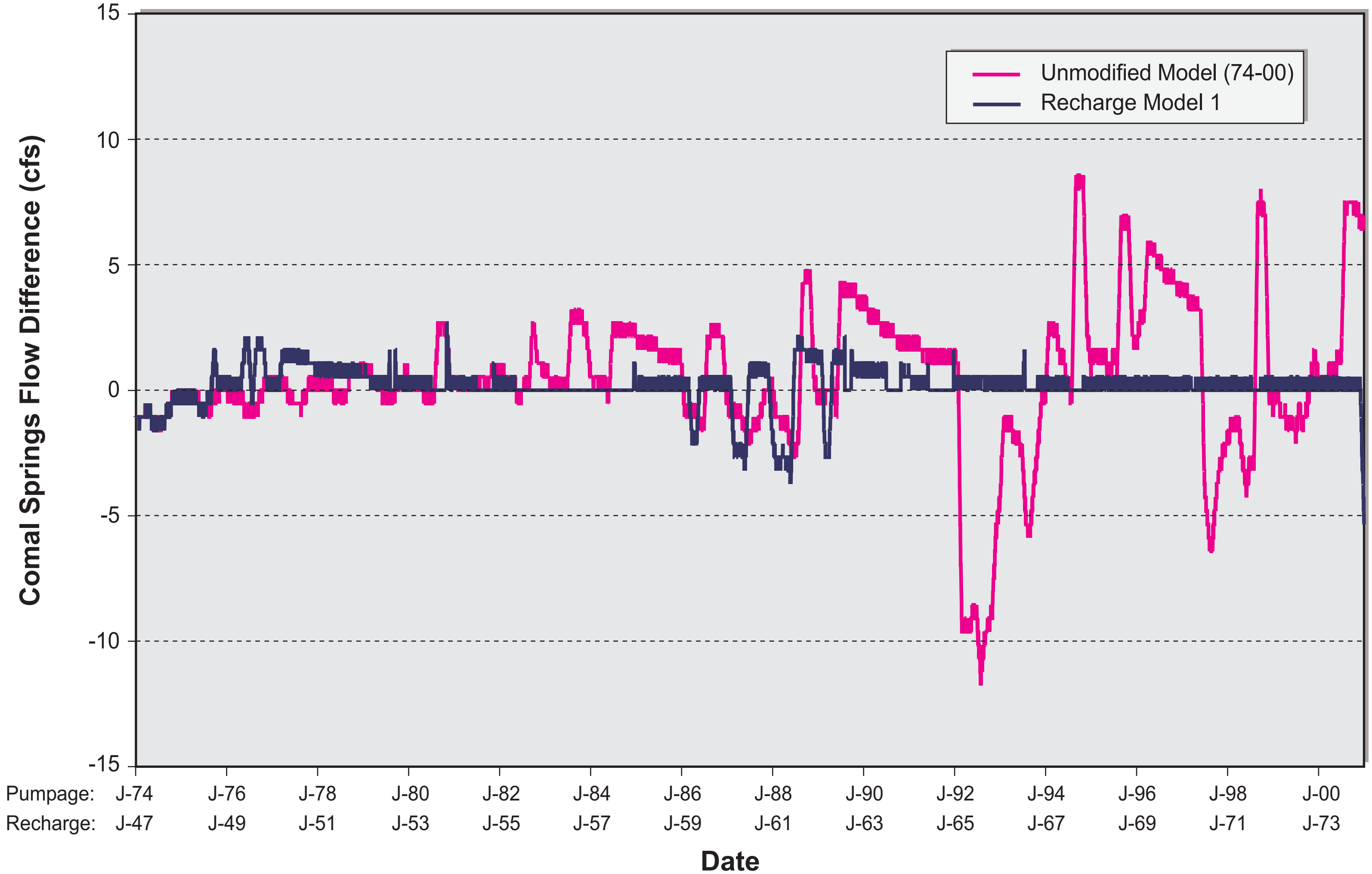
May 2005	**Figure 17** **Comal Springs** **Baseline**
TODD ENGINEERS Emeryville, California	



May 2005	**Figure 18** **Flow With Various Recharge Scenarios Comal Springs**
TODD ENGINEERS Emeryville, California	

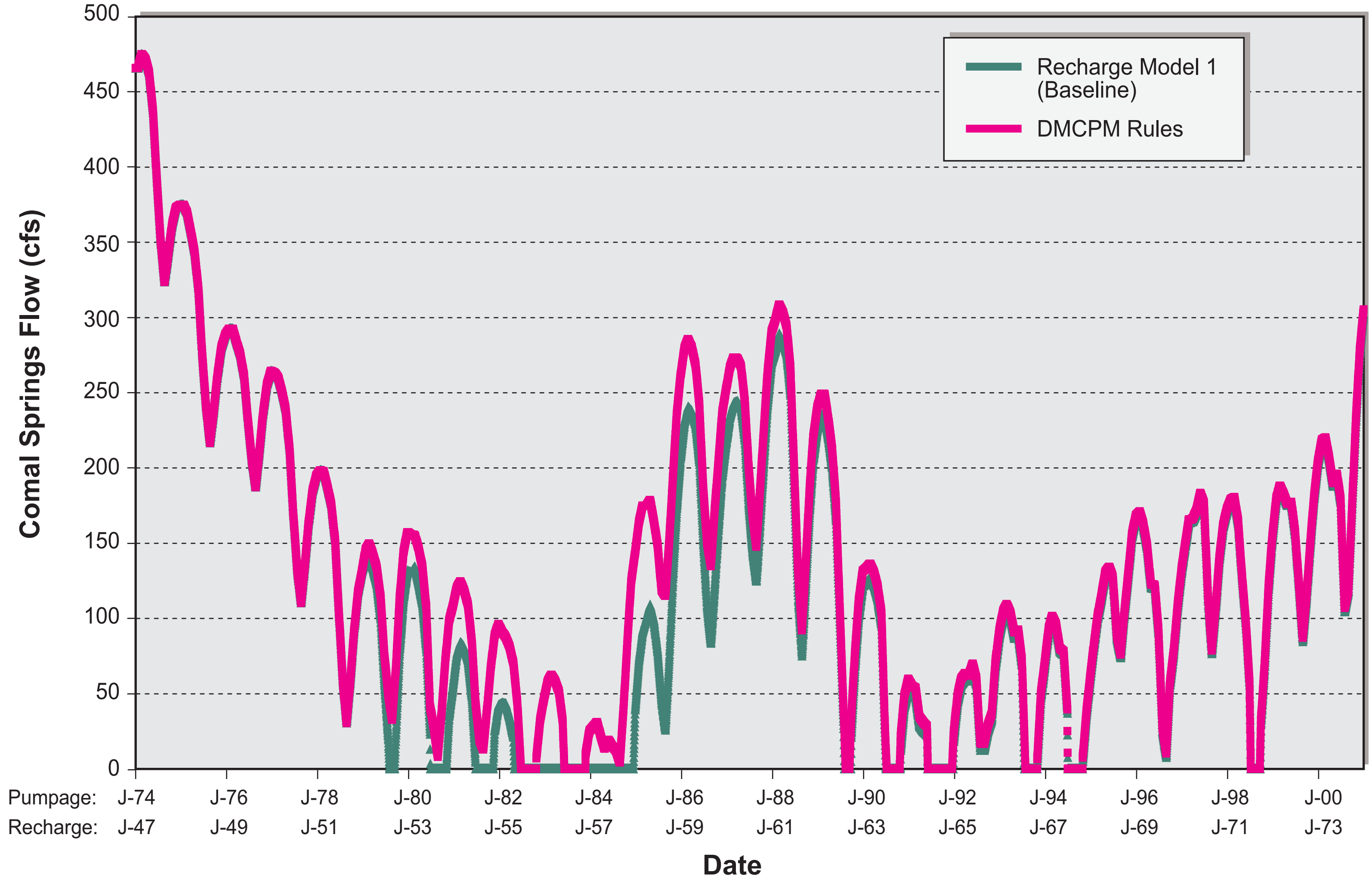


May 2005	**Figure 19** **Impacts on Comal Springs From Focused Recharge**
TODD ENGINEERS Emeryville, California	



Water pumped from Edwards Aquifer and recharged into San Geronimo

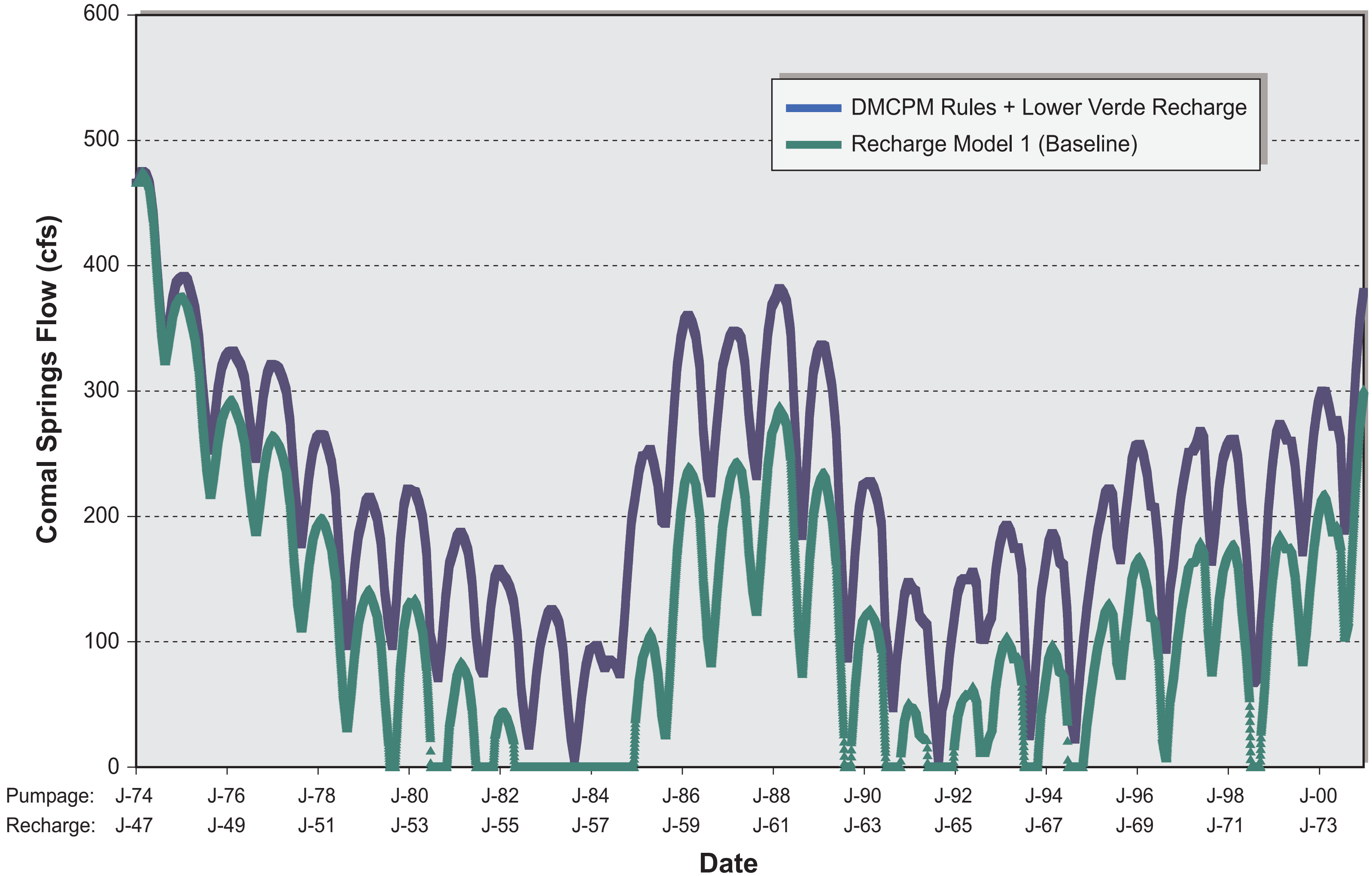
May 2005	Figure 20 Comal Springs Flow Recirculation of Groundwater to San Geronimo
TODD ENGINEERS Emeryville, California	



May 2005

TODD ENGINEERS
Emeryville, California

Figure 21
DMCPM Rules on Comal Springs



May 2005	**Figure 22** **DMCPM Rules and Focused Recharge**
TODD ENGINEERS Emeryville, California	

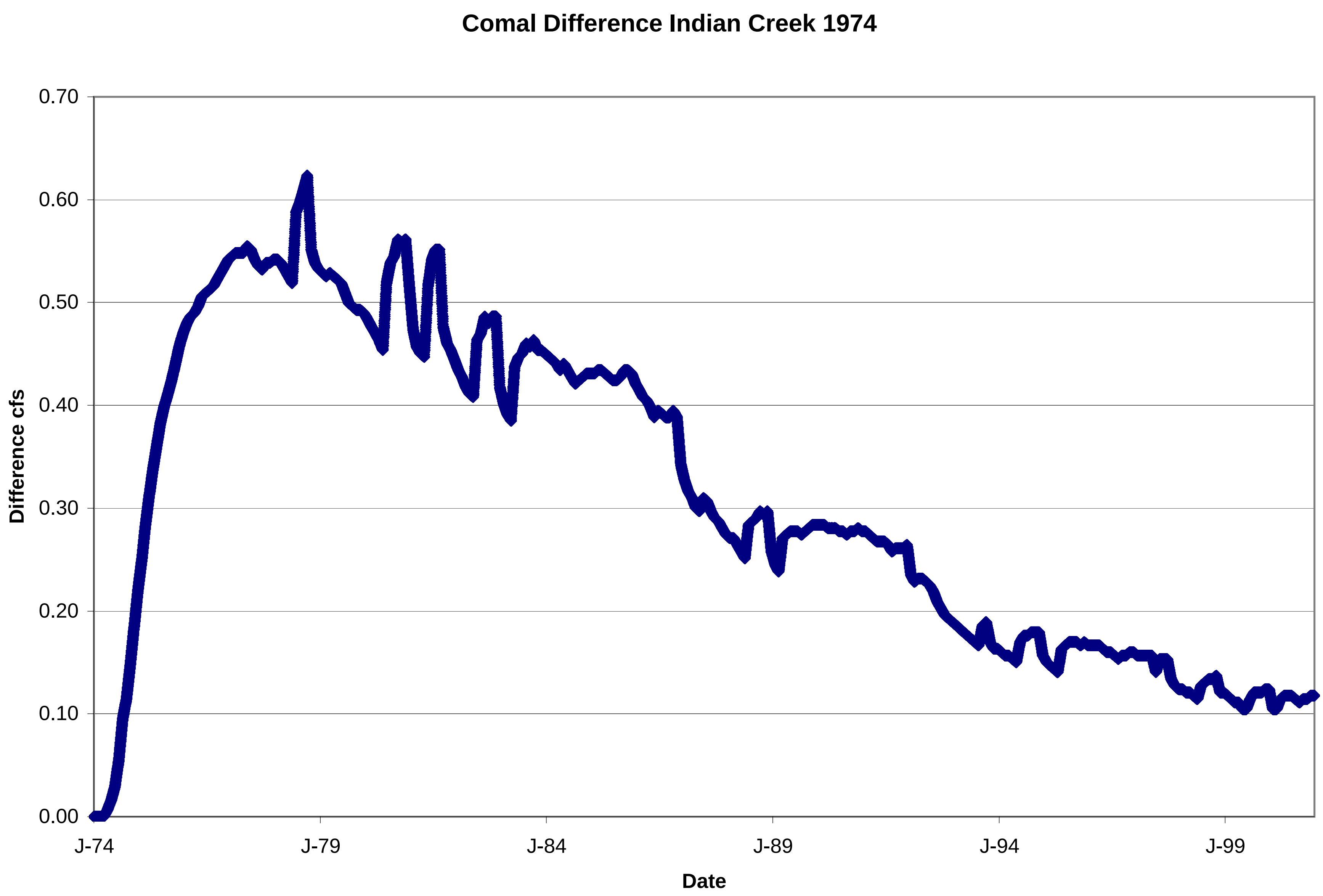
APPENDIX A

Response of Springs and Well J-17 to Enhanced Recharge

Todd Engineers
Analysis of Recharge and Recirculation
Phase 2
5/13/05

Index of Enhanced Recharge Responses

Recharge Scenario	Page Numbers					
	Comal Springs	San Marcos Springs	San Antonio Springs	San Pedro Springs	Leona Springs	Well J-17
Indian Creek						
Recharge 25,000 AFY 1974	A-1	A-25	A-49	A-73	A-97	A-121
Recharge 25,000 AFY 1974-1978	A-2	A-26	A-50	A-74	A-98	A-122
Recharge 25,000 AFY 1974-2000	A-3	A-27	A-51	A-75	A-99	A-123
Lower Frio						
Recharge 25,000 AFY 1974	A-4	A-28	A-52	A-76	A-100	A-124
Recharge 25,000 AFY 1974-1978	A-5	A-29	A-53	A-77	A-101	A-125
Recharge 25,000 AFY 1974-2000	A-6	A-30	A-54	A-78	A-102	A-126
Lower Sabinal						
Recharge 25,000 AFY 1974	A-7	A-31	A-55	A-79	A-103	A-127
Recharge 25,000 AFY 1974-1978	A-8	A-32	A-56	A-80	A-104	A-128
Recharge 25,000 AFY 1974-2000	A-9	A-33	A-57	A-81	A-105	A-129
Lower Hondo						
Recharge 25,000 AFY 1974	A-10	A-34	A-58	A-82	A-106	A-130
Recharge 25,000 AFY 1974-1978	A-11	A-35	A-59	A-83	A-107	A-131
Recharge 25,000 AFY 1974-2000	A-12	A-36	A-60	A-84	A-108	A-132
Lower Verde						
Recharge 25,000 AFY 1974	A-13	A-37	A-61	A-85	A-109	A-133
Recharge 25,000 AFY 1974-1978	A-14	A-38	A-62	A-86	A-110	A-134
Recharge 25,000 AFY 1974-2000	A-15	A-39	A-63	A-87	A-111	A-135
San Geronimo						
Recharge 25,000 AFY 1974	A-16	A-40	A-64	A-88	A-112	A-136
Recharge 25,000 AFY 1974-1978	A-17	A-41	A-65	A-89	A-113	A-137
Recharge 25,000 AFY 1974-2000	A-18	A-42	A-66	A-90	A-114	A-138
Cibolo						
Recharge 25,000 AFY 1974	A-19	A-43	A-67	A-91	A-115	A-139
Recharge 25,000 AFY 1974-1978	A-20	A-44	A-68	A-92	A-116	A-140
Recharge 25,000 AFY 1974-2000	A-21	A-45	A-69	A-93	A-117	A-141
Lower Blanco						
Recharge 25,000 AFY 1974	A-22	A-46	A-70	A-94	A-118	A-142
Recharge 25,000 AFY 1974-1978	A-23	A-47	A-71	A-95	A-119	A-143
Recharge 25,000 AFY 1974-2000	A-24	A-48	A-72	A-96	A-120	A-144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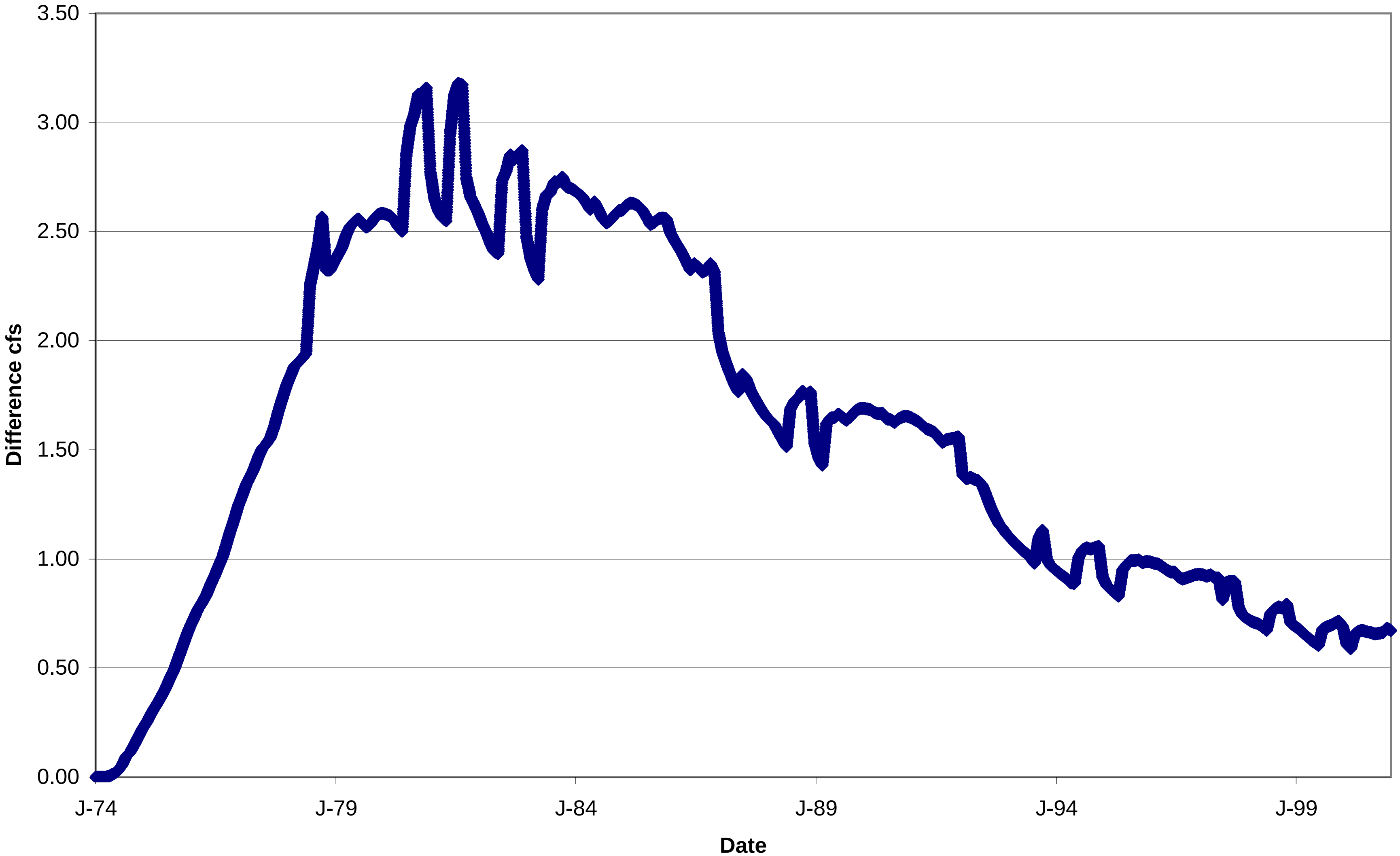
0.30
0.20
0.10
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

Comal Difference Indian Creek 1974-1978



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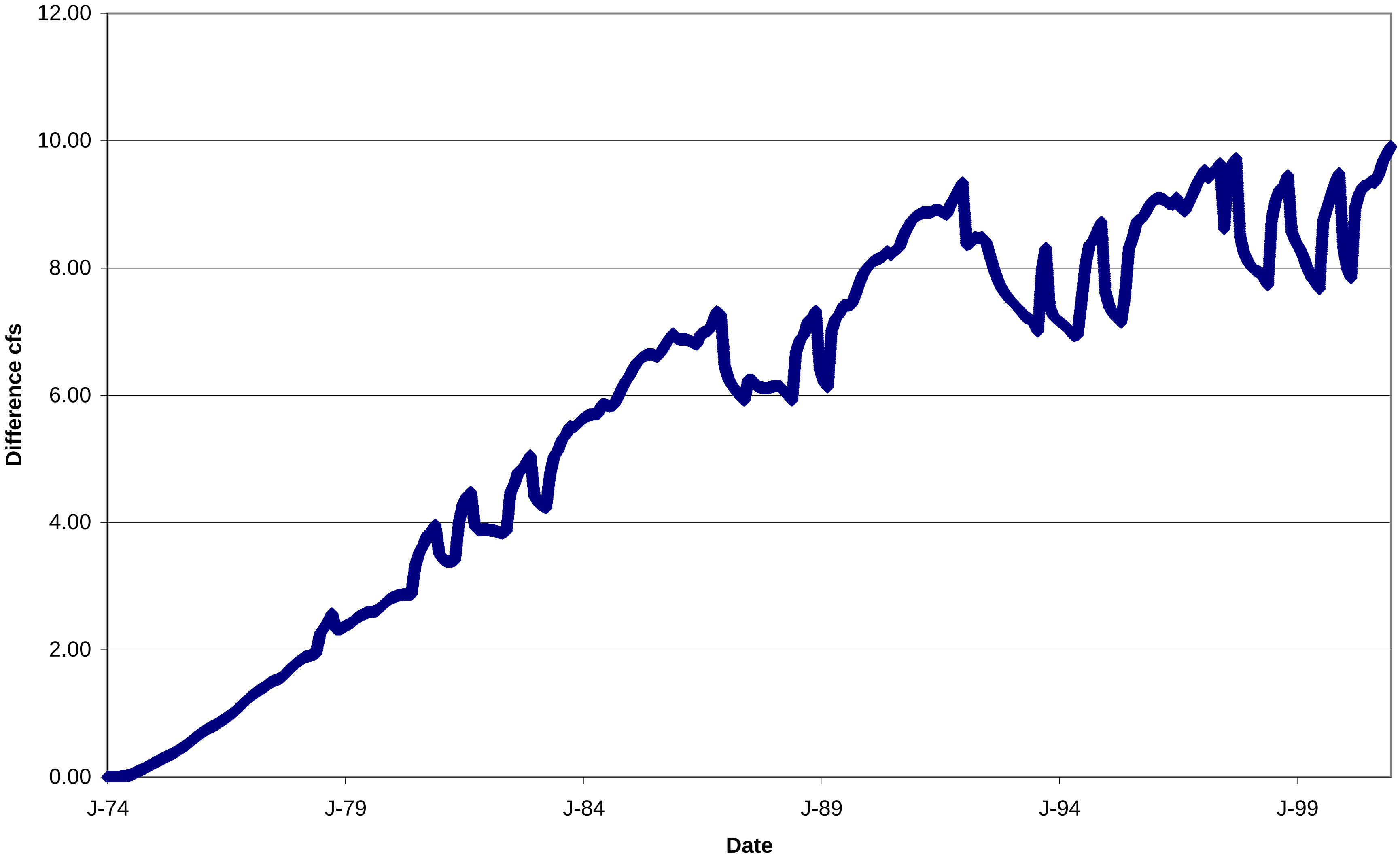

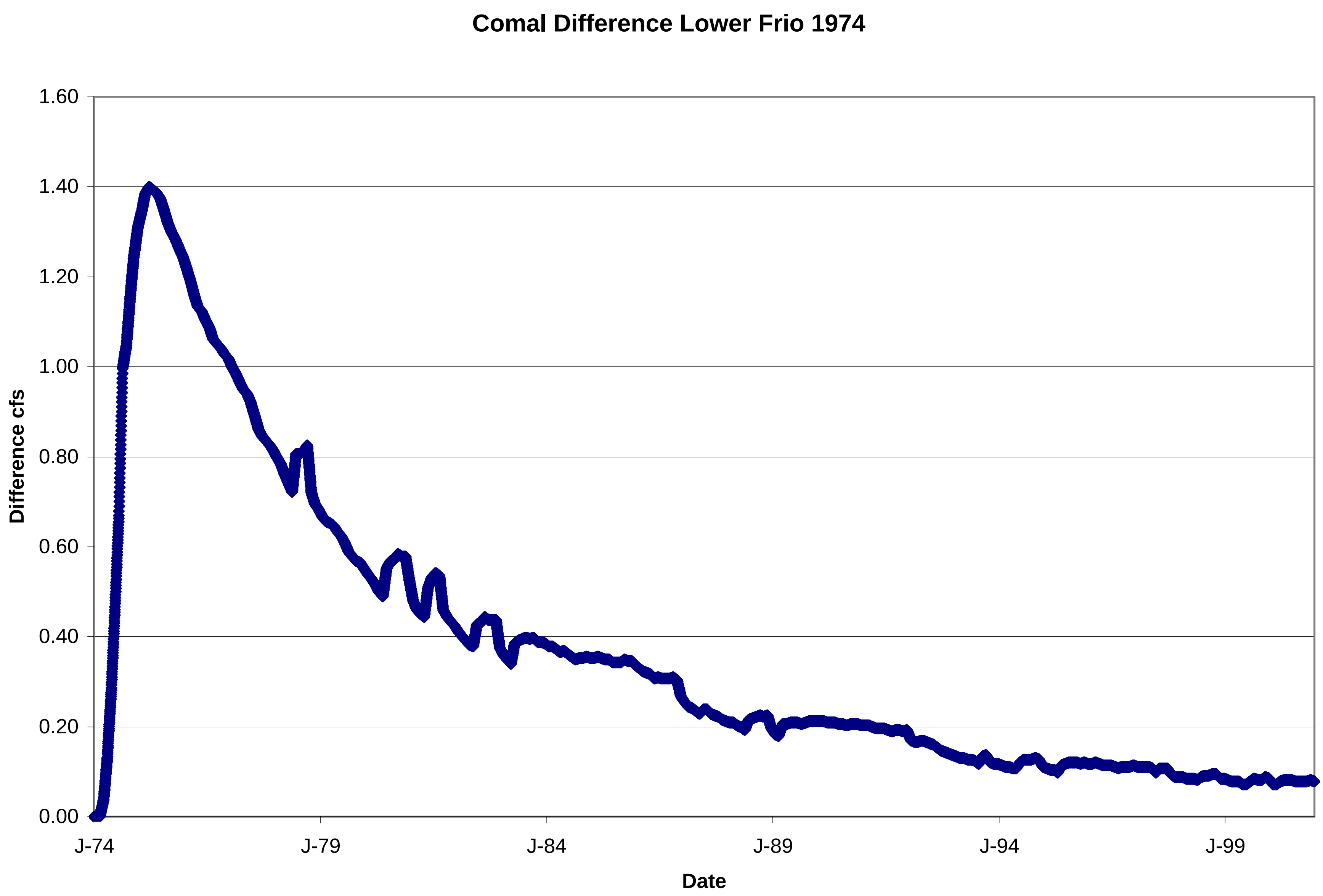
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Difference cfs
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0.60
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0.00
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J-79
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J-89
J-94
J-99
Date

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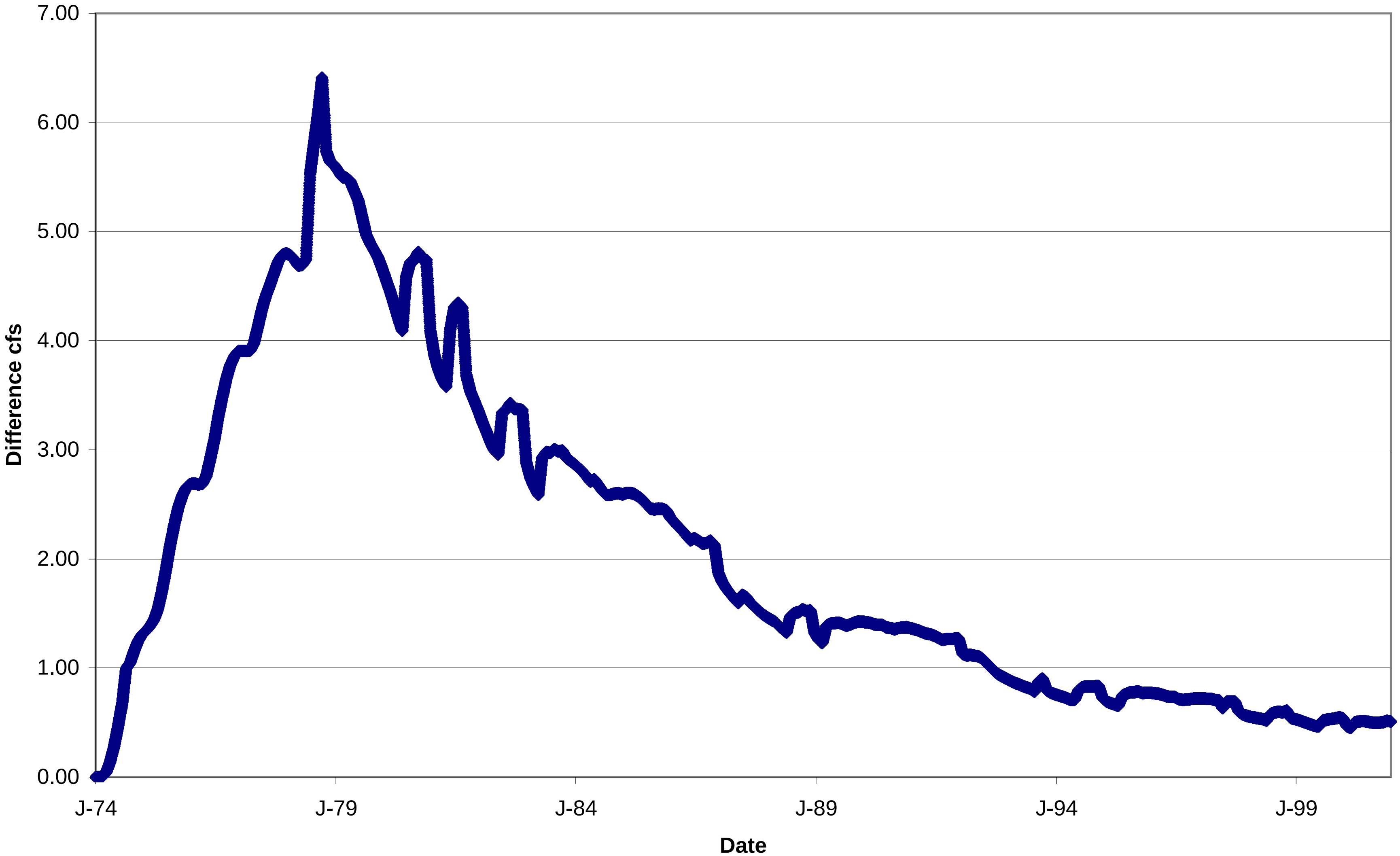

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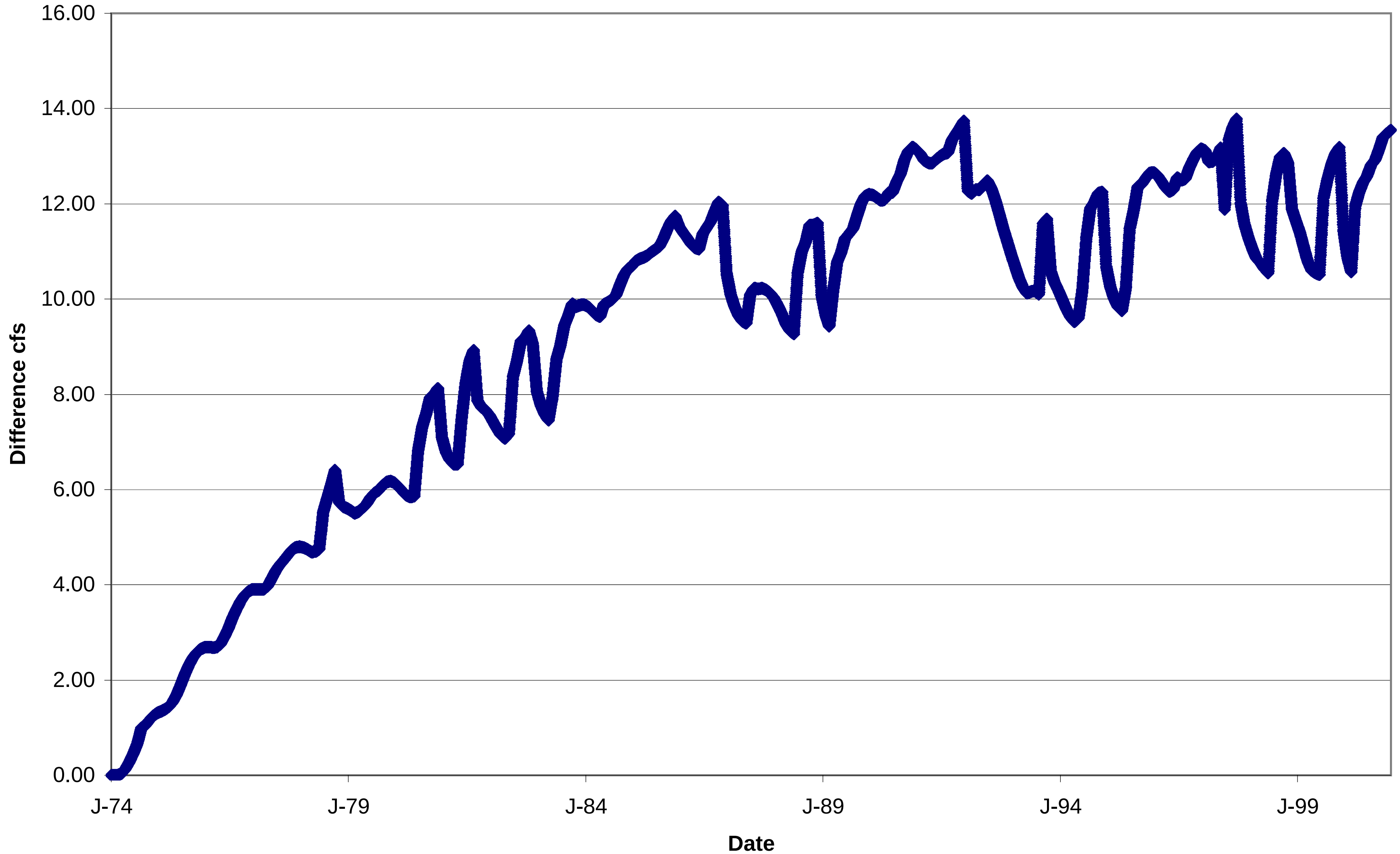

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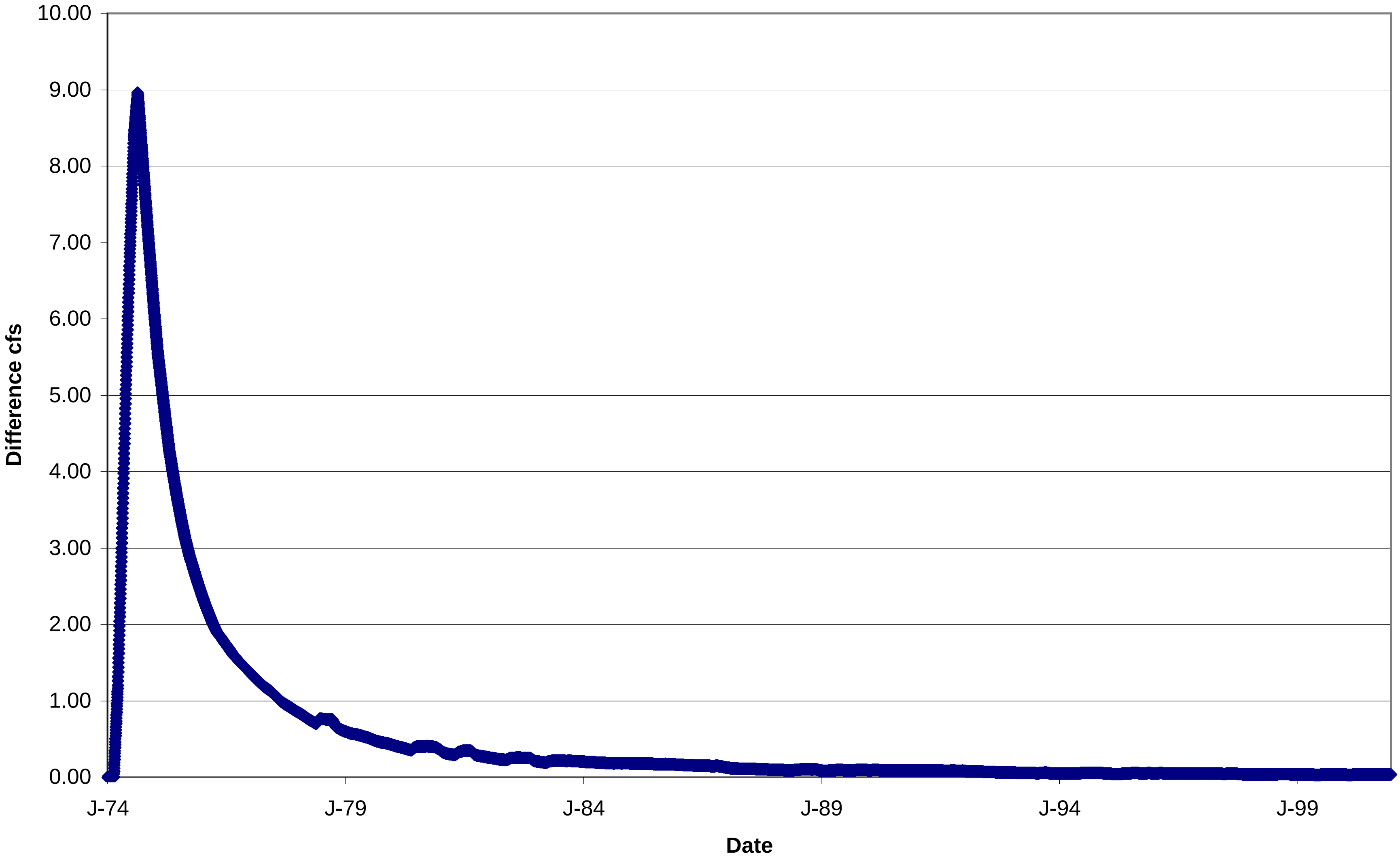

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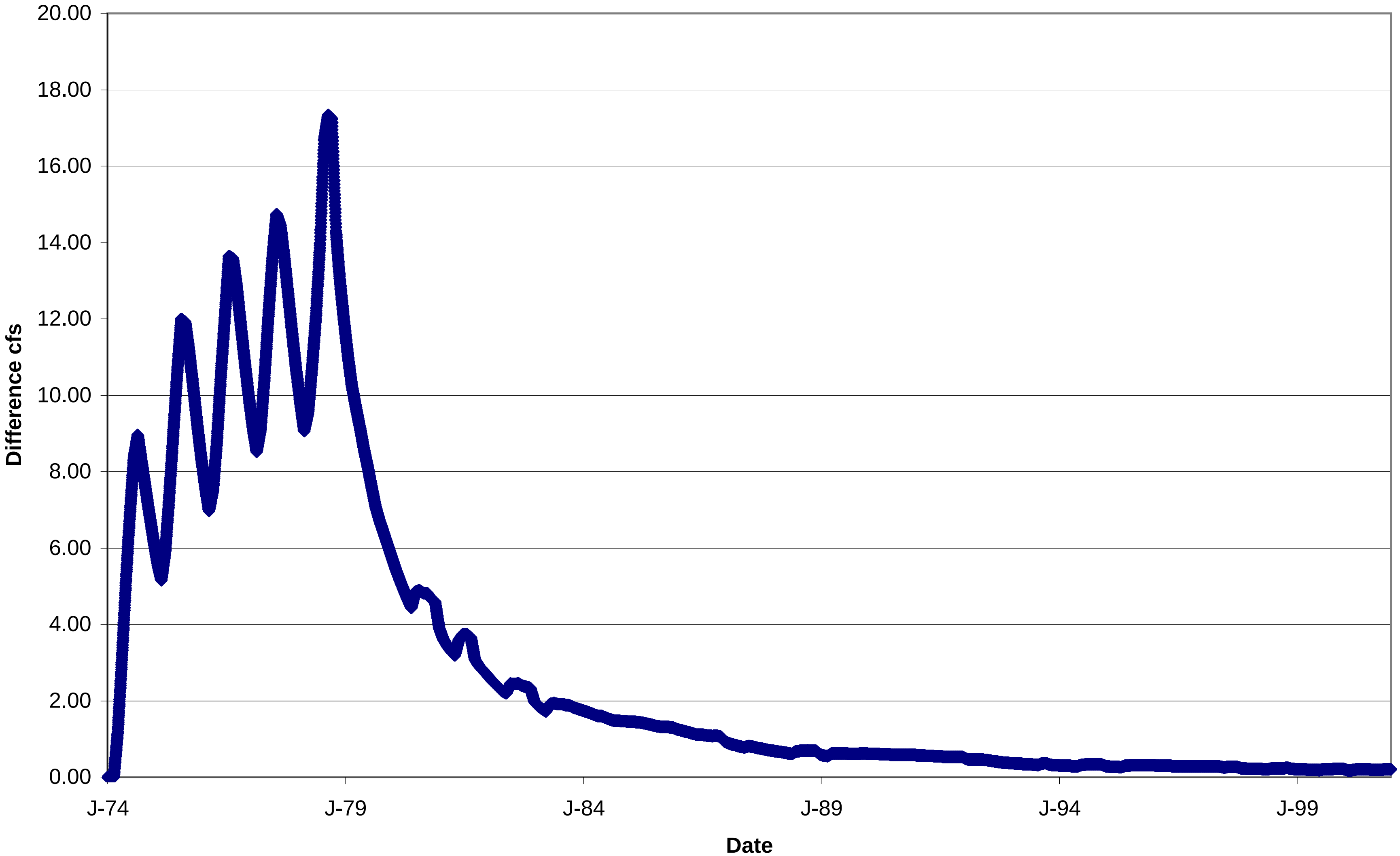

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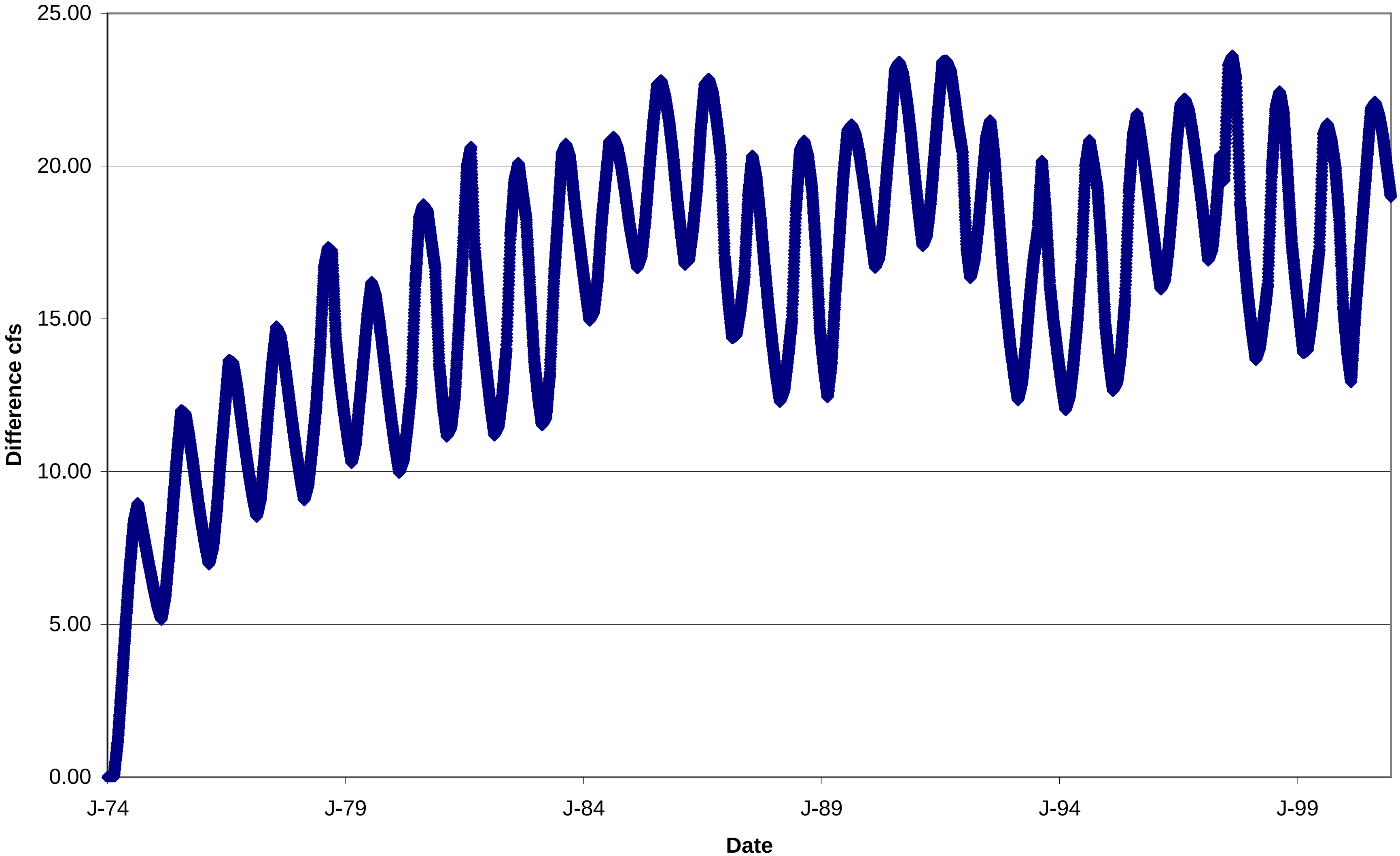

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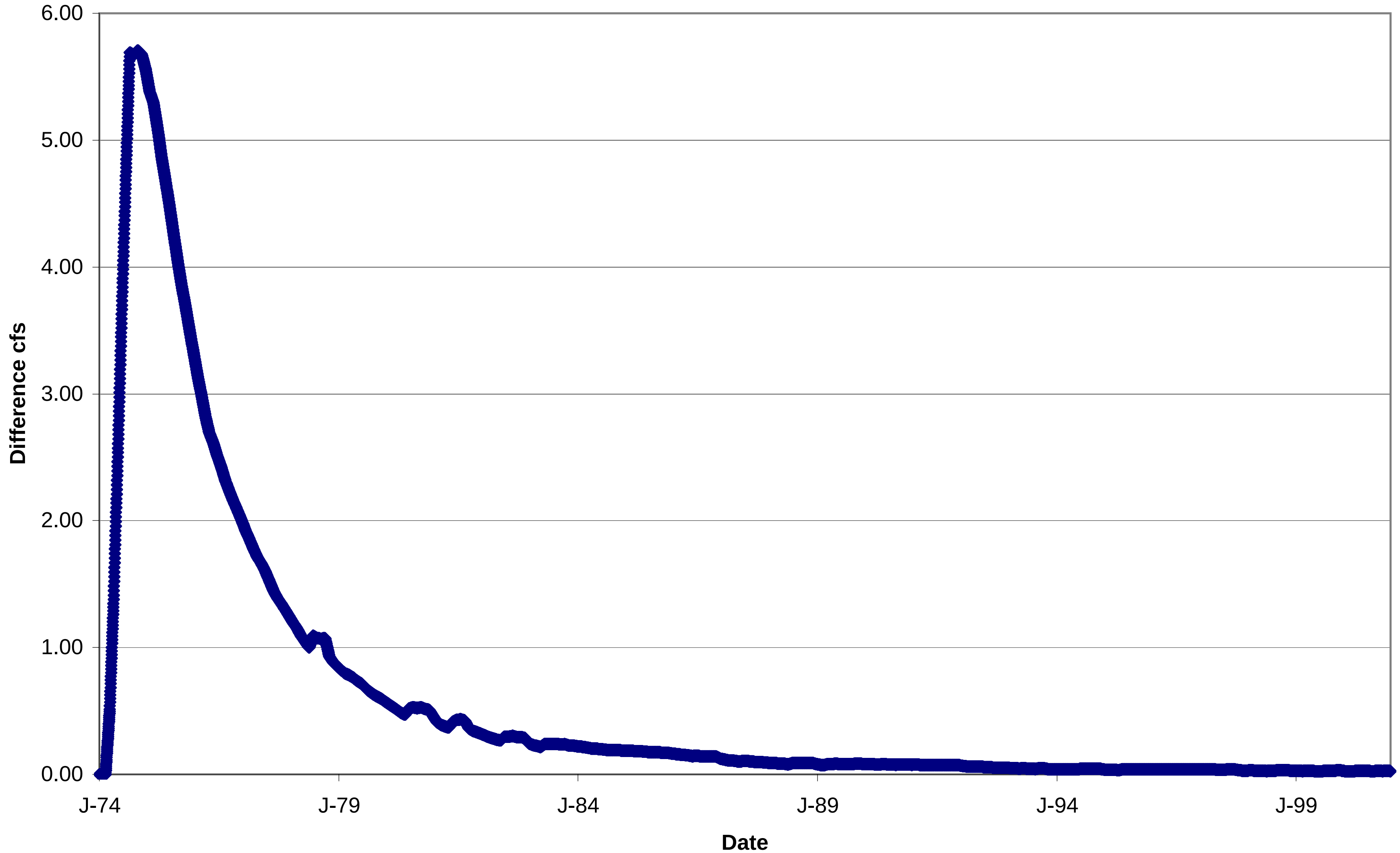

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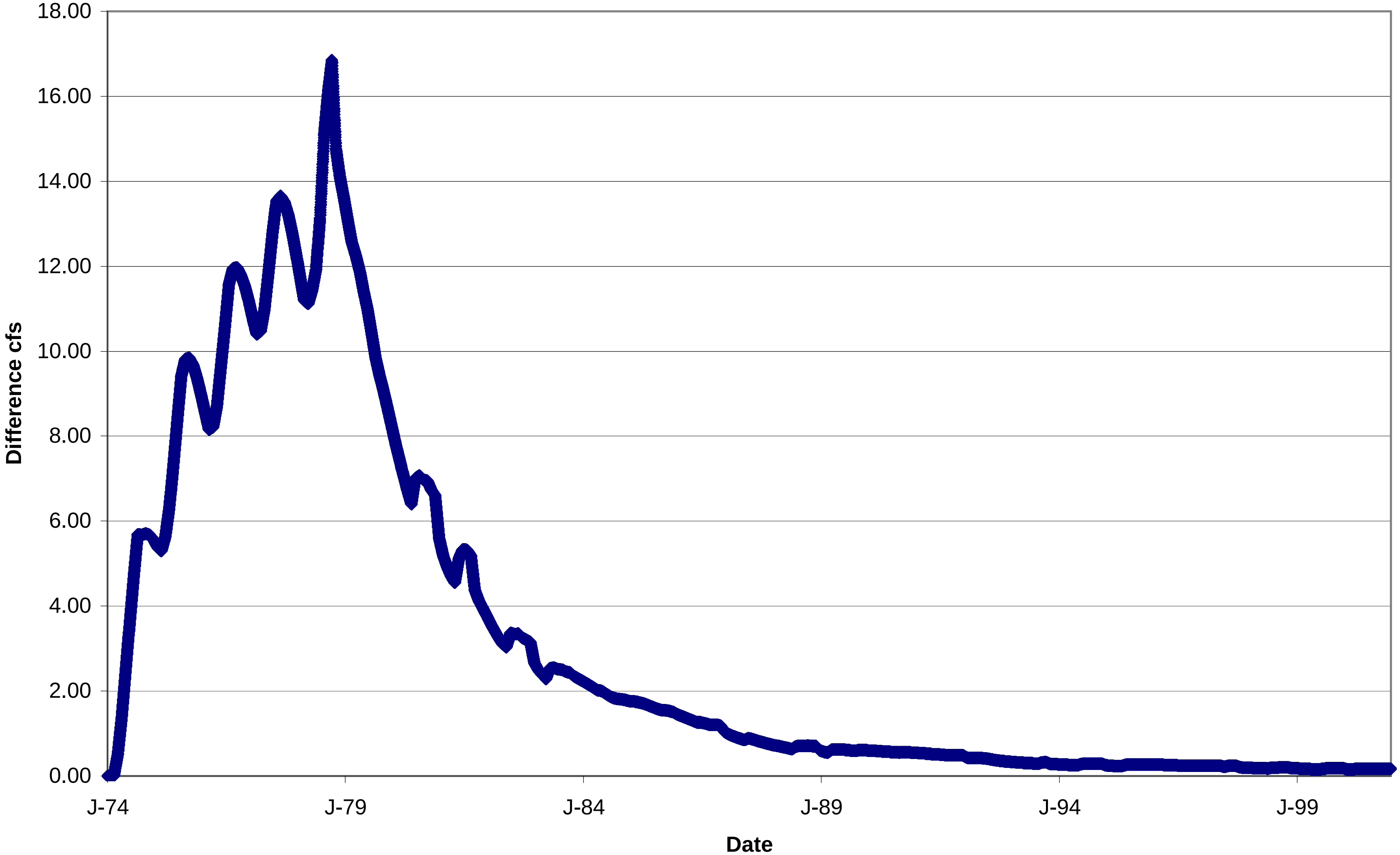

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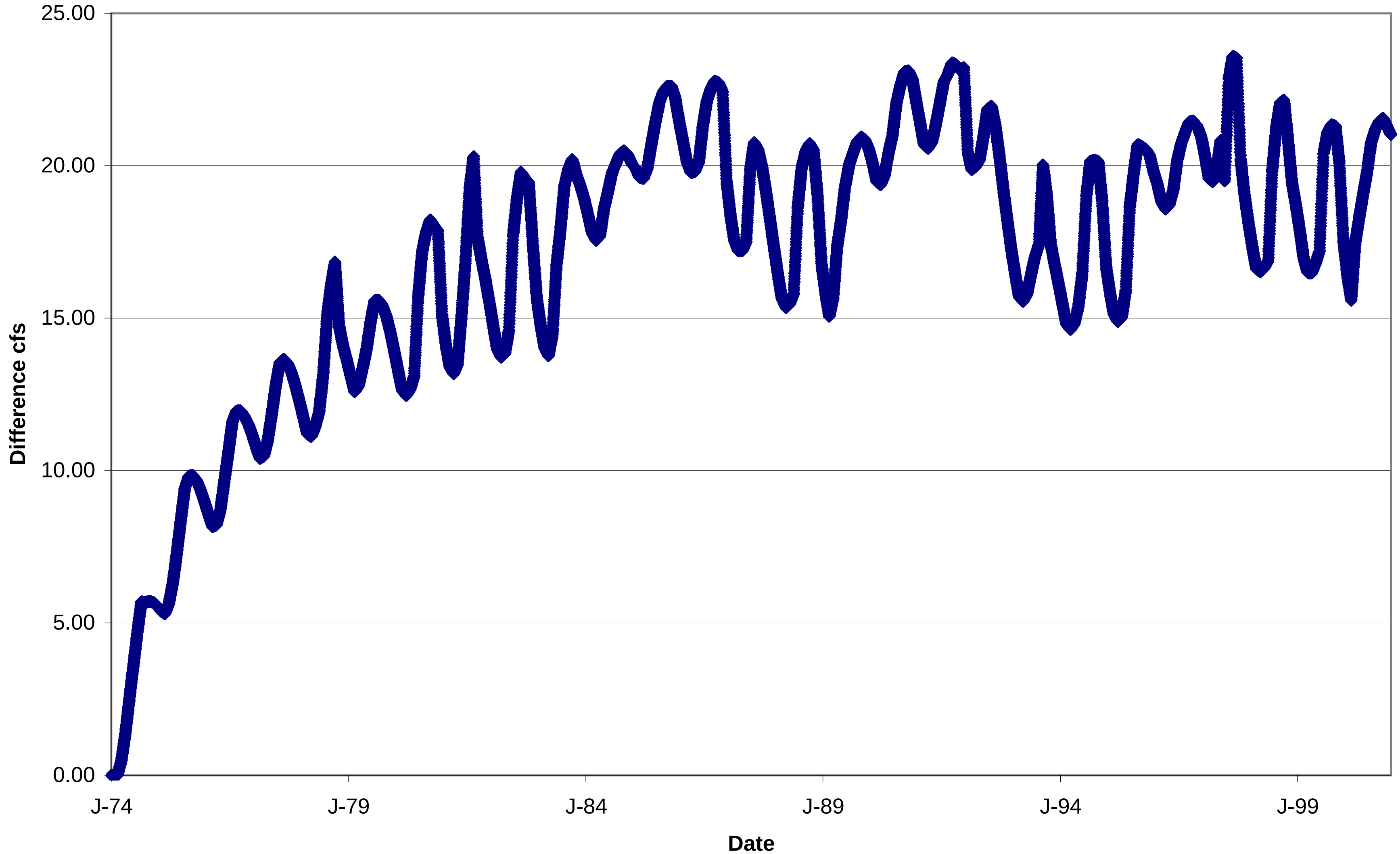

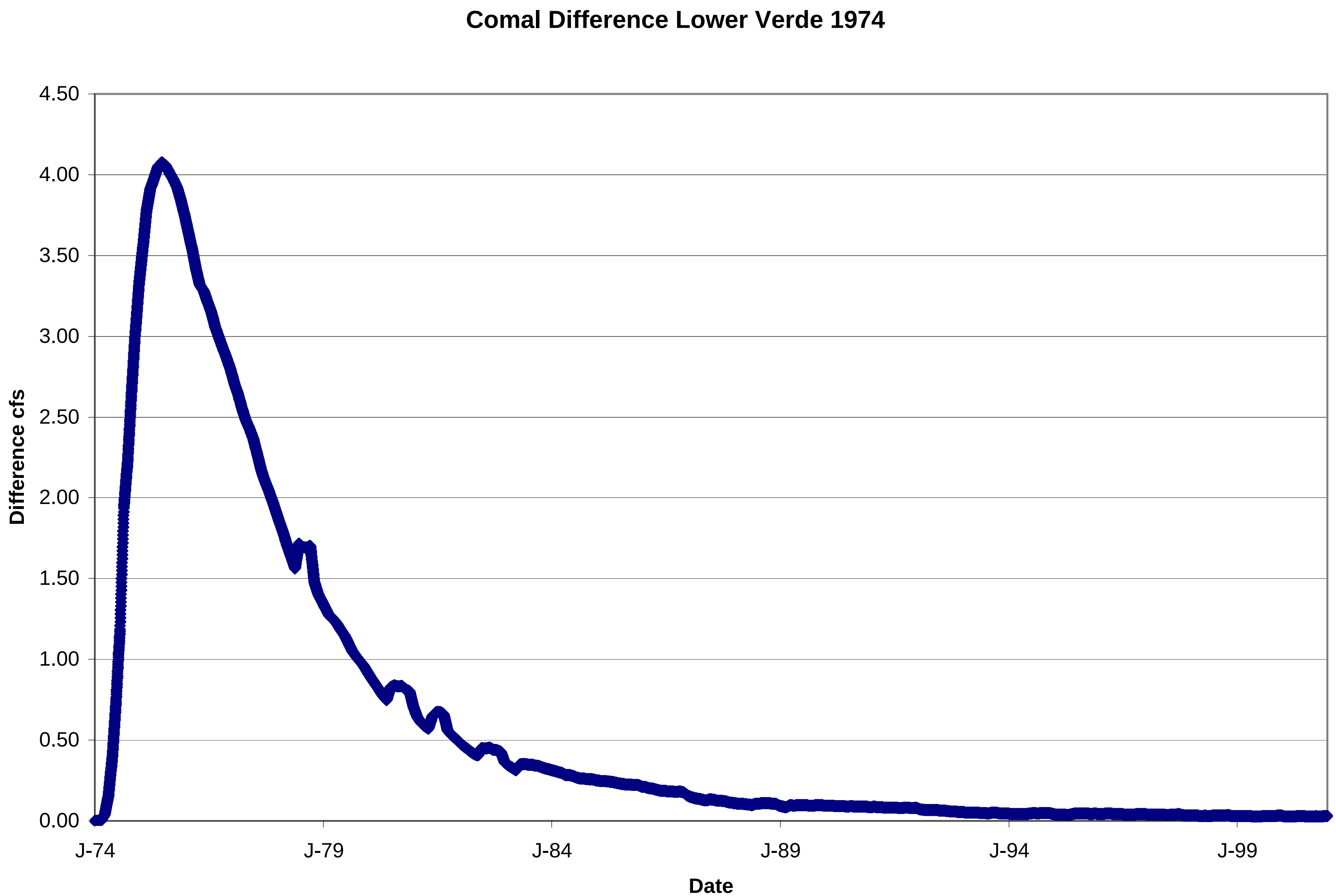
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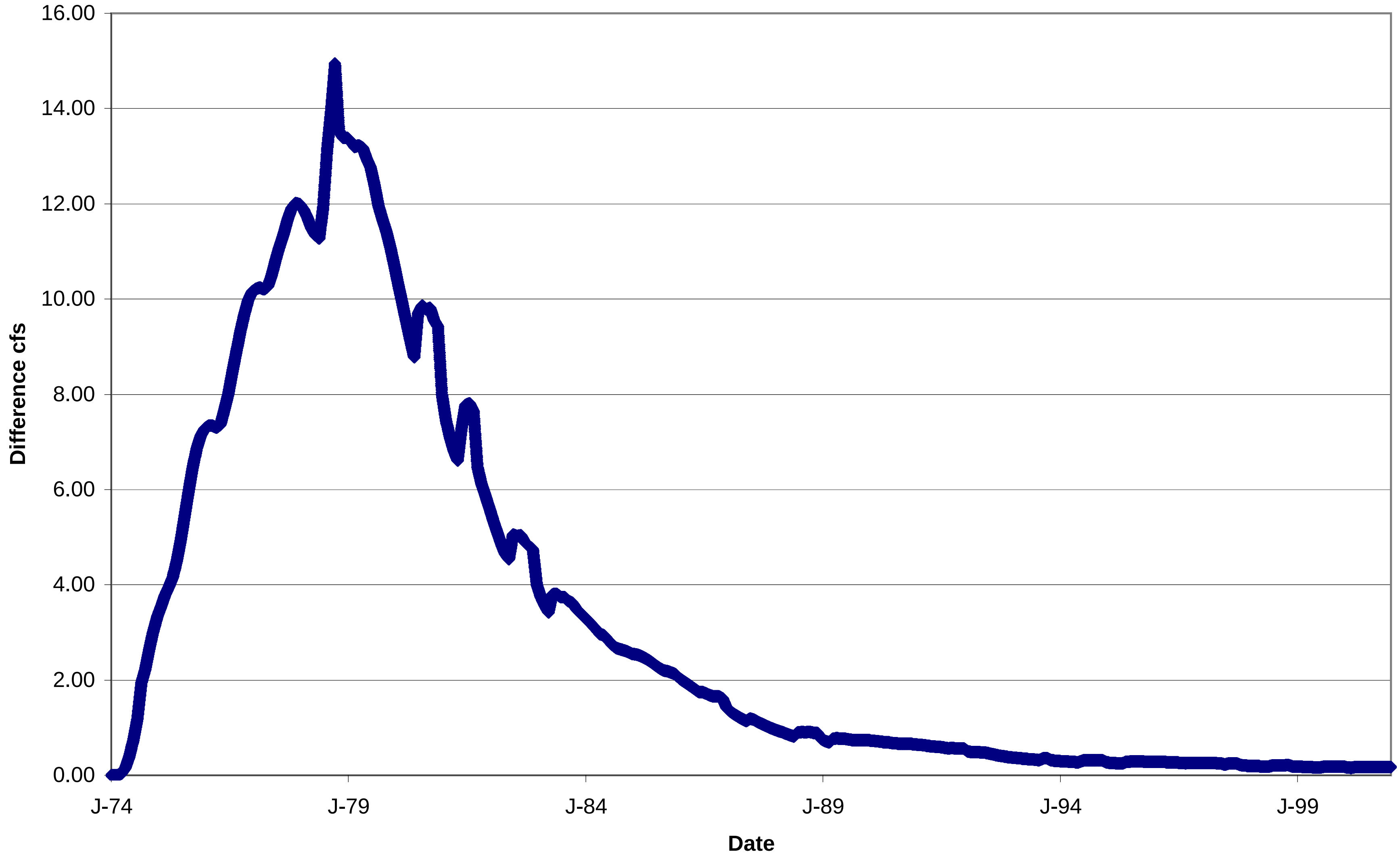
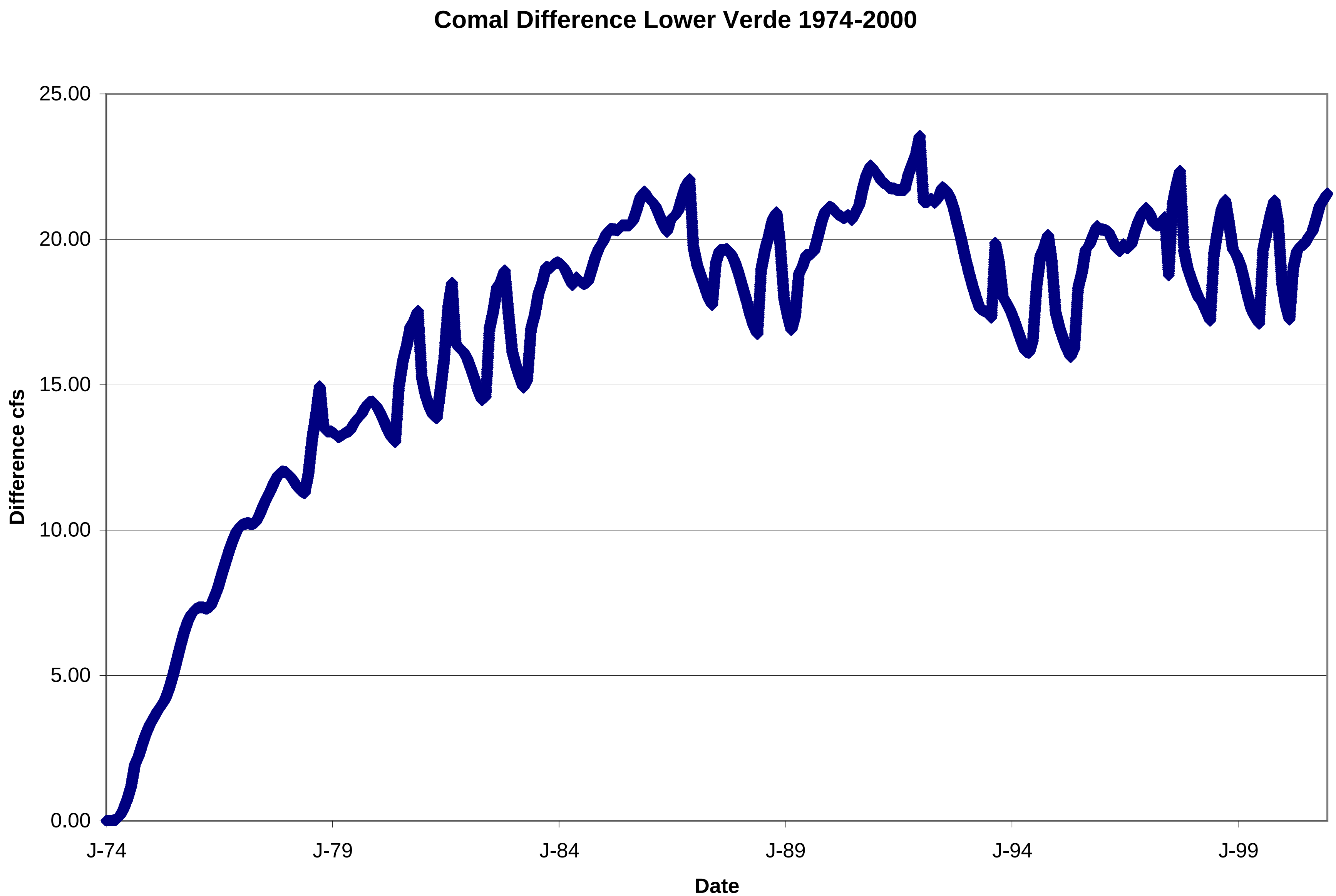
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

Comal Difference Lower Verde 1974-1978

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J-94
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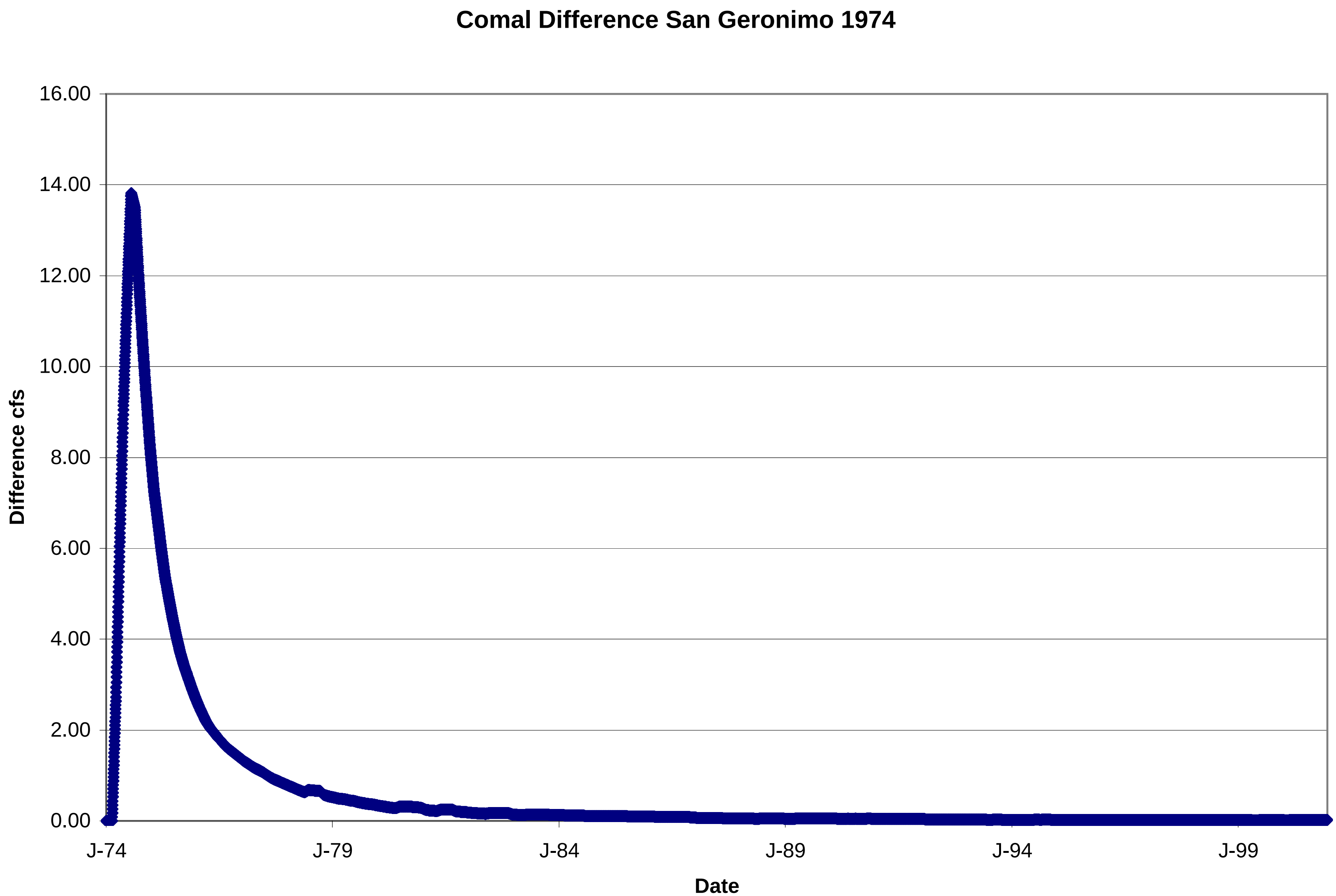
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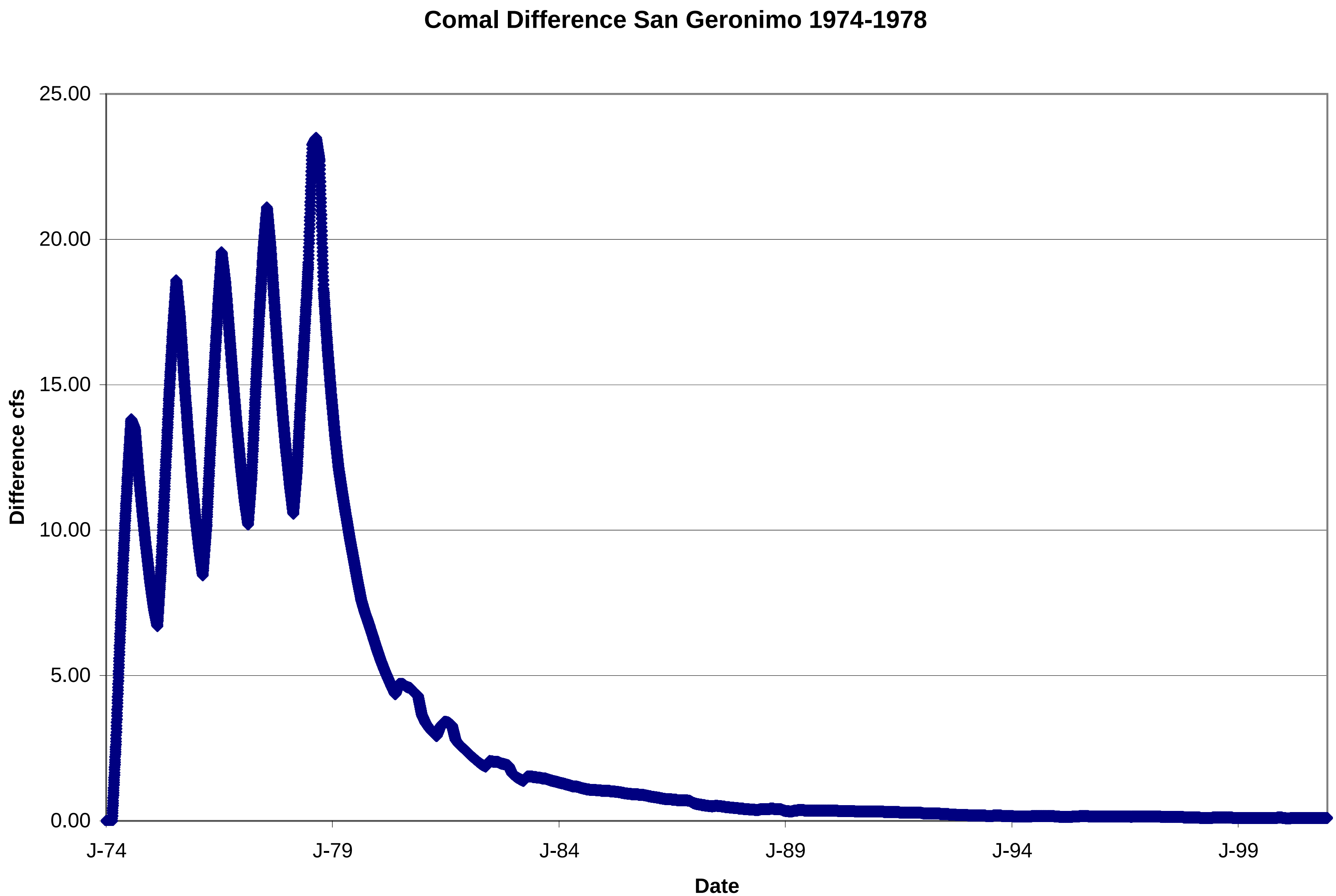
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J-84
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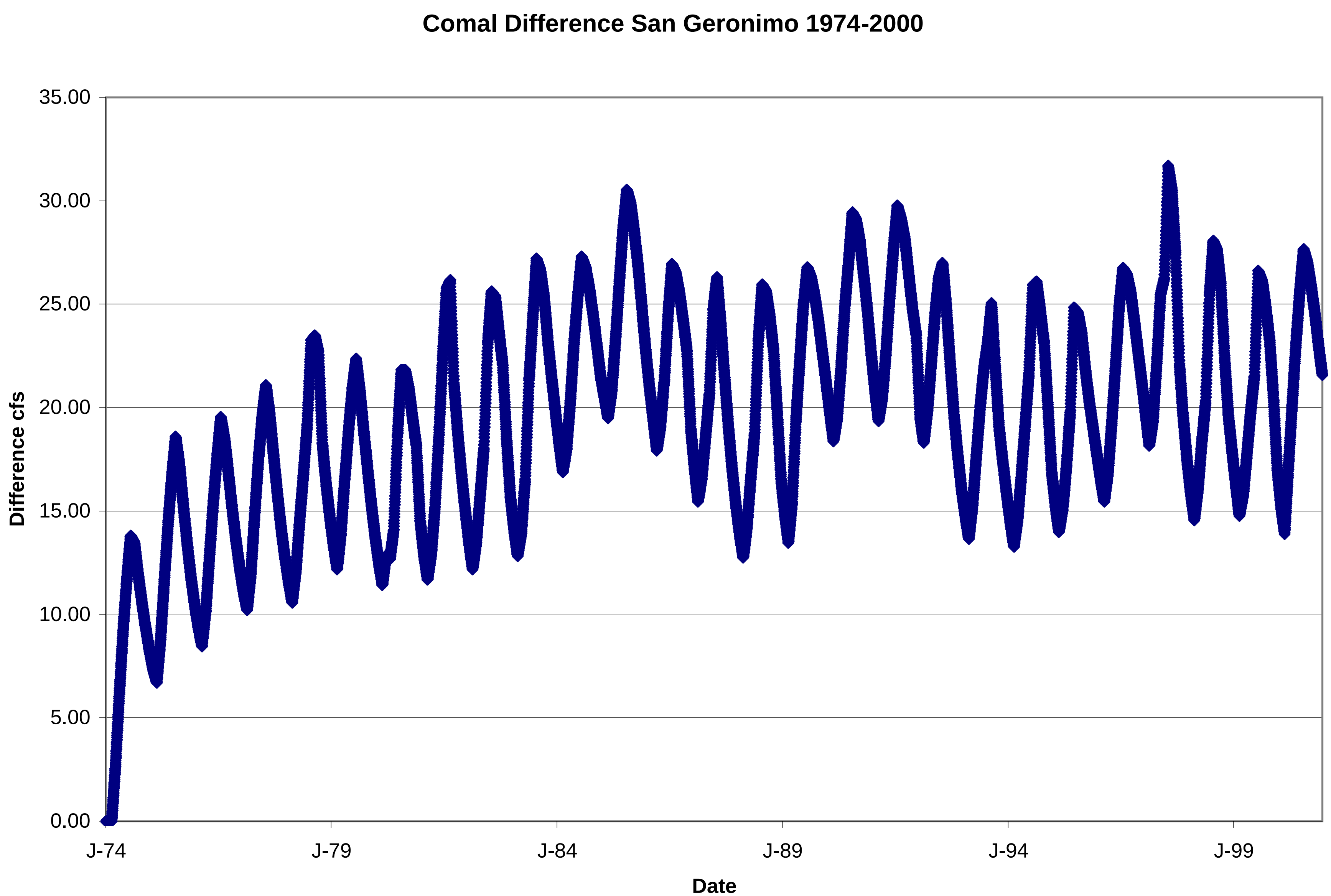
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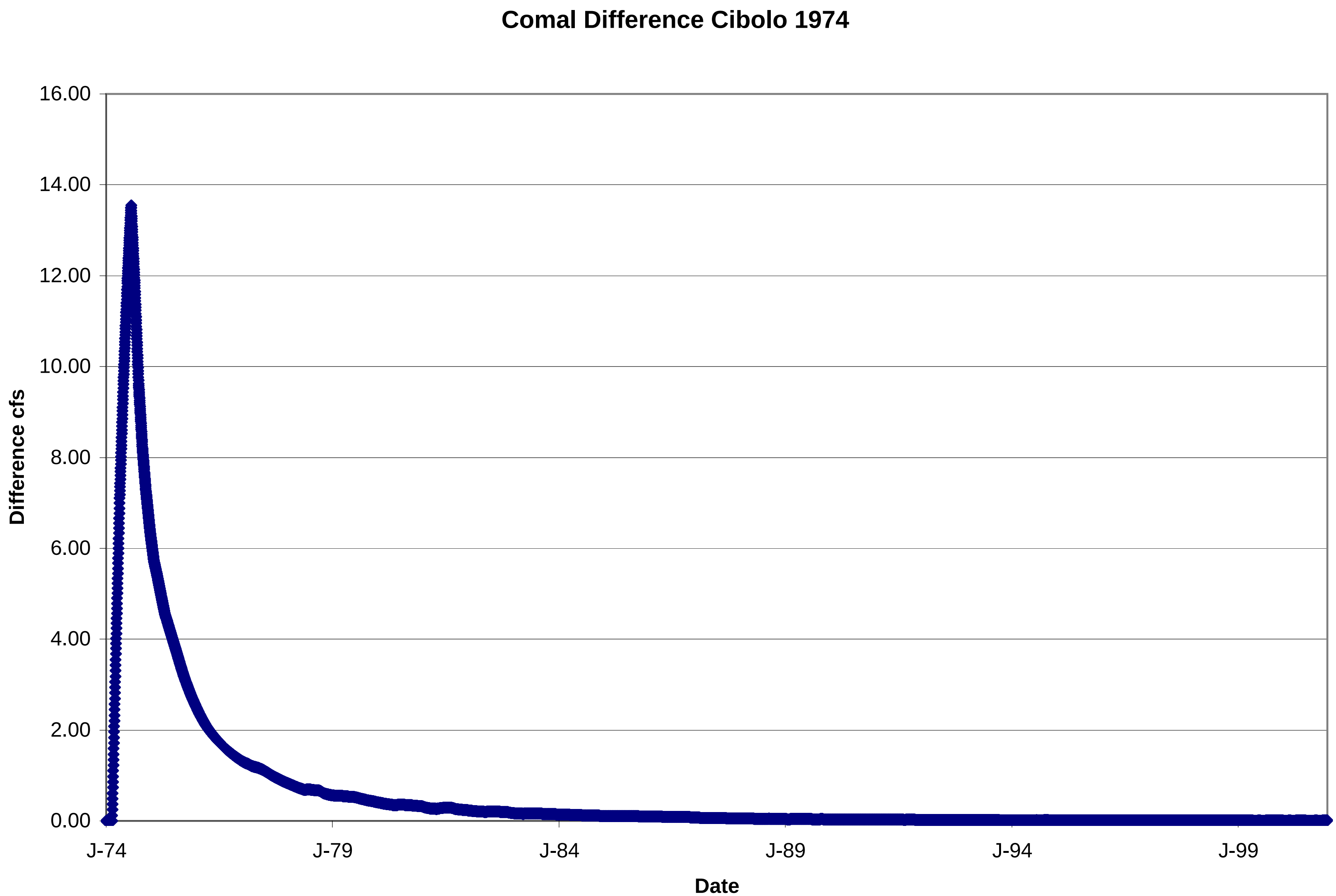
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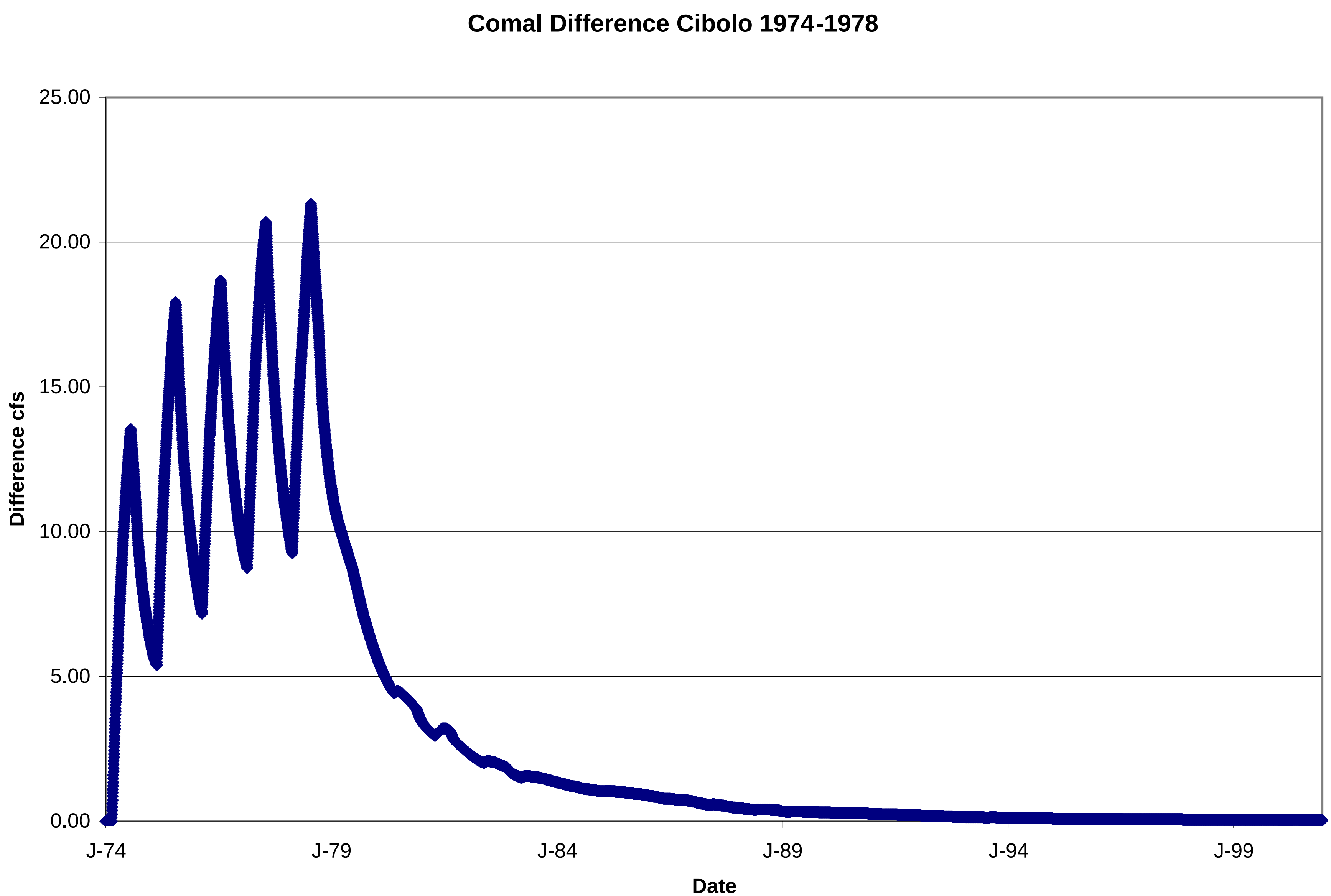

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J-99
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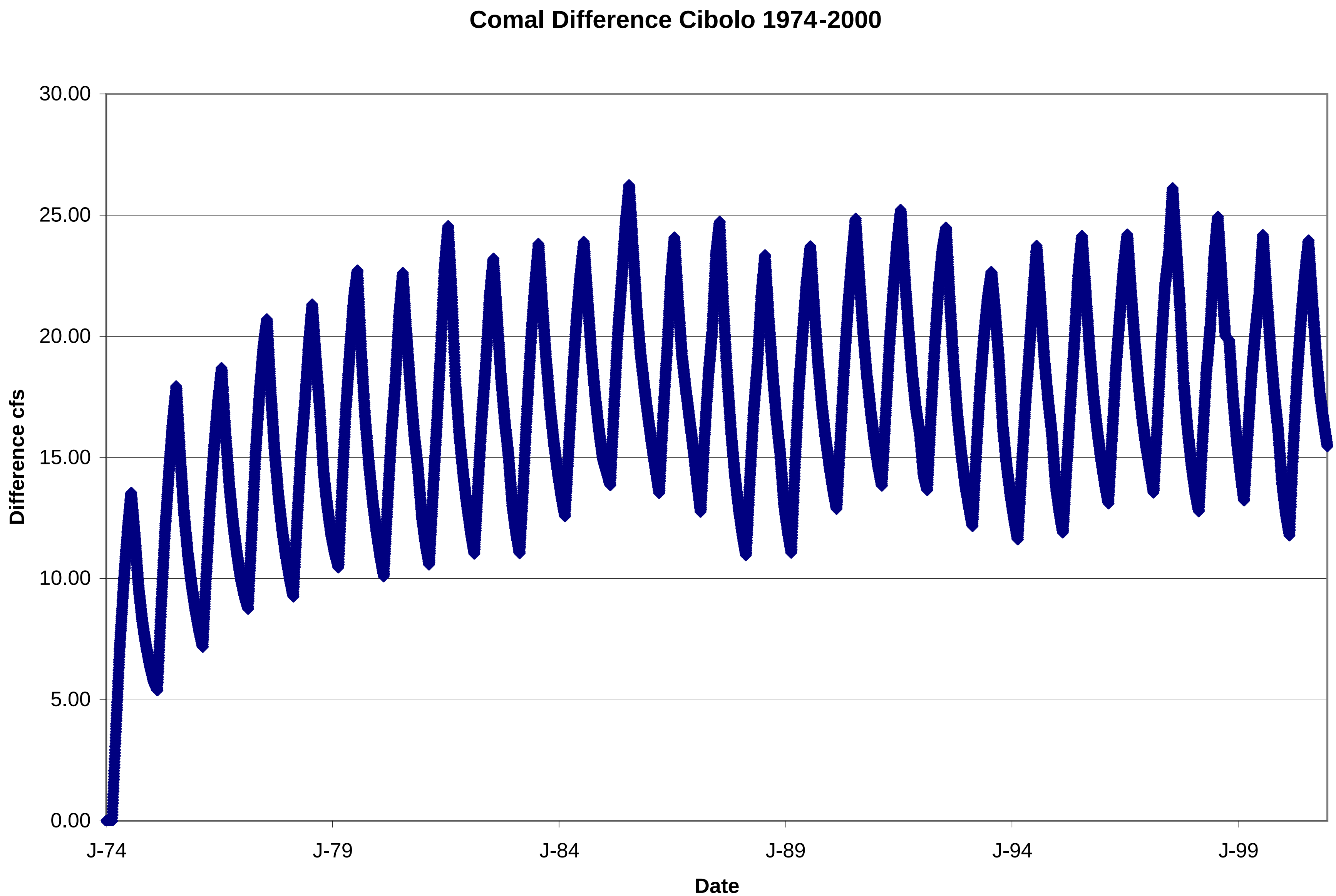
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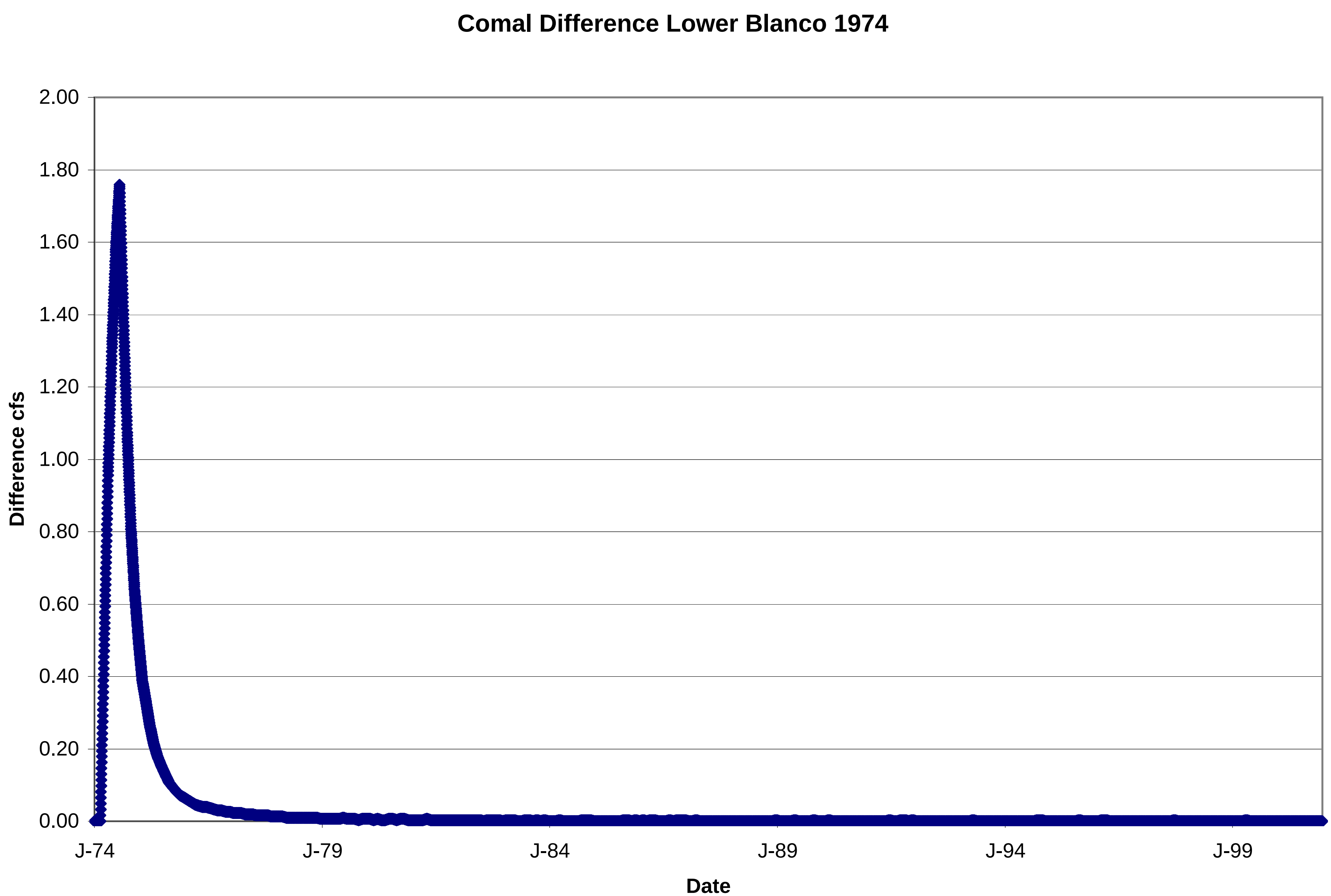
Date



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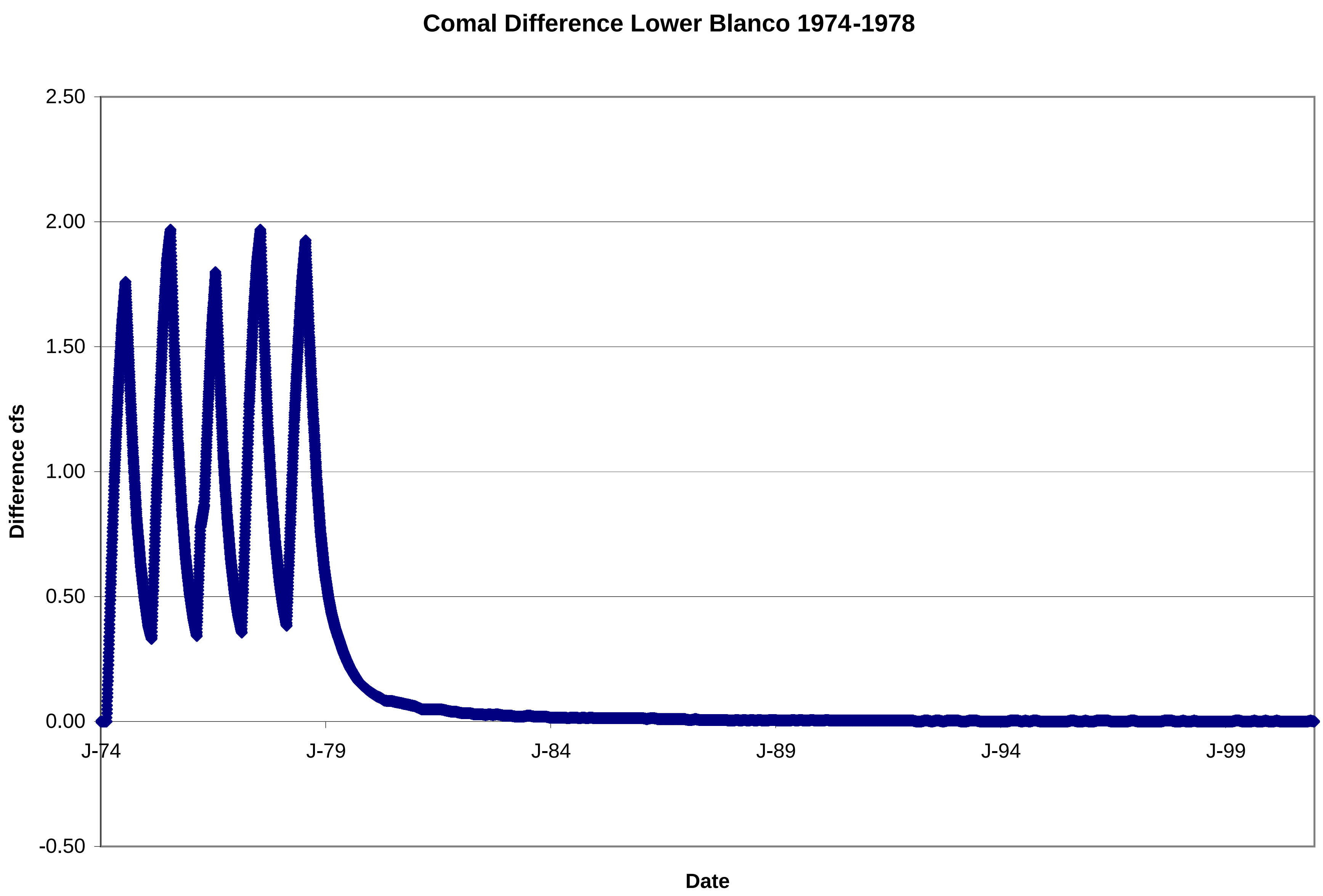
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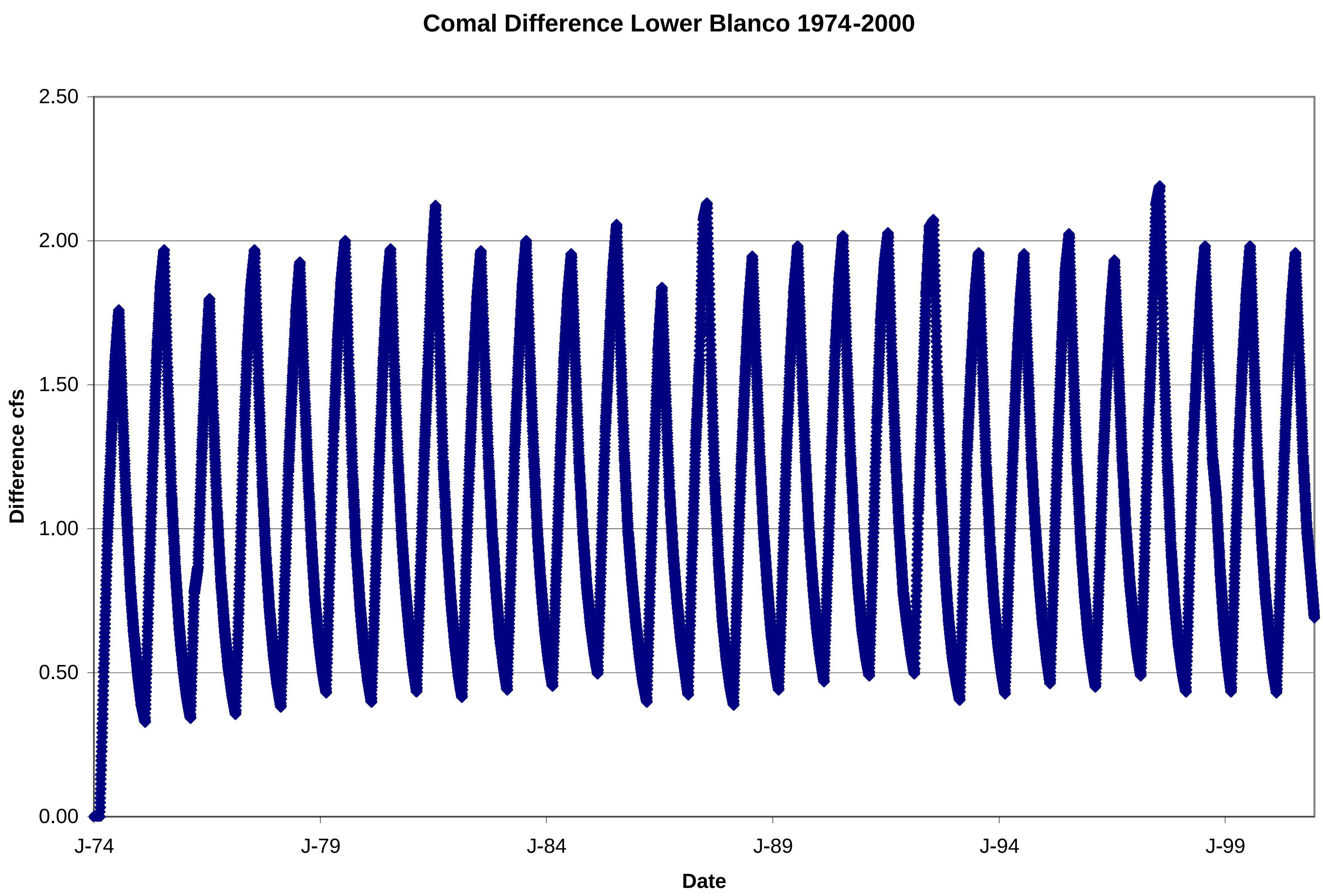
J-89
J-94
J-99
Date



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Difference cfs
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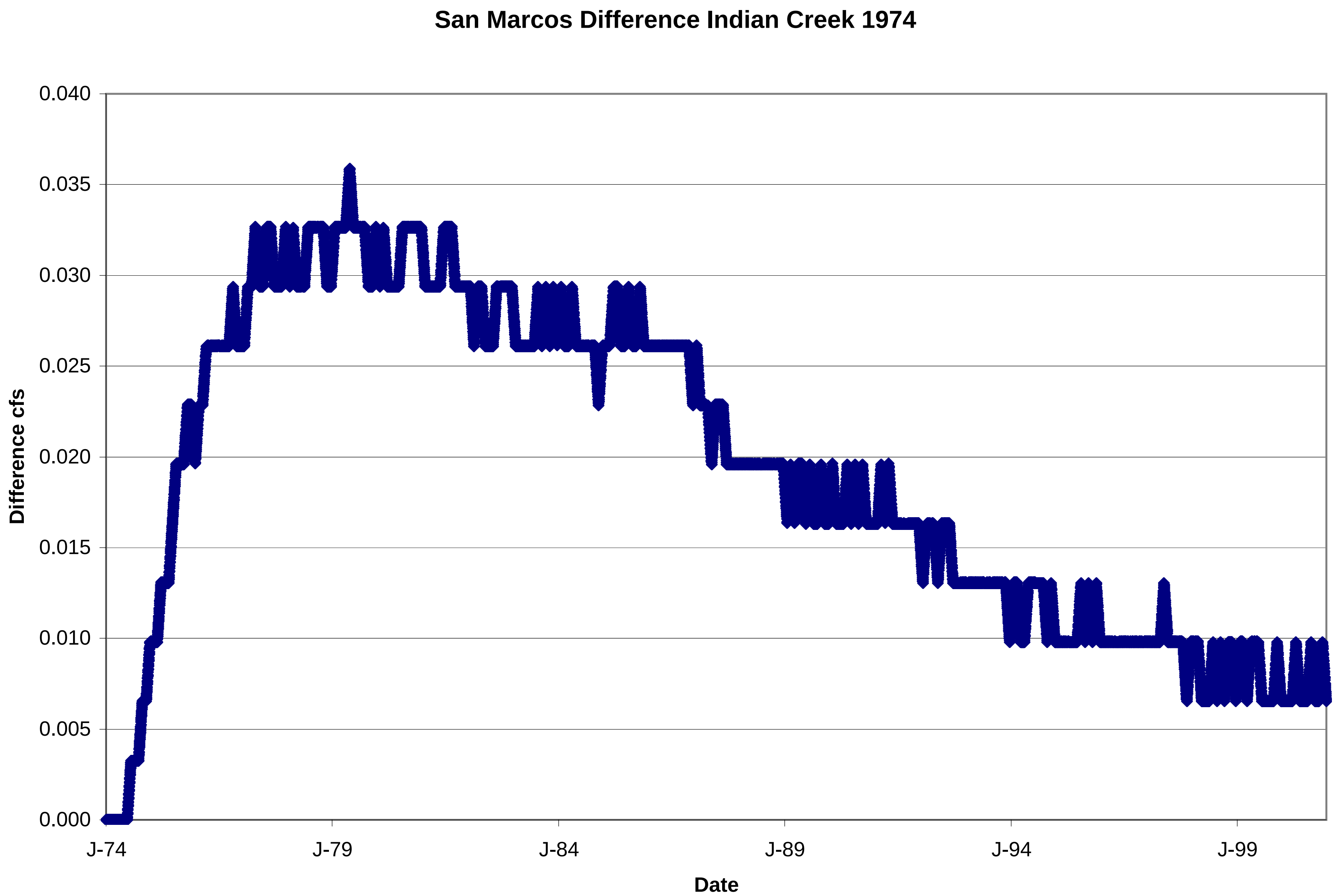
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J-79
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J-99
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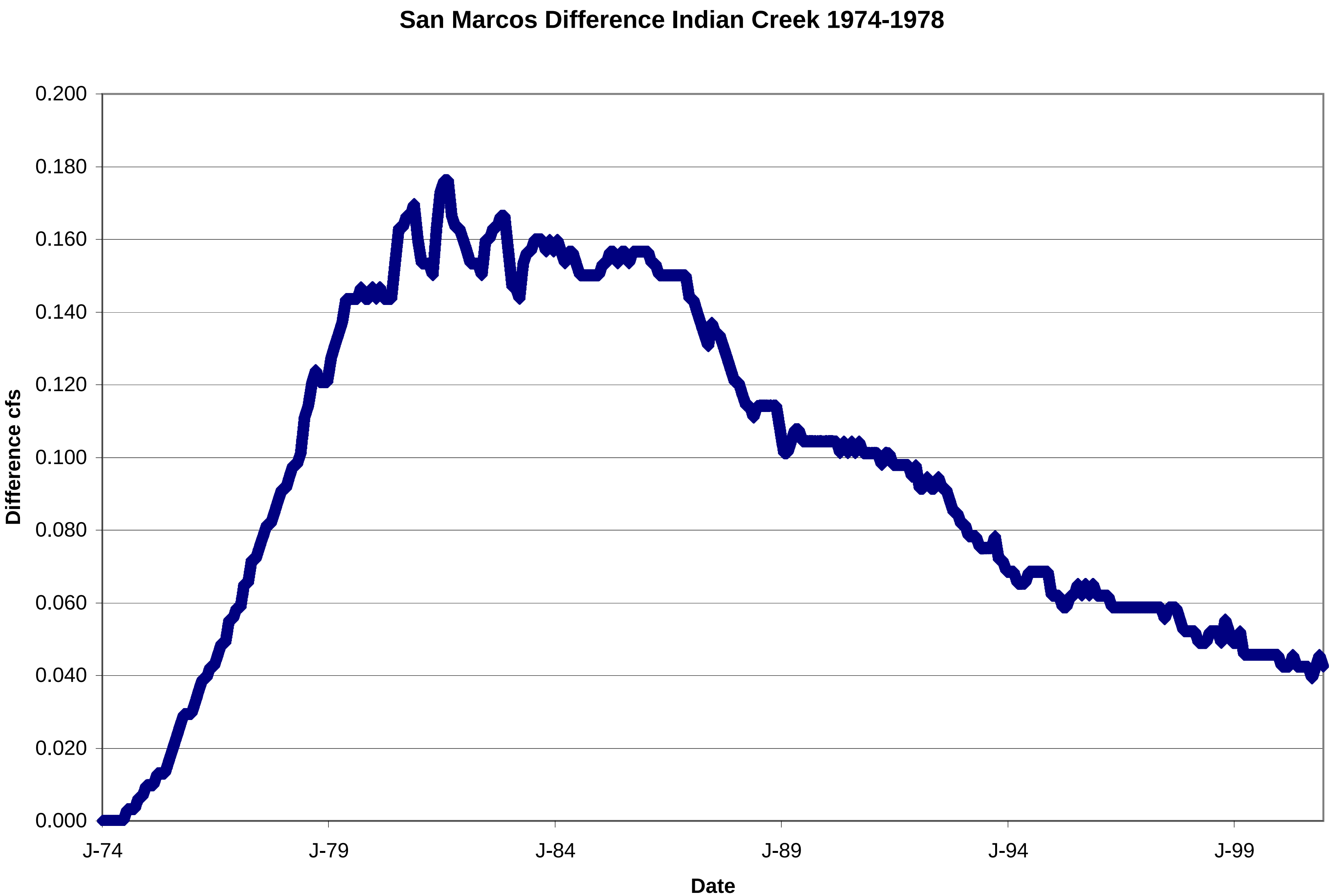
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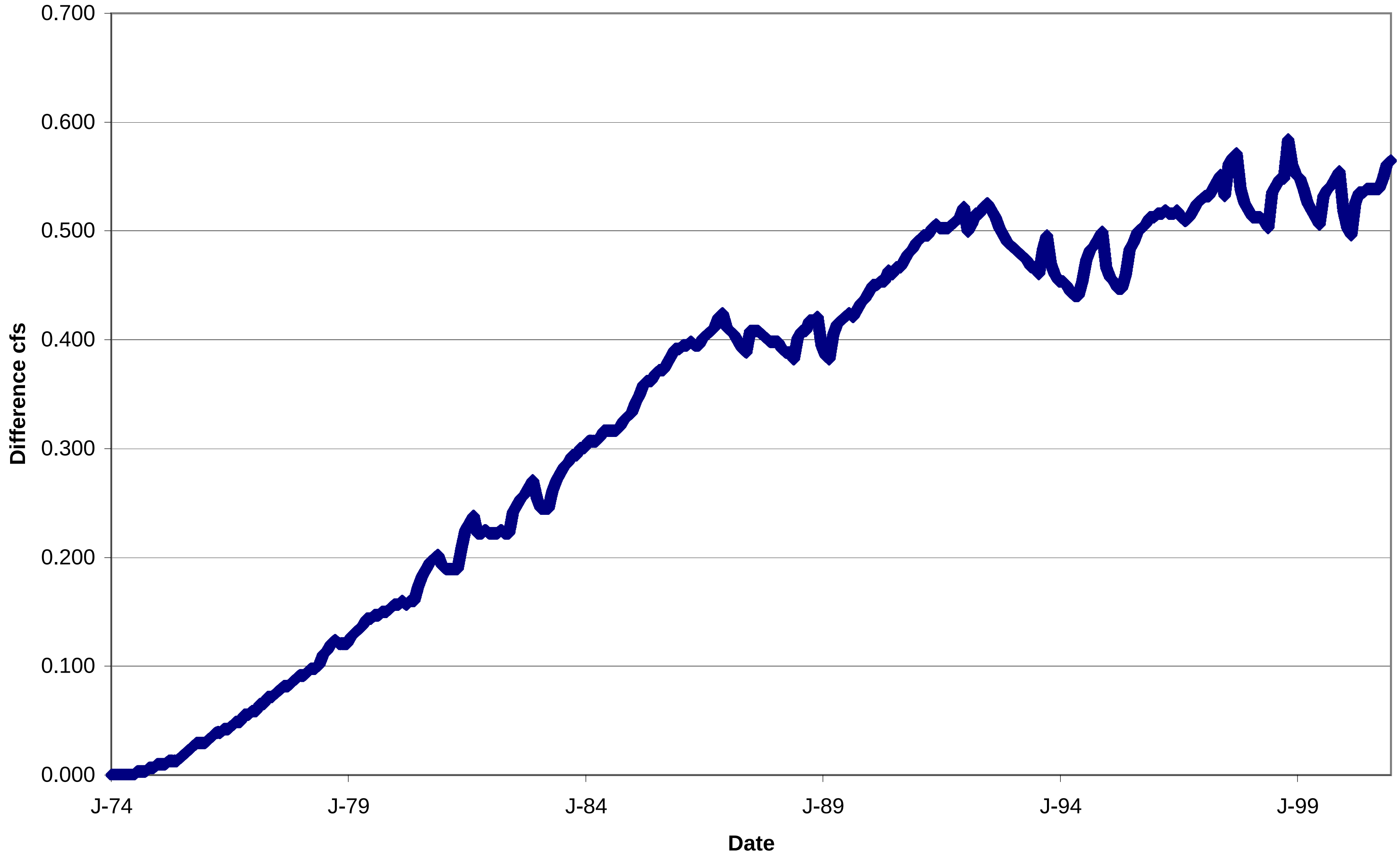
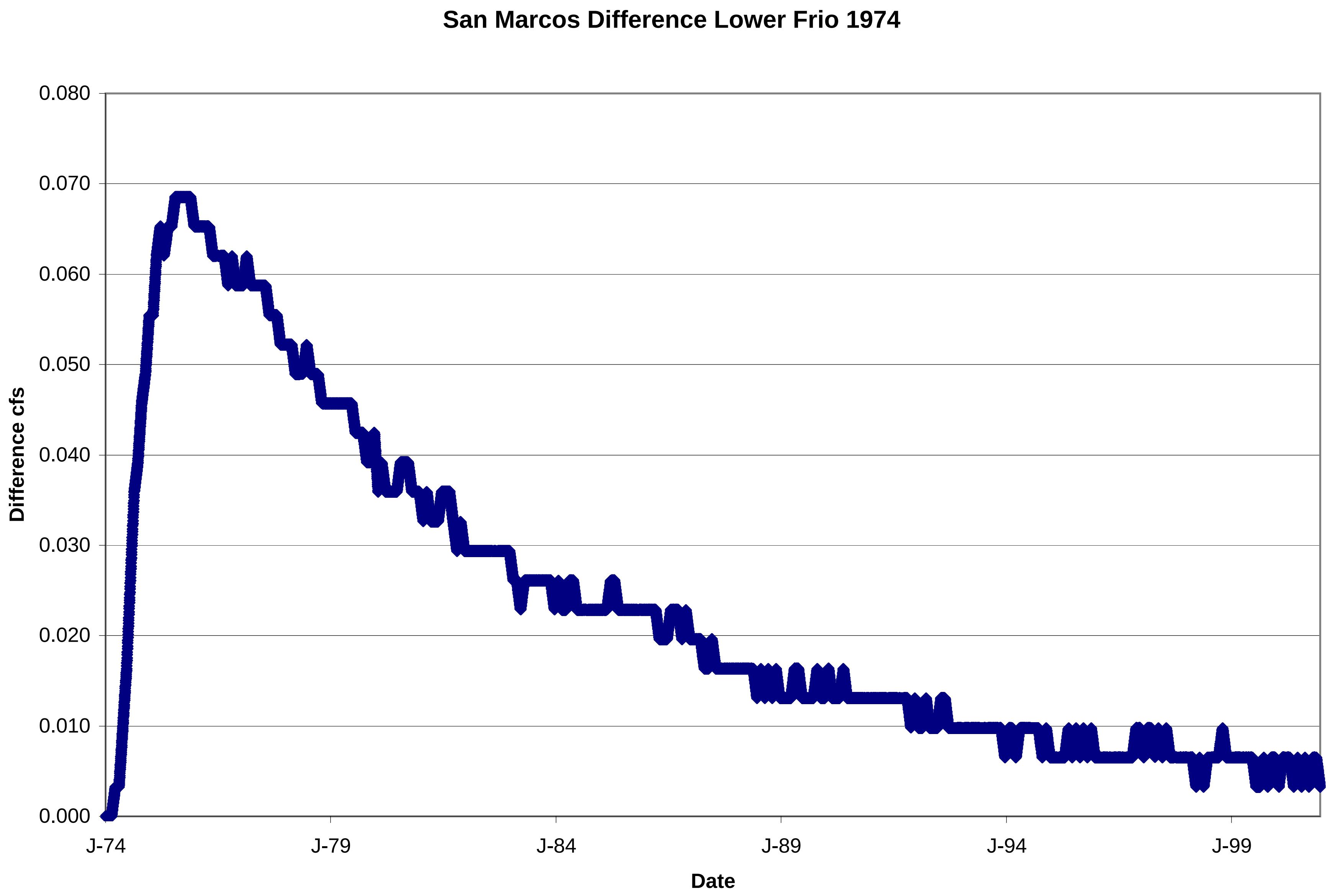
0.100
0.080
0.060
0.040
0.020
0.000
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Marcos Difference Indian Creek 1974-2000

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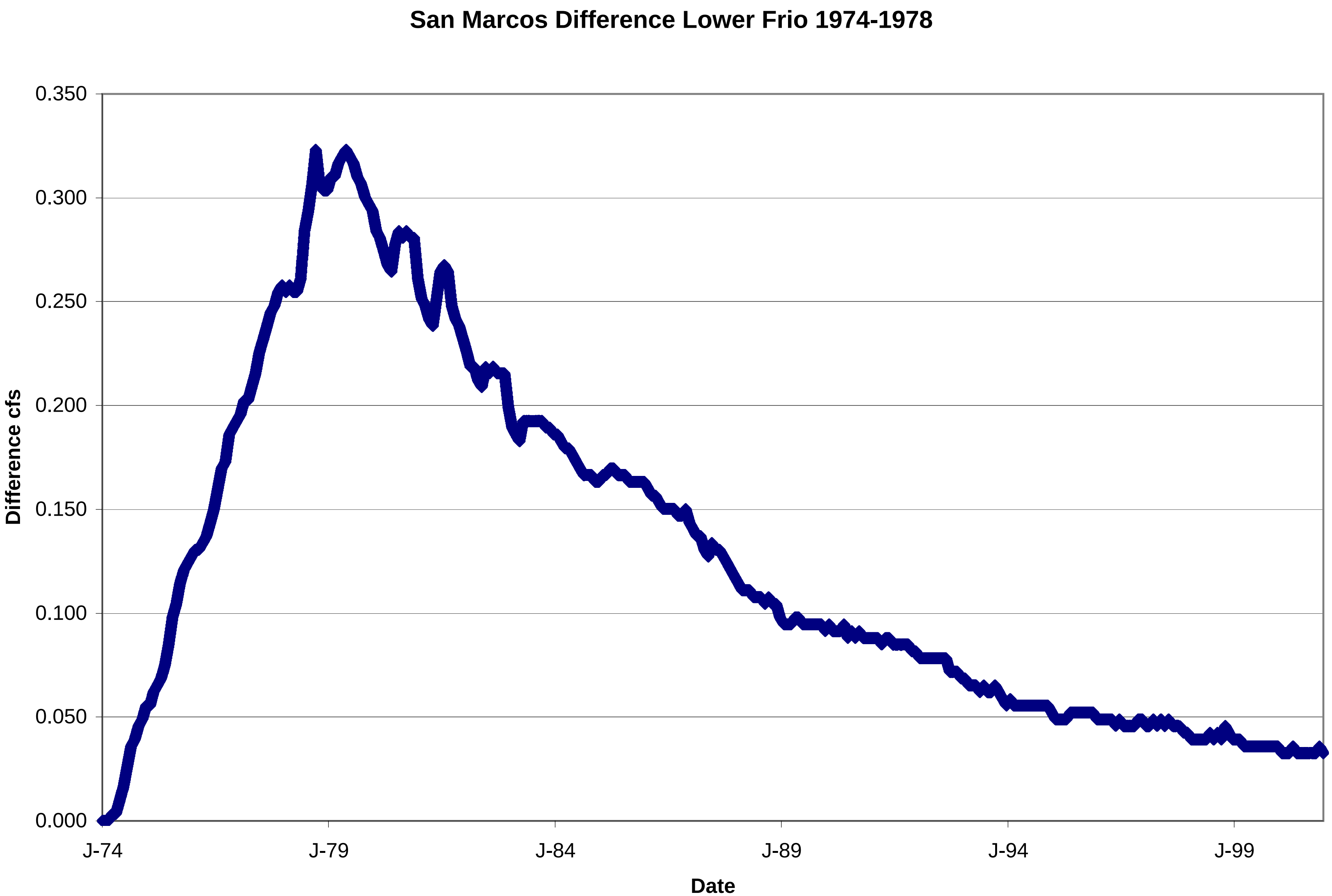
J-94
J-99
Date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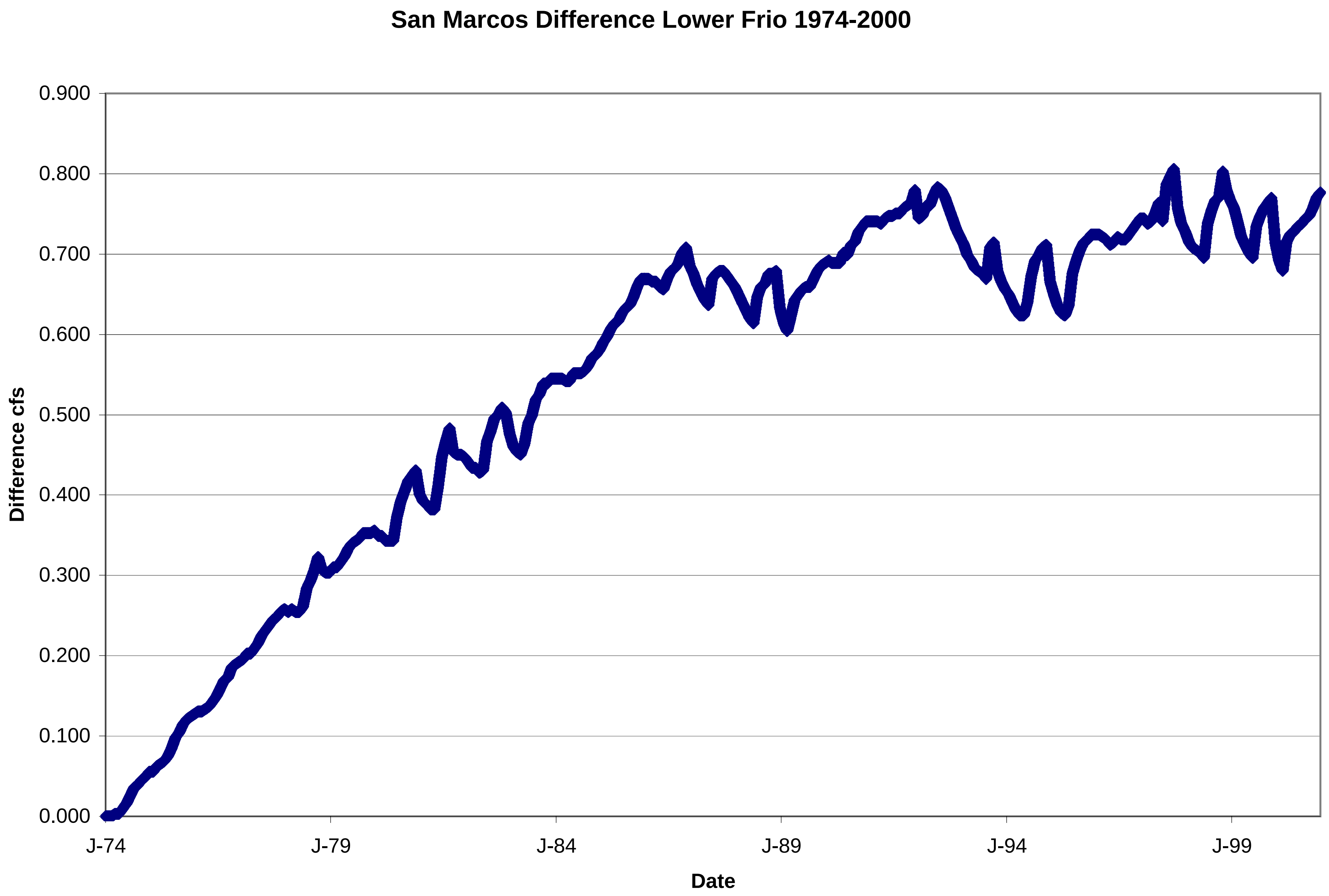
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Difference cfs
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J-94
J-99
Date

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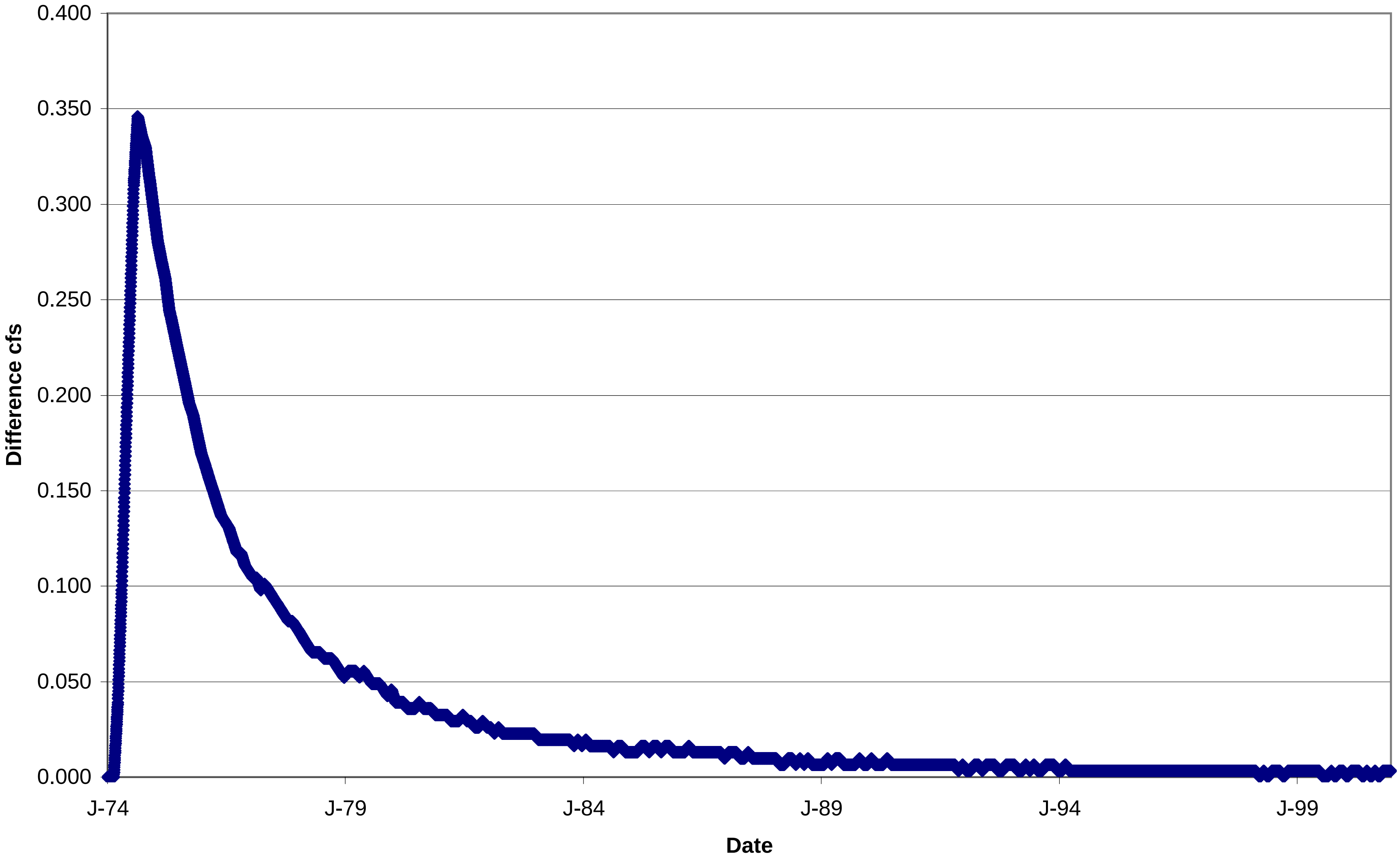

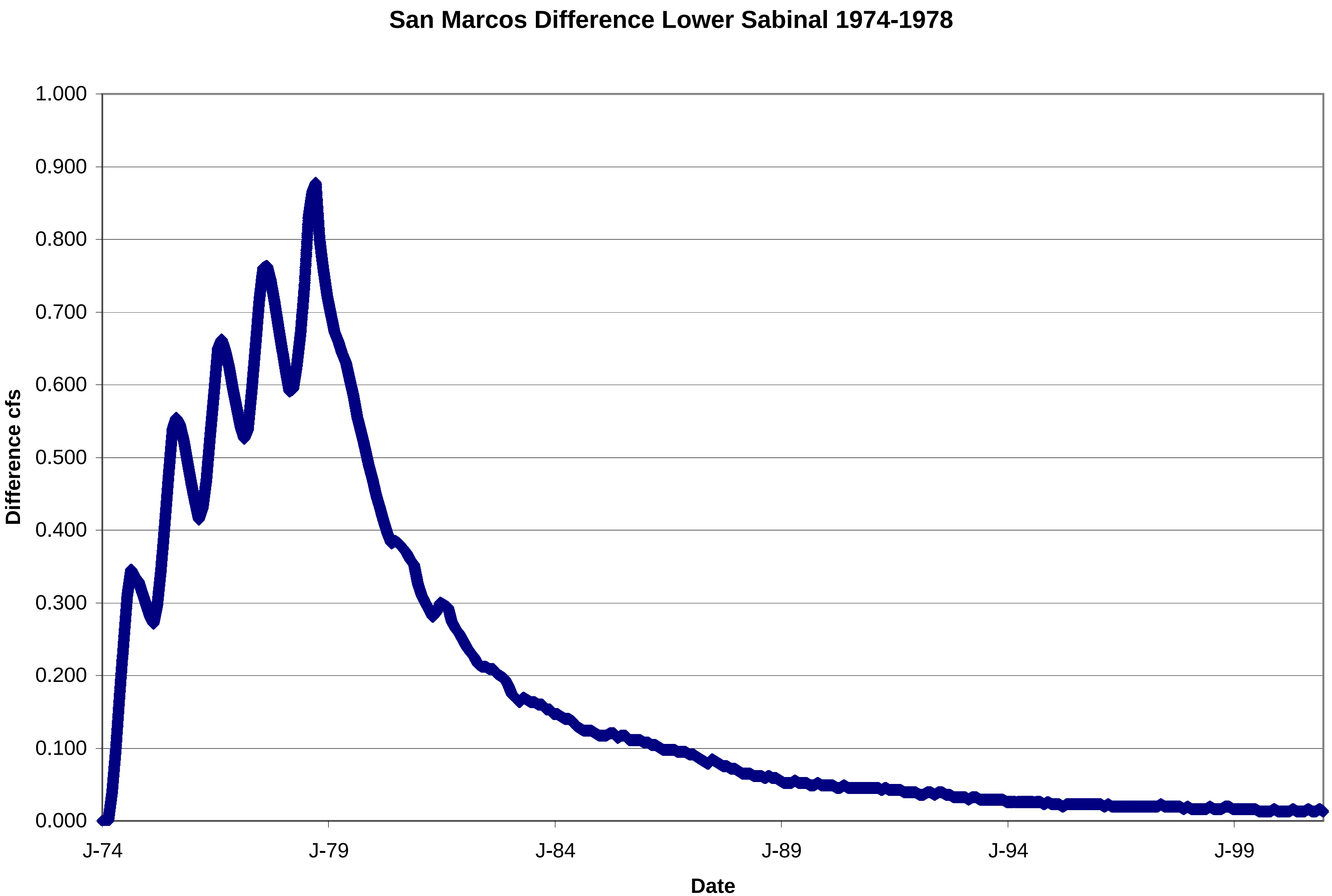
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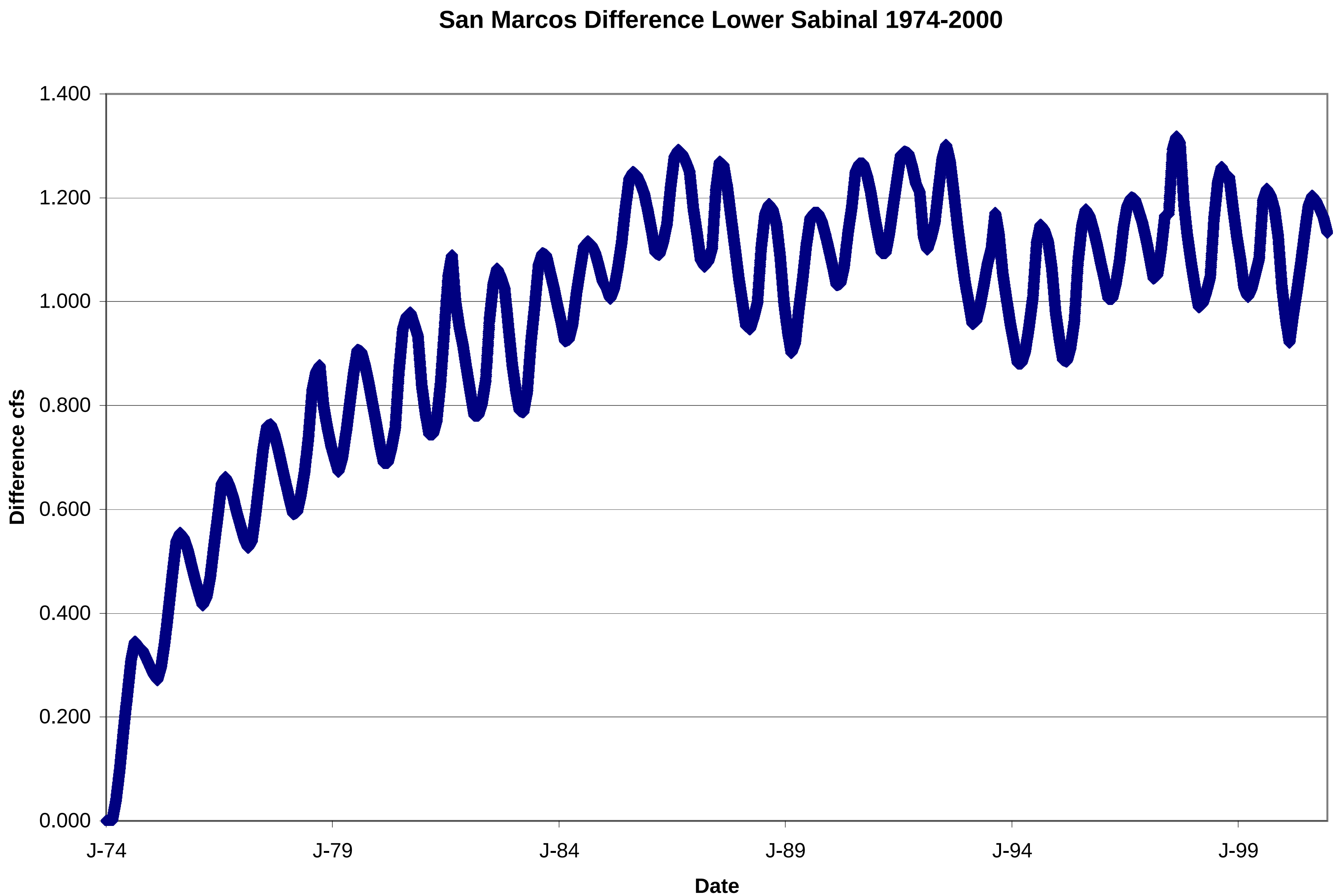
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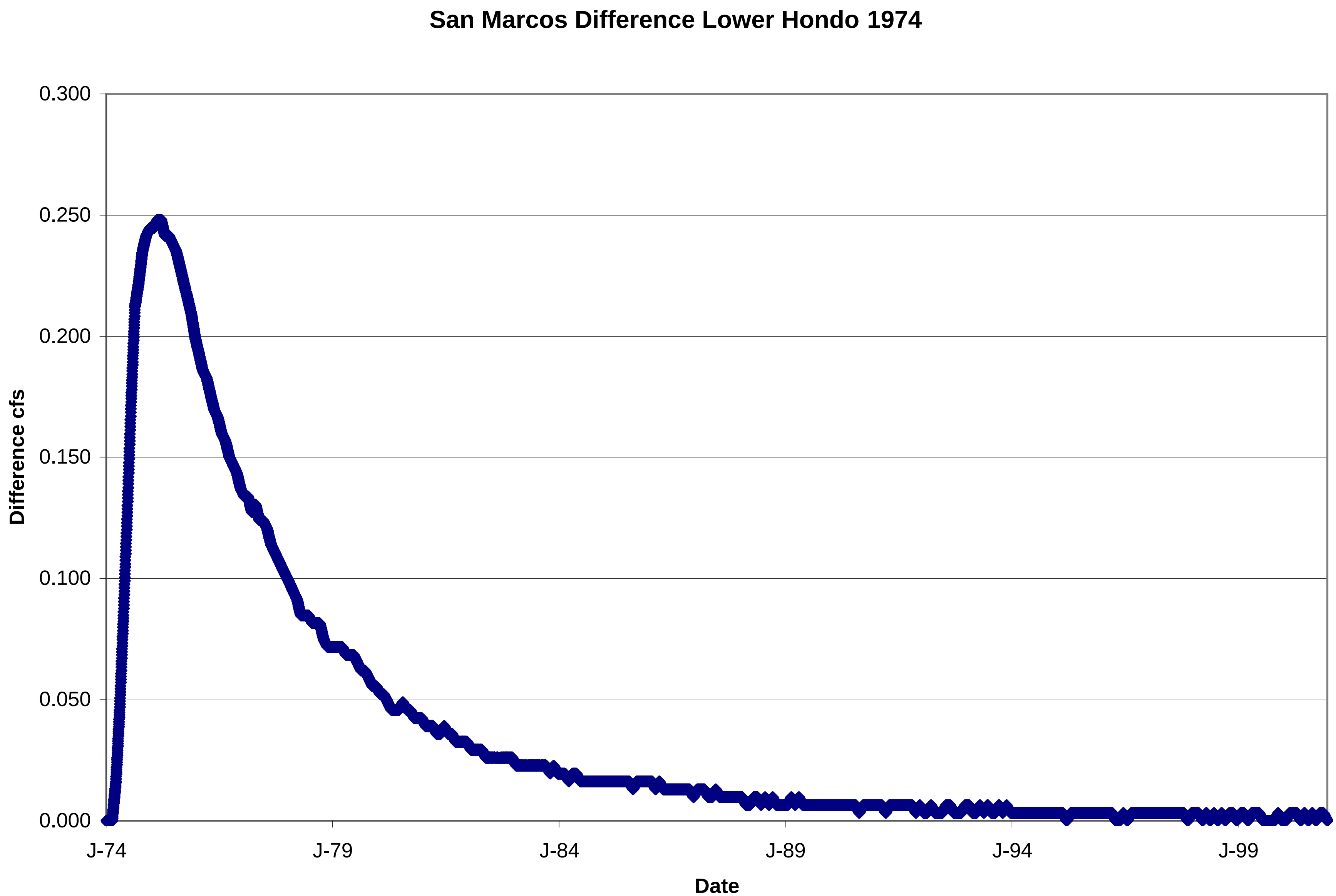
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0.000
Difference cfs
J-74
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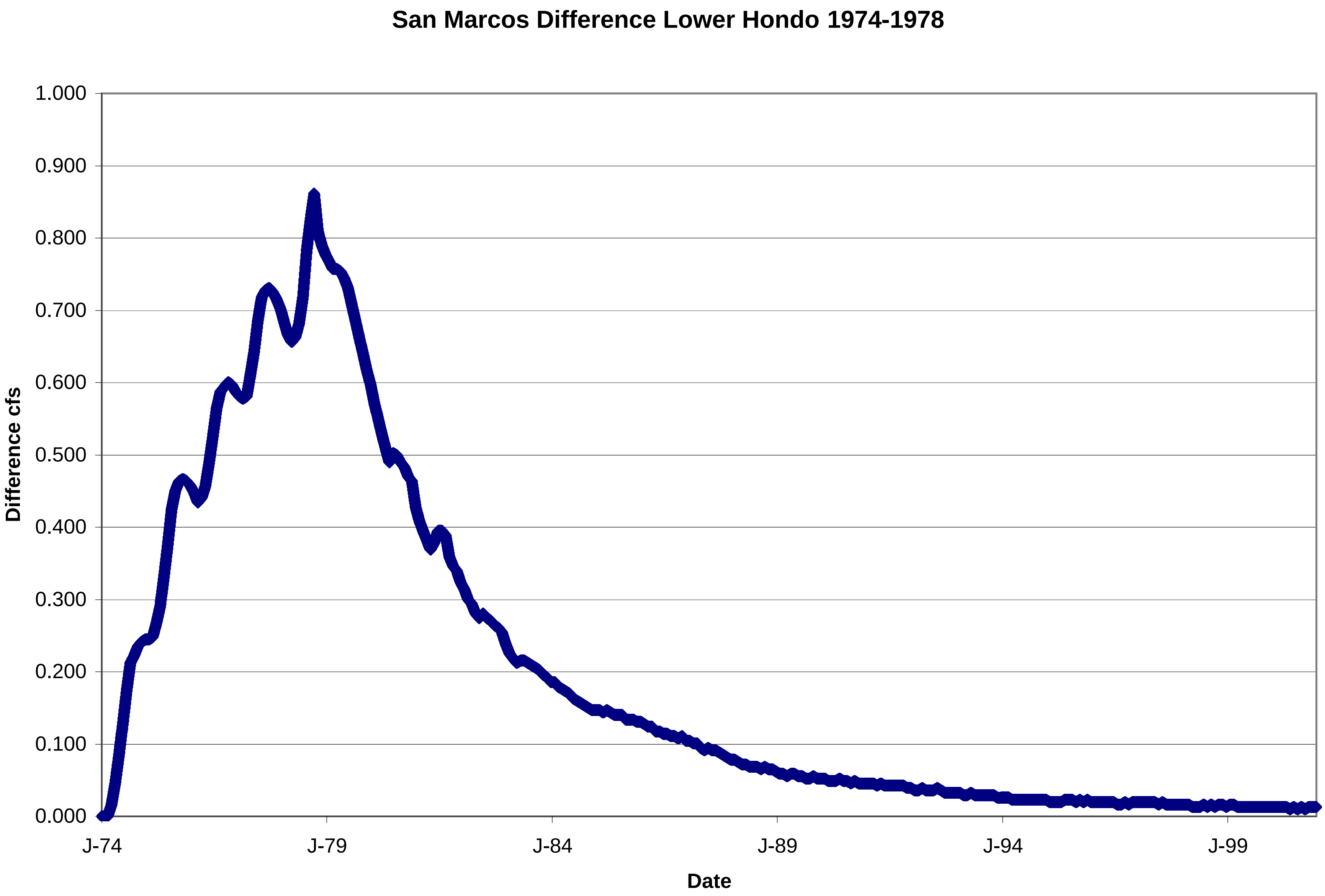
San Marcos Difference Lower Hondo 1974-1978
Difference cfs
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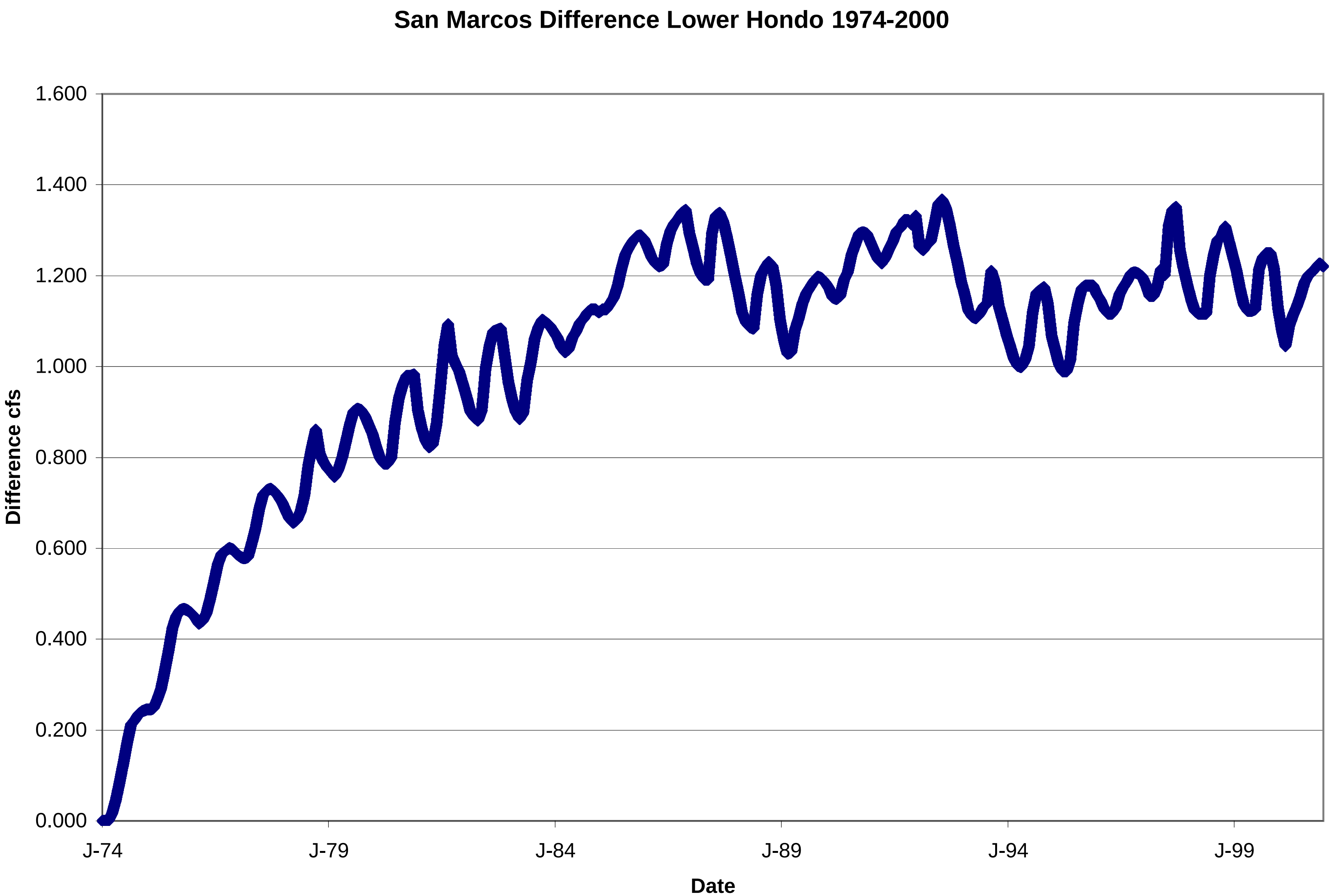
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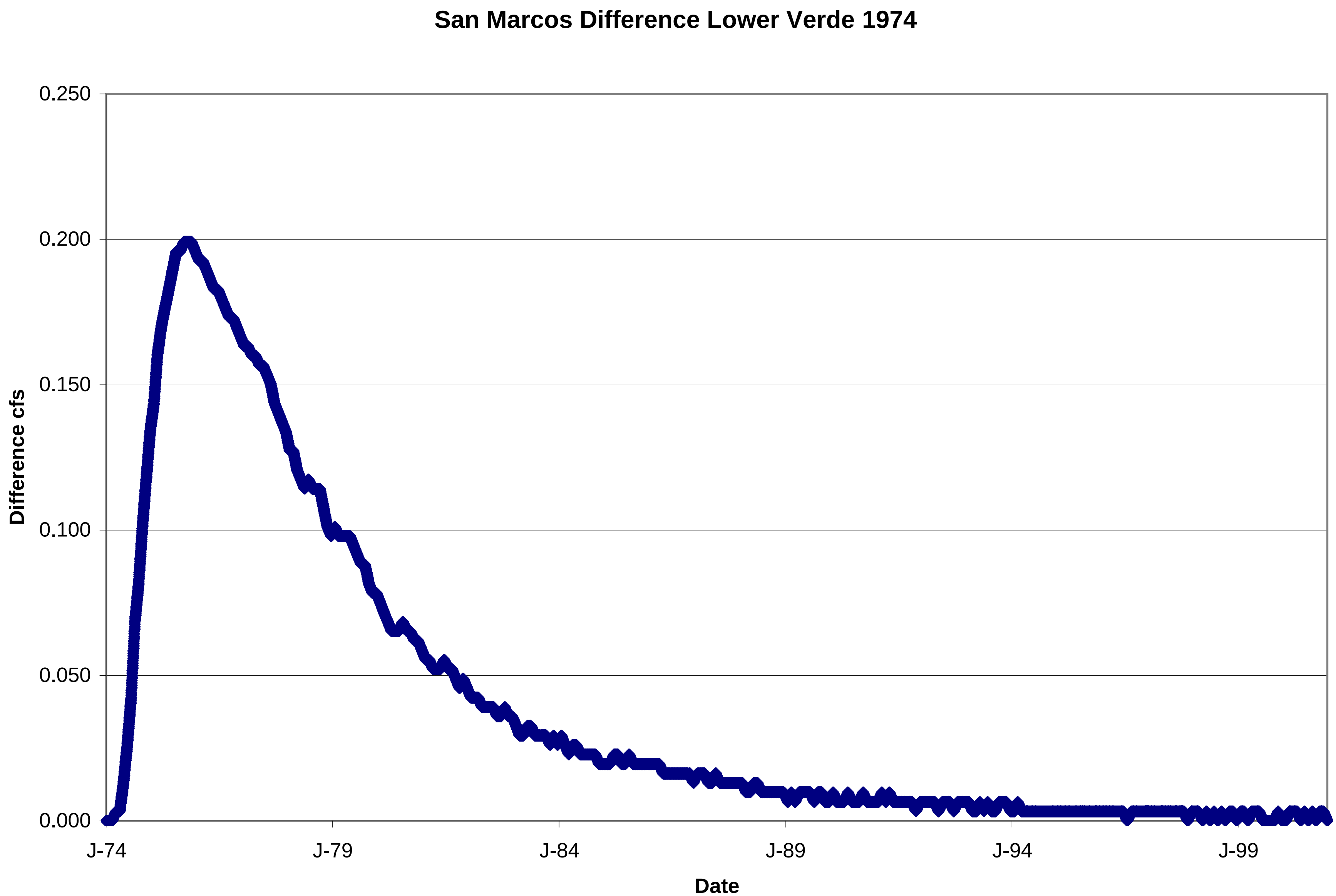
Date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J-74
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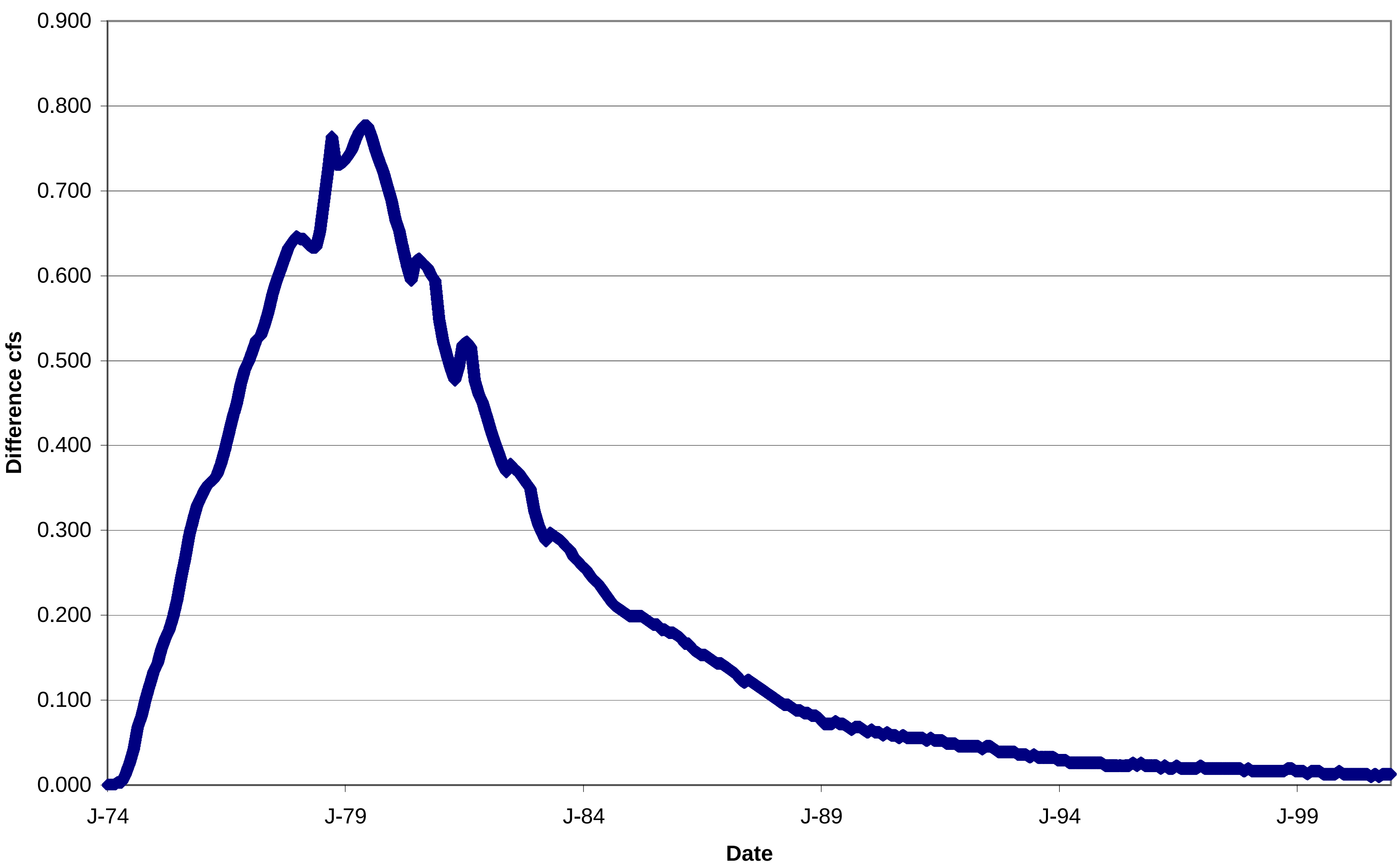
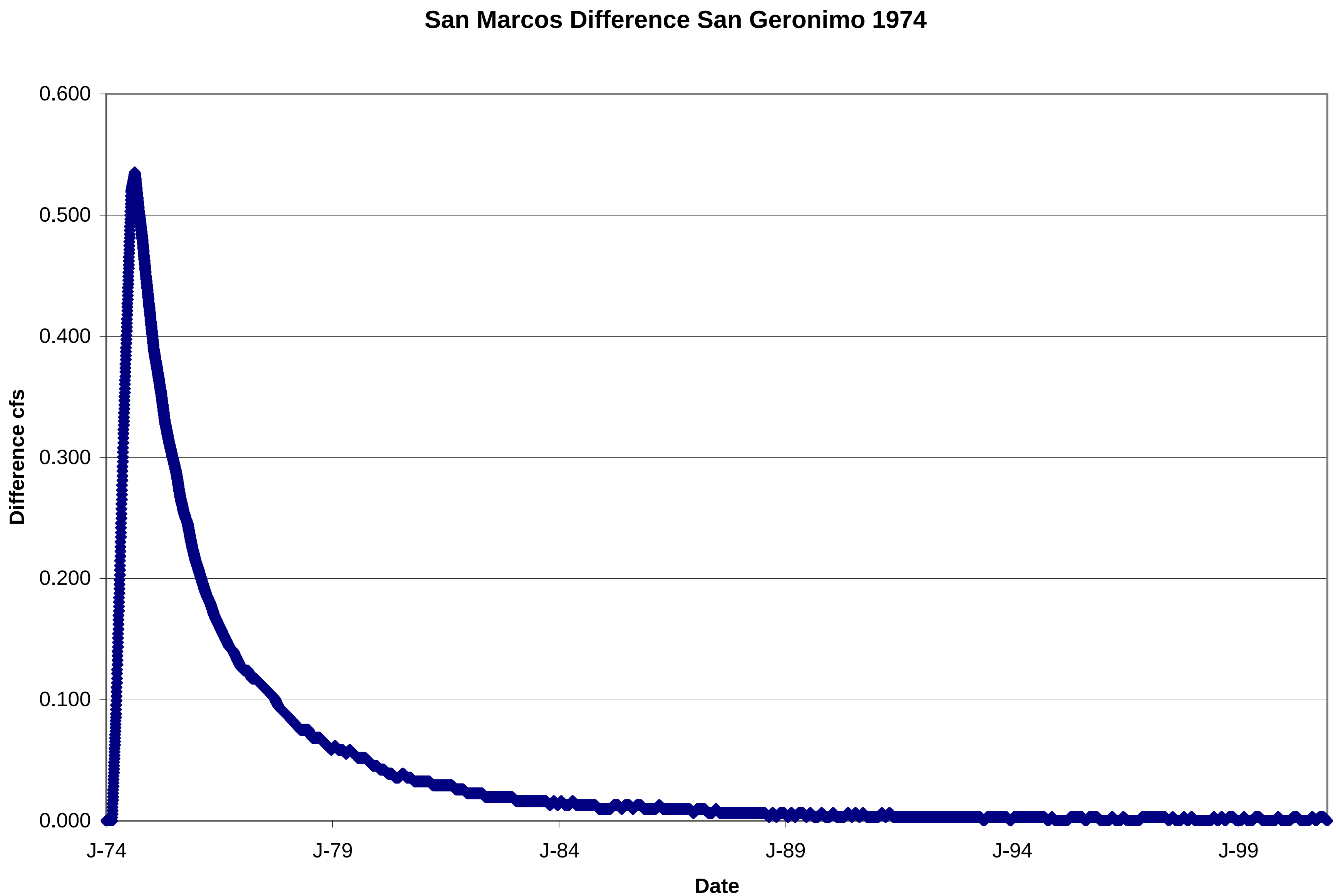
J-94
J-99
Date

San Marcos Difference Lower Verde 1974-1978



San Marcos Difference Lower Verde 1974-2000


San Marcos Difference San Geronimo 1974
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J-79
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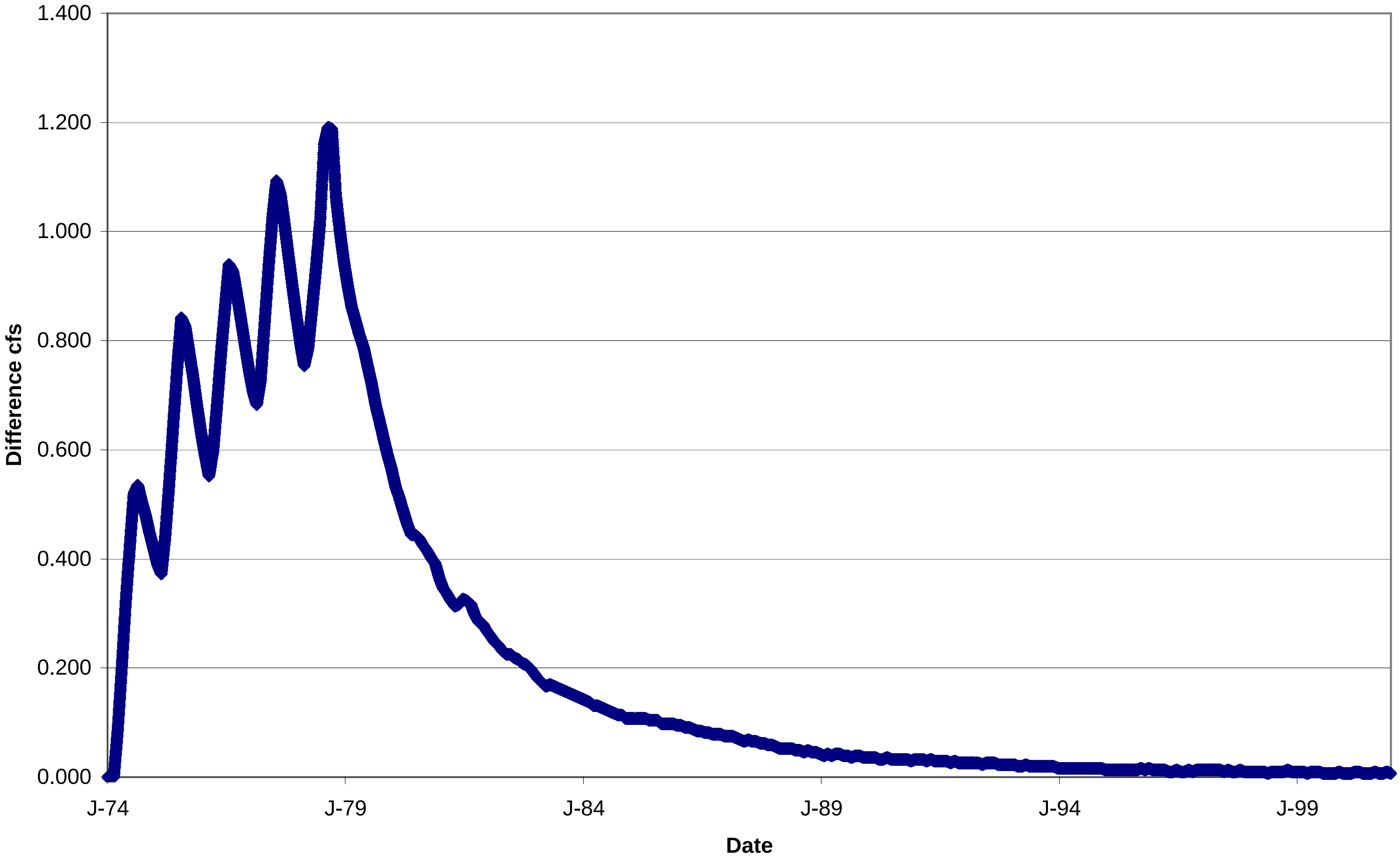
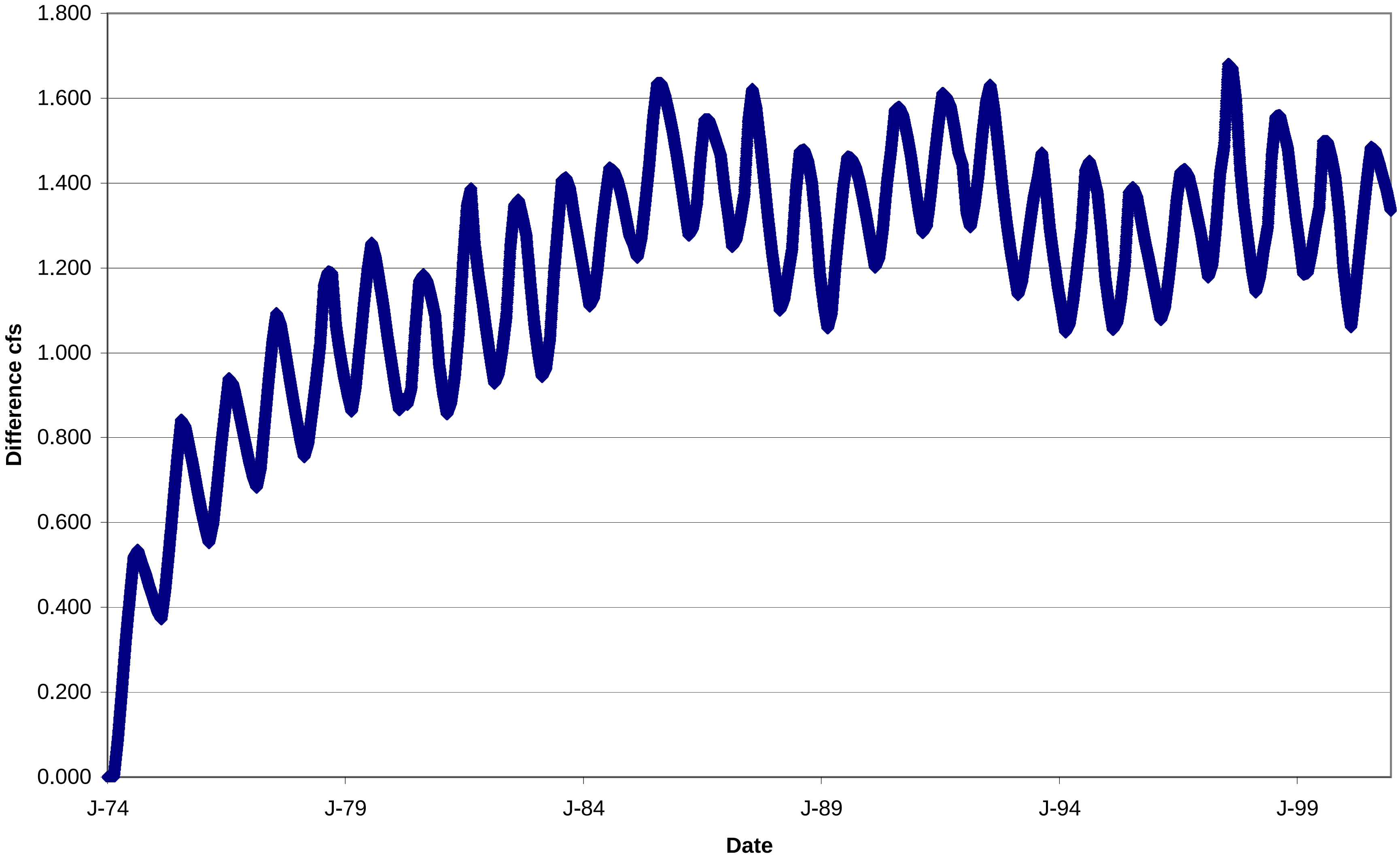
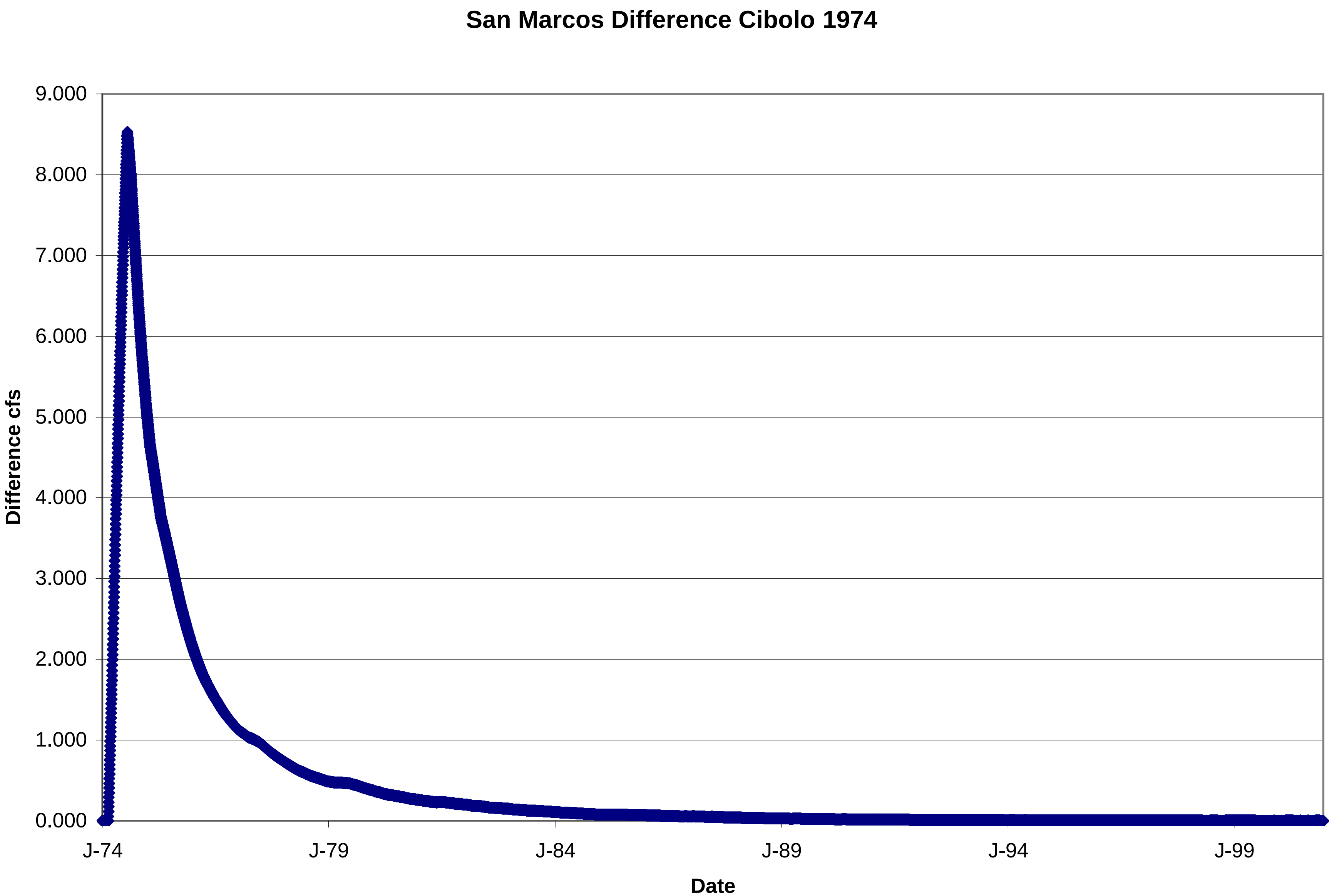
Date

San Marcos Difference San Geronimo 1974-1978

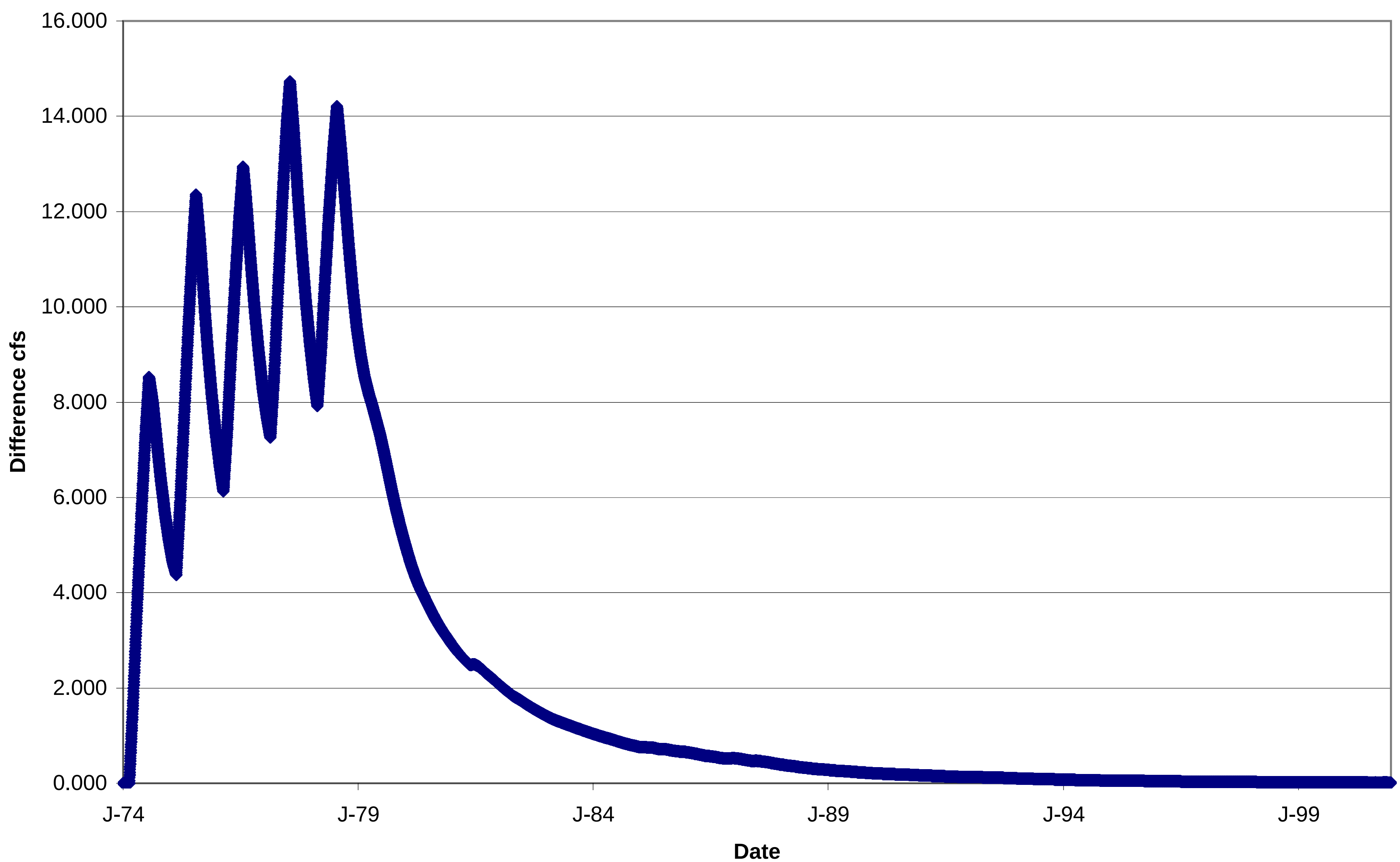


San Marcos Difference San Geronimo 1974-2000

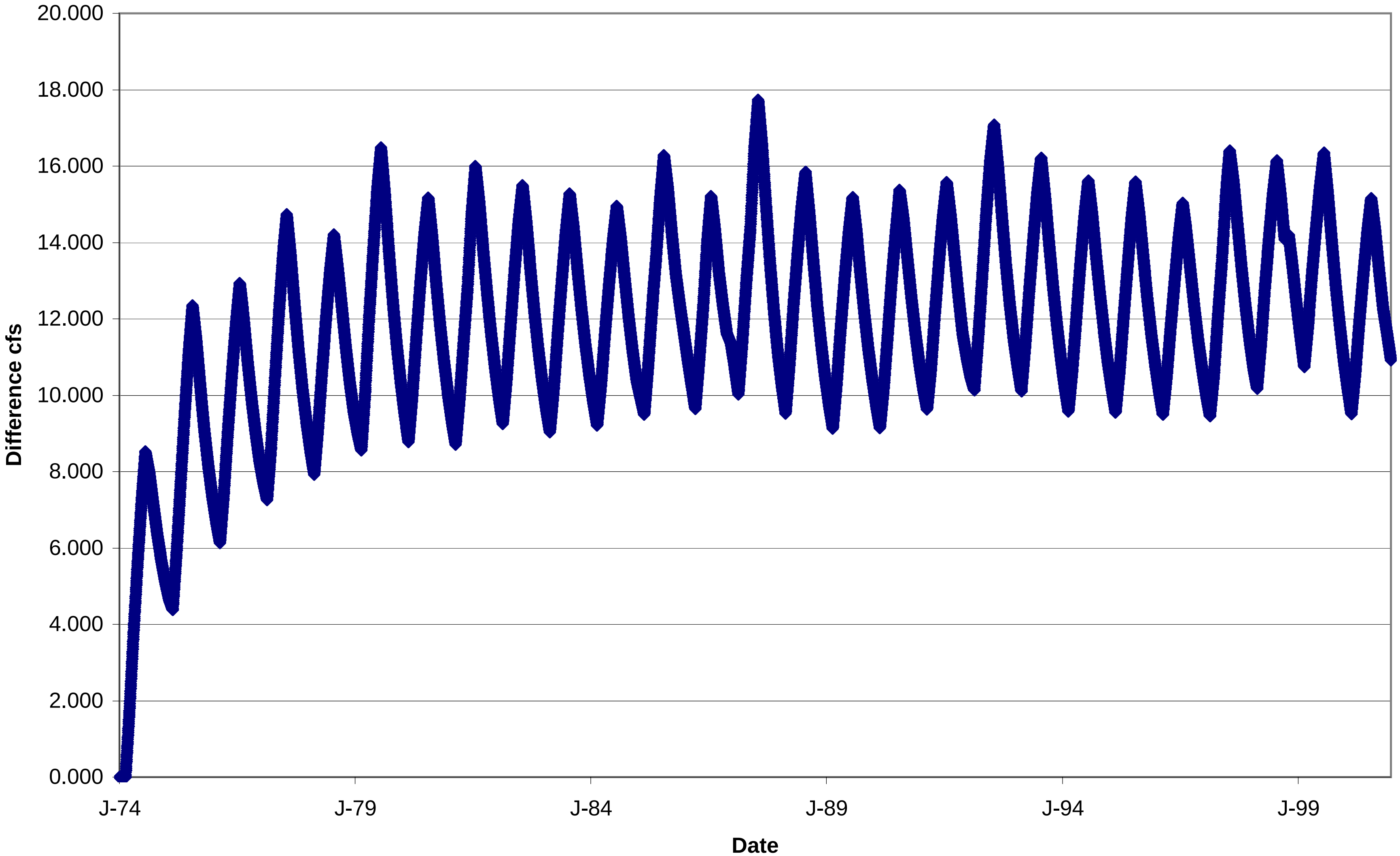



San Marcos Difference Cibolo 1974
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

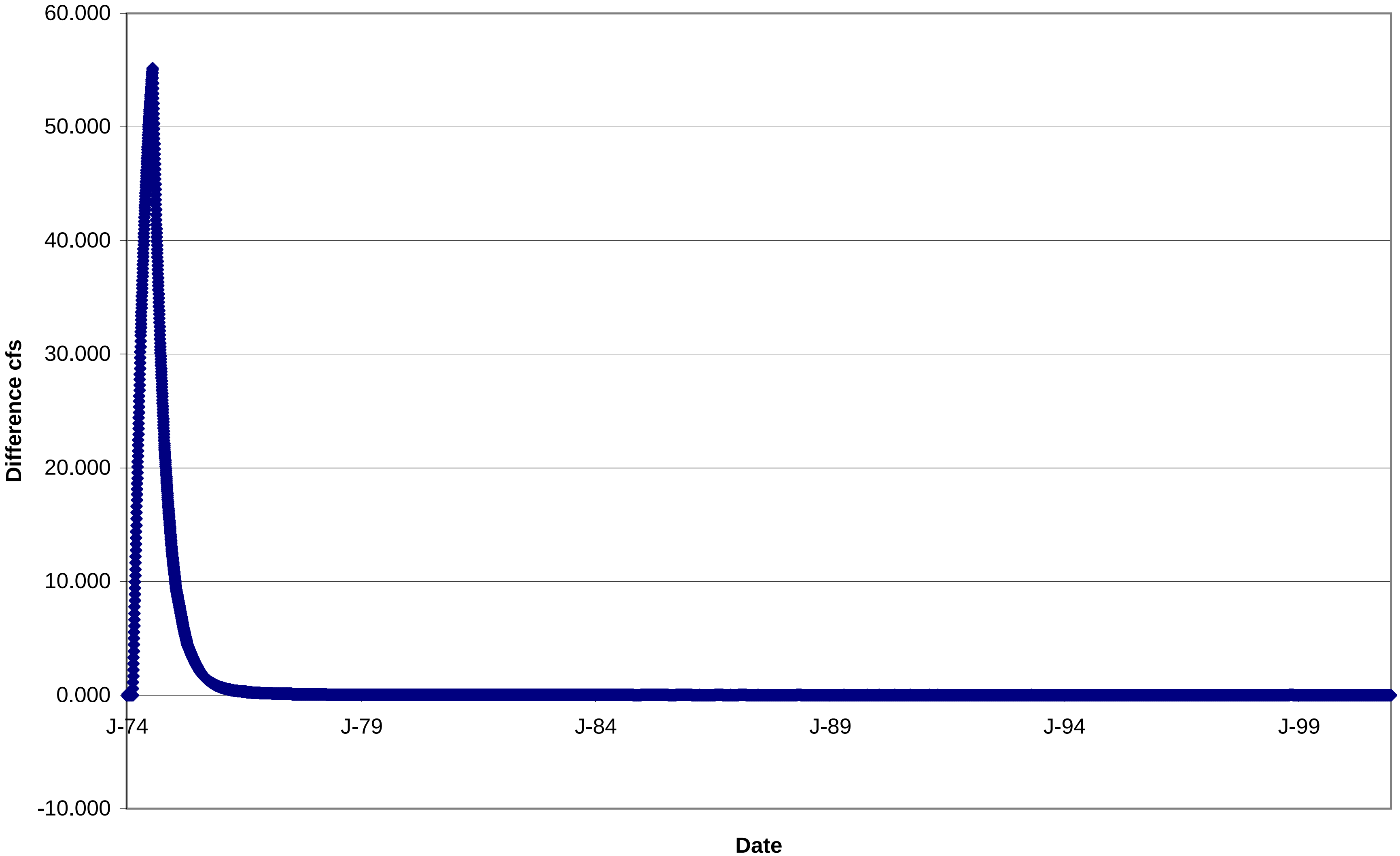
San Marcos Difference Cibolo 1974-1978



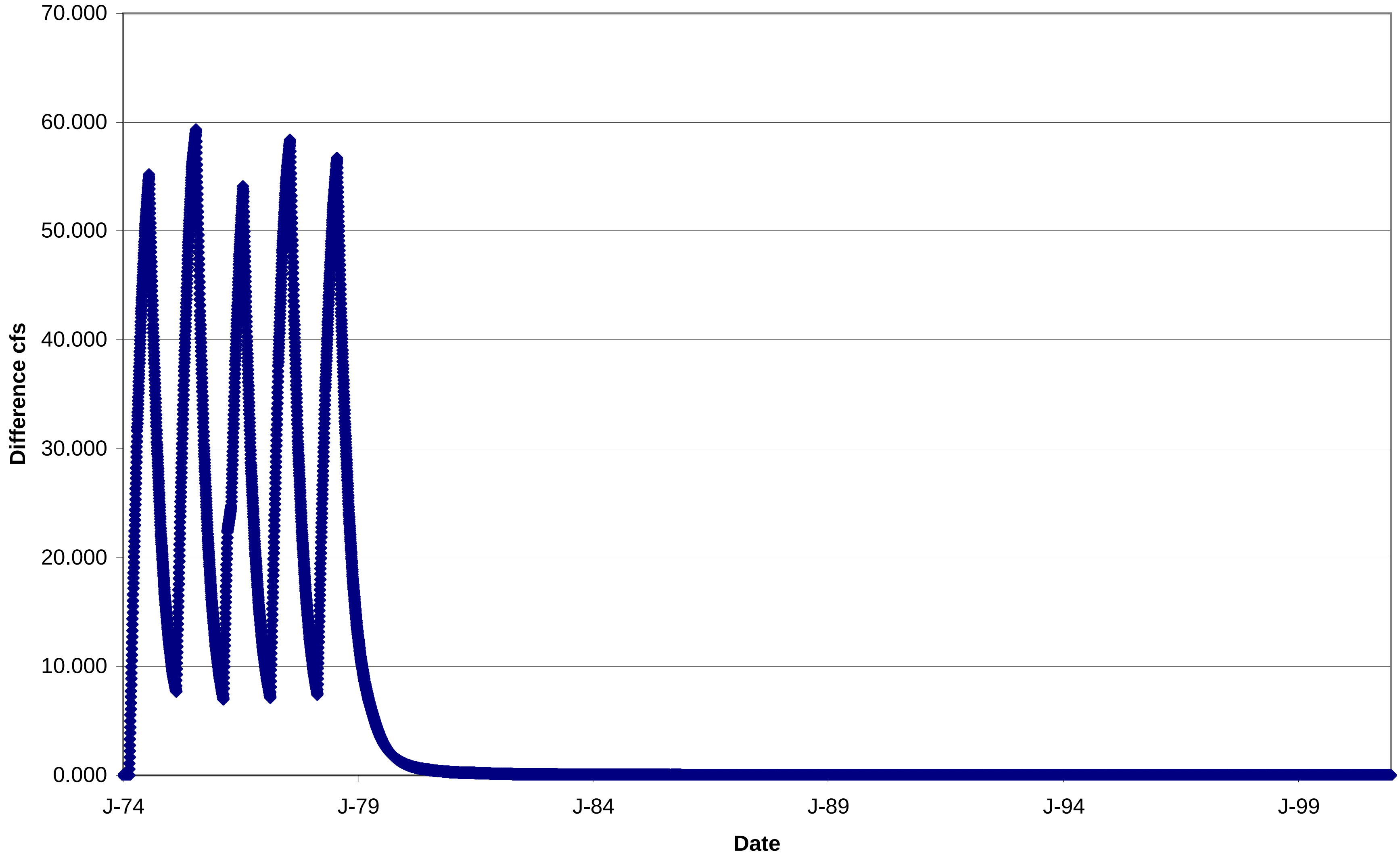
San Marcos Difference Cibolo 1974-2000

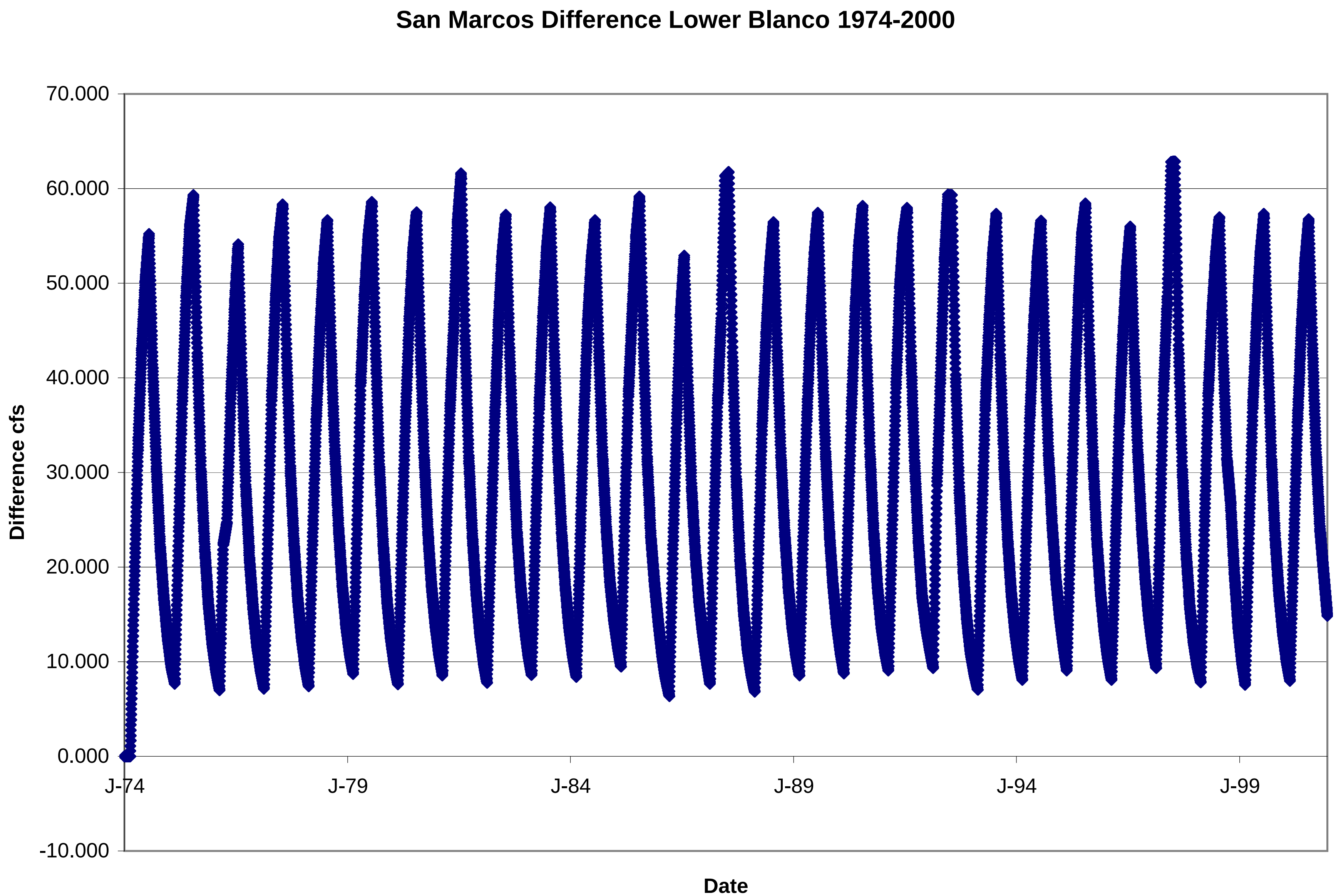


San Marcos Difference Lower Blanco 1974

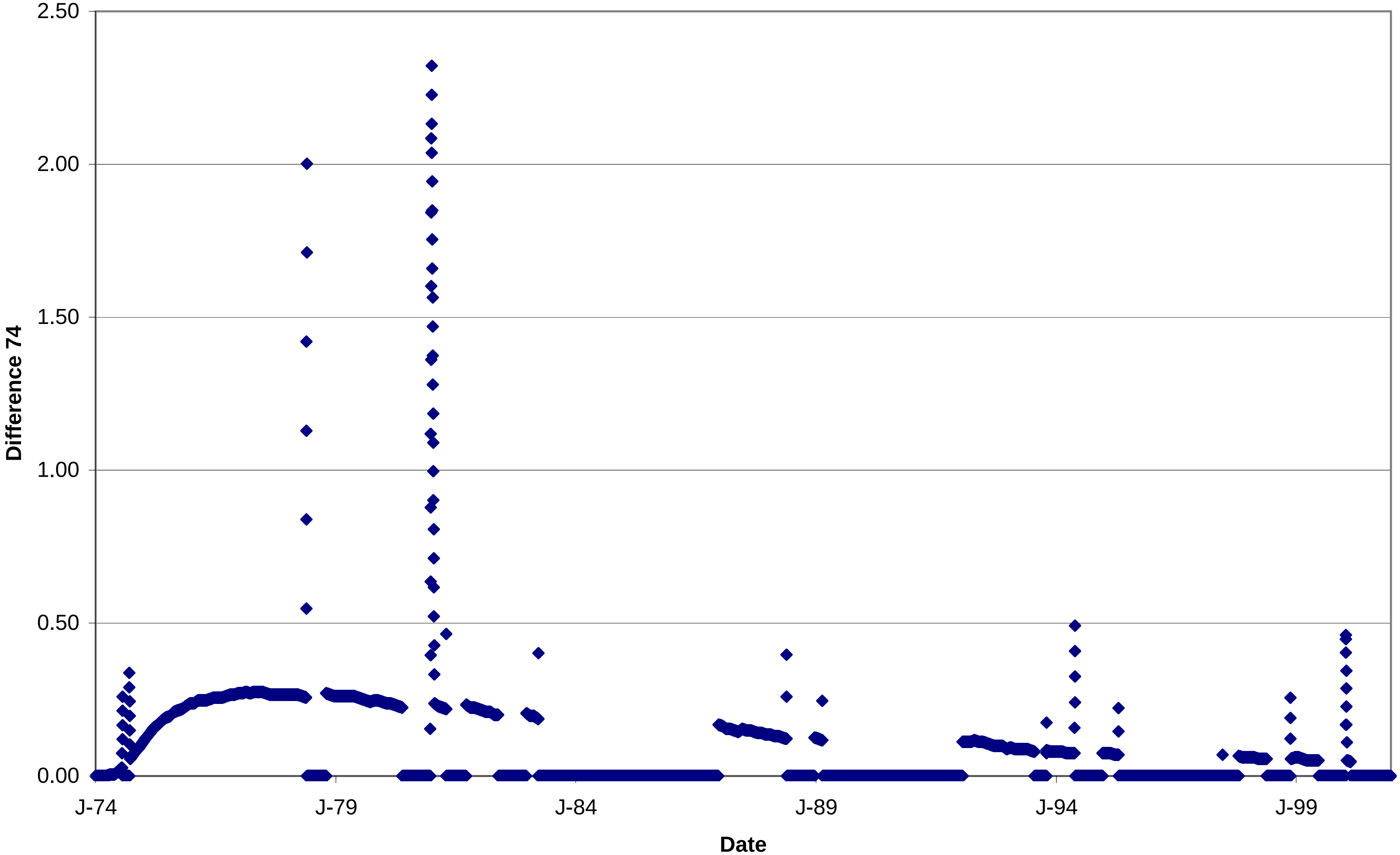


San Marcos Difference Lower Blanco 1974-1978

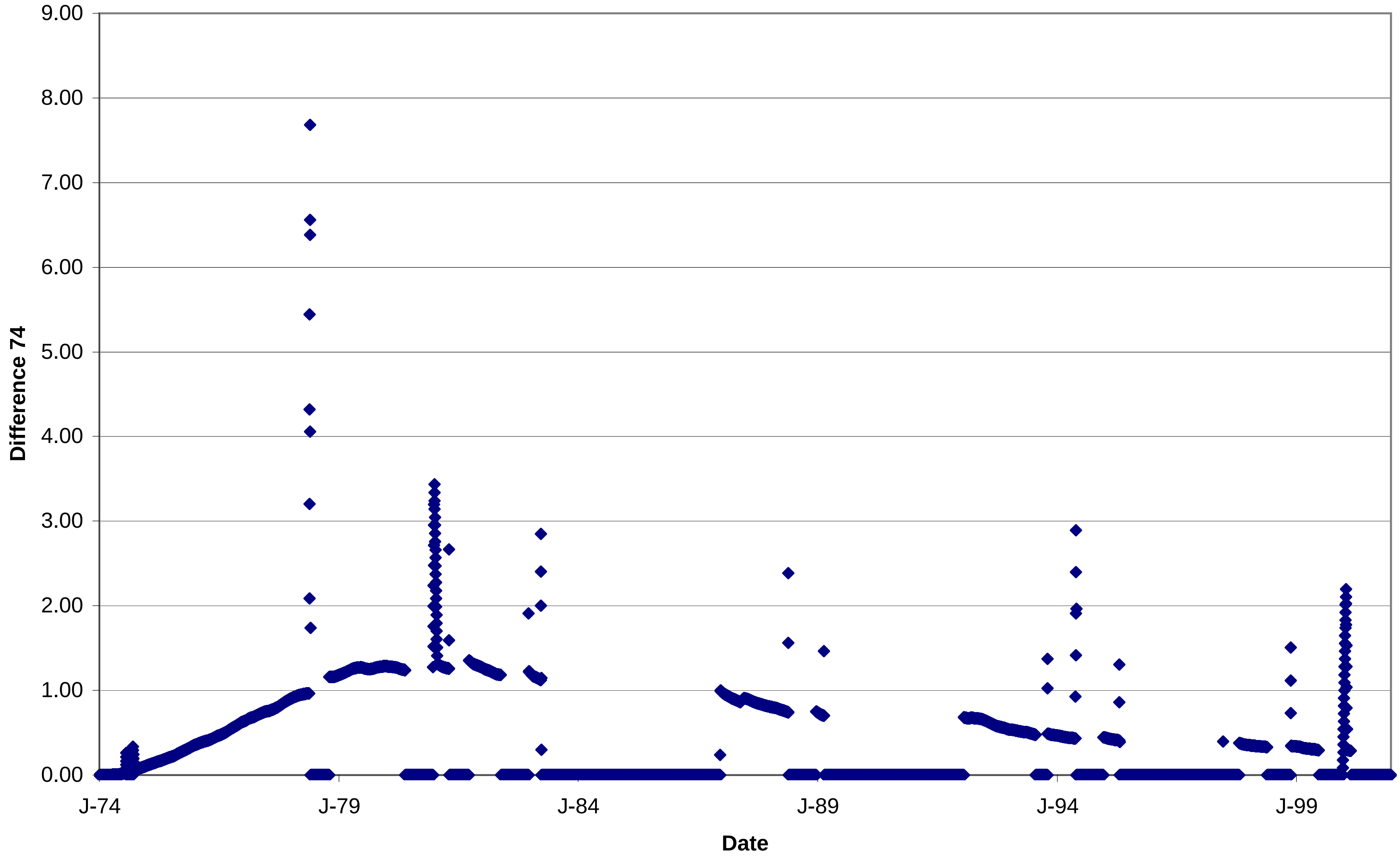


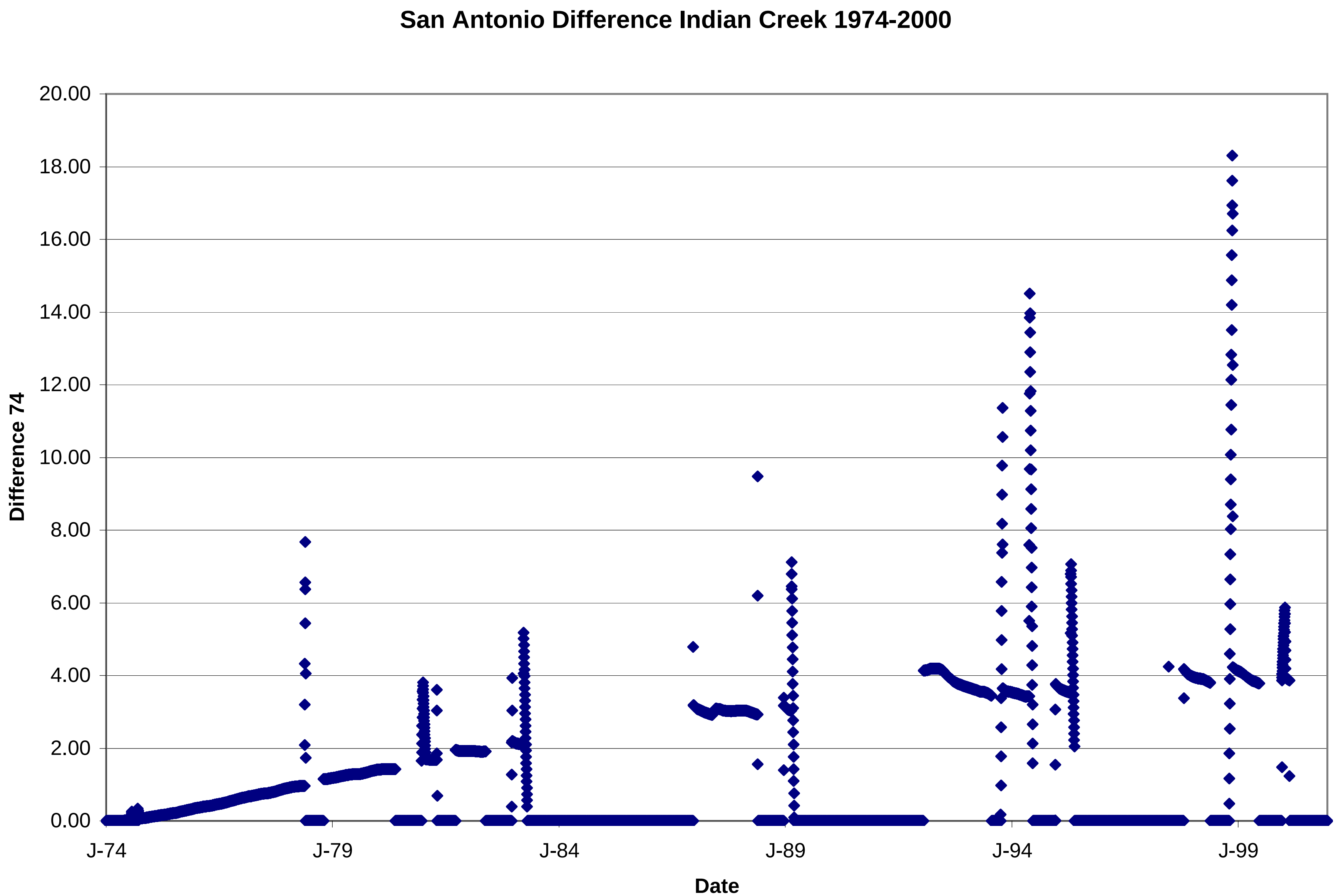

San Marcos Difference Lower Blanco 1974-2000
Difference cfs
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
J-74
J-79
J-84
J-89
J-94
J-99
Date

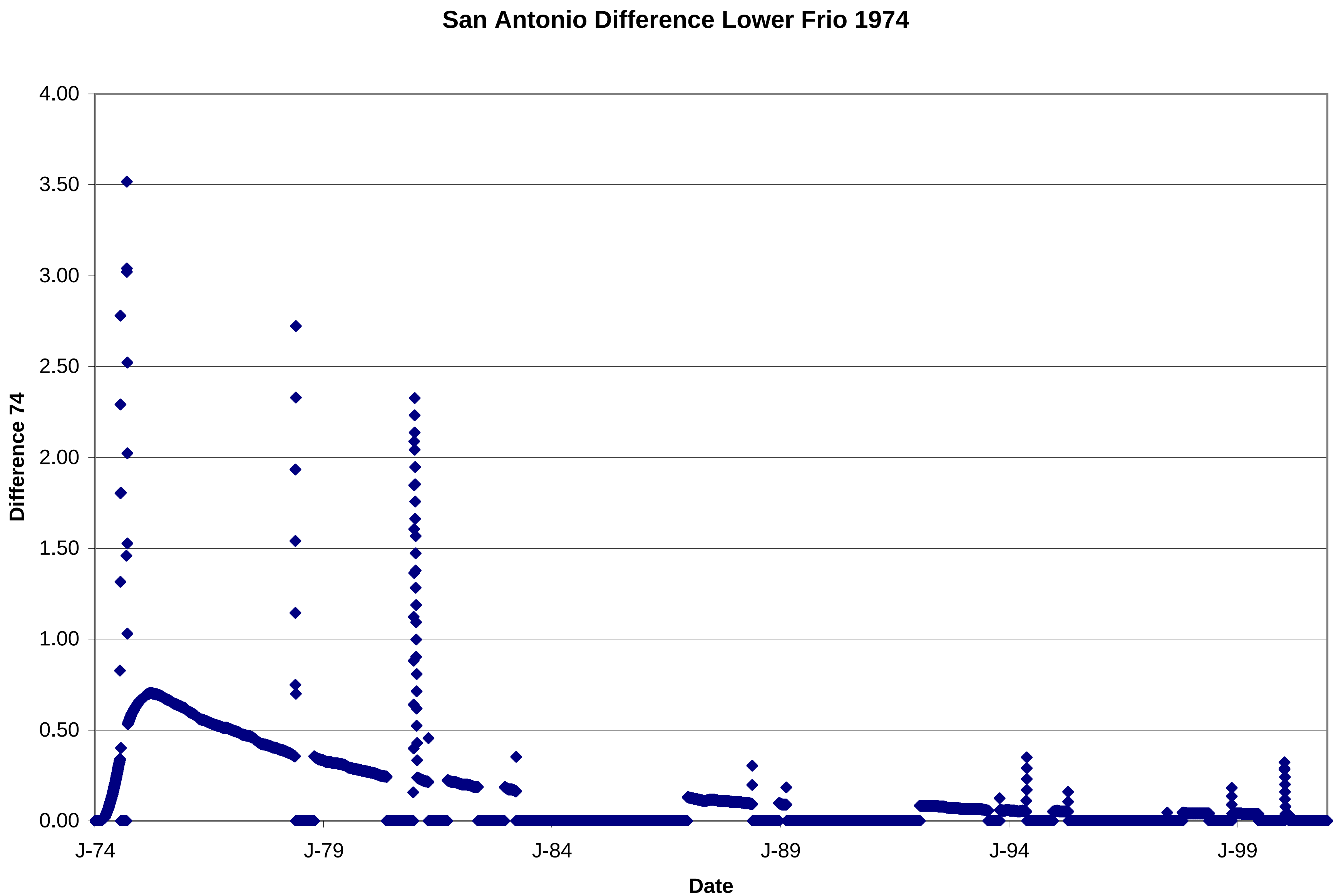
San Antonio Difference Indian Creek 1974

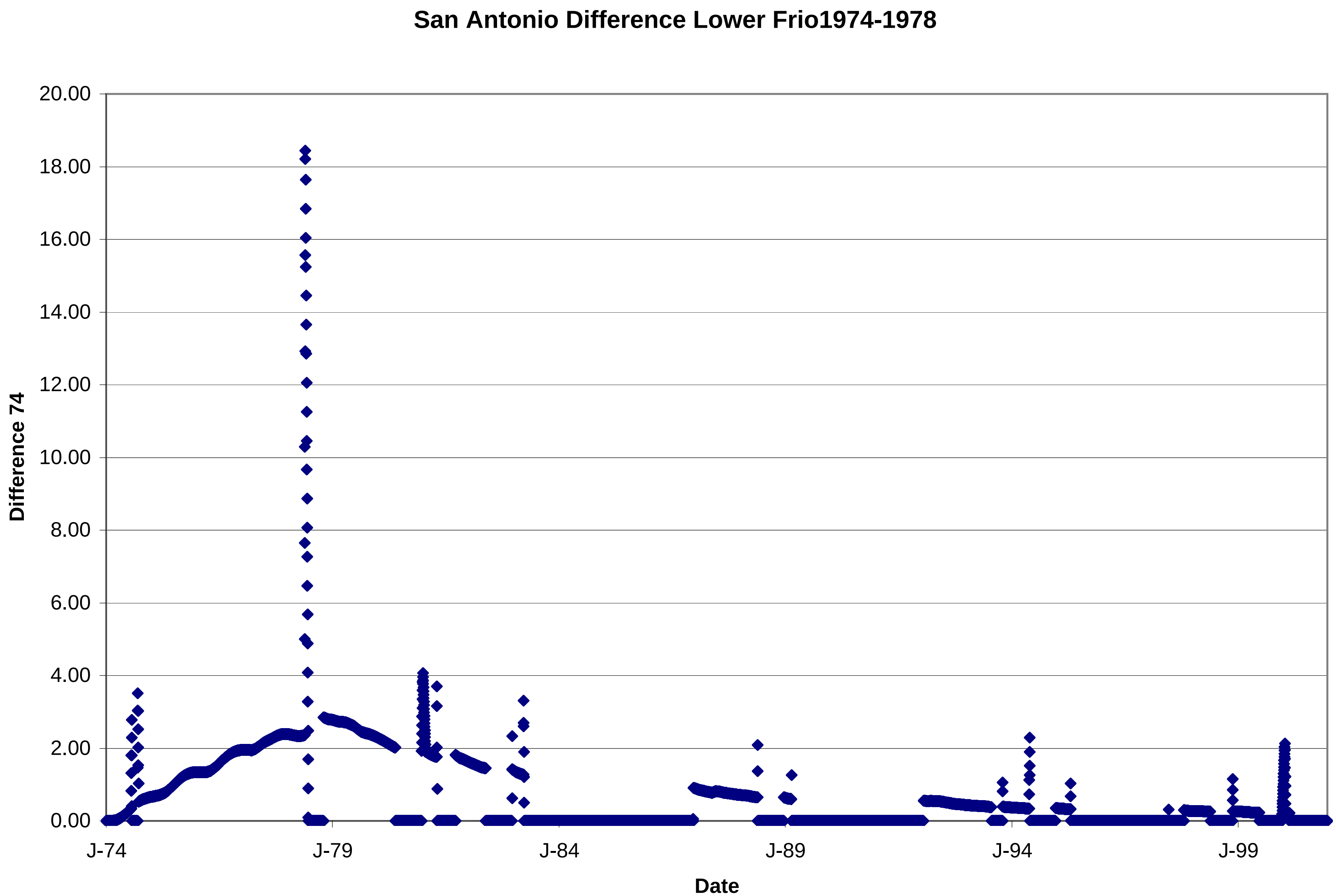


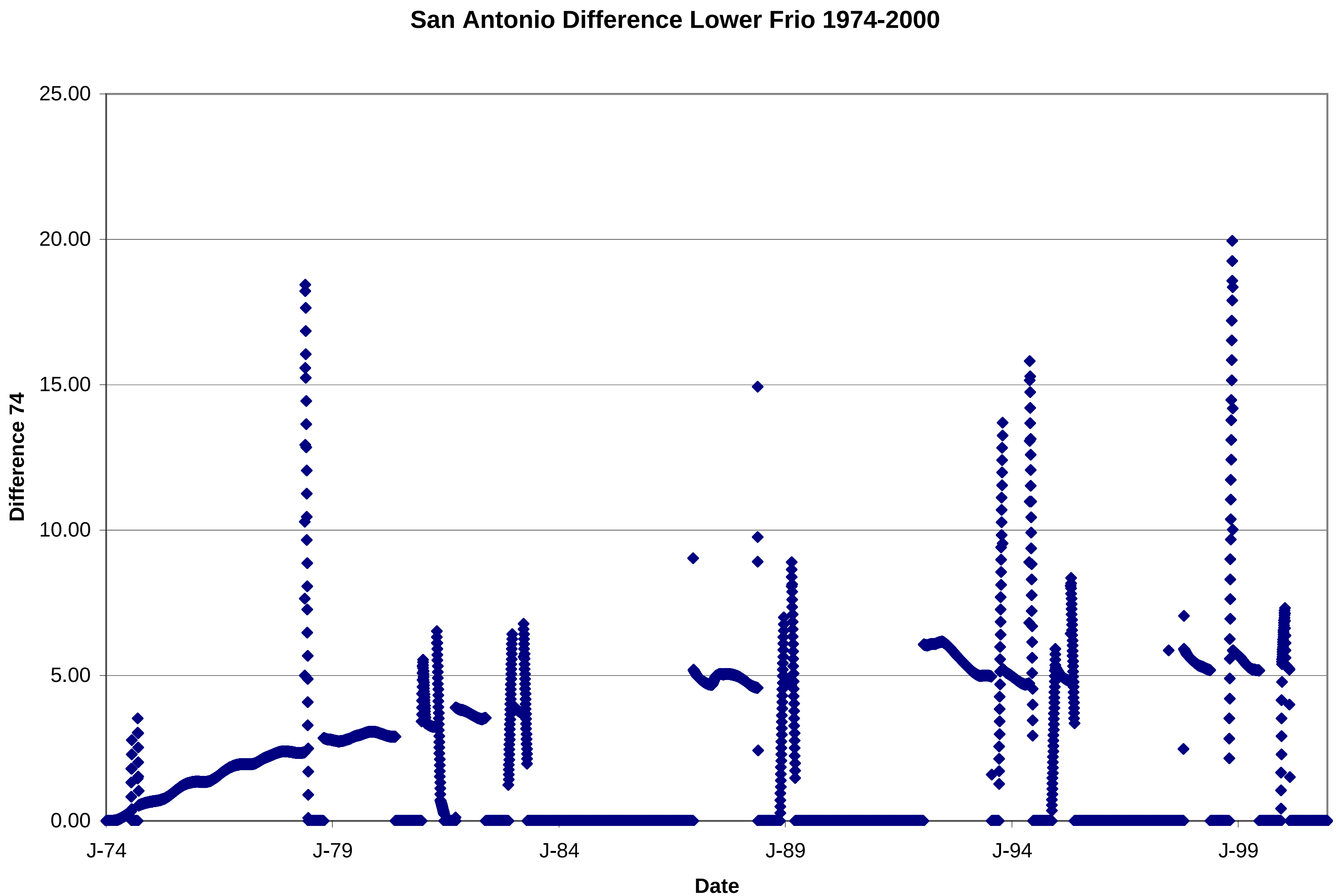
San Antonio Difference Indian Creek 1974-1978

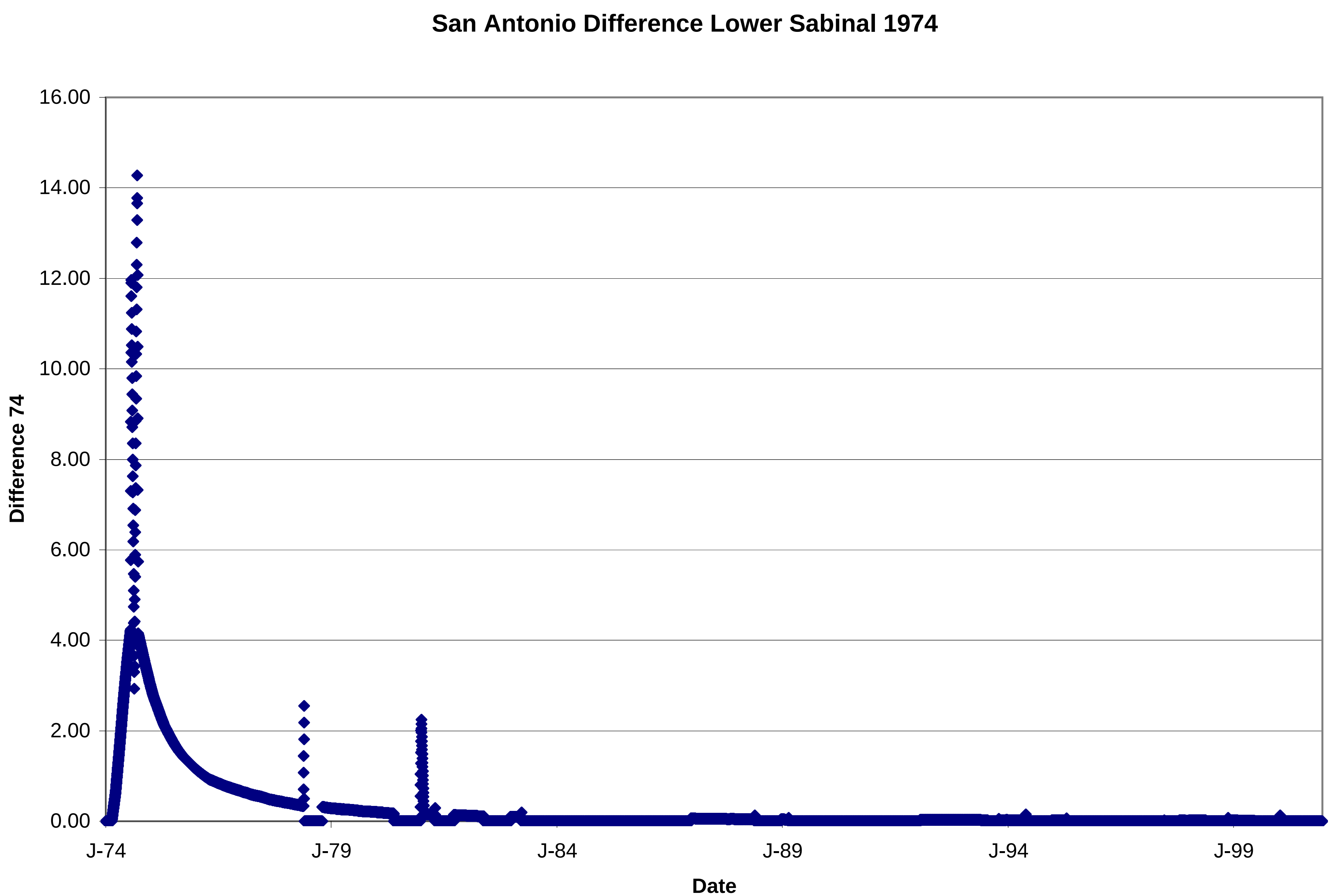



San Antonio Difference Indian Creek 1974-2000
Difference 74
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

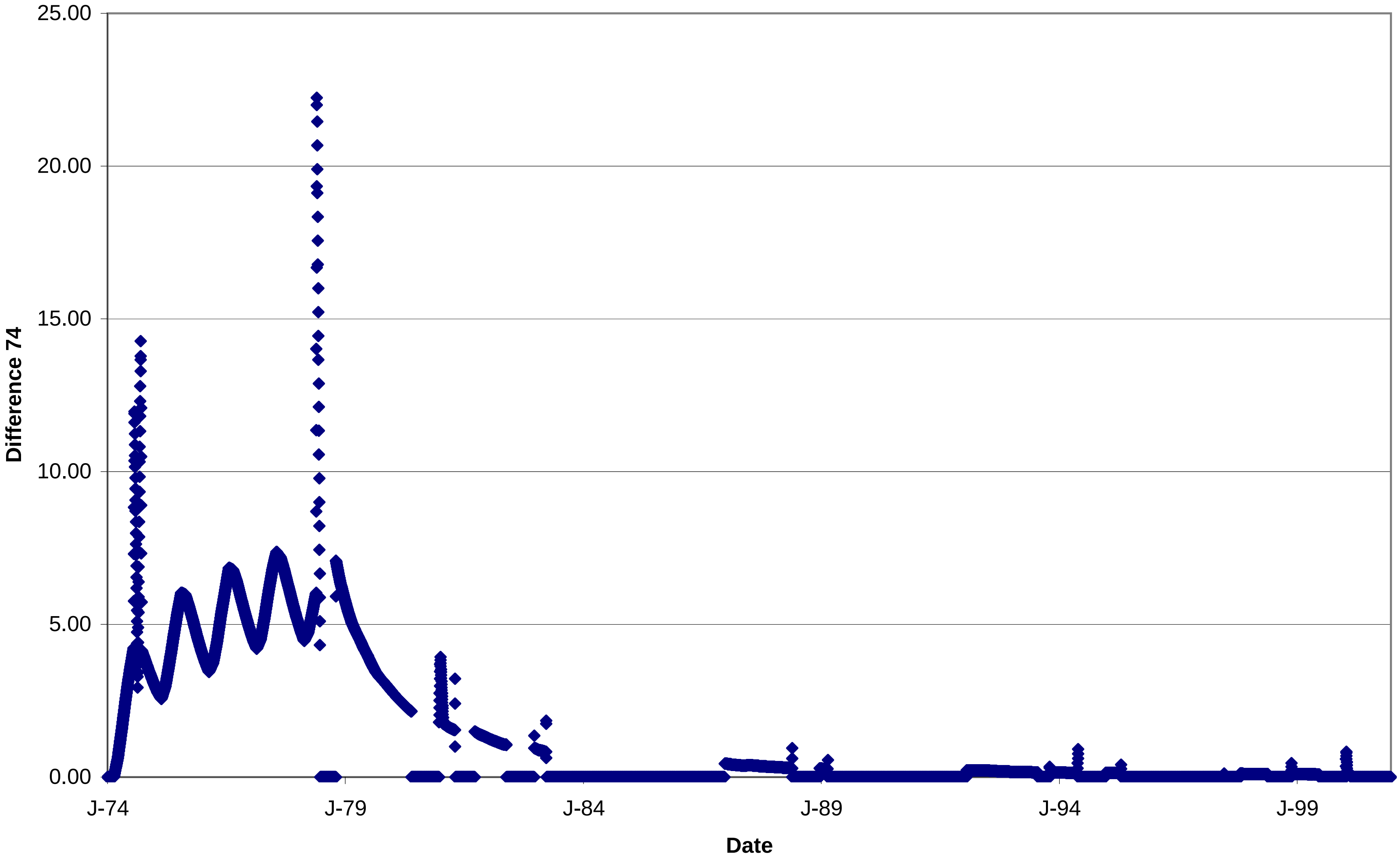

San Antonio Difference Lower Frio 1974
Difference 74
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date


San Antonio Difference Lower Frio1974-1978
Difference 74
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

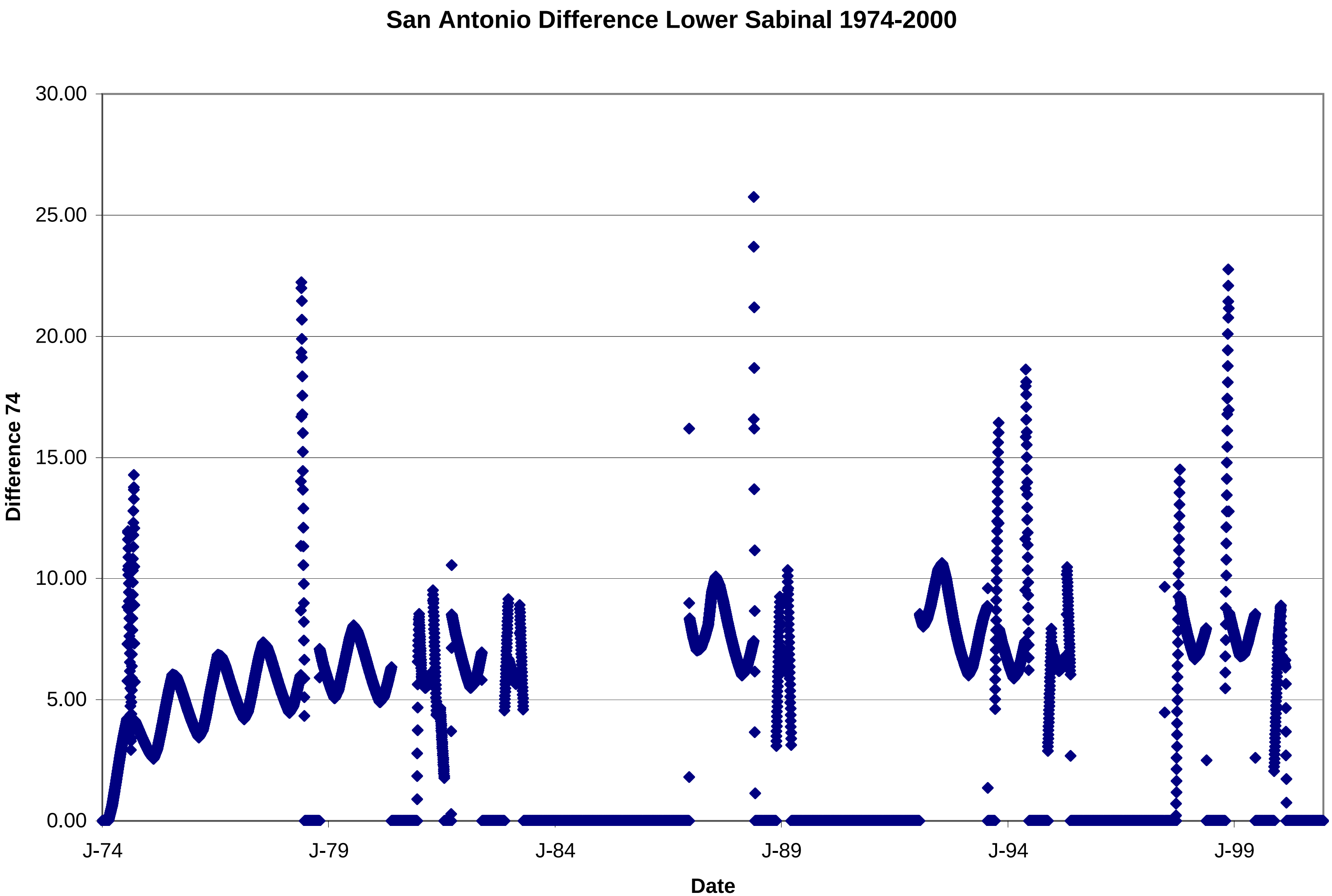

San Antonio Difference Lower Frio 1974-2000
25.00
20.00
15.00
10.00
5.00
0.00
Difference 74
J-74
J-79
J-84
J-89
J-94
J-99
Date

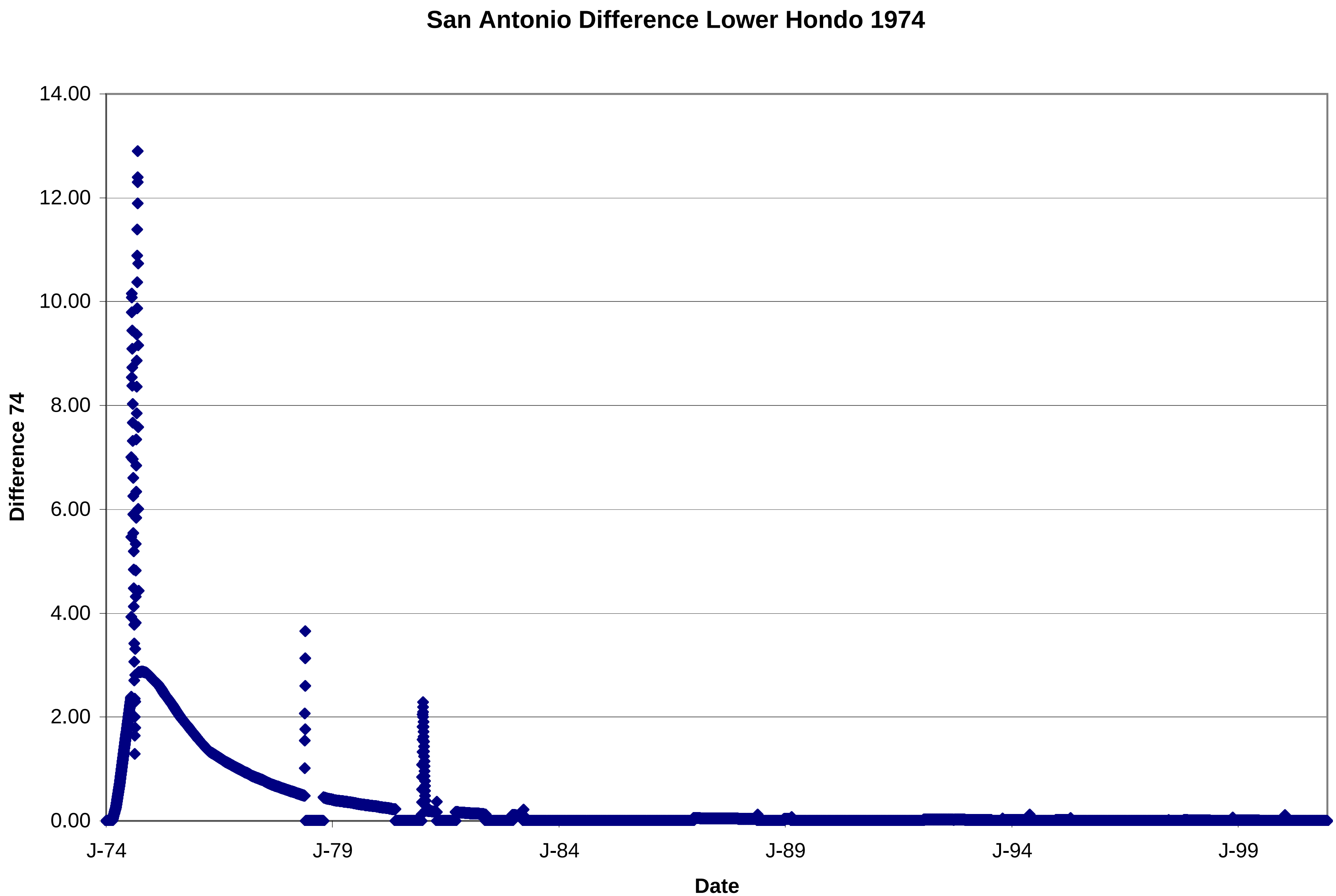

San Antonio Difference Lower Sabinal 1974
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Difference 74
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Antonio Difference Lower Sabinal 1974-1978

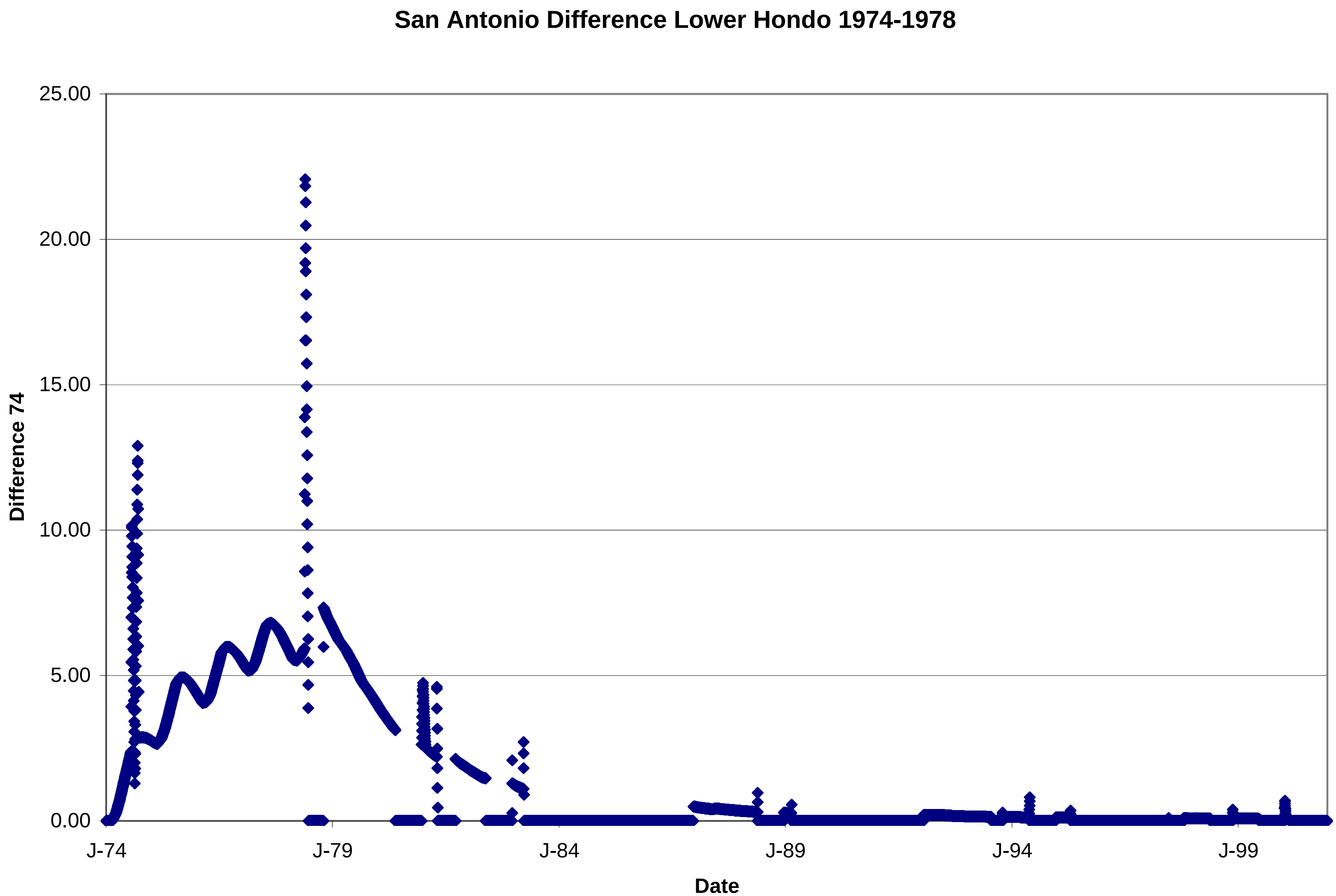


San Antonio Difference Lower Sabinal 1974-2000

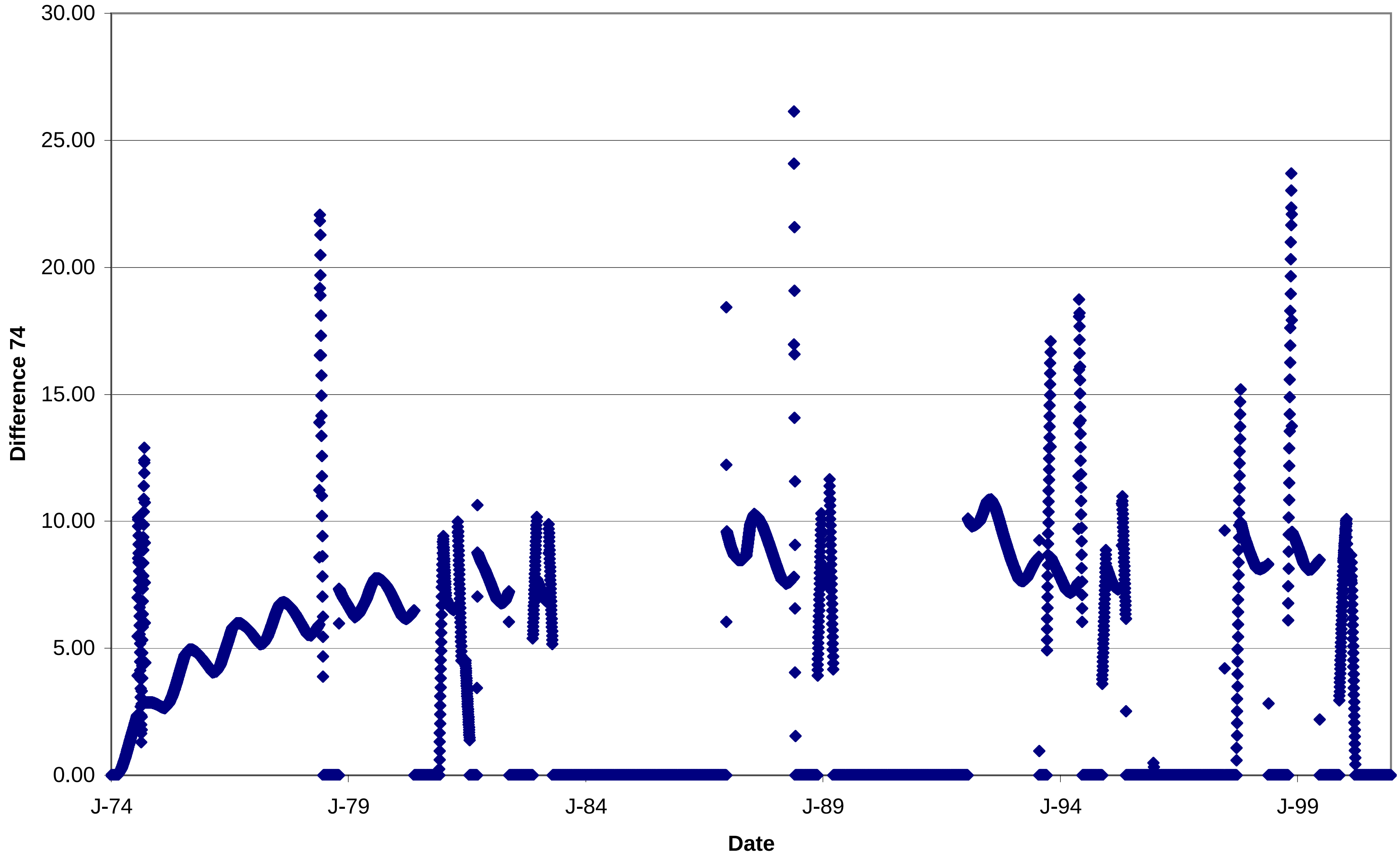




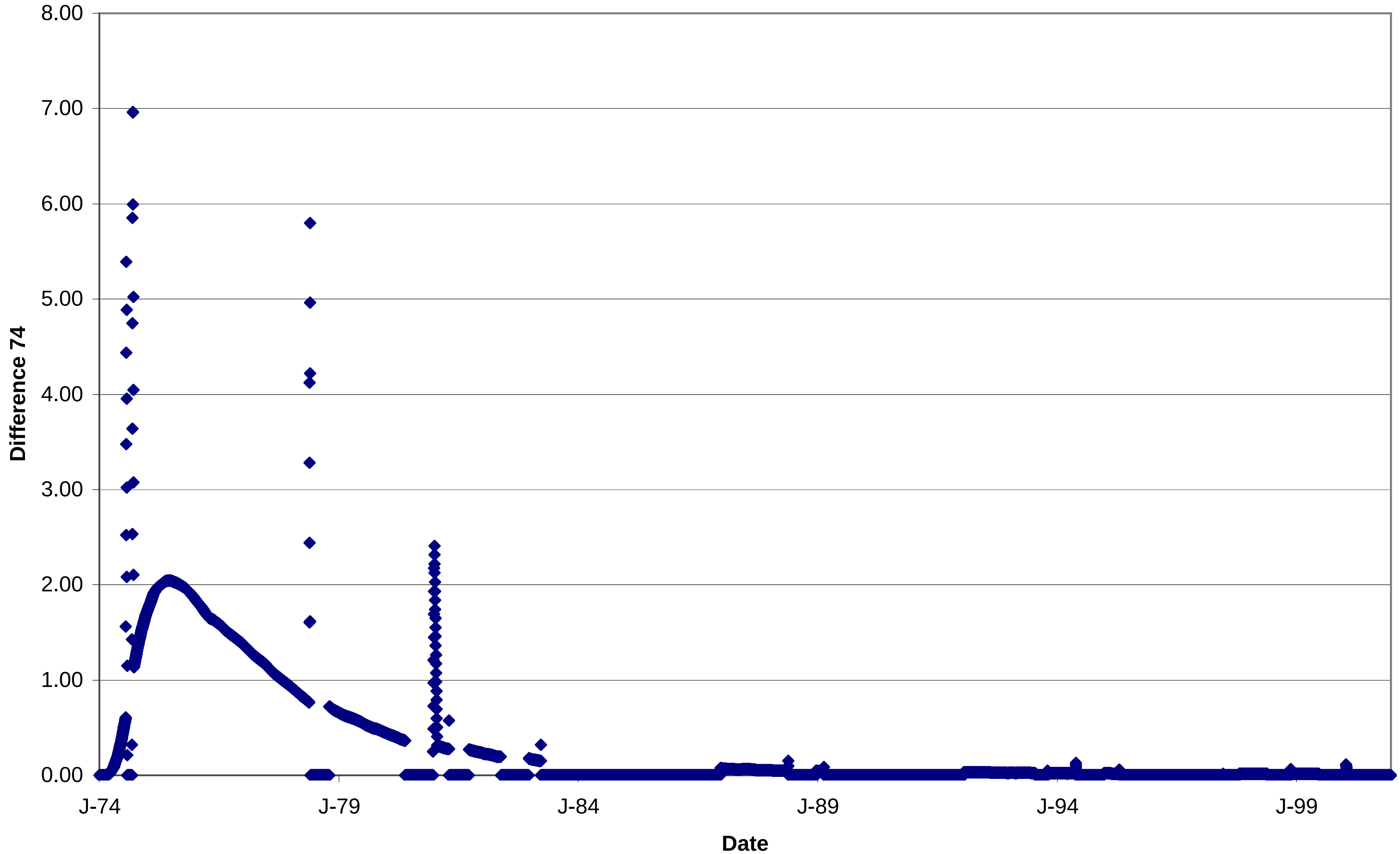
San Antonio Difference Lower Hondo 1974
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Difference 74
J-74
J-79
J-84
J-89
J-94
J-99
Date

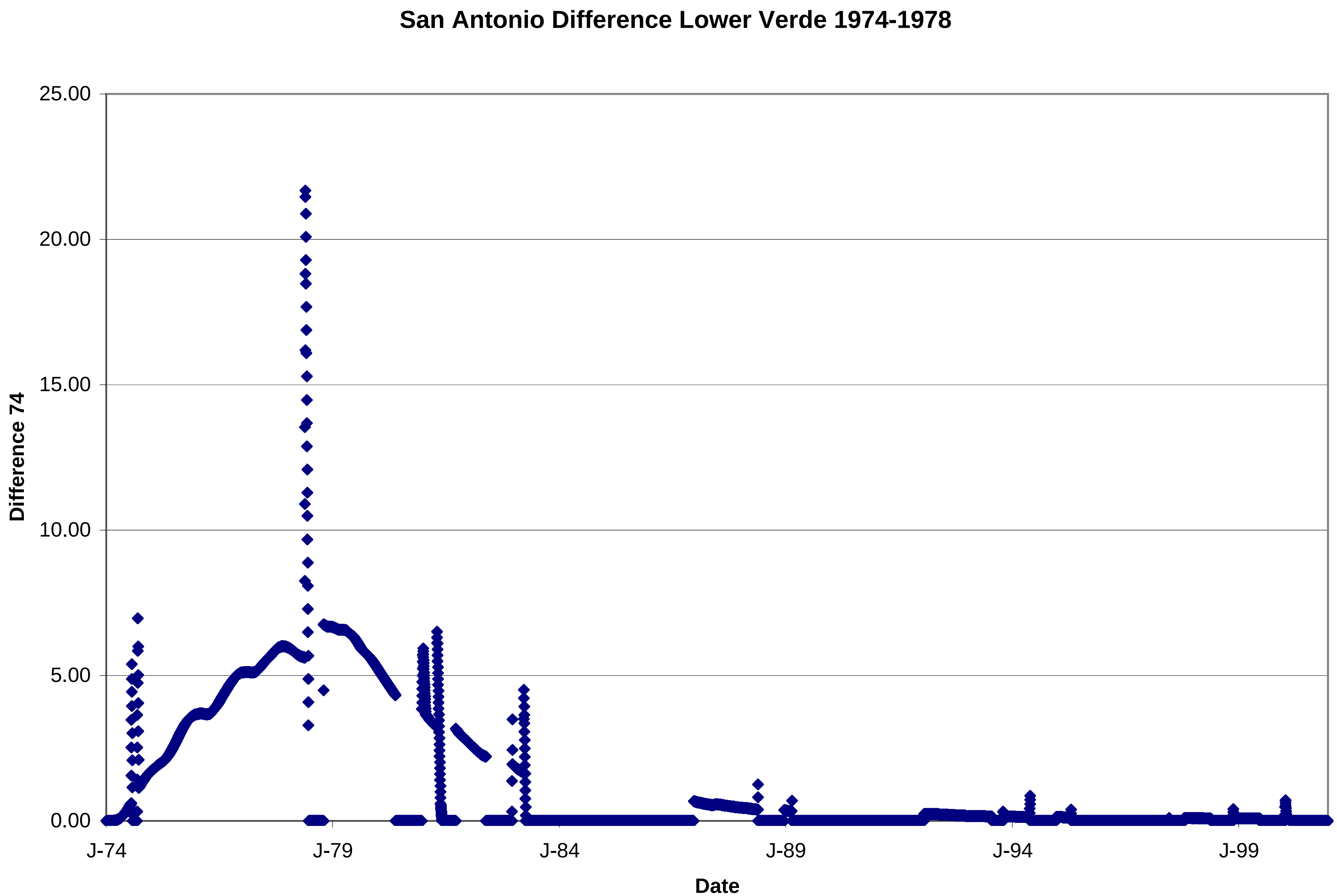

San Antonio Difference Lower Hondo 1974-1978
25.00
20.00
15.00
10.00
5.00
0.00
Difference 74
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Antonio Difference Lower Hondo 1974-2000

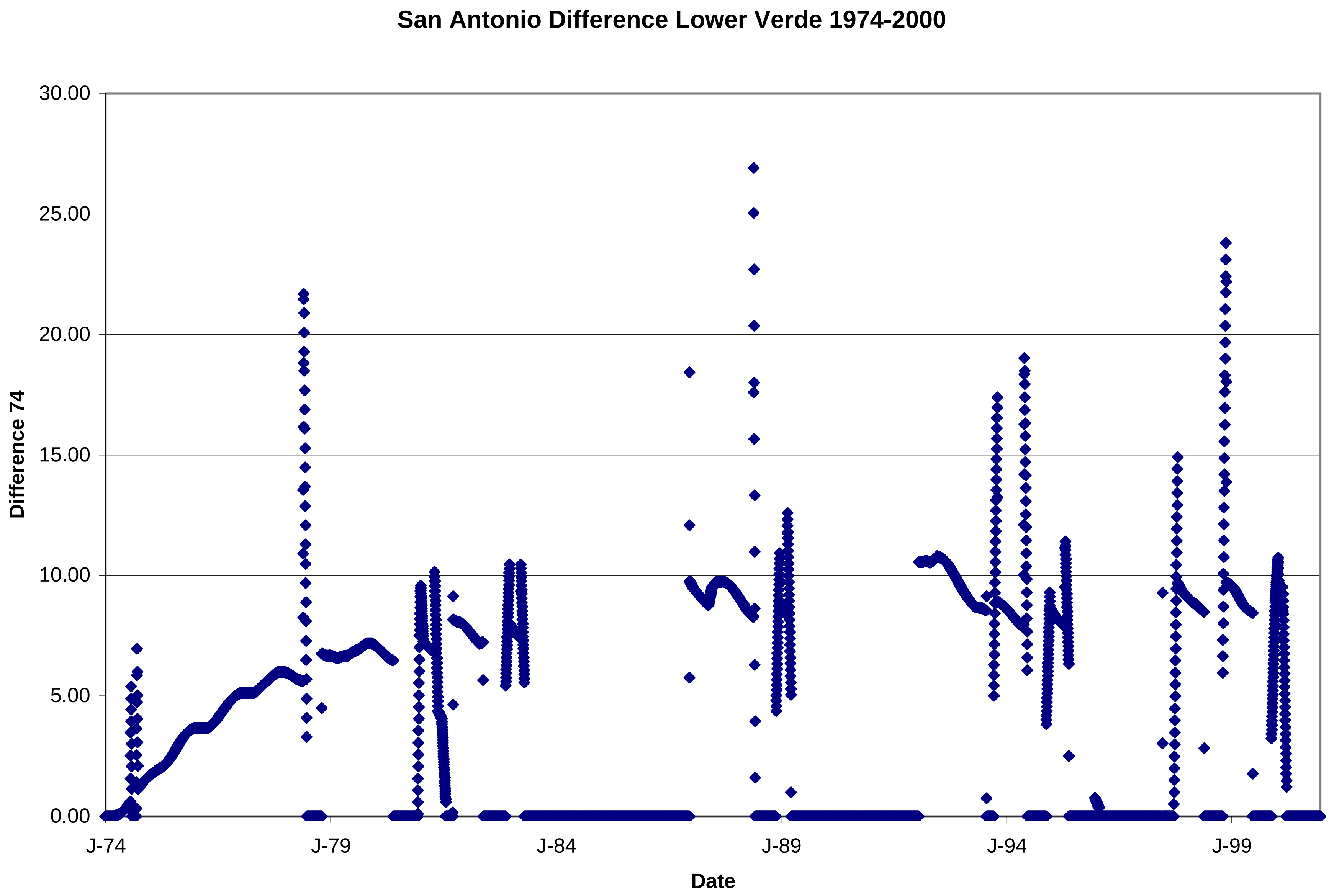


San Antonio Difference Lower Verde 1974

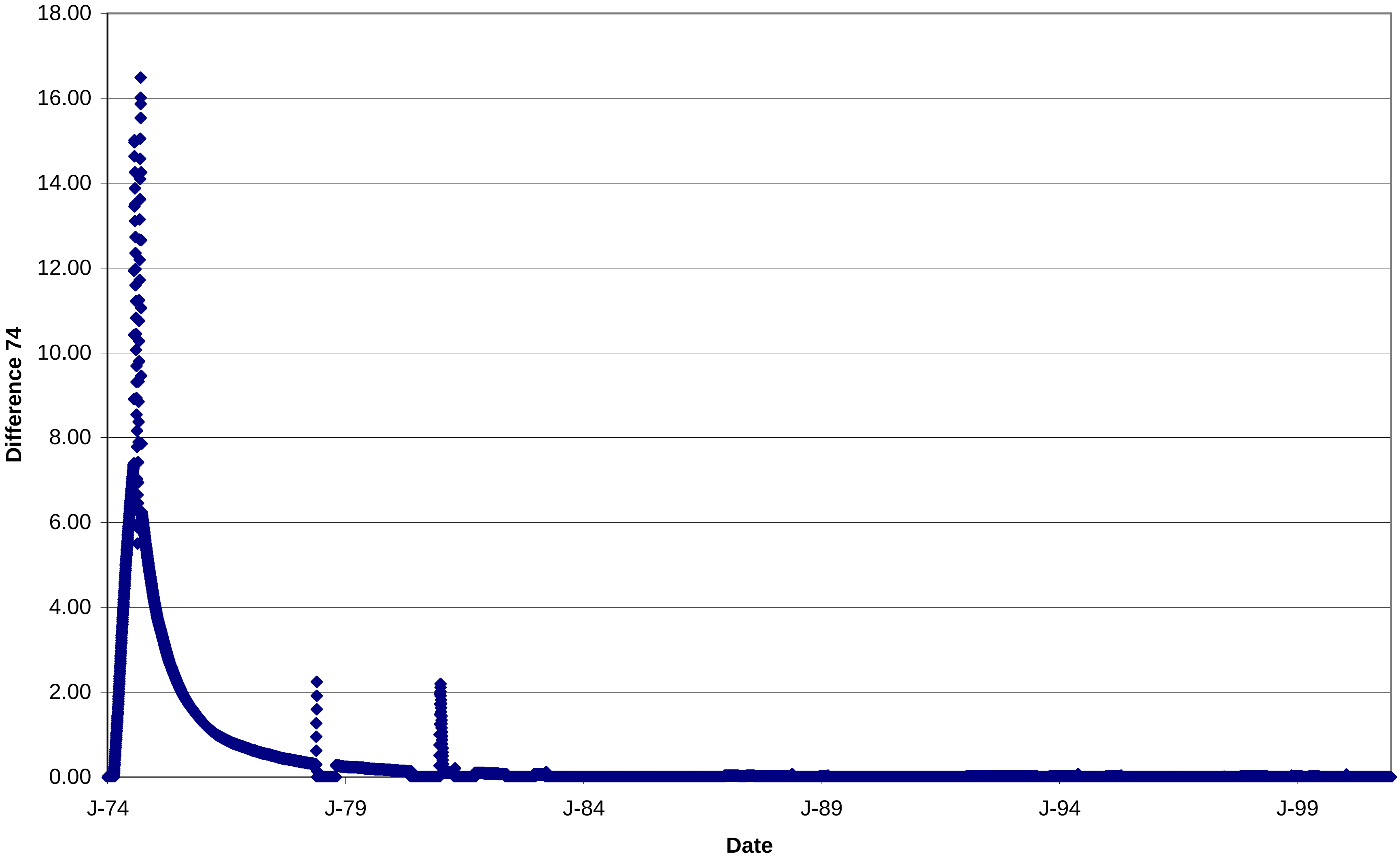


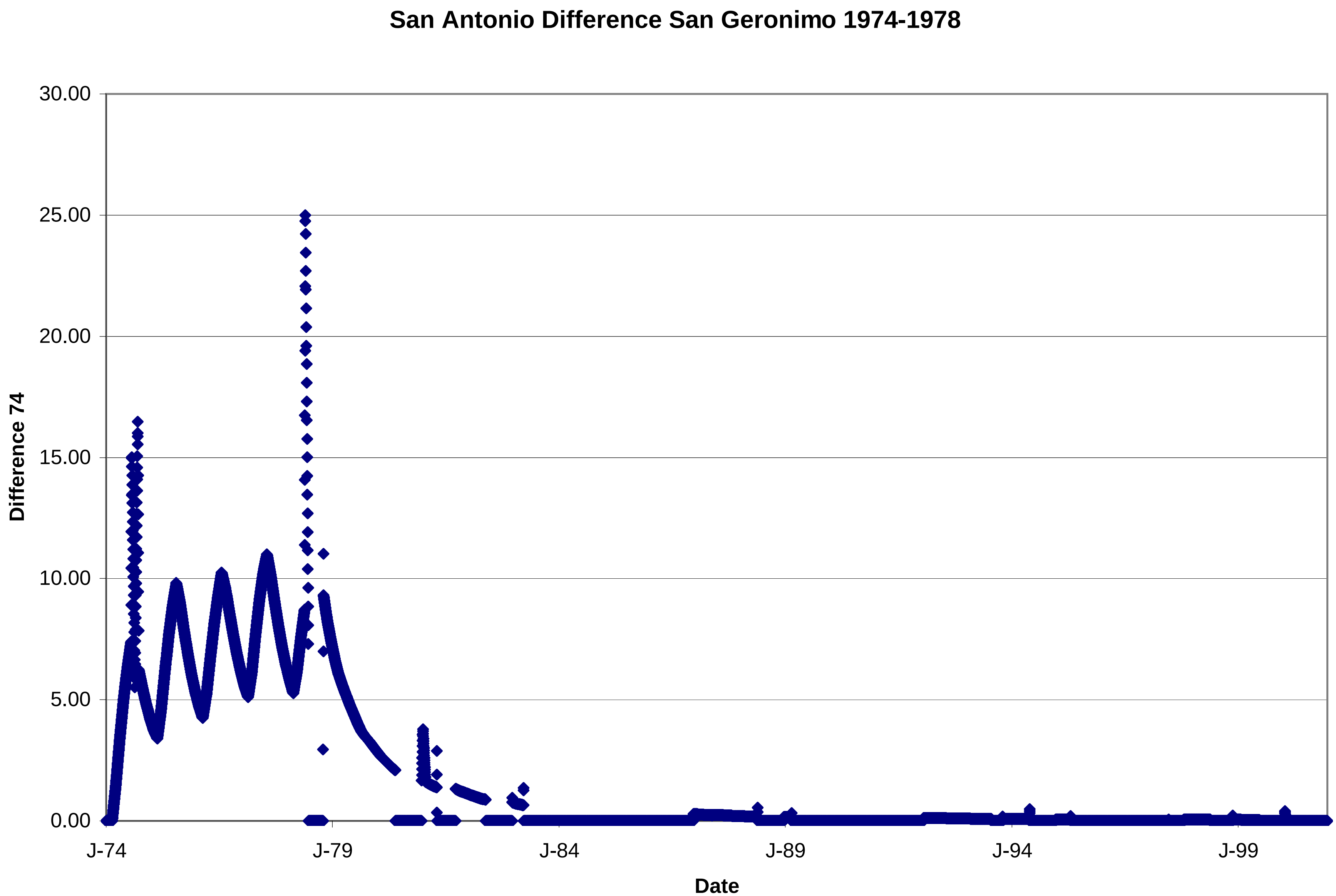

San Antonio Difference Lower Verde 1974-1978
25.00
20.00
15.00
10.00
5.00
0.00
Difference 74
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Antonio Difference Lower Verde 1974-2000

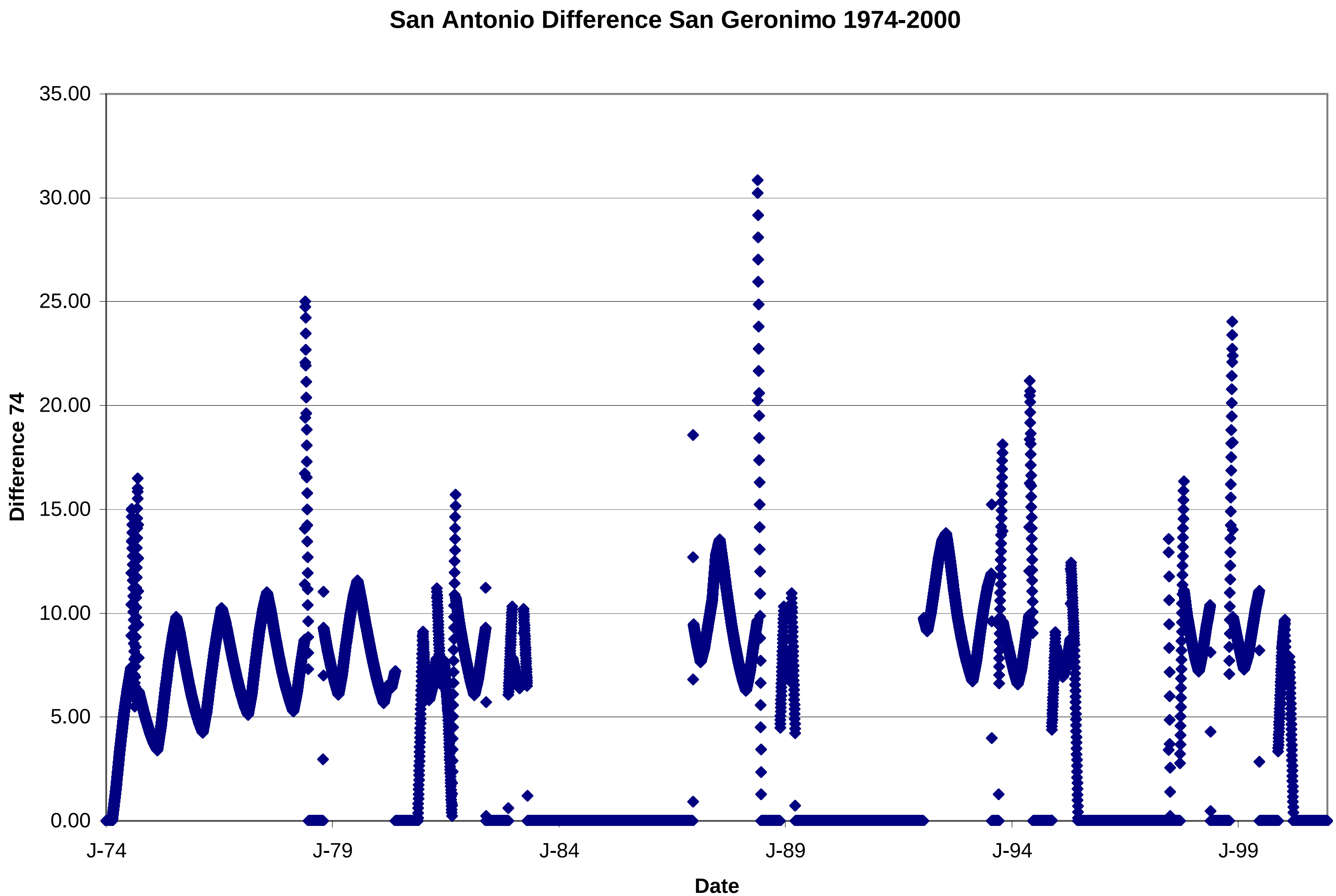


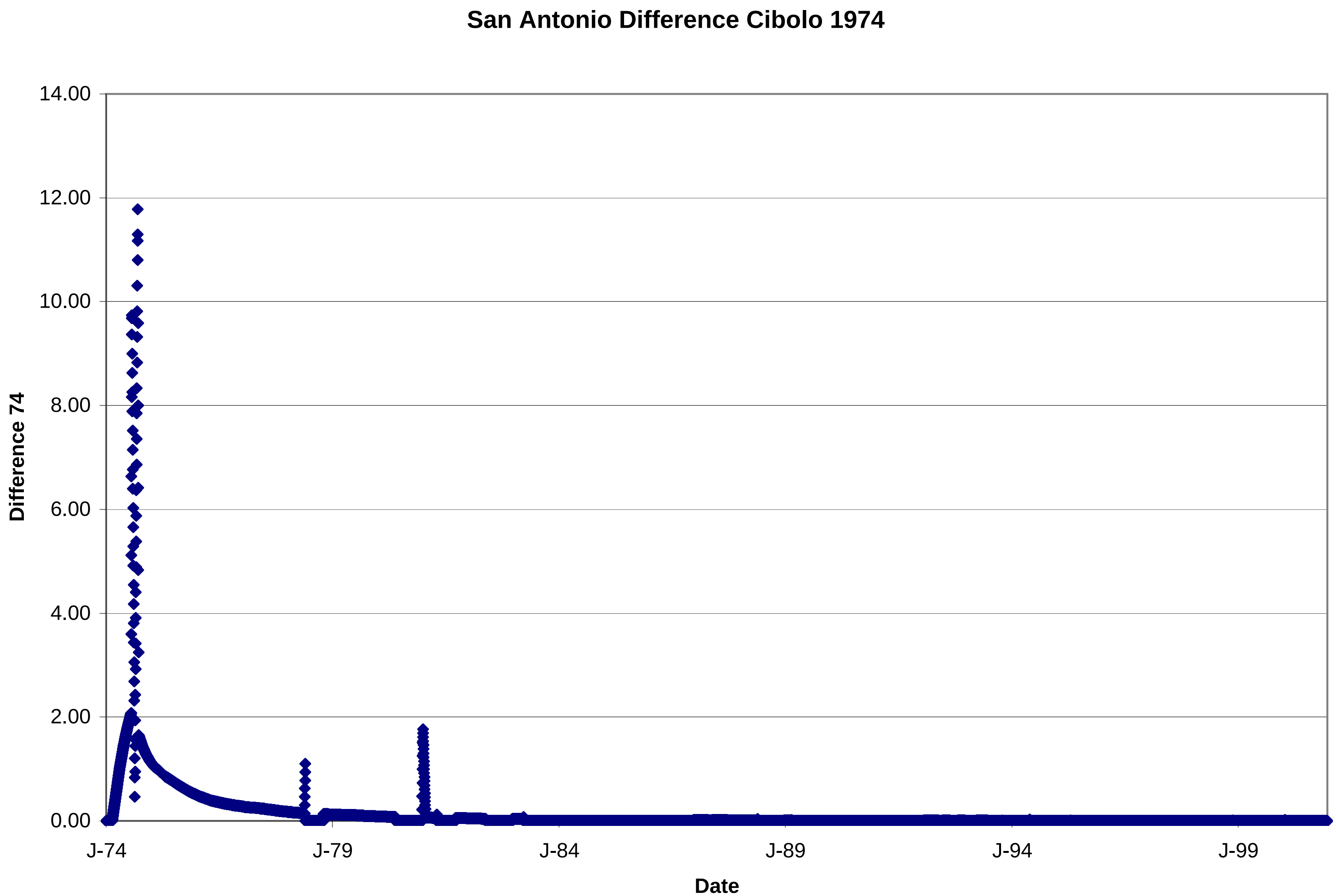
San Antonio Difference San Geronimo 1974

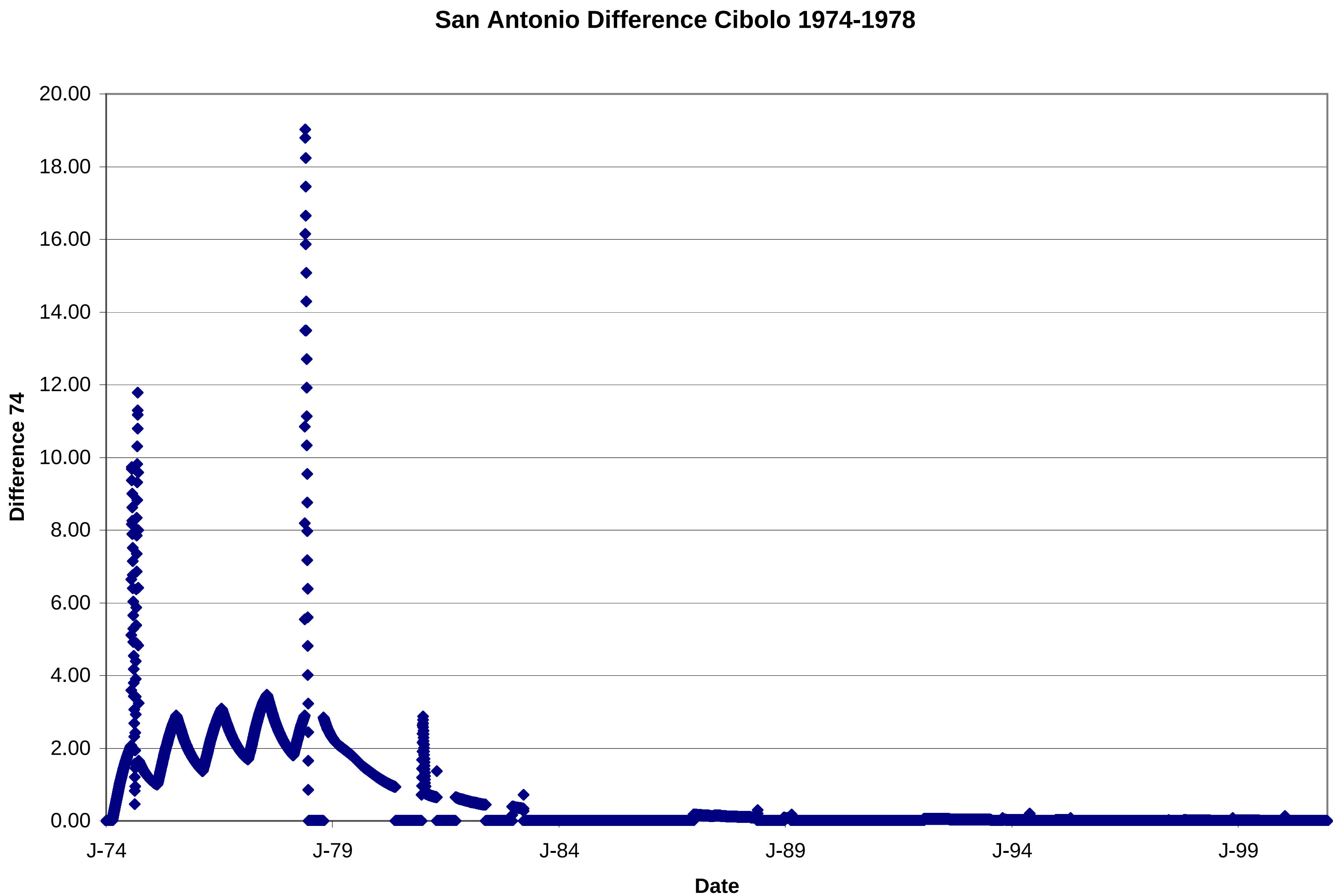




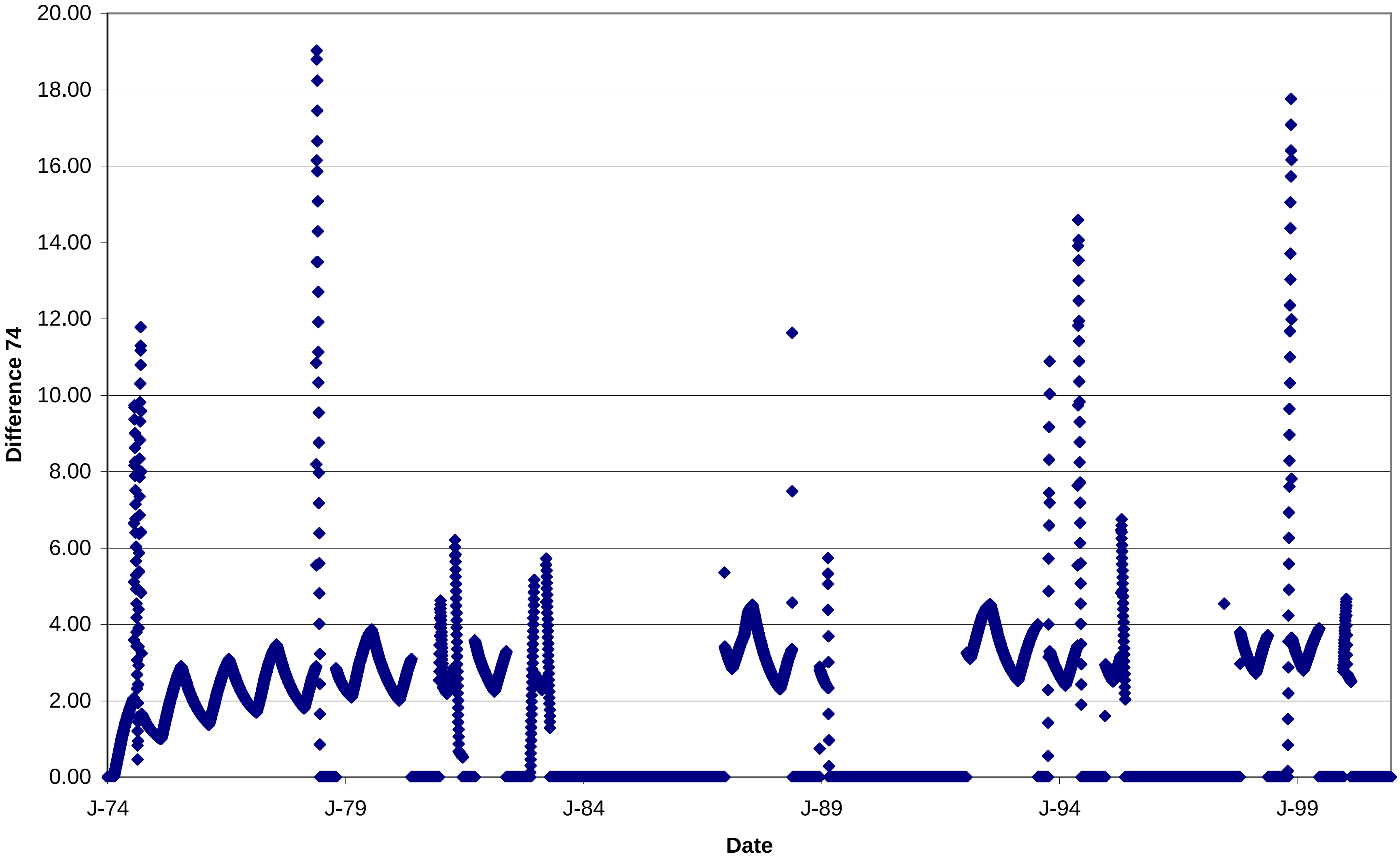
San Antonio Difference San Geronimo 1974-1978
Difference 74
30.00
25.00
20.00
15.00
10.00
5.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

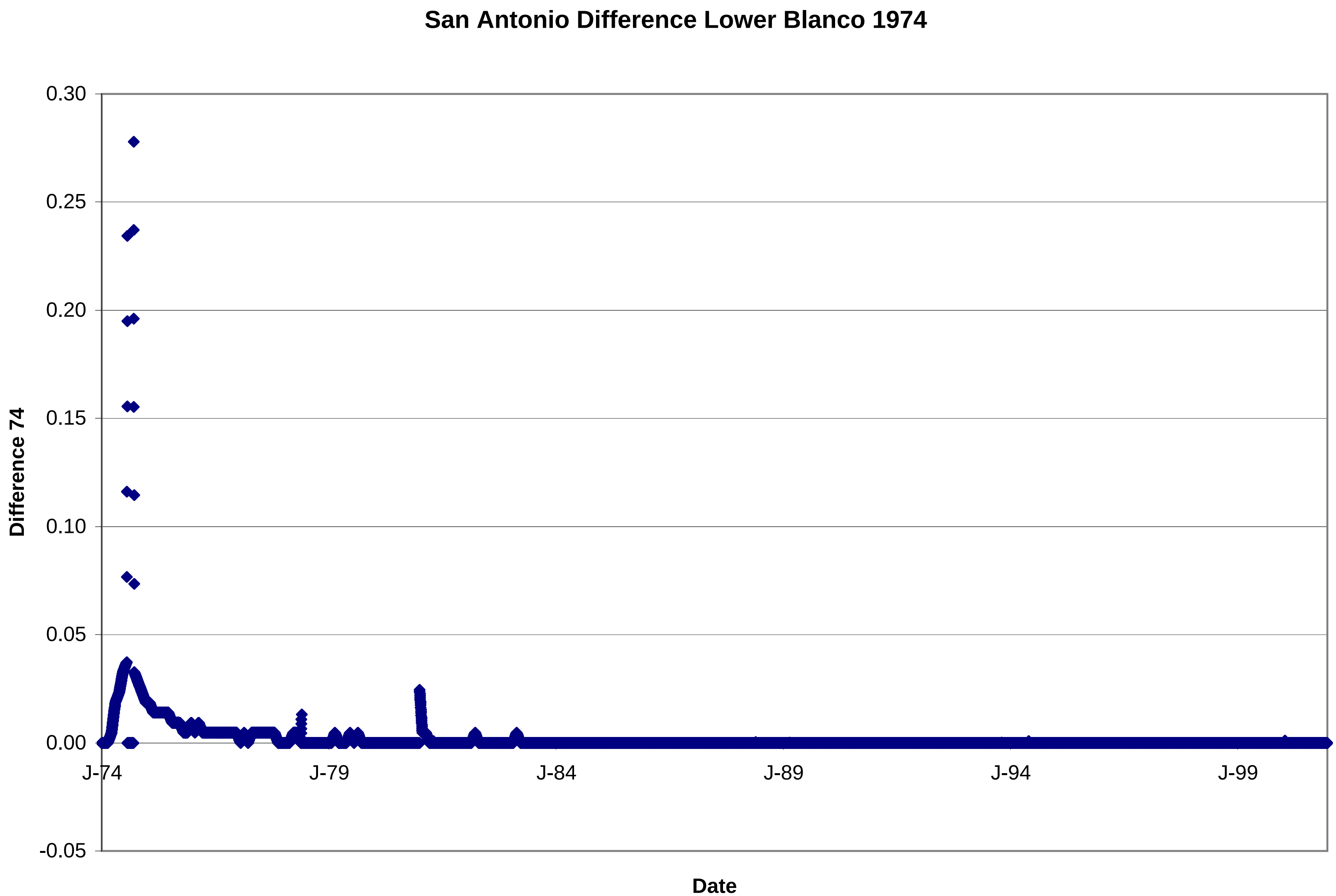

San Antonio Difference San Geronimo 1974-2000
Difference 74
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date


San Antonio Difference Cibolo 1974
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Difference 74
J-74
J-79
J-84
J-89
J-94
J-99
Date

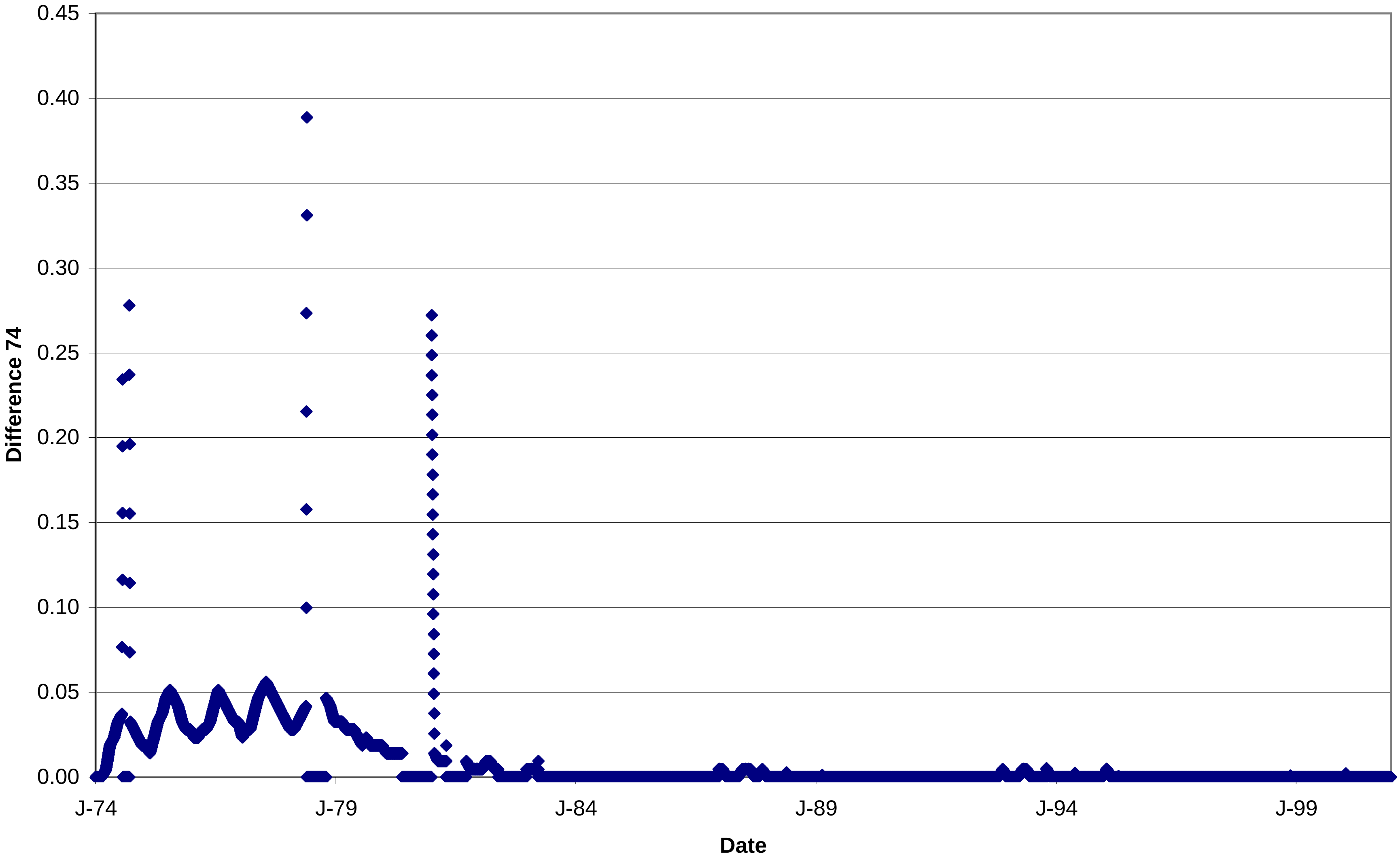

San Antonio Difference Cibolo 1974-1978
Difference 74
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Antonio Difference Cibolo 1974-2000

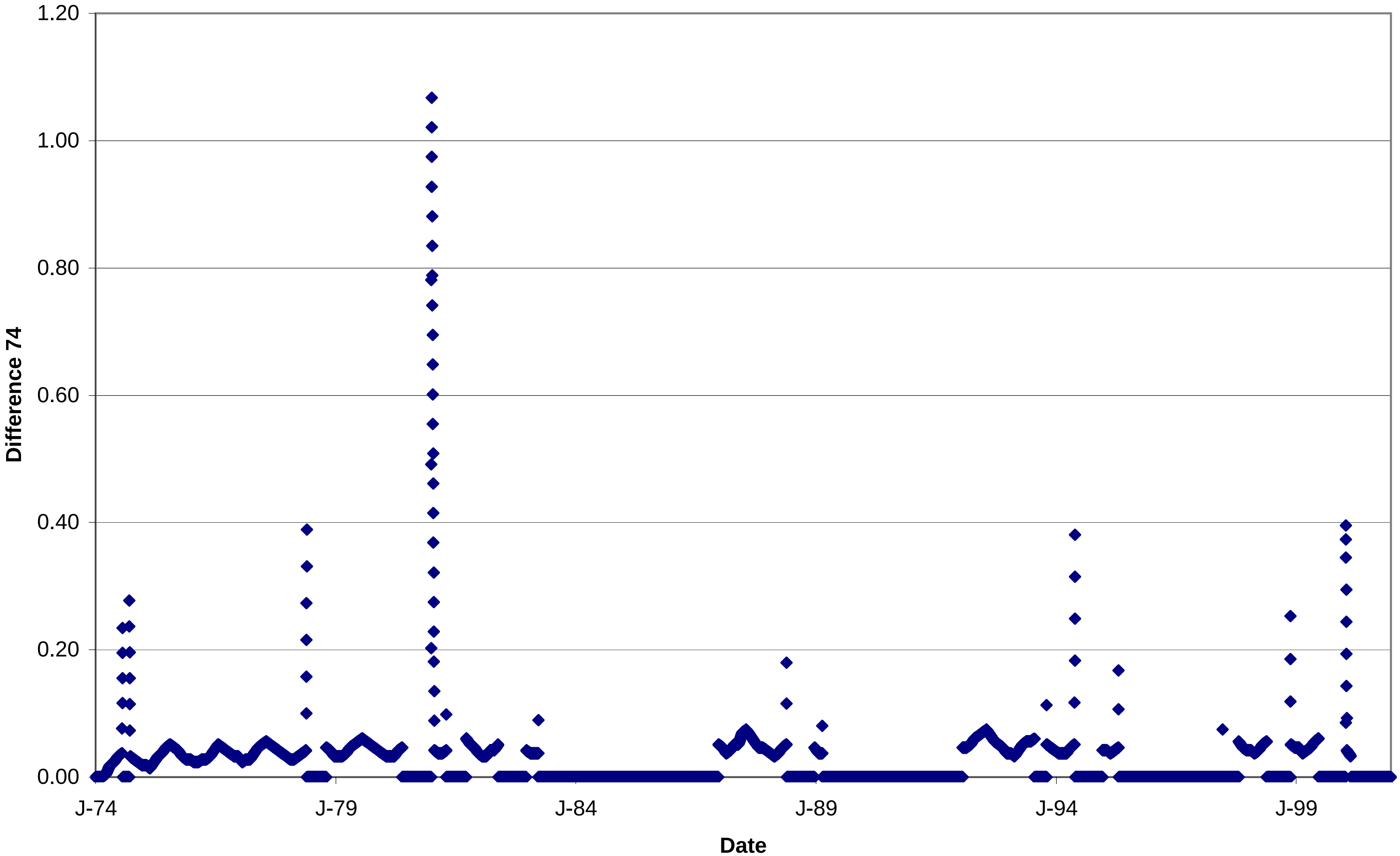


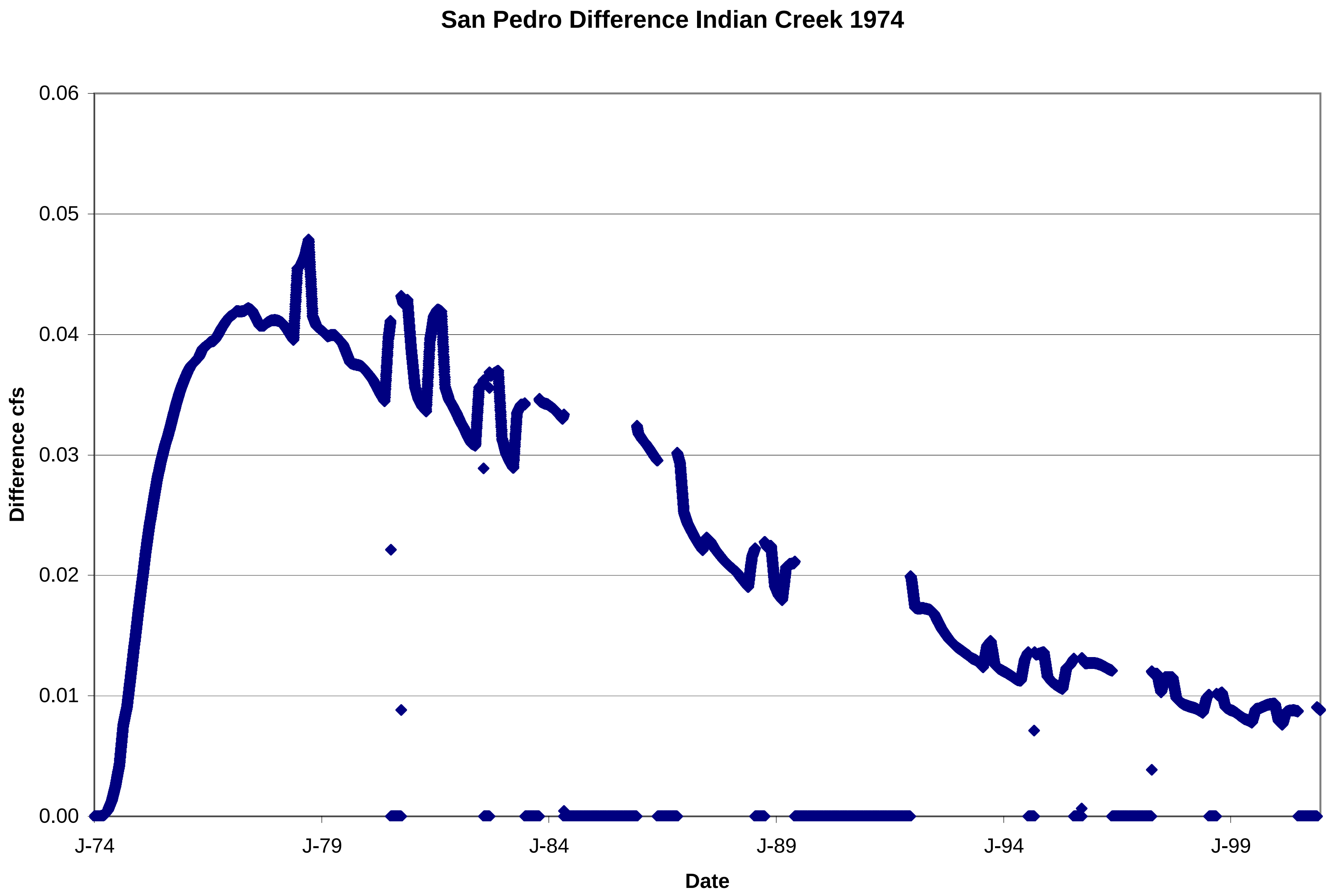

San Antonio Difference Lower Blanco 1974
Difference 74
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
J-74
J-79
J-84
J-89
J-94
J-99
Date

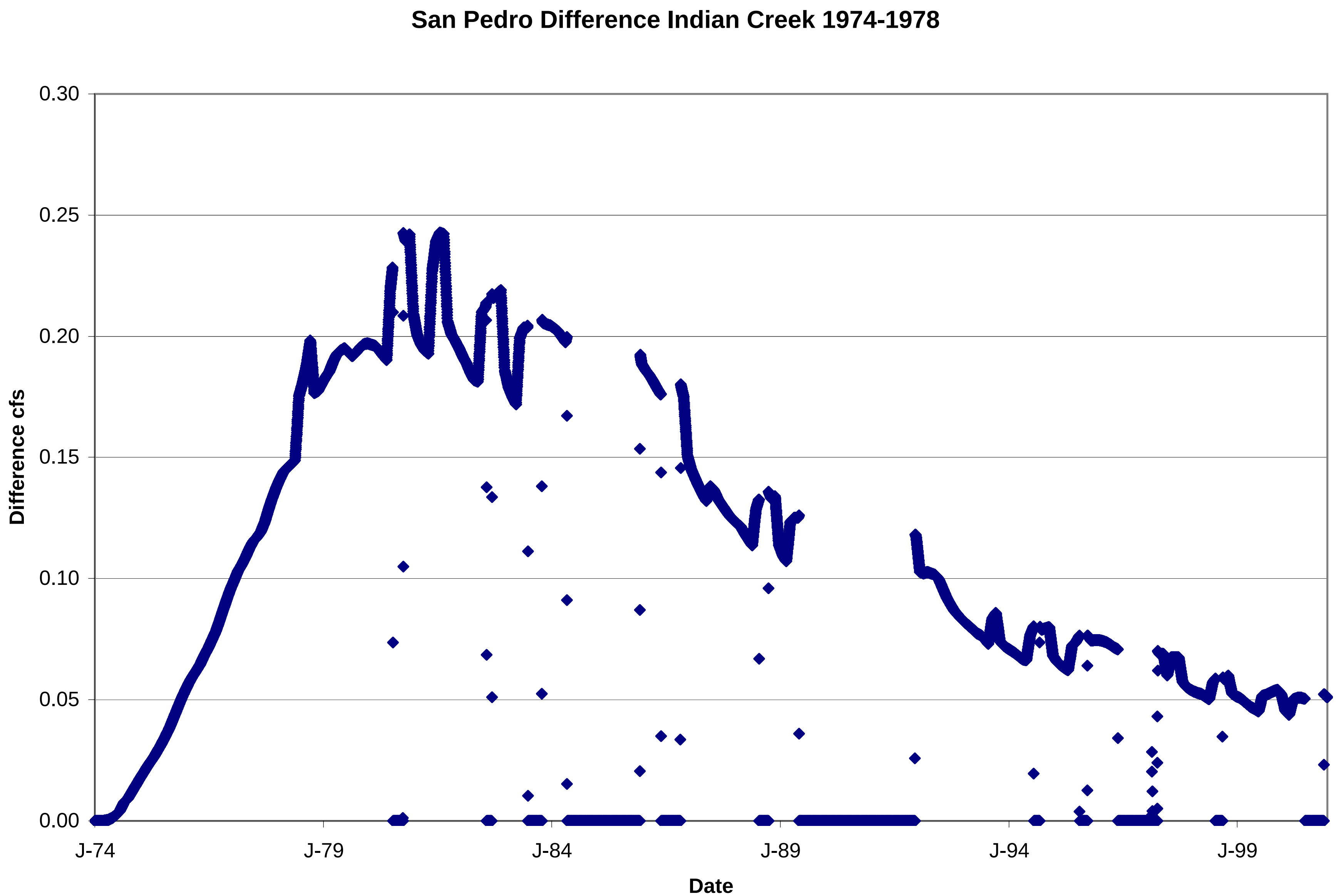
San Antonio Difference Lower Blanco 1974-1978



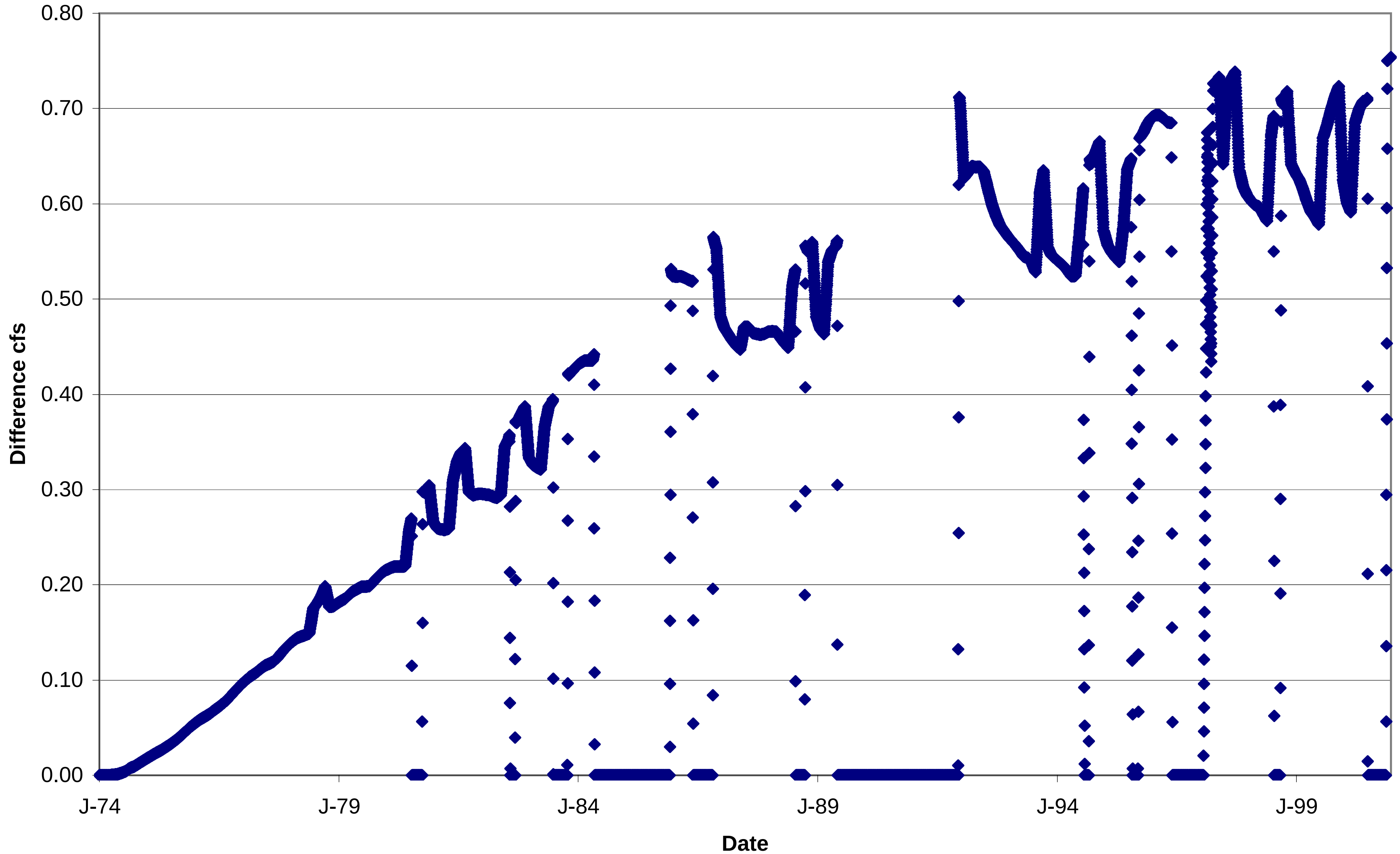
San Antonio Difference Lower Blanco 1974-2000



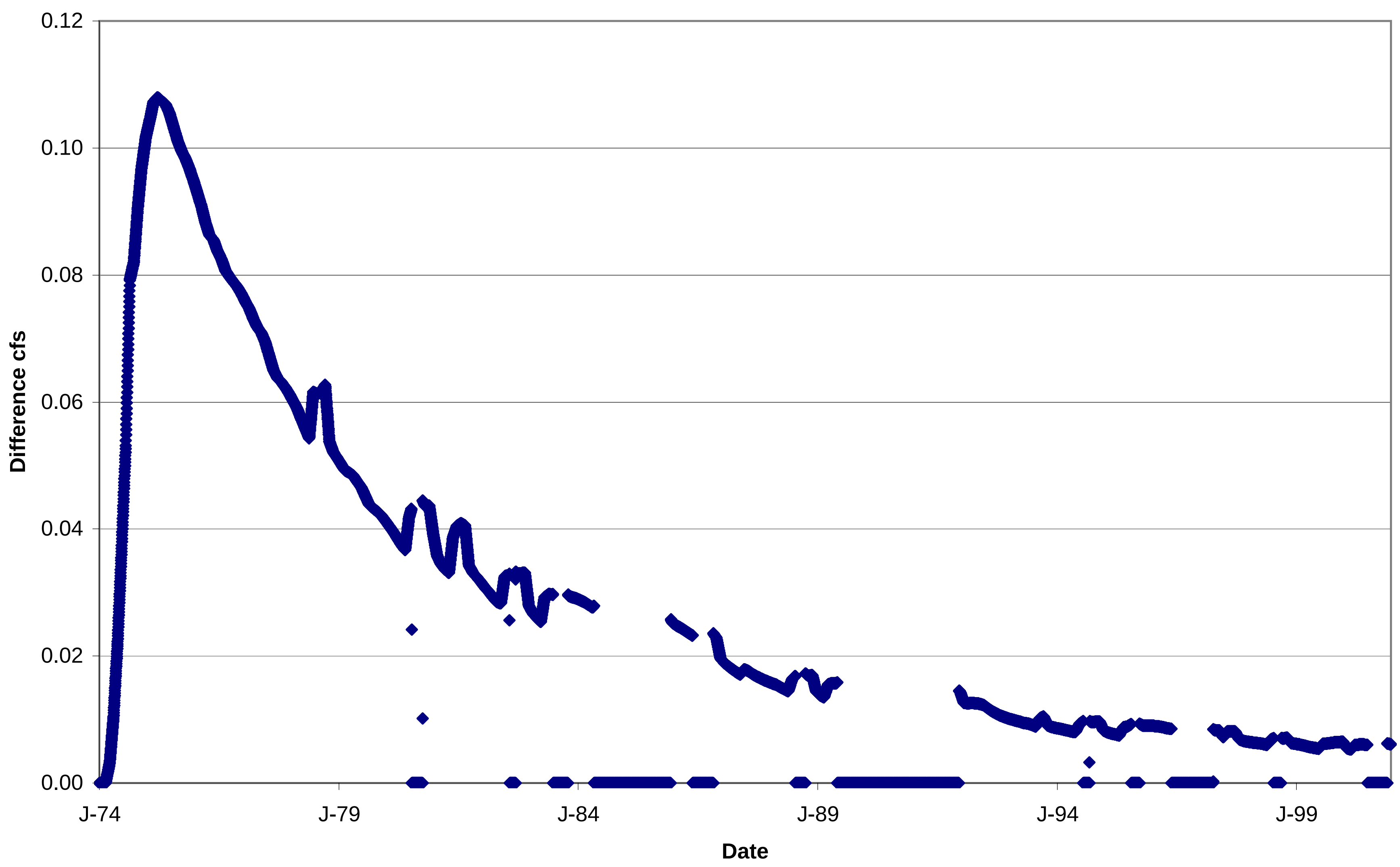

San Pedro Difference Indian Creek 1974
Difference cfs
0.06
0.05
0.04
0.03
0.02
0.01
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

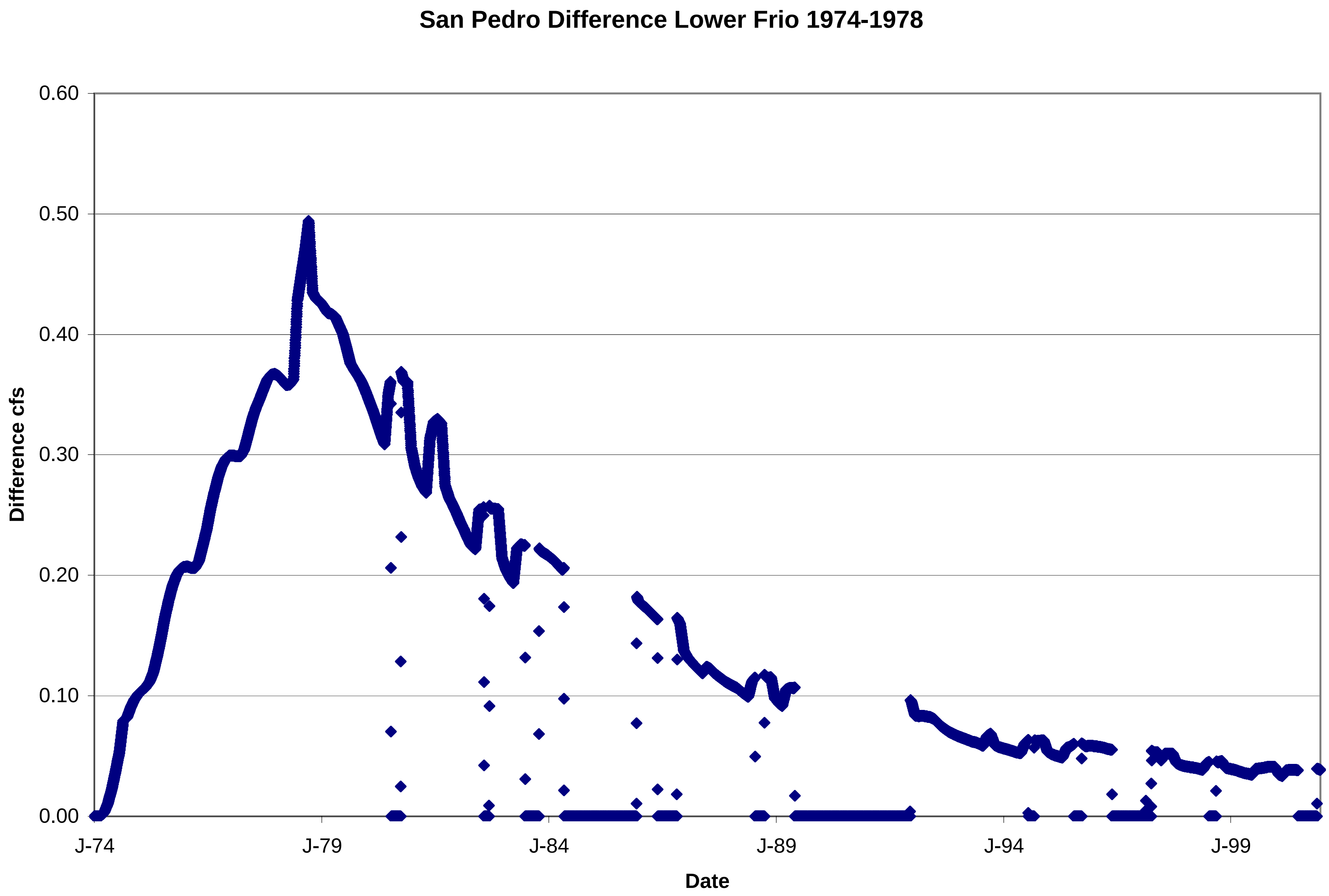

San Pedro Difference Indian Creek 1974-1978
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Pedro Difference Indian Creek 1974-2000



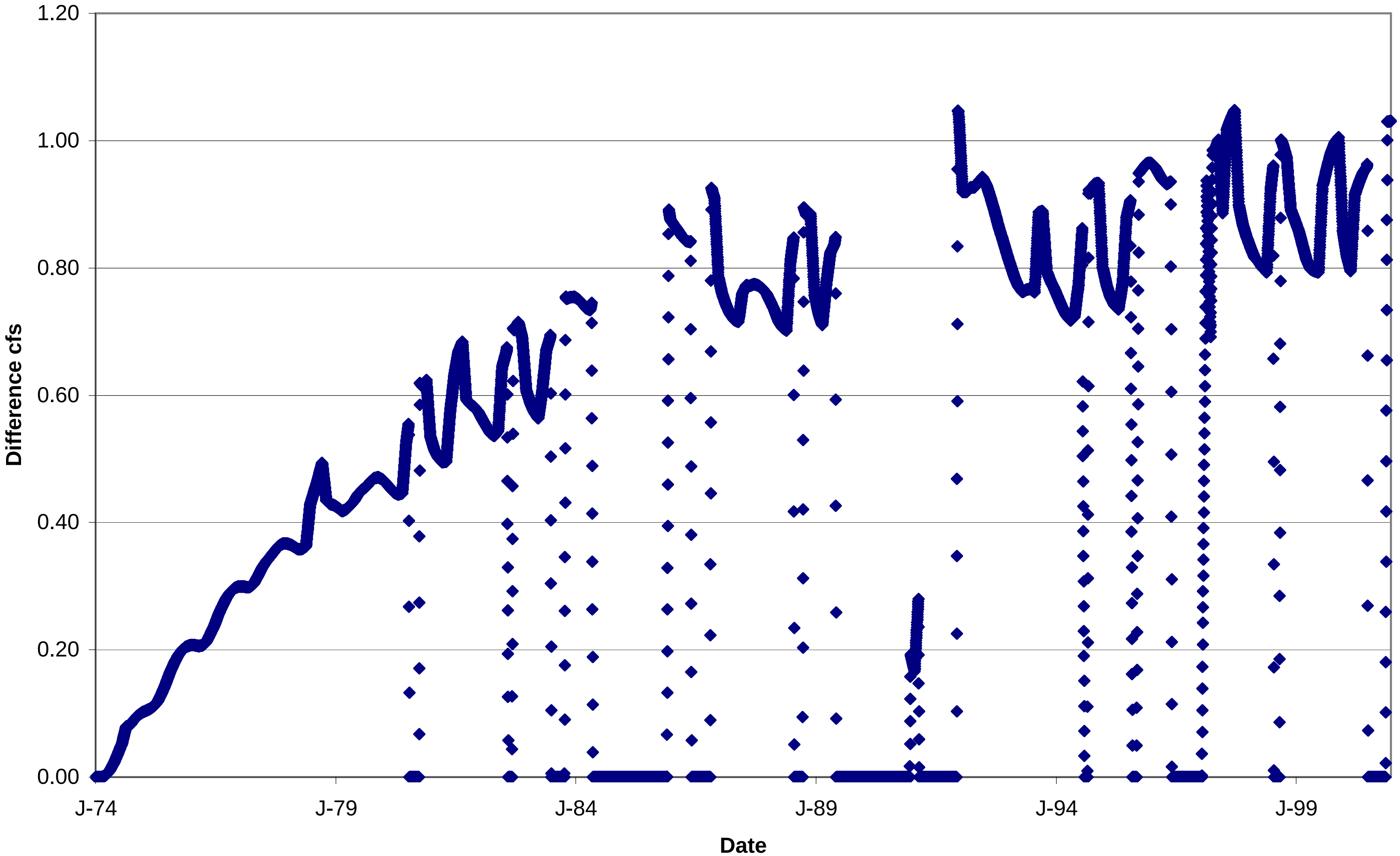
San Pedro Difference Lower Frio 1974

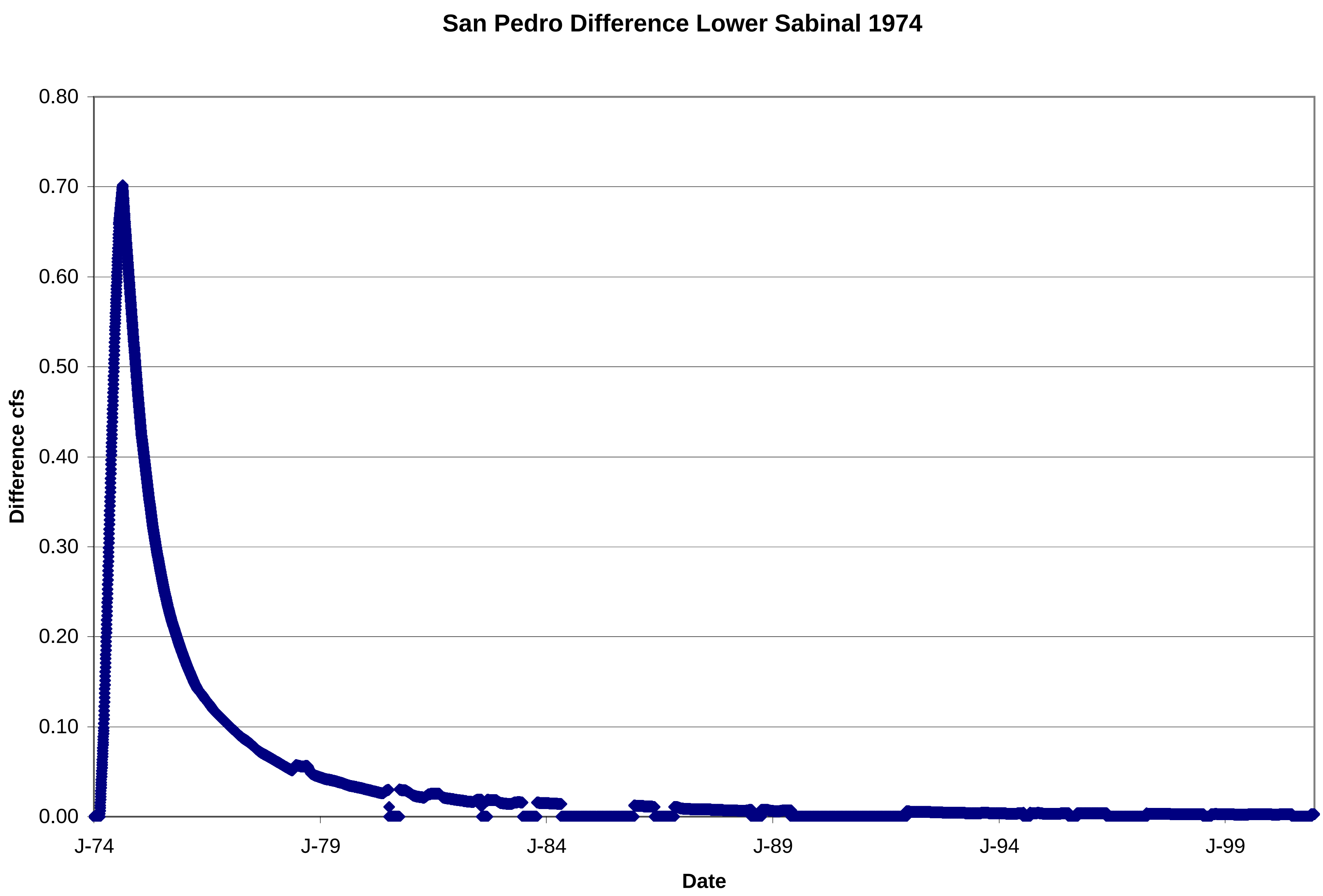




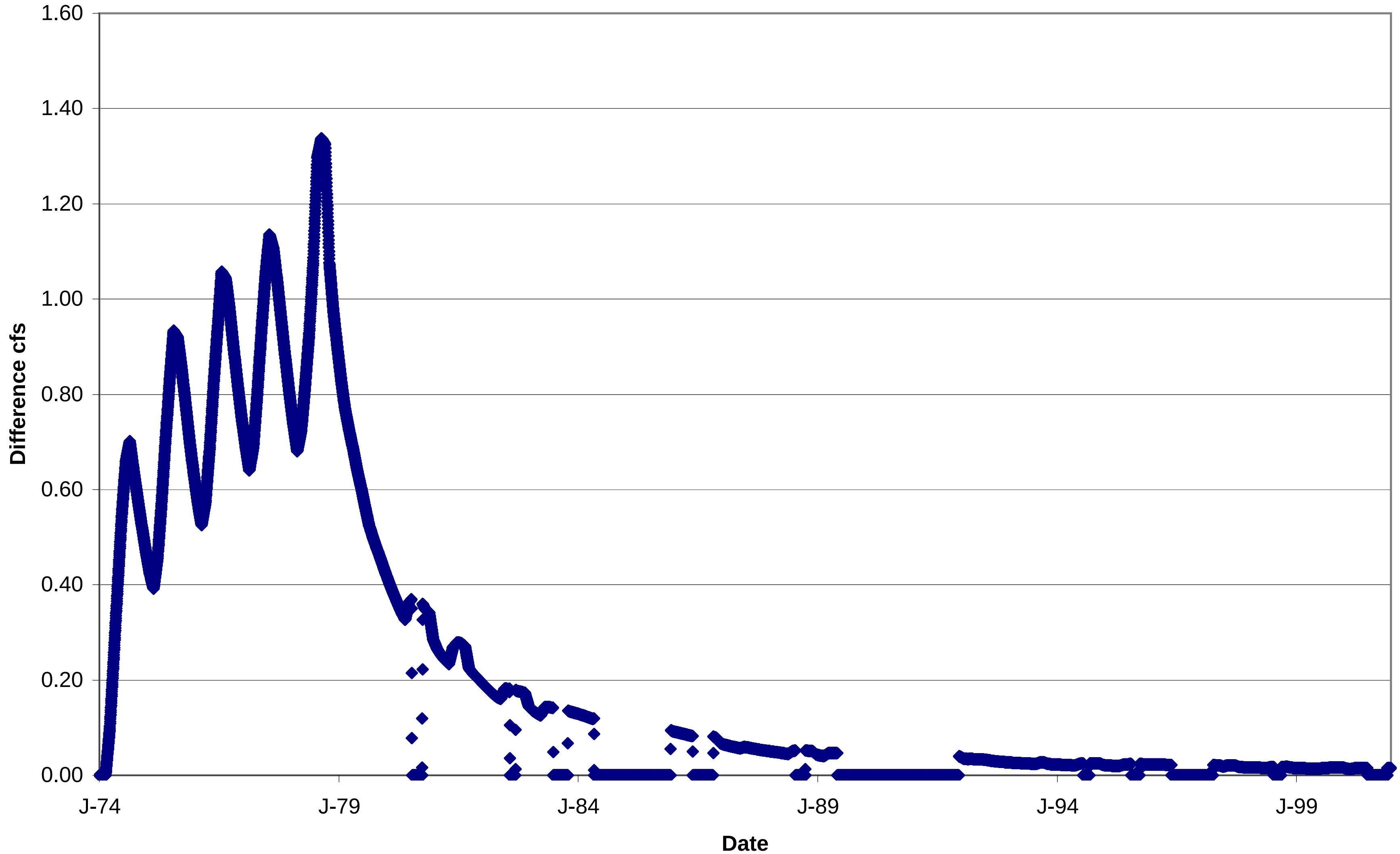
San Pedro Difference Lower Frio 1974-1978
Difference cfs
0.60
0.50
0.40
0.30
0.20
0.10
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Pedro Difference Lower Frio 1974-2000

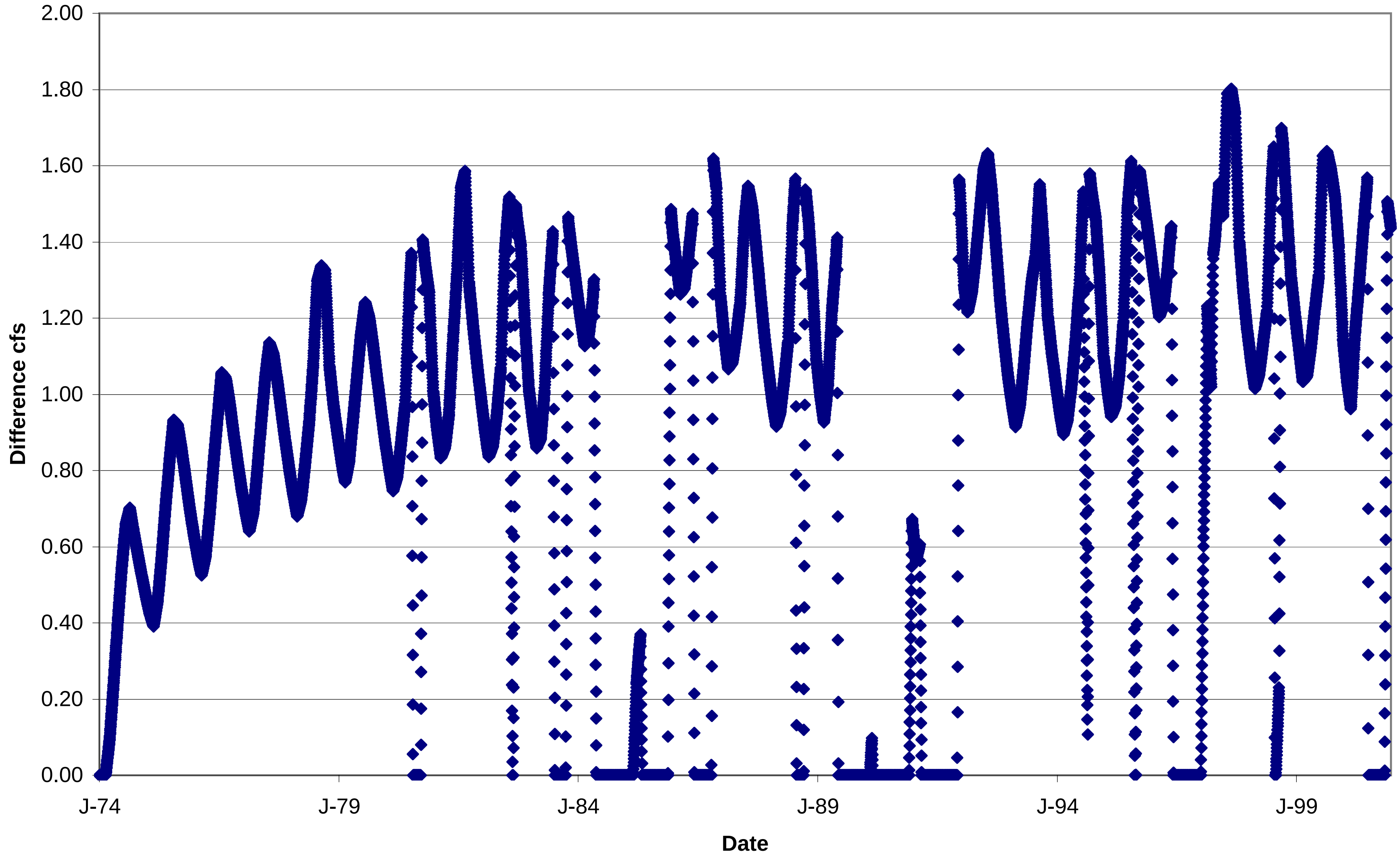


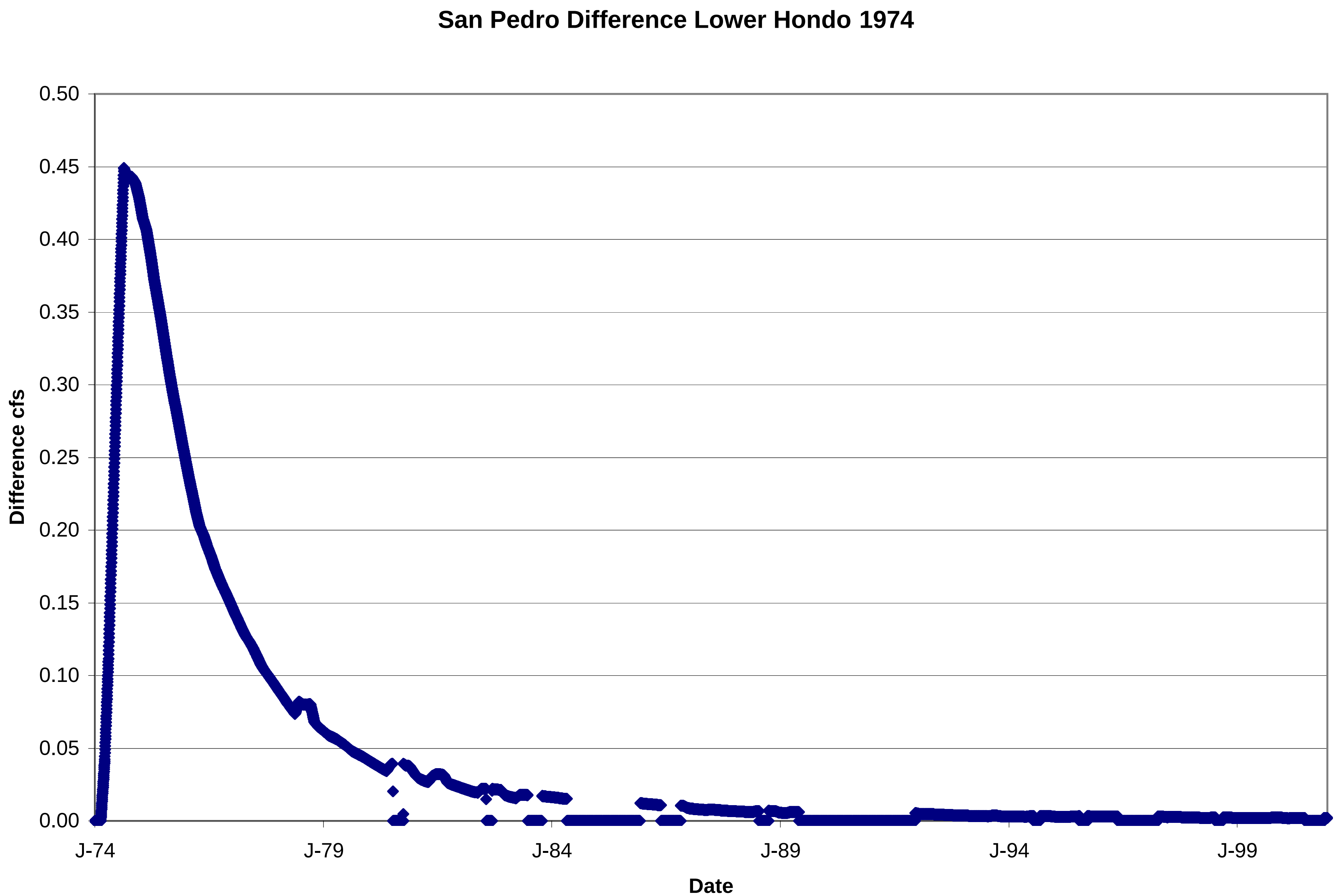

San Pedro Difference Lower Sabinal 1974
Difference cfs
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

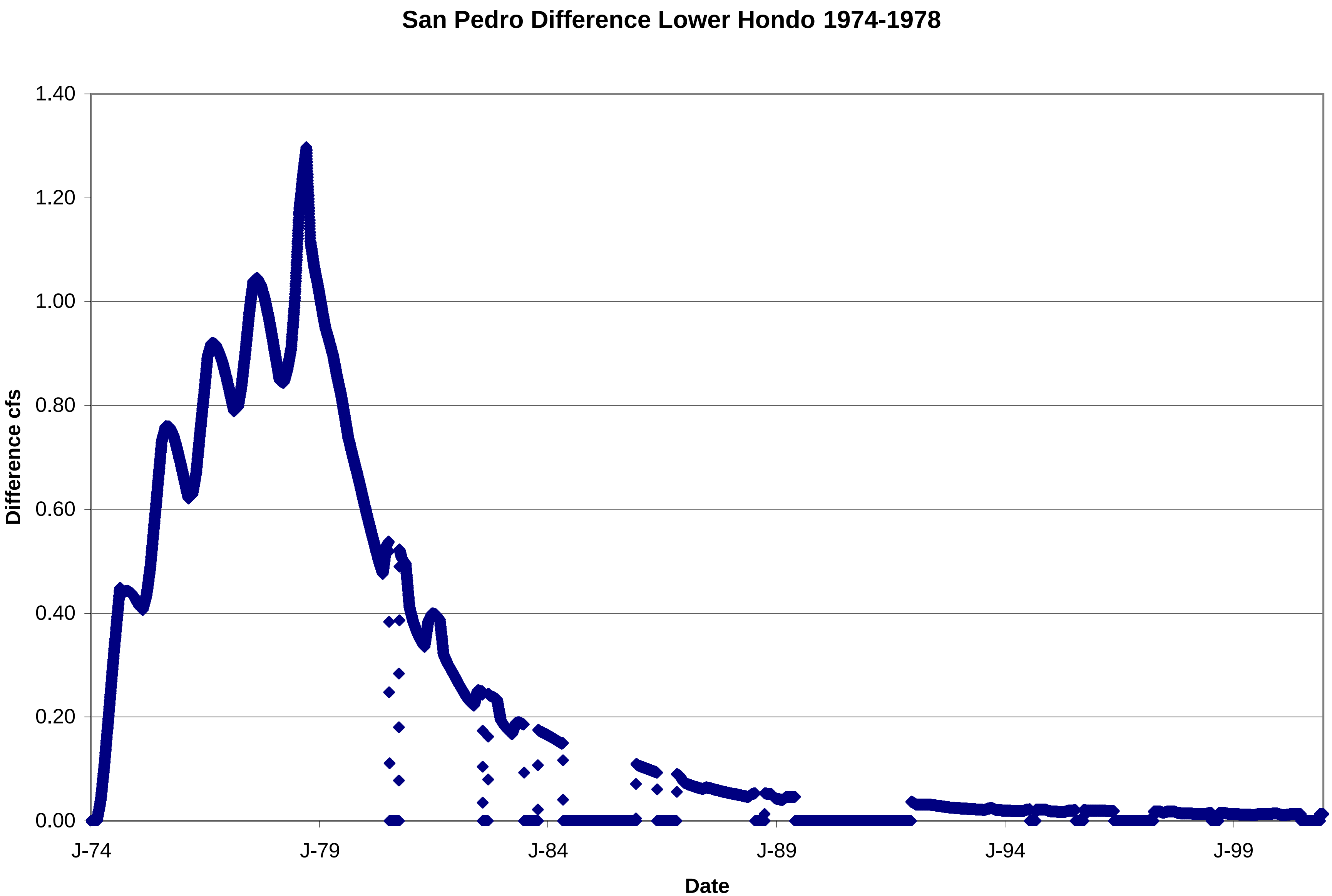
San Pedro Difference Lower Sabinal 1974-1978

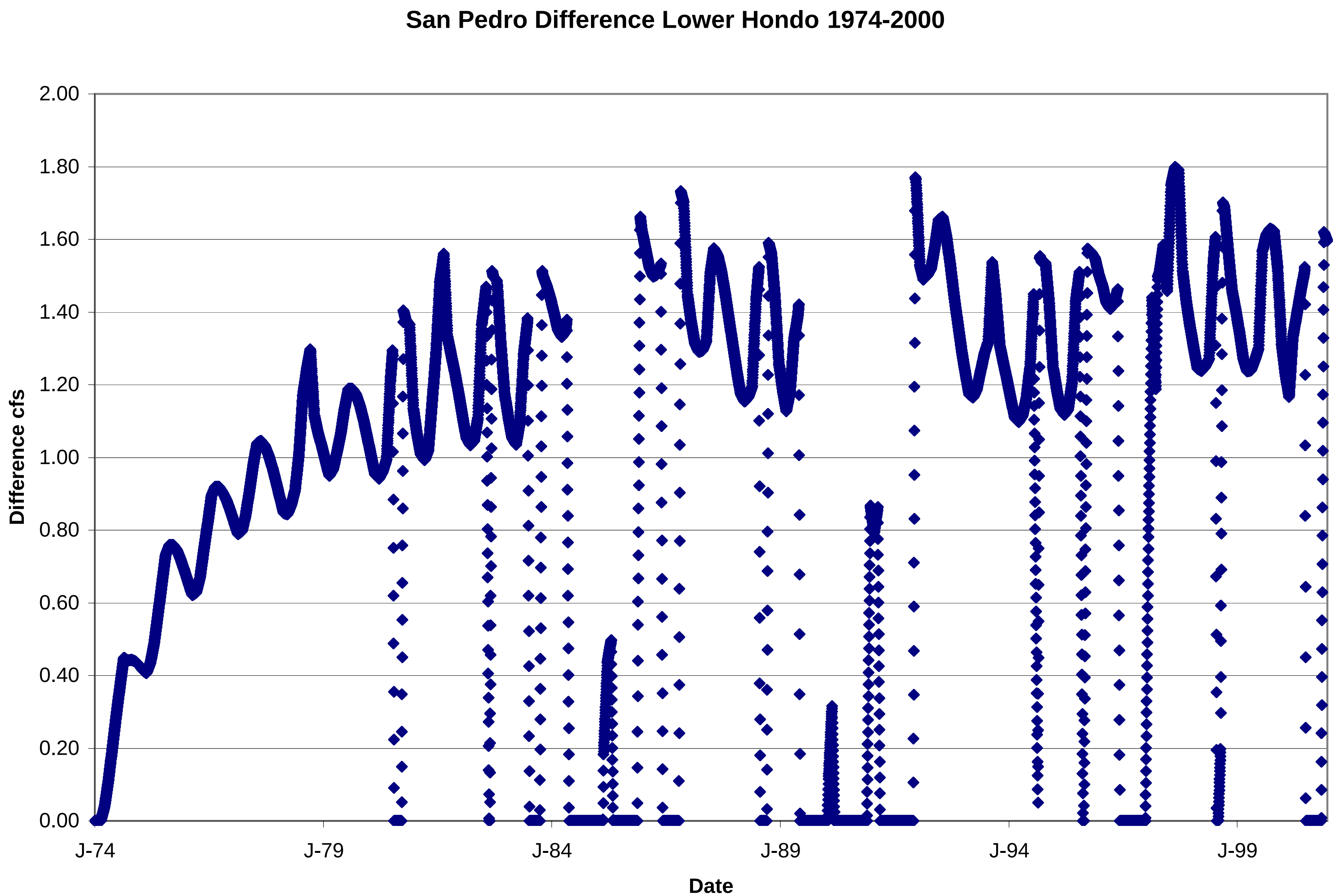


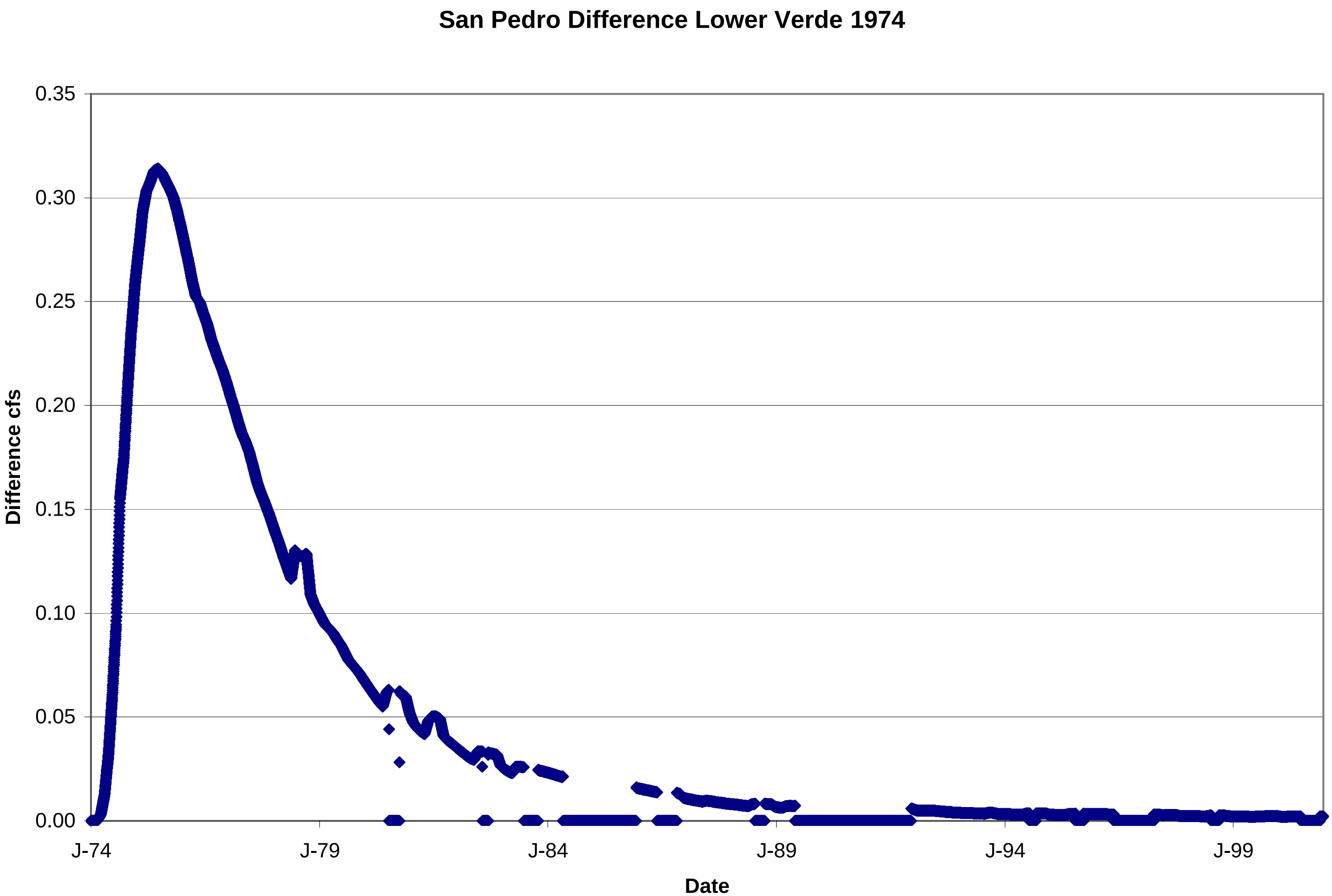
San Pedro Difference Lower Sabinal 1974-2000

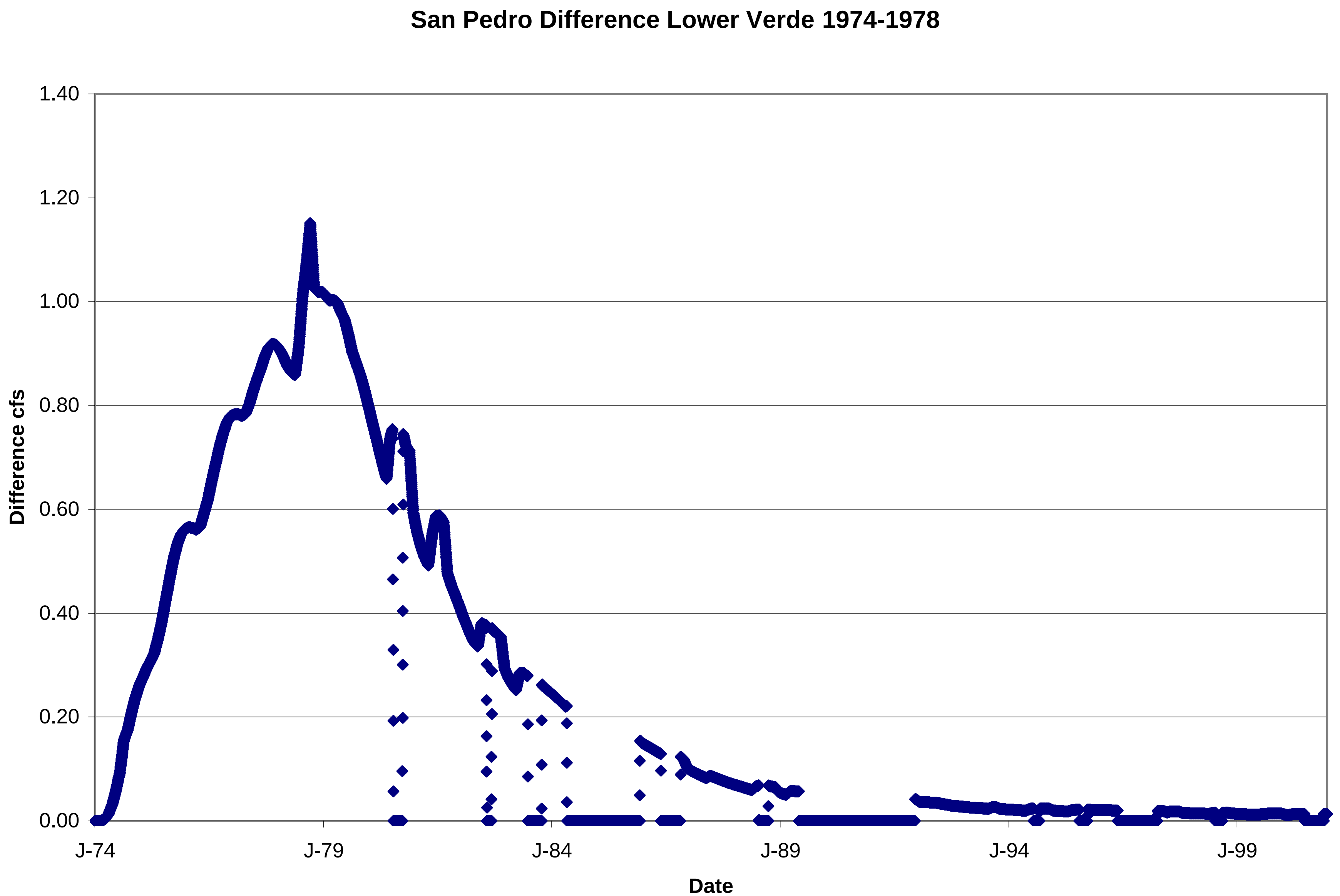


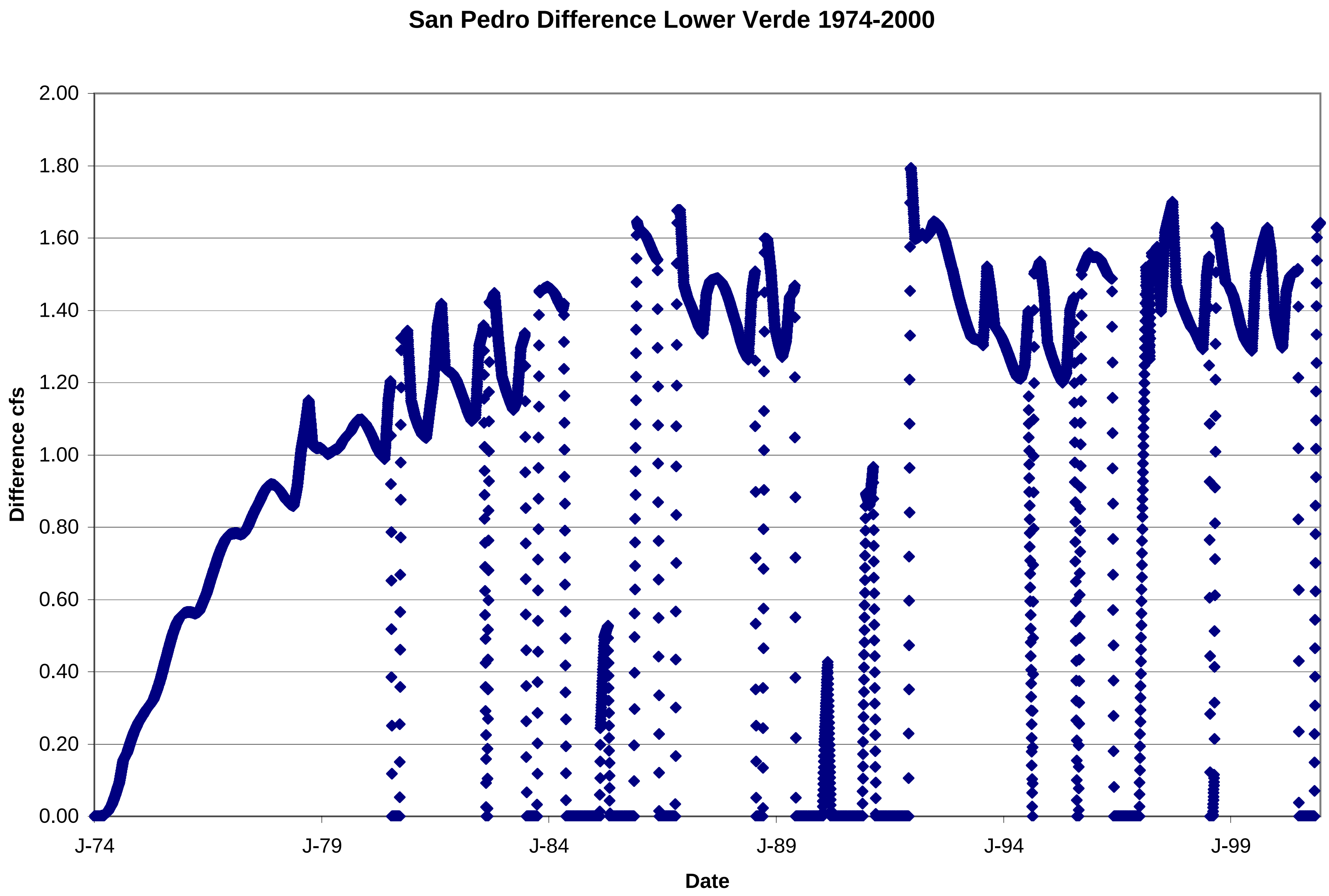

San Pedro Difference Lower Hondo 1974
Difference cfs
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date


San Pedro Difference Lower Hondo 1974-1978
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

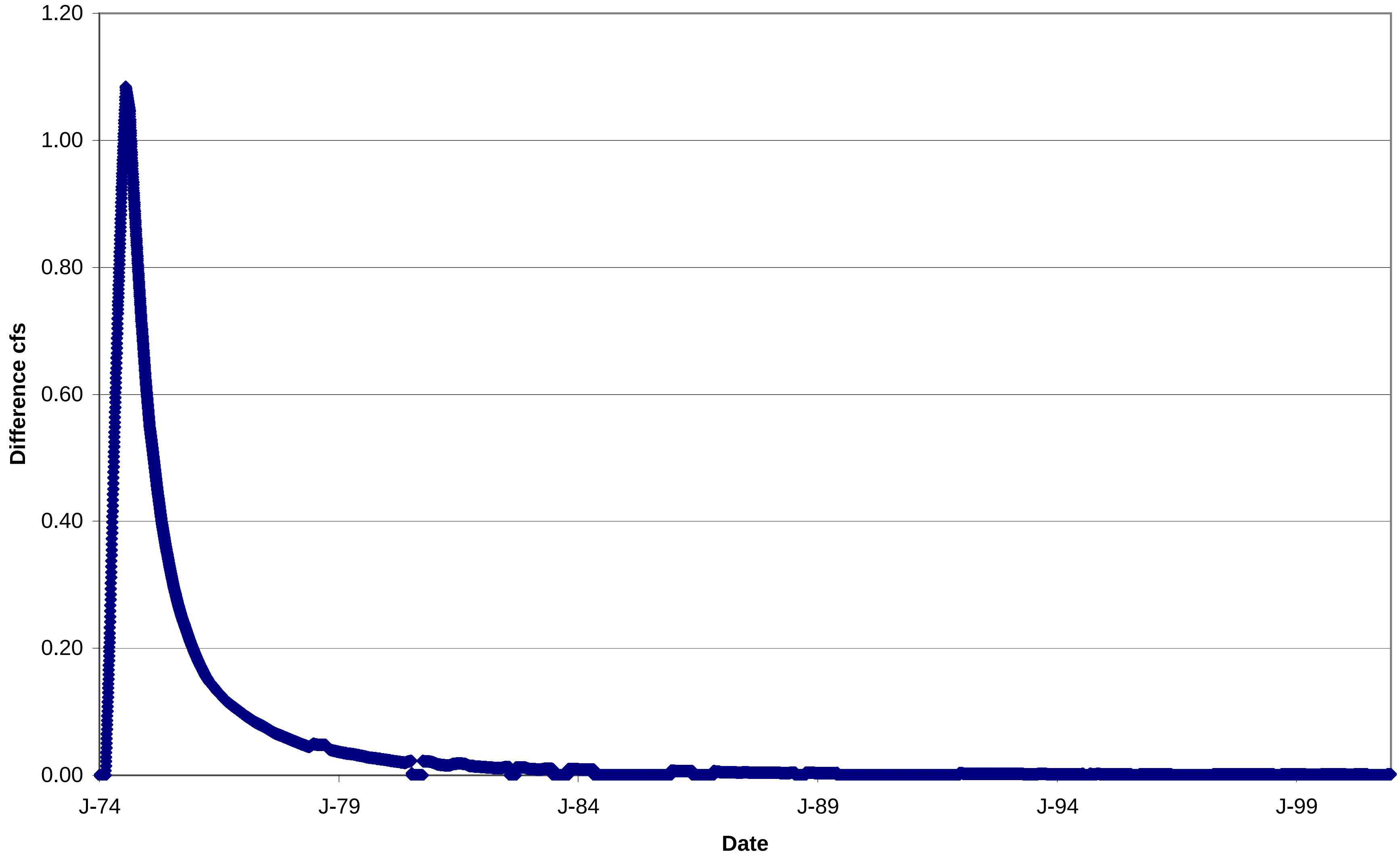

San Pedro Difference Lower Hondo 1974-2000
Difference cfs
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date


San Pedro Difference Lower Verde 1974
Difference cfs
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

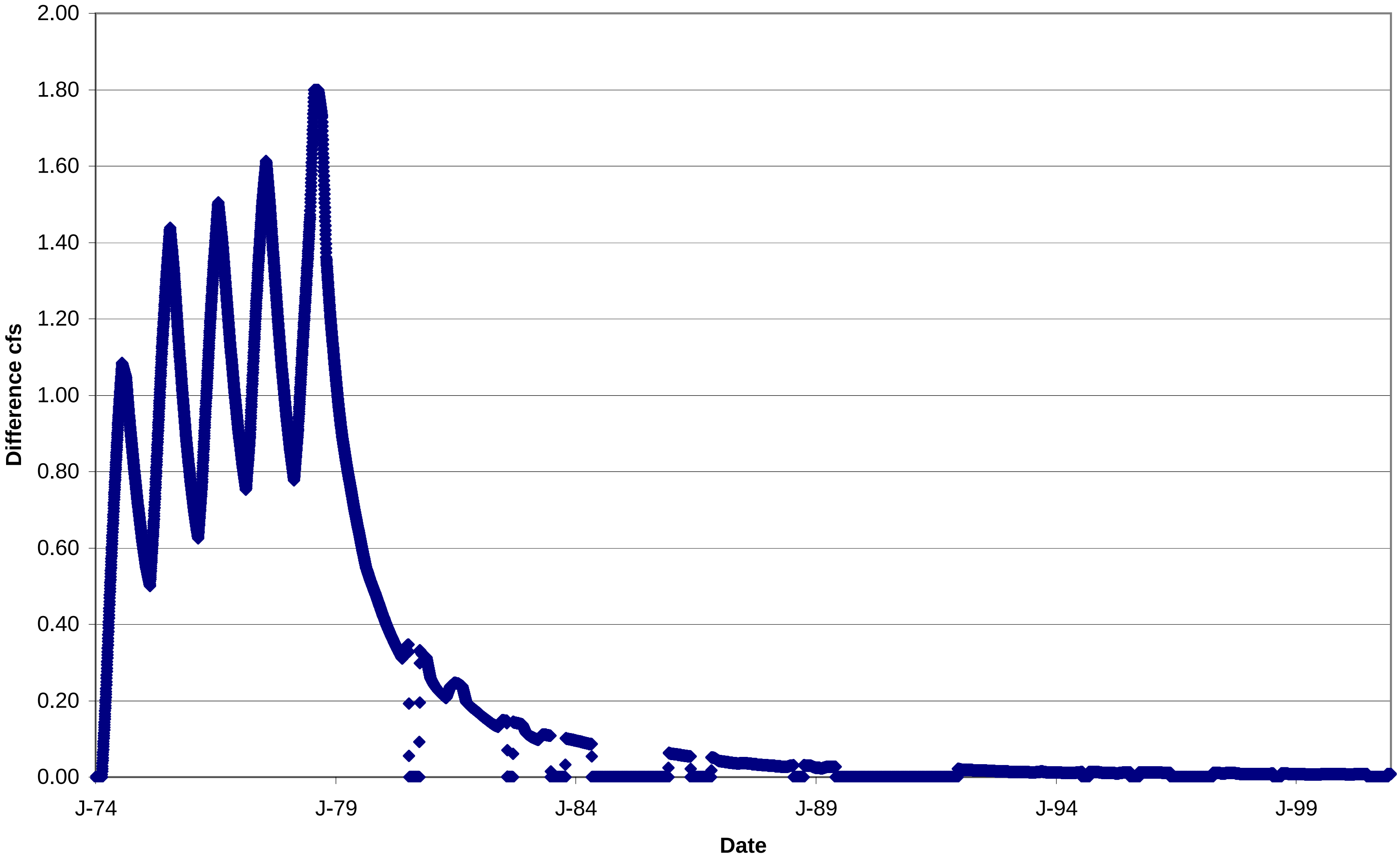

San Pedro Difference Lower Verde 1974-1978
Difference cfs
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

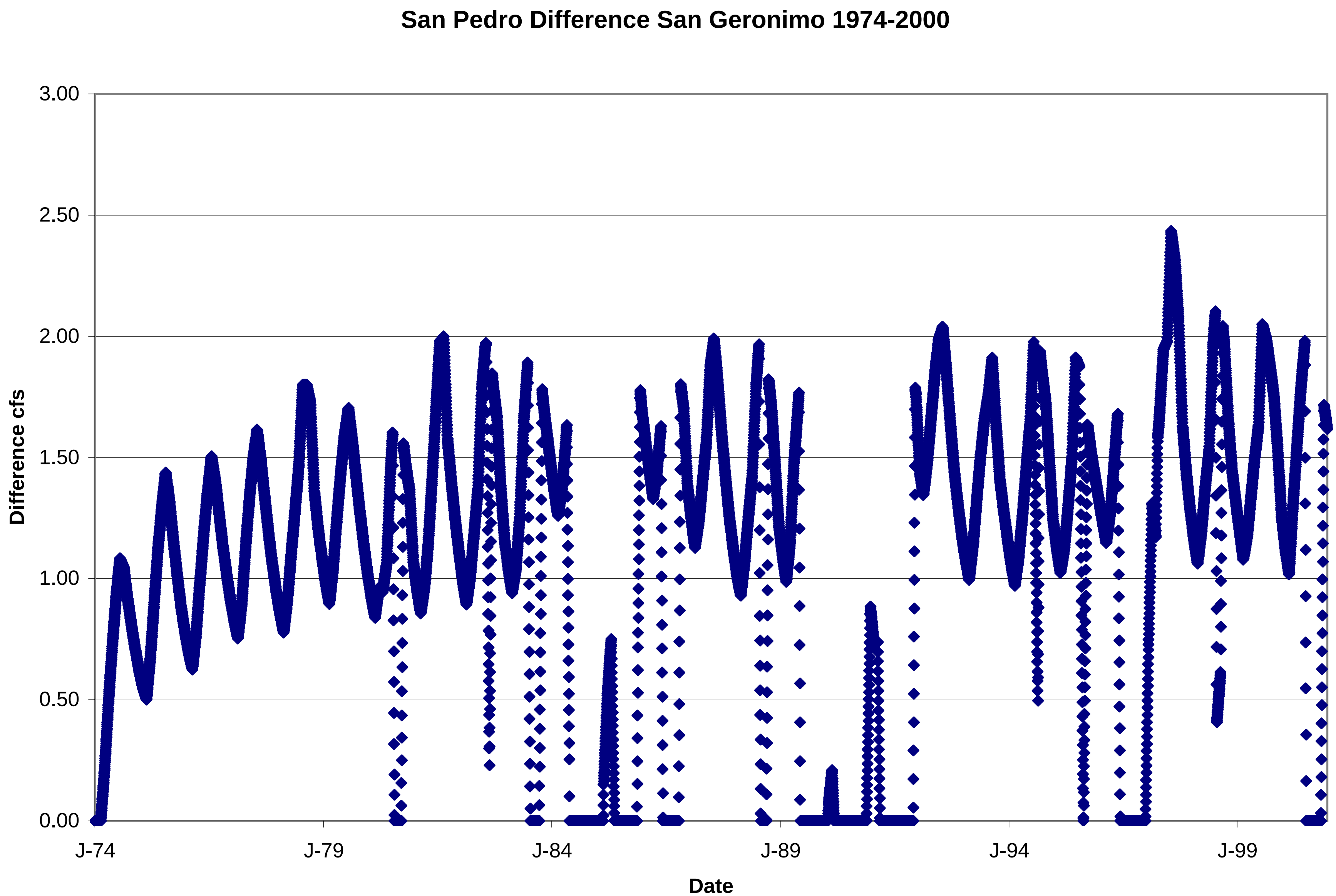

San Pedro Difference Lower Verde 1974-2000
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Pedro Difference San Geronimo 1974

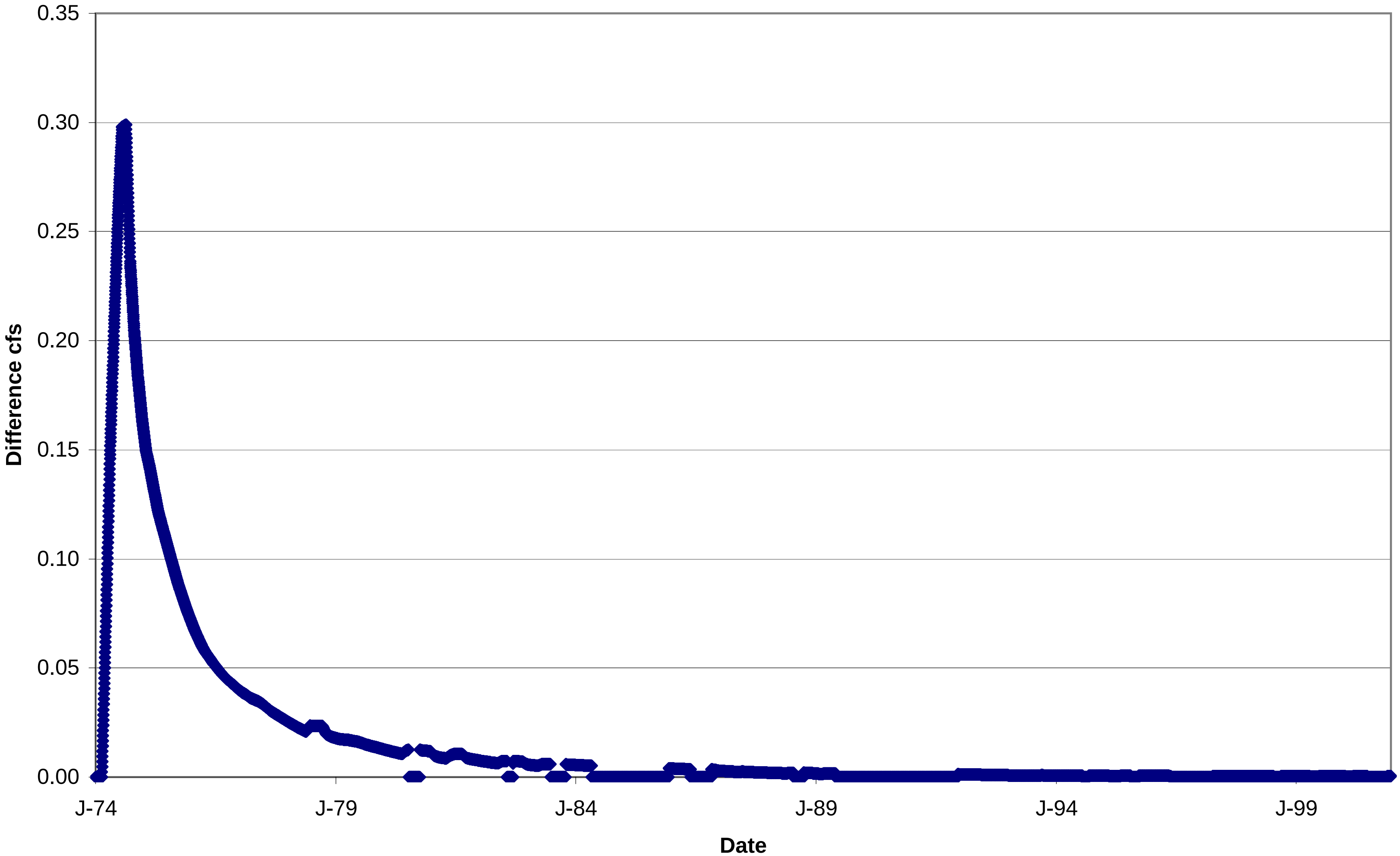


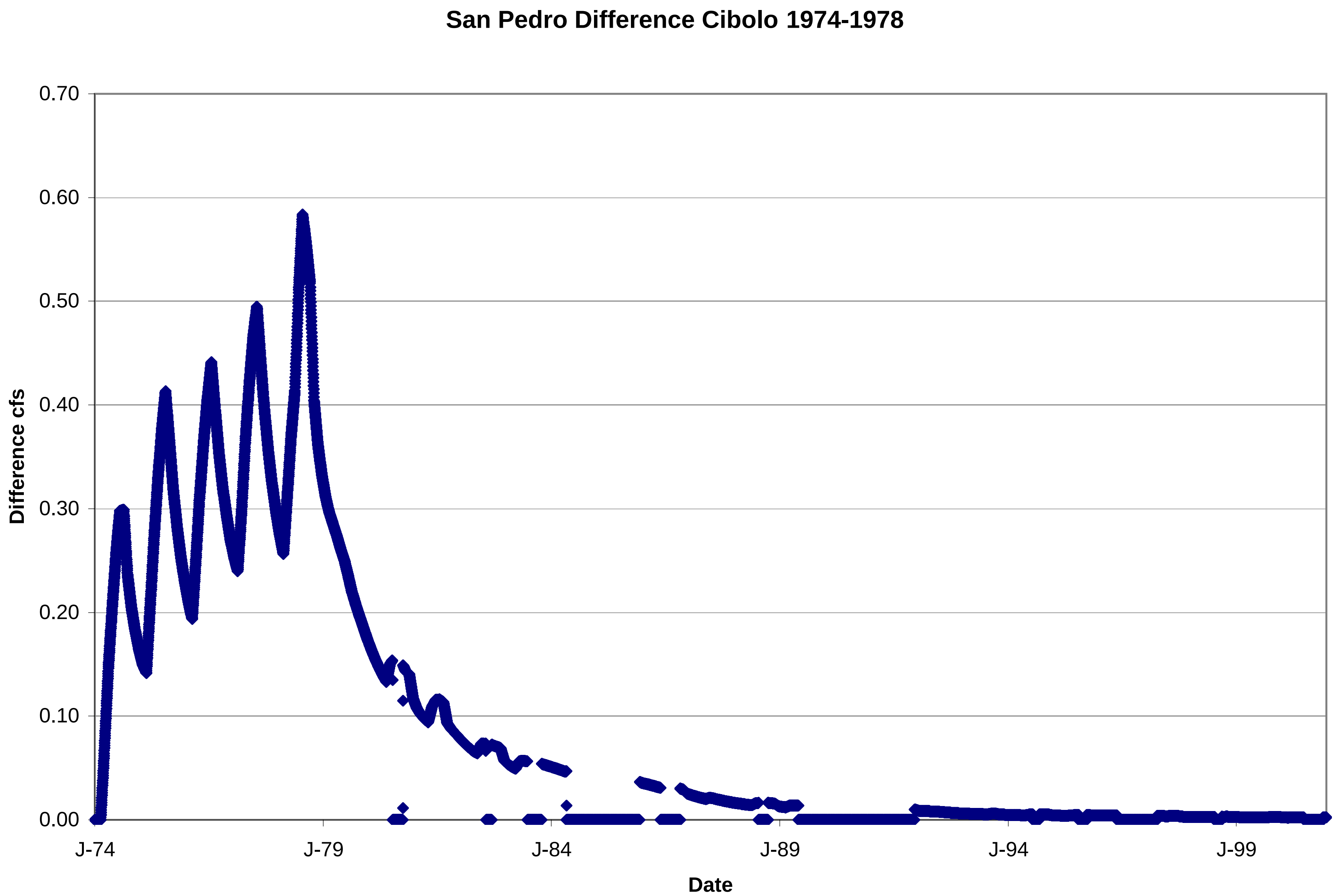
San Pedro Difference San Geronimo 1974-1978



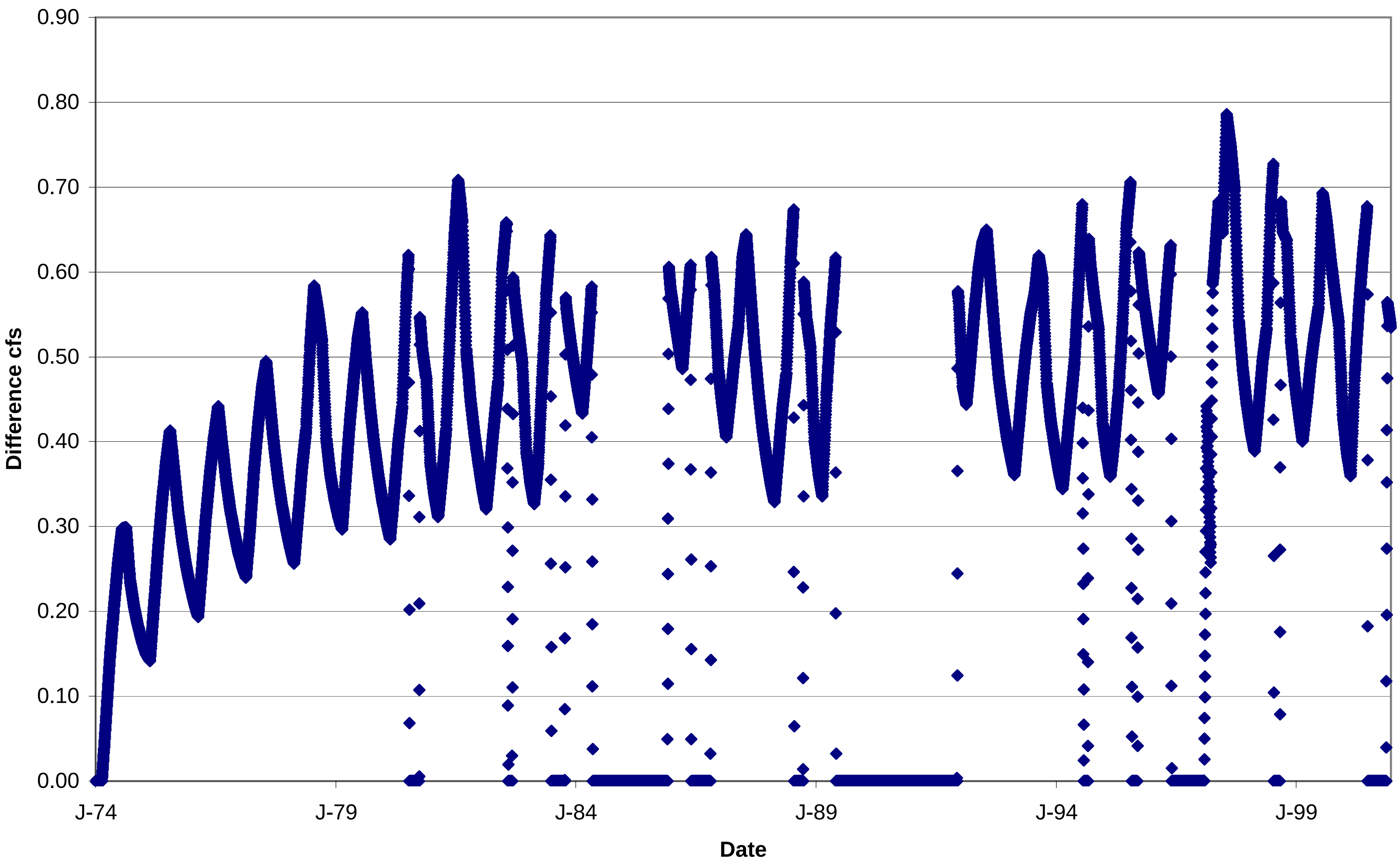

San Pedro Difference San Geronimo 1974-2000
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

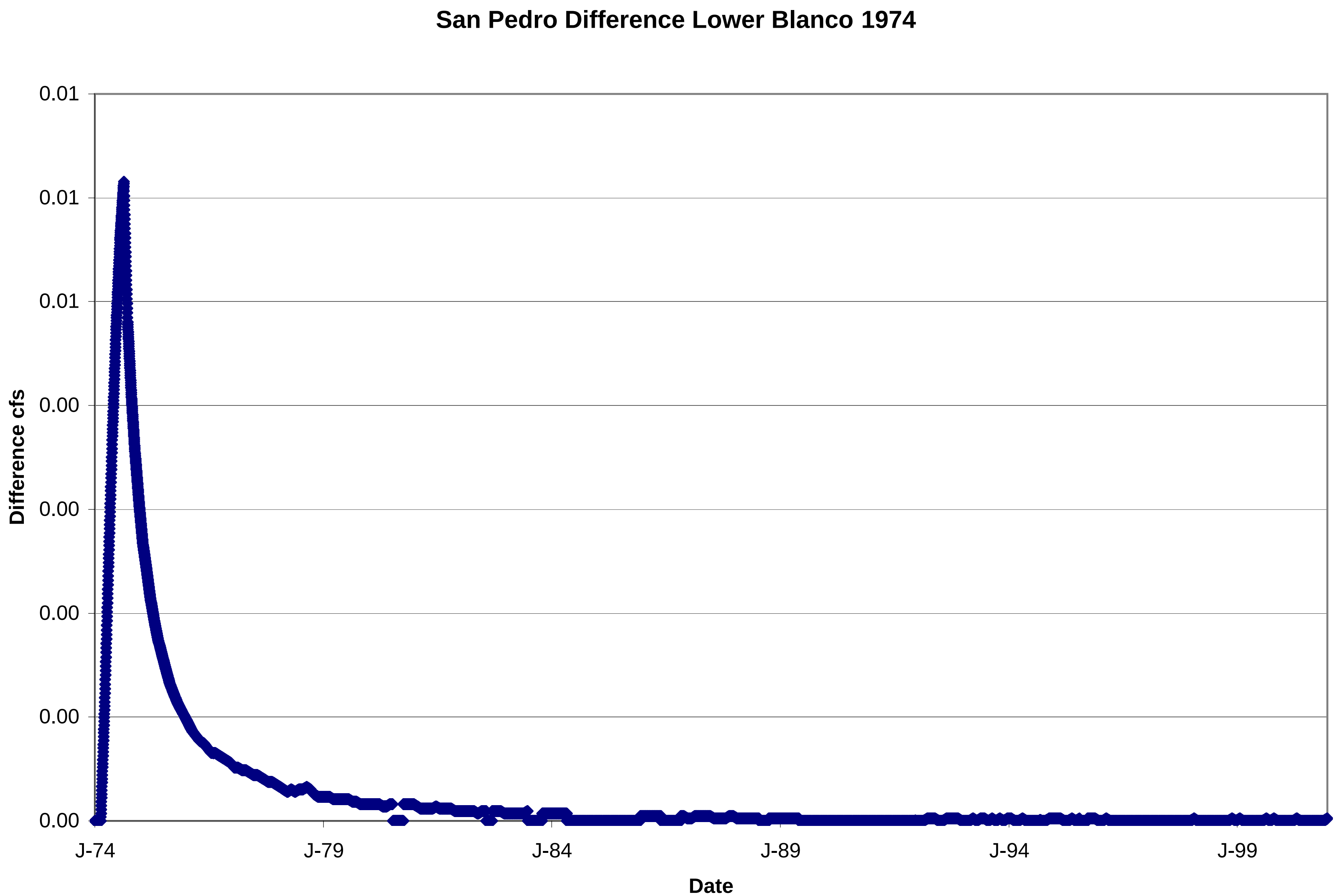
San Pedro Difference Cibolo 1974



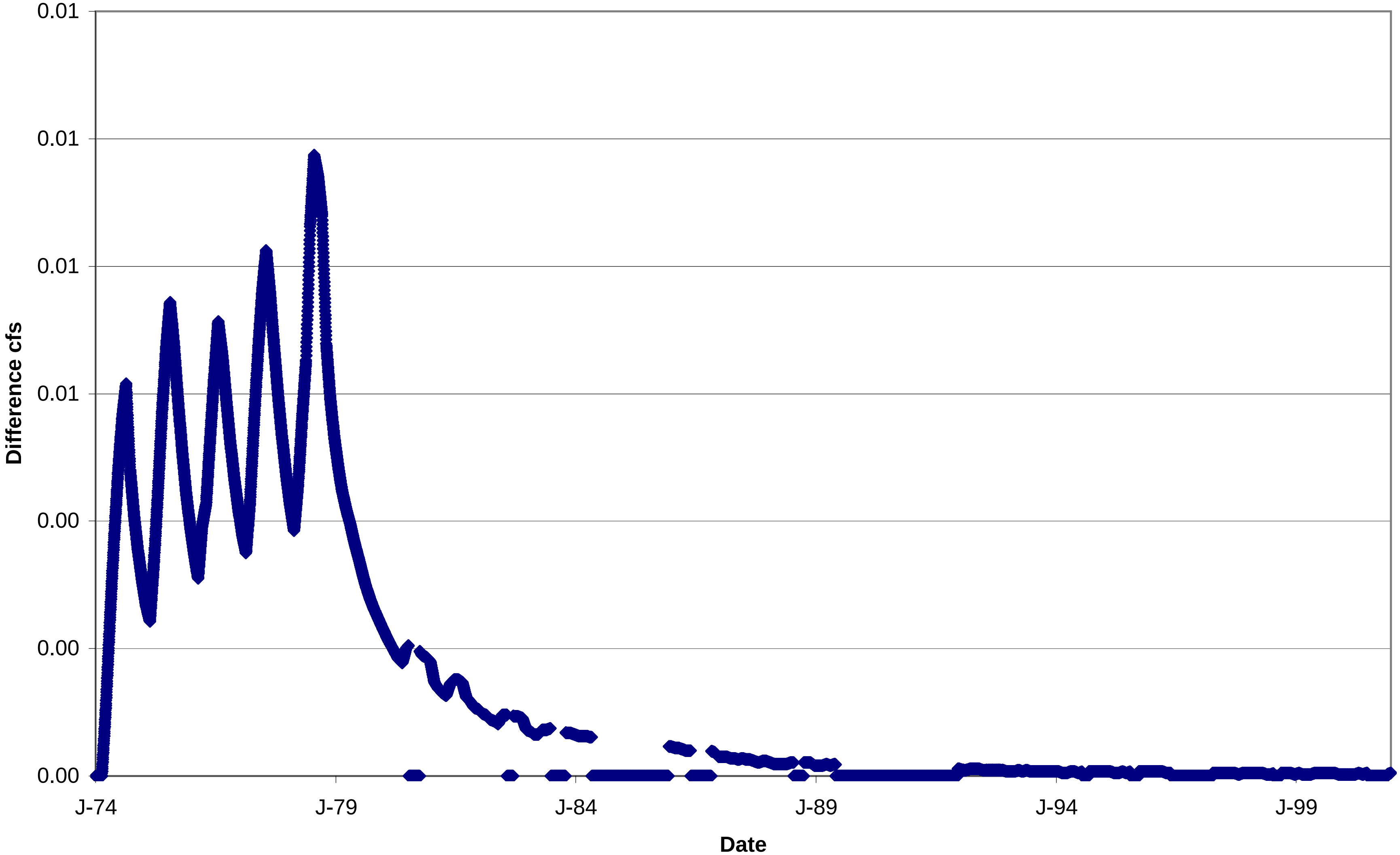

San Pedro Difference Cibolo 1974-1978
Difference cfs
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

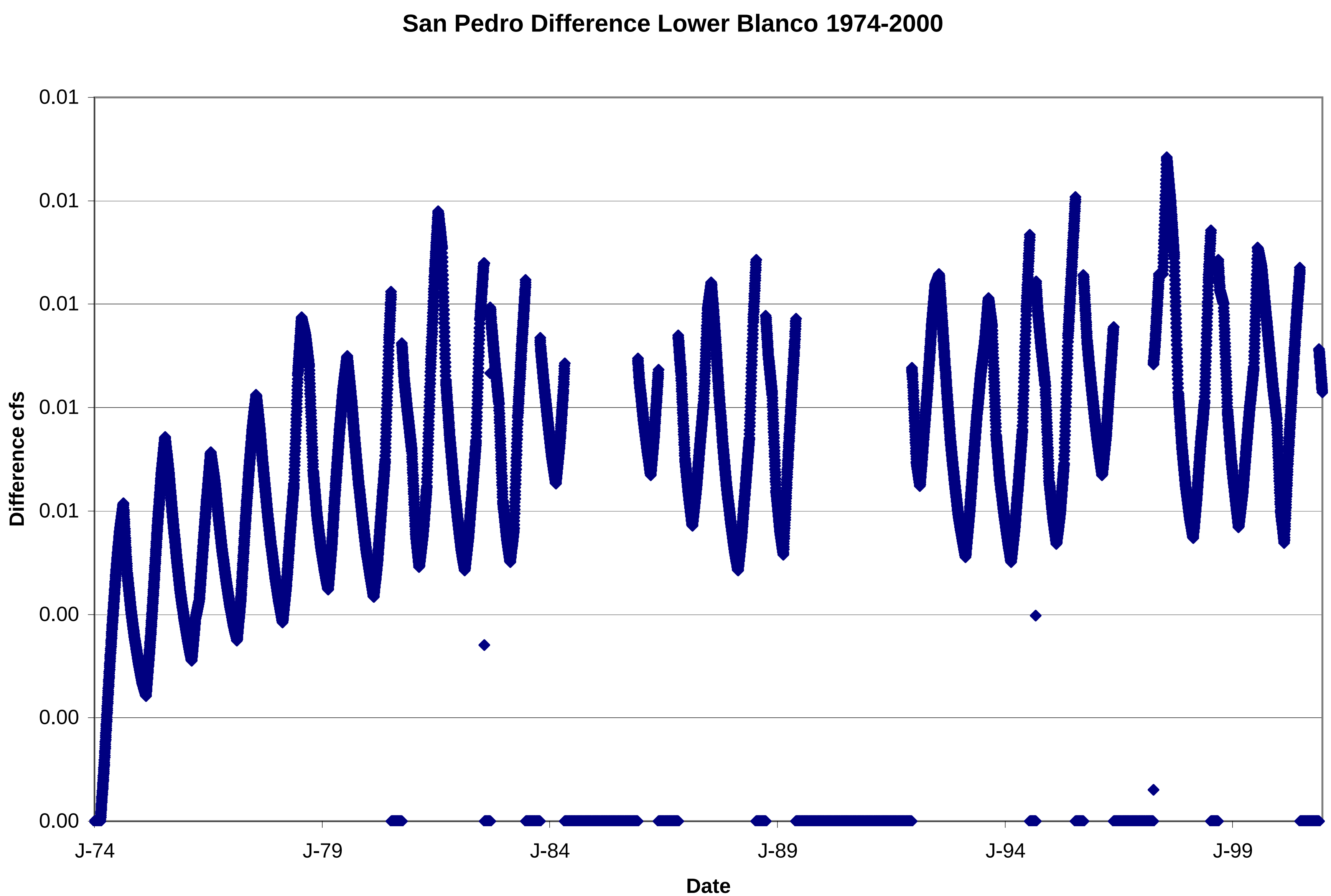
San Pedro Difference Cibolo 1974-2000

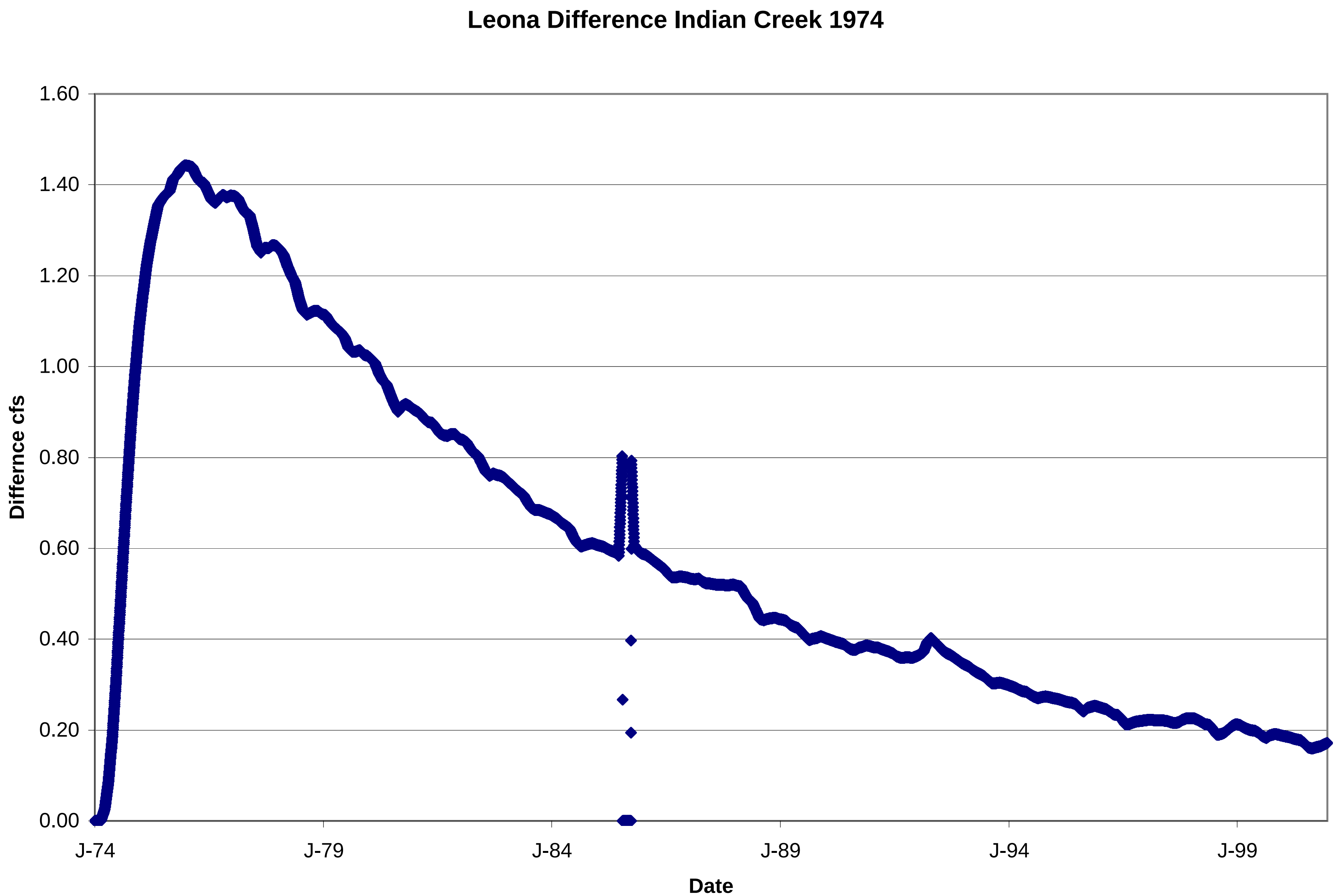


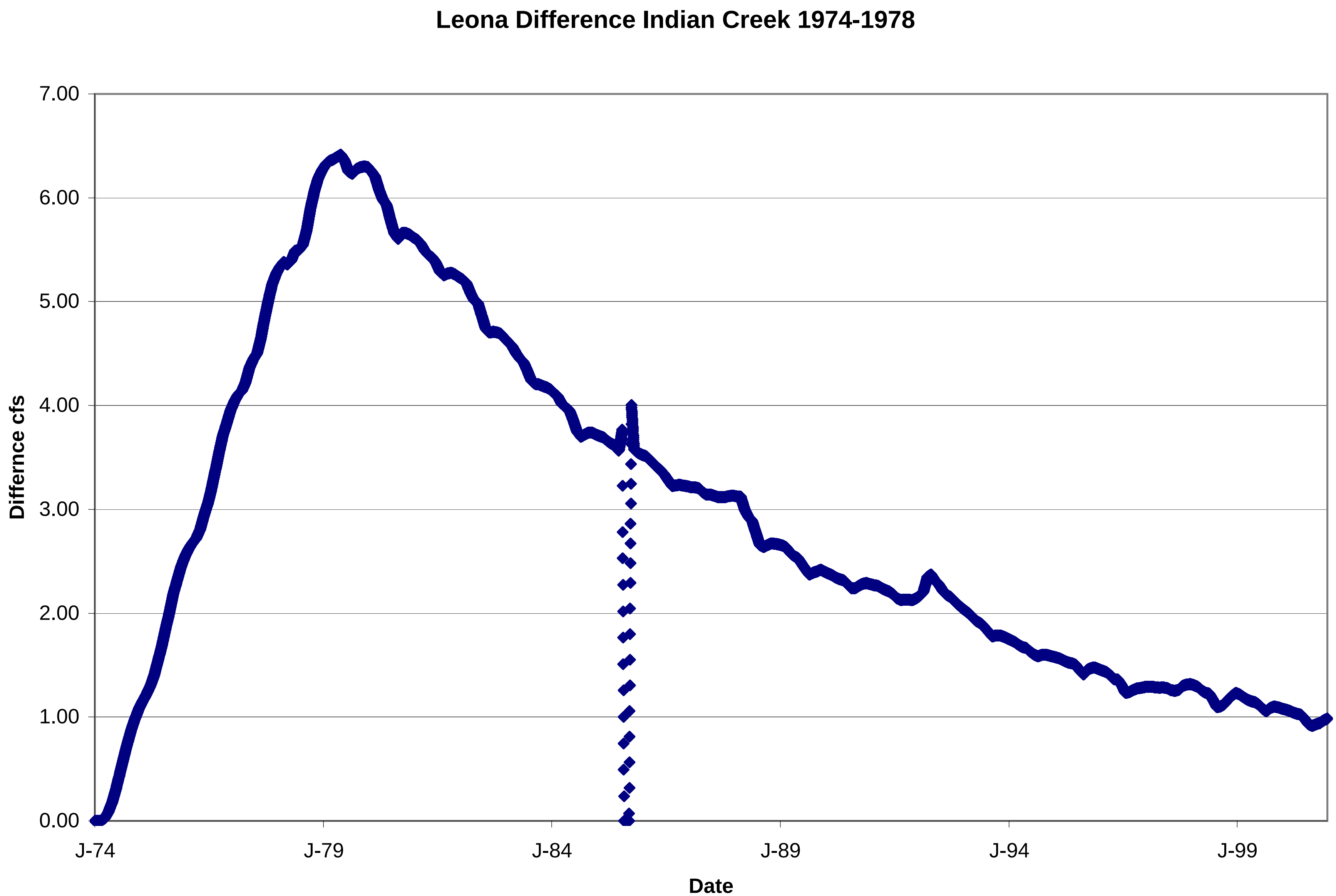

San Pedro Difference Lower Blanco 1974
Difference cfs
0.01
0.01
0.01
0.00
0.00
0.00
0.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

San Pedro Difference Lower Blanco 1974-1978

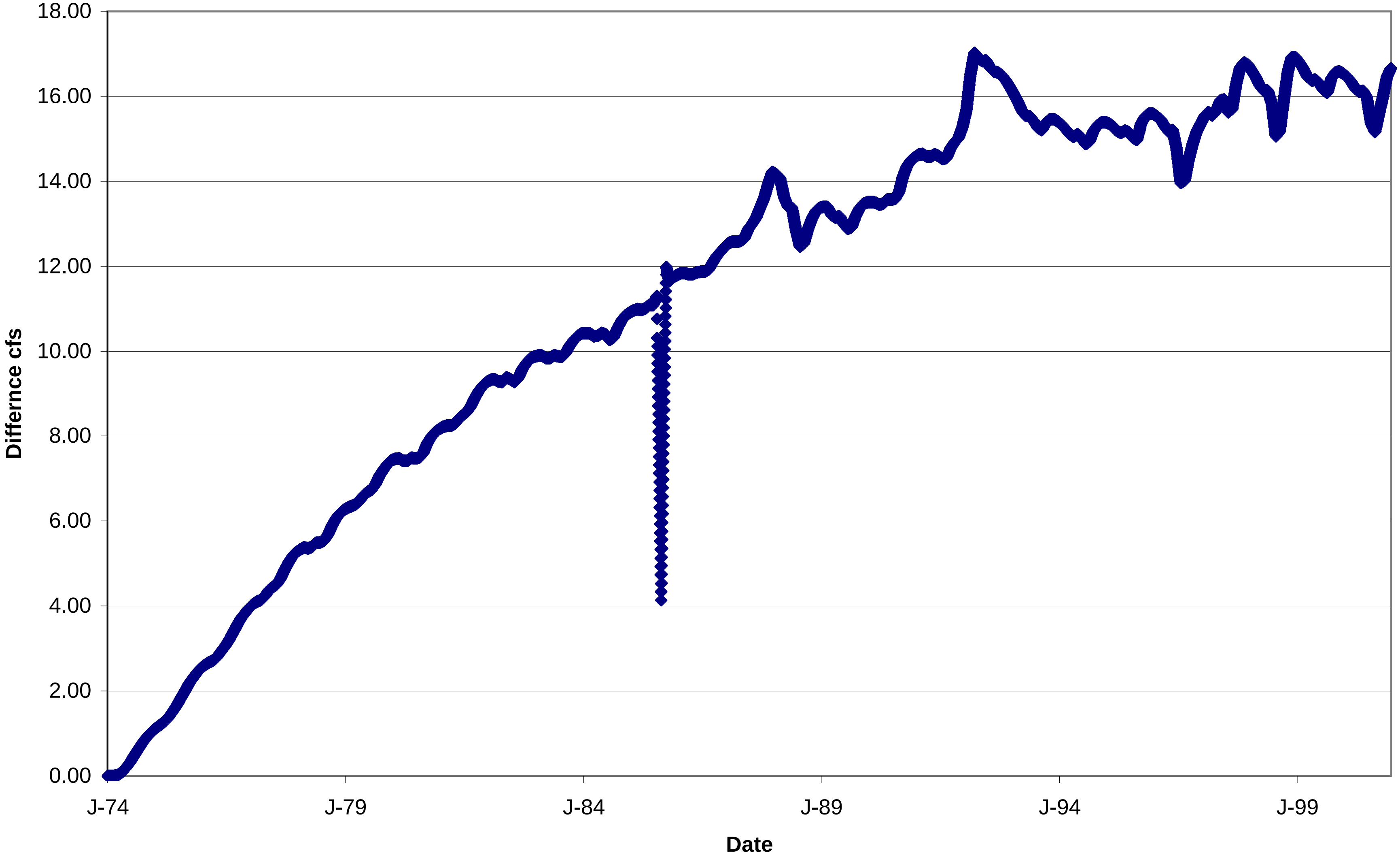


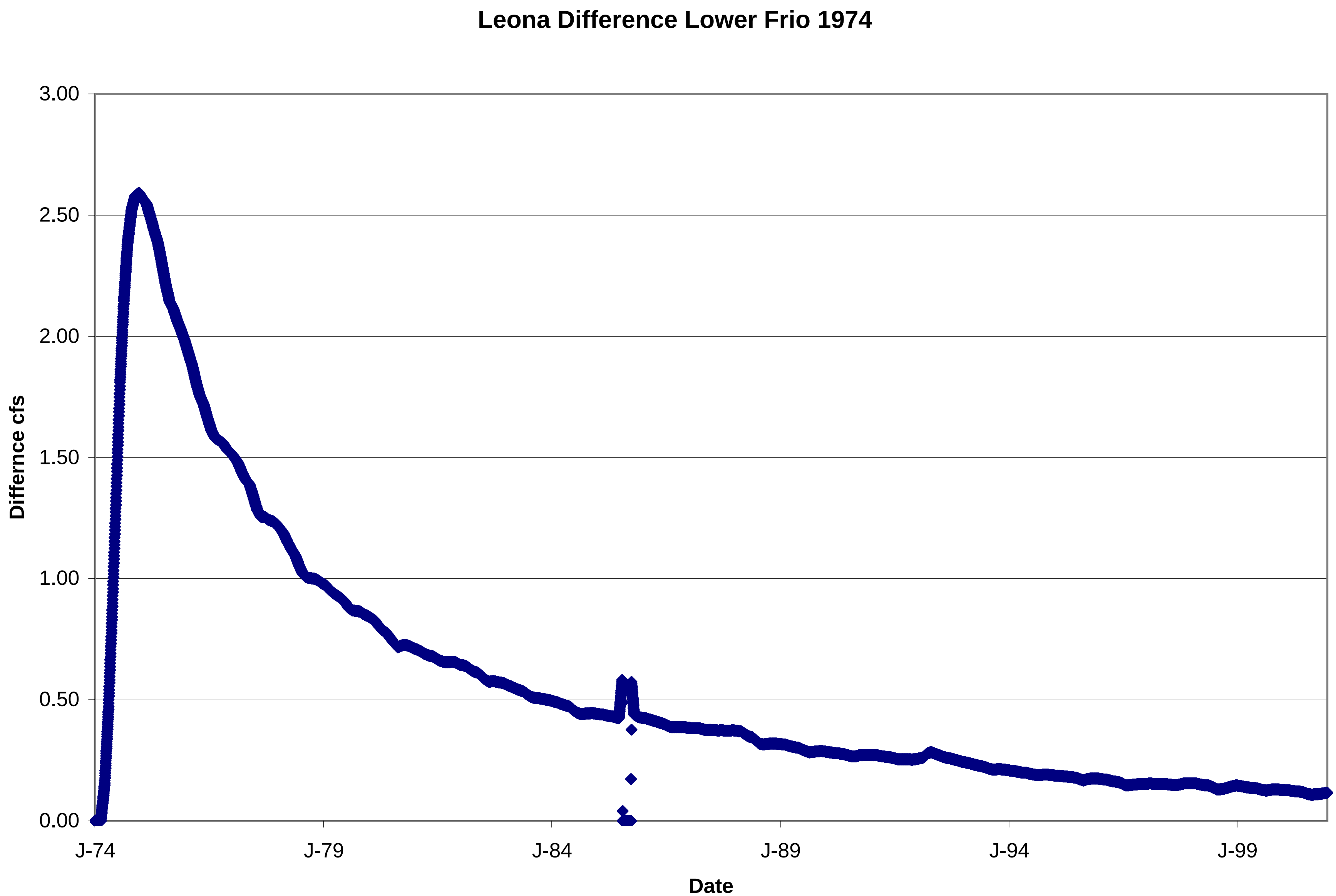

San Pedro Difference Lower Blanco 1974-2000
0.01
0.01
0.01
0.01
0.01
0.00
0.00
0.00
Difference cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date


Leona Difference Indian Creek 1974
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date


Leona Difference Indian Creek 1974-1978
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

Leona Difference Indian Creek 1974-2000





A -100

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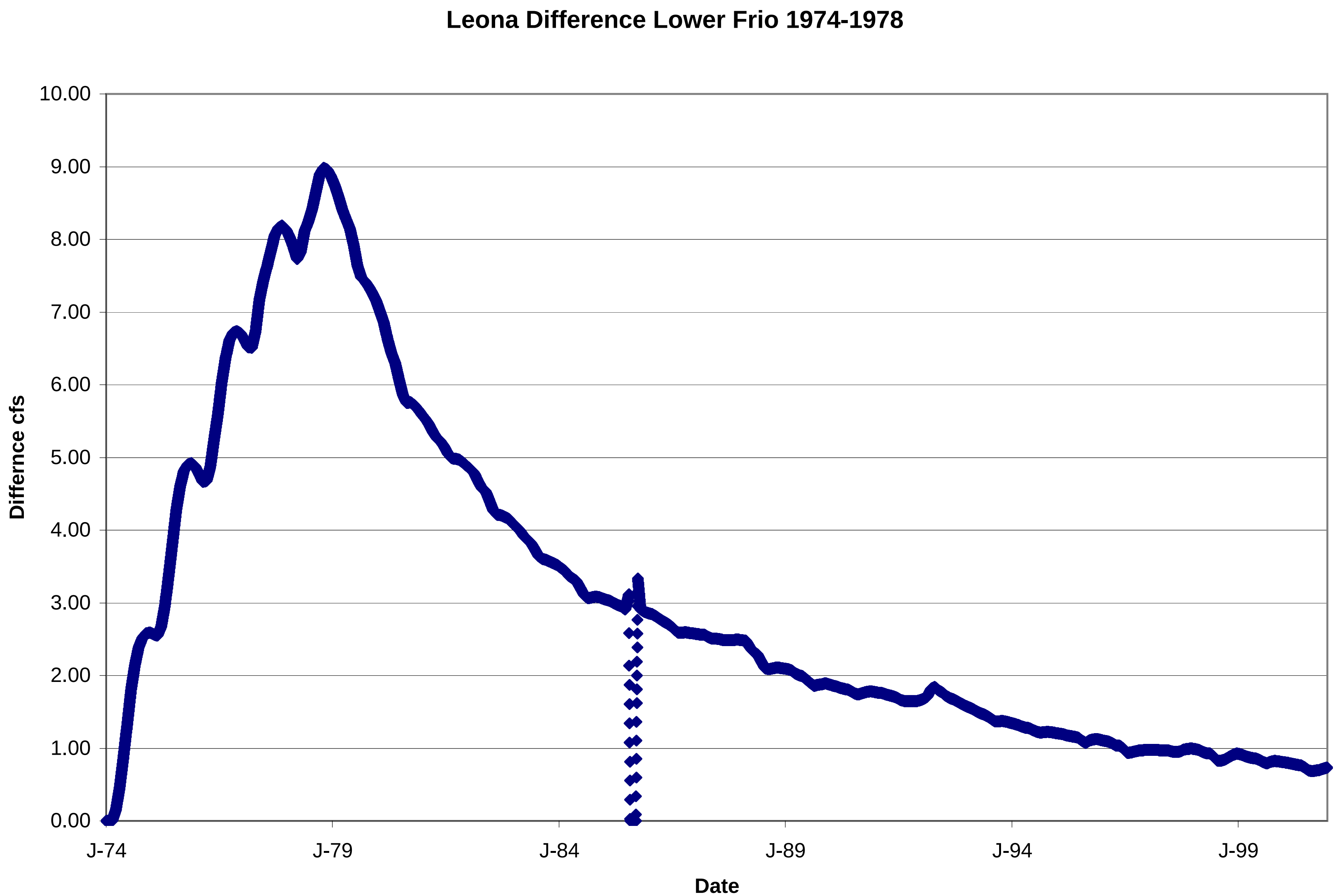
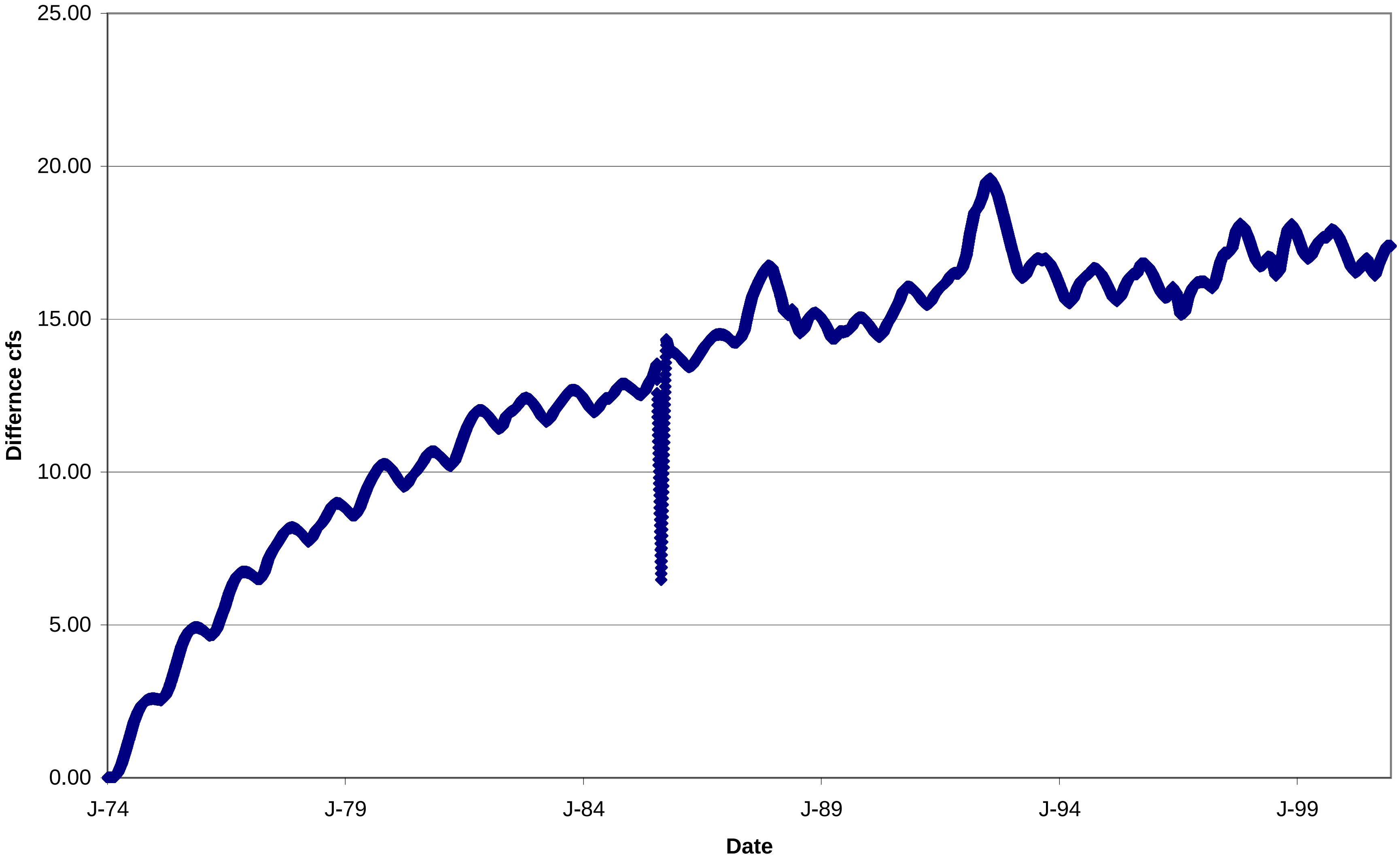
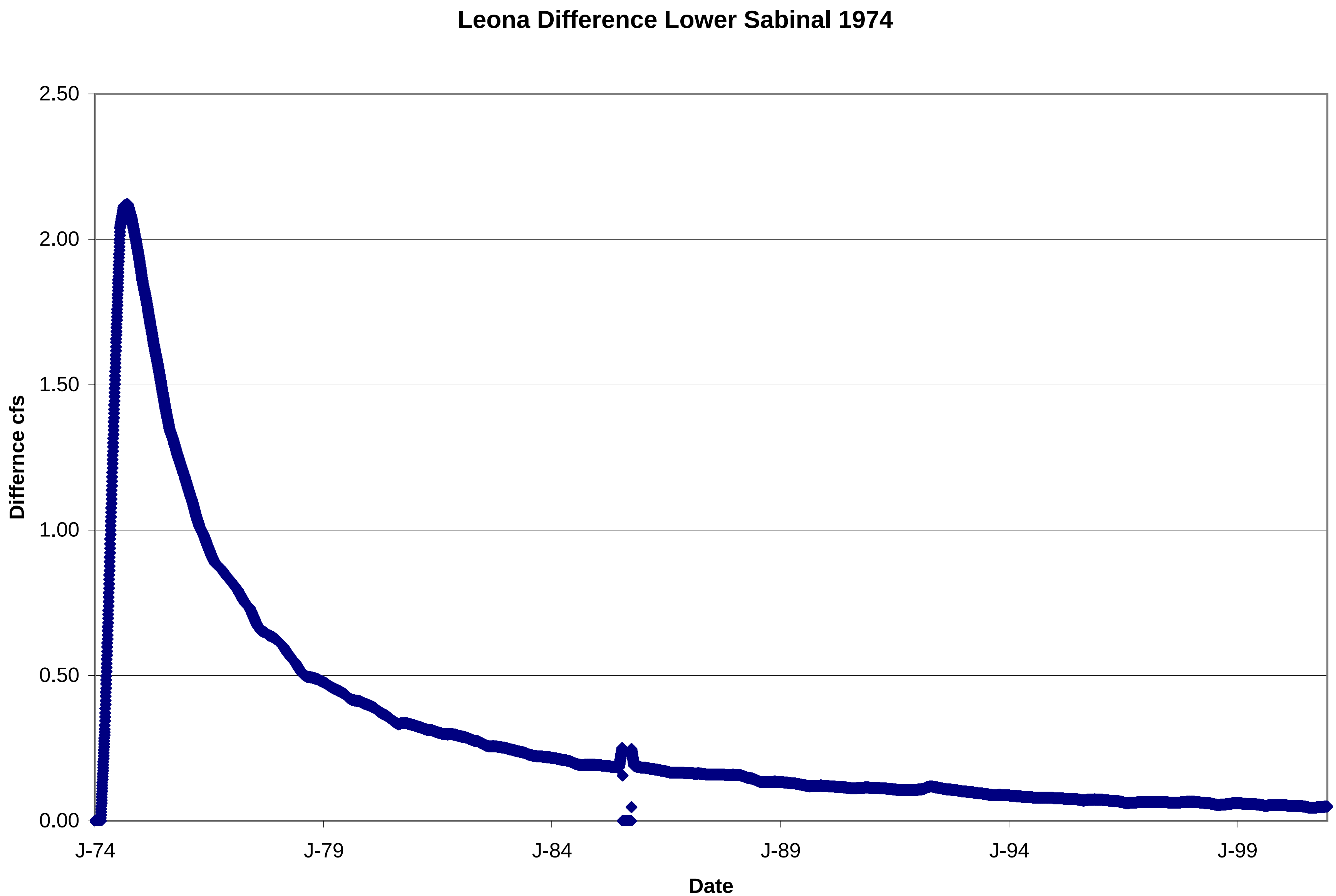
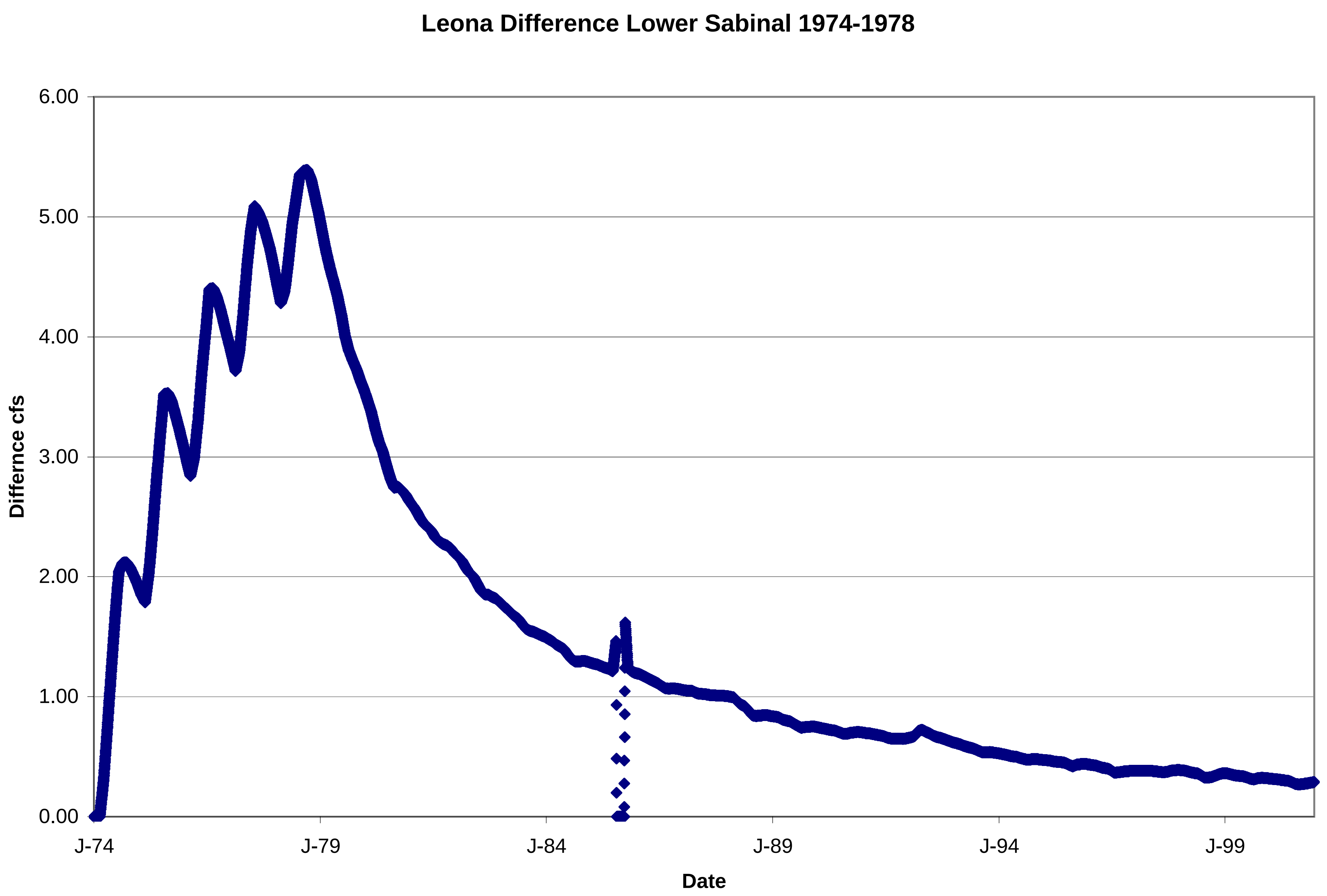

Leona Difference Lower Frio 1974-1978
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

A -101

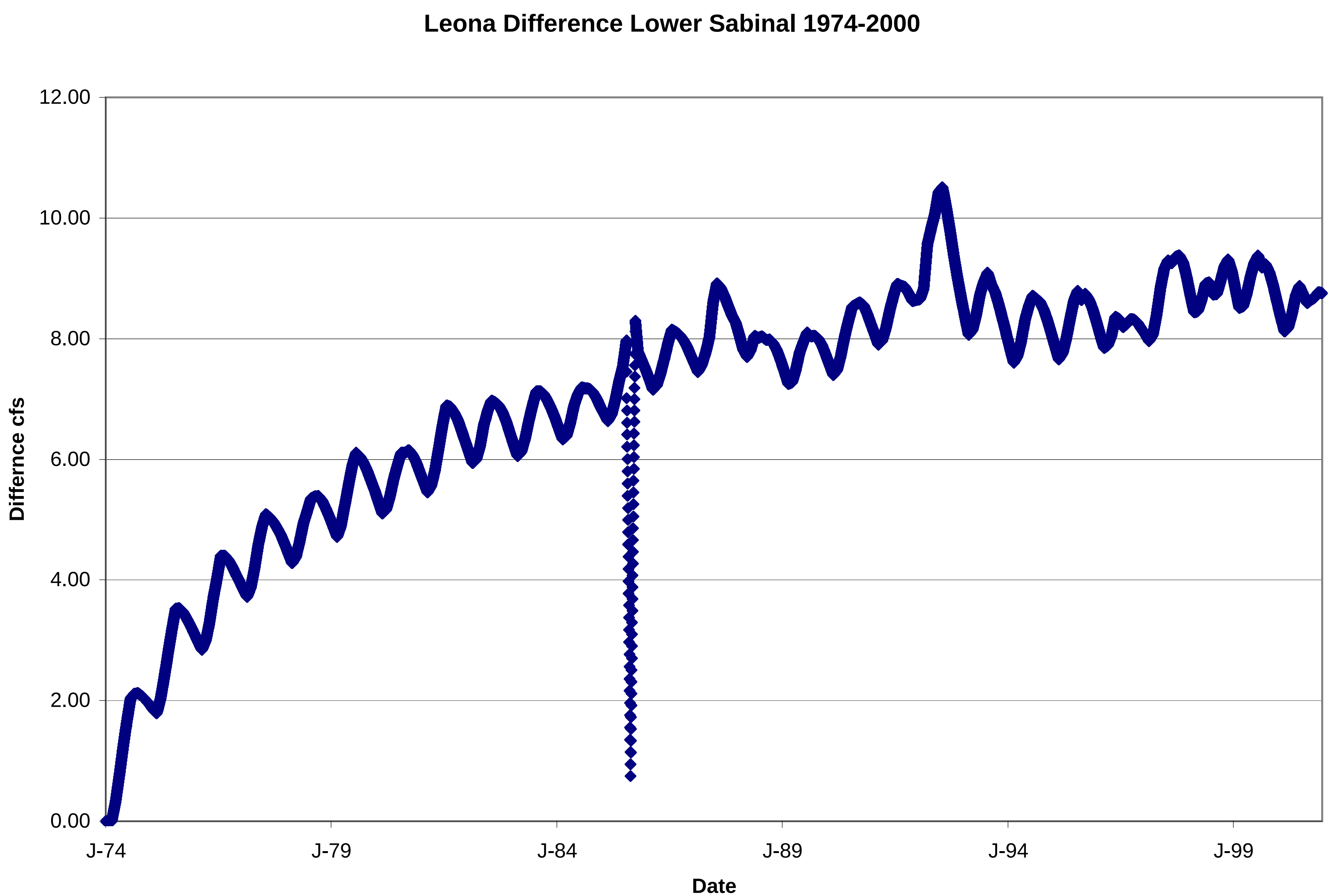
Leona Difference Lower Frio 1974-2000

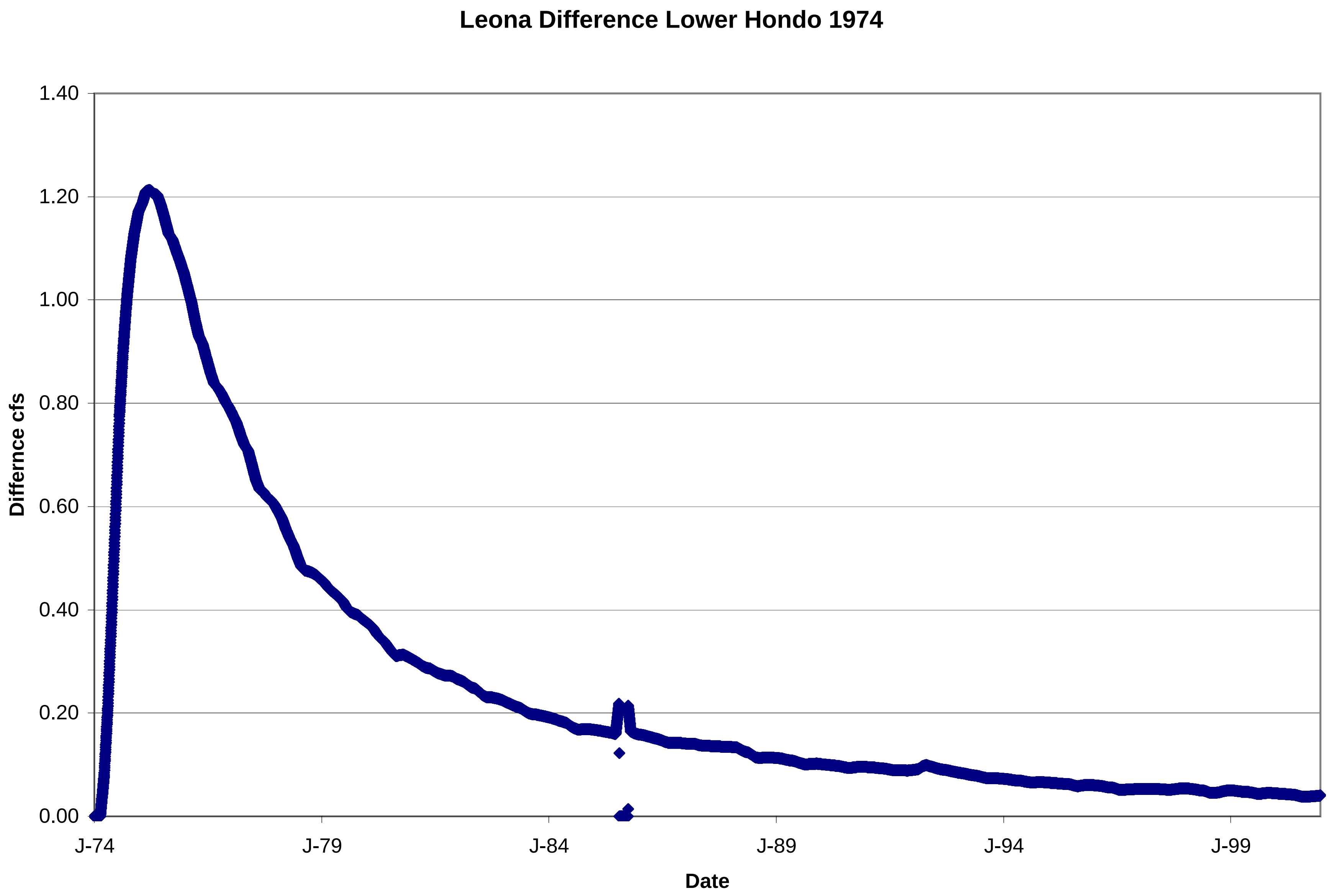



Leona Difference Lower Sabinal 1974
2.50
2.00
1.50
1.00
0.50
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

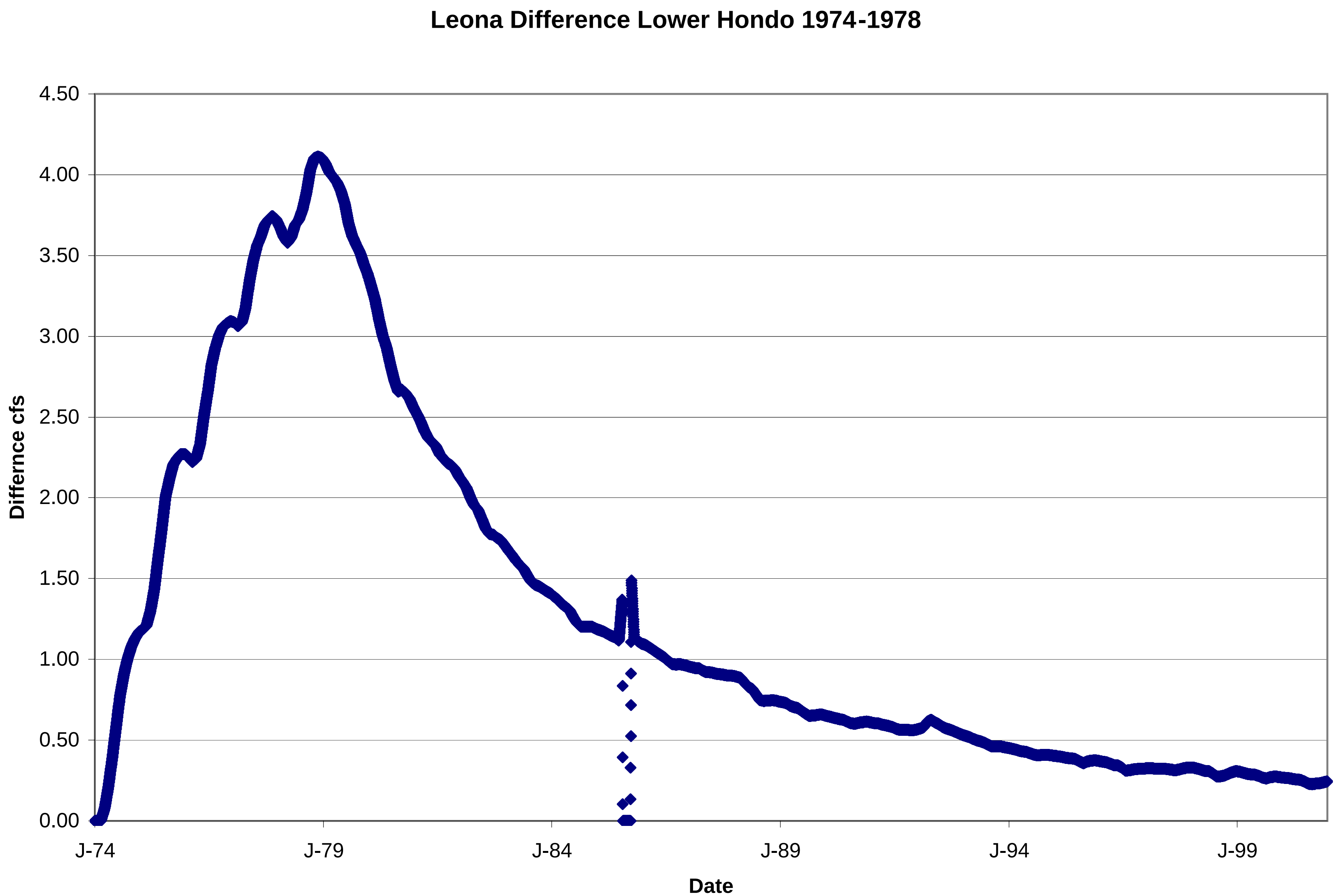


Leona Difference Lower Sabinal 1974-1978
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

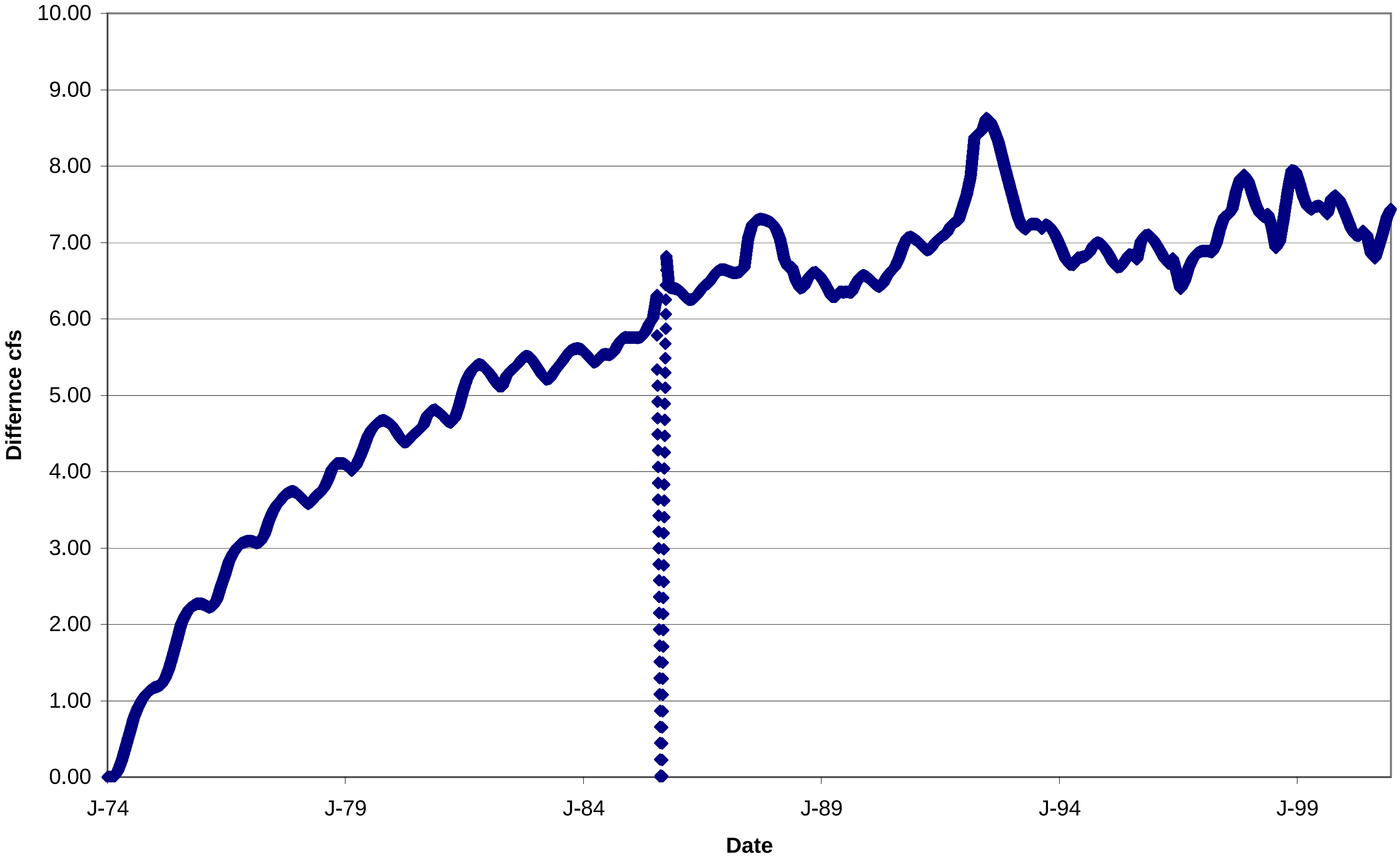

Leona Difference Lower Sabinal 1974-2000
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

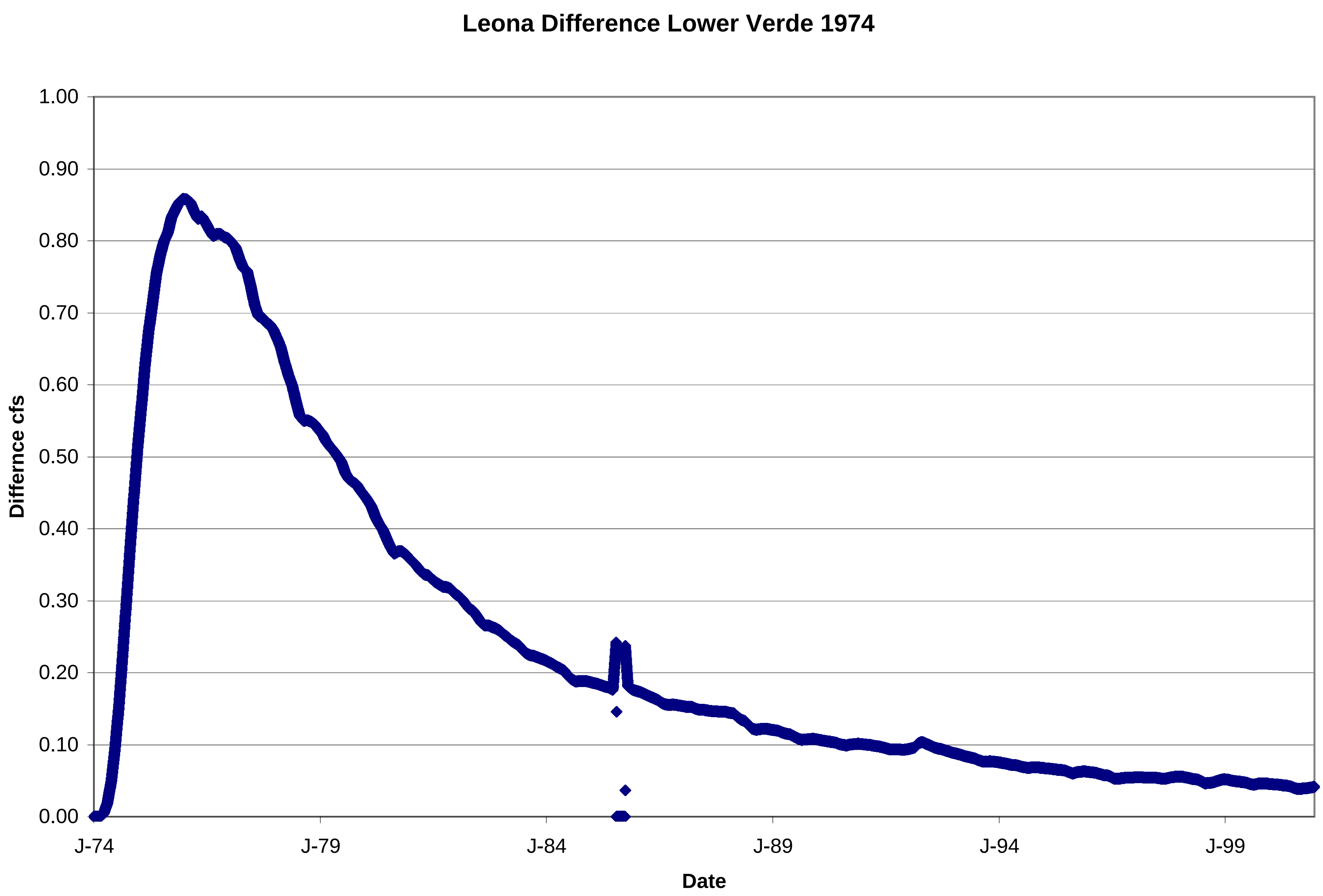


Leona Difference Lower Hondo 1974
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

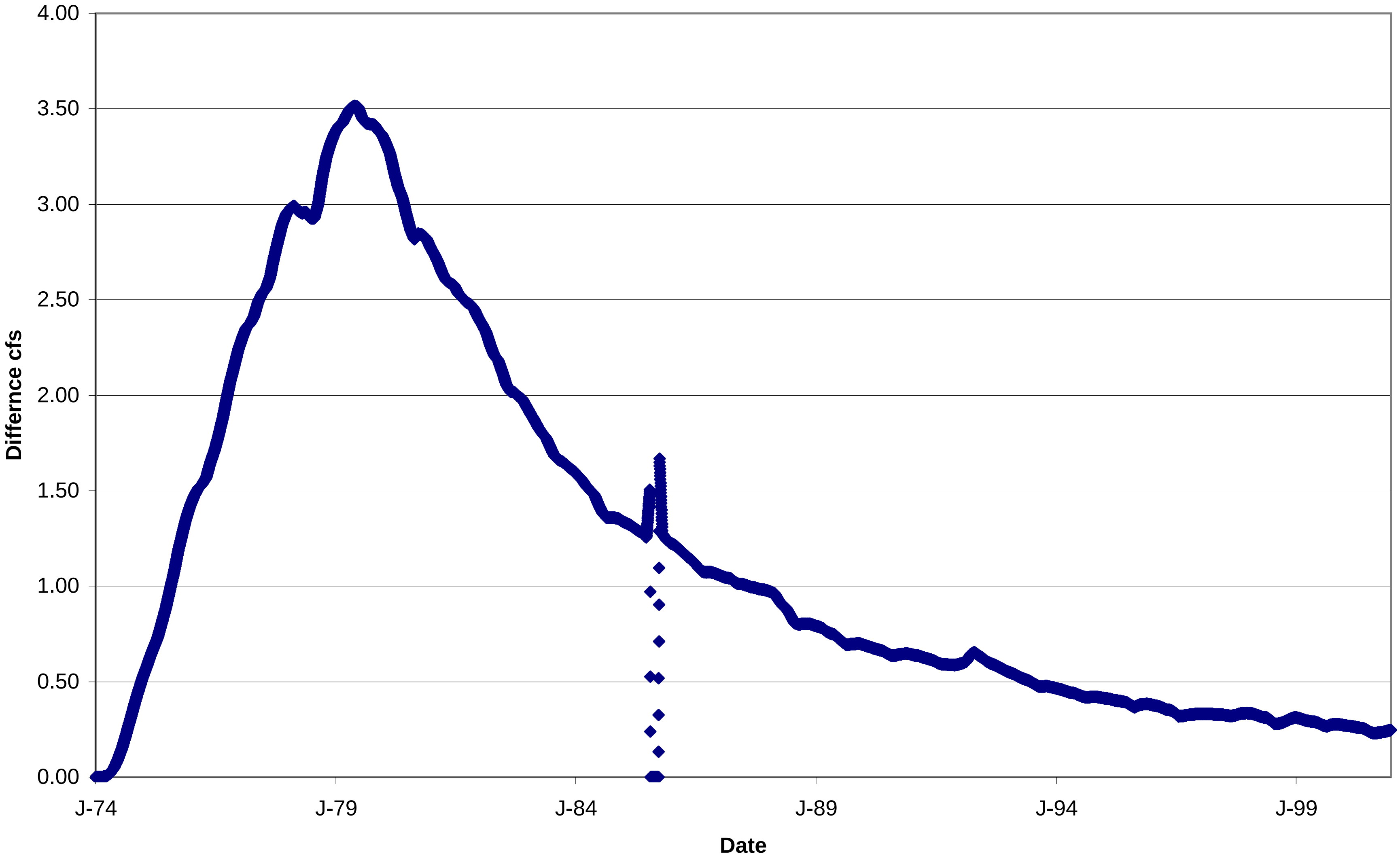

Leona Difference Lower Hondo 1974-1978
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

Leona Difference Lower Hondo 1974-2000

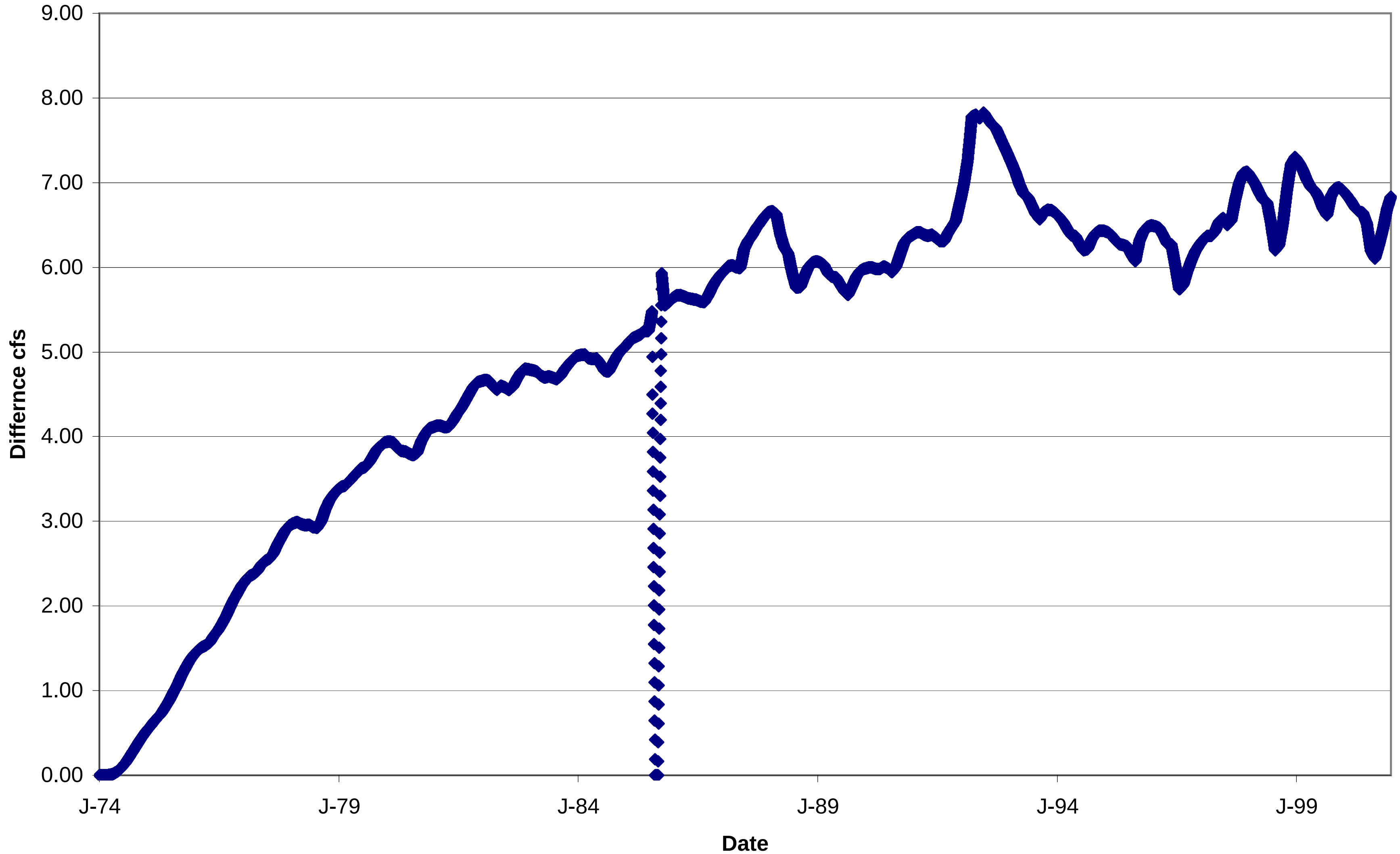


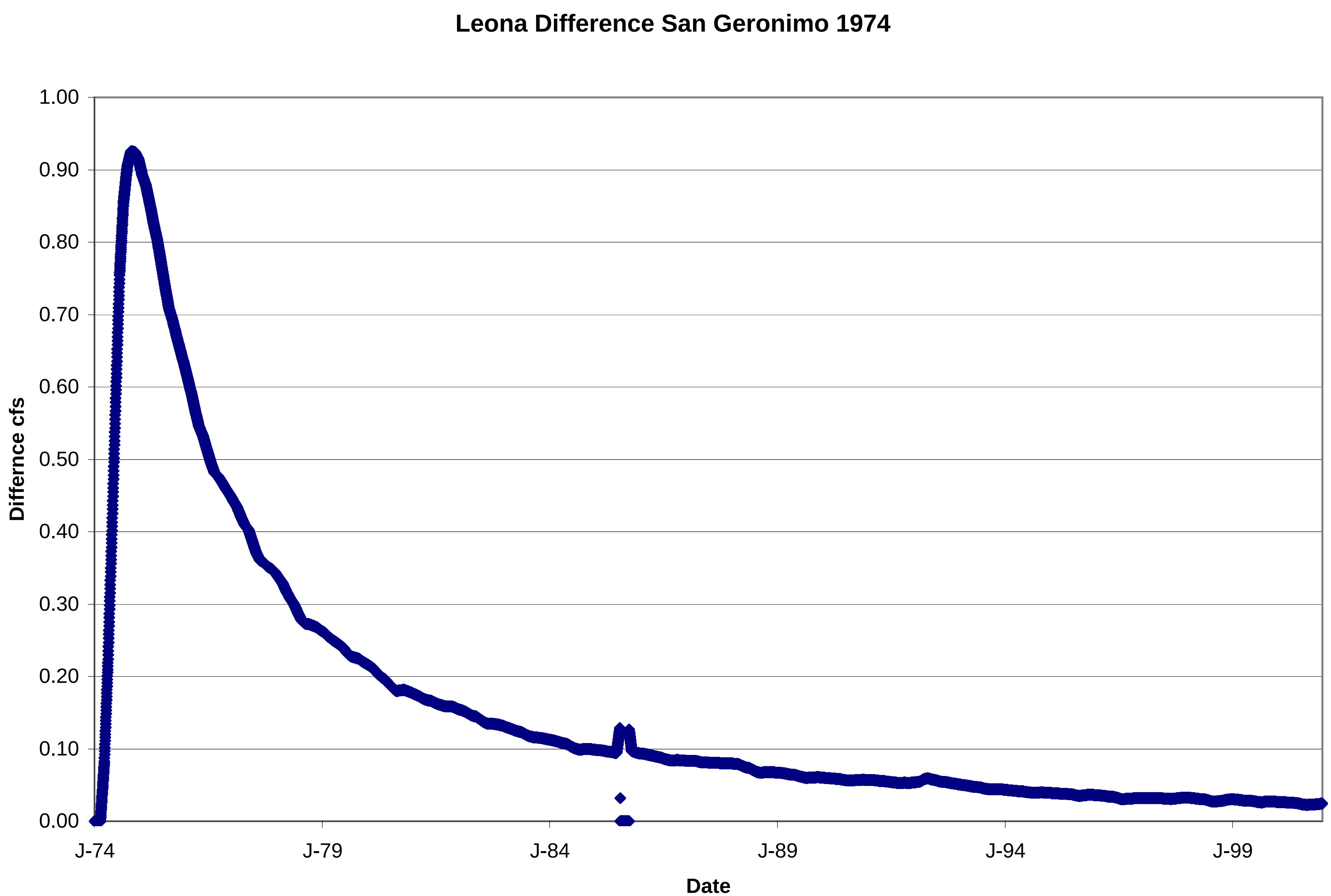

Leona Difference Lower Verde 1974
Differnce cfs
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

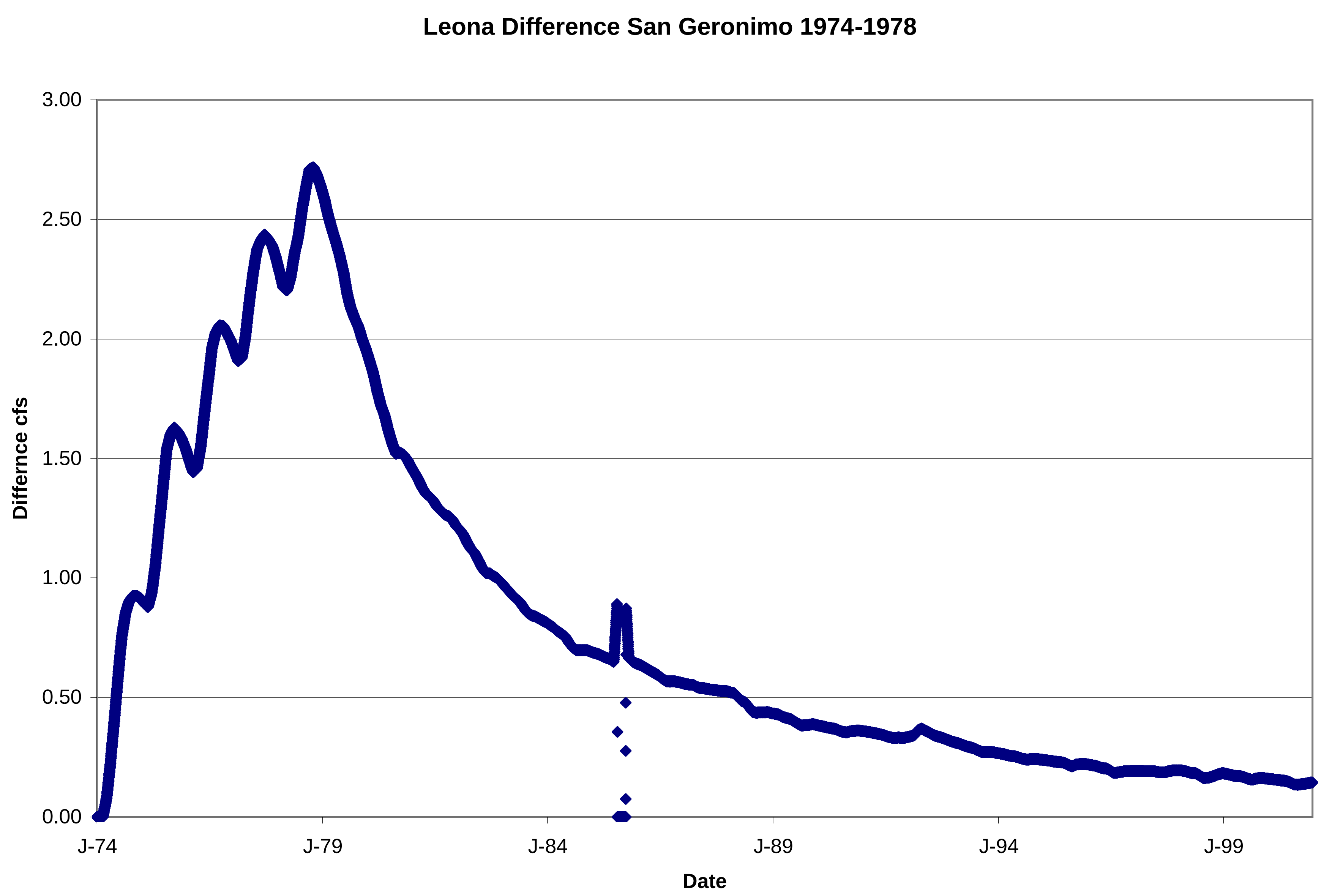
Leona Difference Lower Verde 1974-1978

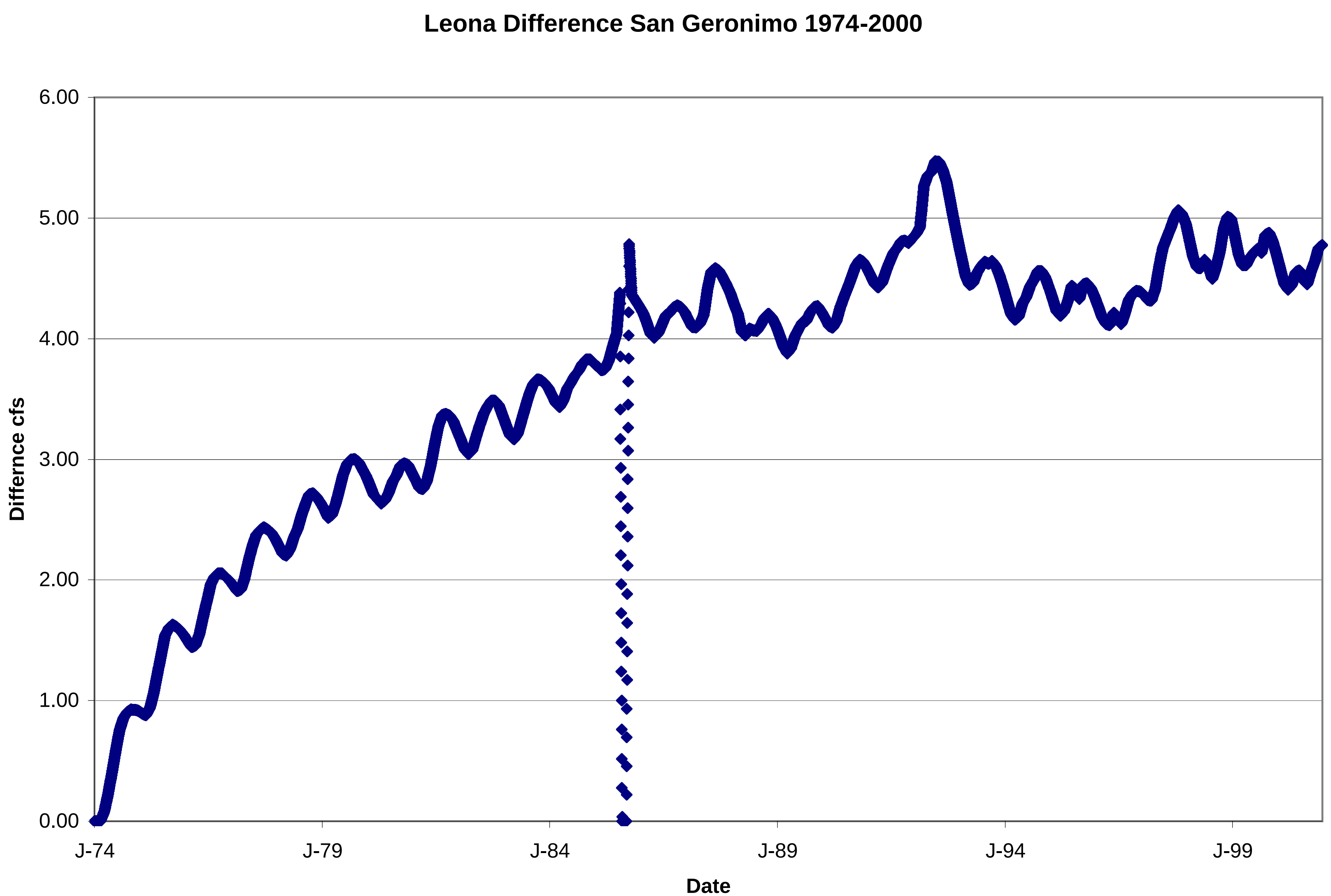


Leona Difference Lower Verde 1974-2000

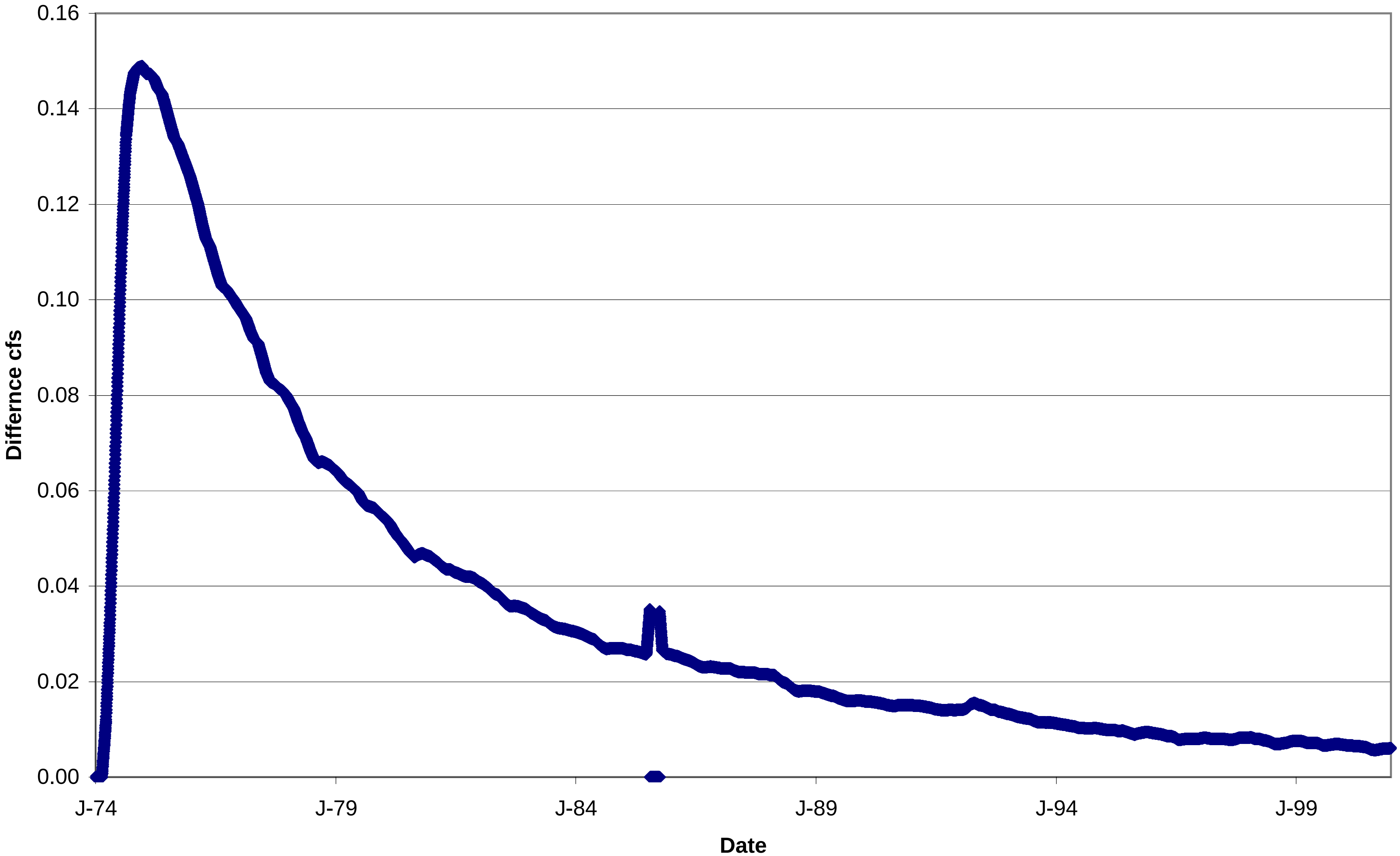


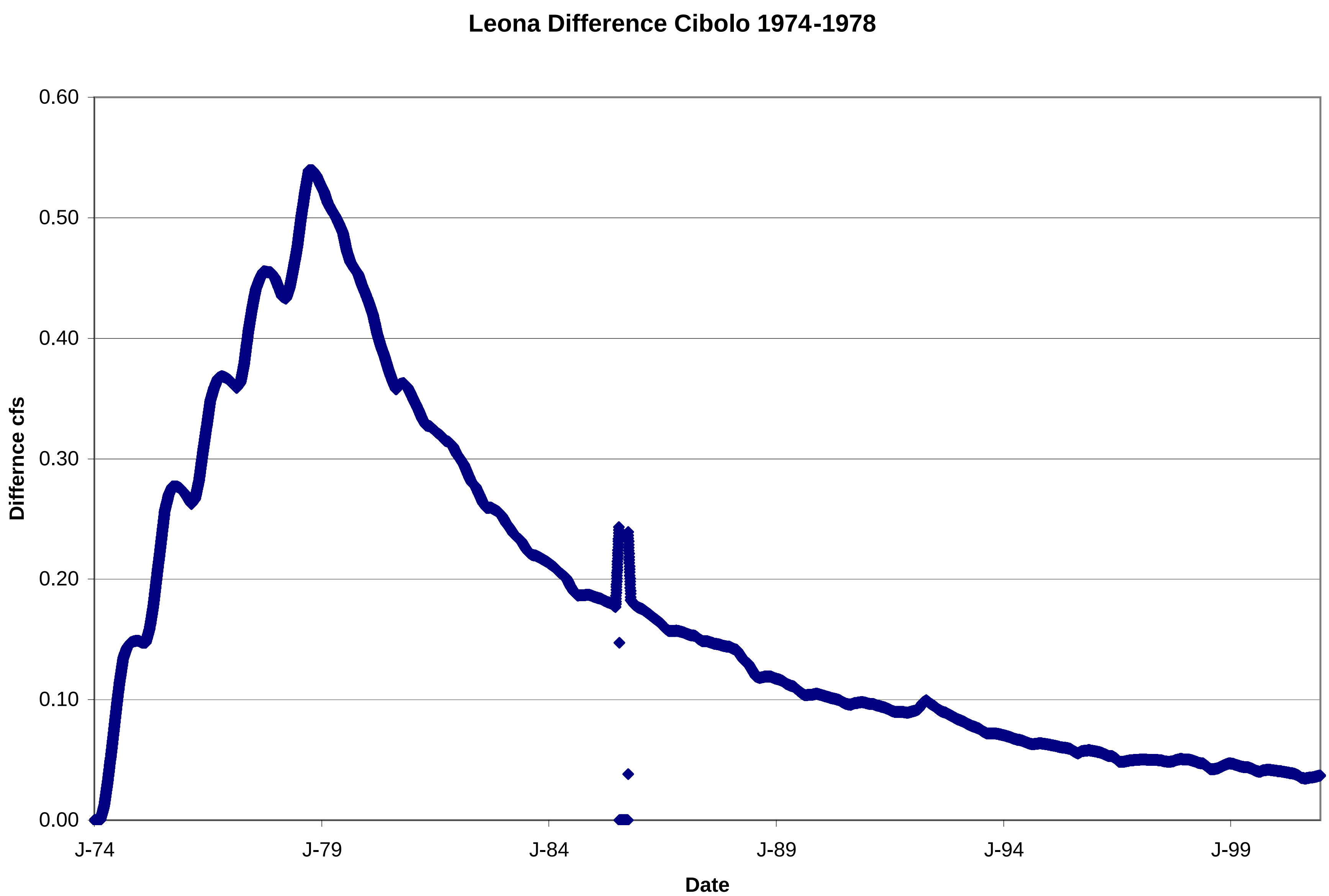

Leona Difference San Geronimo 1974
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

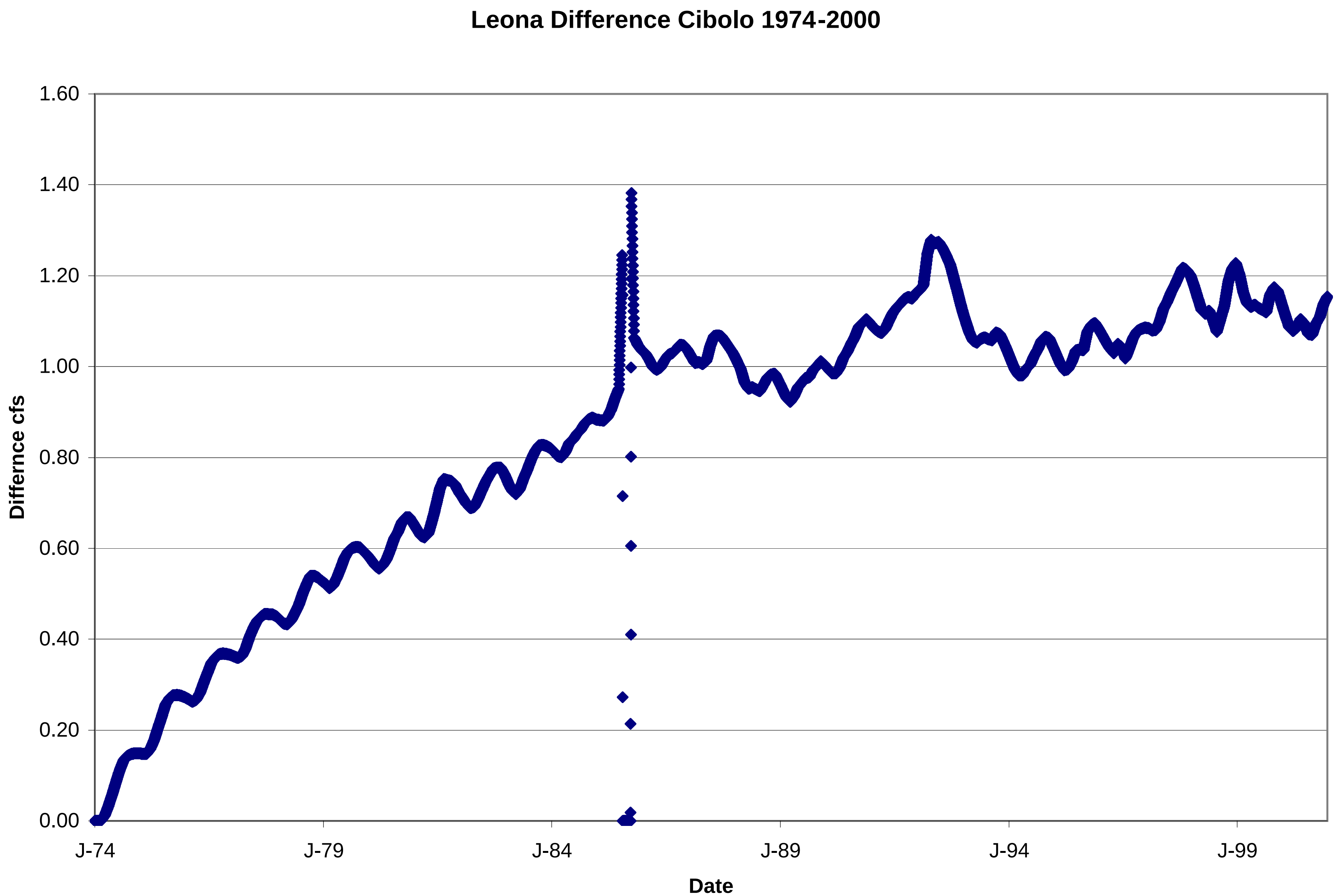

Leona Difference San Geronimo 1974-1978
Differnce cfs
3.00
2.50
2.00
1.50
1.00
0.50
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

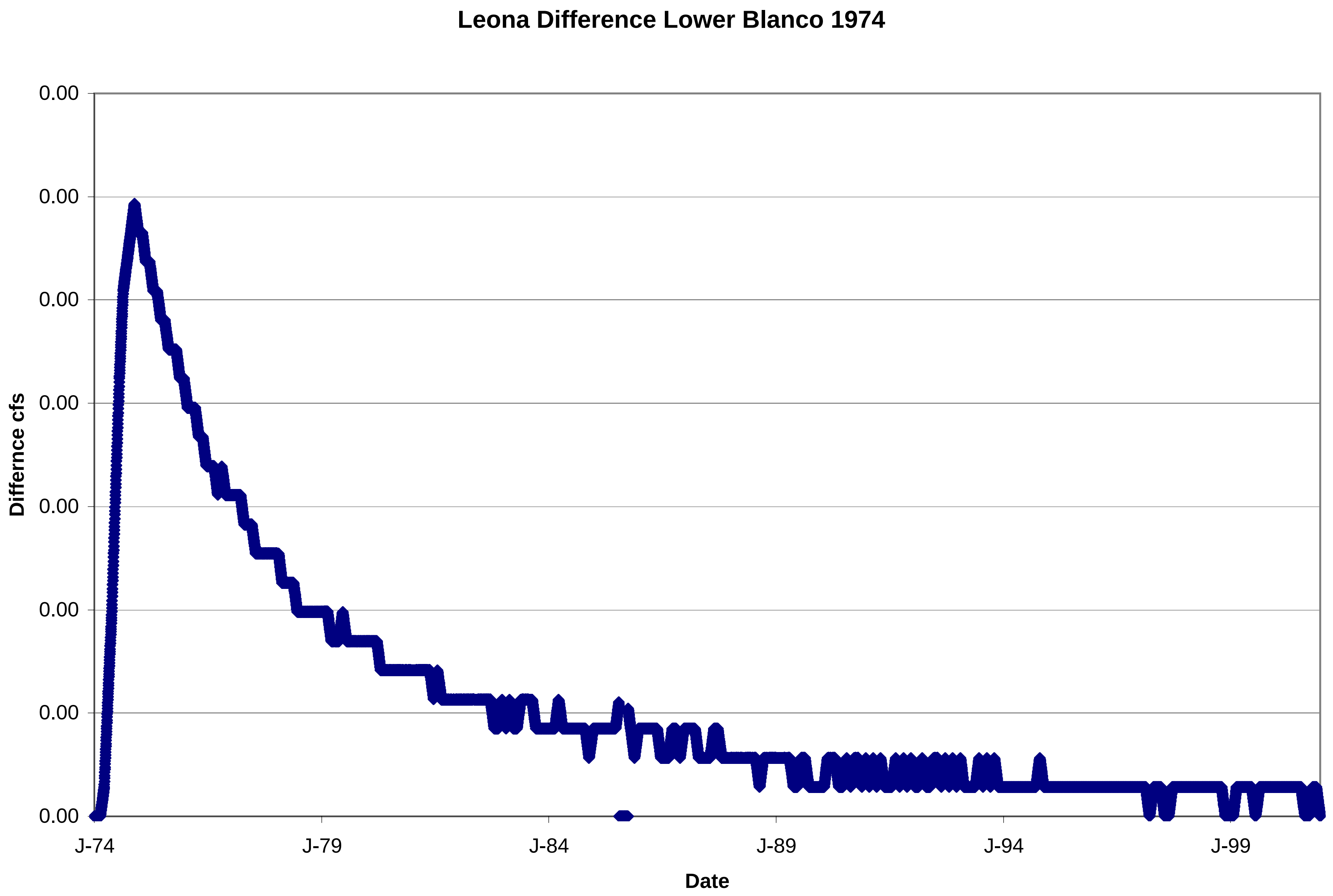

Leona Difference San Geronimo 1974-2000
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

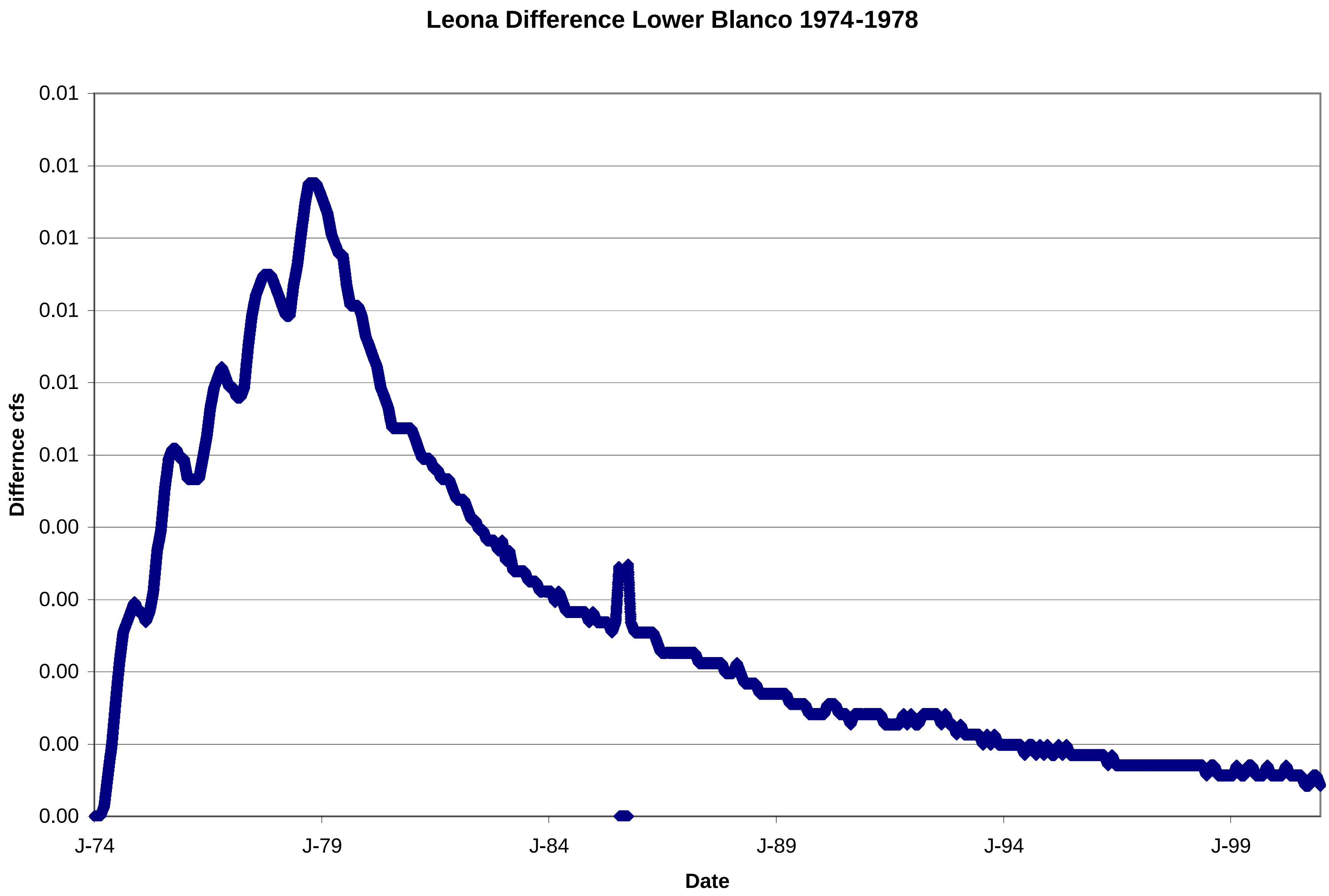
Leona Difference Cibolo 1974



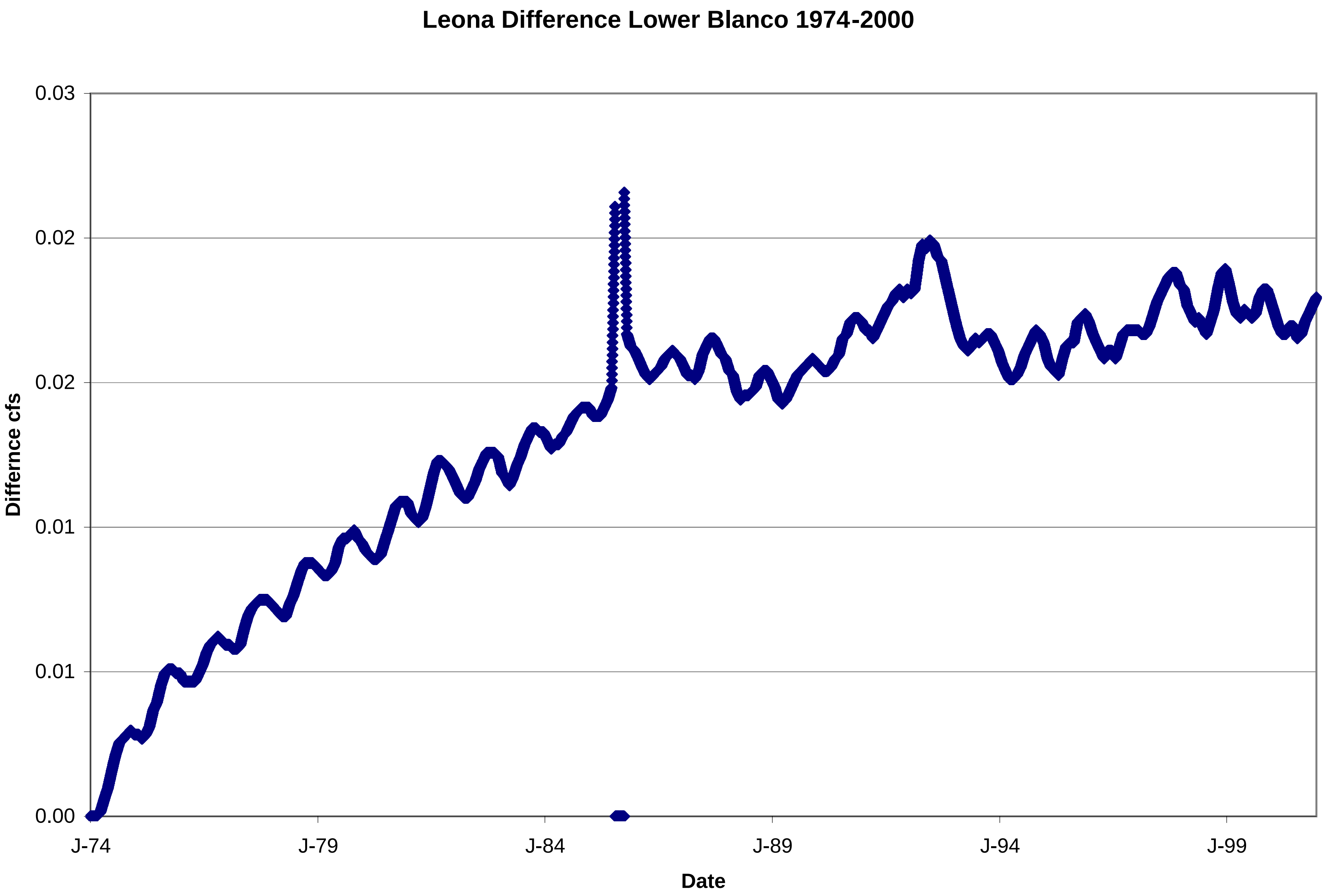

Leona Difference Cibolo 1974-1978
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

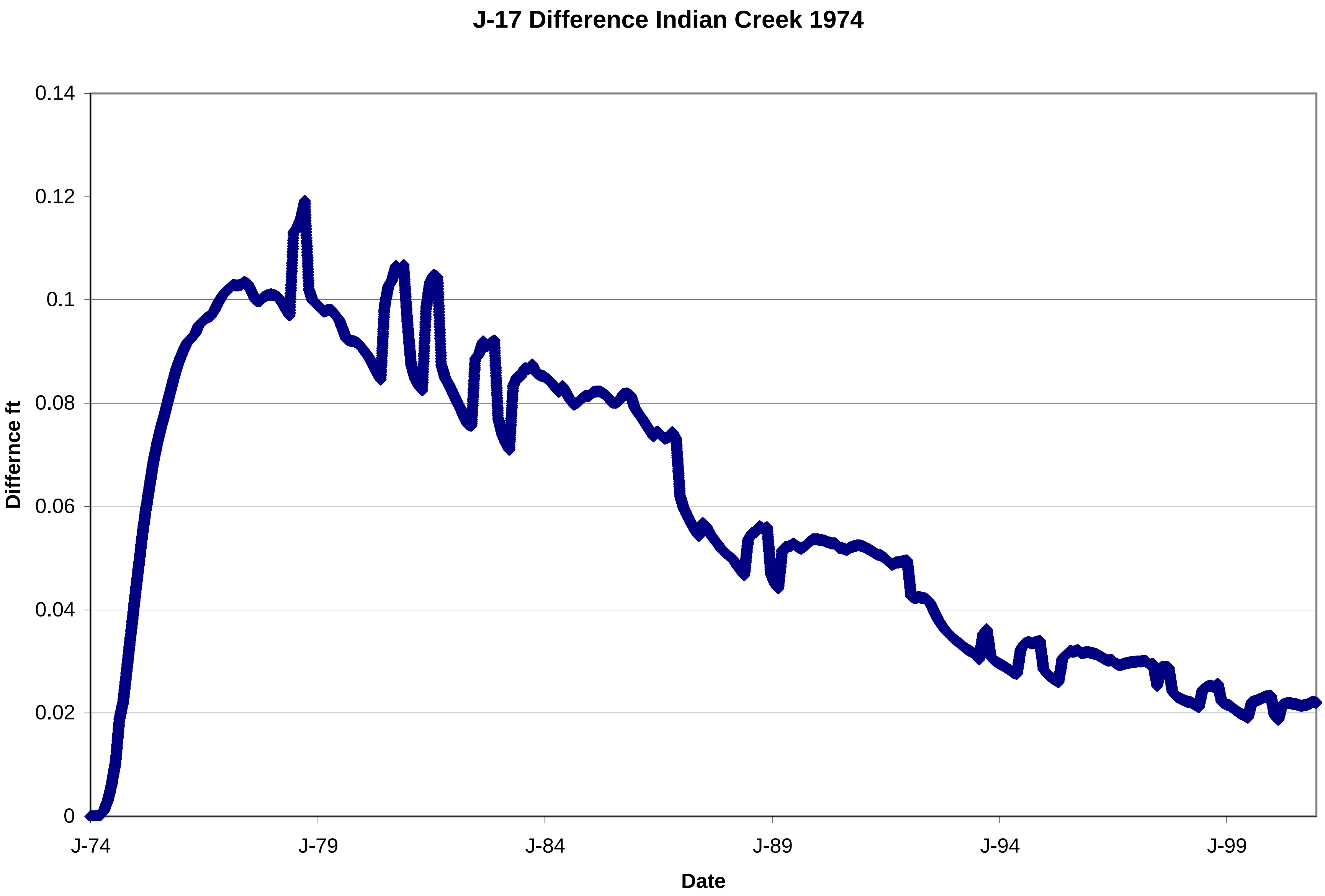

Leona Difference Cibolo 1974-2000
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date


Leona Difference Lower Blanco 1974
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
Differnce cfs
J-74
J-79
J-84
J-89
J-94
J-99
Date

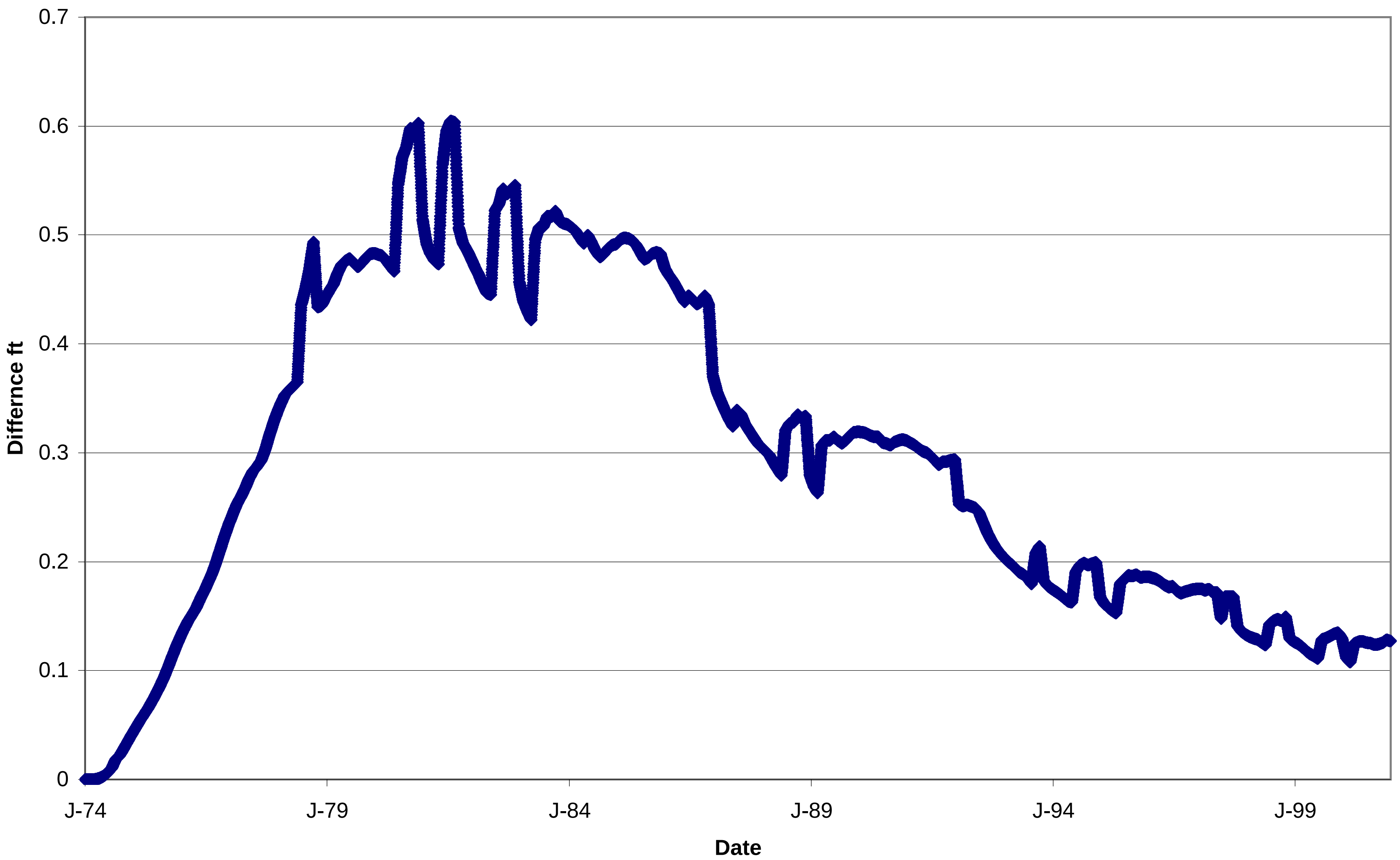


Leona Difference Lower Blanco 1974-1978
Differnce cfs
0.01
0.01
0.01
0.01
0.01
0.01
0.00
0.00
0.00
0.00
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date

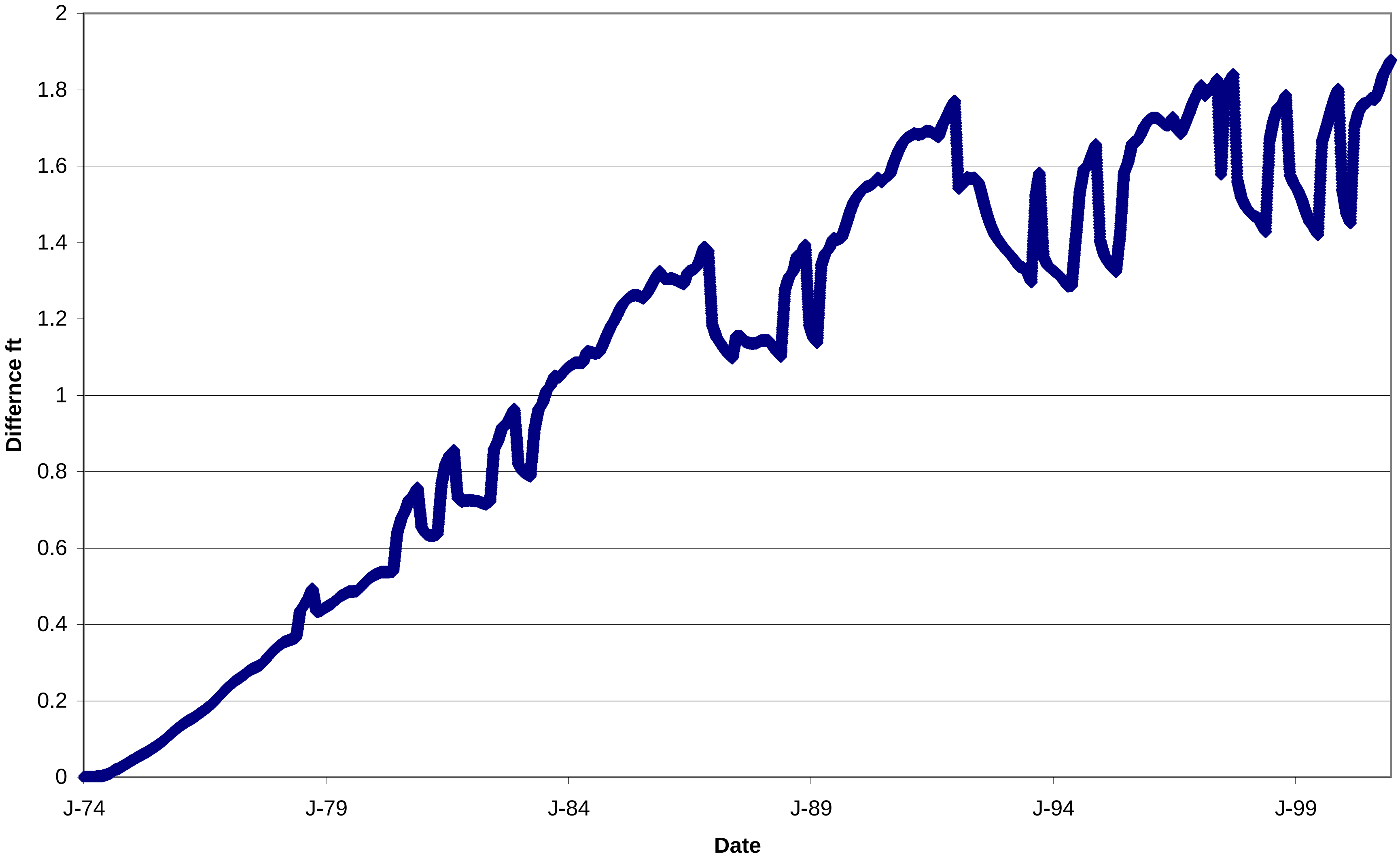

Leona Difference Lower Blanco 1974-2000
Differnce cfs
0.03
0.02
0.02
0.01
0.01
0.00
J-74
J-79
J-84
J-89
J-94
J-99
Date


J-17 Difference Indian Creek 1974
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date

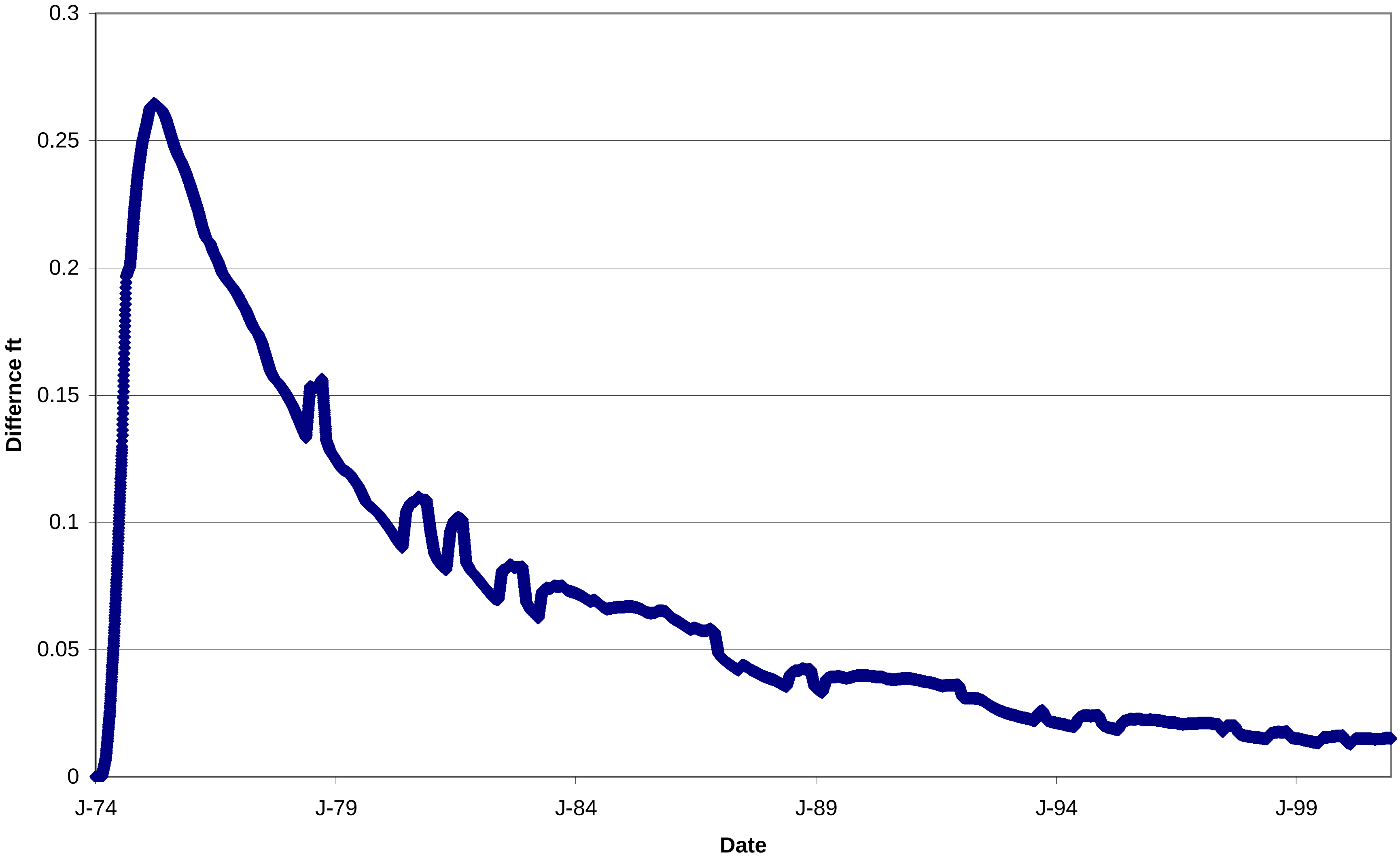
J-17 Difference Indian Creek 1974-1978

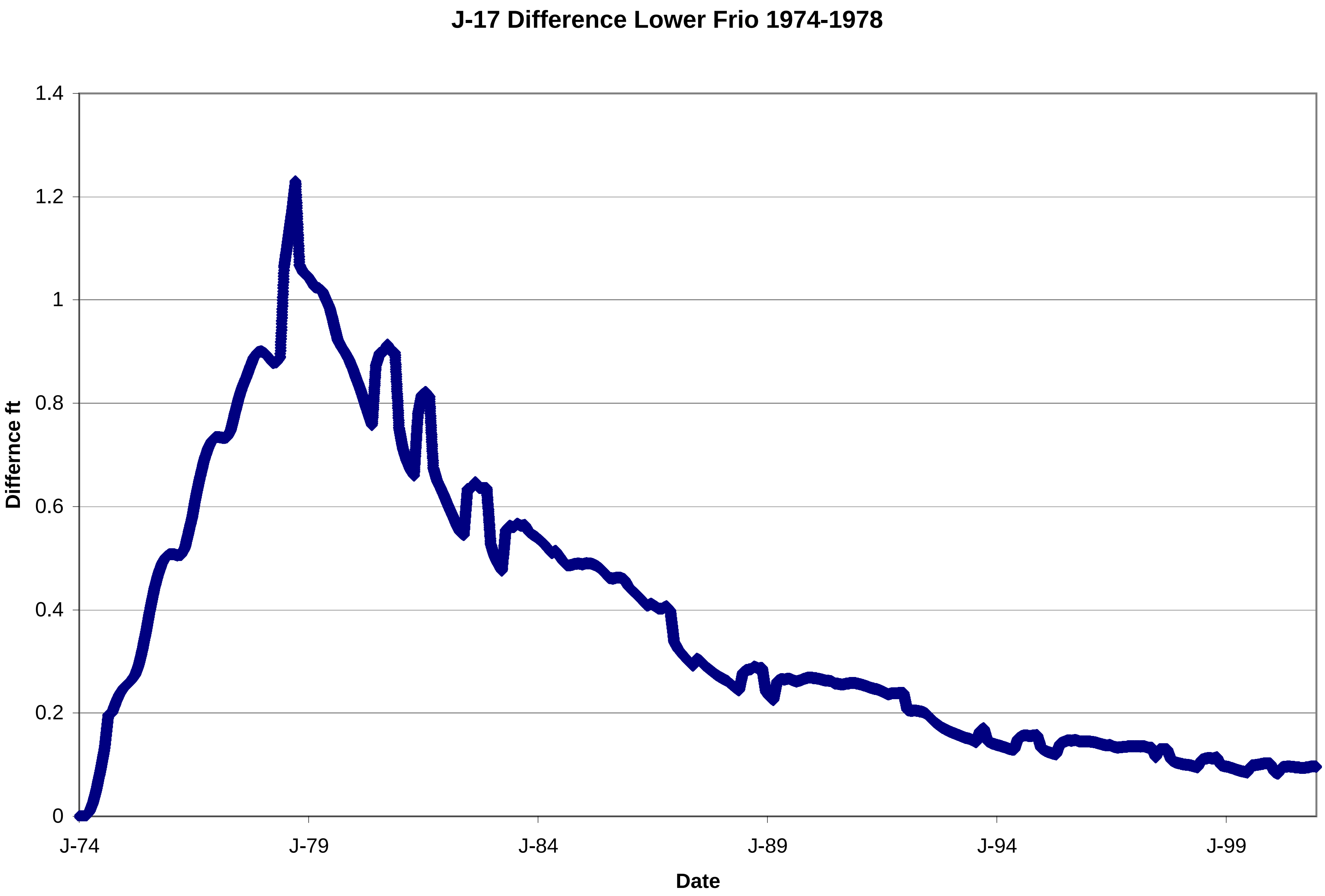


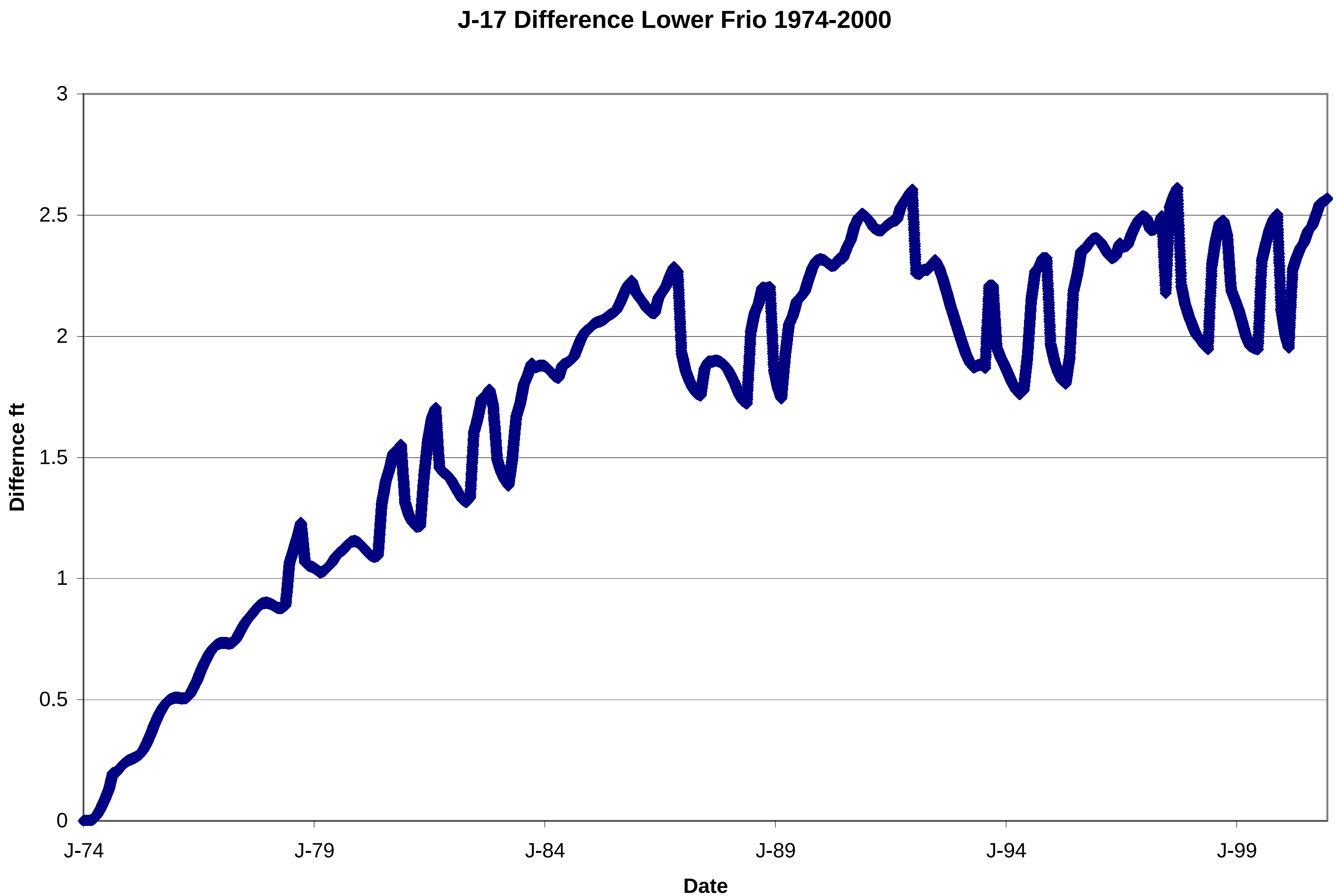
J-17 Difference Indian Creek 1974-2000



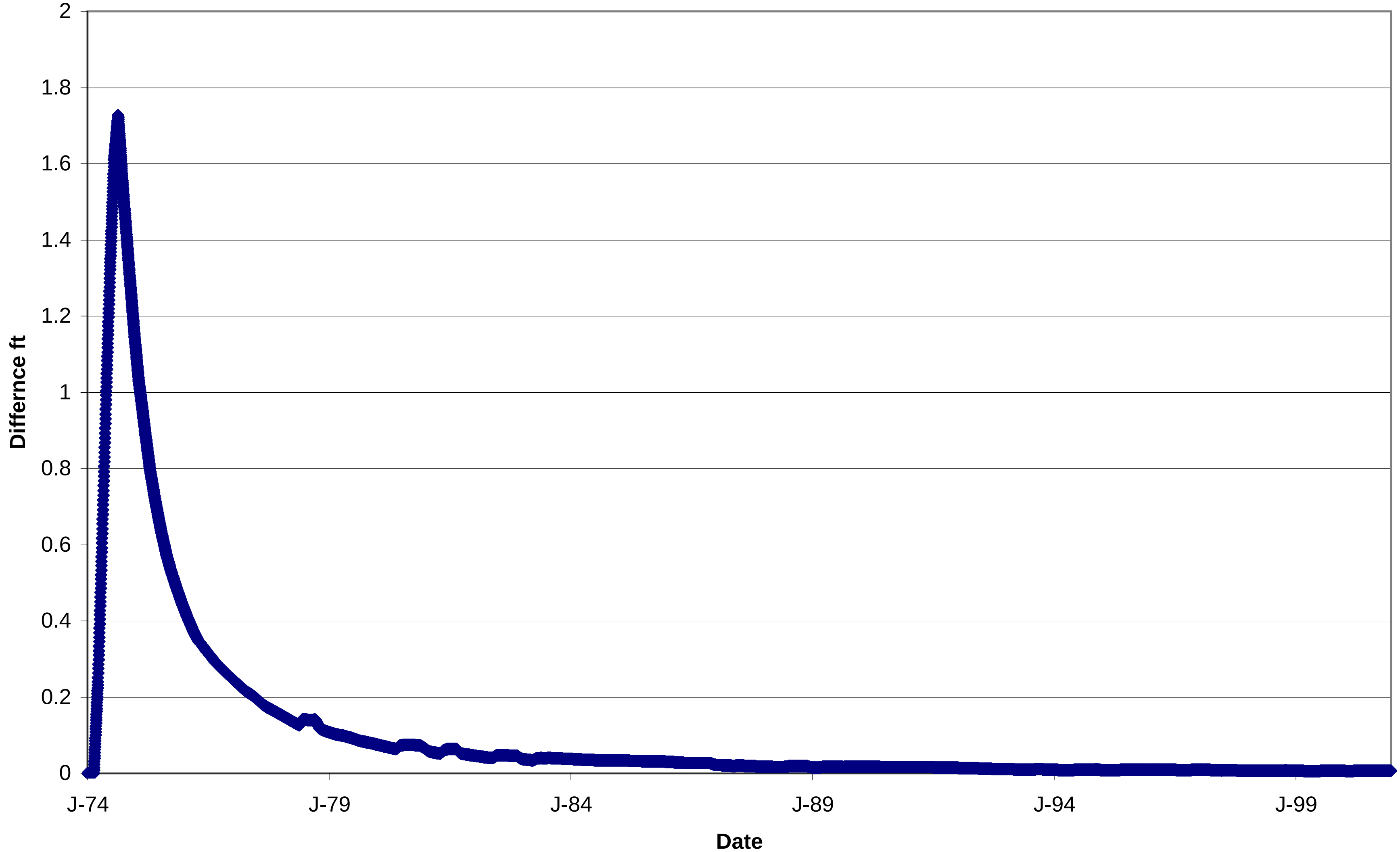
J-17 Difference Lower Frio 1974

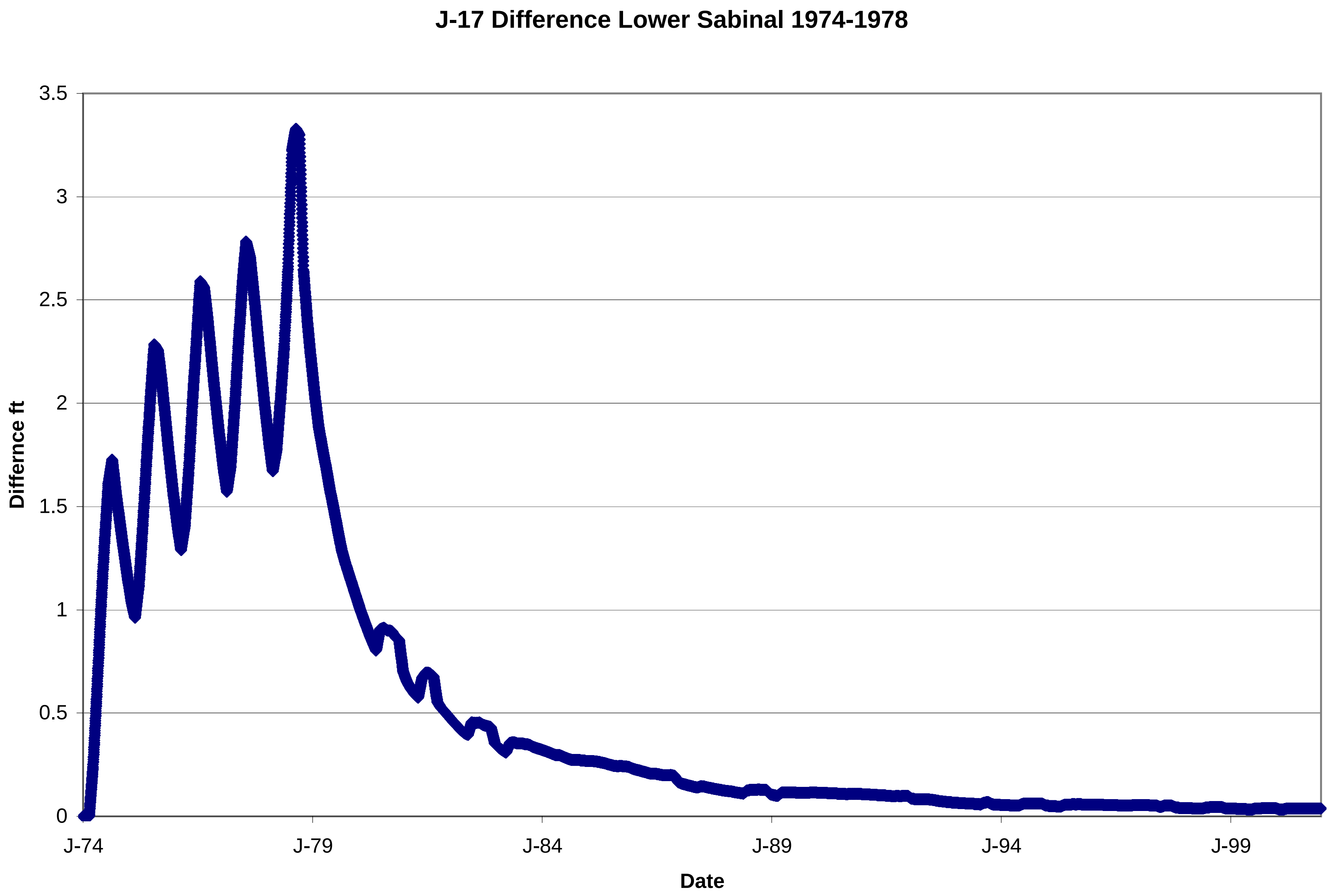


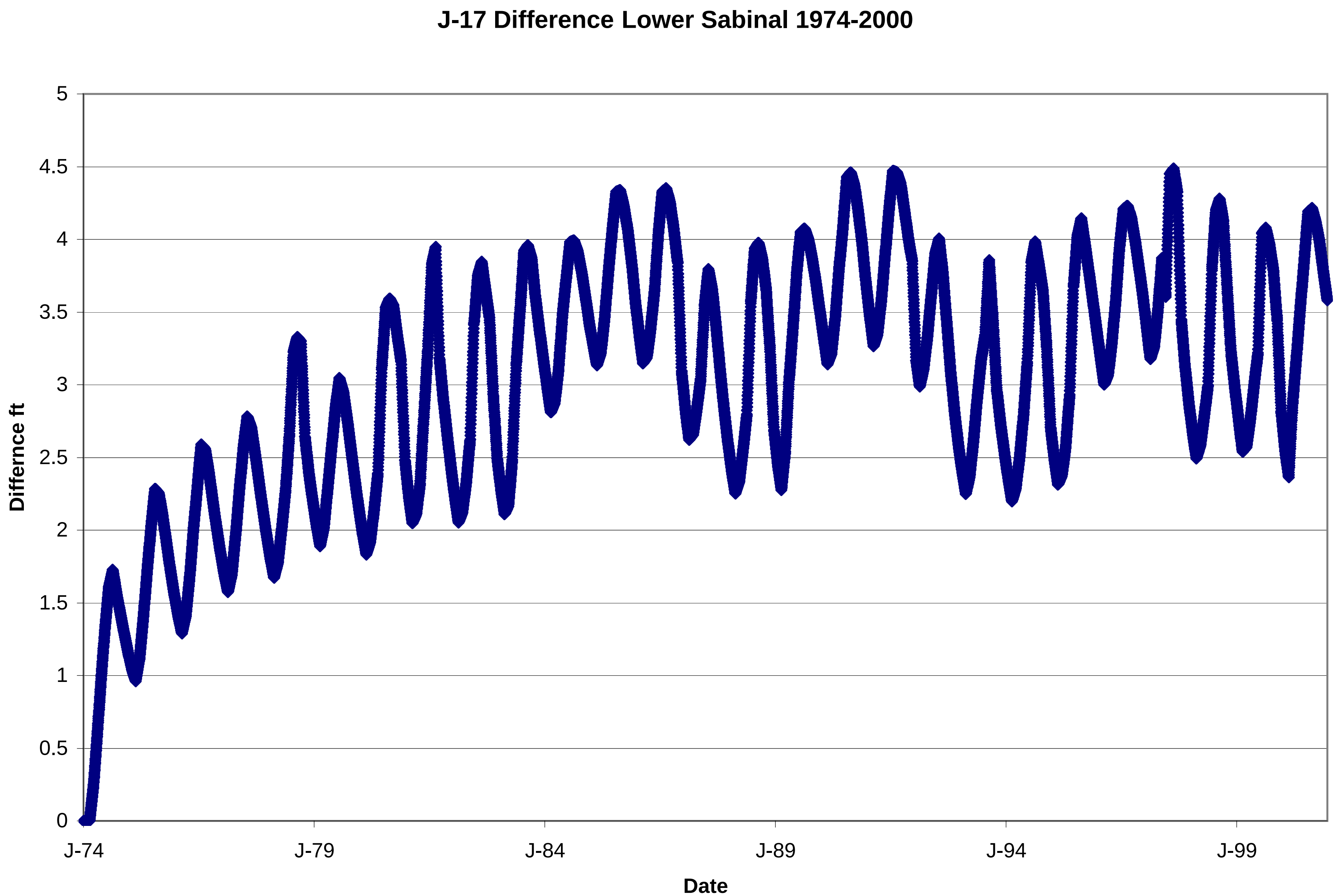

J-17 Difference Lower Frio 1974-1978
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date

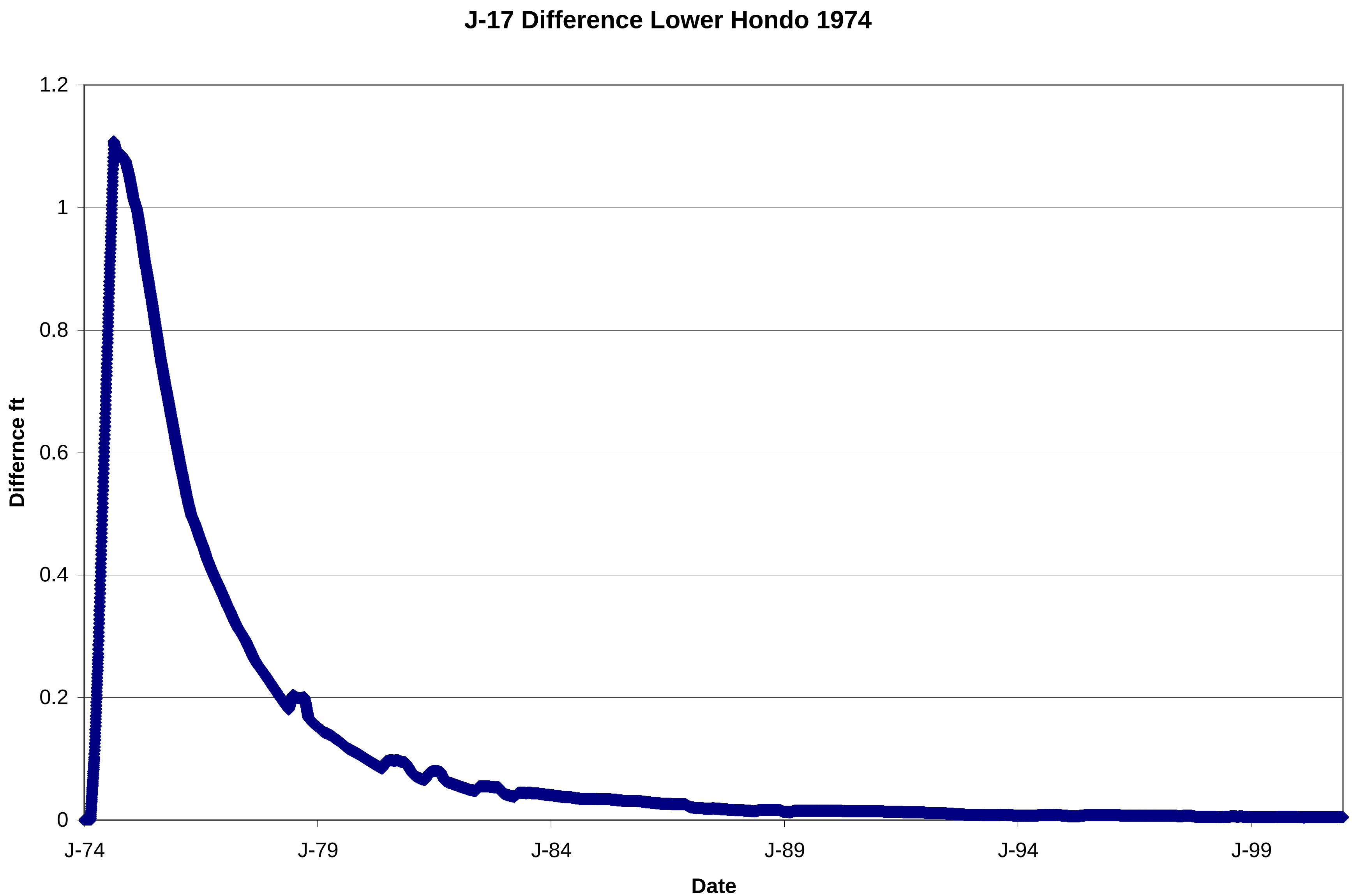

J-17 Difference Lower Frio 1974-2000
3
2.5
2
1.5
1
0.5
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date

J-17 Difference Lower Sabinal 1974

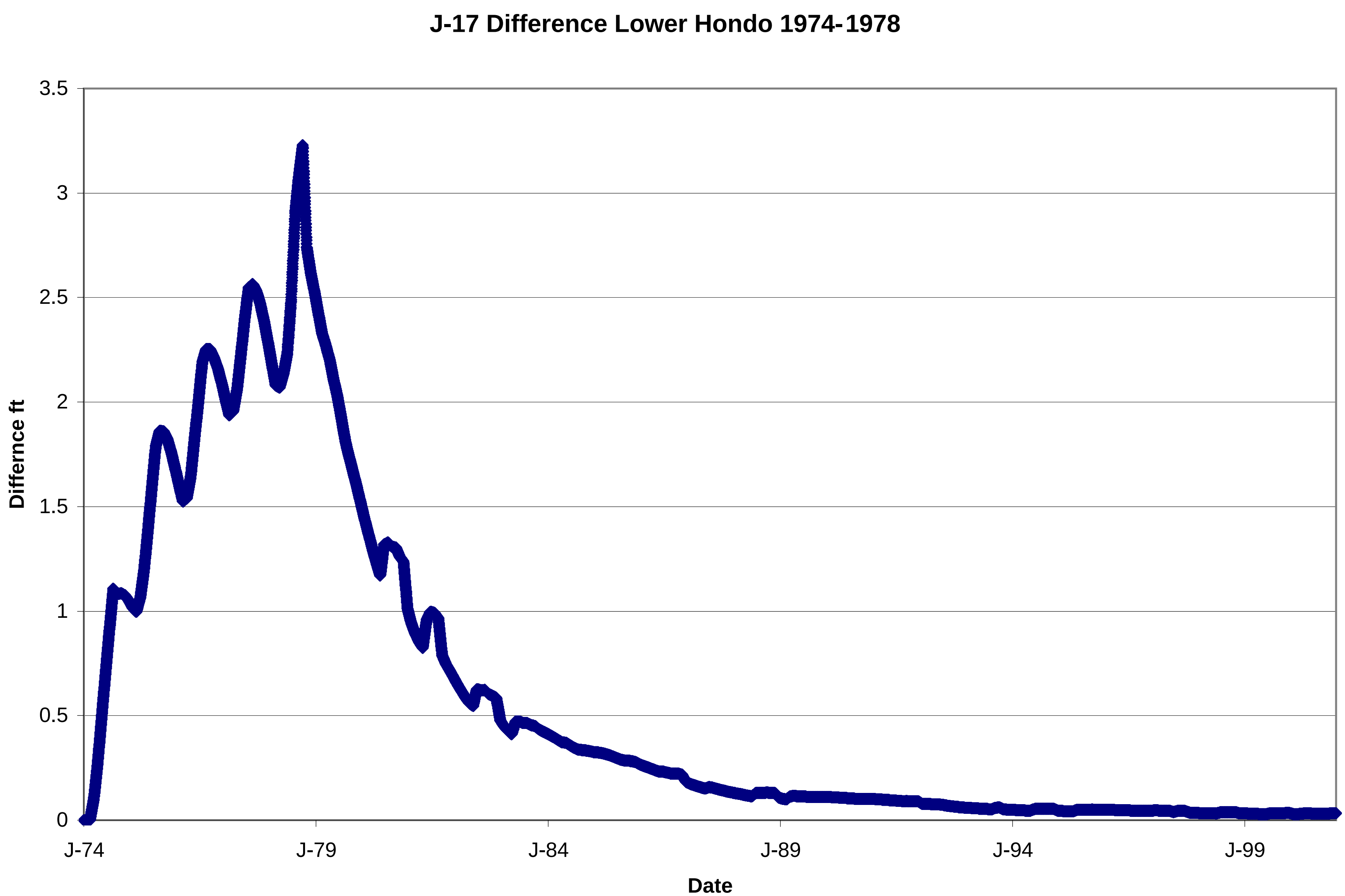



J-17 Difference Lower Sabinal 1974-1978
Differnce ft
3.5
3
2.5
2
1.5
1
0.5
0
J-74
J-79
J-84
J-89
J-94
J-99
Date

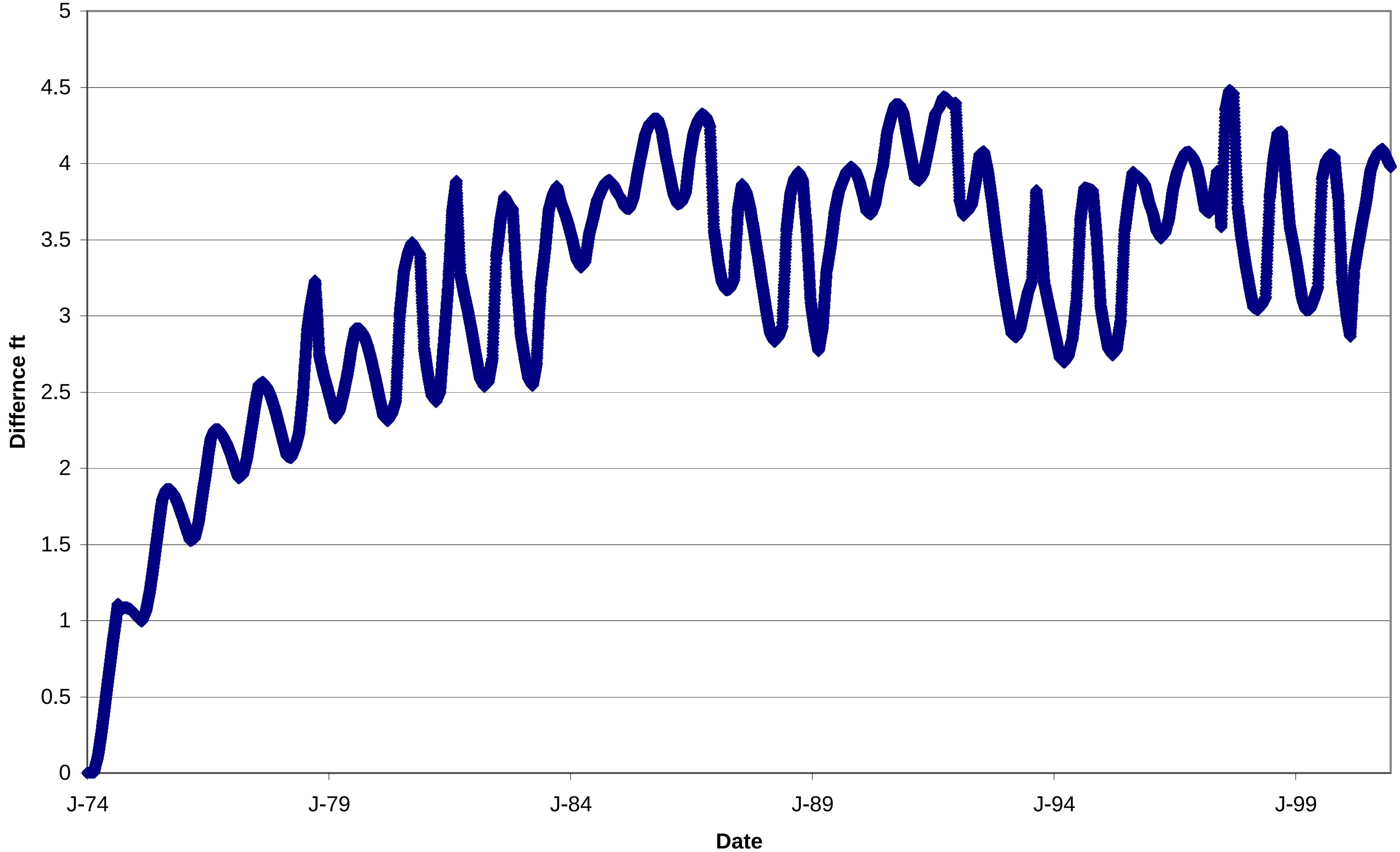

J-17 Difference Lower Sabinal 1974-2000
Differnce ft
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
J-74
J-79
J-84
J-89
J-94
J-99
Date

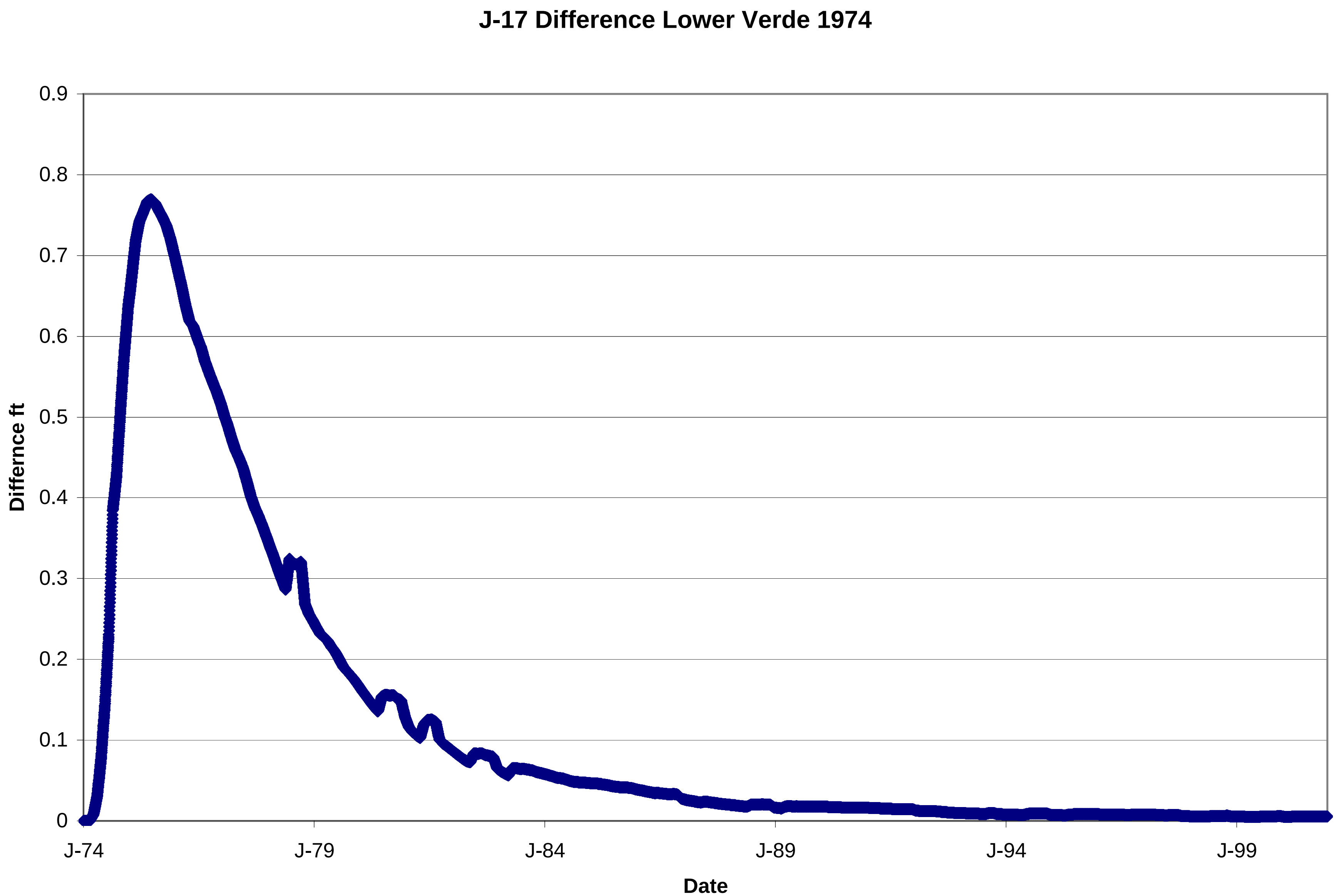


J-17 Difference Lower Hondo 1974
1.2
1
0.8
0.6
0.4
0.2
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date

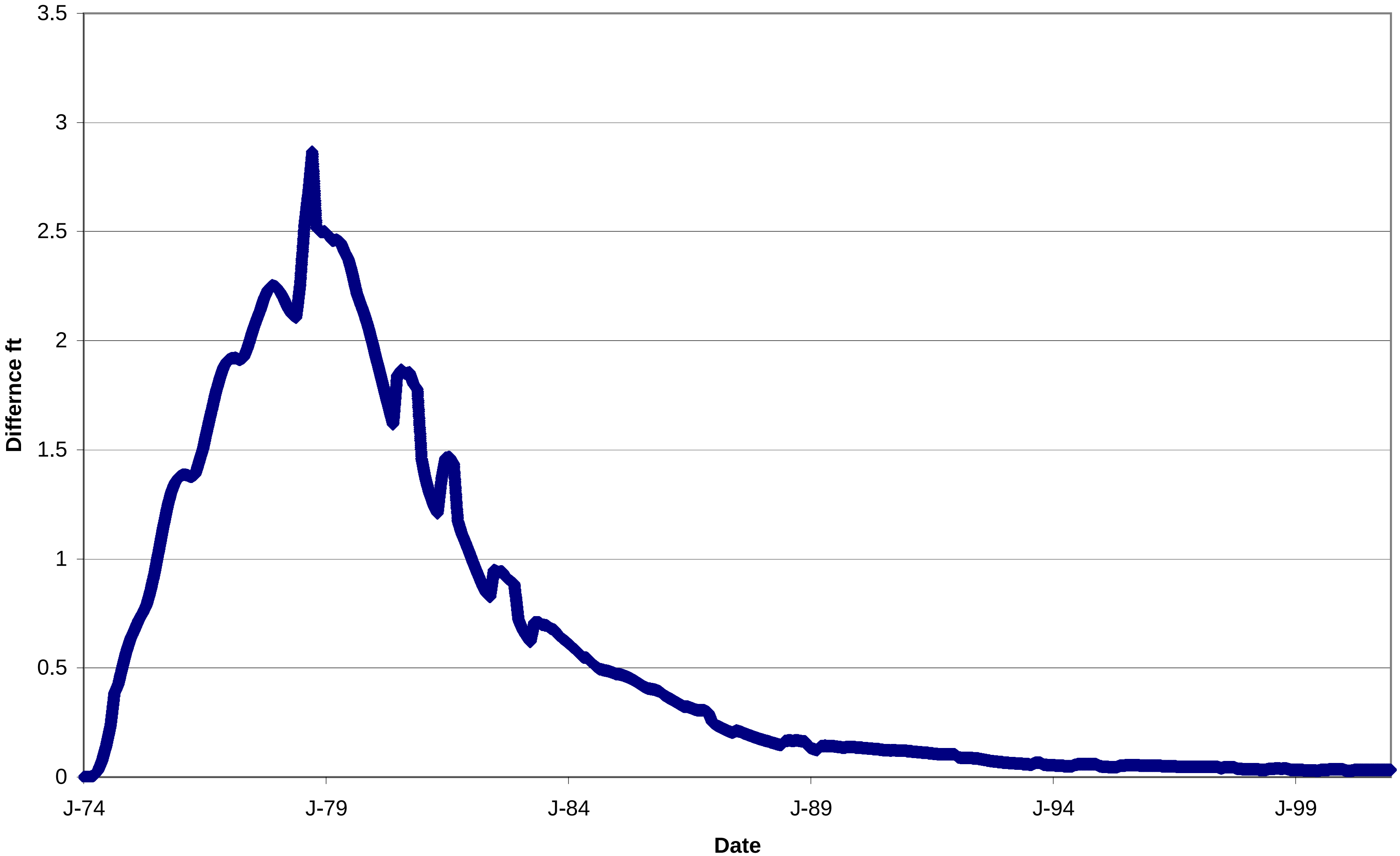

J-17 Difference Lower Hondo 1974-1978
Differnce ft
3.5
3
2.5
2
1.5
1
0.5
0
J-74
J-79
J-84
J-89
J-94
J-99
Date

J-17 Difference Lower Hondo 1974-2000

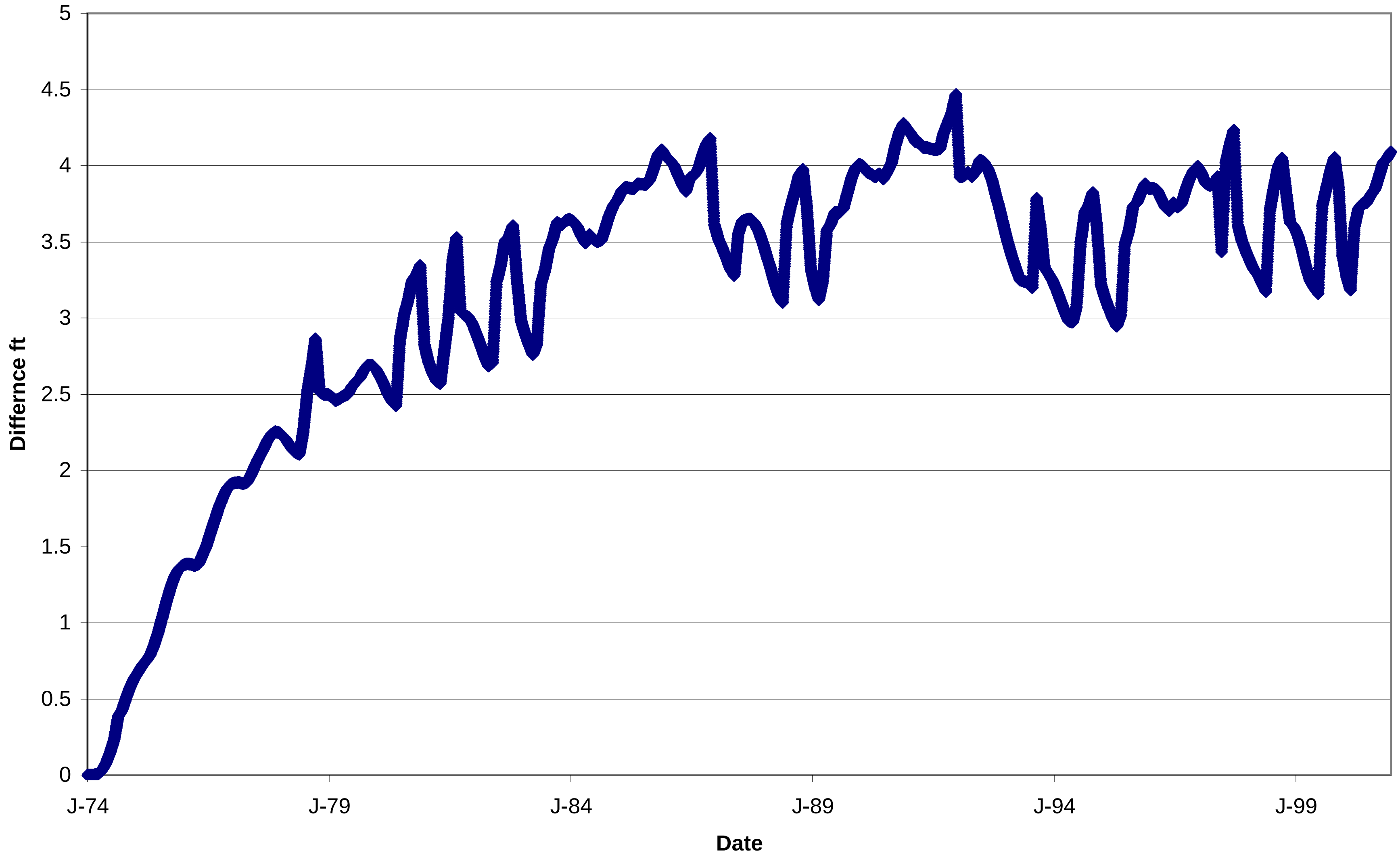


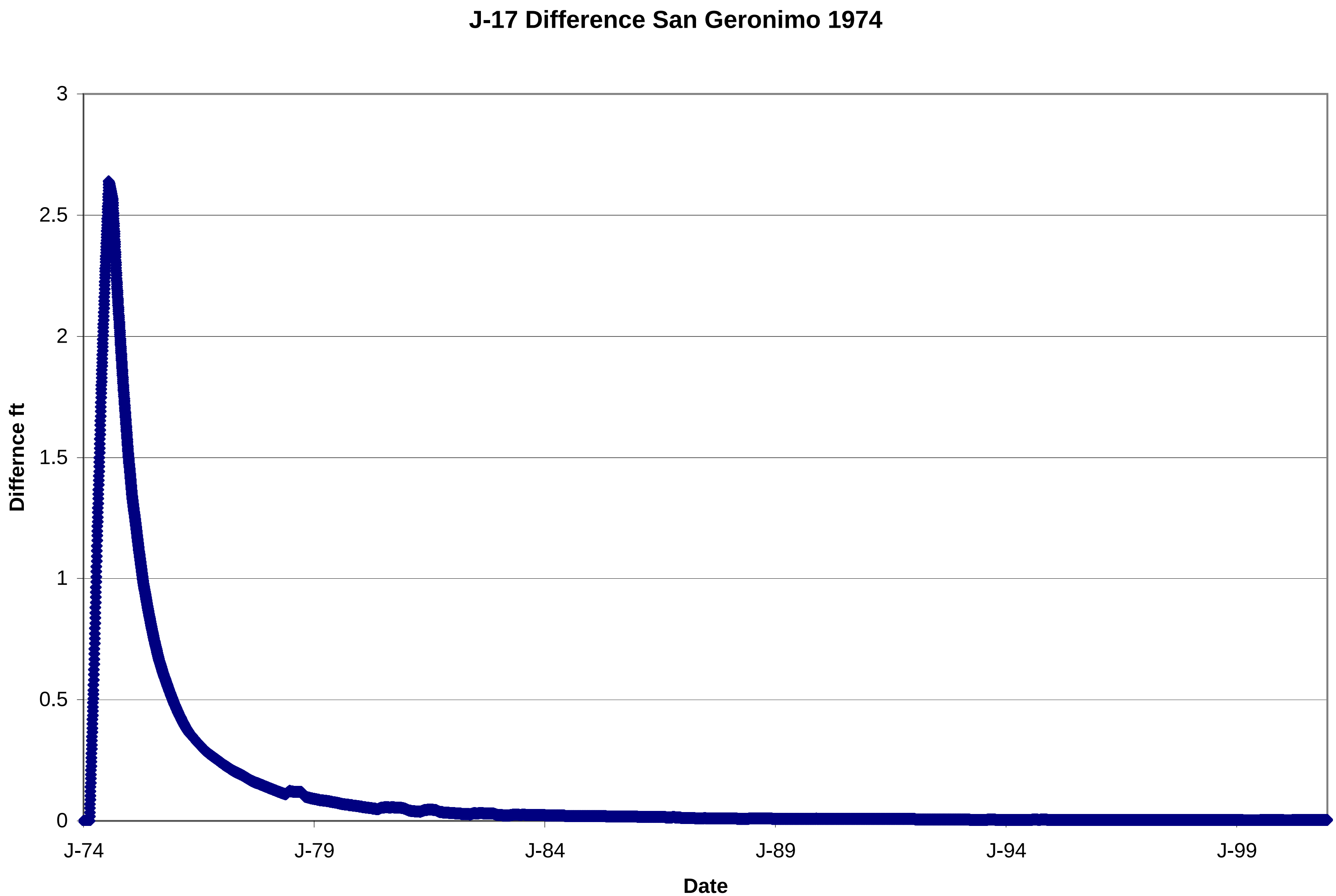

J-17 Difference Lower Verde 1974
Differnce ft
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
J-74
J-79
J-84
J-89
J-94
J-99
Date

J-17 Difference Lower Verde 1974-1978

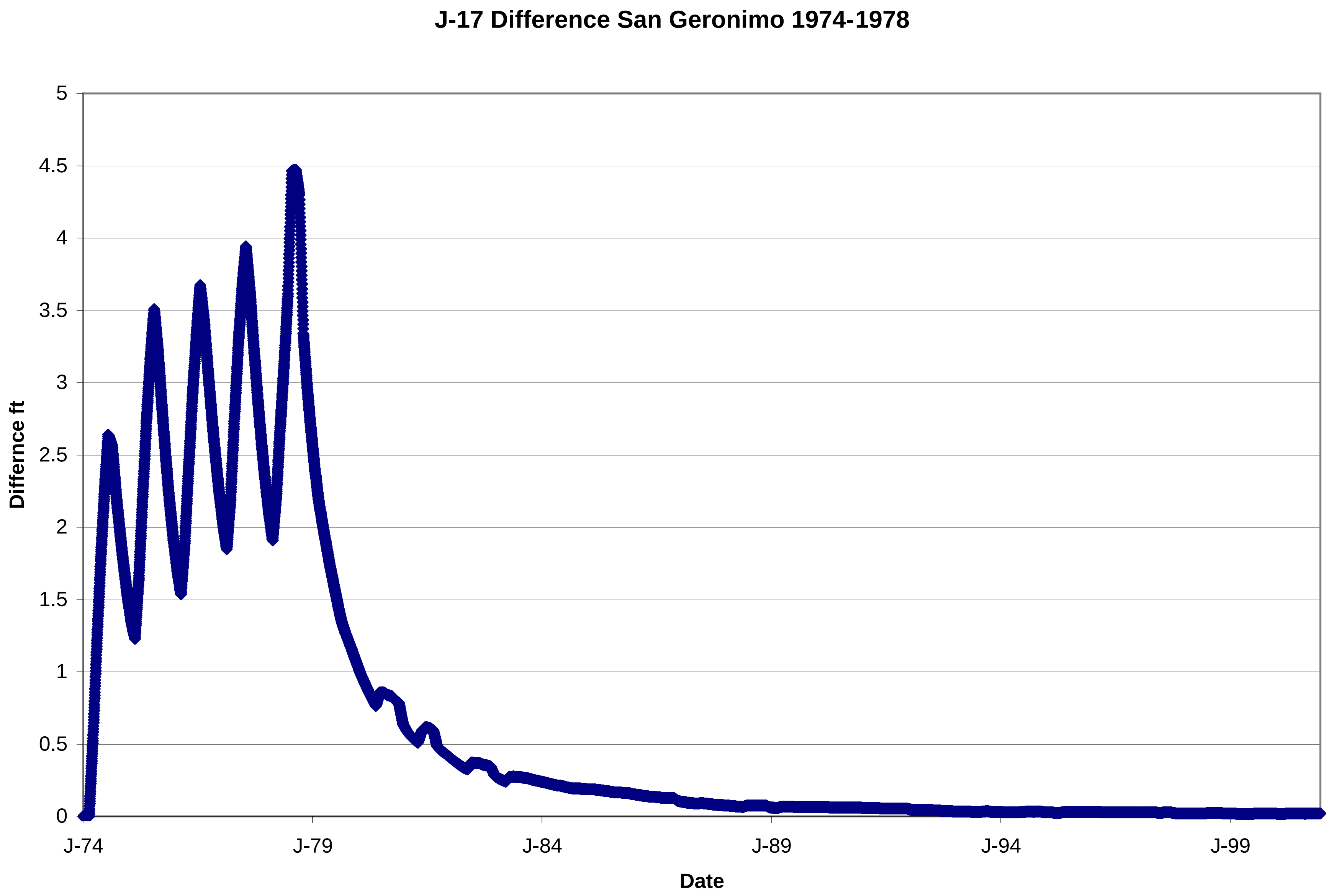


J-17 Difference Lower Verde 1974-2000

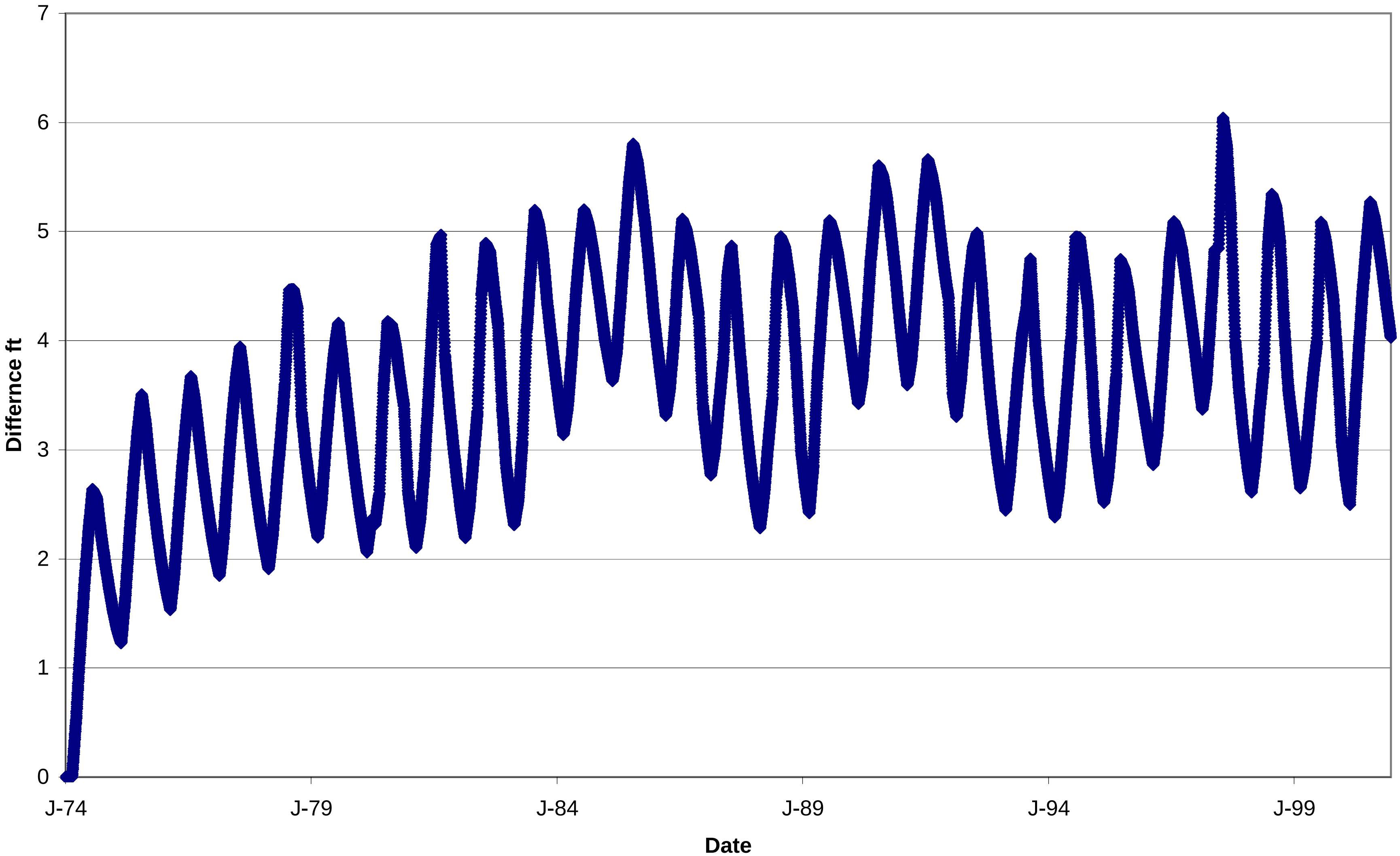


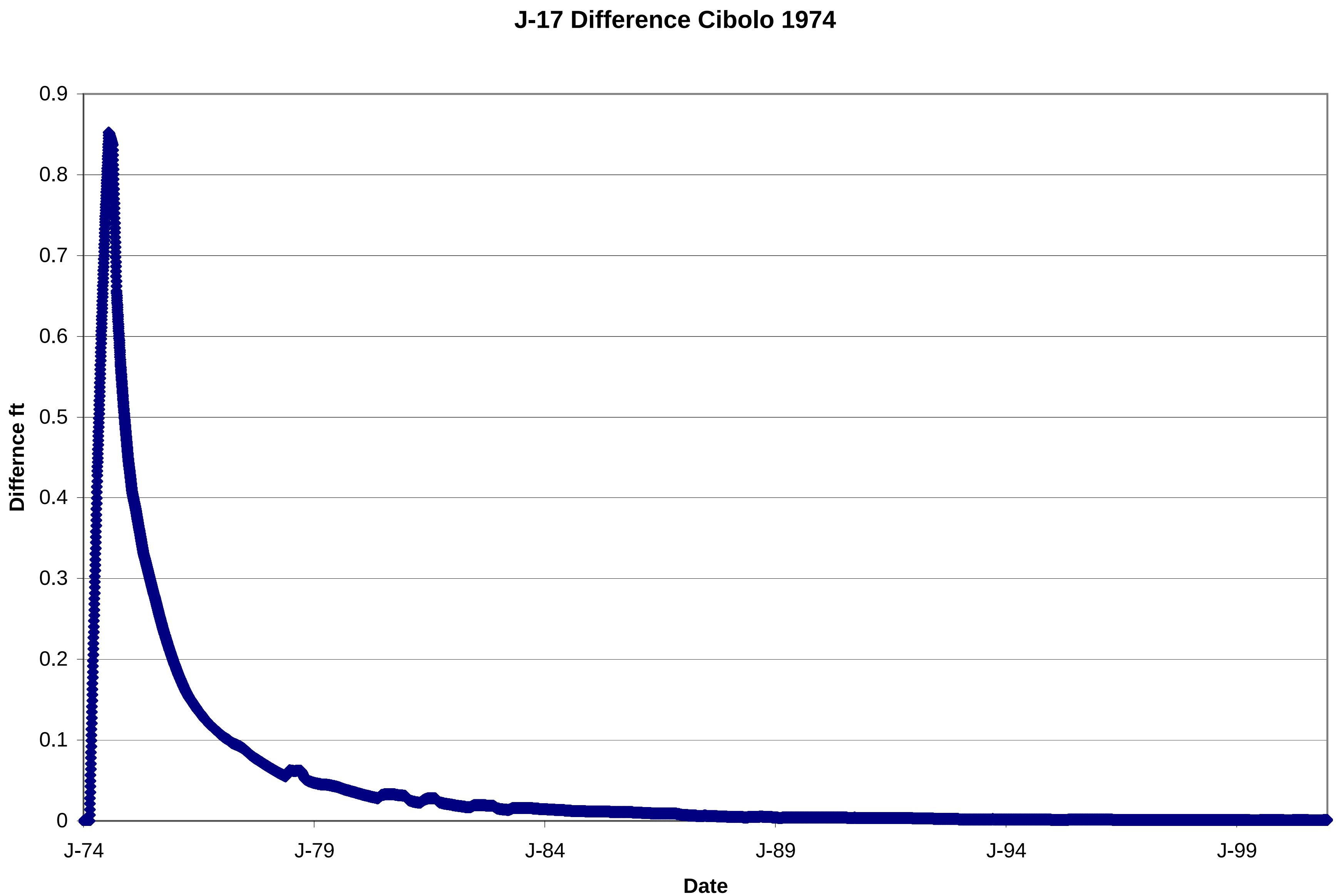


J-17 Difference San Geronimo 1974
3
2.5
2
1.5
1
0.5
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date

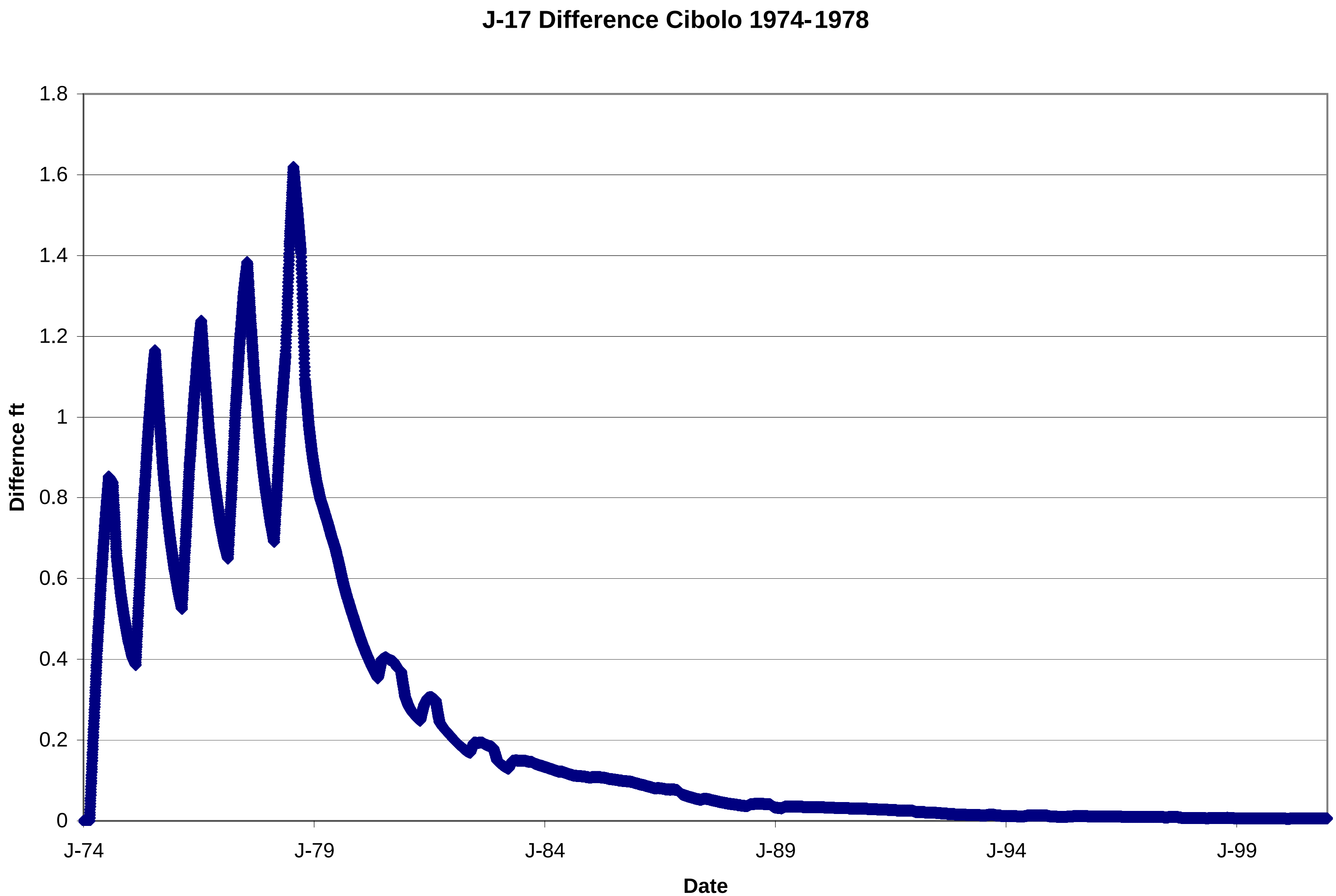

J-17 Difference San Geronimo 1974-1978
Differnce ft
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
J-74
J-79
J-84
J-89
J-94
J-99
Date

J-17 Difference San Geronimo 1974-2000





J-17 Difference Cibolo 1974
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date



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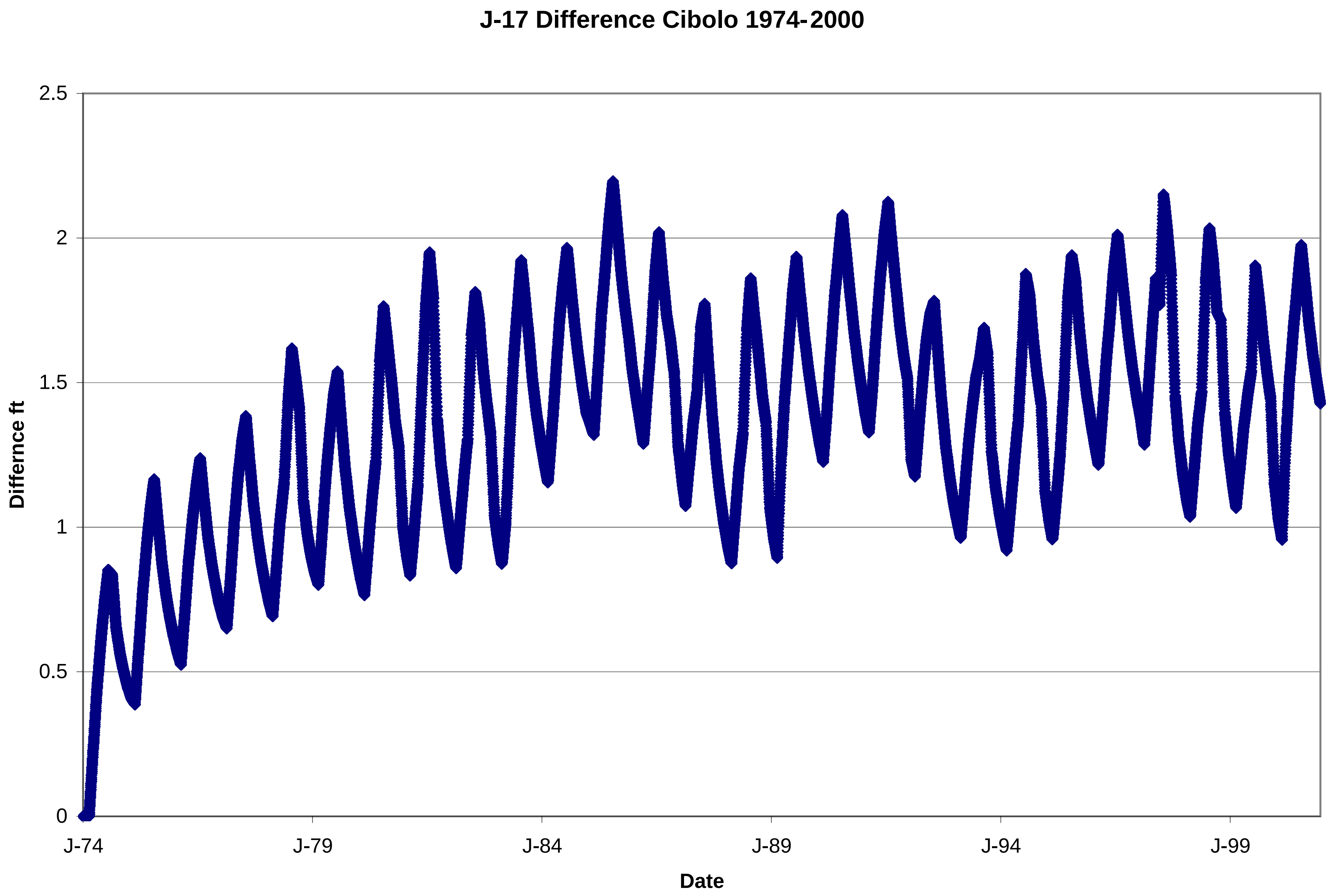
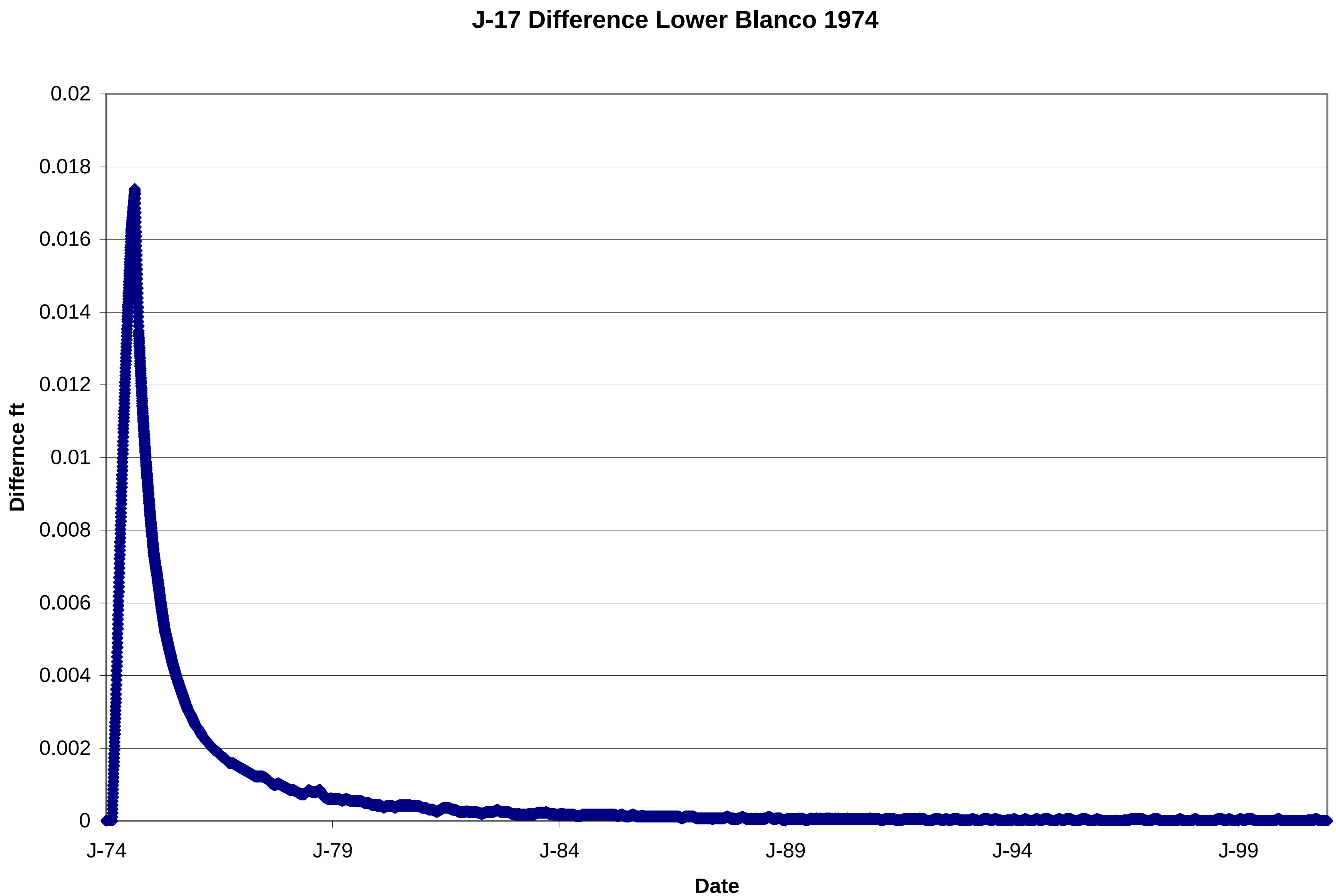
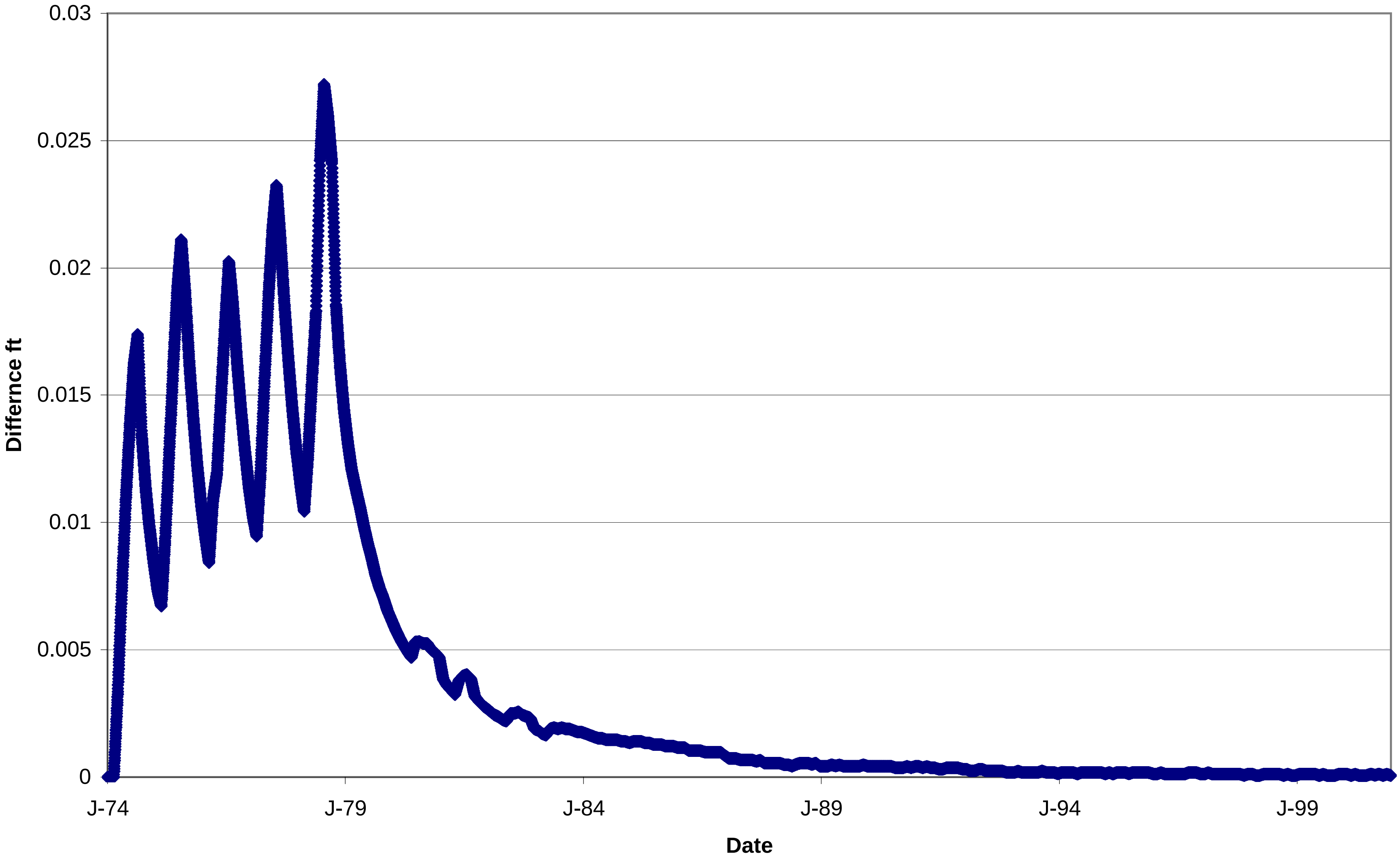
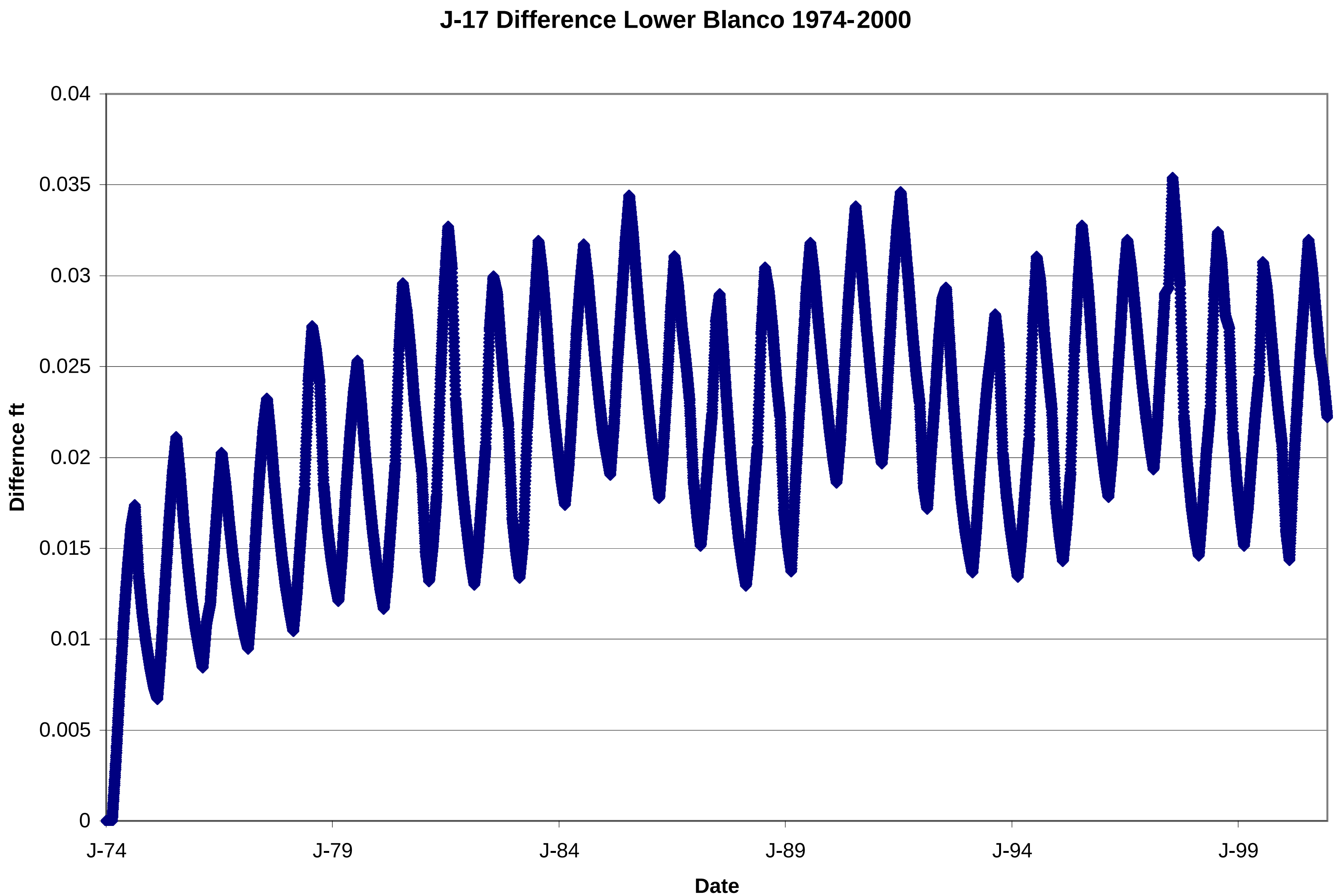

J-17 Difference Cibolo 1974-2000
2.5
2
1.5
1
0.5
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date


J-17 Difference Lower Blanco 1974
Differnce ft
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
J-74
J-79
J-84
J-89
J-94
J-99
Date

J-17 Difference Lower Blanco 1974-1978




J-17 Difference Lower Blanco 1974-2000
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Differnce ft
J-74
J-79
J-84
J-89
J-94
J-99
Date