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(Levy County Nuclear Power Plant, Units 1 and 2)

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RIVER RESEARCH AND APPLICATIONS

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FLORIDA RIVER FLOW PATTERNS AND THE ATLANTIC MULTIDECADAL OSCILLATION

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ABSTRACT

A major step in developing legislatively mandated ecological flows for watercourses in Florida, USA is the selection of an appropriate baseline flow period. Recently climatologists have established a link between multidecadal periods of warming and cooling of the Atlantic Ocean (the Atlantic Multidecadal Oscillation (AMO)) and rainfall patterns across much of North America. During an AMO warm period (pre-1970), much of North America received less than average rainfall, while during a multidecadal cool period (post-1970), much of North America experienced above normal rainfall. There are exceptions to this general trend with some areas of North America showing an opposite relationship with the AMO. Peninsular Florida is one of these exceptions. While analysing flows on a number of rivers in south–central Florida, we observed a step rather than a monotonic trend in flows consistent with a switch from a warm multidecadal period to a cool multidecadal period. We examined river flows at all gaging sites throughout Florida and the southeast United States that had flow records of 60 years or more. Three river flow patterns were clearly discerned: a Southern River Flow Pattern (SRP) where flows are seasonally greatest during the summer months (June–September); a Northern River Flow Pattern (NRP) where flows are seasonally greatest in the spring and a Bimodal River Flow Pattern (BRP) with distinct peaks in rainfall and flow both in spring and summer. Those rivers with a BRP occur in a band that stretches diagonally from the northeast corner of Florida (St. Marys River) and runs in a southwest direction to the big bend area of the state near the mouth of the Suwannee River. Rivers to the north of this line exhibit the NRP, while rivers to the south of this line exhibit the SRP. Rivers with the SRP exhibited consistently lower flows during the AMO cool period and consistently higher flows during the AMO warm period. Differences in flow volumes between multidecadal periods averaged 30% in SRP rivers. Rivers with a NRP showed an opposite trend. Most convincingly, rivers with the BRP exhibited both trends, the spring mode responded similarly to the northern rivers while the summer mode followed the southern river trend. These results have important implications not only for the establishment of ecological flows, but also for water supply planning and development, flood control and stream ecology in general, since there are considerable differences in the magnitude of flows that should naturally be expected between multidecadal periods. Relatively large decreases and increases in flow are attributable to rainfall differences between multidecadal periods. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: Atlantic Multidecadal Oscillation; AMO; minimum flows; environmental flows; hydrographic patterns

INTRODUCTION

The Florida legislature has directed the Florida Department of Environmental Protection (FDEP) and the State's five water management districts (WMDs) to develop ecologically defensible minimum flows and levels (MFLs) that would protect the resources of the State from 'significant harm' due to water withdrawals. It is essential for the development of MFLs that temporal and spatial flow trends are understood in terms of natural and anthropogenic effects.

Beecher (1990) noted that an instream flow (or MFL) standard should include five elements: a goal, identification of the resources of interest, a unit of measure, a benchmark period and a protection standard statistic. Historically, such analysis has relied upon the daily or monthly hydrographic records for the previous two or three decades as the benchmark period for analysis. Even with adjustments for water withdrawals or structural regulation of flows, it

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appears that the effect of climatic change and other phenomena may make this arbitrary benchmark period inappropriate for an analysis which sets a minimum flow standard. For example in Scotland, Werritty (2002) has suggested that increased variability in the hydroclimate since the 1960s (especially between 1970 and 1996) are related to concurrent changes in temperature and precipitation patterns and will make informed water resource decisions more difficult if these decisions depend upon trend analysis over the past 30 or 40 years of record. Similarly, Hannaford and Marsh (2006) have demonstrated a strong correlation between changes in runoff and low flow patterns in the UK and an increase in the North Atlantic Oscillation (NAO), indicating a tendency towards decreasing low flows over the period from 1973 to 2002. In North America, similar changes in large-scale continental climate change and runoff patterns have been connected to multidecadal changes in snow accumulations and decreasing overall soil moisture (Maurer *et al*., 2004). With increasing observations of linkage between long-term oscillations in oceanic temperature and/or changes in climatic trends linked to predictability of runoff patterns, it is increasingly important to understand regional patterns of runoff so that an effective benchmark period can be delimited. In the state of Florida, a unique peninsular subtropical environment, significant declining trends in flow have been documented for a number of streams in the southwest Florida, including the Peace (Hammett, 1990) and Alafia Rivers (Stoker *et al*., 1996).

Among the WMDs, the Southwest Florida Water Management District has developed an approach for establishing benchmark periods that involves consideration of multidecadal climatic oscillations on river flow patterns as an outgrowth of work by Enfield *et al*. (2001) who demonstrated the potential for significant climatic variability in river flows for the Kissimmee (Florida) and Mississippi Rivers. In this paper, we examine the underpinnings of the decision to establish these benchmark periods. The discussion that follows relies heavily on a graphical presentation of flow data to develop a general appreciation of the temporal and spatial variability in river flows in the state of Florida and the southeastern United States, in general. This broader perspective is necessary for developing a consistent approach for setting minimum flow criteria, particularly as they relate to seasonal flow patterns and long-term cycles in rainfall. Climate oscillations, specifically multidecadal differences in rainfall, are a significant and yet relatively under appreciated factor that explains much of the variability in river flow, some of which has been assumed attributable to human alterations of local landscape and instream conditions. This should not be interpreted to mean that humans have not, in some cases, substantially affected river flow volumes and patterns; however, relatively large flow declines (and increases) lasting several decades may in many instances be attributable to regional climate changes.

A fundamental premise of our analysis is that river flows are largely rainfall driven and that patterns and seasonality in flows reflect patterns and seasonality in rainfall. Most would readily agree with this interpretation; however, the tendency has been to move quickly on to flow changes that can be attributed to anthropogenic factors without closely examining the effect that climate may have on decreasing or increasing flow trends. This is a frequent conclusion based upon the underlying bias that in most cases, it is assumed that variation in flow results from a sequence of random independently and identically distributed random variables (see Olsen *et al*., 1999). Most often, streamflow studies have been based upon analysis of mean annual flows; however, the mean annual flow is, for most systems in peninsular Florida, a high flow statistic, approximately equivalent to the 30% exceedance flow on most rivers. In southwest Florida, a large portion (60%) of the total annual flow volume is concentrated in the rainy season (as would be expected) which generally lasts 120 to 135 days. Since anthropogenic withdrawals are typically reduced during the rainy season and greatest during the drier months, one would expect the effects of these withdrawals to be most pronounced during the drier months. Not only are flows greatly diminished due to reduced rainfall, but anthropogenic withdrawals would constitute a greater percentage of the available flow. Even for those withdrawals that remain relatively constant during the year, anthropogenic effects should be most pronounced during the drier (low flow) months.

There is an apparent long-term cycle in rainfall that leads to multidecadal oscillations in stream flow (Enfield *et al*., 2001). In general, rainfall data were not examined directly (see discussion by Enfield *et al*., 2001), but a series of flow plots for various rivers were examined which exhibited similar patterns in flow. Enfield *et al*. argued that the similarity of flows is reflective of similarity in rainfall patterns. Although it has generally been assumed that annual variation in rainfall is a more or less random event, the premise we adopted is that a long-term oscillation in rainfall (approximately 60 to 80 years) is evident (Enfield *et al*., 2001), although this pattern may be affected by other short-term (e.g. El Nino—6 years) or long-term cycles (e.g. Pacific Decadal Oscillation, McCabe *et al*., 2004).

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Sutton and Hudson (2005) have also suggested that decreased summer rainfall, increasing drought frequency and warmer temperatures for much of the United States, as well as increased summer rainfall and warmer temperatures in western Europe were consistent with changes in the Atlantic Multidecadal Oscillation (AMO) and suggested that thermal changes in the Pacific Ocean may play a part as well and that anthropogenic effects on climate may cause a shift back to a negative phase earlier than expected.

Whether this oscillation does or does not exist has more than academic interest, since it should influence the way that minimum flow allocations are developed, particularly for mid to high discharge periods.

METHODS

Considerable discussion related to flow trends has centred on an assessment of mean annual flows and attempts to relate changes in mean flow to changes in total annual rainfall. This approach can be refined by examining differences between wet and dry seasons and high and low flow periods. Inspection of monthly rainfall totals and mean monthly flows demonstrates a clear seasonality in rainfall and consequent flows. For peninsular Florida, the rainy (wet) season is often defined as the months of June through September. The highest flow months typically extend from July through October. The types of data analysis that have routinely been performed on flow data have been repeated here, but other, largely graphical approaches not normally employed are used extensively, since the nature of the analysis relied upon a different perspective for examining the data.

Gauge sites and periods of record

We initially examined records from 122 United States Geological Survey (USGS) gauging sites located throughout Florida. These flow data were used to develop an overall assessment of the temporal and spatial variation in stream flow that can be expected across Florida, and the difficultly that natural variation poses when trying to develop minimum flow allocations. A smaller subset of these sites was examined to assess multidecadal differences in flow. The smaller subset of sites was restricted to those with at least 60 years of record.

To examine multidecadal flow differences, it was desirable to have sites of sufficient record so that two relatively long time periods could be compared. Ultimately, a large number (over 300) of sites outside of Florida, primarily in the southeastern United States, were examined in support of this work, but our primary purpose was to respond to mandates for developing minimum flow criteria for peninsular Florida and we concentrate on that information.

Seasonal flow patterns

Plots of median daily flow (MDQ) were created for (1) the period of record, (2) for each decade in the period of record and (3) two mutidecadal periods (1940–1969 and 1970–1999) for those sites with an adequate period of record (>60 years). These plots were informative in that they provided an easily understood picture of the range of flow that could be reasonably expected at a site over the course of a year and a temporal impression of when those flows are most likely to occur throughout the year (seasonally). Although flows vary considerably from year to year, it is reasonable to expect that flows should vary directly with rainfall.

RESULTS

Geographic differences in river flow patterns

Because of recent developments in the literature related to the AMO (Enfield *et al*., 2001) and interest in changes in the rainfall–runoff relationship (Hammett, 1990) which seem to be centred around the mid-1960s to 1970, MDQ plots for gage sites with at least 60 years of record were examined pre- and post-1970.

There were two distinct seasonal flow patterns among the data we examined. With the exception of spring dominated systems, the Southern River Pattern (SRP) was characteristic of all rivers in central Florida (Figure 1; Myakka River). Clearly evident was a seasonal pattern of higher flows that generally extended from July to October.

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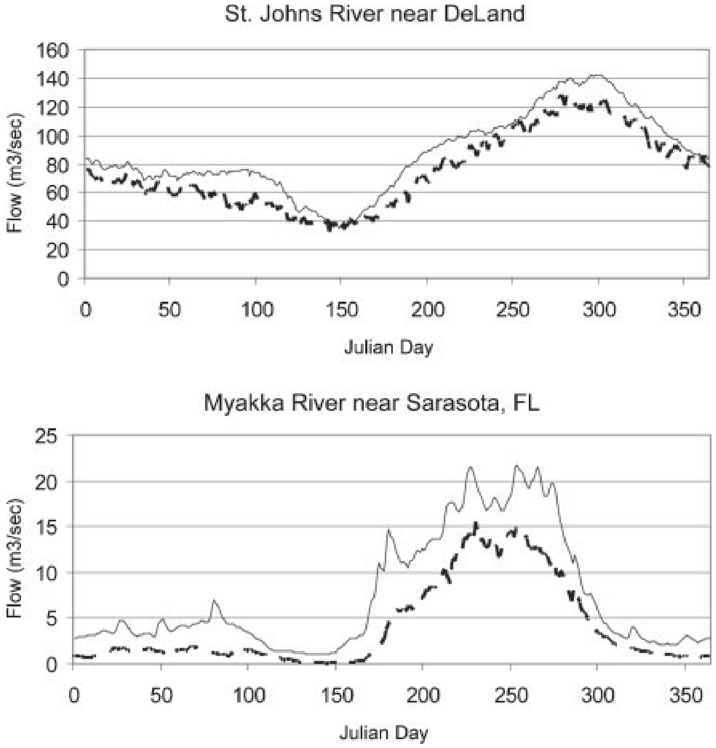

Figure 1. Two Florida rivers demonstrating Southern River Pattern (SRP). The mean daily flow for the period of record is described by the solid line and the median daily flow by the bold broken line

This pattern was apparent on all river systems or reaches in this region without flow-regulating structures. This pattern was also found on a number of rivers in south Florida and northeast Florida (Figure 1, St. Johns River).

The Northern River Pattern (NRP) was characteristic of unregulated rivers in the north and northwestern part of the state such as the Apalachicola and Escambia Rivers (Figure 2). Although there was, at times, a slight peak in flows around March in SRP rivers, peak flows consistently occur in the spring months among those NRP rivers while lowest flows occurred in the summer and fall. This pattern appeared typical of many if not most rivers in the southeast United States and was confirmed by examining flow data for numerous gage sites for the southeastern states (example in Figure 3). In direct contrast to SRP rivers, the lowest flow period for NRP rivers occurred when SRP flows were near their peak flows. The two patterns are roughly 180° out of phase.

In moving from south to north along the peninsula of Florida, we expected to find a transition in flow patterns. However, rather than a sequential blending of two patterns, a clear bimodal distribution in peak flows was found at a number of sites. This Bimodal River Pattern (BRP), for example was evident in the flow records of the Santa Fe River and the St. Marys River which forms Florida's northeastern border with Georgia (Figure 4). There is a fairly clear band of tributaries and rivers that runs from the northeast corner of the state diagonally southwest to the 'Big Bend area' of Florida that exhibited a more or less bimodal flow pattern (Figure 5). Some exhibited almost equivalent spring and summer peaks, while in others one pattern (the SRP or NRP) is more or less dominant. There were observable variations in the magnitude of the bimodal peaks when multidecadal periods were compared. We did not observe a similar bimodal pattern anywhere else across the United States.

Two other types of flow patterns were avoided in our analysis and will not be considered our discussion. These were flow patterns that were (1) obviously affected by significant structural alteration or (2) dominated by spring flows.

Seventeen gage sites, representing 10 river systems, displayed a SRP (Table I(a), Figure 6). Sixteen of the 17 gage sites showed a net decrease in flow between the two 30-year periods. While some of the decrease at any given site may be attributable to anthropogenic factors, a decrease in flows at SRP sites is consistent with predictions by

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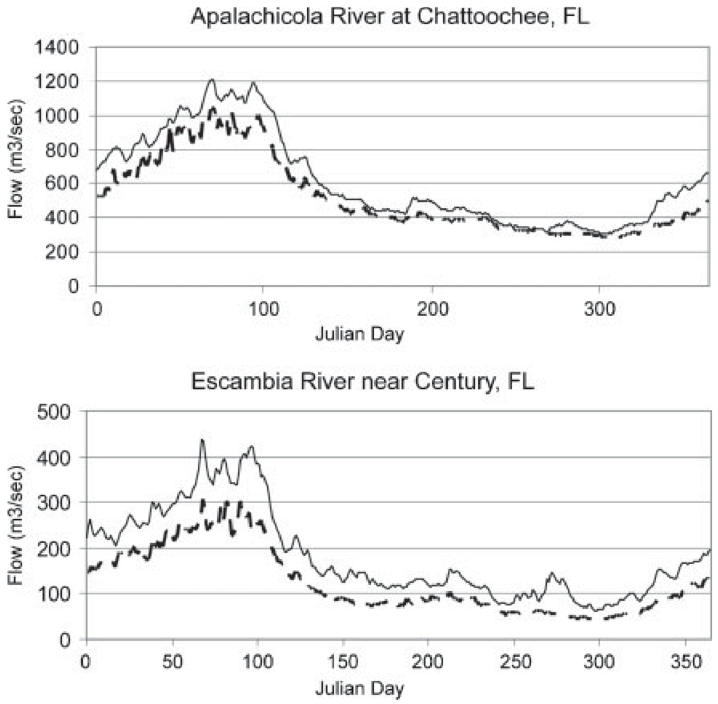

Figure 2. Two Florida rivers demonstrating Northern River Pattern (NRP). The mean daily flow for the period of record is described by the solid line and the median daily flow by the bold broken line

Enfield *et al*. (2001). Of those sites with a SRP and a period of record of at least 60 years, only one, the Econlockhatchee River, showed an overall increase in flows between the two periods. However, all SRP sites showed a decrease in flow between the two 30-year periods during the SRP wet season (defined as the period extending from 14 June to 27 October of each year). The average decrease in MDQs for the SRP wet season was approximately 35%, and ranged from 12 to 68%. Based on a comparison of MDQ, flows at SRP sites were on average approximately 30% lower in the more recent period (1970–1999) when compared to the preceding 30-year period (1940–1969).

All 12 of the 39 long-term Florida sites with an NRP showed an overall increase in flow between the two 30-year periods (Table I(b), Figure 7); the average increase was 14% and ranged from 5 to 35%. All 12 of the NRP sites showed a decrease in flows during that part of the year that represents the SRP wet season, but showed an average increase in MDQ of 27% during the NRP wet season (defined as 1 January–15 May).

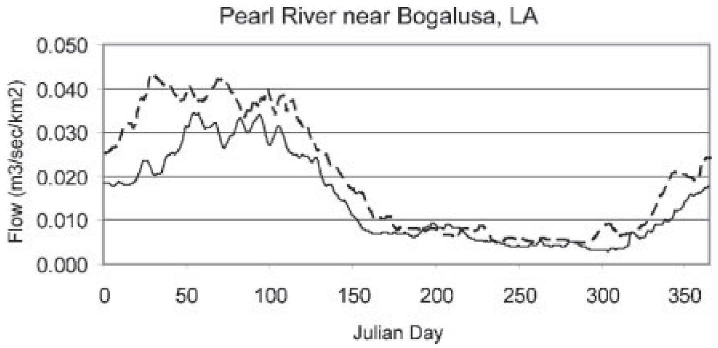

Figure 3. A typical river in the southeastern United States (Pearl River in Louisiana) (over 1000 km west of Florida) demonstrating the NRP pattern. The mean daily flow for the period of record is described by the bold broken line and the median daily flow by the solid line. Flows are standardized per square kilometre of catchment area

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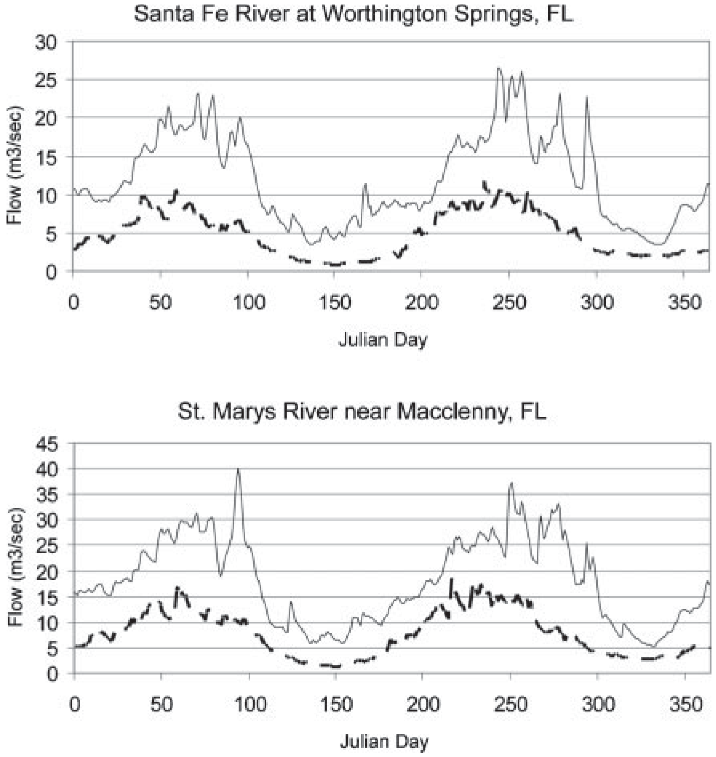

Figure 4. Two Florida rivers demonstrating Bimodal River Pattern (BRP). The mean daily flow for the period of record is described by the solid line and the median daily flow by the bold broken line

Rivers in north Florida have a flow pattern similar to most sites in the southeast United States, and 91% of the 311 sites examined in southeastern states with a 60-year record spanning 1940–1999 showed an average increase in annual MDQ of 15% between the two 30-year periods.

The pattern of increases and decreases in flow observed seen at the five BRP sites (with sufficiently long periods of record) was notable (Table I(c)). As mentioned above, the SRP mode (peak flow occurring between 14 June and 27 October) decreased between the two 30-year periods; the average decrease being 23%. The average increase in flows for the NRP mode (1 January–15 May) was 53%. For gage sites with a BRP, one mode increased while the other decreased and *vice versa*, when comparing the two 30-year intervals (Figure 8).

DISCUSSION

Multidecadal periods of high and low flows

It appears that the AMO offers an apparent explanation for observed rainfall deficits throughout central Florida. Although the WMDs (Basso and Schultz, 2003) and others (Hammett, 1990) have discussed the lack of tropical storm activity and deficit rainfall in recent decades compared with past, the mechanism that would account for such differences was unknown. Unlike most of the continental United States, there is a positive (rather than negative) correlation between rainfall and prolonged periods of North Atlantic Ocean sea surface warming. While warm periods generally resulted in less rainfall over most of the United States, there were some areas, including peninsular Florida, that exhibited strong positive correlations (Enfield *et al*., 2001). This has resulted in periods of generally higher rainfall in Florida when most of the United States experiences periods of reduced rainfall. Therefore, we expected to find Florida gauge sites where flows were highest when sea surface temperatures in the North Atlantic were in a warm period (i.e. positively correlated). At the same time most of the continental United States were expected to be in a period of lower flows during these warm periods (i.e. negatively correlated).

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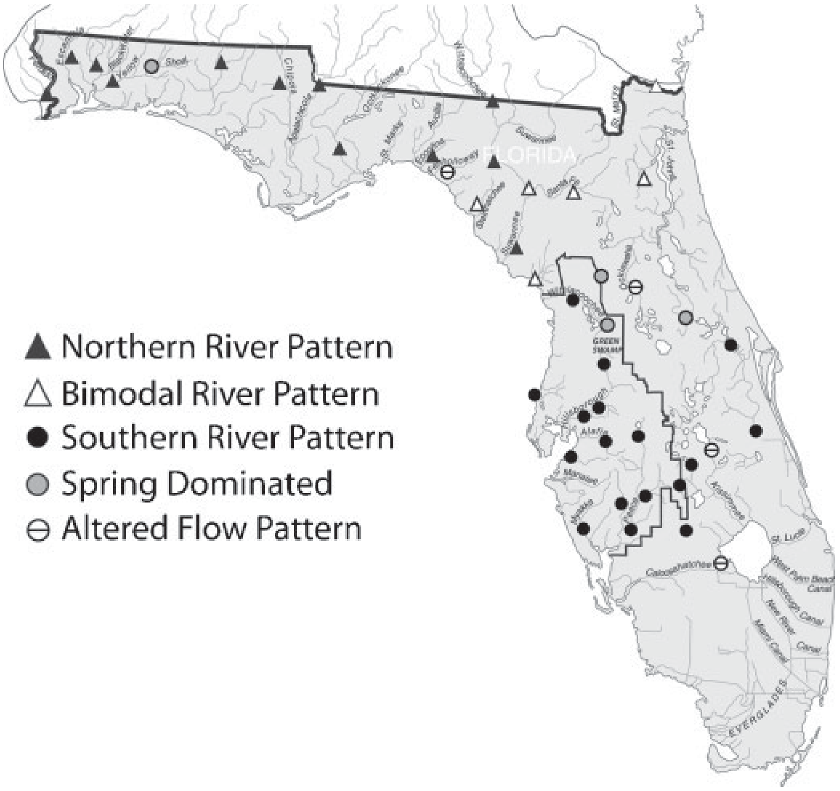

Figure 5. Map of the state of Florida depicting geographic distribution of sites exhibiting various river flow patterns

Conversely the majority of continental gage sites were expected to exhibit higher flows during AMO cool periods; at this same time, sites in much of peninsular Florida would be expected to be in a period of low flows.

North Atlantic sea surface temperatures were in a warm phase from approximately 1935 to 1965. From approximately 1970 to 1995, sea surface temperatures reflected a cooler period and rainfall and, hence, river flows in much of Florida should have been in a low flow phase. In contrast, most sites in the continental United States have exhibited higher flows.

Since a 60-year flow record from 1940 to 1999 would essentially coincide with a 30-year warm phase followed by a 30-year period during a cool phase, flow data for sites with records extending from 1940 to 1999 were examined by comparing plots of MDQs for the two periods pre- and post-1970.

The results of such plots were consistent with the observations of Enfield *et al.* (2001). Sites with a SRP generally exhibited higher flows in the 1940–1969 period compared with flows in the 1970–1999 period (Figure 6).

Sites with a NRP showed the opposite pattern, exhibiting higher flows during the last 30 years (1970–1999) when compared with the preceding 30 years (1940–1969) (Figure 7). NRP sites in Florida closely resembled the flow pattern for the majority of gage sites examined in neighbouring states (see, e.g. Figures 9 and 10). Changes in flow at Florida NRP sites and sites in neighbouring states were consistent with Enfield *et al*.'s (2001) observation; flows in the most recent 30-year period typically exceeded flows in the preceding 30-year period (1940–1969) (Figure 9).

BRP sites appear to be phenomenon unique to the Florida peninsula. With the possible exception of some sites in Arizona (Nichols *et al*., 2002), and we have, thus far, examined flow data from more than 2000 sites with period of record flows of 60 years, there appear to be no sites outside of Florida with a BRP. We believe that the BRP sites were especially interesting, and multidecadal flow differences and the AMO offer the most plausible explanation for long-term flow variation at these sites and provide the strongest support for a larger geographical influence of the AMO. While one might argue that different anthropogenic factors could lead to decreases at SRP gage sites and increases at NRP gage sites, it is difficult to postulate an anthropogenic factor that would cause one mode to increase and the other to decrease during one 30-year period with the reverse occurring in the other 30-year period.

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Table I. Per cent decrease in flows between two multidecadal periods at long-term Florida gage sites with (a) a Southern River Pattern, (b) a Northern River Pattern, (c) Bimodal River Pattern

River/stream	Catchment area (km^2)	Change for year (%)	Change for SRP wet season (%)	Change for NRP wet season (%)
(a)				
Alafia River at Lithia	868	23.7	30.3	13.2
Arbuckle Creek nr De Soto City	982	34.3	29.6	42.1
Econlockhatchee River nr Chuluota	624	−2.7	12.0	−49.6
Fisheating Creek at Palmdale	805	18.6	17.6	21.7
Hillsborough River at Zephyrhills	570	29.2	38.9	13.8
Hillsborough River nr Tampa	1683	70.7	68.3	67.0
Little Manatee River nr Wimauma	386	2.7	24.1	−54.4
Myakka River nr Sarasota	593	6.2	22.5	−150.7
Peace River at Arcadia	3540	36.5	39.0	30.5
Peace River at Bartow	1010	59.1	51.9	67.7
Peace River at Zolfo Spgs	2139	33.2	33.2	33.4
St Johns River nr Christmas	3986	23.8	28	−1.9
St Johns River nr De Land	7951	19.5	24.7	−3.8
St Johns River nr Melbourne	2507	17.0	13.8	−2.8
Withlacoochee River at Croom	2098	46.3	55.5	21.8
Withlacoochee River at Trilby	1476	48.8	55.4	24.0
Withlacoochee River nr Holder	4714	38.3	46.6	24.5
Means	2113.7	29.7	34.8	5.7
Median	1476	29.2	30.3	21.7
Minimum	385.9	−2.7	12.0	−150.7
Maximum	7951.0	70.7	68.3	67.7
(b)				
Apalachicola River at Chattahoochee	44 564	−6.7	1.4	−8.9
Chipola River nr Altha	2023	−7.6	3.2	−15.9
Choctawhatchee River at Bruce	11 354	−12.8	3.2	−19.4
Choctawhatchee River at Caryville	9062	−12.8	3.2	−19.4
Escambia River nr Century	9886	−12.9	4.0	−17.3
Ochlockonee River nr Bloxham	4403	−8.1	24.9	−22.7
Ochlockonee River nr Havana	2952	−21.9	12.0	−33.5
Suwanee River at Branford	20 408	−14.9	7.9	−43.4
Suwanee River at Ellaville	18 052	−17.9	16.3	−49.7
Suwanee River nr Wilcox	24 967	−4.8	9.5	−24.0
Withlacoochee River nr Pinetta	5491	−35.2	12.3	−50.5
Yellow River at Milligan	1616	−12.5	6.6	−19.4
Means	12 896.6	−14.0	8.7	−27.0
Median	9473.9	−12.8	7.2	−21.1
Minimum	1616.1	−35.2	1.4	−50.5
Maximum	44 546.3	−4.8	24.9	−8.9
(c)				
Suwanee River at White Spgs	6293	−23.3	33.5	−79.2
South Fork Black Creek nr Penney Farms	347	9.9	22.6	−11.1
North Fork Black Creek nr MIddleburg	458	−5.7	11.0	−28.4
Santa Fe River at Worthington Spgs	1489	2.9	38.3	−62.1
St Marys River nr Macclenny	1813	−26.9	11.5	−85.7
Means	2080	−8.6	23.4	−53.3
Median	1489	−5.7	22.6	−62.1
Minimum	347	−26.9	11.0	−85.7
Maximum	6293	9.9	38.3	−11.1

Positive percentage values indicate a decrease in flow between the two multidecadal periods (1940–1969 (wet) and 1970–1999 (dry)) since the mean of the more recent periods was subtracted from the earlier period.

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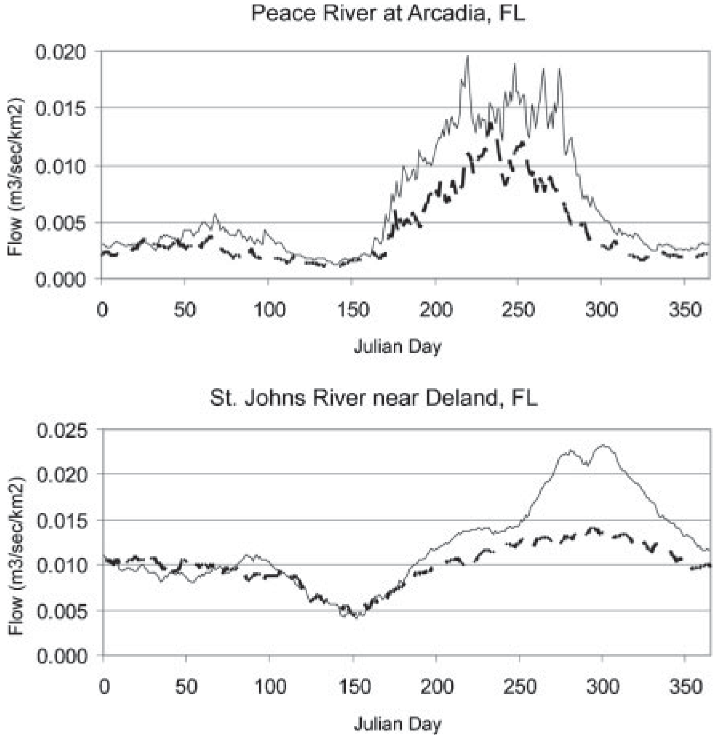

Figure 6. Examples of Southern River Pattern (SRP) gage sites comparing median daily flows for two multidecadal time periods (1940–1969 (solid line) and 1970–1999 (bold broken line)). Flows are standardized per square kilometre of catchment area

Unfortunately, Florida's continued growth and development during the last several decades means that all things have not remained equal. Although consistent with Enfield *et al*. (2001), human factors during the last three decades have likely affected flows to some degree; it is noted, however, that in the northern part of the state growth, has also occurred, yet flows have apparently increased at those sites, as well. Those sites with a BRP actually demonstrate both an increasing and decreasing trend in flow depending on which mode is examined. The mode that is characteristic of the NRP has increased between the two multidecadal periods examined, while the mode that is characteristic of the SRP has decreased between the two mutidecadal periods. Although flow trends at NRP and SRP sites are consistent with AMO predictions, those sites with a BRP offer especially strong support, since they exhibit characteristics of NRP and SRP with each mode responding consistent with Enfield *et al*. (2001).

After reviewing hundreds of multidecadal plot comparisons, we conclude that a strong argument can be made in favour of a multidecadal oscillation in flow as described by Enfield *et al*. (2001). This oscillation has only recently been appreciated and has important implications for many water resource related issues ranging from direct ecological affects to water supply planning and flood management. For example Bradley and Ormerod (2001) found that the resilience of benthic macroinvertebrate communities in rivers in the UK is correlated with the NAO and may alter the ability of riverine ecosystems to recover from disturbances such as acidification or the longer term effects of global warming. Similar observations have been recently reported from Florida (Gore and Kelly, 2006).

AMO or anthropogenic change?—testing for monotonic and step trends

Thus far, our analysis of flow patterns relied upon flow plots and a visual comparison and interpretation of plots between periods that correspond closely with a warm and cool phase of the AMO. A typical statistical approach for assessing flow trends has been the application of the Kendall's τ test to mean annual flows for various time periods (e.g. Hammett, 1990; Stoker *et al*., 1996). This analysis is best suited to determine if a significant monotonic trend has occurred. We used this test to conduct an analysis of mean annual flows for several time periods. For those sites with a sufficient period of record, it was desirable to perform a trend analysis for the two multidecadal periods we

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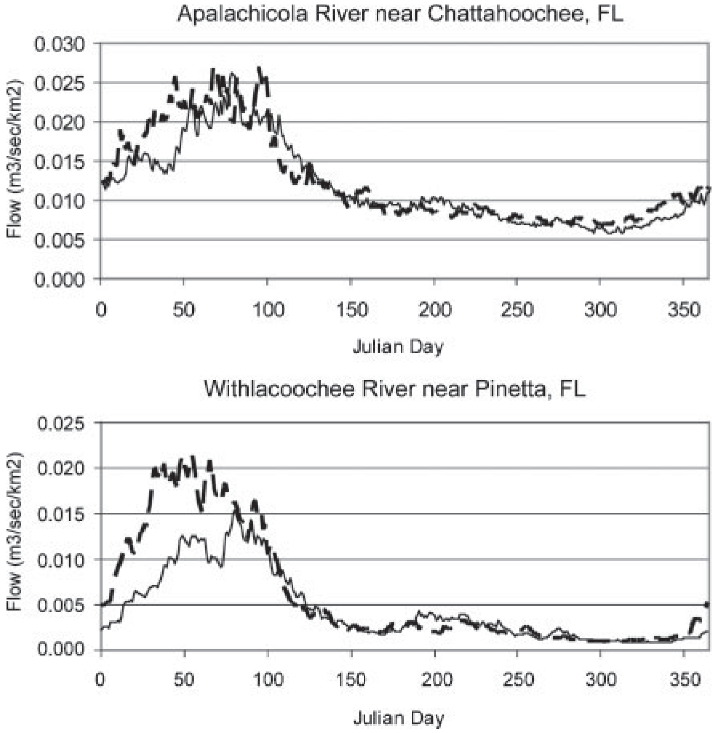

Figure 7. Examples of Northern River Pattern (NRP) gage sites comparing median daily flows for two multidecadal time periods (1940–1969 (solid line) and 1970–1999 (bold broken line)). Flows are standardized per square kilometre of catchment area

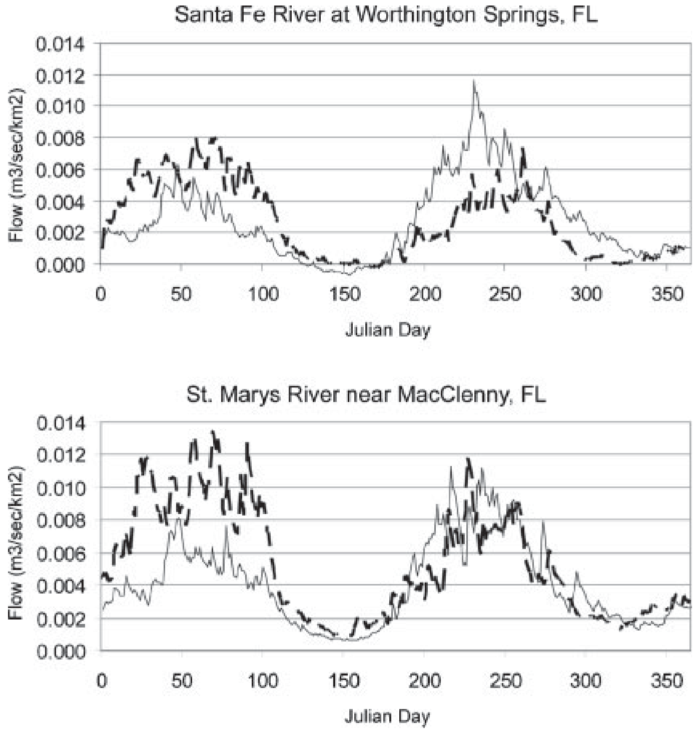

Figure 8. Examples of Bimodal River Pattern (BRP) gage sites comparing median daily flows for two multidecadal time periods (1940–1969 (solid line) and 1970–1999 (bold broken line)). Flows are standardized per square kilometre of catchment area

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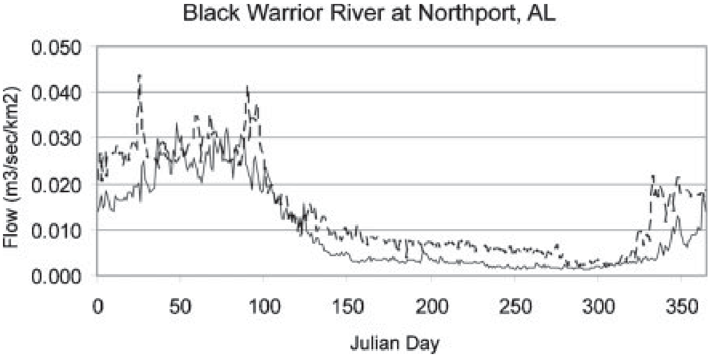

Figure 9. Example of Northern River Pattern (NRP) on the Black Warrior River in Alabama (northeast of Florida) comparing median daily flows for two multidecadal time periods (1940–1969 (solid line) and 1970–1999 (bold broken line)). Flows are standardized per square kilometre of catchment area

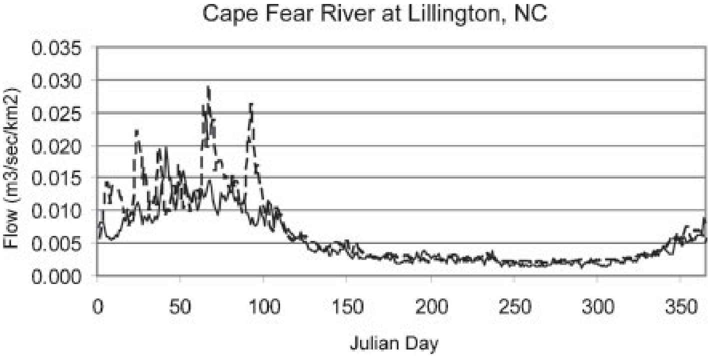

Figure 10. Example of Northern River Pattern (NRP) on the Cape Fear River in North Carolina (1000 km north of Florida) comparing median daily flows for two multidecadal time periods (1940–1969 (solid line) and 1970–1999 (bold broken line)). Flows are standardized per square kilometre of catchment area

defined. The results of Kendall's τ test for all Florida sites with 60 years of data from 1940 to 1999 are presented in Table II. Since we believed that much of the change in river flow before and after the transitional year, 1970, could best be described as a step trend (as suggested by a fairly abrupt change in North Atlantic Ocean sea surface temperature), the Mann–Whitney trend test was used to determine if flows were different between the two periods (1940–1969 and 1970–1999). Mann–Whitney test results for all Florida gage sites for which the Kendall's τ were performed are presented in Tables III and IV.

All SRP sites were tested with the expectation that the pre-1970 period (1940–1969) should exhibit higher flows than the post-1970 period (1970–1999). For example in Table III, the Mann–Whitney test was statistically significant ($p = 0.0079$) for the Anclote River suggesting that pre-1970 period mean annual flows were higher than the post-1970 period. It is possible that there has been both a step and monotonic trend in Anclote River mean annual flows; however, a comparison of pre-1970 and post-1970 Kendall's τ tests (Table II) suggests that a step trend has occurred since pre-1970 and post-1970 Kendall's τ values were not significant (pre-1970 $p = 0.9159$; post-1970 $p = 0.6686$).

The occurrence of a step trend does not imply that anthropogenic factors have not lead to significant flow declines; in fact, anthropogenic changes can lead to rather abrupt changes in flow. We suggest, however, that the AMO would lead to rather abrupt changes in rainfall and consequently river flows.

It was generally expected that rivers with a SRP should show increased flow between periods since this was visually apparent when plots of MDQs were compared and confirmed, in most cases, by a the Mann–Whitney test. Only one Florida site with a SRP exhibited a step trend opposite to that expected (flows increased between the

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Table II. Results of Kendall's τ test on mean annual flows for selected gage sites and time periods

Site name	POR	*t*			1940–1969				1970–1999			
	Mean annual *Q*	Median annual *Q*	Slope	*p*	Mean annual *Q*	Median annual *Q*	Slope	*p*	Mean annual *Q*	Median annual *Q*	Slope	*p*
Alafia River at Lithia	329.8	309.2	−2.314	$\boxed{\boxed{0.0060}}$	388	375	3.796	0.3353	264	268	0.1081	1.0000
Anclote River nr Elfers	63.11	56.21	−0.920	$\boxed{\boxed{0.0050}}$	83.7	70.9	−0.1569	0.9159	50.2	45.2	−0.2417	0.6686
Apalachicola River at Chattahoochee	21 766	22 117	−2.846	0.9108	21 722	21 455	26.897	0.8865	23 021	23 340	−77.22	0.3008
Arbuckle Creek nr De Soto City	313	285	−1.809	$\boxed{\boxed{0.0751}}$	373	313	−3.493	0.4755	247	215	3.642	0.1868
Big Coldwater Creek nr Milton	551	531	1.621	0.1934	513	490	−4.655	0.1640	631	632	5.418	0.1457
Big Creek nr Clermont	22.4	16.4	−0.268	0.1123	43.7	29.2	−0.5518	0.7555	16.5	16.4	0.3527	0.2251
Blackwater Creek nr Knights	78.3	62	−0.434	0.2051	103	85.7	0.9249	0.8796	68.4	59	1.183	0.1164
Brooker Creek nr Tarpon Spgs	18.7	13.7	−0.196	$\boxed{\boxed{0.0325}}$	25.9	16.1	−0.0672	0.7703	13.3	11.2	−0.0095	0.9715
Bullfrog Creek nr Wimauma	42	37.9	0.408	0.2772	33.4	33.4			44.29	46.32	0.6286	0.2452
Caloosahatchee Canal at Moore Haven	839	615	−4.606	0.3162	1070	753	−3.269	0.8038	681	254	7.369	0.1339
Catfish Creek nr Lake Wales	41.1	36.9	−0.485	0.0003	51.1	45	−0.8068	0.2839	33.7	33.7	0.0032	1.0000
Charlie Creek nr Gardner	255	222	−1.802	0.2213	324	292	1.004	1.0000	221	195	1.961	0.2687
Chipola Creek nr Altha	1457	1382	−0.043	0.9596	1450	1286	−14.43	0.4691	1538	1456	3.5113	0.6427
Choctawhatchee River at Caryville	5513	5269	4.530	0.6997	5306	4968	−46.5	0.2250	6060	5792	−6.918	0.8584
Choctawhatchee River at Bruce	7085	6862	0.907	0.9729	6922	6460	−50.03	0.2535	7644	7474	−13.88	0.7753
Cypress Creek	80.1	71.9	−2.070	$\boxed{\boxed{0.0008}}$	121	147	−18.66	0.4624	74.6	72.4	−1.25	0.2251
Ecofina Creek nr Bennett	535	538	0.430	0.5741	532	513	−1.817	0.3353	564	572	2.986	0.1039
Econlockhatchee River nr Chuluota	277	267	1.258	0.1761	295	262	2.046	0.4324	269	278	7.704	$\boxed{0.0021}$
Escambia River nr Century	6198	6268	2.106	0.9367	5821	5381	−72.8	0.1989	6865	6645	−29.82	0.4324
Fenholloway River at Foley	130	114	0.097	0.7827	126	107	2.414	0.2673	140	134	−0.3694	0.3986
Fisheating Creek at Palmdale	251	238	0.290	0.7810	284	278	−1.004	0.7753	241	218	3.185	0.2251
Hillsborough River nr Tampa	443	381	−6.863	$\boxed{\boxed{0.0001}}$	632	516	3.149	0.6947	276	264	0.1813	0.9147
Hillsborough River at Zephyrhills	240	203	−1.453	$\boxed{\boxed{0.0091}}$	292	247	1.189	0.6427	202	187	1.703	0.4754
Horse Creek nr Ardadia	191	176	−0.533	0.6643	230	207	2.036	0.7796	165	161	2.928	0.1989
Josephine Creek nr De Soto City	71.8	53.9	−0.614	$\boxed{\boxed{0.0524}}$	97.3	72.2	−3.039	0.1696	52.6	47.3	0.3168	0.3330
Joshua Creek at Nocatee	106	100	0.034	0.9559	120	122	−1.246	0.7796	99.5	98.5	1.872	$\boxed{0.0804}$
Jumper Creek Canal nr Bushnell	22.2	23.3	−0.591	$\boxed{\boxed{0.0005}}$	28.7	28.6	−1.211	1.0000	23	23.9	−0.5514	$\boxed{\boxed{0.0185}}$
Kissimmee River nr Okeechobee	1773	1609	−10.474	$\boxed{\boxed{0.0166}}$	2144	2010	−13.77	0.6391	1332	1305	22.13	0.1989
Little Econlockhatchee River nr Union Park	30.7	29.6	0.508	$\boxed{0.0074}$	20	27.1	1.249	0.4743	31.9	32.3	1.034	$\boxed{0.0009}$
Little Haw Creek nr Seville	81.1	79.6	−0.085	0.9224	93.4	73.1	3.194	0.2889	73	79.6	0.1281	0.8028
Little Manatee River nr Ft Lonesome	30.7	31.1	0.101	0.5615	33.5	33.8	2.236	0.2597	30.7	28.1	0.5564	0.1007
Little Manatee River nr Wimauma	171	159	−0.486	0.3997	184	178	0.3341	0.9431	158	139	2.318	$\boxed{0.0867}$
Myakka River nr Sarasota	253	235	0.013	0.9911	261	215	1.721	0.5680	241	228	4.405	0.1435
North Fork Black Creek nr Middleburg	187	190	0.320	0.5252	212	208	3.462	0.1535	191	202	−0.1544	0.9715
North Prong of Alafia River at Keysville	150	130	−1.470	$\boxed{\boxed{0.0309}}$	187	181	5.296	0.1417	134	129	0.0851	0.8900
North Prong St Marys River at Moniac, GA	146	131	−1.065	$\boxed{\boxed{0.0937}}$	130	103	6.379	$\boxed{0.0688}$	147	140	−3.6490	$\boxed{\boxed{0.0353}}$
Ochlockonee River nr Bloxham	1695	1514	1.594	0.7434	1707	1503	4.687	0.8865	1855	1588	−5.0127	0.6427
Ocholockonee River nr Havana	1028	941	0.860	0.7638	1004	857	−0.7014	0.9715	1163	1054	−5.593	0.6174

Continues

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Table II. (Continued)

Site name	POR	t			1940–1969				1970–1999			
	Mean annual Q	Median annual Q	Slope	p	Mean annual Q	Median annual Q	Slope	p	Mean annual Q	Median annual Q	Slope	p
Ocklawaha at Moss Bluff	239	210	−5.242	$\boxed{\boxed{0.0001}}$	363	409	−3.662	0.7665	197	181	−0.7777	0.6685
Outlet River at Panacoochee Retreat	173	162	−2.881	$\boxed{\boxed{0.0094}}$	202	228	−5.903	0.7639	177	165	−2.357	0.1751
Peace River at Arcadia	1061	1003	−7.019	$\boxed{\boxed{0.0213}}$	1289	1113	−1.947	0.8028	856	738	3.759	0.5880
Peace River at Bartow	219	173	−2.715	$\boxed{\boxed{0.0010}}$	295	241	−1.367	0.6427	161	145	3.335	0.2251
Peace River at Zolfo Spgs	635	561	−5.132	$\boxed{\boxed{0.0016}}$	751	636	−3.084	0.4754	477	422	1.231	0.8305
Pithlachascotee nr New Port Richey	26.4	23.7	−0.554	$\boxed{\boxed{0.0136}}$	38.7	39.6	−8.036	0.4523	25.6	23.7	−0.3096	0.3435
Rainbow River nr Dunnellon	700	692	−3.844	$\boxed{\boxed{0.0086}}$	784	769	−30.49	0.7341	697	687	−0.8021	0.7212
Rocky Creek nr Sulphur Spgs	37.4	29.3	0.027	0.8699	39.8	31.1	−0.1148	1.0000	37.3	29.2	0.7598	0.1083
Santa Fe River at Worthington Spgs	412	397	−1.126	0.4747	478	431	1.901	0.7212	420	414	−3.335	0.5207
Santa Fe River nr Ft White	1525	1439	−6.053	$\boxed{\boxed{0.0311}}$	1683	1630	3.763	0.8305	1469	1424	−13.16	0.2389
South Fork Black Creek nr Penney Farm	147	138	−0.843	$\boxed{\boxed{0.0854}}$	163	155	0.6173	0.8304	141	138	−0.7443	0.6685
Shoal River nr Crestview	1098	1050	1.239	0.6472	1062	973	−6.04	0.4537	1203	1105	5.532	0.4536
Silver Springs nr Ocala	779	778	−2.425	$\boxed{\boxed{0.0029}}$	829	845	1.428	0.7212	758	752	−2.8825	0.2535
Sopchoppy River nr Sopchoppy	195	176	−0.446	0.7248	184	201	−27.37	0.2207	192	172	−0.8393	0.6427
South Prong of Alafia River	98	92.4	−1.445	$\boxed{\boxed{0.0277}}$	140	123	16.41	$\boxed{0.0242}$	93.7	87.5	−0.1917	0.8027
Steinhatchee River nr Cross City	306	286	−0.956	0.5753	316	261	0.6287	0.7796	322	343	−1.813	0.6174
St Johns River nr Melbourne	684	654	−0.494	0.7397	762	639	−2.548	0.7212	608	633	17.53	$\boxed{0.0185}$
St Johns River nr Cocoa	1102	1008	2.947	0.5292	1145	1051	4.989	0.8926	912	971	22.84	$\boxed{0.0244}$
St Johns River nr De Land	3092	2968	−3.697	0.5929	3432	3066	−7.408	0.7753	2813	2843	37	0.1595
St Johns River nr Christmas	1306	1237	−1.150	0.7363	1491	1237	1.928	0.8865	1176	1185	20.57	0.1007
St Marks River nr Newport	695	689	0.108	0.9765					728	707	7.137	0.1595
St Marys River nr Macclenny	636	598	−2.081	0.3394	688	510	2.921	0.8584	643	631	−6.608	0.2687
Sulphur Springs at Sulphur	38.1	36.1	−0.455	$\boxed{\boxed{0.0001}}$	47.5	46.5	−1.326	0.2831	35.4	34.7	0.2168	0.6174
Suwannee River at Branford	6811	6286	4.870	0.7810	7068	6084	43.26	0.6427	7478	7163	−77.77	0.3177
Suwannee River at Ellaville	6293	5760	−7.718	0.6020	6373	5412	36.39	0.6947	6702	6405	−68.02	0.2389
Suwannee River at White Spgs	1778	1518	−3.224	0.5986	1868	1736	11.47	0.7481	1882	1686	−28.39	0.2535
Suwannee River nr Wilcox	10 048	9444	−30.542	0.2965	10 298	9546	−12.92	0.9252	10 519	10 009	−98.26	0.1534
Sweetwater Creek nr Sulphur Spgs	6.09	3.67	−0.002	0.9352	7.71	4.06	0.0079	1.0000	5.72	3.72	0.0665	0.2389
Telogia Creek nr Bristol	212	193	−0.314	0.7004	211	189	6.813	0.1617	225	223	−1.159	0.3956
Tomoka River nr Holly Hill	51.7	52.8	−0.419	0.3145	73.2	89.6	14.03	0.4624	47.6	45.1	−0.2169	0.7212
Wekiva River nr Sanford	286	278	0.487	0.1626	291	277	2.239	$\boxed{0.0635}$	293	283	0.1092	0.9148
Withlacoochee River at Croom	415	356	−4.458	$\boxed{\boxed{0.0045}}$	531	431	1	0.7752	325	330	−0.3577	0.9147
Withlacoochee River nr Holder	1019	910	−8.319	$\boxed{\boxed{0.0007}}$	1206	1028	1.153	0.9147	810	742	−9.271	0.3008
Withlacoochee River at Trilby	334	281	−2.522	$\boxed{\boxed{0.0117}}$	401	340	2.069	0.4537	244	244	1.301	0.8027
Withlacoochee River (northern) nr Pinetta	1683	1582	4.848	0.3716	1661	1474	3.485	0.9148	1956	1822	−7.768	0.7481
Yellow River at Milligan	1130	1029	−2.872	0.3559	1106	1003	−8.312	0.2251	1230	1084	−5.11	0.3956

p-values that represent an increase in flow are enclosed in a single-line box while those that represent a decrease are enclosed in a double-line box. The slope of the monotonic trend is also included. POR, period of record from earliest reading (most commonly in the 1930's) to year 2002.

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Table III. Mann–Whitney test for flow differences between mean annual flows for two multidecadal time periods (1940–1969 and 1970–1999)

River/stream	River pattern	1940–1969 median Q ($m^3 s^{-1}$)	1970–1999 median Q ($m^3 s^{-1}$)	p
North Prong St Marys River at Moniac, GA	Bimodal	2.92	3.96	0.3001
Steinhatchee River nr Cross City	Bimodal	7.39	9.71	0.6180
Suwanee River at White Spgs	Bimodal	49.16	47.71	0.6952
Big Creek nr Clermont	Bimodal	0.83	0.46	$\boxed{0.0165}$
Little Haw Creek nr Seville	Bimodal	2.07	2.24	0.4123
North Fork Black Creek nr Middleburg	Bimodal	5.89	5.72	0.5493
Santa Fe River at Worthington Spgs	Bimodal	12.2	11.72	0.2367
Sopchoppy River nr Sopchoppy	Bimodal	5.69	4.84	0.9812
South Fork Black Creek nr Penney Farms	Bimodal	4.39	3.91	0.2707
St Marys Rive nr Macclenny	Bimodal	17.27	17.87	0.9705
Apalachicola River at Chattahoochee	NRP	607.54	660.92	0.1895
Chipola River nr Altha	NRP	36.42	41.23	$\boxed{\boxed{0.0868}}$
Choctawhatchee River at Bruce	NRP	182.93	211.64	$\boxed{\boxed{0.0834}}$
Choctawhatchee River at Caryville	NRP	140.68	163.98	$\boxed{\boxed{0.0687}}$
Escambia River nr Century	NRP	152.37	188.17	$\boxed{\boxed{0.0362}}$
Ochlockonee River nr Bloxham	NRP	42.56	44.97	0.1386
Ochlockonee River nr Havana	NRP	24.27	29.82	$\boxed{\boxed{0.0812}}$
Suwanee River at Branford	NRP	172.31	202.83	0.2145
Suwanee River at Ellaville	NRP	153.25	181.37	0.2601
Suwanee River nr Wilcox	NRP	270.31	283.42	0.3005
Talogia Rier nr Bristol	NRP	5.35	6.31	0.2613
Withlacoochee River (north) nr Pinetta	NRP	41.74	51.59	$\boxed{\boxed{0.0893}}$
Yellow River at Milligan	NRP	28.4	30.7	0.1504
Fenholloway River at Foley	NRP—regulated	3.03	3.79	$\boxed{\boxed{0.0893}}$
Big Coldwater Creek nr Milton	NRP—spring-fed	13.87	17.91	$\boxed{\boxed{0.0027}}$
Ecolina Creek nr Bennett	NRP—spring-fed	14.53	16.2	$\boxed{\boxed{0.0763}}$
Shoal River nr Crestview	NRP—spring-fed	27.58	31.29	$\boxed{\boxed{0.0724}}$
St Marks River nr Newport	NRP—spring-fed	18.52	20.02	0.2639
Alafia River at Lithia	SRP	10.62	7.69	$\boxed{0.0054}$
Anclote River nr Elfers	SRP	2.01	1.38	$\boxed{0.0079}$
Arbuckle Creek nr De Soto City	SRP	8.87	6.10	$\boxed{0.0069}$
Blackwater Creek nr Knights	SRP	2.43	1.67	$\boxed{0.0312}$
Brooker Creek nr Tarpon Spgs	SRP	0.45	0.31	$\boxed{0.0166}$
Bullfrog Creek nr Wimauma	SRP	0.93	1.30	N/A
Catfish Creek nr Lake Wales	SRP	1.27	0.96	$\boxed{0.0007}$
Charlie Creek nr Gardner	SRP	8.27	5.52	$\boxed{0.0222}$
Cypress Creek nr Sulphur Spgs	SRP	4.16	2.04	$\boxed{0.0752}$
Econlockhatchee River nr Chuluota	SRP	7.42	7.87	N/A
Fisheating Creek at Palmdale	SRP	7.87	6.17	$\boxed{0.2698}$
Hillsborough River at Zephyrhills	SRP	6.99	5.30	$\boxed{0.0021}$
Hillsborough River nr Tampa	SRP	14.61	7.48	$\boxed{0.0001}$
Horse Creek nr Arcadia	SRP	5.86	4.56	$\boxed{0.0452}$
Josephine Creek nr De Soto City	SRP	2.04	1.33	$\boxed{0.0088}$
Joshua Creek at Nocatee	SRP	3.45	2.80	0.1806
Little Econlockhatchee River nr Union Park	SRP	0.73	0.91	0.1952
Little Manatee nr Fort Lonesome	SRP	0.96	0.79	0.2833
Little Manatee nr Wimauma	SRP	5.04	3.94	$\boxed{0.0954}$

(*Continues*)

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Table III. (Continued)

River/stream	River pattern	1940–1969 median Q (m^3 s^{-1})	1970–1999 median Q (m^3 s^{-1})	p
Myakka River nr Sarasota	SRP	6.09	6.46	0.4094
North Prong of Alafia River at Keysville	SRP	5.13	3.65	$\boxed{0.0065}$
Peace River at Arcadia	SRP	31.52	20.90	$\boxed{0.0035}$
Peace River at Bartow	SRP	6.82	4.11	$\boxed{0.0003}$
Peace River at Zolfo Spgs	SRP	18.01	11.95	$\boxed{0.0007}$
Pithlachascotee nr New Port Richey	SRP	1.12	0.67	$\boxed{0.0557}$
Rocky Creek nr Sulphur Spgs	SRP	0.88	0.83	0.4862
South Prong of Alafia River	SRP	3.48	2.46	$\boxed{0.0356}$
St Johns River nr Christmas	SRP	35.03	33.53	$\boxed{0.0812}$
St. Johns River nr Cocoa	SRP	29.76	27.6	0.1418
St Johns River new De Land	SRP	86.85	80.51	$\boxed{0.0532}$
Sweetwater Creek nr Sulphur Spgs	SRP	0.11	0.11	N/A
Tomokoa River nr Holly Hill	SRP	2.54	1.27	$\boxed{0.0348}$
Withlacoochee River at Croom	SRP	12.20	9.34	$\boxed{0.0033}$
Withlacoochee River at Trilby	SRP	9.60	6.91	$\boxed{0.0054}$
Withlacoochee River nr Holder	SRP	29.39	21.01	$\boxed{0.0023}$
Caloosahatchee Canal at Moore Haven	SRP—regulated	21.32	7.19	$\boxed{0.0768}$
Kissimmee River nr Okeechobee	SRP—regulated	58.92	36.95	$\boxed{0.0039}$
Ocklawaha at Moss Bluff	SRP—regulated	11.58	5.13	$\boxed{0.0004}$
Jumper Creek Canal nr Bushnell	SRP—spring-fed	0.82	0.68	0.1132
Outlet River at Panacoochee Retreat	SRP—spring-fed	6.43	4.67	0.1614
Rainbow Springs nr Dunnellon	SRP—spring-fed	21.78	19.45	$\boxed{0.0198}$
Santa Fe River nr Ft White	SRP—spring-fed	46.16	40.32	0.2009
Silver Springs nr Ocala	SRP—spring-fed	23.93	21.29	$\boxed{0.0146}$
Sulphur Springs at Sulphur	SRP—spring-fed	1.33	0.99	$\boxed{0.0001}$
Wakiva River nr Sanford	SRP—spring-fed	7.84	8.01	N/A

For p values of 0.1 or less, those that represent an increase between periods are enclosed by a single-line box and those that represent a decrease are enclosed by a double-line box.

critical periods for the Econlockhatchee River near Chuluota; Table I(b)). The increase was small and amounted to less than 3% between periods, based on a comparison of MDQs. However, considering other sites with a SRP, a 30–35% decline might be anticipated. Close inspection of flow plots and Table I(b) suggests that summer flows had decreased as expected (although by only 12%), but typical dry season flows (January through May) increased by almost 50%; it is unlikely that these increases can be attributed to increased dry season rainfall; thus, these data suggest that some anthropogenic flow increases have offset much of the expected decline (a monotonic increasing trend is clearly evident in a plot of the annual minimum flow of the Econlockhatchee River). Only three others of the 45 sites examined with an SRP dominated pattern showed post-1970 flows greater than pre-1970 flows; Bullfrog Creek (near Wimauma), Sweetwater Creek (near Sulphur Springs) and the Wekiva River (near Sanford). In all cases known anthropogenic changes could have resulted in increased flows; increases in Bullfrog Creek attributable to increased agriculturally related discharges and Sweetwater Creek being developed into a heavily urbanized area with greater runoff related to increased impervious area and drainage improvements. The flow increase on the Wekiva River appears to be related to water treatment plant discharges (Hupalo *et al*., 1994).

Of the 45 sites with an SRP pattern, 30 showed a significant decrease in flow between the two periods and 11 of the sites had no significant differences; however, several of the sites that fell into this category have experienced agriculturally related monotonic increases in flow (e.g. Little Manatee River, Myakka River and Joshua Creek) that have partially offset expected natural flow declines (Tables II and III).

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Table IV. Mann–Whitney test results for differences in rainfall between two multidecadal periods: 1940–1969 versus 1970–1999; the presumptive test being that the earlier period had significantly more rainfall than the more recent

Rainfall site		1940–1969 median (mm)	1970–1999 median (mm)	*p*-value
Arcadia	Total	1399	1177	$\boxed{0.0128}$
	Wet	847	693	$\boxed{0.0264}$
	Dry	515	481	0.2668
Archibold	Total	1415	1276	$\boxed{0.0472}$
	Wet	865	746	$\boxed{0.0204}$
	Dry	502	580	N/A
Avon	Total	1394	1208	$\boxed{0.0178}$
	Wet	847	737	$\boxed{0.0092}$
	Dry	583	521	0.2075
Bartow	Total	1355	1269	$\boxed{0.0594}$
	Wet	791	725	$\boxed{0.0467}$
	Dry	587	589	0.2796
Bradenton	Total	1362	1318	0.2846
	Wet	886	837	0.1486
	Dry	469	526	N/A
Brooksville	Total	1451	1298	$\boxed{0.0527}$
	Wet	864	691	$\boxed{0.0268}$
	Dry	580	622	N/A
Bushnell	Total	1387	1193	$\boxed{0.0141}$
	Wet	753	632	$\boxed{0.0050}$
	Dry	603	570	N/A
Clermont	Total	1306	1288	0.5493
	Wet	756	717	0.1538
	Dry	555	565	N/A
Inverness	Total	1370	1319	0.1113
	Wet	816	694	$\boxed{0.0027}$
	Dry	522	632	N/A
Lake Alfred	Total	1370	1227	0.1452
	Wet	782	698	0.1935
	Dry	562	557	N/A
Lakeland	Total	1201	1276	N/A
	Wet	694	699	N/A
	Dry	493	540	N/A
Ocala	Total	1452	1247	$\boxed{0.0135}$
	Wet	800	599	$\boxed{0.0001}$
	Dry	583	650	N/A
Plant City	Total	1353	1300	$\boxed{0.0954}$
	Wet	791	687	$\boxed{0.0182}$
	Dry	517	575	N/A
Punta Gorda	Total	1307	1258	0.1895
	Wet	778	716	0.1170
	Dry	494	516	0.4912
St Leo	Total	1441	1309	0.2601
	Wet	784	706	$\boxed{0.0399}$
	Dry	565	611	N/A
St Petersburg	Total	1356	1205	$\boxed{0.0577}$
	Wet	807	672	$\boxed{0.0238}$
	Dry	513	537	0.4383
Tampa Int. Airport	Total	1168	1100	$\boxed{0.0594}$
	Wet	692	628	$\boxed{0.0603}$
	Dry	465	479	0.3531
Tarpon Springs	Total	1361	1279	0.2601

(*Continues*)

Table IV. (Continued)

Rainfall site		1940–1969 median (mm)	1970–1999 median (mm)	*p*-value
	Wet	786	697	$\boxed{0.0312}$
	Dry	484	633	N/A
Wauchula	Total	1372	1281	$\boxed{0.1024}$
	Wet	829	733	$\boxed{0.0956}$
	Dry	535	517	0.3808
Winter Haven	Total	1269	1242	0.2130
	Wet	716	716	0.4607
	Dry	520	552	N/A

For all *p*-values given, values enclosed by a single-line box indicate an alpha of 0.1 or less. Wet season (June–September), dry season (October–May) and total annual rainfall for each site are listed.

Of the 18 NRP sites tested for a positive step increase in flow between the two periods, none showed an opposite trend (decrease in flow). Ten of the 18 sites examined had significantly higher flows.

Those sites that exhibited a bimodal flow pattern were analysed with the assumption that flows between periods were different; however, there was no *a priori* expectation that flow differences would be either positive or negative. Of the 10 biomodal sites tested, only one showed a significant change in flow between the two periods. The single exception was Big Creek (near Clermont), where there was a significant decline in flow ($p = 0.0165$). Overall, bimodal sites behaved as might be expected due to compensating increases and decreases in the two flow modes and reflected by no significant trend in any one particular direction.

Based upon our analysis of those Florida sites with 60 years of flow data spanning the two periods of interest, along with analysis of an additional 32 sites with shorter flow periods, we concluded that there has been a step trend change in flow. The Mann–Whitney test confirmed that for SRP sites there was a rather abrupt (step) decrease in flows between the two periods tested, while there was a step increase in flows at most NRP sites. Bimodal flow sites essentially showed no step change in flow between the two periods examined; however, inspection of individual flow plots for each river indicated that, in general, the SRP mode decreased between periods while the NRP mode increased. These increases and decreases in flow were essentially offsetting, resulting in little net change in mean or median annual flows. However, there was considerable seasonal variation in the magnitude of flows between the two modes between the two periods.

Rainfall trends and the AMO

Since the change between multidecadal periods was considered a step trend, we analysed total annual, wet (June–September) and dry (October–May) season rainfall to determine if similar step trends could be found, with the assumption that rainfall was higher for the 1940–1969 period than for the period 1970–1999 at southwest Florida sites.

Fourteen of 20 sites showed a significant decrease in rainfall between the two periods examined (Table IV). While it is interesting to note that one site, the Lakeland site, actually showed an increase in rainfall between the two periods, the vast majority of sites had a significant decrease in rainfall between the two periods. This analysis was performed for the wet season in addition to total annual rainfall because comparison of period flows on SRP sites suggested that the largest difference in flows occurred during the rainy season (June–September). These results are consistent with an abrupt change in rainfall, and also confirm the results of Enfield *et al*. (2001) who found a significant positive correlation between rainfall in south Florida and the AMO.

CONCLUSIONS

The main premise of this paper has been that climatic factors can explain much of the relatively large flow declines that have been observed on watercourses in Florida with a SRP over the past 30 years. While there is certainly the possibility that additional flow declines have also occurred as a consequence of anthropogenic impacts, it may be difficult to quantify or in some cases even identify these impacts. It is generally acknowledged that there can be extreme annual variation in flow and most data suggest that this variation is more or less random. As a result, when flow declines (or inclines) occur, the tendency has been to assume an anthropogenic explanation for these flow trends. Olsen *et al*. (1999), when examining flood frequency estimation for the upper Mississippi and lower Missouri Rivers observed that the annual maximum peak floods were considered to be a sample of random, independent and identically distributed events. Thus, they implicitly assumed that climatic trends or cycles are not affecting the distribution of flood flows in a significant way. Olsen *et al*. (1999) concluded that current interest in climate change and its potential impacts on hydrology in general and on floods in particular called into question the 'independent and identically distributed' assumption.

Beecher (1990) correctly identified a 'baseline' (or benchmark time) period as a necessary element when developing minimum flows. However, we suggest that care should be taken when selecting the baseline, because minimum flows developed in ignorance of multidecadal variations in flow could lead to either unreasonably high or low expectations, particularly if the acceptable flow decline is expressed as a decrease to a particular mean or median flow based on a relatively short flow record (say, less than 40–50 years), despite the fact that 20 years or so of record is generally considered sufficient (e.g. Richter *et al*., 1996). We further suggest that it may be appropriate to have at least two baseline periods; one based on a 'wet' period and one based on a 'dry' period.

McCabe and Wolock (2002), in examining 400 streamflow sites in the conterminous United States for the period 1941–1999, observed a noticeable increase in annual minimum and median streamflow around 1970 and, importantly, noted that the change did not appear monotonic, but was a 'step' change rather than a gradual trend. They did not mention a causative factor, but their step is consistent with the one demonstrated in this study. Further, this study shows that, for peninsular Florida, the step is in the opposite direction than that for most of the conterminous United States.

Changes in climate, whether related to global warming or natural climatic oscillations such as the AMO, have important implications not routinely considered in the development of environmental flows. There are additional implications related to changes in expected flood and drought frequency (Olsen, *et al*., 1999) and water supply development. Milly *et al*. (2005) used an assortment of climate models and projected significant increases and decreases on a global scale, projecting 10–40% increases in runoff in eastern equatorial Africa, the La Plata basin, and at high latitudes in North America and Eurasia, and 10–30% decreases in runoff in southern Africa and Europe, and in the Middle East and at mid-latitudes in western North America by the year 2050 as a result of global climate change. Enfield *et al*. (2001) showed changes of similar magnitude in Mississippi River (10% increase) and Kississimee River (30% decrease) flows between two multiple decades and attributed these to the effects of the AMO. Regardless, such multidecadal changes in flow have rarely been considered from an ecological perspective (Stenseth *et al*. 2003) and raise important questions regarding the ecological consequences or adaptations that species and ecosystems may have experienced or acquired as the result of natural multidecadal processes.

Ecologists and river managers need to be aware of 'climatic oscillations' and adjust their flow paradigm in consideration of recent climatological thinking. This consideration adds an additional level of complexity to an already challenging problem.

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REFERENCES

Basso R, Schultz R. 2003. *Long-term variation in rainfall and its effect on Peace River flow in West-Central Florida* (Personal Communication). Hydrologic Evaluation Section, Southwest Florida Water Management District.

Beecher H. 1990. Standards for instream flows. *Rivers* **1**(2): 97–109.

DOI: 10.1002/rra

Bradley DC, Ormerod SJ. 2001. Community persistence among stream invertebrates tracks the North Atlantic Oscillation. *Journal of Animal Ecology* **70**: 987–996.

Enfield D, Mestas-Nunez A, Trimble P. 2001. The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* **28**: 2077–2080.

Gore JA, Kelly MH. 2006. The Atlantic Multidecadal Oscillation (AMO) and its influence on instream flow analysis and management decisions: examples from Florida. In *International Conference on 'Riverine Hydroecology: Advances in Research and Applications'*. University of Stirling, Scotland.

Hammett K. 1990. Land use, water use, streamflow characteristics, and water-quality characteristics of the Charlotte Harbor inflow area, Florida. *United States Geological Survey Water-Supply Paper 2359*. Tallahassee, FL.

Hannaford J, Marsh T. 2006. An assessment of trend in UK runoff and low flows using a network of undisturbed catchments. *International Journal of Climatology* **26**: 1237–1253.

Hupalo R, Neubauer C, Keenan L, Clapp D, Lowe. E. 1994. Establishment of minimum flows and levels for the Wekiva River system. *Technical Publication SJ94-1*. St. Johns River Water Management District, Palatka, FL.

Maurer EP, Lettenmaier DP, Mantua NJ. 2004. Variability and potential sources of predictability of North American runoff. *Water Resources Research* **40**(9): W09306, DOI: 10.1029/2003WR002789

McCabe G, Palecki M, Betancourt J. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proceedings of the National Academy of Sciences of the United States of America* **101**(12): 4136–4141.

McCabe G, Wolock D. 2002. A step increase in streamflow in the conterminous United States. *Geophysical Research Letters* **29**: 2185–2188.

Milly PCD, Dunne KA, Vecchia AV. 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**: 347–350.

Nichols M, Renard K, Oborn H. 2002. Precipitation changes from 1956 to 1996 on the Walnut Gulch Experimental Watershed. *Journal of the American Resources Association* **38**(1): 161–172.

Olsen J, Stedinger J, Matalas N, Stakhiv E. 1999. Climate variability and flood frequency estimation for the upper Mississippi and lower Missouri Rivers. *American Water Resources Association* **35**(6): 1509–1523.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* **10**: 1163–1174.

Stenseth NC, Ottersen G, Hurrell JW, Mysterud A, Lima M, Cha K, Yoccoz NG, Adlandsvik B. 2003. Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Nino Southern Oscillation and beyond. *Proceedings of the Royal Society of London B* **270**: 2087–2096.

Stoker Y, Levesque V, Woodham W. 1996. The effect of discharge and water quality of the Alafia River, Hillsborough River, and the Tampa Bypass Canal on nutrient loading to Hillsborough Bay, Florida. *U.S. Geological Survey. Water Resources Investigations Report 95-4107*.

Sutton RT, Hudson DL. 2005. Atlantic Ocean forcing of North American and European summer climate. *Science* **309**: 115–118.

Werritty A. 2002. Living with uncertainty: climate change, river flows and water resource management in Scotland. *Science of the Total Environment* **294**: 29–40.

DOI: 10.1002/rra