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LOWER OCKLAWAHA RIVER BASIN HYDROLOGIC DATA REVIEW AND DISCHARGE ANALYSIS

Lower Ocklawaha River Basin Hydrologic Data Review and Discharge Analysis

by

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EXECUTIVE SUMMARY

Overview

The Ocklawaha River Basin (ORB), with an effective tributary area of approximately 2,000 square miles, is a major and important water resource located within the St. Johns River Water Management District (SJRWMD). It is located in portions of six central and north Florida counties including Polk, Lake, Orange, Marion, Alachua and Putnam and is a major tributary to the St. Johns River just south of Palatka Florida.

Unlike the St. Johns River, significant portions of which are brackish to saline, the Ocklawaha River is a fully fresh water system. Approximately half of the total watershed yield is derived from Floridan Aquifer discharge via springs, including the world famous Silver Springs. Because it provides a large quantity of reliable high quality fresh water, the Ocklawaha River is a potential water supply source, which could provide a portion of the region's future public supply needs.

An overall characterization of basin discharge (total yield) and trends over time is an important initial step in the establishment of minimum flows and levels (MFLs) and in the assessment of water supply potential.

This report has several goals. The first is to identify long-term trends, in ORB rainfall and discharge, if such trends exist. If trends are identified, then the second major goal is to determine to the extent practical the underlying cause(s). In addition, previous investigations dealing in whole or in part with ORB yield were reviewed and summarized. Finally, as a prerequisite to this analysis, available hydrologic data including rainfall records, stream discharge records and individual spring discharge measurements were compiled, reviewed and compared.

Hydrologic Records Review

There are extensive rainfall and stream discharge records available for the ORB. Rainfall records begin in the 1880s and stream discharge records begin in the 1930s. However, except for the continuous record available for the Silver River, discharge records are discontinuous and characterized by data gaps and gaging station relocation.

Results of the hydrologic data review indicated that discharge records for the several Lower Ocklawaha River Basin (LORB) stream gages appear to be internally consistent with the possible exception of the Riverside Landing gage. Relatively large discharge values for the Riverside Landing gage, as compared to upstream discharge records, suggest the possibility of large spring flow/groundwater contribution in the last nine mile river reach (between the Orange Springs gage and the Riverside Landing gage) or a net overestimate of discharge at the Riverside Landing gage.

The procedure used in this investigation is to develop a total ORB composite discharge record, assuming that Riverside Landing data are accurate. This composite record is the base case for analysis (i.e., large groundwater inflow contribution with no gaged flow overestimate). The base case is then adjusted for a possible gaged flow overestimate to provide a sensitivity analysis that addresses uncertainty related to Riverside Landing discharge records.

Analysis and Results

Long-term discharge records at three locations within the LORB were evaluated in detail. These were: 1) Moss Bluff which is the upstream boundary of the LORB, 2) the Silver River which provides nearly half the total watershed yield and, 3) the basin outlet. For the basin outlet, both a base case discharge and an adjusted discharge record were considered. In each case, trends in the discharge record were found to be consistent with peninsular Florida river flow patterns associated with the Atlantic Multidecadal Oscillation (AMO) climatic cycle, as reported by Kelly and Gore (2008).

The AMO is a climatic cycle characterized by an approximately 30-year period of warm Atlantic Ocean temperatures followed by an approximately 30-year period of cooler Atlantic Ocean temperatures. During the warm period, tropical (warm season) rainfall is increased over peninsular Florida resulting in proportionately greater stream discharge. During the cool period, tropical rainfall is reduced resulting in proportionately less stream discharge.

This pattern was observed at all three LORB locations. In addition, the magnitude of the differences in observed warm period versus cool period discharge was consistent with the regional range reported by Kelly and Gore (2008) and was very comparable to the results obtained at benchmarking stations from the adjacent and similar Withlacoochee River watershed.

Total long-term average ORB discharge is 1,664 cubic feet per second (cfs), for the base case (measured discharge), and 1,542 cfs for the adjusted discharge case. In either case, the long-term average discharge is on the order of one billion gallons per day. Warm AMO period discharge can be expected to average 15 to 20% greater than the long-term average and cool AMO period discharge can be expected to average 15 to 20% less than the long-term average.

Recommendations

LORB Measured Discharge Investigation

The hydrologic data review has demonstrated consistency in the data for all LORB stream discharge stations with the exception of the Riverside Landing gage. The records for this gage show a very large increase in measured flow relative to upstream measurements. This large increase is not fully explained and may arise from either a very large spring flow/groundwater contribution in the river reach between Orange Springs and Riverside Landing, or it could be due to an overestimate of net discharge at the Riverside Landing gage.

Both possibilities deserve further investigation, if a complete understanding of ORB hydrology (required for realistic hydrologic modeling) is to be developed.

AMO Influence

Understanding the influence of the AMO, as well as other climate cycles in peninsular Florida river flow patterns is important to sound water resources management and decision making. Overall, the results reported by Kelly and Gore (2008), as well as the results of the current investigation, would suggest that 60 or more years of stream discharge data are desirable to recognize the effects of a complete AMO climatic cycle. Evaluation of a shorter record such as an AMO warm period or a cool period could lead to poor conclusions. Also, if data are available from only one period (warm or cool) it is important to consider the probable influence of the AMO on the available record.

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PURPOSE AND SCOPE

This investigation was completed in support of the St. Johns River Water Management District (SJRWMD) water supply planning process and ongoing efforts to develop minimum flows and levels (MFLs) for the Ocklawaha River Basin (ORB).

This report has several goals. The first is to identify long-term trends, in ORB rainfall and discharge, if such trends exist. If trends are identified, then the second major goal is to determine to the extent practical the underlying cause(s). To help accomplish these goals, previous investigations dealing in whole or in part with ORB yield were reviewed and summarized. Also, as a prerequisite to this analysis, available hydrologic data including rainfall records, stream discharge records and individual spring discharge measurements were compiled, reviewed and compared.

THE OCKLAWAHA RIVER BASIN

The ORB is located in central Florida and is a major tributary to the St. Johns River (Figure 1). It is located primarily within the SJRWMD. However, the extreme southern headwater portion, in Polk County, is located within the Southwest Florida Water Management District (SWFWMD).

Like the St. Johns River, the Ocklawaha is a northward flowing river. Its headwaters are in the Green Swamp in northern Polk County. From there it forms the Clermont Chain of Lakes in southern Lake County and becomes the Palatlakaha River where it discharges into Lake Harris in central Lake County. The Lake Apopka Basin, located partially in Orange County and partially in Lake County is also a tributary. Following discharge from Lake Griffin the river enters southern Marion County and the river system is called the Ocklawaha River.

The Moss Bluff water control structure, located in southern Marion County, currently controls water levels in Lake Griffin. However, flow control at Moss Bluff began in 1925 with the installation of a U. S. Army Corps of Engineers power dam. Further downstream, at its confluence with the Silver River, near State Road 40 (SR-40), river flow is greatly increased by the contribution of Silver Springs.

Rodman Reservoir, located in Marion and Putnam counties, was created in 1968 by the construction of Rodman Dam (also known as the George C. Kirkpatrick Dam). Ocklawaha River flow enters the southern (upstream) end of Rodman Reservoir at Eureka, Florida, near County Road 316 (CR-316). The reservoir (and river) also receives inflow from Orange Creek, the last major tributary before the Ocklawaha River’s confluence with the St. Johns River. The Orange Creek Basin includes Orange Lake, Lake

Lochloosa and Newnans Lake and drains portions of Alachua, Marion, and Putnam counties.

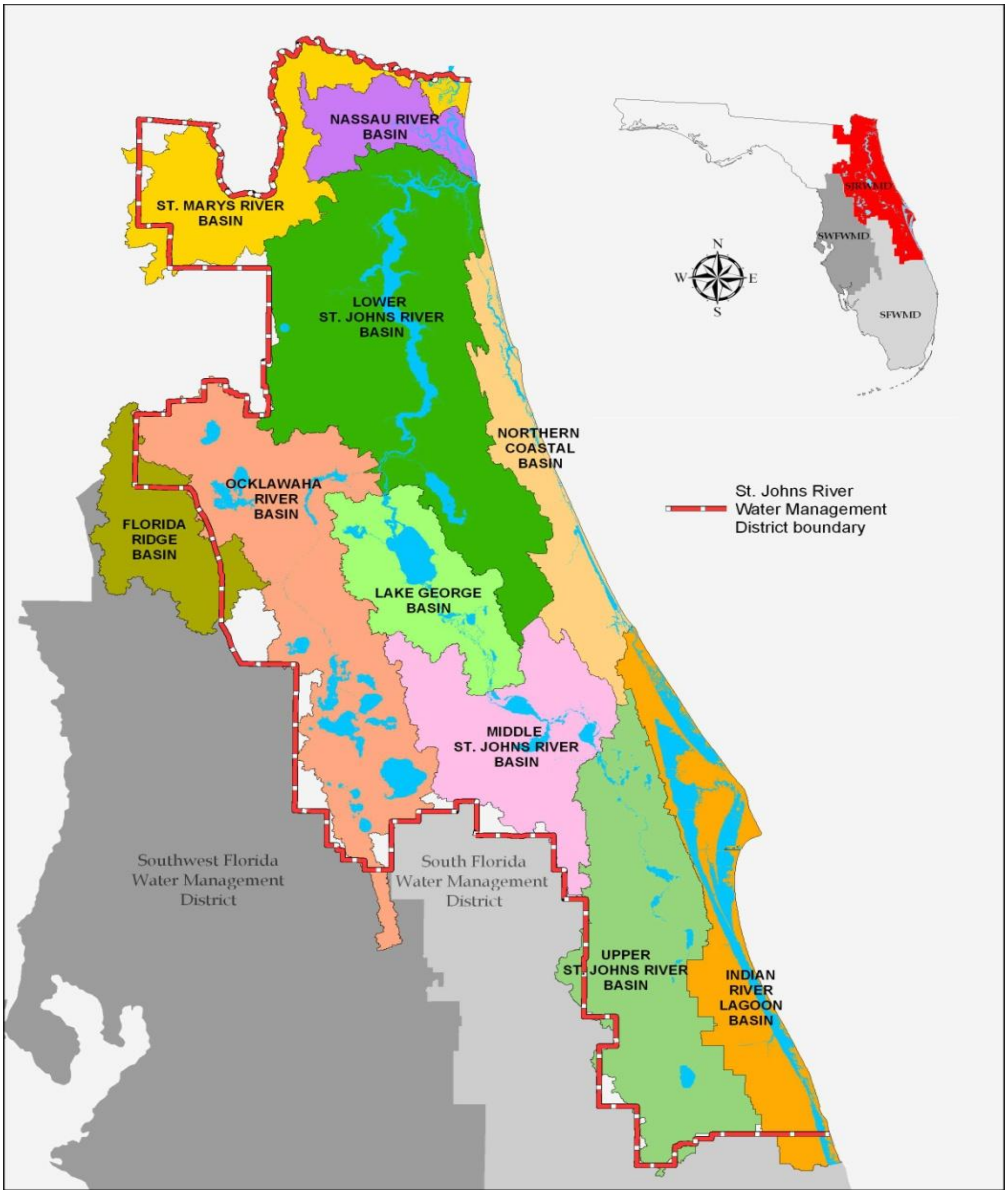

Figure 1. Major SJRWMD basins showing the location of the Ocklawaha River Basin

That portion of the ORB located upstream of Moss Bluff is considered to be the Upper Ocklawaha River Basin (UORB). Conversely, that portion of the basin located downstream from Moss Bluff is the Lower Ocklawaha River Basin (LORB) and the LORB is the primary focus of this investigation.

The ORB (Figure 2) contains significant storage in the form of lakes reservoirs and wetlands and the abundant storage has a pronounced effect on the hydrologic response of the basin. Table 1 provides a summary of the area and (where known) the volume of major ORB lakes and reservoirs.

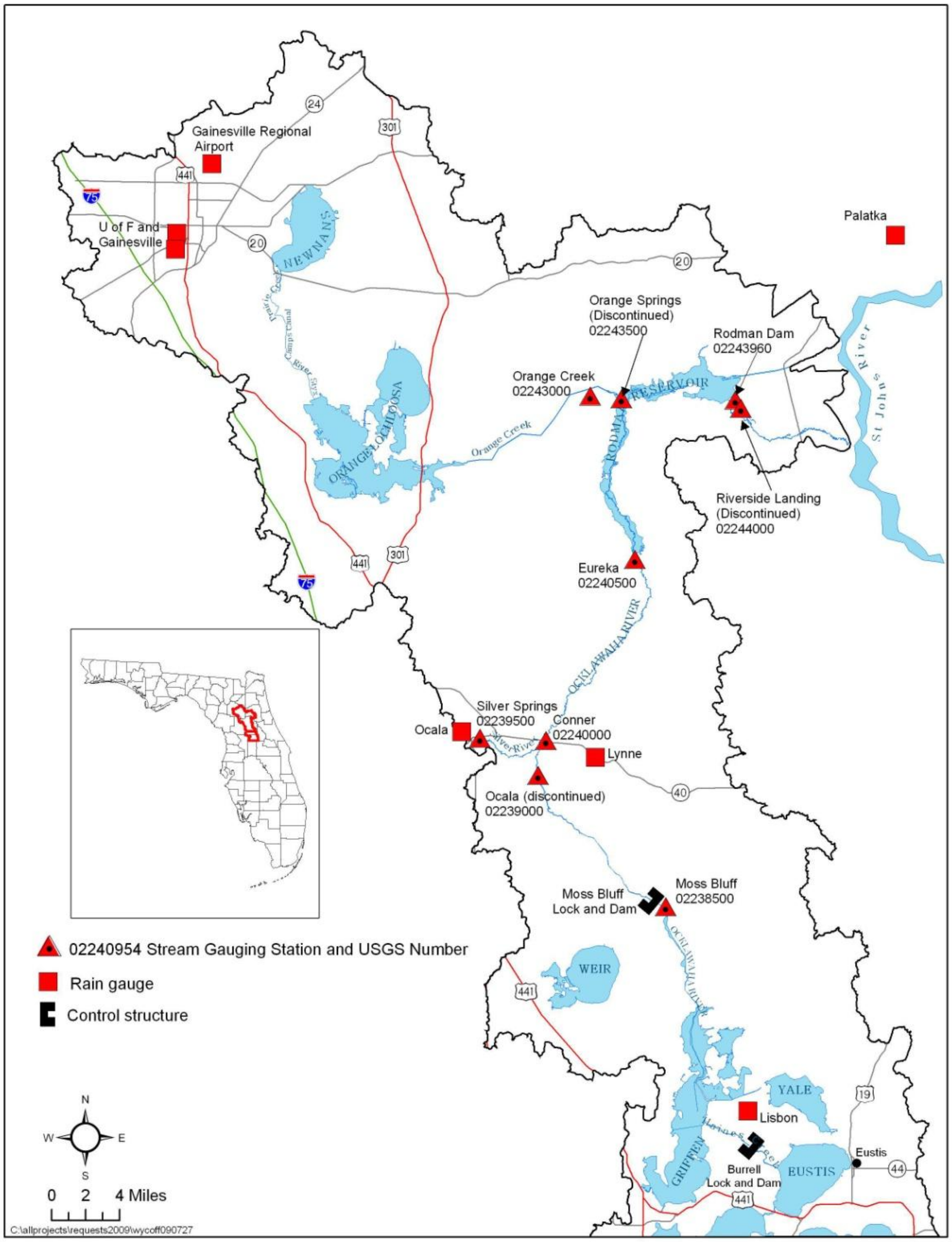

Figure 2. Middle and Lower Ocklawaha River Basin with stream and rain gage locations

Table 1. Characteristics of major Ocklawaha River Basin lakes and reservoirs
Part a) Clermont Chain of lakes (3 largest)

Lake	Surface Area -- acres	Volume -- ac. ft.
Minneola	1,890	na
Minnehaha	2,411	na
Louisa	3,573	na
Sub Total	7,874	

Part b) Upper Ocklawaha River Lakes

Lake	Surface Area -- acres	Volume -- ac. ft.
Apopka	30,863	167,880
Carlton	384	3,990
Beauclair	1,134	7,059
Dora	4,502	41,740
Harirs and Little Harris	19,039	200,719
Eustis	7,833	79,797
Yale	4,044	53,709
Griffin	9,428	63,837
subtotals	77,227	618,730

Part c) Lower Ocklawaha River lakes and reservoirs (including Orange Creek Basin)

Lake	Surface Area -- acres	Volume -- ac. ft.
Weir	6,269	na
Newnans	7,374	na
Lochloosa	8,673	na
Orange	14,680	na
Rodman Reservoir (at 18 ft. NVGD)	9,601	49,145
subtotals	46,597	
ORB TOTAL	131,698	

Sources: Lake County Water Atlas, SJRWMD Watershed Facts, Bush (1974) and Rao and others (1994)

PREVIOUS INVESTIGATIONS

There are four previous investigations, dealing in whole or in part with ORB yield, that are relevant to this investigation, including:

- An investigation of streamflow reduction from the UORB (Tibbals and others 2004)
- An investigation of annual rainfall and discharge from the ORB (Wycoff 2008)
- A technical review of the statistical analysis employed by Wycoff (2008) (Bloom 2008), and
- A peer review of the methodologies employed by both Wycoff (2008) and Bloom (2008) by Rouhani (2008).

Upper Ocklawaha River Streamflow Reductions (Tibbals and others 2004)

The investigation by Tibbals and others (2004) was conducted in 2003 and considered UORB discharge and rainfall data available through 2002. Several double mass curves were developed, including one presenting cumulative Moss Bluff annual discharge as a function of cumulative annual rainfall measured at Lisbon Florida. A break-point was identified occurring about 1970. The authors concluded that discharge at Moss Bluff had abruptly decreased by about 217 cubic feet per second (cfs), based on a comparison of pre-1970 to post-1970 annual discharge records.

Prior to the break-point, discharge for 13 years of record, averaged 400 cfs. After the break, discharge averaged 183 cfs (for 33 years of record) resulting in a substantial 217 cfs, or 54%, reduction in observed discharge. Although only a fraction (15% to 20%) of the total ORB discharge originates from the upper basin, a reduction in upper basin discharge of more than 200 cfs is of concern.

The authors discussed several possible reasons for the break. Although they reached no definitive conclusion, it was hypothesized that an increase in upper basin lake stages, as well as a general decrease in the potentiometric surface elevation of the Floridan aquifer could have increased groundwater recharge thereby decreasing surface water discharge.

Ocklawaha River Basin Rainfall-Yield Analysis (Wycoff 2008)

The second relevant previous investigation (Wycoff 2008) focused on the total ORB watershed yield. Specifically, the primary concern was the relationship between annual rainfall and total annual basin discharge, as measured at the basin outlet.

This analysis relied on water year data published by the United States Geological Survey (USGS) and concurrent rainfall data published by the National Oceanic and Atmospheric Administration (NOAA). The annual discharge data for gaging stations located at or near the basin outlet, were used to construct a composite 76-year period of record (POR).

The analysis, including development of the composite ORB annual discharge time series, was conducted with the assumption that individual records, from the several discharge gaging stations, were of equal quality. No attempt was made to evaluate the data for internal consistency and/or possible flow overestimate.

Correlation analysis, linear regression analysis, and double mass curves were used to investigate relationships between annual rainfall and annual ORB yield. The results of the correlation analysis indicated that annual Ocklawaha River discharge is highly correlated to current year and prior year total annual rainfall recorded at Ocala Florida.

It was also concluded that almost half of the ORB yield is provided by discharge from the Silver River and that variation in observed annual Ocala rainfall (current year and prior year) can explain approximately 63% of the observed variance in annual basin discharge.

Statistical Methods Technical Review (Bloom 2008)

Bloom (2008) conducted a technical review of the statistical analysis contained in Wycoff (2008), provided a critique of the methods applied, and presented several alternative analyses resulting in somewhat different conclusions.

A key difference between the two approaches is the method used for compositing discharge data from the several stream gages of interest into a single long-term total watershed discharge record. Wycoff (2008) assumed all data were of equally quality and made adjustments between nearby gaging stations based on drainage area ratio. When records for two outlet gaging stations overlapped the average of the two annual measurements (drainage area adjusted) were used.

Bloom (2008) implicitly assumed that the most downstream gaging station (Riverside Landing, Figure 2) was the most reliable and statistically adjusted upstream values (Orange Springs, Figure 2) to match the downstream measurements. Because of the difference in compositing methods a different discharge time series was evaluated by each investigator. The Bloom (2008) composite time series provides higher estimates of total basin discharge prior to the construction of Rodman Reservoir then those provided by the Wycoff (2008) composite time series. Both composite time series are in agreement for the post-Rodman time period (i. e. after construction of Rodman Reservoir).

Bloom (2008) also provided the following conclusions regarding watershed yield

- The data available do not demonstrate any cyclic trends in total basin yield.
- The data available demonstrate a net reduction in water flow over time for the Ocklawaha Basin of 1201 cfs (776 mgd) over the 77 year period of record or a decline of 48.3%.
- The Silver River has shown a 26% decline in flow since 1970.

Previous Investigations Peer Review (Rouhani 2008)

Given the statistical methods issues raised by Bloom (2008), as well as the associated estimated decline in total watershed yield, SJRWMD sponsored a peer review of both investigations. The peer review was conducted by Dr. Shahrokh Rouhani of NewFields Companies, LLC, and is reported in an October 31, 2008, memorandum (Rouhani, 2008). General recommendations, presented in the October 31, 2008 memorandum are as follows:

- *Compile the raw, unsummarized discharge and rainfall data from all stations of interest. For example, daily measurements are always preferred to pre-computed mean annual values.*
- *Subject both the rainfall and discharge datasets to a thorough review in order to identify and discard poor quality or suspicious outlier data.*
- *Subject the compositing of the four time series to a thorough hydrologic review. Specifically, address concerns, such as: (a) the reliability of the estimated tributary areas of different stations; (b) the large percent differences between the concurrent Orange Springs and Riverside measured flows; (c) unaccounted potential sources of discharge into the river between the two stations; and (d) the impacts of Rodman Dam and Buckman Lock on the hydrology and hydraulics of the Lower Ocklawaha River.*
- *Compute representative, time-specific rainfall values, which are spatially compatible with the effective tributary areas of the investigated locations. In my experience, in many parts of Florida measurements at individual rain stations vary significantly from those measured concurrently at nearby locations. These regional climatic variations must be accounted for during the estimation of the representative rainfall values for a given basin. For this purpose, geostatistical interpolations are highly recommended.*
- *Conduct a series of thorough double mass analysis based on mean and*

median annual discharge rainfall values. Median values are especially useful in instances where large, isolated events can significantly skew the computed mean values.

- *Slope changes in double mass plots should be thoroughly investigated in order to detect any change in the basin rainfall yield.*
- *In all the above analyses, the unaltered Silver River, or other equally unaltered hydrologic time series, should be used as benchmarks.*

PROJECT APPROACH

Considering the general recommendations of Rouhani (2008), as well as the purpose of this investigation, seven primary tasks were identified, as follows:

1. Compile a rainfall and discharge database
2. Conduct data quality review
3. Conduct hydrologic review of discharge data time series
4. Compute rainfall time series for basins of interest
5. Conduct single and double mass analysis
6. Conduct hydrologic benchmarking
7. Prepare report

The task outline was used to guide the analysis and to maintain focus on the overall project purpose and scope. In addition, a project team including SJRWMD staff and consultants assisted in database development and helped to identify alternative avenues of analysis. The team members and primary roles are discussed, in greater detail, in the acknowledgements section of this report.

HYDROLOGIC RECORDS

Hydrologic records of interest include USGS stream discharge records for the LORB gaging stations and rainfall records for nearby NOAA rainfall stations (Figure 2). In addition, similar records were accessed, for other selected gaging stations for the benchmarking task.

Discharge data for individual local springs located downstream of the Eureka USGS gaging station are also of interest to this analysis. Unfortunately, local springs discharge measurements are sparse and were not available from a single comprehensive source. Spring discharge data were extracted from the literature and other sources and are included here (Appendix A) as part of the hydrologic records compilation task.

Stream Discharge Data

Table 2 presents a listing of the LORB USGS stream gages. The first column reports the short version station location and name used in this report. The second column reports the official USGS station number and name.

Two drainage area estimates are reported in the last two columns of Table 2. The first is the drainage area published by the USGS and the second is an estimate of the drainage area obtained from the current SJRWMD geographical information system (GIS) database. In general, both drainage area estimates are in substantial agreement, with the SJRWMD GIS based estimate usually somewhat smaller than the corresponding USGS published value. Hydrologic data analysis presented herein, requiring application of tributary drainage area values, applied both values for ease of comparison.

Table 2. Lower Ocklawaha River Basin stream gaging stations and drainage areas

ORB Location/Report Name	USGS Gage Number/Name	USGS Drainage Area (sq. mi.)	SJRWMD Drainage Area (sq. mi.)
Moss Bluff	USGS 02238500 OCKLAWAHA RIVER AT MOSS BLUFF, FL	879	820.9
Ocala	USGS 02239000 OCKLAWAHA RIVER NR OCALA, FLA.	1,018	1,023.0
Silver River	USGS 02239501 SILVER RIVER NR OCALA	na – Indeterminate (Spring Basin) as per USGS gage description	
Conner	USGS 02240000 OCKLAWAHA RIVER NEAR CONNER, FL	1,196	1,043.5
Eureka	USGS 02240500 OCKLAWAHA RIVER AT EUREKA, FL	1,367	1,231.9
Orange Creek	USGS 02243000 ORANGE CREEK AT ORANGE SPRINGS, FL	***469***	407.1
Orange Springs	USGS 02243500 OCKLAWAHA RIVER NR ORANGE SPRINGS, FLA.	***2007***	1,836.0
Riverside Landing	USGS 02244000 OCKLAWAHA R AT RIVERSIDE L NR ORG.SPRINGS, FLA	***2097***	1,968.0
Rodman Dam	USGS 02243960 OCKLAWAHA R AT RODMAN DAM NEAR ORANGE SPRINGS, FL	***2097***	1,968.0
Buckman Lock	USGS 02244032 CROSS FL BARGE CANAL AT BUCKAN LOCK NR PALATKA, FL	na – secondary outlet to Rodman Dam	

Drainage areas shown in ***Bold Italics*** are effective areas = Total area minus 650 square miles non contributing area (Payne's Prairie portion of Orange Creek basin)

Table 3 provides a summary of the daily discharge records available for each of ten stations at the time of the data download from the USGS web site. As can be seen from the table, several stations have gaps in the data as illustrated in the POR summary bar chart (Figure 3).

Table 3. USGS Ocklawaha River Basin discharge data period of record index

ORB Location/Report Name	Period of Record							
	Begin	**End**		**Begin**	**End**		**Begin**	**End**
Moss Bluff	10/1/1943	9/30/1955		9/1/1967	9/30/2007			
Ocala	3/1/1930	7/2/1968						
Silver River	10/1/1932	1/13/2009						
Conner	2/13/1930	9/30/1946		10/1/1977	1/12/2009			
Eureka	3/1/1930	9/30/1934		10/1/1943	12/31/1952		1/31/1981	1/12/2009
Orange Creek	8/1/1942	12/31/1952		10/1/1955	9/30/1971		5/1/1975	1/13/2009
Orange Springs	3/1/1930	12/31/1952						
Riverside Landing	10/1/1943	9/30/1968						
Rodman Dam	10/1/1968	12/22/2008						
Buckman Lock	11/20/1969	9/30/2004						

A stream discharge database was prepared in Microsoft Excel. A separate workbook was prepared for each of the ten stream gaging stations. Data downloaded directly from the USGS web site included daily, monthly and annual discharge records. The annual discharge summaries were compiled on a standard USGS water year basis which begins in October and runs through the following September. All downloads occurred in January 2009.

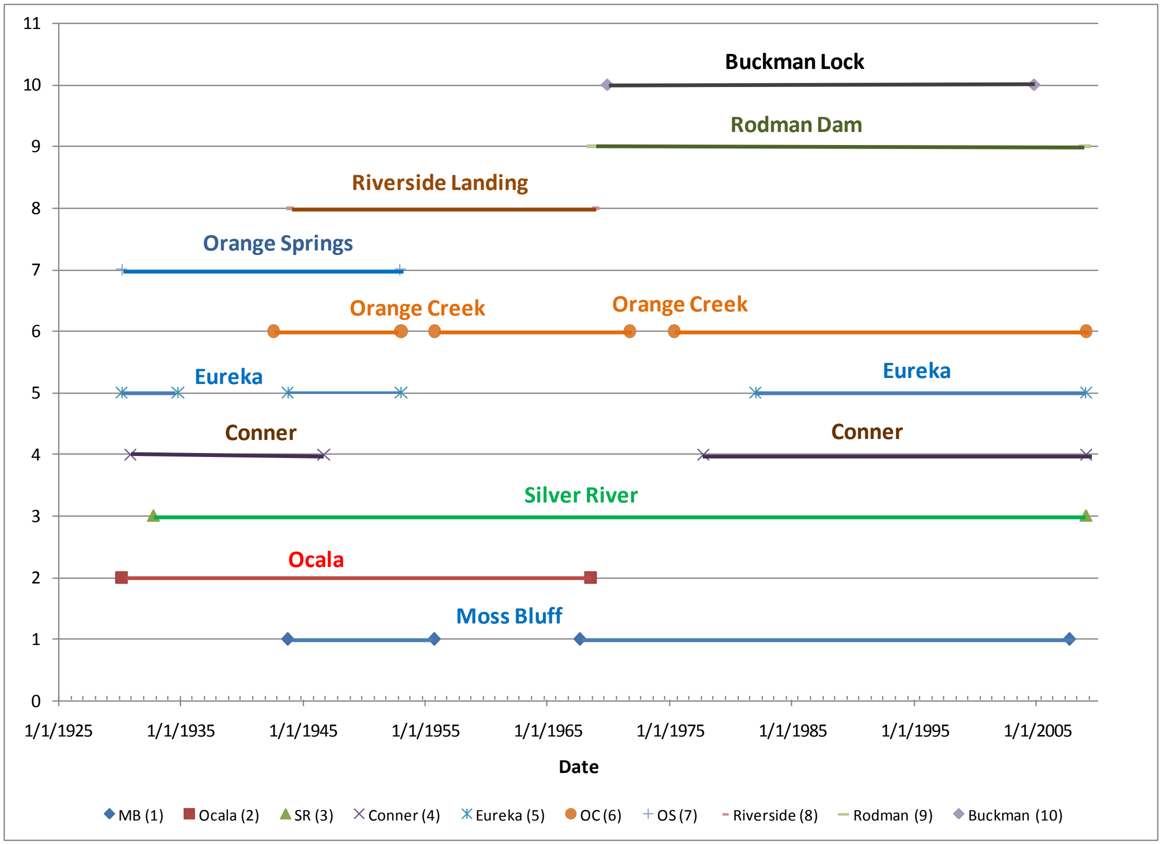

Figure 3. Period of record summary for ten USGS discharge gaging stations in the Ocklawaha River Basin

Rainfall Data

SJRWMD routinely maintains NOAA rainfall records within the District's data management system. Because all rainfall data have been subject to NOAA quality controls, as well as subsequent District staff review, these data are considered by the project team to be the best available and were used as obtained. Information from the existing database was extracted for use in the current investigation. An Excel workbook was prepared for each rain gage of potential interest. NOAA gaging station identification numbers for each of the rain gages included are summarized as follows:

- Clermont – FL081641
- Gainesville – FL0833221 & FL083326 (Gainesville Airport)
- Lisbon – FL085076
- Lynne – FL085237
- Ocala – FL086414
- Palatka – FL086753

The workbooks contain NOAA monthly rainfall totals for each rain gage and were prepared by Donthamsetti Rao, PhD, P.E, a water resources engineer with several decades of experience in analysis of SJRWMD rainfall patterns.

In general, the monthly rainfall records are complete. Rainfall records at Lynne begin in 1942 and Palatka records begin in 1923. All other station records begin in the 1880s or 1890s and all stations are complete through December 2007.

Local Springs Discharge Data

The LORB includes a number of springs located downstream of Eureka. The contribution of these springs to the total ORB yield is potentially important to the development of a complete understanding of the watershed hydrology.

Unfortunately, direct measurements of the discharge from these springs are few. An effort was made to assemble all available local spring discharge measurements from the literature, as well as from the SJRWMD hydrologic database. A total of 25 spring discharge measurements for nine different springs were found, as reported in Appendix A.

DISCHARGE DATA INTERNAL CONSISTENCY REVIEW

The discharge data, downloaded directly from the USGS surface water data web site (http://waterdata.usgs.gov/usa/nwis/sw), were reviewed and subjected to USGS quality controls prior to release. In addition, the daily values were plotted and visually inspected for any apparent outliers and none were identified. Therefore, the discharge data were used as obtained.

Daily, monthly and annual (water year) data were obtained for each gaging station and water year data were used in several preliminary analyses. However, both the rainfall data and discharge data are available on a monthly time step and the monthly time step was chosen as the basis of trend and yield analysis. Given that the primary graphical analysis tools applied herein are cumulative rainfall and discharge curves, and that long-term trends (occurring over years or decades) in watershed yield are of primary interest, there is little practical value to be gained by working directly with daily values.

Basin Outlet Gages and Discharge Record Compositing

Because basin outlet gage locations and outlet conditions have changed over time, construction of a representative composite total basin discharge time series requires compositing of records from several individual stream gages. The original outlet gage (i.e., most downstream gage), Orange Springs (02243500), provides records from March 1, 1930, through December 31, 1952. The Orange Springs gage measures discharge just below the confluence of the Ocklawaha River and Orange Creek, approximately 16 miles upstream from the confluence with the St. Johns River (Figure 2). The total effective tributary area, at this point, is about 2,007 square miles, according to published USGS data and 1,836 square miles, based on current SJRWMD basin maps (Table 2).

A second downstream gage located at Riverside Landing (02244000), provides discharge records from October 1, 1943, through September 30, 1968. This gage was located about eight miles downstream from the Orange Springs gage. The effective tributary area at Riverside Landing is estimated to be 2,097 square miles according to the USGS and 1,968 square miles, based on current SJRWMD basin maps (Table 2).

Beginning October 1, 1968, and extending to the present, discharge measurements have been made at Rodman Dam (02243960). The effective tributary area and location of this gage are essentially the same as the Riverside Landing gage. In addition, a small supplemental discharge occurs via the Cross Florida Barge Canal. This additional discharge is measured at Buckman Lock (02244032).

Development of a single representative composite discharge time series using data from four individual gaging stations can be challenging. As previously discussed, the peer review (Rouhani 2008) of Wycoff (2008) and Bloom (2008) concluded that both prior compositing methods were suspect and that a more in-depth analysis was warranted.

Specifically, there is a relatively large difference in measured discharge between the Orange Springs and Riverside Landing gages. Fortunately, a portion of the period of record overlaps for these two gages. This overlap provides an opportunity to compare the record at these gaging stations as well as to several other upstream ORB discharge stations.

Concurrent POR Analysis

The concurrent POR for the Orange Springs and Riverside Landing stream gages begins in October 1943 and extends through December 1952, a total of nine years and three months (111 months). In addition, complete discharge records for this time period are also available for five upstream gages including Moss Bluff, Ocala, Silver River, Eureka and Orange Creek. Concurrent rainfall records are also available for Lisbon (measured at Eustis during this time period), Ocala, Gainesville and Palatka. This concurrent set of rainfall and discharge records provides a basis for comparisons among the gages to evaluate internal consistency and/or possible inconsistencies.

Concurrent POR Discharge Records

Figure 4 illustrates the concurrent POR monthly discharge hydrographs for the seven discharge stations. Figure 5 presents the corresponding cumulative discharge curves. Concurrent POR summary statistics for each discharge gaging station are reported in Table 4.

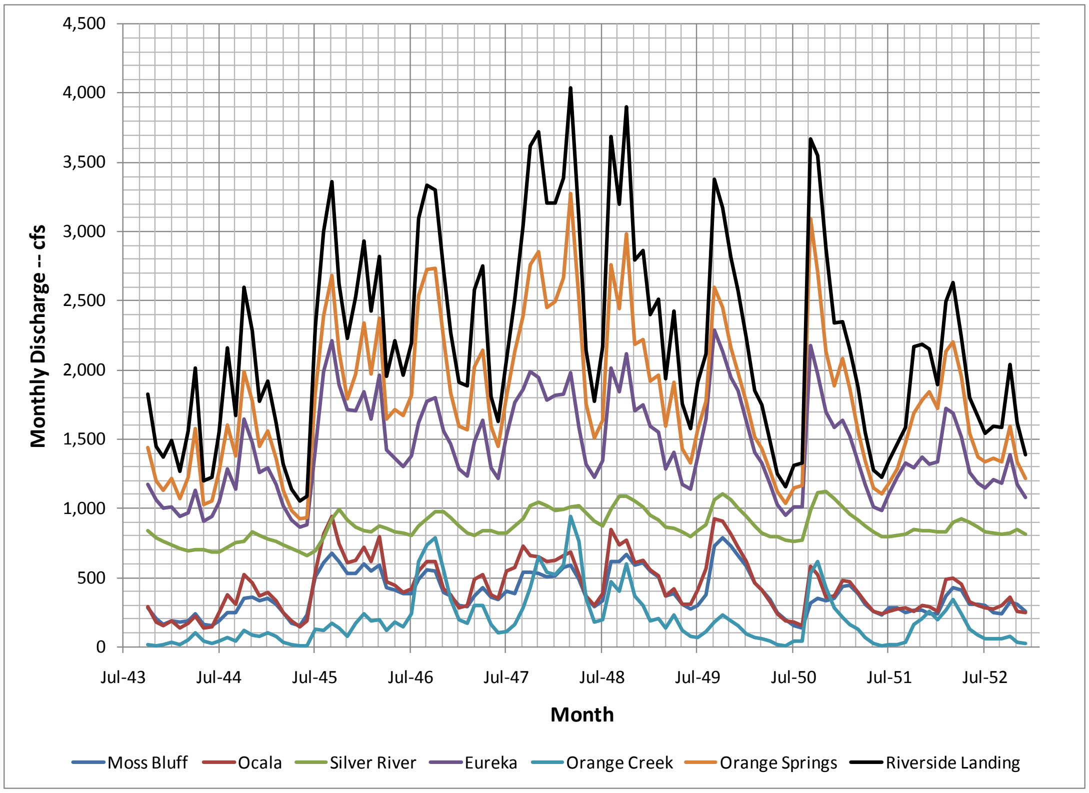

Figure 4. Monthly discharge hydrographs for concurrent period of record

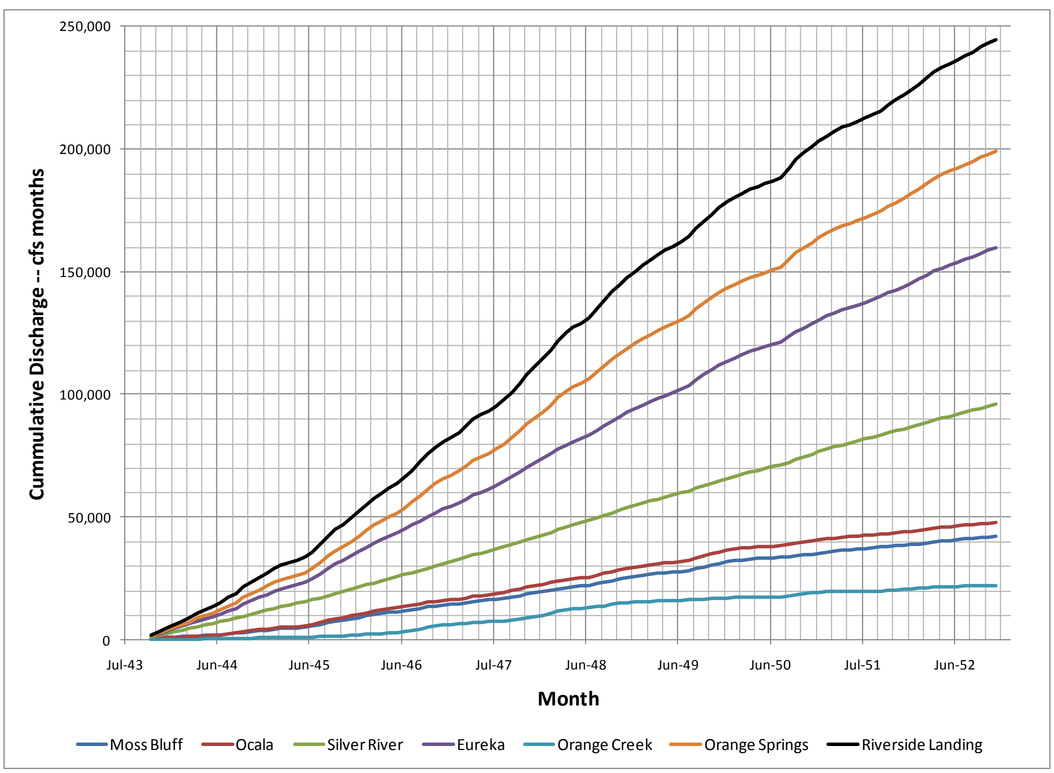

Figure 5. Cumulative discharge curves for concurrent period of record

Table 4. Concurrent period of record summary statistics for monthly discharge

Parameter	Moss Bluff	Ocala	Silver River	Eureka	Orange Creek	Orange Springs	Riverside Landing
Average (cfs)	380	430	864	1,440	200	1,792	2,204
Median (cfs)	353	389	837	1,370	139	1,722	2,151
Std. dev. (cfs)	151	198	110	349	198	541	731
Coeff. of Var.	0.397	0.461	0.127	0.242	0.990	0.302	0.332
Max (cfs)	783	936	1,120	2,287	938	3,270	4,038
Min (cfs)	134	129	653	859	9	922	1,047

The concurrent POR discharge summary provides an informative picture of the relative contribution of the major Lower Ocklawaha River tributaries, including: the Upper Ocklawaha River as measured at Moss Bluff (380 cfs), the Silver River (864 cfs) and Orange Creek (200 cfs). Together these tributaries account for 1,444 cfs, or about 81% for the discharge measured at Orange Springs and 67% of the discharge measured at Riverside Landing. It is of interest to note that the average difference between the measured discharge at Riverside Landing and Orange Springs (412 cfs) is larger than the upper basin yield, twice as large as the Orange Creek Basin yield and about 48% of the measured Silver River discharge.

Concurrent POR Rainfall Records

Similar summaries for the concurrent POR rainfall data are presented in Figure 6 (monthly hyetograph), Figure 7 (cumulative rainfall curves) and Table 5 (summary monthly rainfall statistics).

Monthly rainfall is highly variable and ranged from zero to more than 16 inches per month for the concurrent POR. However, total cumulative rainfall for the Ocala, Gainesville and Palatka stations, is very similar, ranging from 504 inches (Gainesville) to 531 inches (Palatka). Only Lisbon, at 457 inches, is noticeably different from the others. Overall, the four station average is about 505 inches or approximately 54.6 inches per year. This four station concurrent POR average is approximately 3.6% greater than the total complete POR (1891 through 2007) average, of 52.7 inches per year, for Ocala.

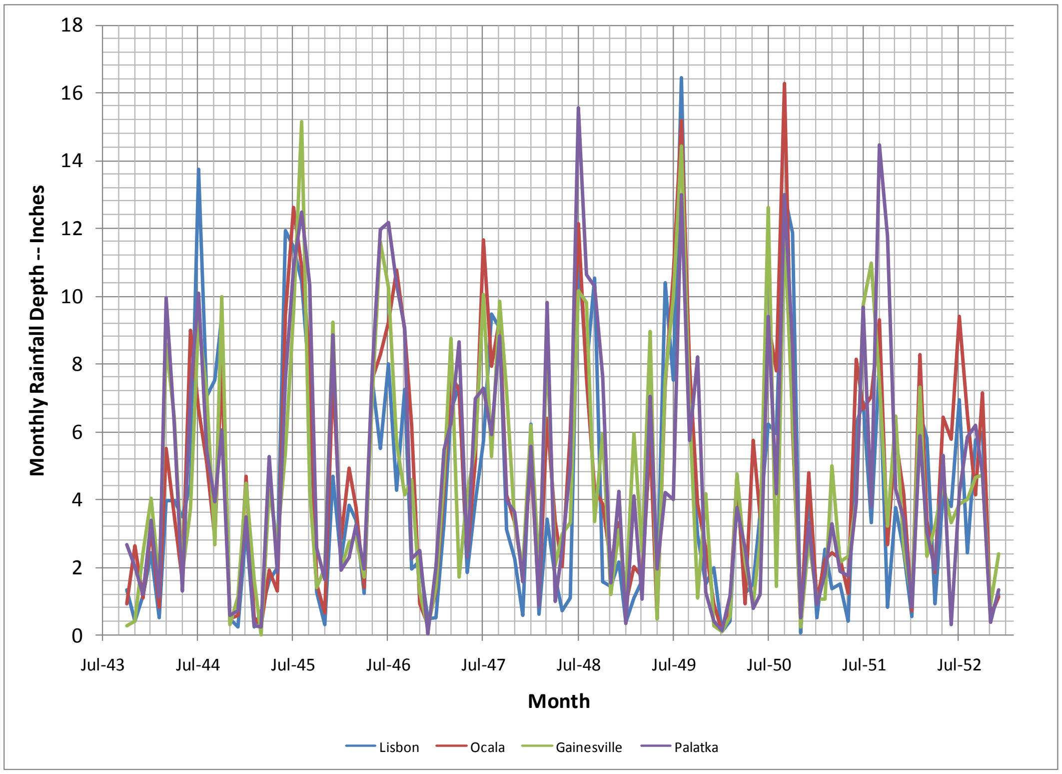

Figure 6. Monthly rainfall hyetographs for concurrent period of record

Figure 7. Cumulative monthly rainfall curves for concurrent period of record

Table 5. Concurrent period of record summary for rainfall gaging stations

Parameter	Lisbon	Ocala	Gainesville	Palatka
POR Total (in.)	457	526	504	531
Average monthly (in/mo)	4.12	4.74	4.54	4.78
Std. dev. (in/mo)	3.59	3.56	3.50	3.79
Coeff. of var.	0.873	0.751	0.771	0.792
Max (in/mo)	16.44	16.26	15.15	15.57
Min (in/mo)	0.06	0.09	0.00	0.03
Average annual (in. /yr.)	49.40	56.92	54.50	57.41

Concurrent POR Unit Yield Comparison

A yield ratio was defined and calculated, for the several LORB stream gaging stations, to compare total concurrent POR yield on a consistent and dimensionless basis. The concurrent POR yield ratio considers individual watershed average discharge, cumulative rainfall depth and tributary area and is defined as follows:

$$\textbf{Yield Ratio}\ (\%) = \frac{\text{Concurrent POR yield (inches)}}{\text{Concurrent POR rainfall (inches)}} \times 100$$

Where, the concurrent POR yield is the watershed yield, expressed in inches, and is calculated as follows:

$$\textbf{Concurrent POR yield} = \frac{\text{Concurrent POR average discharge (cfs)}}{\text{Tributary drainage area (square miles)}} \times 125.6$$

Where the constant (125.6) converts the concurrent POR unit yield, in cfs/square mile, to equivalent inches of discharge for the111 month analysis period.

Dividing the concurrent POR yield by the total rainfall depth for the same time period, produces the yield ratio as a fraction and multiplication by 100 results in a yield ratio expressed as a percentage.

The yield ratio represents the ratio of cumulative basin discharge to cumulative rainfall expressed as a percentage. It provides a uniform metric for comparison for all discharge gaging stations, as well as for incremental differences between gaging stations.

The total concurrent POR yield ratio was computed for each gaged tributary area, as well as for selected incremental tributary areas between gages. Because there are two different estimates of gaged tributary area (USGS and SJRWMD) watershed yield, in inches, was computed based on each. These watershed yields were then divided by the concurrent POR rainfall for a selected nearby rain gage in order to calculate the yield ratio. The results are reported in Table 6.

Yield ratios are reported for the six ORB stream gages, with associated surface tributary areas, as well as for Eureka without the Silver River contribution and the incremental tributary areas between Eureka and Orange Springs and between Orange Springs and Riverside Landing. For visual perspective, the calculated yield ratios are illustrated as a bar chart on Figure 8.

Inspection of Table 6 and Figure 8 reveals several significant patterns. First, consider the stream gages primarily measuring surface water (rainfall-runoff) discharge only. These include Moss Bluff, Ocala, Orange Creek and Eureka minus the Silver River. Yield ratios for these gages range from

11.1% to 12.7% based on SJRWMD drainage areas and 10.1% to 11.9% based on the USGS drainage areas.

There are two fully independent (non-overlapping tributary area) surface water watersheds included among the four gaging stations discussed above. These are: 1) Eureka minus the Silver River (which includes upstream flow measured at both Moss Bluff and Ocala) and, 2) Orange Creek. Using the drainage area yield ratios for these two independent watersheds, overall surface water yield ratios can be computed. The drainage area weighted surface water yield ratios are 11.4%, based on SJRWMD drainage areas, and 10.2% for USGS drainage areas see Table 6). Clearly, the data for the surface water discharge component, derived from these four gages, appear to be internally consistent.

Considering the three stream gages below the Silver River (Eureka, Orange Springs and Riverside Landing) the yield ratios are larger, due in part to the Silver River spring flow contribution. Considering the SJRWMD drainage areas, yield ratios are 27.9%, 23.3% and 26.7%, respectively.

Further insight may be gained by examining the incremental increase in yield ratio between Eureka and Orange Springs and between Orange Springs and Riverside Landing. The incremental yield ratio between Eureka and Orange Springs (18.4% SJRWMD drainage areas and 21.2% USGS drainage areas) appears reasonable. A relatively large incremental yield ratio is expected due to the presence of local springs, as well as additional surface runoff within this river reach.

However, the incremental yield ratio for the final river reach, between Orange Springs and Riverside Landing, is four to five times greater than the incremental yield ratio between Eureka and Orange Springs. This incremental yield ratio is much larger than any of the other yield ratios computed for the concurrent POR, as illustrated on Figure 8.

Table 6. Concurrent period of record yield ratio calculation for Lower Ocklawaha River stream gages

Discharge Gage or Composite Tributary	Concurrent POR Yield (inches)		Selected Representative Rain Gage	Total Rainfall (inches)	Yield Ratio (%)		Comment
	based on SJRWMD DA	based on USGS DA			based on SJRWMD DA	based on USGS DA	
Moss Bluff	58.1	54.3	Lisbon	457	12.7%	11.9%	
Ocala	52.7	53.0	Lisbon	457	11.5%	11.6%	
Eureka	146.8	132.3	Ocala	526	27.9%	25.2%	Includes Silver River
Orange Creek	61.7	53.5	Gainesville	504	12.2%	10.6%	
Orange Springs	122.5	112.1	Ocala	526	23.3%	21.3%	Includes Silver River
Riverside Landing	140.6	131.9	Ocala	526	26.7%	25.1%	Includes Silver River
Eureka minus Silver River	58.7	52.9	Ocala	526	11.1%	10.1%	
Orange Springs minus (Orange Creek plus Eureka)	96.6	111.3	Ocala	526	18.4%	21.2%	Includes local springs
Riverside Landing minus Orange Springs	391.8	574.7	Palatka	531	73.8%	108.2%	Includes local springs

Basin wide area weighted average surface water yield ratios (drainage areas from Table 2)

a) for SJRWMD drainage areas = (1,231.9*(11.1%) + 407.1*(12.2%))/1,639 = 11.4%

b) for USGS drainage areas =(1,367*(10.1%) + 469*(10.6%))/1,836 = 10.2%

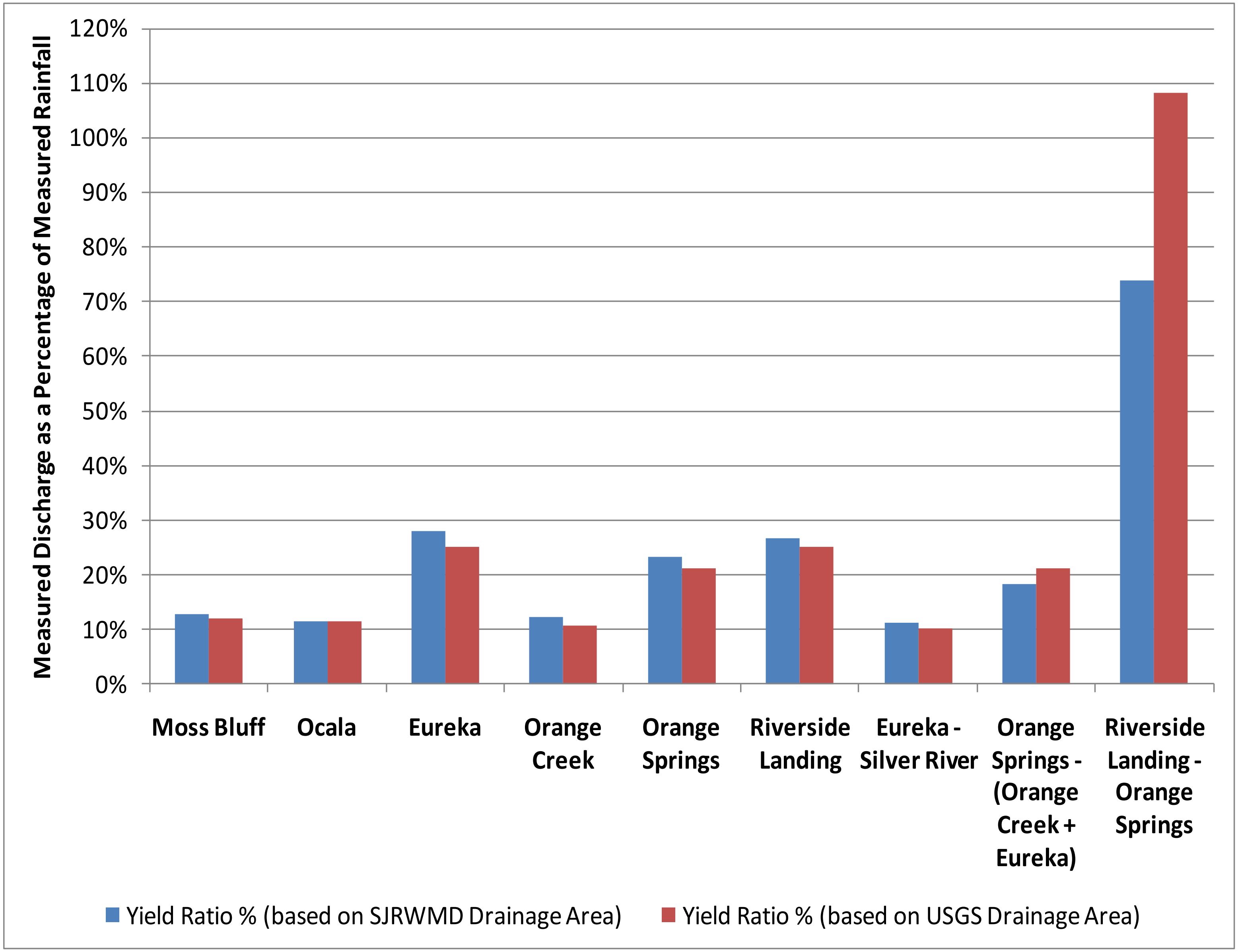

Figure 8. Concurrent period of record yield ratio comparison

Possible Implications

Considering the measured incremental concurrent POR discharge, between Eureka and Orange Springs and between Orange Springs and Riverside Landing, the increased measured discharge may arise from some combination of three sources.

1. Increase surface water (rainfall-runoff) inflow
2. Increased local spring discharge and/or local groundwater inflow
3. Possible flow overestimate within the historic discharge data

All individual stream discharge measurements include measurement error. However, when individual measurement errors are random some will overestimate the true value and some will underestimate the true value and the sample mean will be an accurate estimate of the true mean. In this case, no net flow overestimate or underestimate will exist. An unbiased data set is always the goal of hydrologic monitoring.

However, if a data set exhibits a net over or under estimate it is often not readily apparent. It is unknown if a net flow overestimate exists for the Riverside Landing discharge data but it is possible.

It is not feasible, within the scope of this hydrologic data review, to accurately establish the magnitude of each of the three potential sources. However, likely ranges are estimated.

The expected increase in the surface water (rainfall-runoff) contribution can be estimated by application of the area wide yield ratios (Table 6), applied to the incremental reach drainage area and concurrent POR rainfall. The difference then, between the total measured increased reach discharge and the expected surface water component yields an estimate of the sum of the local spring /groundwater contribution and possible flow overestimate. Unfortunately, the sparse and relatively recent discharge data for local springs prevents a precise independent evaluation of the magnitude of the local spring flow component. Therefore, the split between the local spring/ groundwater contribution and potential flow overestimate is uncertain.

Eureka to Orange Springs

The river reach between Eureka and Orange Springs is about eleven miles in length. A qualitative survey of the Lower Ocklawaha River springs (Abbott 1971) identified ten small springs within this reach of the river.

The additional drainage area (excluding the Orange Creek Basin) is estimated at 197 square miles, based on SJRWMD GIS measurements and 171 square miles, based on USGS published information (Table 2). The incremental measured increase in average discharge (excluding the Orange Creek Basin) is 152 cfs (Table 4).

Table 7 presents an analysis of the incremental discharge components based on known river reach characteristics. Two analyses are presented. Part a is based on the SJRWMD drainage area estimate and associated basin wide surface water unit yield ratio, and part b is based on the USGS values.

Table 7. Concurrent period of record incremental discharge analysis Eureka to Orange Springs

Part a) SJRWMD drainage area

Parameter	Units	Value	Comment
Incremental Drainage Area	sq. mi.	197	SJRWMD DA
Incremental Average Discharge	cfs	152	Concurrent POR average
Incremental Total Discharge	inches	97	Concurrent POR total
Surface Water Yield Ratio	%	11.4%	SJRWMD DA Based
Incremental Total Basin Rainfall	inches	526	Concurrent POR Total based on Ocala rain gage
Expected Incremental Average Surface Water Discharge	cfs	94	Expected surface water yield ratio times rainfall, reported in cfs
Estimated Local Spring/Groundwater Average Discharge and/or Flow overestimate	cfs	58	Total discharge minus estimated surface water discharge
Average Local Spring Discharge Measurements for Incremental Reach	cfs	15.4	3 springs only -- Measured values all post-Rodman.

Part b) USGS drainage area

Parameter	Units	Value	Comment
Incremental Drainage Area	sq. mi.	171	USGS DA
Incremental Average Discharge	cfs	152	Concurrent POR average
Incremental Total Discharge	inches	112	Concurrent POR total
Surface Water Yield Ratio	%	10.2%	USGS DA Based
Incremental Total Basin Rainfall	inches	526	Concurrent POR Total based on Ocala rain gage
Expected Incremental Average Surface Water Discharge	cfs	73	Expected surface water yield ratio times rainfall reported in cfs
Estimated Local Spring/Groundwater Average Discharge and/or Flow overestimate	cfs	79	Total discharge minus estimated surface water discharge
Average Local Spring Discharge Measurements for Incremental Reach	cfs	15.4	3 springs only -- Measured values all post-Rodman.

The resulting estimated expected increase in surface water contribution ranges from 73 to 94 cfs. The remaining measured increase (58 to 79 cfs) is likely due to some combination of local spring discharge/groundwater inflow and possible gaged flow overestimate.

However, given that the average measured local spring discharge since the construction of Rodman Reservoir is 15.4 cfs for only 3 springs and the presence of Rodman Reservoir has likely suppressed natural spring flow, the entire remaining incremental discharge (58 to 79 cfs) could logically be explained by natural spring /groundwater discharge. Also, this residual incremental discharge is small (3 to 4%) compared to the total average concurrent POR average discharge (1,793 cfs) measured at Orange Springs. It is concluded that the net flow overestimate, at the Orange Springs gage, is likely negligible and that the concurrent POR spring discharge/groundwater component, for this river reach, ranged from 58 to 79 cfs.

Orange Springs to Riverside Landing

The river reach between Orange Springs and Riverside Landing is about nine miles in length. Abbott (1971) also identified ten small springs located within this river reach.

The additional drainage area between Orange Springs and Riverside Landing is estimated at 132 square miles and 90 square miles, based on SJRWMD GIS measurements and USGS published information, respectively (Table 2). The incremental increase in measured discharge is 412 cfs, which is about 18.7% of the total discharge measured at Riverside Landing (Table 4).

Table 8 presents an analysis of the incremental discharge components based on known river reach characteristics. Two analyses are presented. Part a is based on SJRWMD drainage area estimates and part b is based on the USGS values.

Based on this incremental yield analysis, the expected increase in surface water contribution ranges from 39 to 64 cfs. The remaining measured increase (348 to 373 cfs) is likely due to some combination of local spring discharge and/or groundwater inflow and possible gaged flow overestimate.

The average measured local springs discharge for this river reach is 18.35 cfs which includes measurements from a total of six individual springs. All local spring discharge measurements, except one, were made after the construction of Rodman reservoir. The sole pre-Rodman discharge determination was for Blue Spring, where a discharge of 10.6 cfs was reported for October 8, 1935 (Ferguson, G.E. and others, 1947). Blue Spring was noted by Abbott (1971) to be the largest of the several small springs of the Lower Ocklawaha River.

Table 8. Concurrent period of record incremental discharge analysis Orange Springs to Riverside Landing

Part a) SJRWMD drainage area

Parameter	Units	Value	Comment
Incremental Drainage Area	sq. mi.	132	SJRWMD DA
Incremental Average Discharge	cfs	412	Concurrent POR average
Incremental Total Discharge	inches	392	Concurrent POR total
Surface Water Yield Ratio	%	11.4%	SJRWMD DA Based
Incremental Total Basin Rainfall	inches	531	Concurrent POR Total based on Palatka rain gage
Expected Incremental Average Surface Water Discharge	cfs	64	Expected surface water yield ratio times rainfall reported in cfs
Estimated Local Spring/Groundwater Average Discharge and/or Flow overestimate	cfs	348	Total discharge - estimated surface water discharge
Average Local Spring Discharge Measurements for Incremental Reach	cfs	18.35	6 springs only -- Measured values all post-Rodman except one.

Part b) USGS drainage area

Parameter	Units	Value	Comment
Incremental Drainage Area	sq. mi.	90	USGS DA
Incremental Average Discharge	cfs	412	Concurrent POR average
Incremental Total Discharge	inches	575	Concurrent POR total
Surface Water Yield Ratio	%	10.2%	USGS DA Based
Incremental Total Basin Rainfall	inches	531	Concurrent POR Total based on Palatka rain gage
Expected Incremental Average Surface Water Discharge	cfs	39	Expected surface water yield ratio times rainfall reported in cfs
Estimated Local Spring/Groundwater Average Discharge and/or Flow overestimate	cfs	373	Total discharge minus estimated surface water discharge
Average Local Spring Discharge Measurements for Incremental Reach	cfs	18.35	6 springs only minus Measured values all post-Rodman except one.

Because of a lack of pre-Rodman local springs discharge measurements; development of an accurate estimate of the total local springs flow component for the reach is not possible. However, certain judgments can be applied. First, given that the number of local springs located within each river reach (ten each), as well as the post-Rodman measured spring discharges, are similar it is considered likely that the pre-Rodman local spring contribution would also be similar for both reaches.

If it is concluded that the concurrent POR local spring discharge for the Eureka to Orange Springs reach is in the range of 58 to 79 cfs then a reasonable (expected) value for the similar Orange Springs to Riverside Landing reach would be approximately the same.

An estimate of the likely maximum possible gaged flow overestimate can be developed by subtracting the minimum likely values for surface water Inflow (39 cfs) and spring flow/groundwater discharge (58 cfs) from the total measured increase (412 cfs). The resulting estimate of maximum potential flow overestimate, at Riverside Landing, is 315 cfs or about 14% of the total measured discharge (2,204 cfs). Therefore, the range of possible Riverside Landing gaged flow overestimate is estimated to be from zero to 14% of the total measure discharge.

It is possible that there is no flow overestimate in the observed record. In this case, the pre-Rodman local springs/groundwater inflow contribution would be in the range of 348 to 373 cfs, which is equivalent to more than 40% of the Silver River discharge for the same time period.

SUB-BASIN RAINFALL AND THE ROLE OF GEOSTATISTICAL ANALYSIS

In the work plan, for this investigation, the feasibility of using a geostatistical analysis to develop sub-basin specific rainfall arrays was envisioned. In this manner, rainfall records from a number of nearby stations would be used to construct rainfall arrays representative of a particular tributary sub-basin.

Based on screening analysis of available rainfall data, geostatistical analysis proved to be impractical due to a lack of spatial correlation among the available rainfall stations (Osburn W., personal communication, 2008). The project team decided that the analysis should proceed using direct rain gage measurements for selected gages within or near the catchment of interest.

SINGLE MASS CURVE ANALYSIS OF UPPER OCKLAWAHA RIVER BASIN RAINFALL AND DISCHARGE

The Moss Bluff stream gaging station establishes the downstream limit of the UORB and the upstream limit of the LORB. As previously discussed, Tibbals and others (2004) investigated the hydrologic regime of the UORB and found a distinct reduction in upper basin discharge beginning in 1970. The analysis for Moss Bluff, presented by Tibbals and others (2004) is updated herein.

Specifically, the current analysis considers discharge records from Moss Bluff and from the nearby downstream Ocala stream gage. The original analysis considered Moss Bluff discharge data only. The Ocala monthly discharge data are used to estimate corresponding Moss Bluff monthly discharge values thereby extending the period of analysis. The period of analysis is further extended by consideration of rainfall and discharge data acquired since 2002.

Moss Bluff Period of Record Extension

Discharge records for Moss Bluff prior to September 1967 are few and include only the 12-year period from October 1943 through September 1955 (Table 2 and Figure 4). However, the Ocala stream gage, located about eleven miles downstream from Moss Bluff, provides discharge records from March 1930 through June 1968 (Table 3). These data overlap the early Moss Bluff data (Figure 3) and can be used to estimate missing Moss Bluff monthly discharge prior to September 1967. Figure 9 presents the complete monthly discharge hydrographs for both Moss Bluff and Ocala.

It is difficult to observe the difference in measured monthly discharge between the Moss Bluff and Ocala gages at the POR time scale presented in Figure 9. However, there are 154 concurrent observations of monthly flow as illustrated in Figure 10. A linear trend line analysis with a zero intercept was used to estimate a constant of proportionality, or scaling factor, (0.8699) between the measured Ocala monthly discharge and the measured monthly Moss Bluff discharge values.

Multiplication of the observed Ocala monthly discharge by the trend line constant (0.8699) provides an estimate of the monthly discharge at Moss Bluff. These estimated values were used to fill in missing values between March 1930 and June 1968. The extended (composite) Moss Bluff discharge record contains a total of 931 monthly observations; 478 months prior to 1970 and 453 months thereafter.

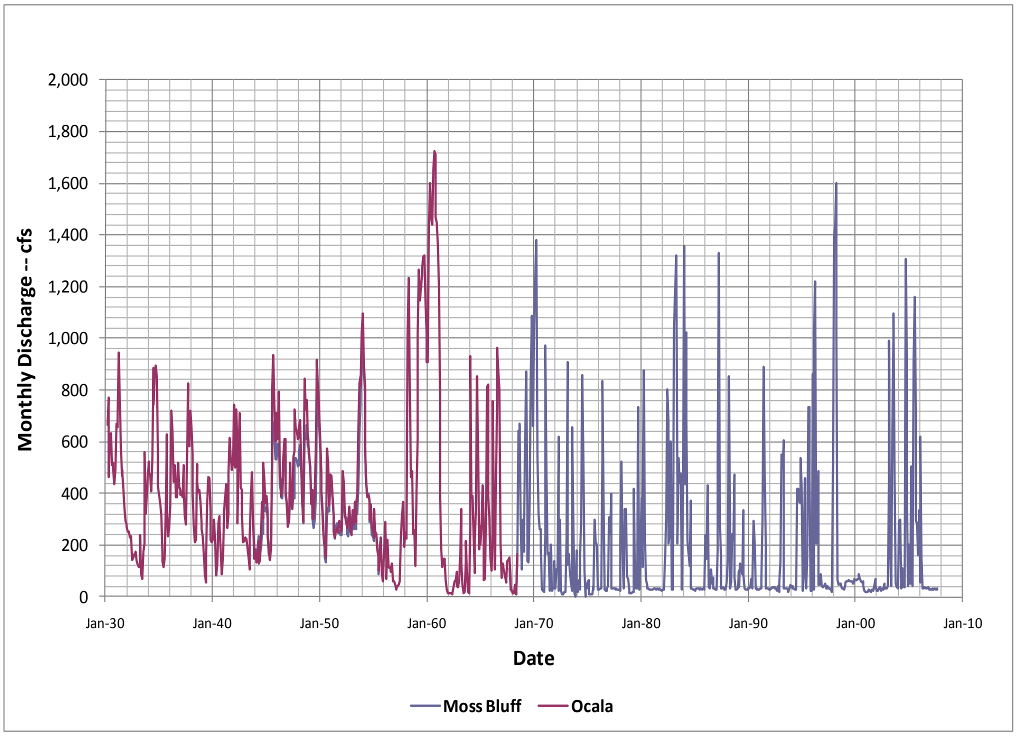

Figure 9. Monthly discharge hydrograph for Moss Bluff and Ocala stream gages

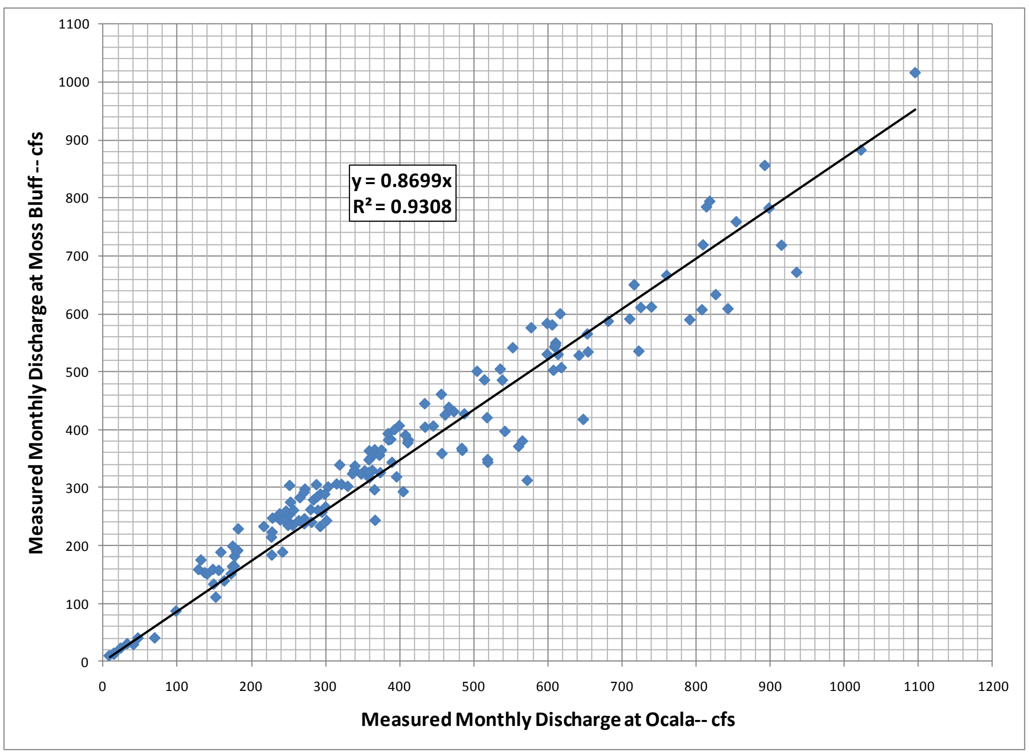

Figure 10. Scattergram of concurrent monthly discharge observations for Moss Bluff and Ocala stream gages

Moss Bluff Cumulative Discharge Analysis

Single mass curves for the extended Moss Bluff monthly discharge (Figure 11) and for Lisbon and Ocala monthly rainfall (Figure 12), for the same period of analysis, are developed and compared.

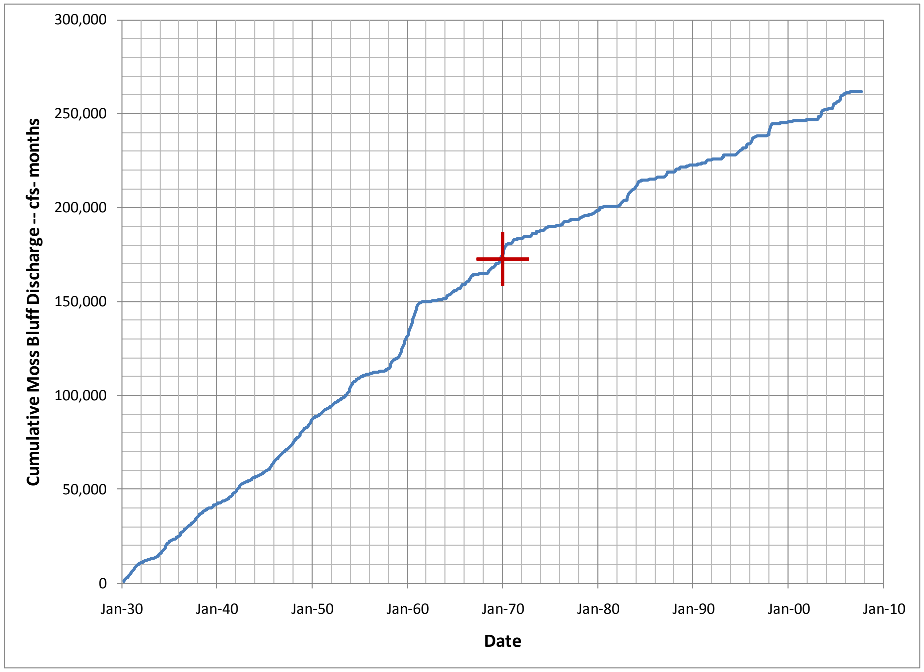

Figure 11. Cumulative monthly discharge for Moss Bluff from extended period of record (+ marks 1970 coordinates)

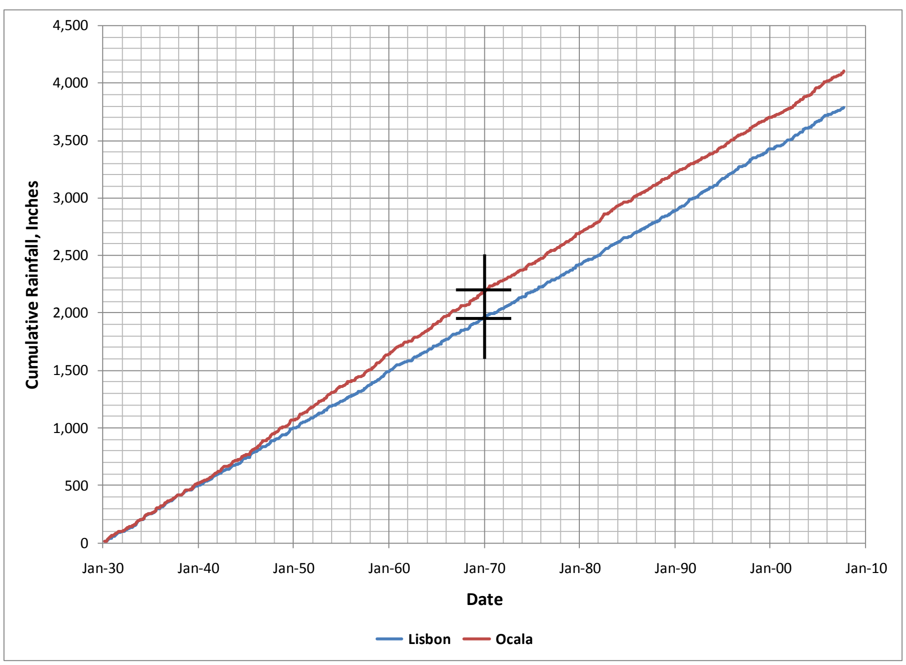

Figure 12. Cumulative monthly rainfall for Lisbon and Ocala (+ marks 1970 coordinates)

As can be seen from Figure 11, the hydrologic regime break-point, at or near 1970, identified by Tibbals and others (2004) is apparent. The average Moss Bluff discharge for the total extended POR is compared to the pre-1970 and post-1970 discharge in Table 9.

Table 9. Pre- and Post-1970 discharge for the Ocklawaha River at Moss Bluff

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Mar-30	Sep-07	931	281	Total POR	100.0%	47.0%
Mar-30	Dec-69	478	365	pre -1970 POR	129.6%	
Jan-70	Sep-07	453	193	post - 1970 POR	68.7%	

The total discharge for the extended POR (77-years 7-months) is 281 cfs. The pre-1970 average discharge (365 cfs) is about 30% greater, and the post-1970 discharge (193 cfs) is about 30% less, than the long-term average. Compared directly to the pre-1970 discharge, the post-1970 discharge represents a 47% reduction.

Tibbals and others (2004) calculated a pre-break mean discharge of 400 cfs and post-break mean discharge at 183 cfs for a net decrease of 217 cfs or 54%. The current discharge reduction estimate (172 cfs and 47%) is less but of similar magnitude.

Lisbon rainfall for the same time period averaged 4.07 inches per year less than the Ocala Rainfall (Figure 12). This represents an 8.3% difference between the two rainfall stations. Although not visually obvious on Figure 12, the average rainfall for each rain gage is also less for the post-break period. For the Lisbon gage, the difference is only 0.97 inches per year (1.8%). For the Ocala gage, the difference is a more substantial 3.92 inches per year or 7.2%. Therefore, the post-1970 period produced less rainfall and less stream discharge than the pre-1970 period.

Regional Influence of the Atlantic Multidecadal Oscillation

Recent research linking the Atlantic Multidecadal Oscillation (AMO) to variations in Florida rainfall and river flow patterns (Kelly and Gore, 2008) demonstrate the role of climate cycles in observed variations in long-term stream flow patterns in peninsular Florida. This linkage between ocean temperature cycles, and Florida tropical season rainfall and stream discharge patterns was not well understood or documented at the time that Tibbals and others (2004) investigated the UORB.

Kelly and Gore (2008) identify the 30-year period prior to 1970 as an AMO warm period and the 30-year period beginning in 1970 as a 30-year cool period. The warm period is associated with greater regional wet season (i.e., tropical) rainfall and the cool period is associated with a relative reduction in wet season rainfall.

Several seasonal river flow patterns were identified including the southern river pattern within which the annual maximum flow rate tends to occur in late summer or early fall corresponding to the later portion of the wet season. This flow pattern is associated with peninsular Florida streams including the St. Johns River.

Kelly and Gore (2008) compared the 30-year warm period (1940 through 1969) discharge to the 30-year cool period (1970 through1999) discharge for 17 peninsular Florida stream gaging stations and found that decreases, averaging 29.7%, were observed in 16 of the 17 cases.

An "AMO test" based on the Kelly and Gore (2008) regional investigation is applied here. In this test, the 30-year pre-1970 average monthly discharge is compared to the 30-year post-1970 average monthly discharge. The results, for Moss Bluff, are reported in Table 10.

Table 10. AMO test applied to expanded Moss Bluff monthly discharge record

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Jan-40	Dec-99	720	283	60 year test period	100.0%	46.2%
Jan-40	Dec-69	360	368	30 year pre-1970	130.1%	
Jan-70	Dec-99	360	198	30 year post-1970	69.9%	

These results, for this 60-year AMO test period, are nearly identical to the results obtained for the entire (77-year 7-month) period of record (Table 9). An overall 46% reduction in observed discharge is indicated. This compares to the regional value, reported by Kelly and Gore (2008), for the same 60-year AMO test period, of about 30%.

These results indicate that the UORB behaves much like other peninsular Florida watersheds and that much, if not most, of the overall observed decline in Moss Bluff discharge, since 1970, could be due to the AMO natural climatic cycle. However, it is also considered likely, that some portion of the observed stream flow reduction is due to regulation of the Harris Chain of Lakes and potentiometric declines in the Floridan aquifer, as suggested by Tibbals and others (2004).

SINGLE AND DOUBLE MASS CURVE ANALYSIS OF SILVER RIVER DISCHARGE AND OCALA RAINFALL

The Silver River is the single largest tributary to the Lower Ocklawaha River. Continuous discharge records begin in October 1932 (Table 2). For the 75-year period of analysis (October 1932 through September 2007), measured Silver River discharge has averaged 768 cfs or about 2.7 times the UORB contribution. The period of record monthly discharge hydrograph is presented in Figure 13.

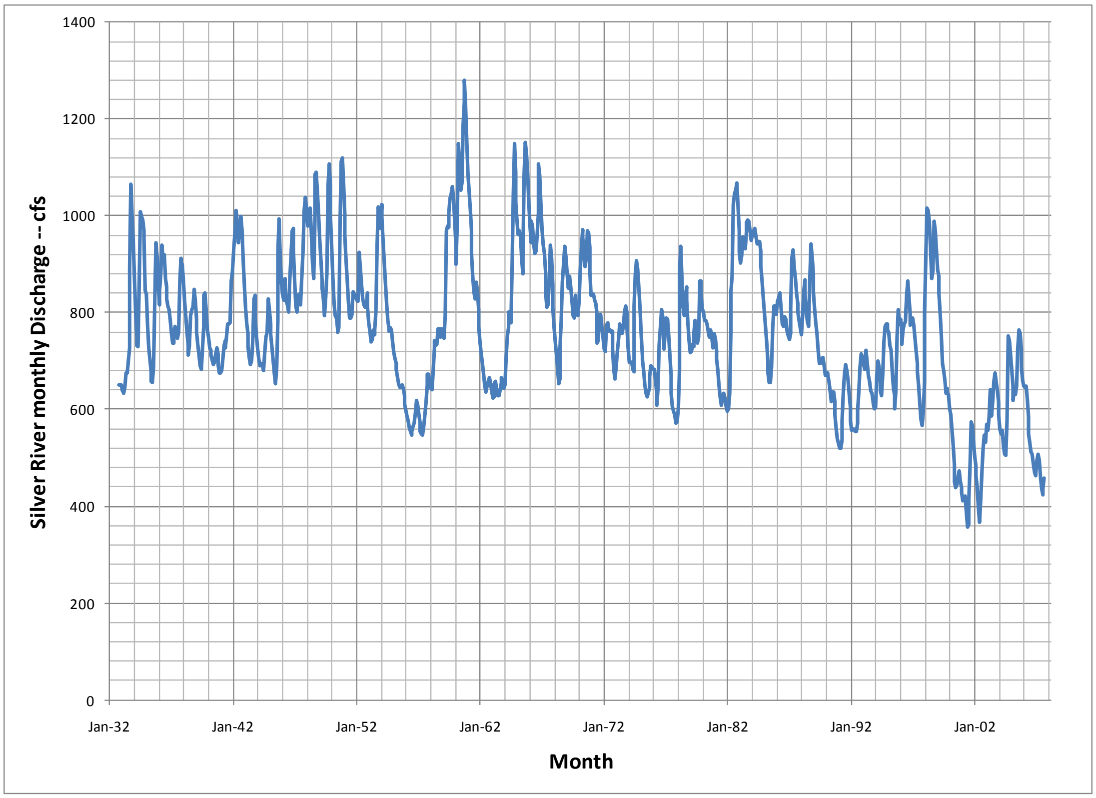

Figure 13. Silver River monthly discharge (October 1932 through September 2007)

An important feature of the Silver River contribution is the very large base flow. For the 75-year period illustrated on Figure 13, monthly discharge seldom falls below 600 cfs and only during 2001 and 2002, does monthly discharge fall below 400 cfs.

Silver River Cumulative Discharge Analysis

The single mass curve for Silver River discharge is presented in Figure 14.

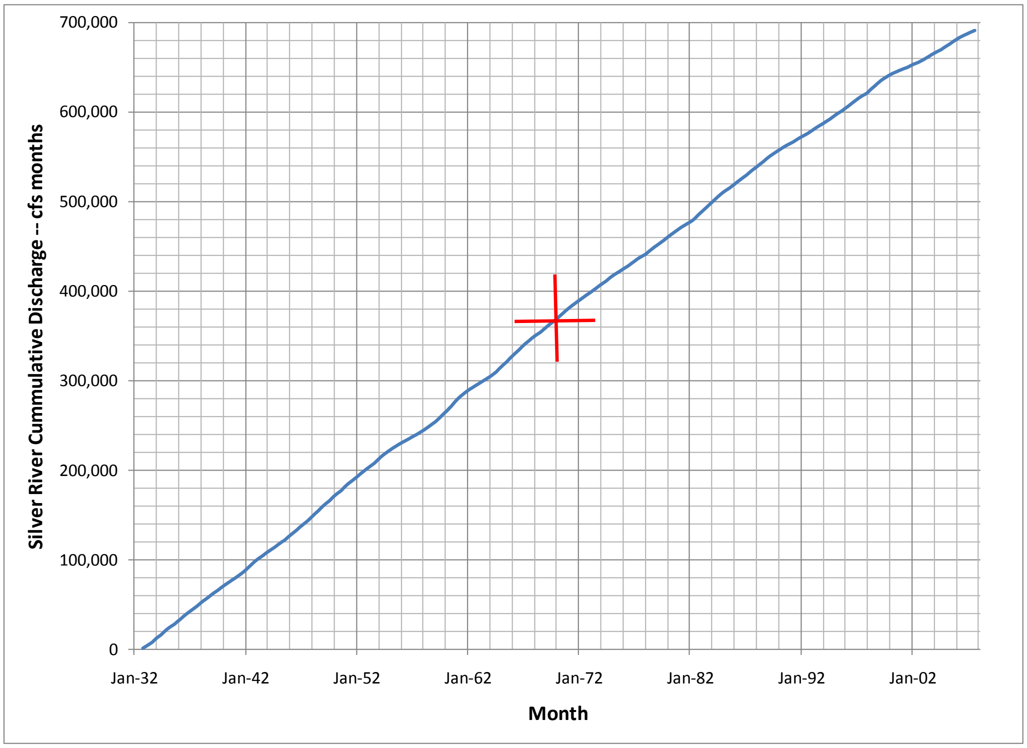

Figure 14. Silver River cumulative discharge (+ marks 1970 coordinates)

Visually, there is little evidence of a break point in slope of the Silver River cumulative discharge curve at or near 1970. However, there is an apparent mild break occurring at about the year 2000 which is concurrent with the observed minimum discharge. A comparison of the pre- and post-1970 Silver River average discharge, for the 75-year period of analysis, is presented in Table 11.

Table 11. Pre- and post-1970 discharge for the Silver River

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Oct-32	Sep-07	900	768	Total POR	100.0%	13.2%
Oct-32	Dec-69	447	823	pre - 1970 POR	107.1%	
Jan-70	Sep-07	453	714	post -1970 POR	93.0%	

For the total pre-1970 period, Silver River discharge averaged 823 cfs or about 107% of the long-term average. For the post-1970 period Silver River discharge averaged 714 cfs or about 93% of the long-term average. The overall post-1970 versus pre-1970 decline was 13.2%.

Considering the 60-year AMO test period, the pre and post-1970 Silver River discharge comparison is as summarized in Table 12.

Table 12. AMO test applied to Silver River discharge record

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Jan-40	Dec-99	720	793	60 year test period	100.0%	8.5%
Jan-40	Dec-69	360	829	30 year pre-1970	104.4%	
Jan-70	Dec-99	360	758	30 years post-1970	95.6%	

The results are similar to those reported in Table 11, for the 75-year period of analysis, except that the post-1970 versus pre-1970 decline is only 8.5%. It is also of interest to note that, for the same 60-year AMO test period, Ocala rainfall was 8.7% less during the post-1970 period as compared to the pre-1970 period.

These results suggest that the AMO signal is likely much weaker in the Silver River, a groundwater discharge dominated system, than in the UORB, which is a rainfall-runoff dominated system.

Silver River Discharge and Ocala Rainfall Double Mass Curve Analysis

Figure 15 presents the double mass curve illustrating cumulative Silver River discharge as a function of cumulative Ocala rainfall for the 75-year period of analysis.

The double mass curve indicates a uniform and stable relationship between cumulative Ocala rainfall and cumulative Silver River discharge for almost all of the entire 75-year period of analysis. Similar to the cumulative discharge curve (Figure 14), a departure from the long-term trend is observed in recent years. This departure begins at a cumulative rainfall value of about 3,600 inches which occurs in 2001. The reason for and importance of this recent break point is uncertain but it does coincide with a significant regional drought and the occurrence of the POR lowest measured monthly discharge.

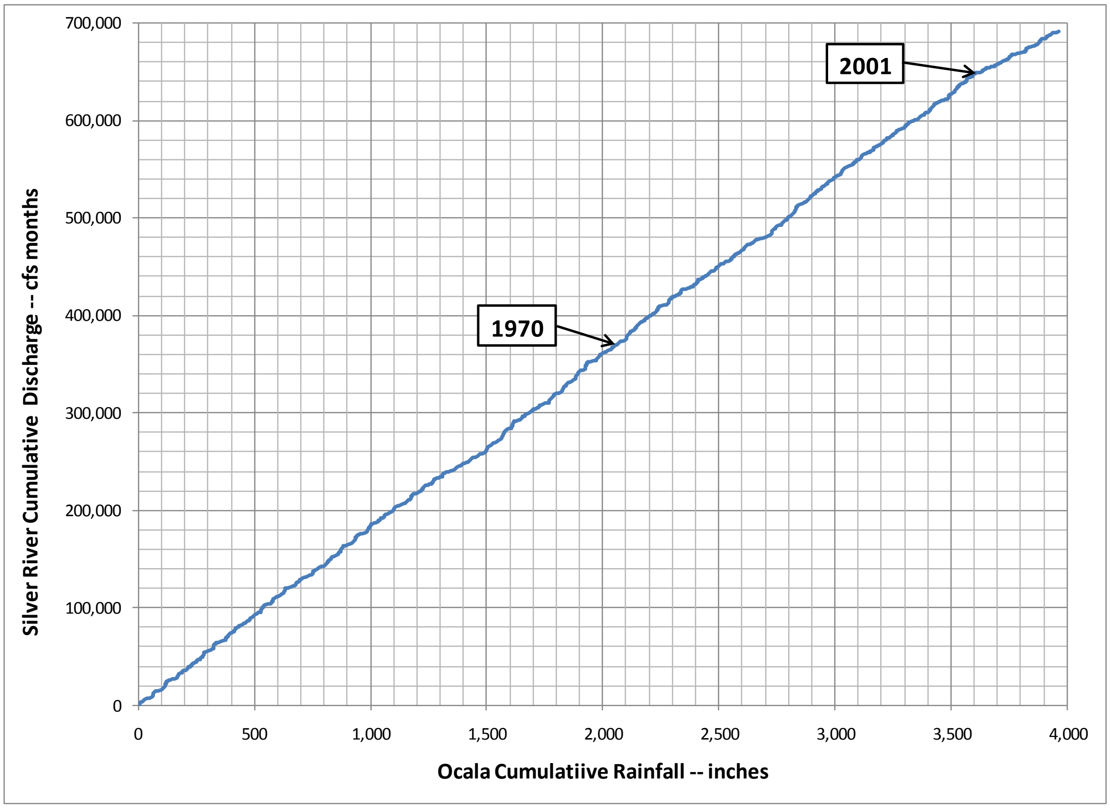

Figure 15. Double mass curve for Silver River discharge and Ocala rainfall (October 1932 through September 2007).

SINGLE AND DOUBLE MASS CURVE ANALYSIS OF LOWER OCKLAWAHA RIVER BASIN RAINFALL AND DISCHARGE

Evaluation of long-term ORB yield requires the development of a composite discharge time series using data from four different stream gages, including:

- Orange Springs
- Riverside Landing
- Rodman Dam
- Buckman Lock

As previously discussed, the discharge data compositing task is subject to a degree of uncertainty due to the fact that outlet gaging station locations and outlet conditions have changed over time. One of the primary objectives of this investigation was to evaluate the various discharge data sets for internal consistency. The discharge data review, documented in the *Discharge Data Internal Consistency Review* portion of this report, showed that the data from the Riverside Landing gage may be inconsistent with data for other upstream gages including Orange Springs. It was concluded that a possible flow overestimate of up to 14% of the total measured Riverside Landing discharge may exist based on a comparison of Riverside Landing to Orange Springs and other upstream gaging stations.

Although a flow overestimate, at Riverside Landing, is a possibility it is not a certainty. Therefore, the LORB total yield analysis, developed herein considers two possibilities. A base case is defined assuming no flow overestimate. Adjustments to the base case are then applied to provide a sensitivity analysis to evaluate gaged flow overestimate uncertainty.

Base Case Composite Discharge Record for Total Lower Ocklawaha River Basin Yield

Bloom (2008) developed a composite discharge record, for the pre-Rodman period, by adjusting the Orange Springs record to match the downstream Riverside Landing record. In this manner, differences between the Orange Springs measurements and the Riverside Landing measurements are resolved by assuming that Riverside data are the most representative of total basin discharge and adjusting the Orange Springs record upward, by application of a scaling factor (1.21). If there is no flow overestimate in the Riverside Landing data, then this procedure will yield good results. For this analysis, the Bloom (2008) scaling factor is used to establish a base case total discharge time series. This base case represents conditions assuming that the Riverside Landing data accurately represent total basin discharge. Flow overestimate uncertainties are addressed separately.

The base case composite ORB total discharge time series is developed as follows:

1. For the time period when only Orange Springs discharge measurement are available (March 1930 through September 1943) the Orange Springs observations are multiplied by the Bloom (2008) scaling factor (1.21).
2. For the time period (October 1943 through September 1968) the Riverside Landing observations are used.
3. From the time period after construction of Rodman reservoir (October 1968 through September 2007) the sum of the Rodman Dam and the Buckman Lock discharge measurements are used.

Figure 16 presents the monthly discharge hydrographs for the four individual basin outlet stream gages, as well as the base case composite time series. Given that the base case composite time series includes the Riverside Landing data these data are obscured by the composite time series and cannot be identified on Figure 16.

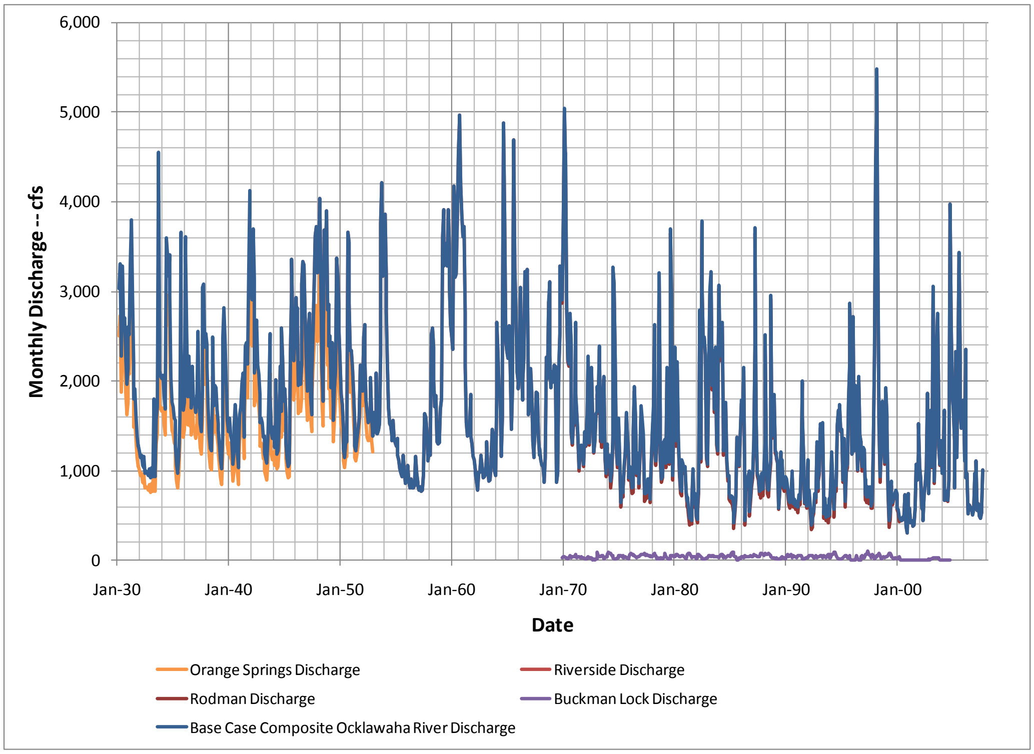

Figure 16. Ocklawaha River Basin monthly discharge hydrographs and base case composite discharge time series

Lower Ocklawaha River Basin Cumulative Rainfall and Discharge Analysis

Cumulative discharge for the LORB, for the base case composite discharge time series, is illustrated on Figure 17. In this case, characteristics of the pre and post-Rodman reservoir construction, as well as pre and post-1970 time periods are of interest.

Like the UORB a break point in the cumulative discharge curve is evident. In this case, the break appears to occur at or about 1971 or 1972. There is no clear break associated with the completion of Rodman Dam in 1968.

Figure 18 presents a double mass curve illustrating cumulative ORB base case composite discharge as a function of cumulative Ocala rainfall.

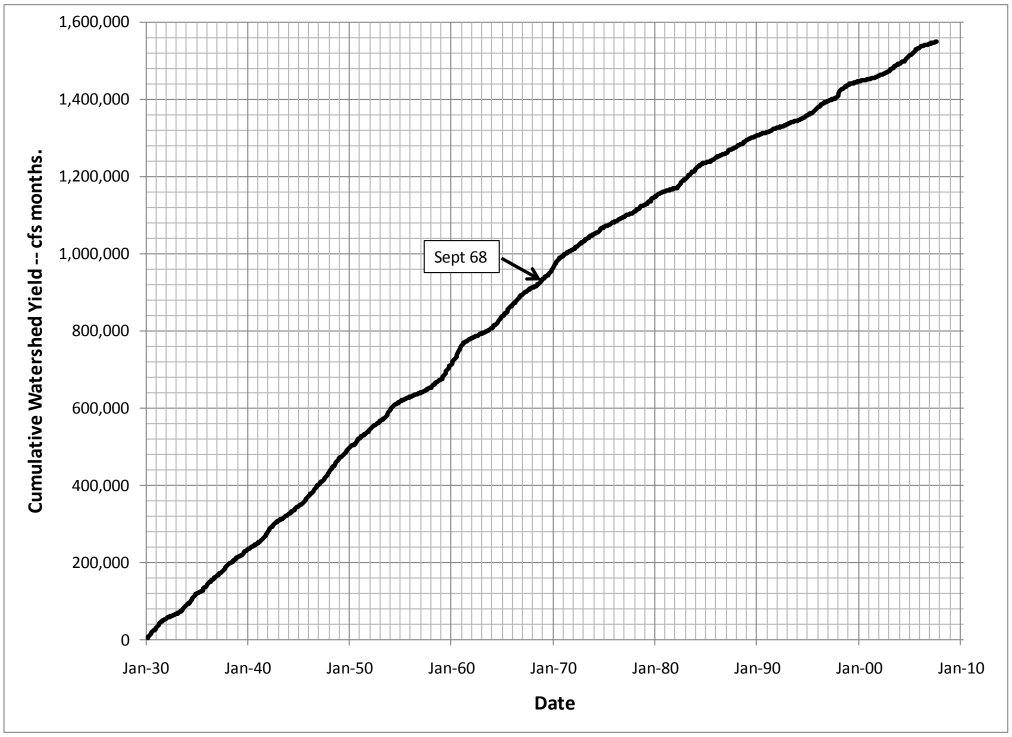

Figure 17. Cumulative total Ocklawaha River Basin discharge for base case composite discharge time series

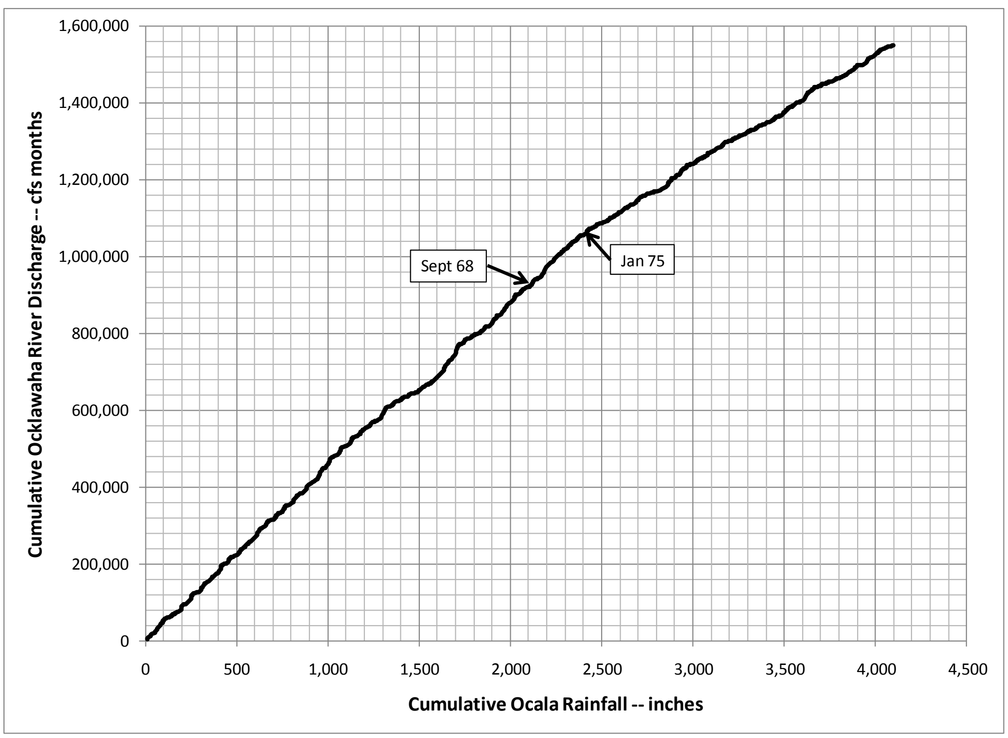

Figure 18. Double mass curve for Lower Ocklawaha River Basin base case composite discharge and Ocala rainfall

The double mass curve (Figure 18) is slightly smoother than the single mass curve (Figure 17) but both exhibit the same general characteristics. However, for the double mass curve, the break point occurs at about 1975.

Characteristics of the base case cumulative discharge curve are evaluated for three different periods. The first (Table 13) is for pre and post-Rodman, the second (Table 14) is for pre and post-1970 and the third (Table 15) is for the 60-year AMO test period, 30-years pre-1970 and 30-years post-1970.

Table 13. Pre- and post-Rodman Reservoir Lower Ocklawaha River discharge characteristics (base case)

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-Rodman Reduction Percentage
Begin	End					
Mar-30	Sep-07	931	1664	Total POR	100.0%	33.1%
Mar-30	Sep-68	463	1997	Pre-Rodman	120.0%	
Oct-68	Sep-07	468	1335	Post-Rodman	80.2%	

Table 14. Pre- and post-1970 Lower Ocklawaha River discharge characteristics (base case)

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Mar-30	Sep-07	931	1664	Total POR	100.0%	34.9%
Mar-30	Dec-69	478	2005	pre -- 1970	120.5%	
Jan-70	Sep-07	453	1305	post -- 1970	78.4%	

Table 15. AMO test applied to Lower Ocklawaha River base case composite discharge

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Jan-40	Dec-99	720	1686	60 year test period	100.0%	32.8%
Jan-40	Dec-69	360	2018	30 year pre-1970	119.6%	
Jan-70	Dec-99	360	1355	30 year post-1970	80.4%	

As can be seen from the tabular results, all three base case evaluations are very similar. Considering the entire base case POR, the mean discharge is 1664 cfs. During the pre-Rodman and/or pre-1970 period, discharge averaged about 20% greater than the POR average. During the post-Rodman and post-1970 period discharge averaged about 20% less than the POR average. The overall post versus pre decline ranged from 33% to 35%.

Considering the AMO test period, results are nearly identical. Pre-1970 and post-1970 discharge averaged 20% greater and 20% less than the 60-year mean respectively and the overall post-1970 versus pre-1970 decline was about 33% as compared to a reported regional value, of about 30% (Kelly and Gore, 2008).

Sensitivity Analysis

The base case results provide an opportunity to evaluate the sensitivity to uncertainty related to possible Riverside Landing gaged flow overestimate. For the base case composite discharge time series, all pre-Rodman discharge values are based on the assumption that the Riverside Landing data provide an accurate representation of pre-Rodman discharge. If a net flow overestimate of 14% exists then the pre-Rodman discharge values are skewed, on average, 14% too high, and the actual pre-Rodman discharge values would be 0.877 (1/1.14) times the values included in the base case discharge array. Adjusting the pre-Rodman average discharge results in the pre versus post-Rodman comparison reported in Table 16.

Table 16. Pre- and post-Rodman Reservoir Lower Ocklawaha River discharge characteristics (adjusted for possible Riverside Landing gaged flow overestimate)

Dates		Duration months	Average Discharge cfs	Period	Percentage of Long-term Mean	Post vs. Pre-Rodman Reduction Percentage
Begin	End					
Mar-30	Sep-07	931	1542	Total POR	100.0%	23.8%
Mar-30	Sep-68	463	1751	Pre-Rodman	113.6%	
Oct-68	Sep-07	468	1335	Post-Rodman	86.6%	

The greatest effect of a possible maximum 14% flow overestimate in Riverside Landing discharge measurements is to reduce the pre-Rodman average discharge from 1,997 cfs to 1,751 cfs (246 cfs) which also reduces the POR average discharge from 1,664 cfs to 1,542 cfs (122 cfs). Post-Rodman versus pre-Rodman discharge reduction is 23.8% compared to 33.1% for the base case.

Considering the pre and post-1970 comparison the summary for the adjusted Lower Ocklawaha River total discharge array is presented in Table 17.

Table 17. Pre- and post-1970 Lower Ocklawaha River discharge characteristics (adjusted for possible Riverside Landing gaged flow overestimate)

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-Rodman Reduction Percentage
Begin	End					
Mar-30	Sep-07	931	1542	Total POR	100.0%	26.2%
Mar-30	Dec-69	478	1767	Pre-Rodman	114.6%	
Jan-70	Sep-07	453	1305	Post-Rodman	84.6%	

As expected these results are nearly the same the pre and post-Rodman results (Table 16).

Similarly, results using the adjusted pre-Rodman discharge data applied to the 60-year AMO test period are reported in Table 18.

Table 18. AMO test applied to Lower Ocklawaha River adjusted composite discharge (adjusted for possible Riverside Landing gaged flow overestimate)

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Jan-40	Dec-99	720	1568	60 year test period	100.0%	23.9%
Jan-40	Dec-69	360	1781	30 year pre-1970	113.6%	
Jan-70	Dec-99	360	1355	30 year post-1970	86.4%	

Compared to the base case AMO Test (Table 15) accounting for possible flow overestimate reduces the post-1970 discharge reduction from about 33% to about 24%.

The sensitivity analysis summaries presented in Tables 16 through 18 provide an estimate of the uncertainty associated with possible Riverside Landing flow overestimate. The results are in the range expected based on the AMO climatic cycle, with or without possible gaged flow overestimate adjustment.

HYDROLOGIC BENCHMARKING

Regional Benchmarking

The results of the investigation of Florida river flow patterns and the AMO, reported by Kelly and Gore (2008) provide an applicable and important regional benchmark for understanding and interpreting the results of the current ORB yield analysis. The AMO is a 60 plus year climatic cycle consisting of approximately 30 years of higher ocean temperatures (warm period) followed by approximately 30 years of lower ocean temperatures (cool period). Kelly and Gore (2008) identified 1970 as the approximate break point between the AMO warm period and cool period.

In peninsular Florida, the warm period was found to induce more tropical system (wet season) rainfall and therefore higher stream flow. Conversely, the cool period produces less tropical system rainfall and lower stream flow.

Kelly and Gore (2008) evaluated a total of 17 stream gaging stations located in peninsular Florida exhibiting the southern river pattern, whereby maximum discharge is associated with late summer/early fall wet season rainfall. Discharge for the 30-year warm period (pre-1970) was compared to discharge for the 30-year cool period (post-1970). It was found that 16 of the 17 sample stations exhibit a reduction in discharge for the post-1970 cool period relative to pre-1970 warm period. The discharge reduction averaged 29.7%. The maximum reduction was 70.7%.

Withlacoochee River Benchmarking

The Withlacoochee River Basin is located west of and adjacent to the ORB. The two river basins have very similar characteristics. Both basins are of similar size, have upland tributary areas with significant natural system storage and receive inflow from a first magnitude spring in the lower reaches. In the case of the Withlacoochee River, the Rainbow River, fed by Rainbow Springs, is a major tributary near Dunnellon just upstream from Lake Rousseau. However, continuous discharge records for the Rainbow River do not begin until 1965. Therefore, the Rainbow River is not included in this benchmarking analysis.

Two Withlacoochee River USGS stream gages were selected for benchmarking analysis based on tributary area and availability of sufficient discharge record. The selected gaging stations are the Withlacoochee River at Croom (drainage area = 810 square miles) and the Withlacoochee River at Holder (drainage area = 1,825 square miles).

The Croom watershed is similar in size to the Ocklawaha River watershed above Moss Bluff. These watersheds are located adjacent to each other (share a common boundary), both have head waters in the Green Swamp area of Polk County and both contain significant natural system storage (i. e., lakes and wetlands). The results of the AMO Test for Croom are reported in Table 19.

Table 19. AMO test results for the Withlacoochee River at Croom (USGS gage number 02312500)

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Jan-40	Dec-99	720	428	60 year test period	100.0%	38.7%
Jan-40	Dec-69	360	530	30 year pre-1970	123.8%	
Jan-70	Dec-99	360	325	30 year post-1970	75.9%	

The observed reduction in post-1970 discharge for Croom (38.7%) is somewhat less, but similar to, the post-1970 reduction for Moss Bluff of 46.2%.

The Withlacoochee River at Holder watershed is similar in size to the Ocklawaha River outlet watershed as measured at Rodman Dam. However, Holder is upstream of the Rainbow River confluence and does not include the spring flow contribution of Rainbow Springs. The results for the AMO test period for Holder are reported in Table 20.

Table 20. AMO test results for the Withlacoochee River at Holder (USGS gage number 02313000)

Dates		Duration (months)	Average Discharge (cfs)	Period	Percentage of Long-term Mean	Post vs. Pre-1970 Reduction Percentage
Begin	End					
Jan-40	Dec-99	720	1,008	60 year test period	100.0%	32.7%
Jan-40	Dec-69	360	1,205	30 year pre-1970	119.5%	
Jan-70	Dec-99	360	811	30 year post-1970	80.5%	

The observed reduction in post-1970 discharge for Holder (33%) is comparable to the post-1970 reduction range estimated for the total Ocklawaha River discharge of 24% to 33%.

DISCUSSION AND CONCLUSIONS

Ocklawaha River Basin Characteristics

The Ocklawaha River watershed is a complex interconnected hydrologic system including lakes, wetlands, river channels, springs and groundwater recharge and discharge areas. The headwaters are located in the eastern Green Swamp of Polk County. From the headwater, the river flows approximately 130 miles north and discharges into the St. Johns River in Putnam County. In all, portions of six counties are included within the watershed boundary.

The UORB is characterized by extensive natural system storage including lakes and wetlands. The LORB includes a mixture of recharge and discharge areas and is characterized by the significant base flow contribution of many springs, including the nationally known first magnitude Silver Springs.

In addition to the major spring discharge from Silver Springs there are a number of small springs located along the Lower Ocklawaha River. In total, spring flow accounts for about half of the total basin yield and half is rainfall-runoff generated by the surface watershed. During low flow periods, base flow, provided by the springs and diffuse groundwater inflow, will account for most of the basin discharge.

The watershed has been modified by the construction of hydraulic structures, influencing at least the short term time distribution of discharge from the basin and possibly total discharge. Known hydraulic modifications date back to 1925 with the construction of a hydroelectric dam at Moss Bluff. Therefore, some flow control has been in place prior to the beginning of discharge measurement.

The Harris Chain of Lakes, located in the UORB, provides extensive natural storage and is controlled to maintain desired lake water levels. In the LORB, Rodman Reservoir was constructed in 1968 flooding a portion of the natural river channel. Each of these modifications could have some influence on the total basin yield and/or flow pathways.

Rainfall records, for the ORB begin in the 1880s and stream discharge records begin in the 1930s. However, except for the continuous record available for the Silver River, discharge records are discontinuous and characterized by data gaps and gaging station relocation. These discontinuities in the available discharge record, present challenges in understanding possible trends and changes in hydrologic response. However, the available records can be assembled (with some compositing of two or more gaging stations) for a period of about 75 years at Moss Bluff, the Silver River and the basin outlet.

Discharge Records Internal Consistency Review

One of the major objectives of this investigation was to provide a comprehensive review of the relevant discharge records particularly as related to development of an appropriate total basin composite discharge record. The review demonstrated consistency in the data for all stream gages except for the Riverside Landing gage. A relatively large increase in measured discharge between the Orange Springs and Riverside Landing gages was identified. Measured discharge between Orange Springs and Riverside Landing, for a 111 month concurrent POR, increased 412 cfs or 23%, whereas the drainage area increases by only 5 to 7%.

Discharge measurements for Riverside Landing are relatively large compared with upstream stations and indicate either very large groundwater and/or local spring inflow or a net gaged flow overestimate. It is concluded that a Riverside Landing gaged flow overestimate of up to 14% may exist. However, because of a lack of independent local spring discharge measurements, the exact magnitude of the local springs discharge, and therefore the actual gaged flow overestimate (if any), cannot be accurately determined.

The procedure used to account for Riverside Landing gaged flow uncertainty is to develop a total ORB composite discharge record assuming that Riverside Landing data are accurate and adjusting the upstream Orange Springs data to match. This is the compositing procedure used by Bloom (2008). This composite record becomes the base case for analysis. The base case is then adjusted for an estimated maximum possible 14% gaged flow overestimate to provide a sensitivity analysis that addresses uncertainty related to Riverside Landing discharge records.

Discharge Trends and the Atlantic Multidecadal Oscillation

One of the primary goals of this investigation was to identify long-term trends in rainfall and/or discharge if such trends exist. It is concluded that such trends do exist.

A trend, manifested as a sharp break point, was first identified by Tibbals and others (2004) for Moss Bluff discharge. The authors report that post-1970 Moss Bluff discharge was much less than pre-1970 Moss Bluff discharge. The difference amounted to a 54% reduction (from 400 cfs to 183 cfs).

The updated Moss Bluff analysis presented herein, using Ocala discharge records to extend the pre-1970 Moss Bluff POR, is in substantial agreement with the results of Tibbals and others (2004). The current estimates are 365 cfs for pre-1970 average discharge and 193 cfs for post-1970 average discharge, a reduction of 47%.

Tibbals and others (2004) concluded that the primary cause of the reduced discharge from the UORB is likely a combination of lower potentiometric surface levels for the Floridan aquifer and implementation of new regulation schedules in the Harris Chain of Lakes. The net effect of these factors is to increase groundwater recharge and reduce surface water discharge. However, more recent work by Kelly and Gore (2008) has become available. This work evaluated the influence of the AMO climatic cycle on river flow patterns, including peninsular Florida Rivers, and provides an explanation for the observed discharge reduction at Moss Bluff as well as at downstream locations.

Kelly and Gore (2008) compared the 30-year pre-1970 warm period (1940 through 1969) discharge to the 30-year post-1970 cool period (1970 through1999) discharge for 17 peninsular Florida stream gaging stations and found that decreases, averaging 29.7%, were observed in 16 of the 17 cases.

Analysis of the individual or composite records at Moss Bluff, Silver River and the basin outlet revealed the same general pattern. Average discharge occurring prior to 1970 was larger than average discharge occurring after 1970.

An AMO test was applied to each of the three LORB gaging stations as well as the two Withlacoochee River benchmark gaging stations. In this test the 30-year pre-1970 average discharge is compared to 30-year post-1970 average discharge (Table 21).

Table 21. AMO test results summary

Part a) Ocklawaha River locations

Location	AMO Test Results			
	Pre-1970 Discharge (cfs)	Post-1970 Discharge (cfs)	Discharge Reduction	
			(cfs)	(%)
Moss Bluff	368	198	170	46.2%
Silver River	829	758	71	8.6%
Total ORB (Base Case)	2,018	1,355	663	32.9%
Total ORB (Adjusted) [1]	1,781	1,355	426	23.9%

[1] Pre-Rodman measured discharge reduced to account for possible Riverside Landing flow overestimate.

Part b) Withlacoochee River benchmark locations

Location	AMO Test Results			
	Pre-1970 Discharge (cfs)	Post-1970 Discharge (cfs)	Discharge Reduction	
			(cfs)	(%)
Croom	530	325	205	38.7%
Holder	1,205	811	394	32.7%

The ORB AMO test results are similar to the results obtained in the adjacent and similar Withlacoochee River benchmarking AMO tests (Table 21 part b). For the 810 square mile Croom watershed, the post versus pre-1970 discharge reduction was about 39% as compared to 46% for the similar Moss Bluff watershed.

For the downstream 1,825 square mile Holder watershed the post versus pre-1970 discharge reduction was about 33% as compared to 24% to 33% for the Ocklawaha River outlet. Holder is similar in size to the ORB outlet but does not include discharge from a major first magnitude spring.

The results obtained in this analysis for the ORB exhibit an AMO signature as expected based both on comparisons to the regional results reported by Kelly and Gore (2008) and by the benchmarking analysis for the Withlacoochee River basin gaging stations.

Ocklawaha River Basin Discharge

Upper Ocklawaha River Basin

With headwaters located within the Green Swamp, the UORB is characterized by extensive surface storage. Further, downstream large lakes dominate the upper basin. The Upper Ocklawaha River Lakes (also known as the Harris Chain of Lakes) alone provide a surface area of about 120 square miles and a volume of over 618,000 acre feet (Table 1). The Upper Ocklawaha River Lakes provide a theoretical water residence time of about 3 years.

Additionally, discharge at Moss Bluff has been controlled since 1925, well before the beginning of systematic discharge measurement. The combination of extensive surface storage and discharge control has impacted the natural time distribution of outflow from the UORB. However, the impact of outflow control on the total volume of discharge is less certain.

The UORB has a surface tributary area of about 821 square miles, which is approximately 42% of the total basin tributary area. Total discharge, for the 60-year AMO test period (1940 though 1999), averaged 283 cfs or about 17% of the total measured basin discharge (1,686 cfs) for the same period.

Like other peninsular Florida streams, the AMO climatic cycle appears to have a pronounced impact on the yield of the UORB

Spring Flow Contribution

One of the most important hydrologic features of the LORB is the contribution of spring flow from both major and minor springs located along the lower river. The contribution of the major springs (i. e. Silver Springs via the Silver River) is well documented and readily quantifiable. Smaller local springs, located along the river, downstream from the Silver River confluence are sparsely documented and therefore the contribution of these smaller springs and associated diffuse groundwater inflow is more difficult to quantify and subject of a high degree of uncertainty.

Silver River

Silver River discharge, for the 60-year AMO test period, averaged 793 cfs. This is about 47% of the total basin discharge and more than 2.8 times the quantity contributed by the UORB. The Silver River discharge provides a hydrologically reliable base flow and because it is primarily groundwater, rather than surface water, exhibits a much smaller AMO response.

The AMO test, applied to the Silver River discharge record, results in a pre-1970 average discharge of 829 cfs and a post-1970 average discharge of 758 cfs, for a pre versus post-1970 reduction of 71 cfs or 8.6%. This suggests that the AMO induced seasonal rainfall shift (as discussed in Appendix B) is less important for groundwater derived spring discharge than for surface water discharge.

Lower Ocklawaha River Springs

Abbott (1971) reported the approximate location of 20 small springs along the Lower Ocklawaha River. Ten springs are located along the reach between Eureka and Orange Springs and ten are located between Orange Springs and Riverside Landing.

All known direct discharge measurements for the Lower Ocklawaha River springs are reported in Appendix A. A total of 25 measurements for nine springs are available and only one of these measurements was obtained prior to construction of Rodman Dam. Therefore, estimates of the magnitude of the Lower Ocklawaha River springs discharge/groundwater inflow are developed, by indirect methods, primarily from analysis of stream discharge records. Both the pre-Rodman and post-Rodman periods are investigated.

Pre-Rodman. The hydrologic data review portion of this investigation provides an indirect estimate of the likely range of pre-Rodman local springs and diffuse groundwater inflow along the lower river reaches. An internal consistency review for concurrent data available for the Ocklawaha River stream gages (Moss Bluff to Riverside Landing) provides an incremental discharge analysis which includes estimates of the local spring flow plus possible net gaged flow overestimate component (Table 22).

Table 22. Local springs plus groundwater inflow and possible flow overestimate estimates from concurrent period of record analysis (October 1943 through December 1952)

Lower Ocklawaha River Reach	Increased Discharge (cfs)	Estimated surface water inflow (cfs)		Remaining Discharge = local springs + diffuse groundwater + flow overestimate (cfs)	
		Based on SJRWMD drainage area	Based on USGS drainage area	Based on SJRWMD drainage area	Based on USGS drainage area
Eureka to Orange Springs	152	94	73	58	79
Orange Springs to Riverside Landing	412	64	39	348	373
Eureka to Riverside Landing	564	158	112	406	452

For the Eureka to Orange Springs reach the measured increase in discharge is 152 cfs, of which 73 to 94 cfs is expected increased surface water runoff, leaving 58 to 79 cfs remaining. The remaining discharge consists of some combination of local spring discharge, groundwater inflow and possible gaged flow overestimate. Given that the magnitude of the remaining discharge is on the order of 3 to 4 percent of the total discharge measured at Orange Springs and that local springs are known to exist, it is concluded that the records for these gages are internally consistent and that there is likely little or no flow overestimate (flow overestimate = 0). Therefore, the remaining discharge (58 to 79 cfs) is considered to be a reasonable estimate of the pre-Rodman local springs and groundwater inflow for this river reach.

For the Orange Springs to Riverside Landing reach the measured increase in discharge is 412 cfs, of which 39 to 64 cfs is expected increased surface water runoff, leaving 348 to 373 cfs remaining. As above, the remaining discharge consists of some combination of local spring discharge, groundwater inflow and possible gaged flow overestimate. In this case, the magnitude of the remaining discharge is large, on the order of 16 to 17 percent of the total discharge measured at Riverside Landing.

It is possible that the Riverside landing discharge data are accurate (flow overestimate = 0) and that all of the remaining measured discharge is local spring and groundwater discharge. However the magnitude of the remaining unexplained measured discharge is quite large amounting to the equivalent of about 40% of the measured Silver River discharge for the same period. Given that there is no mention in the literature of very large springs located in this nine mile river reach, it is considered possible that a substantial flow overestimate may exist for the Riverside Landing discharge record.

The only individual spring mentioned in the pre-Rodman period, for this river reach, is Blue Spring which was described by Abbott (1971) as the largest of the local springs. The only pre-Rodman local spring discharge measurement is for Blue Spring, where a discharge of 10.6 cfs was measured on October 8, 1935. (Ferguson and others, 1947).

If it is assumed that the ten springs located between Orange Springs and Riverside Landing are similar to the ten springs located between Eureka and Orange Springs then a reasonable estimate for expected pre-Rodman spring discharge (plus groundwater inflow), for each reach is the 58 to 79 cfs value previously developed for the Eureka to Orange Springs reach. This assumption would yield an expected value of 116 to 158 cfs for the entire river reach from Eureka to Riverside Landing.

Obviously there is a high degree of uncertainty associated with the magnitude of the pre-Rodman local springs and groundwater inflow component, which likely lies somewhere between 116 cfs and 452 cfs.

Post-Rodman. It is expected that spring discharge and diffuse groundwater inflow would be reduced for post-Rodman conditions. Filling of the reservoir increased the discharge head on spring vents located within the reservoir pool thus decreasing the net available discharge head. The impact would vary with reservoir pool stage and spring vent location. For normal pool elevation (18 feet NGVD) the increased head is about 12 feet at Rodman Dam decreasing in an upstream direction, with the impact fully dissipated at Eureka.

Local spring and diffuse groundwater discharge for post-Rodman conditions are developed in two ways. First, by analysis of the available individual spring discharge measurements (Table 23) and second by indirect calculation based on the Rodman Reservoir water budget analysis reported in Appendix C.

Table 23. Summary of post-Rodman spring discharge measurements (from Appendix A)

Spring	Average measured Discharge (cfs)
Blue	11.45
Catfish	4.18
Bright Angel	0.45
Sims	0.83
Fish Hook 2	1.02
Fish Hook 1	0.83
Riversites	3.05
Tobacco Patch Landing	3.92
Well Landing	8.44
Total (9 springs)	**34.17**

Blue Spring is the largest of the measured springs and accounts for about 33% of the total measured spring discharge of 34.17 cfs. An estimate of the total post-Rodman spring discharge can be obtained by extrapolating the nine measured springs to the 20 known springs. The total discharge is estimated as (20/9)*34.17=76cfs. This local springs discharge estimate does not include the diffuse groundwater contribution which cannot be measured directly.

The Rodman Reservoir water budget analysis, fully documented in Appendix C, results in an estimated post-Rodman spring discharge plus diffuse groundwater inflow of 138 cfs (Table 24). This value is comparable to the 76 cfs local springs only discharge estimate derived from the limited individual spring discharge measurements. However, the local springs component of the water balance also includes any cumulative error associated with the several time series data sets applied in the water budget calculations.

For the Rodman Reservoir water budget period of analysis, the Silver River is the main inflow source at nearly 55% of the total inflow. With the estimated local spring discharge added the total spring flow plus diffuse groundwater contribution is about 65% or nearly 2/3 of the total reservoir inflow.

Table 24. Inflow summary for Rodman Reservoir water balance analysis (May 1975 through September 2007)

Source	Mean Value (cfs)	Percentage of Total
Silver River	700.8	54.63%
Moss Bluff	185.2	14.44%
Orange Creek	72.8	5.67%
Ungaged Surface Inflow	132.3	10.31%
Rainfall Inflow	53.7	4.19%
Local Springs + error	**138.1**	**10.76%**
TOTAL	1,282.9	100.00%

Total Ocklawaha River Basin Discharge

For the total ORB yield two scenarios are defined. The first, termed the base case, uses all data as reported and represents conditions if all Riverside Landing measurements are accurate. The second case termed the adjusted case adjusts the Riverside Landing data by 14%. All other streamflow arrays are used as recorded. The AMO signature is apparent in both cases.

For the base case, the AMO test results in a pre-1970 average discharge of 2,018 cfs and a post-1970 average discharge of 1,355 cfs, resulting in a pre versus post-1970 reduction of 663 cfs or 32.8%. For the entire 60-year AMO test period total basin yield averaged 1,686 cfs (1.09 billion gallons per day)

For the adjusted case, the AMO test results in a pre-1970 average discharge of 1,781 cfs and a post-1970 average discharge of 1,355 cfs, resulting in a pre versus post-1970 reduction of 426 cfs or 23.9%. For the entire 60-year AMO test period total basin yield averaged 1,568 cfs (1.01 billion gallons per day)

The similar benchmarking station, Withlacoochee River at Holder, exhibits a comparable 32.7% reduction in average discharge for the same test period. In either case (base or adjusted) the observed post versus pre-1970 average discharge reductions are in the range of expected AMO influence.

Implications for Establishment of Minimum Flows and Levels and Water Supply Planning

Understanding the role of the AMO as well as other climate cycles in peninsular Florida river flow patterns is important to sound water resources investigations and decision making. Overall, the results reported by Kelly and Gore (2008), as well as the results of the current investigation, would suggest that 60 or more years of stream discharge data are desirable for water resources investigation and decision making to account for the effects of a complete AMO climatic cycle and that analysis of only an AMO warm period or cool period could lead to poor conclusions. Also, if data are available from only one period (warm or cool) it is important to understand the probable influence of the AMO on the available record in order to reach appropriate conclusions.

Additional LOR Measured Discharge Investigation

The hydrologic data review has demonstrated consistency in the data for all LOR stream discharge stations with the exception of the Riverside Landing gage. The records for this gage show a very large increase in measured flow relative to upstream measurements. This large increase is not fully explained and may arise from either a very large spring flow/groundwater contribution in the river reach between Orange Springs and Riverside Landing, or it could be due to net gaged flow overestimate at the Riverside Landing gage.

Both possibilities deserve further investigation, if a complete understanding of ORB hydrology (required for realistic hydrologic modeling) is to be developed.

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APPENDIX A

Lower Ocklawaha River Spring Discharge Observations

Spring Name	Date	Discharge -- cfs	Source
Blue Spring	10/8/1935	10.6	1
	5/18/1999	5	2
	9/27/2007	0.78	3
	1/24/2008	27.5	HDS
	2/21/2008	20	HDS
	3/6/2008	3.96	HDS
Catfish Spring	3/6/2008	4.18	HDS
Bright Angel	9/27/2007	0.45	3
Sims Spring	12/27/2007	0.68	HDS
	2/21/2008	0.45	HDS
	2/13/2009	1.36	HDS
Fish Hook 2	2/21/2008	1.02	HDS
Fish Hook 1	9/27/2007	0.09	3
	1/24/2008	0.8	HDS
	2/21/2008	1.59	HDS
Riversites	1/31/2008	3.3	HDS
	2/20/2008	2.79	HDS
Tobacco Patch Landing	3/3/1999	2.8	2
	2/6/2002	4.98	HDS & 4
	1/31/2008	4.09	HDS
	2/20/2008	3.8	HDS
Wells Landing	3/8/1999	9.88	2
	2/6/2002	8.3	HDS & 2
	1/31/2008	7.77	HDS
	2/20/2008	7.8	HDS

Local Spring Discharge Measurement Source

1) Ferguson G.E., Lingham C.W., Love S.K. and Vernon R.O. 1947. *Springs of Florida* Geological Bulletin No. 31, Florida Geological Survey, Tallahassee Florida.

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APPENDIX B

The Impact of the AMO Climatic Cycle on Seasonal and Annual Rainfall and Linkage to Stream Discharge

The main report is primarily concerned with the watershed yield of the ORB and therefore includes various analyses of discharge data. It is concluded, based on the discharge data analysis as well as on the results of previous regional investigations (Kelly and Gore, 2008) that the AMO climatic cycle is likely responsible for much of the long-term observed variations in both UORB and LORB discharge. However, rainfall is the primary driver of ORB hydrology and therefore it is also important to investigate and understand the AMO impact on seasonal and annual rainfall as well as the hydrologic linkage between rainfall characteristics and surface water discharge.

This Appendix presents supplemental analysis and summaries of rainfall records for the rainfall stations included in the main report. The locations of these rainfall stations are shown on report Figure 2 and are listed as follows:

- Lisbon
- Ocala
- Gainesville
- Palatka

AMO Rainfall Test

The AMO rainfall test compares average monthly rainfall for the AMO warm period (30-years from 1940 through 1969) to the AMO cool period (30-years from 1970 through 1999). This test is similar to the AMO discharge test applied extensively within the main report. The discharge test compared average annual discharge for the same pre and post-1970 test periods.

The AMO rainfall test results are illustrated in Figures B1 through B4 for the Lisbon, Ocala, Gainesville and Palatka rainfall stations respectively.

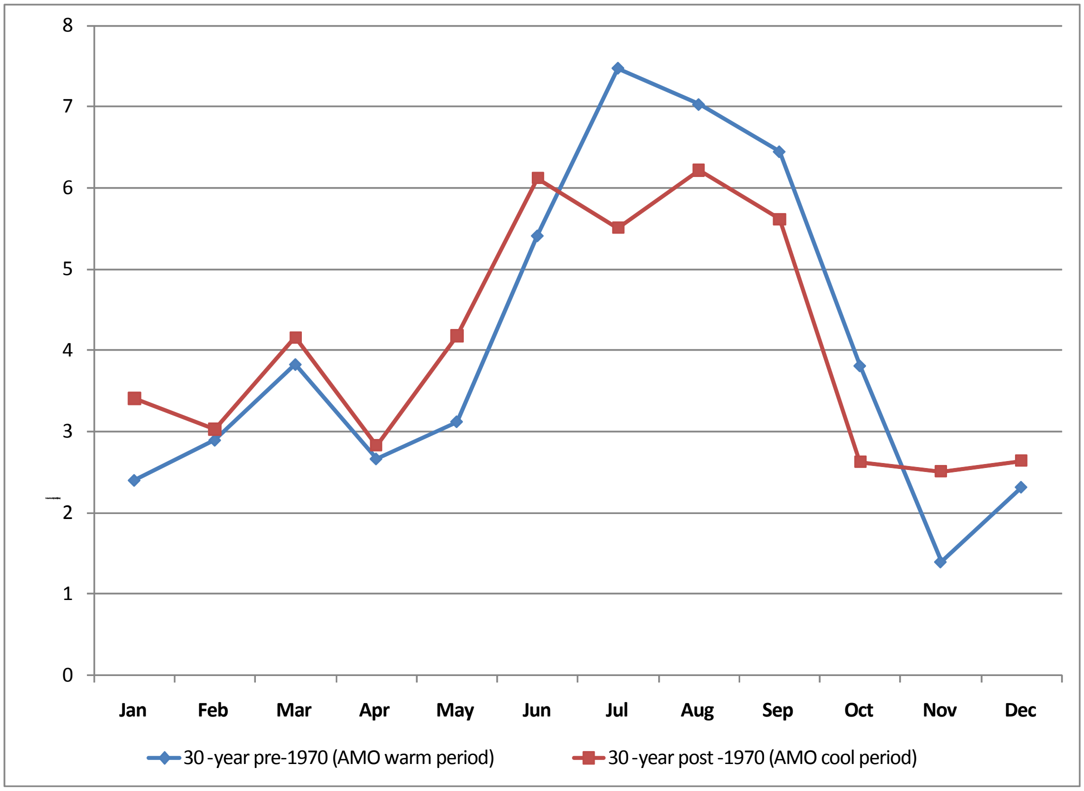

Figure B1. Monthly pre and post-1970 rainfall distribution for Lisbon

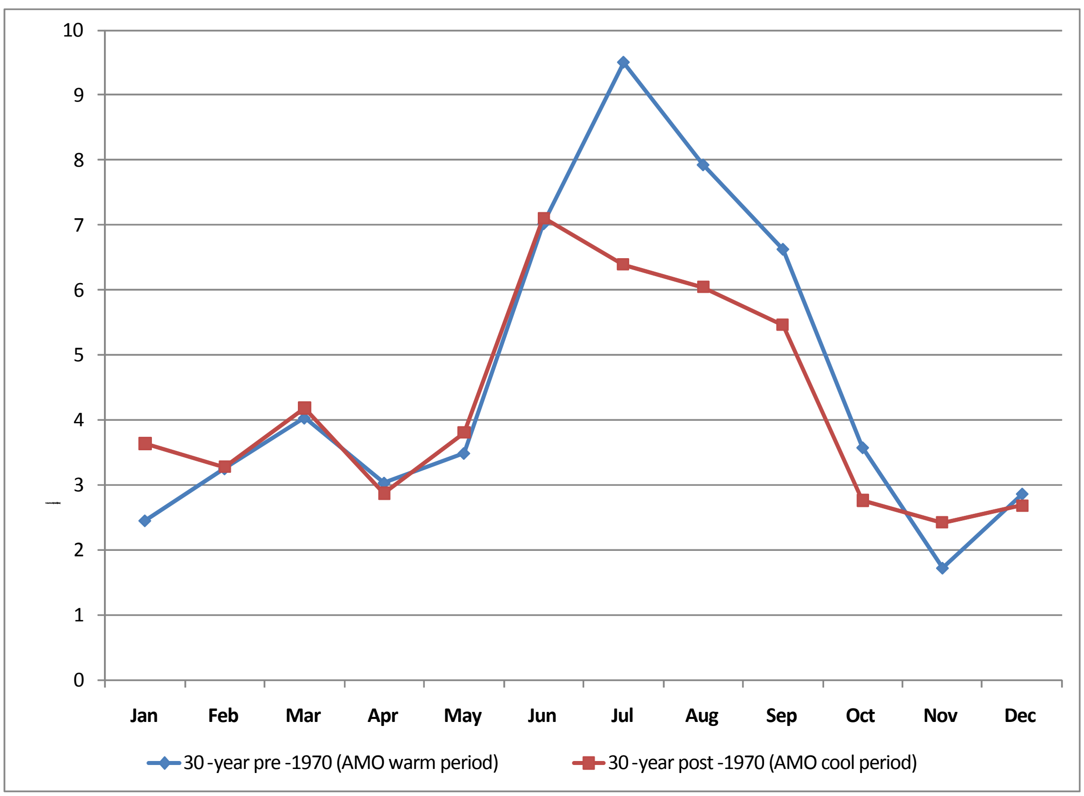

Figure B2. Monthly pre and post-1970 rainfall distribution for Ocala

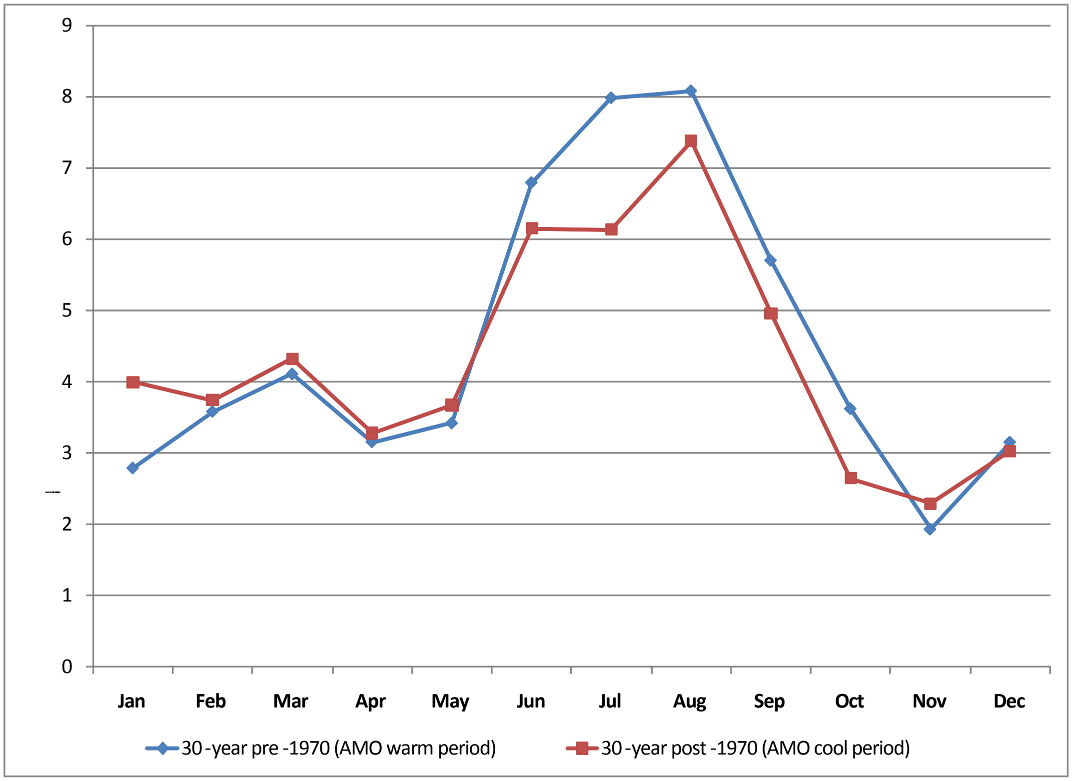

Figure B3. Monthly pre and post-1970 rainfall distribution for Gainesville

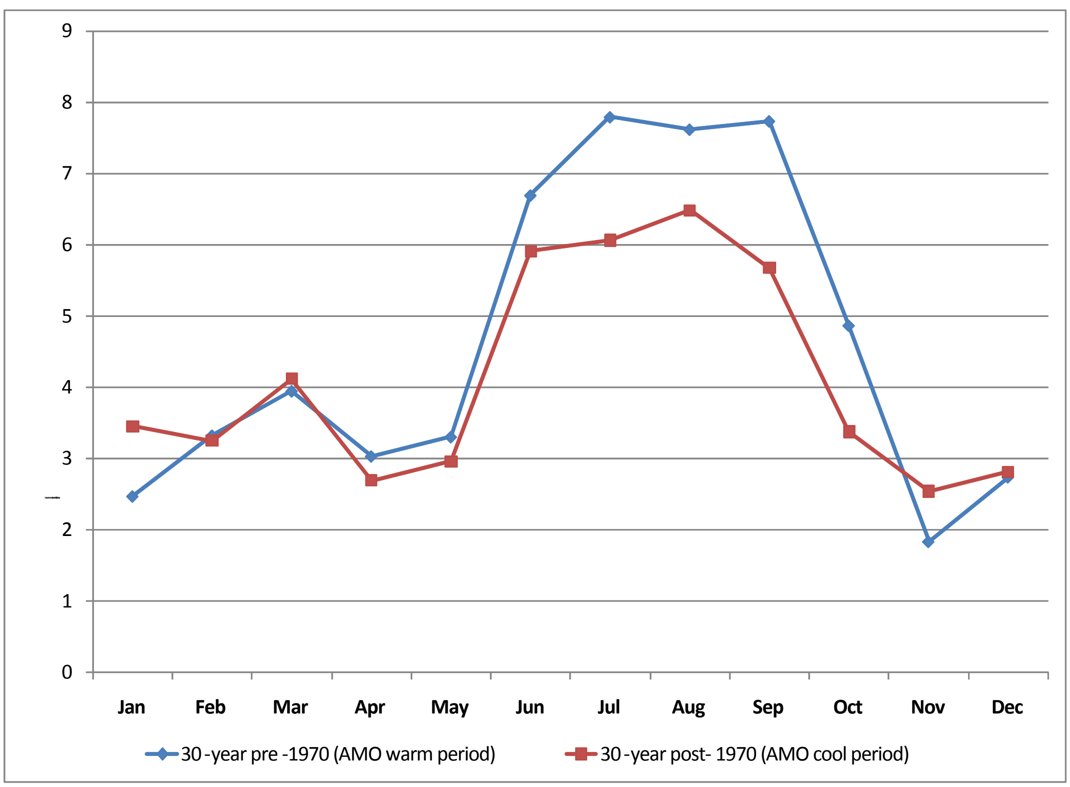

Figure B4. Monthly pre and post-1970 rainfall distribution for Palatka

Seasonal Rainfall Pattern Comparison

The AMO influence on seasonal rainfall is very similar for all four stations. In each case, average monthly rainfall is greater for the AMO warm period (pre-1970) during the months of July, August, September and October. For these four stations, June appears to a transitional month from the non-tropical dry season the tropical wet season and is not greatly influenced by the AMO. November is one of the driest months of the year and is somewhat dryer during the AMO warm period. Given that AMO warm period (pre-1970) July through October average monthly rainfall is greater than AMO cool period (post-1970), for all four stations, the four-month July through October period is considered to be the ORB tropical wet season and the remainder of the year is consisted to be the non-tropical dry season.

The 60-year AMO test period average annual rainfall along with the respective warm and cool period averages are reported in Table B1 part a. Table B1 part b reports similar averages for the four month tropical season.

Table B1. Summary results for the AMO rainfall test

Part a) annual rainfall

Rainfall Station	Average Annual Rainfall (inches)			Post-1970 vs. Pre-1970 Reduction	
	60-year AMO test period	30-year pre-1970	30-year post-1970	(inches/year)	(percentage)
Lisbon	48.80	48.77	48.83	-0.06	-0.13%
Ocala	53.10	55.51	50.68	4.82	8.69%
Gainesville	52.91	54.27	51.55	2.72	5.01%
Palatka	52.32	55.33	49.31	6.02	10.87%
Four Station Average	51.78	53.47	50.09	3.37	6.31%

Part b) tropical season (July through October) rainfall

Rainfall Station	July thru October Rainfall (inches)			Post-1970 vs. Pre -1970 Reduction	
	60-year AMO test period	30-year pre-1970	30-year post-1970	(inches/year)	(percentage)
Lisbon	22.36	24.75	19.97	4.79	19.33%
Ocala	24.16	27.64	20.67	6.97	25.21%
Gainesville	23.24	25.37	21.10	4.27	16.82%
Palatka	24.80	28.02	21.59	6.42	22.93%
Four Station Average	23.64	26.44	20.83	5.61	21.22%

As can be seen by inspection of Figures B1 through B4, as well as by the summaries reported in Table B1, the AMO climatic cycle impacts both total annual rainfall and tropical season rainfall. The impacts to annual rainfall are modest and range from a zero percent difference (for Lisbon) to a nearly 11% difference for Palatka with the four station average equal to a 3.37 inch per year reduction, or about 6.3%. The AMO impacts to seasonal rainfall are considerably greater and range from about 17% to 25% difference with a four station average equal to a 5.61 inch (21.2%) reduction for the 4-month tropical wet season.

Discharge Response

Rainfall is the source of all ORB discharge. However, total basin discharge including surface water runoff and spring discharge is only a small fraction of the total rainfall input. When rain falls upon the land it first wets the surface and then enters the soil matrix. Most of the soil moisture will be returned to the atmosphere as a combination of free water surface evaporation and plant transpiration (evapotranspriation). The remaining water can either become groundwater recharge or surface runoff.

On a local scale, direct stormwater runoff only occurs once available soil moisture storage is filled. Thus, direct runoff tends to be the last component of the hydrologic budget occurring only after evapotranspiration and at least some groundwater recharge. Therefore, surface runoff and rainfall are not directly proportional. Runoff producing rainfall events tend to be the larger events occurring during wet antecedent conditions. Small rainfall events, occurring under dry antecedent conditions, will become evapotranspriation but will not produce surface runoff.

Bush (1974) reported that evapotranspriation within the Ocklawaha lakes area (UORB) is likely to equal or exceed 30 inches per year. The four station 60-year AMO test period average annual rainfall totals about 51.8 inches per year (Table B1). If it is assumed that at least 30 inches of this annual total is evapotranspriation then the remaining 21.8 inches per year is the maximum available for both groundwater recharge and/or surface runoff.

The AMO discharge test results for the ORB presented in the main report are summarized in Table B2. For the purpose of comparison to the rainfall AMO test results, annual discharge for the various discharge locations and scenarios are reported in units of inches per year.

Table B2 Discharge AMO test summary for comparison to rainfall AMO test results.

Discharge Location/ Scenarios	Annual Discharge (inches)			Post-1970 vs. Pre-1970 Reduction	
	60-year AMO test period	30-year pre-1970	30-year post-1970	(inches / year)	(percentage)
Moss Bluff	4.68	6.09	3.28	2.81	46.2%
ORB (base case)	11.66	13.93	9.35	4.58	32.9%
ORB (adjusted)	10.82	12.29	9.35	2.94	23.9%
ORB (base case) w/o Silver River	6.18	8.21	4.12	4.09	49.8%
ORB (adjusted) w/o Silver River	5.35	6.57	4.12	2.45	37.3%

Considering Moss Bluff (UORB) it is apparent that surface water discharge is a relatively small fraction the total basin water budget. The 60-year average annual discharge of 4.68 inches is only about 9% of the four station 60-year average annual rainfall of 51.78 inches per year. At 30-inches per year, evapotranspiration represents about 58% of the UORB water budget, or about 6.4 times greater than the surface water discharge component.

During the 30-year AMO warm period, surface water discharge at Moss Bluff averages 6.09 inches per year, or about 1.41 inches per year greater than the 60-year average. Conversely, during the 30-year AMO cool period, surface water discharge averages about 3.28 inches per year or 1.40 inches per year less than the 60-year average. This 2.81 inches per year total reduction in surface water discharge represent a significant reduction in total discharge (46.2%) but only a small portion (about 5%) of total UORB rainfall.

The 2.81 inches per year reduction in total UORB discharge at Moss Bluff compares to a corresponding 3.37 inches per year reduction in total annual rainfall and a 5.61 inches per year reduction in the runoff producing tropical or wet season rainfall.

The ORB (base case) includes the 60-year composite discharge of the ORB outlet as discussed in the main report. It includes all surface runoff, as well as spring discharge measured above the basin outlet (Rodman Dam). In this case, total average basin discharge is 11.66 inches per year for the 60-year AMO test period. The ORB (adjusted) includes the 60-year composite discharge, adjusted for possible Riverside Landing flow overestimate, as also discussed in the main report. In this case, total discharge is 10.82 inches per year.

The final two Table B2 entries represent ORB discharge without the Silver River contribution, which is predominantly surface water discharge. Considering the ORB (base case) without the Silver River, the total 60-year average discharge is 6.18 inches per year or about 12% of total rainfall. During the 30-year AMO warm period, surface water discharge averages 8.21 inches per year or about 2.03 inches per year greater than the 60-year average. Conversely, during the 30-year AMO cool period surface water discharge averages about 4.12 inches per year or 2.06 inches per year less than the 60-year average.

Considering the ORB (adjusted) without the Silver River, the results are very similar to the UORB at Moss Bluff. The total 60-year average discharge is 5.35 inches per year. During the 30-year AMO warm period, surface water discharge averages 6.57 inches per year or about 1.22 inches per year greater than the 60-year average. Conversely, during the 30-year AMO cool period surface water discharge averages about 4.12 inches per year or 1.23 inches per year less than the 60-year average.

The 2.45 inches per year reduction in total LORB discharge compares to a corresponding 2.81 inches per year reduction for the UORB at Moss Bluff. These surface water discharge reduction values compare to a corresponding 3.37 inches per year reduction in total annual rainfall and a 5.61 inches per year reduction in the runoff producing tropical or wet season rainfall (Table B1).

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APPENDIX C

Rodman Reservoir Water Balance and Estimated Local Springs Discharge

Background and Purpose

Since its construction in 1968, Rodman Reservoir discharge has been controlled by the gated spillway structure of Rodman Dam. In general, water level above the dam has been maintained at or near 18 feet NGVD, with occasional drawdowns below and excursions above the normal pool elevation.

Nearly all inflow sources are either measured directly or can be estimated indirectly. For example, inflow via the Silver River is available directly from USGS discharge records and direct rainfall input (onto the Rodman Reservoir pool) can be estimated using Palatka rainfall records. Nearly all discharge is via the Rodman Dam spillway with a relatively small volume discharged via Buckman Lock.

The only inflow source for which direct measurements or indirect estimates are not available are the several local springs located along the Ocklawaha River below the Silver River confluence and above Rodman Dam. The local springs inflow term as defined and used herein also includes diffuse groundwater inflow occurring along this river reach. The purpose of this analysis is to estimate the magnitude of the local spring inflow by accounting for all other inflow sources and outflow sinks and solving for the remaining inflow required to provide the period of analysis water balance.

This water budget analysis relies entirely on available hydrologic records including, discharge, rainfall, evaporation and stage measurements. Each of these measurements includes error and the magnitude of the error is and will remain unknown. Error associated with the individual time series measurements and with the assumptions related to extrapolation of, or spatial transfer of, these data results in uncertainty in the accuracy of the final local springs discharge estimates.

Rodman Reservoir Inflow and Outflow Components

The following reservoir inflow sources and outflow sinks (Figure C1) are considered in this analysis.

- Inflow
    - Silver River (SR)
    - Moss Bluff (MB)
    - Orange Creek (OC)
    - Ungaged surface water (USW)
    - Rainfall (RI)
    - Local springs plus groundwater inflow (LS)
- Outflow
    - Rodman Dam discharge (RD)
    - Buckman Lock discharge (BL)
    - Evaporation (EO)

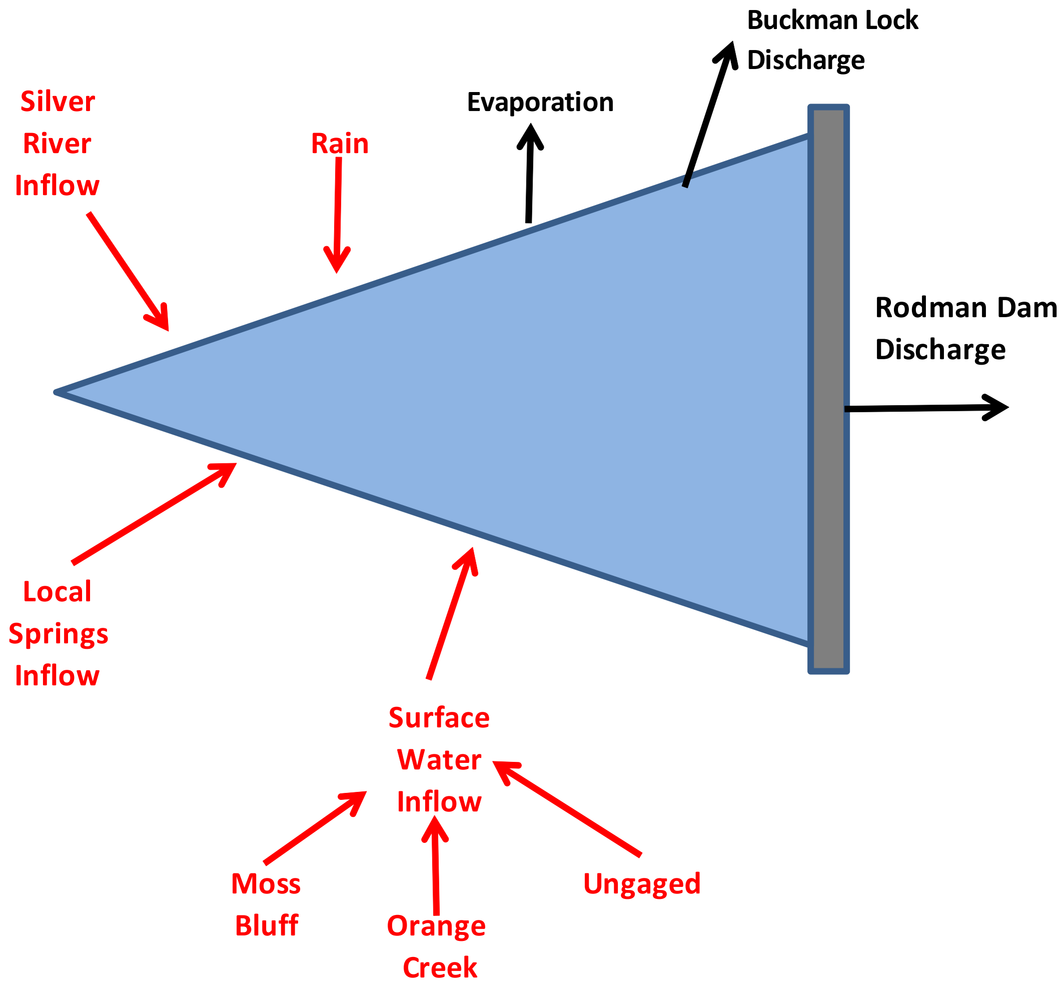

Figure C1. Schematic diagram illustrating Rodman Reservoir inflow sources and outflow sinks

Water Balance Equation

The water balance calculations are based on the hydrologic routing equation.

$$\mathrm{I} - \mathrm{O} = \Delta S/\Delta \mathrm{t} \qquad (1)$$

Where:

I = summation of all inflow sources
O = summation of all outflow sinks
$\Delta S/\Delta \mathrm{t}$ = change in storage with respect to time

For this analysis, a monthly time step was selected for all calculations thereby eliminating the Δt term. Substituting the individual inflow and outflow variables and solving for the unknown local spring (LS) inflow (plus error) yields the following Rodman Reservoir water balance equation.

$$\mathrm{LS} + \mathrm{error} = \Delta \mathrm{S} + (\mathrm{RD} + \mathrm{BL} + \mathrm{EO}) - (\mathrm{SR} + \mathrm{MB} + \mathrm{OC} + \mathrm{USW} + \mathrm{RI}) \qquad (2)$$

Given the monthly time step, all Equation 2 units are expressed in cfs-months and for computational simplicity all months are considered to be of equal length (30.44 days). Therefore, one cfs-month is approximately equal to 60.38 acre feet of water.

Rodman Reservoir Surface Area and Volume

Converting rainfall and evaporation, in inches per month to cfs-months, requires estimates of the monthly average reservoir surface area. In addition, calculation of the monthly change in reservoir storage volume (ΔS) requires knowledge of the beginning and end of month reservoir storage volume.

Rodman reservoir stage versus water surface area estimates were published in a previous hydraulic and hydrologic evaluation of various alternatives for Rodman Reservoir (Rao and others, 1994). This previous evaluation developed water surface profiles from Rodman Dam to Eureka Dam for various starting pool elevations. The entire 16.5 mile river section, between the two dams, was divided into 4 reaches and the water surface elevation and surface area for each reach was calculated as a function of starting pool elevation at Rodman Dam (Table C1).

Table C1. Rodman pool elevation and area data from Rao and others (1974).

Stage (pool Elev. at Rodman Dam)	Reach 1		Reach 2		Reach 3		Reach 4		Total Water Surface Area (acres)
	Elev. @ centroid.	Water surface area (acres)	Elev. @ centroid	Water surface area (acres)	Elev. @ centroid	Water surface area (acres)	Elev. @ centroid	Water surface area (acres)	
5.64	7.62	1793	10.62	593	14.7	1047	18.21	1061	4494
12.31	12.33	3428	12.44	872	15.22	1151	18.42	1144	6595
13.28	13.29	3597	13.36	1001	15.36	1180	18.45	1156	6934
14.26	14.27	3801	14.31	1124	15.39	1185	18.46	1160	7270
15.24	15.25	4091	15.27	1222	15.95	1298	18.55	1194	7805
16.22	16.23	4406	16.24	1320	16.6	1343	18.67	1241	8310
18.19	18.19	5226	18.2	1507	18.27	1443	19.14	1425	9601

The pool elevation and total water surface area data reported in Table C1 were used to construct the Rodman Reservoir stage area curve illustrated in Figure C2.

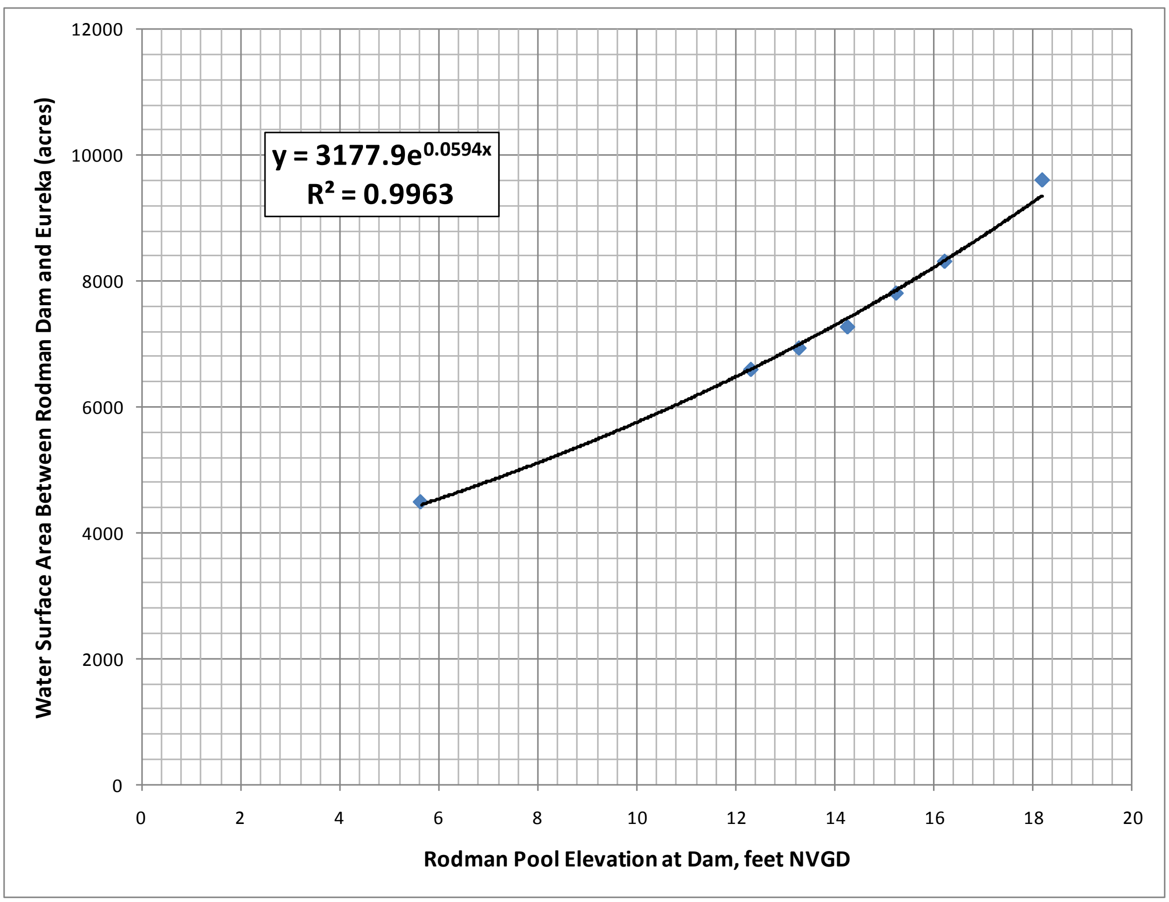

Figure C2. Stage area curve for Rodman Reservoir

The exponential trend line, shown on Figure C2 and presented below, is the relationship used in this analysis to calculate water surface area as a function of pool elevation at Rodman Dam.

$$A = 3{,}177.9\ e^{0.0594(\text{Stage})} \quad (3)$$

Where:

A = Rodman pool surface area, in acres
Stage = water surface elevation, in feet NGVD at Rodman Dam

The elevation and water surface area data for each reservoir segment reach (Table C1) were used to calculate incremental and cumulative storage volume. The individual reach values were then summed to develop the stage versus storage volume relationship shown in Figure C3.

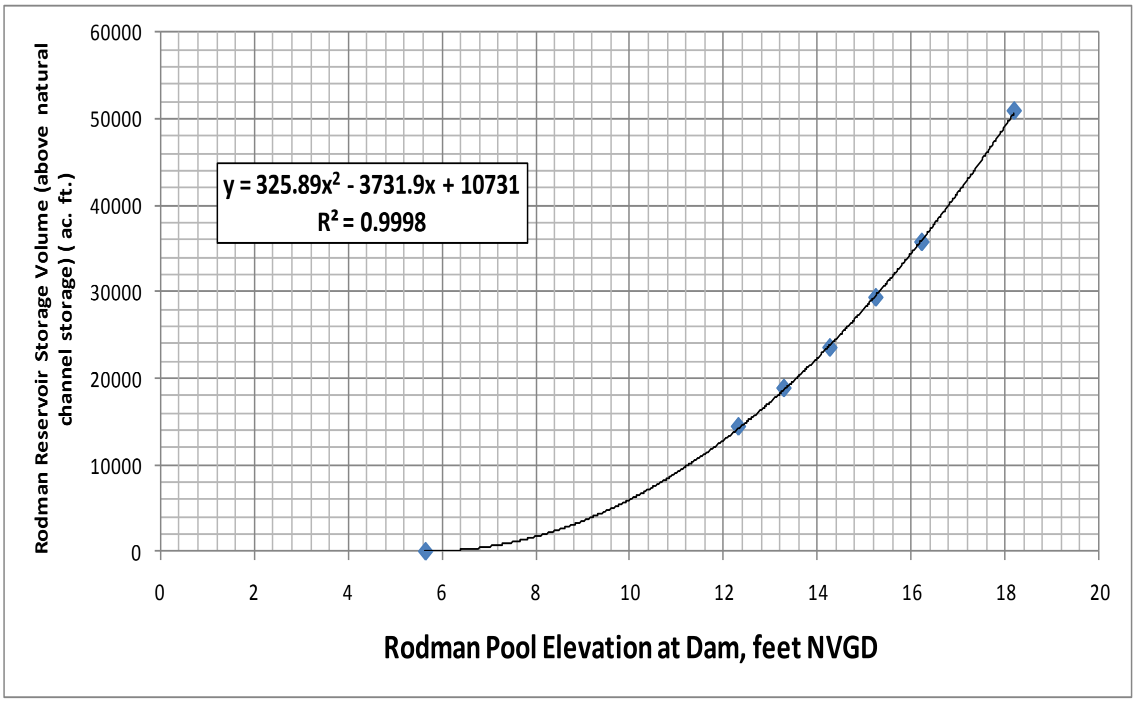

Figure C3. Stage volume curve for Rodman Reservoir

The polynomial trend line (Figure C3) defined below, is the relationship used in this analysis to calculate reservoir storage volume as a function of pool elevation at Rodman Dam.

$$V=325.89(\text{Stage})^2 - 3{,}731.9(\text{Stage}) + 10{,}731 \quad (4)$$

Where:

V = total storage volume above natural stream channel storage, in acre-feet.
Stage = water surface elevation, in feet NGVD at Rodman Dam

Data Preparation and Water Balance Calculations

Time Series Data Sources and Preparation

Several time series data sets were acquired and applied in the water budget analysis. These included monthly USGS discharge records for Rodman Dam (RD), Buckman Lock (BL), Silver River (SR) Moss Bluff (MB) and Orange Creek (OC). These monthly discharge data were used directly in the monthly water budget calculations.

Monthly rainfall data (R) for Palatka Florida, obtained from SJRWMD hydrologic records, were used to calculate Rodman pool rainfall inflow (RI). Monthly potential evapotranspriation (PET) estimates for Gainesville Florida, were provided by David Clapp (SJRWMD). The monthly PET estimates were used to calculate Rodman Reservoir monthly evaporation outflow (EO). The application of Palatka rainfall and Gainesville evaporation data to the Rodman Reservoir water balance is the same approach applied by Rao and others (1994).

Daily Rodman Reservoir pool elevation data are available from USGS records beginning October 2, 1999. However, earlier historic data beginning in July 1969 are also available and were provided by Awes Karama (SJRWMD). These early year surface water elevation data combined with the USGS record provide a complete daily time series beginning shortly after the reservoir was first filled.

For application to the water budget analysis, end of the previous month pool elevation values were extracted from the daily time series. This parameter establishes starting conditions for each month which are then applied to the rainfall (RI), evaporation (EO) and change in storage (ΔS) calculations.

Ungaged Surface Water Inflow (USW)

The ungaged surface water (USW) inflow originates entirely within the LORB. It includes the surface tributary area located above Rodman Dam (RD) and below Moss Bluff (MB) excluding the gaged Orange Creek (OC) Basin. Discharge from the ungaged tributary area (USW) is assumed to be proportional to the measured Orange Creek (OC) discharge.

The applicable tributary areas, based on the SJRWMD GIS database, are 820.9 square miles for Moss Bluff, 407.1 square miles for Orange Creek and 1,968 square miles for the entire ORB. Therefore, with both Moss Bluff and Orange Creek monthly discharge data available, 1,228 square miles of the ORB is gaged and 740 square miles is ungaged. The UWS water budget component is calculated as follows.

$$USW = (740/407.1)*(OC) \quad (5)$$

Where: all terms are as previously defined.

The water budget calculations are limited to the continuous period of record for which all needed time series data are available. This period begins in May 1975 and extends through September 2007, a period of 34 years 5 months.

Rainfall Inflow (RI) and Evaporation Outflow (EO)

The rainfall (RI) and evaporation (EO) calculations begin with the calculation of the beginning of the month reservoir surface area (A) by application of Equation 3. The monthly time step beginning surface area and the end of month surface area are then averaged and multiplied by the monthly rainfall (R) and potential evapotranspiration (E) in inches and converted to units of cfs-months.

Change in Storage (∆S)

Change in storage (∆S) is calculated as the end of month reservoir storage volume minus the beginning of month reservoir storage volume expressed in cfs-months.

Local Spring Inflow (LS) plus error

The final calculation is application of Equation 2 to solve for the volume of water needed to provide the monthly flow balance. This value is the estimated local spring (LS) inflow plus net monthly error.

Results

Results are summarized and discussed in two ways. First, the period of analysis total water budget is presented. Thereafter, characteristics of the calculated local springs inflow time series are explored.

Period of Analysis Water Balance Results

The period of analysis Rodman Reservoir water balance results are summarized in Table C2.

Table C2. Rodman Reservoir water balance summary (Begin May 1975 -- End September 2007 (34.42 years))

Part a) Inflow

Source	Symbol	Mean Inflow (cfs)	Percentage of Total
Silver River	SR	700.8	54.63%
Moss Bluff	MB	185.2	14.44%
Orange Creek	OC	72.8	5.67%
Ungaged Surface Water	**USW**	**132.3**	**10.31%**
Rainfall Inflow	RI	53.7	4.19%
Local Springs + error	**LS**	**138.1**	**10.76%**
TOTAL		1,282.9	100.00%

Part b) Outflow

Sink	Symbol	Mean Outflow (cfs)
Rodman Dam Discharge	RD	1,194.2
Buckman Lock Discharge	BL	33.2
Evaporation Outflow	EO	54.8
TOTAL		1,282.2

The local springs component is estimated to average about 138 cfs or approximately 10.8% of the total Rodman Reservoir inflow and 19.7% of the discharge contributed by the Silver River.

It is important to keep in mind that the estimated local springs inflow component also includes all errors associated with the individual water budget measurements and estimates. However, if the month to month errors are assumed to be random, then the overall average water balance provided in Table C2, for the 413 month period of analysis, can be consider a reasonable estimate of the local springs inflow component.

The uncertainty associated with the ungaged surface water (USW) inflow component must also be considered in addressing uncertainty in the local springs inflow estimate. Both the local springs component and the ungaged surface water component are estimated values and, for the assumptions applied herein, are of approximately the same magnitude. The ungaged surface water component is assumed to be directly proportional to the measured Orange Creek component which, for the period of analysis, is 0.179 cfs per square mile. If the USW component were actually larger, then the LS component would be smaller by an equal amount. Conversely, if the USW component is actually smaller, then the estimated LS component would be larger.

Local Springs (LS) Inflow Time Series

Selected sample statistics for four discharge time series for the 413 month period of analysis are reported and compared in Table C3.

Table C3. Sample statistics for selected monthly time series (begin May 1975 -- end September 2007 (34.42 years))

Parameter	Silver River (SR) Discharge (cfs)	Moss Bluff (MB) Discharge – (cfs)	Orange Creek (OC) Discharge – (cfs)	Local Springs Inflow (LS) + error (cfs)
mean	700.8	185.2	72.8	138.1
median	693.3	39.7	27.2	90.5
stdev	145.6	293.6	127.4	281.2
CV	0.208	1.585	1.750	2.036
max	1,067.0	1,603.0	1,095.0	1374.1
min	358.1	7.6	1.5	-742.3

The Silver River time series, derived from spring discharge, is relatively uniform when compared to the two surface water discharge time series (Moss Bluff and Orange Creek). For the Silver River, the mean and median are nearly equal and the coefficient of variation (CV), at 0.208, is small. The two surface water discharge sites are much more variable. The median values are much smaller than the mean values and the coefficient of variation (1.585 and 1.75) are much larger than the spring discharge dominated Silver River.

The individual calculated local springs values are the most variable. The coefficient of variation (2.036) is greater than all three observed time series and is an order of magnitude greater than the Silver River. The range from 1,374 cfs to -742 cfs is also much larger than for the observed discharge values even though this component represents only about 11% of the total reservoir inflow.

It appears that the error component could dominate individual computed monthly values of local spring inflow and, therefore, the individual values may be of limited use as a meaningful time series.
Figure C4 is a plot of the individual local springs (+ error) inflow estimates as a function of Rodman Reservoir monthly average pool elevation.

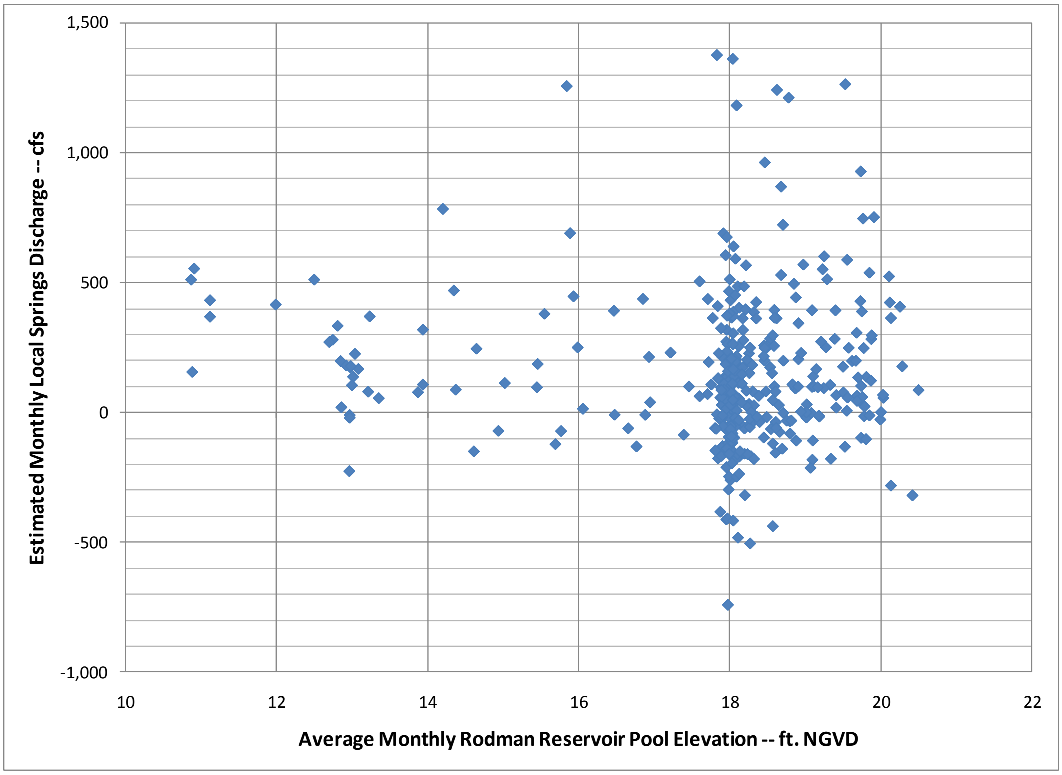

Figure C4 Estimated monthly local springs inflow (plus error) as a function of reservoir pool elevation

The individual monthly local spring inflow estimates exhibit little correlation to corresponding pool elevation. The R^2 value for these paired data is only 0.0038. These results are somewhat contrary to expected results based on physical principals of spring or diffuse groundwater discharge whereby an increase pool elevation would be expected to decrease the net driving head and therefore decrease the discharge magnitude.

The lack of such a relationship may be due to a dominance of the error term in the individual monthly estimates and/or a weak physical relationship. In either case a strong relationship between pool elevation and local springs inflow is not exhibited.

References

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