Peer Review Comments on: "Florida River Flow Patterns and the Atlantic Multidecadal Oscillation"

Draft Report
Ecologic Evaluation Section
Southwest Florida Water Management District (SWFWMD)
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Summary

This draft report presents a persuasive and thoroughly documented illustration of the spatial patterns of annual streamflow hydrographs in Florida rivers. Evidence for the existence of shifts in these streamflow patterns from wetter to drier conditions and vice versa on a multidecadal time span is produced from daily streamflow records by calculating the daily median average flow (MDQ) for each calendar day in multi-year time series. MDQ hydrographs are derived for various sets of years and are considered using previously defined shifts in the "Atlantic Multidecadal Oscillation" (or AMO). This analysis procedure allows examination of the role of climate variability as a potential influence on long-term shifts in river flows in Florida. The report provides a convincing argument that much of the variability in streamflow hydrographs is strongly related to long-term climate oscillations associated with the AMO. The draft report concludes with a persuasive argument that this climate-driven variability in streamflow is a major factor influencing observed hydrologic changes in particular rivers in southwest Florida, even in cases with known anthropogenic sources of hydrologic alteration.

I. General Comments

Overall, we find the arguments in the report persuasive, the methods sound, and the conclusions well founded. We find no serious scientific flaws or technical errors in the work. The results have profound implications for water management, especially the establishment of instream flows (Minimum Flows and Levels, abbreviated MFLs) and water allocation, and for our understanding of the hydrology and long-term ecosystem dynamics of Florida's rivers. The principal results of the report are:

A. There is a pronounced difference in the seasonal cycle of river flows between peninsular Florida (where maximum flows occur in late summer -- the so-called "SRP" or Southern River Pattern), and northern Florida (where maximum flows occur in late winter -- the "NRP" or Northern River Pattern). Several rivers in a narrow geographical region between these two flow regimes exhibit an unusual long-term average annual hydrograph featuring two seasonal flow peaks (the "BRP" or Bimodal River Pattern). These rivers show hydrographic characteristics of both the SRP and NRP.

B. Average flow conditions in most rivers throughout the state changed markedly around 1970. In the three decades prior to 1970, when the AMO was in its positive phase, the SRP seasonal flow peak was pronounced. SRP rivers exhibit systematic decreases in their seasonal peak flows in subsequent decades. In contrast, NRP peak flows tended to be relatively low in the pre-1970 decades followed by abrupt increases in annual peak flows post-1970. Rivers with bimodal flow captured both features -- decreased summer peak flows and increased winter peak flows following the AMO shift around 1970. These changes are entirely consistent with previously documented multidecadal shifts in rainfall associated with a statistical mode of variability of North Atlantic Ocean temperatures known in the climate variability literature as the AMO. The very important implication from this set of results is that river flows increase and decrease in association with entirely natural shifts in the "climatic regime", apparently modulated by large-scale Atlantic Ocean temperature changes. Thus "average flow conditions" in rivers throughout Florida determined from data that do not span both phases of the AMO can seriously underestimate the long-term range of flow conditions that should be expected on these rivers.

C. Based on results summarized in the previous paragraph, AMO-related shifts in precipitation should be part of any assessment of the causes of flow changes on rivers in Florida, and should be considered in future development of regulatory MFLs on these rivers. The third section of the document presents several case studies of rivers in the SWFWMD, placing AMO-related variability into context with the individual histories of selected rivers.

In our opinion, this work represents one of the more important contributions to hydrologic science in Florida (and perhaps elsewhere) in the past several decades. We firmly believe this work should be published as soon as possible in a scientific journal with wide exposure among hydrologic scientists and practitioners (e.g., *Water Resources*

Research, *Journal of Hydrology*, *Water Resources Bulletin*, *Hydrological Processes*), and we would encourage the author to further document and publish his findings with respect to AMO-flow relationships for streams beyond Florida and the SWFWMD.

In this spirit, the comments below are suggestions for strengthening an already strong report by bolstering and documenting certain assumptions, reasoning, and methods. These comments should not detract from the overall merit of this work. A compiled summary of minor editorial comments is also provided as an edited version of the report sent separately to the author.

II. Principal Recommendations By Topic

A. General Recommendations

1. The report mentions several times that a "fundamental premise" of the analysis and discussion is that river flows are largely rainfall driven and seasonality in streamflow reflects seasonality in rainfall. Although we agree with this premise, it may be useful to cite some references that clearly demonstrate this for Florida, especially given that many streams in the SWFWMD are influenced by spring flow and groundwater discharge, which is commonly thought to reflect the seasonality of rainfall, but at a considerable time lag.

2. Because this analysis began as an outgrowth of the District's work in establishing Minimum Flows and Levels (MFLs) and will likely have important ramifications on how MFLs are set in the future, it would be useful to include a more thorough discussion of the results in the context of MFLs. What are the implications of multidecadal streamflow variability on establishing MFLs? How can the District incorporate knowledge of this variability into its MFLs? What do the results here imply about the dynamics of the natural systems being protected? This could be accomplished in the Executive Summary as described in Section II. B below.

3. Some modifications to the plotting format used throughout the report, including the appendix document, would streamline and enhance the graphical presentation: [a] Addition of labels along the top of the MDQ hydrographs to show midpoints of months (J, F, M, ..., N, D). At a minimum, we strongly suggest adding such labels to at least one MDQ hydrograph (perhaps the first one shown -- Fig. 2) so the reader could refer back to that figure when dates are mentioned with reference to subsequent plots. [b] Addition of a second set of y-axis labels along the right edge of the same plots to indicate the normalized flows (cfs/mi^2). Addition of these axis labels removes the need to produce two separate plots for actual and watershed-normalized flows, because each such pair of plots shows exactly the same annual hydrograph plotted on different scales.

4. We recognize that replotting every figure at this point would be a huge task and these plotting suggestions are not essential. However, these recommendations might be implemented on just a few plots for presentations, or for subsequent development of plots to be included in shorter articles that may be derived from this report.

5. We suggest expanding the concluding remarks to present a concise summary and synthesis. As written, the text on page 77 simply presents a few (rather vague) philosophical points and ends abruptly. An expanded concluding section would serve to tie together the various sections of the report.

B. Executive Summary

The Executive Summary presents a well-written overview of the scope of work in the report. It could be usefully augmented with a short discussion of MFLs before these are first mentioned. Specifically, clarifying and emphasizing the importance of flow conditions throughout the year for development of MFL regulations needs to be plainly stated for the reader, because most of the analysis pertains to changes in high flow times of the year, not annual minimum flow conditions on the rivers. The draft report does not emphasize that MFL regulations will be drafted to pertain to flows needed at various times of year (in different seasonal "blocks"). The relevance of multidecadal shifts in peak flow seasons (result A. 2 above) was not apparent when we read the draft report, but was made abundantly clear at our meeting at the SWFWMD on 21 October 2004. Again, this need not be lengthy (we recognize that this document is not intended to provide a full justification for specific MFL requirements), but a concise explanation of the relevance of these results to MFL development would be useful. Finally, the Executive Summary should clarify how the first two sections of the report will be related to the third section.

C. Atlantic Multidecadal Oscillation

1. The body of the report would be enhanced with some additional review material on the AMO. This need not constitute a lengthy addition of text. The purpose of an augmented introductory discussion would be to emphasize that extensive peer-reviewed documentation exists describing the existence of the AMO, its basic temporal behavior, and its correlation with precipitation across Florida and the U.S. These studies have been carried out by climatologists, hydrologists, and ecologists who are completely independent of the SWFWMD, providing strong scientific justification for interpreting changes in river flows at that time in terms of natural climatic change processes. Thus the methodology used in the report, dividing river flows into pre-1970 and post-1970 epochs, is based on solid and widely accepted (albeit recent) climatological analysis. Some useful citations in this regard include: Schlesinger et al. (Nature, 2000, v. 367, p. 723-726), who are generally credited with being the first to point out a slow sub-century "oscillation" in Atlantic Ocean temperatures, and recent European studies on river flow and other indices related to Atlantic Ocean temperature such as the

North Atlantic Oscillation (e.g. Wedgbrow et al., International Journal of Climate, 2002, v. 22, p. 219-236, and Kiely, Advances in Water Resources, 1999, v. 23, p. 141-151). It's also important to emphasize that future shifts of the AMO are not predictable at the present time, and there is very little understanding of the mechanism(s) responsible for this component of climate variability. Therefore, while it is appropriate to look backward in time to see what shifts in river flow patterns may have occurred in conjunction with AMO shifts, it is not possible to look forward in time to project future shifts in river flows (or anything else).

2. The relationship between multidecadal streamflow patterns and the AMO, while convincingly argued, is understandably limited in a statistical sense by the fact that few streamflow records in Florida extend back far enough to encompass more than the most recent single cycle (one high SST period and one low SST period) of the AMO. It would help strengthen the argument for a relationship between streamflow and AMO if the report included a few (or even one) examples using a streamflow record that extends back to the early 1900s and would thus include one additional low SST phase of the AMO. If such records exist in Florida, they would most likely be found in north Florida and/or the Florida Panhandle. If no such records exist in Florida, then perhaps an example using a record from a stream in a nearby state could be included.

D. Median Daily Flow Plots and River Flow Patterns

1. Depicting long-term annual streamflow hydrograph patterns using the Median Daily Flow (MDQ) plots is a sound and particularly illuminating approach for demonstrating spatial and temporal patterns of the type discussed in this report. Although not as common as other graphical approaches for depicting streamflow variability, it is not without precedent in hydrology. Similar approaches, most recently in conjunction with modeling and negotiations over Apalachicola-Chattahoochee-Flint basin water allocations are published in the literature. It might be helpful to cite instances in the literature where similar approaches have been used to lend the method more credibility.

2. Given that conclusions are drawn from visual inspection and comparison of MDQ plots from different time periods, it would be helpful to know more about the natural variability inherent in those plots for each day of the year. For example, similarly derived plots of annual hydrographs from long-term data tend to be more tightly clustered around the mean (or median) daily flow in certain seasons of the year than in others. It would be helpful to have some depiction of the "uncertainty" envelope around these curves so that the reader would have a better sense of the validity and significance of the visual comparisons. This would especially aid the reader in determining, for example, whether the percent change values summarized in Table 2 are significant, especially for those with relatively small changes. It is tempting to look at the results summarized in Table 4 and ask why flows in the Apalachicola and Chattahoochee Rivers increased between the two periods, while those of the Flint River decreased for the same period. Since the Flint and Chattahoochee are the two major tributaries that give rise to the Apalachicola, this kind of mass balance issue should not be left unanswered. Similarly, the Oconee and Ocmulgee Rivers in Georgia decrease, whereas the river those streams combine to form, the Altamaha River, increases over the same time period. We suspect that the answer here lies in the fact that all of these changes, regardless of direction, are rather small and are likely statistically insignificant. This type of comparative analysis, however, underscores the need for a better handle on the natural variability of the MDQ plots as noted above.

3. We don't necessarily favor the use of smoothing algorithms for the MDQ plots. However, the uncertainties in estimating individual calendar day median flows would be reduced by combining adjacent calendar days (e.g. considering a sample of five adjacent days in each year to determine "pentad average" mean daily flows). Retaining daily resolution to describe the seasonal cycle of river flows is not necessary (unless there is good reason to suppose that the daily flow will change abruptly on the same specific day of the year). It is standard practice in the climatological literature to keep just the few gravest harmonics of the seasonal cycle, or to smooth the daily data using pentad or similar averages. Combining X adjacent days for this purpose increases the sample size for each estimate of the daily median from N (the number of years) to N*X, although the X days for an individual year are not statistically independent due to autocorrelation of daily flow values.

4. Amplifying comment D. 2, estimates of MDQ are subject to considerable statistical sampling uncertainties. These uncertainties are not discussed in the report but should be acknowledged. Although a completely rigorous statistical evaluation of uncertainties in the annual MDQ hydrographs is probably not needed to establish the desired conclusions, a brief description of uncertainties is warranted. The large uncertainty in estimating the median value of fairly small samples of years makes the use of daily median flows potentially misleading. For example, specifying May 21 and September 22 for the date of minimum and maximum daily flows on the Peace River (page 13, figure 2) is probably not defensible statistically (as opposed to "late May" and "late September", or wording like that). For each of 365 calendar days, the uncertainty in estimating the average of the median flows is (very approximately, because the population of median values cannot be assumed to follow a Gaussian distribution) $\sigma/\sqrt{N}$, where σ is the interannual standard deviation of the daily flow values for that day and N is the number of years in the sample. One suggestion is to show an example of an MDQ hydrograph that illustrates the envelope of variability of the individual daily median flows, perhaps augmented with a histogram of daily flows for one particular calendar day.

5. The identification and illumination of distinct spatial patterns of streamflow seasonality in Florida is particularly well documented using the MDQ approach. Although the conclusions regarding north to south differences in streamflow seasonality are not novel (see the 1984 Water Resources Atlas of Florida for a similar depiction of streamflow patterns in Florida), the MDQ approach and the inclusion of a large number of streamflow records in the analysis make this presentation particularly illuminating because it frames the subsequent discussion regarding the influence of the AMO. Identification of a narrow transition band in north central Florida where a bimodal MDQ pattern is found is a striking finding. Although the "bimodality" of certain rivers in this region (e.g., the Santa Fe) is well known, the existence of a spatially explicit transition zone between the northern (temperate) and southern (subtropical) flow patterns has not been previously identified to our knowledge. It is intriguing to speculate whether the bimodal pattern observed in the MDQ plots is the result of a large number of years in which streamflow peaked both in the spring and late summer/fall or from a large number of years in which one or the other (but not both) seasonal peaks dominated. The answer to this question might help better interpret the underlying climatic patterns that lead to the existence of the bimodal flow pattern and the transition zone in which it occurs.

6. It would strengthen the presentation on the different spatial patterns of river flow patterns if the report included more discussion of the criteria used to classify each stream as one type or another, especially for "Spring-dominated" and "Altered" patterns. For example, one might expect the station on the Apalachicola River at Chattahoochee, which is located immediately below Jim Woodruff Dam, to be identified as "Altered." Yet, sufficient characteristics of the NRP were evident for the author to classify this stream as such. There are many more possible examples of this type included in Table 1. For example, it is not clear why a stream like the Fenholloway River would be as obviously altered as the upper Caloosahatchee River unless such determination was made a priori. Further explanation of the criteria used to classify altered streams would be helpful.

7. Given the prominence of springs in the SWFWMD, we believe more, rather than less, discussion of the spring-dominated pattern is needed. Were climate-driven patterns associated with the region evident in spring-dominated rivers despite the lower seasonal variability typical in these kinds of ecosystems? This information would increase the usefulness of this analysis by other river managers. We were intrigued by several streams in Table 1 identified as spring-dominated patterns (e.g. Big Coldwater Creek, Blackwater River, Catfish Creek and Shoal River), which are commonly considered blackwater streams. These streams do not receive direct discharge from discrete Floridan Aquifer springs, but do derive a considerable amount of their flow from laterally distributed seepage from the surficial aquifer. Also intriguing are similar streams in nearly identical settings not identified in the table as spring-dominated. Please note that Outlet River is classified as spring dominated, even though the flow is governed by the level of Lake Panasofkee (which is itself influenced by spring flow in its contributing watershed). Also, why are some streams that are commonly considered spring-influenced classified as such but some are not? For example, the Suwannee and Santa Fe Rivers, which some consider "linear springs" given the huge number of springs lining those rivers, are classified as NRP and BRP, respectively. Different river flow patterns are sometimes attributed to different stations in the same stream (e.g., Withlacoochee River). This is not to imply that these classifications are incorrect, but only to recommend that the criteria used in the classification be documented and clarified so that interpretation of the results is less ambiguous.

8. Although the author makes the case that the BRP is unique within the United States, we suspect the SRP is also unique since few if any other places in the continental U.S. outside of south Florida have a subtropical climate. Possible exceptions could include extreme south Texas and southern Arizona, both of which are comparatively arid. However, the inclusion of the Paria River as a possible example of a transitional bimodal pattern is somewhat misleading since the two seasonal peaks are likely the result of spring snowmelt and summer rainfall events, both of which would tend to occur in each year (or most years) of the record.

9. Table 1 would be easier to read with a comprehensive caption that explains the various column headings. Some entries in the "River Pattern" column were unclear. We assume that there are inconsistencies in the entries (for example: do entries "Bimodal", "Bimodel SRP/NRP", and "Bimodal NRP/SRP" all mean the same thing?) We have two additional questions concerning Table 1. How are twice-attributed rivers (e.g. "NRP/Spring") determined? What is the meaning of the "Count" column (is this the number of days in the data record)?

10. The report would be strengthened by clearly showing the distinction between SRP, NRP, and bimodal flow regimes for sets of gage stations, instead of just showing individual gage time series. The purpose of this is to emphasize that the SRP/NRP/bimodal groupings are robust. There are two complementary ways to show this.

(a) Create a single plot showing all of the SRP flow sites from Table 1/Figure 8 to illustrate in a single graph the similarity of their annual hydrographs. Perhaps replacing the triangular symbols with similarly colored numbers referenced to Table 1 would improve Figure 8. Is the solid black polygon the SWFWMD boundary? We recommend expanding Figure 8 so that individual rivers and gage sites can be easily found. Create corresponding graphs for the collection of NRP and bimodal flow sites. This would need to be done using data normalized by watershed area. For clarity, it might be necessary to plot only one-third or one-half of the SRP or NRP sites on a graph.

(b) Is it possible to construct composite median daily flow hydrographs for the SRP, NRP, and bimodal flow patterns by averaging over many different rivers? The compositing would need to be done using normalized data. It may be necessary to carry out normalization in addition to the watershed area normalization, perhaps by dividing each hydrograph by the maximum daily value so that each individual hydrograph has a maximum median daily flow of 1.00. Either or both of these approaches would be extremely useful for illustrative purposes and would provide a way to summarize visually a large amount of information on just a few plots.

E. Analysis of Flow Changes in Specific Streams

1. It would help to bolster the argument on page 30 that the Econlockhatchee River is the "exception that proves the rule" for SRP streams. The report could be more specific about possible causes of the increasing trend in low flows at that site (Fig. 18). This was done for hydrologically altered streams in the SWFWMD such as the Myakka River.

2. On page 58, the assertion is made that "if flows decline as percent of mined area increases, one would expect to see monotonic flows declines in both sub-basin watersheds…" Without additional justification, the reader may be hard pressed to agree with this assertion, making the rest of the author's argument suspect. The temporal resolution of the data in Table 9 doesn't adequately demonstrate a monotonic trend in percent of mined area over time, though an additional data point or two in the late 1970s/early 80s and perhaps mid-1980s would help clear up this issue. However, even if mined area increased monotonically over time, it doesn't necessarily follow that flows would decline likewise without a better understanding of the mechanisms by which mines are suspected of altering streamflow. While not the author's argument, because he is discussing the argument of others, more discussion of the hydrologic basis of those arguments would strengthen this observation. Similarly, no hydrologic explanation is given for the possible finding that mining may have slightly increased low flows in one stream. Despite the overall convincing argument that climate is playing the major role in influencing observed changes in flow in the Alafia River, the focus of this discussion is solely on changes in mined land with no explanation of the physical/hydrologic relationships between percent mined area and streamflow. It is equally likely that changes in other land uses could have profound impacts on the hydrology of these streams that would not necessarily be reflected in percent change in land cover. For example, changes from pasture to irrigated row crops, both of which would be considered agricultural land uses in the charts in Fig. 23, could have profoundly different implications on stream hydrology (as was demonstrated in the discussion of the Myakka River).

3. The discussion of the Myakka River seems somewhat abbreviated compared to other streams discussed in the final section of the report. Given some of the material that was presented in our in-person peer review meeting, we would add a bit more discussion on page 65 about the climate driven variability identified in the Myakka River data, despite the strong signal of anthropogenic alteration. As written, this discussion contains no mention of the AMO at all.

4. On page 68, the author notes parenthetically that the Charlie Creek watershed is part of the larger Peace River at Arcadia watershed. This suggests that the results shown for the latter station may be influenced by those of the former (i.e., those two stations are cross-correlated). It may be helpful to show the relative contribution of water coming from Charlie Creek as opposed to the rest of the Upper/Middle Peace to the flow at the Arcadia gauge to strengthen the argument here.

III. Concluding Remarks

This report analyzes and summarizes a considerable amount of hydrological data from the state of Florida to make a convincing link between temporal flow patterns and the AMO. The report also documents an intriguing spatial pattern in flow variability and seasonality from south to north in Florida. The report is an excellent example of a high caliber interdisciplinary study where the fields of climatology, hydrology, and ecology are linked effectively. We hope that the report is widely circulated and read by people interested in water resources in Florida. Sustainable use of this valuable resource by a burgeoning human population requires a clear knowledge of natural variability in water supply.

Key components of this report could be extracted and prepared for peer-review journal publication. This effort would require some additional analyses of the statistical robustness of the spatial and temporal patterns discussed in the report. This peer review document makes some suggestions concerning how such additional analyses might be carried out and presented. We feel that the insights gathered by this rigorous analysis of the hydrology of Florida rivers in the context of the AMO should be published in the widely distributed peer-reviewed literature. The novel approaches and main conclusions in this report may well find general applications in many other regions worldwide. We encourage the author with support from the SWFWMD to prepare and submit a paper for journal publication in the near future.