No. 142, Original

In the

Supreme Court of the United States

STATE OF FLORIDA,

Plaintiff,

v.

STATE OF GEORGIA,

Defendant.

Before the Special Master

Hon. Ralph I. Lancaster

PRE-FILED DIRECT TESTIMONY OF FLORIDA WITNESS DENNIS LETTENMAIER, PH.D

PAMELA JO BONDI
ATTORNEY GENERAL, STATE OF FLORIDA

JONATHAN L. WILLIAMS
DEPUTY SOLICITOR GENERAL
JONATHAN GLOGAU
SPECIAL COUNSEL
OFFICE OF THE ATTORNEY GENERAL

FREDERICK L. ASCHAUER, JR.
GENERAL COUNSEL
FLORIDA DEPARTMENT OF
ENVIRONMENTAL PROTECTION

GREGORY G. GARRE
Counsel of Record
PHILIP J. PERRY
CLAUDIA M. O'BRIEN
ABID R. QURESHI
JAMIE L. WINE
LATHAM & WATKINS LLP
555 11th Street, NW
Suite 1000
Washington, DC 20004
Tel.: (202) 637-2207
gregory.garre@lw.com

PAUL N. SINGARELLA
LATHAM & WATKINS LLP

CHRISTOPHER M. KISE
JAMES A. MCKEE
ADAM C. LOSEY
FOLEY & LARDNER LLP

MATTHEW Z. LEOPOLD
CARLTON FIELDS JORDEN BURT P.A.

ATTORNEYS FOR THE STATE OF FLORIDA

October 14, 2016

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1. My name is Dennis Lettenmaier. I have a Ph.D. in Civil Engineering, and for over 40 years I have been a professor with specialization in hydrologic modeling and prediction, hydrology-climate interactions, and long-term hydrologic change. I am an elected member of the National Academy of Engineering. In this testimony, I describe my analysis of whether changes in climate variables and land cover in the Apalachicola-Chattahoochee-Flint River Basin ("ACF Basin") are causing the observed decrease in streamflows on the Apalachicola River. This is a typical exercise in hydroclimatology (my discipline) and I was able to use a variety of commonly used, reliable tools and data in my analysis

2. A summary of my opinions is as follows:

a. Climate variables that affect runoff (runoff is synonymous with streamflow for this testimony), including precipitation, temperature, and evapotranspiration have changed at most modestly in the ACF Basin, both over the last century and since about 1970. Overall, there has not been a statistically significant change in runoff in the ACF Basin that can be attributed to changes in climate variables either over the last century or since 1970. As discussed further below, I relied on a variety of reliable, publicly available data sets and peer-reviewed models in my analysis. (Expert Report of Dr. Dennis Lettenmaier, February 29, 2016 ("Lettenmaier Report"), FX-793 at 1, 38-40.) Exhibit FX-793 is a true and accurate copy of my February 29, 2016 report, and exhibit FX-810 is a true and accurate copy of the errata to this report.

b. I also examined whether there has been a shift in precipitation from summer to other seasons that might explain the observed decrease in streamflows on the Apalachicola River during summer months. I found no statistically significant shift in precipitation during the year (i.e., from summer to other seasons) that would explain the decreased flows on the Apalachicola River during summer months. As discussed further below, I relied on a variety of reliable, publicly available data sets and peer-reviewed models, all of which are typically relied upon by experts in my field, in my analysis. (Defensive Report of Dr. Dennis Lettenmaier ("Defensive Report"), FX-809 at 5, 12-13.) Exhibit FX-809 is a true and accurate copy of my May 20, 2016 report.

c. Future changes in climate variables are not predicted to significantly reduce streamflow on the Apalachicola River. The average of projections from 38 global climate models indicate that changes in climate variables (especially precipitation) will have no material effect on Apalachicola River annual flows through at least 2050. (Lettenmaier Report, FX-793 at 6, 43-44.)

d. Georgia has argued that substantial amounts of water are being lost in the Florida portion of the ACF Basin and that these losses have increased over time. My analysis indicates there is no climatological reason for this purported trend and that there is no sound hydrological reason to believe that the trend is real. (Lettenmaier Defensive Report, FX-809 at 5.) The most likely reason for the purported losses is that Georgia relied on uncorrected gage data (Apalachicola River near Sumatra) and the Sumatra Gage has become prone to measurement error at high flows over the last 20-30 years, which has introduced an artificial trend into estimates of the incremental inflows to the Apalachicola River between the Sumatra and Chattahoochee gages. The United States Geological Survey ("USGS") is in the process of correcting the Sumatra Gage for errors.

e. Between 1950 and 2015, Georgia's water use has reduced streamflow on the Apalachicola River by at least 3,800 cfs on an average annual basis. (Lettenmaier

Report, FX-793 at 8, 41.) This net reduction includes the effects of land cover change (mostly urbanization) across the basin since the 1970s.

f. Georgia's scientists, Drs. Irmak and Panday, employ non-standard techniques to interpret rainfall in the ACF Basin. Their rainfall and rainfall trend interpretations are neither correct nor reliable.

I. PROFESSIONAL BACKGROUND

3. I am a Distinguished Professor of hydrology at the University of California, Los Angeles, where I have worked since 2014. Before my current employment, I spent 39 years as a Professor of Civil and Environmental Engineering at the University of Washington. Additionally, in 1997 and 1998, I served as Program Manager for the Land Surface Hydrology Program at NASA headquarters. My areas of expertise include hydrologic modeling and prediction, hydrology-climate interactions, and long-term hydrologic change.

4. I hold a Bachelor of Science degree in Mechanical Engineering from the University of Washington, where I graduated *summa cum laude* in 1970. In 1972, I received a Master of Science in Civil, Mechanical, and Environmental Engineering from the George Washington University. I received a Ph.D. in Civil Engineering from the University of Washington in 1975.

5. I have published over 300 scholarly articles in refereed journals of the highest caliber, including *Nature*, *Science*, the *Journal of Climate*, *Water Resources Research*, and *Climatic Change*. As early as 1978, I authored papers on the detection of climate change and its impact on hydrologic design, and the relationship of climate to hydrology has remained a central focus of my career.

6. Throughout my career, I have been a member and leader of numerous professional organizations. I am a past President of the Hydrology Section of the American

Geophysical Union (2010-2012). Among numerous other professional memberships, I have also been a member of the National Oceanic and Atmospheric Administration ("NOAA") Climate Prediction Program for the Americas Advisory Committee, and I have served as a member of the Science Steering Group for the Study of Environmental Arctic Change and the U.S. Global Change Research Program Water Cycle Study Group. In 1990, I acted as co-convenor of an American Geophysical Union Chapman Conference on Hydrologic Aspects of Global Climate Change. I was also the first Chief Editor of the American Meteorological Society's *Journal of Hydrometeorology*.

7. I have received a number of honors and awards for my work over the years. In 2010, I was elected a member of the National Academy of Engineering, the most prestigious engineering organization in the country. I was named the Walter Orr Roberts Lecturer and Robert E. Horton Lecturer by the American Meteorological Society in 2005 and 2008, respectively, and the Walter E. Langbein Lecturer by the American Geophysical Union in 2013. I am also a Fellow of the American Society for the Advancement of Science and the American Meteorological Society.

II. DATA, METHODS, AND KEY TERMS

8. In this first section, I describe some terms, data, and tools that I use in my testimony. All of these terms, data, and tools are widely used in hydroclimatology. All of the data sets and tools that I describe below are reliable and commonly used by practitioners in my field. (Lettenmaier Report, FX-793 at 12-15.)

9. **Hydroclimatology**: This is the study of how climate interacts with hydrology, including streamflow. My testimony here addresses whether changes in hydroclimatic variables are driving the loss of streamflow in the Apalachicola River. This is a typical sort of question that hydrologists study.

10. **Evapotranspiration**: This is water that this lost to the atmosphere through the combination of transpiration from plants and evaporation from bare soil and open water surfaces.

11. **Climate variables**: The climate data I used in my analysis include a variety of data that affect streamflow. This includes precipitation and temperature, but also data that are important for hydroclimatology, but less widely used in everyday life, such as evapotranspiration, diurnal temperature range (the difference between the high and low temperature in a day), solar and longwave radiation, and other climate variables. For my analysis of past hydroclimatological changes in the ACF Basin, I analyzed as many as seven different data sets for a range of hydroclimatic variables.

12. **Runoff/streamflow**: I use these terms synonymously to mean the volume of water in a stream passing a given point over a given time interval. The units commonly used are cfs (cubic feet per second). In the long term, runoff is the difference between precipitation (water going into the river basin) and evapotranspiration (water leaving the river basin), although groundwater recharge can affect surface runoff as well. If evapotranspiration is held constant, an increase in precipitation will cause an increase in runoff, assuming that other factors, such as land cover and other human interventions are held constant. Evapotranspiration itself depends on temperature, humidity, solar and longwave radiation, wind, and other variables. This relationship is shown schematically in Figure 1 below.

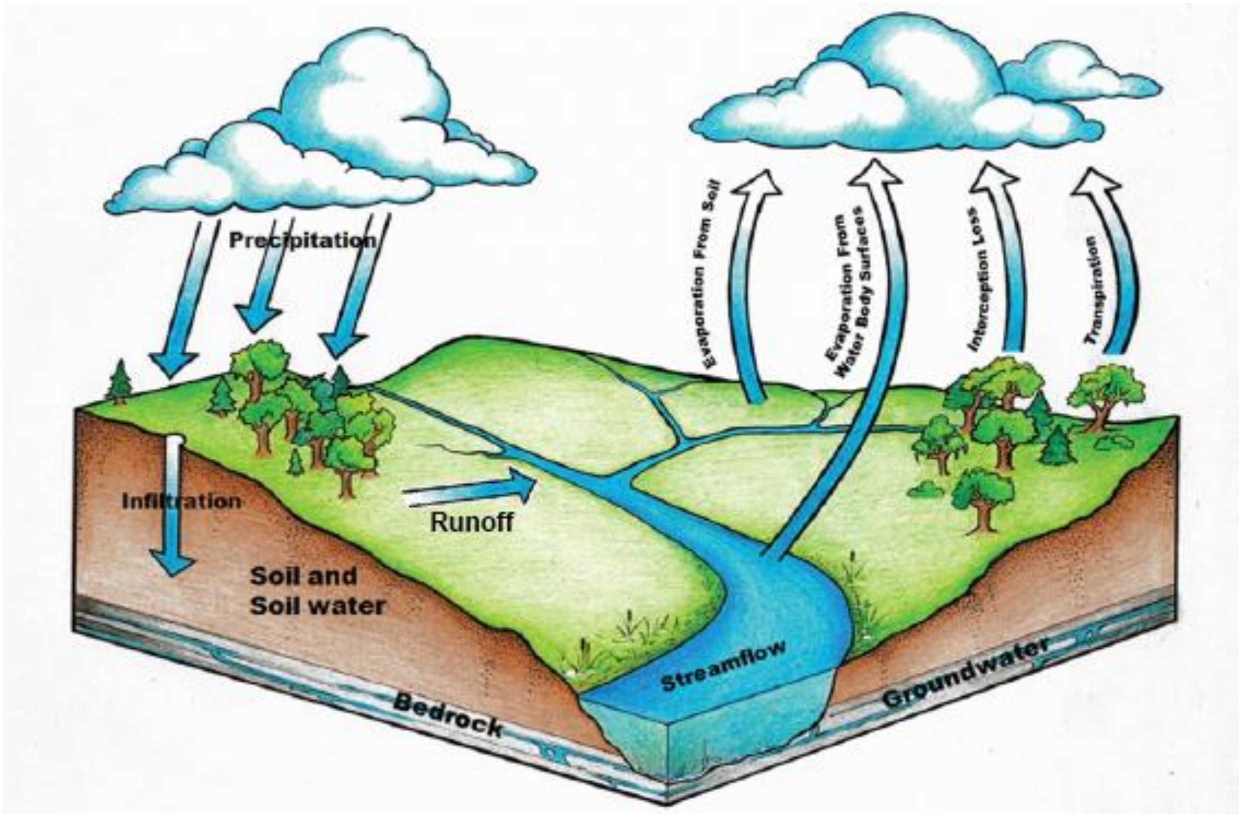

Figure 1: Schematic of hydrologic land surface fluxes (evapotranspiration, runoff, and precipitation) and storage (soil moisture; groundwater) (illustrating relationship described in Lettenmaier Report, FX-793 at 7). Adapted from Edwards, et al. (2015).

13. **Gridded climate data**: In my testimony and in my February 29 and May 20 Expert Reports, I rely upon gridded climate data from several sources. (Lettenmaier Report, FX-793, at 12-14; Lettenmaier Defensive Report, FX-809 at 5-6, 8.) This term is used to describe climate data—including temperature and precipitation—that are collected, over time, through direct measurements at observing stations. Daily precipitation and temperature maxima and minima (highs and lows) are collected (mostly by volunteer observers) across the country at some 12,000 locations coordinated and archived by NOAA. The climate data collected at these stations are weighted and interpolated onto a latitude/longitude grid that covers the land surface of the U.S. The gridded values at each grid node are comprised of weighted averages of

observations at nearby observing stations. Gridded climate data are now widely used for weather and climate, and hydrologic, forecasting and analysis.

14. When evaluating climate variables (e.g., temperature or precipitation) in a given region during a given time period, hydroclimatologists customarily rely upon gridded climate data, as opposed to, for instance, climate data from individual monitoring stations. (Lettenmaier Dep. Tr. (June 11, 2016), 579:17-580:10-14.) That is because the gridded climate data more accurately reflect the climatological conditions at the regional scale than can individual monitoring stations, which are subject to bias, variability, and inconsistency. For example, to determine how much precipitation occurred in a particular county during a particular month, a gridded data set comprised of interpolated precipitation observations at multiple monitoring stations throughout that county will more reliably indicate how much precipitation occurred in the county during that month than data gathered from any single rain gage, or even a small group of rain gages, in that county. This is primarily because precipitation measurements can vary considerably—even within small spatial areas—due to numerous variable factors such as wind speed, elevations, and the effects of structures in the vicinity of the measuring device. One rain gage in a county might measure a certain precipitation amount, another rain gage in the same county might measure more or less rain due to such variable factors. The gridded data sets account for this variability by averaging across multiple monitoring stations. Accordingly, they more reliably reflect precipitation occurrences in the county during the given period than a single rain gauge.

15. Whereas temperature and precipitation data are directly observed at monitoring stations, observations of other hydroclimatic variables, such as evapotranspiration, runoff, and soil moisture are much sparser. As a result, hydroclimatologists often employ modeling tools to

quantify evapotranspiration, runoff and other hydroclimatic variables for which direct observations are difficult to obtain or nonexistent. Directly observable hydroclimatic variables, such as temperature and precipitation, are used as inputs to these models, which derive evapotranspiration, runoff, and other hydroclimatic variables. Much like the gridded temperature and precipitation data, these derived climate variables can also be usefully incorporated into gridded data sets.

16. The gridded hydroclimatic variables I have used here are presented graphically for one of the datasets (the 1/16th degree (latitude by longitude) Livneh et al. (2013) data set) in Figure 2 below. The black dots in Figure 2 depict the 136 observation stations that the data set draws data from. In addition to avoiding the bias potential associated with individual monitoring stations, gridded data are useful because they allow me to estimate climate factors even in areas that lack observation stations.

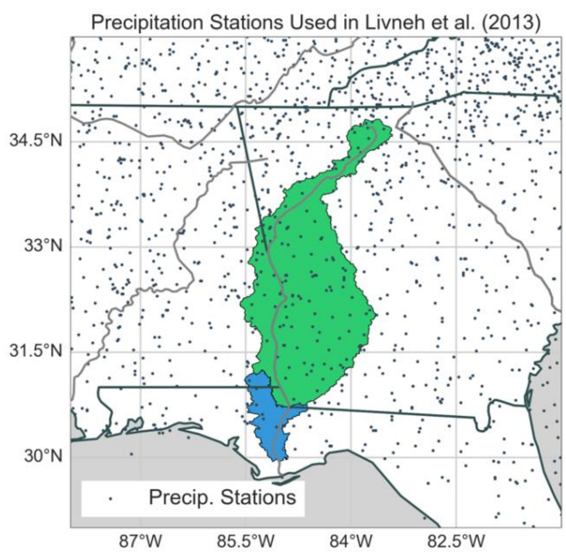

Figure 2: Apalachicola River drainage area between Sumatra and Chattahoochee (blue) and upstream of Chattahoochee (green). Circles represent the locations of in situ precipitation and temperature measurement stations used in the generation the Livneh et al. (2013) dataset (as described in Lettenmaier Report, FX-793 at 12, 13).

17. **Rainfall runoff model**: The data sets that I used to assess basin runoff included output from rainfall runoff models, including Precipitation Runoff Modeling System ("PRMS") developed by the U.S. Geological Survey and the Variable Infiltration Capacity ("VIC") Model (which I played a key role in developing) to calculate predicted runoff. These models take gridded climate data as inputs—including temperature and precipitation, wind speed, topography, land use patterns, vegetation and soil type, and solar radiation. They use first principles of physics and mathematical formulas to produce modeled runoff or streamflow, evapotranspiration, and other hydrologic variables as outputs.

18. **Global climate model**: In my analysis of the effects of climate change on the hydroclimate of the ACF Basin, I analyzed climate change projections from 38 global climate models. The climate models are based on systems of equations derived from the basic laws of physics, fluid motion, and chemistry and generate projections for numerous climate variables, including temperature and precipitation. These models divide the atmosphere, as well as the oceans and land surface, into a three-dimensional grid and evaluate the results of the equations that describe the fluid motion of the atmosphere and oceans. This is depicted schematically in Figure 3 below.

19. These future climate data sets are then processed to higher spatial resolution in a step known as downscaling, the output of which is gridded data sets representative of future conditions that are similar to those produced for the historical period from gridded observations. These gridded fields are in turn used as input to a hydrological model, which produces runoff, evapotranspiration, and other hydroclimatic variables comparable to those that result from historical runs of the same model. The downscaled climate model and hydrological datasets that I used were developed by the U.S. Bureau of Reclamation and a consortium of other federal

agencies, universities, and non-governmental organizations. They used the VIC hydrological model in essentially the same form as I used to reproduce historical hydroclimate conditions over the ACF Basin in the SWM and Livneh data sets, which are two of the data sets I used in my analysis. (Lettenmaier Report, FX-793 at 12-14.)

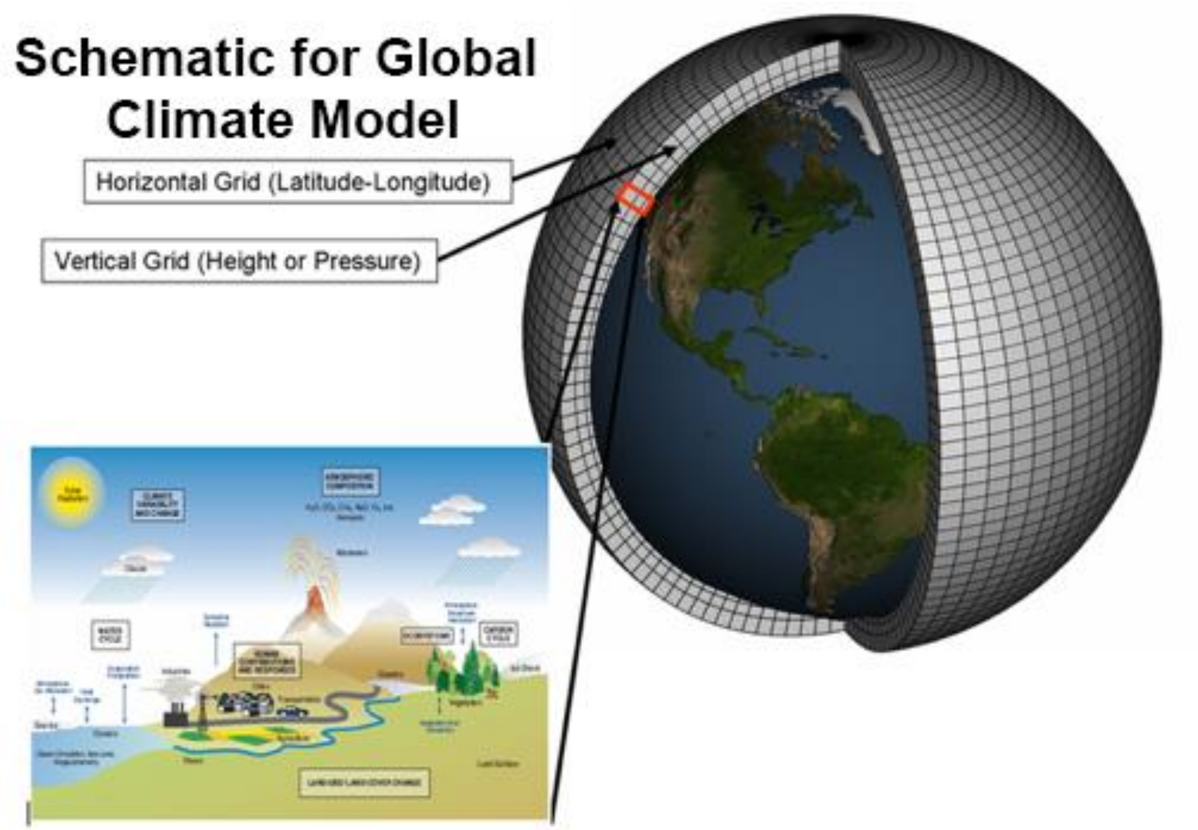

Figure 3: Global climate models are made up of a series of equations that describe the main biogeophysical processes of the Earth's climate system, evaluated on a spherical grid mesh. I obtained this figure from NOAA's website as a general illustration of the global climate models described in my expert report (Lettenmaier Report, FX-793 at 13). Available at: http://celebrating200years.noaa.gov/breakthroughs/climate_model/modeling_schematic.html.

20. **Chattahoochee Gage**: To measure streamflow in the Apalachicola River, I used observed streamflow data reported by the USGS at the Chattahoochee Gage (formally, USGS 02358000, Apalachicola River near Chattahoochee, FL). The Chattahoochee Gage is located just south of Lake Seminole, and is the northernmost gage in Florida. Based on my own

investigations, correspondence with the USGS, and the fact that this gage is included in the USGS's Hydro-Climate Data Network—a network of high-quality gages—I concluded that the Chattahoochee Gage is reliable for the purpose for which I used it. (The Sumatra Gage, in contrast, is not part of the Hydro-Climate Data Network.)

III. CHANGE IN CLIMATE VARIABLES IS NOT DRIVING THE DECREASE IN FLOWS ON THE APALACHICOLA RIVER

21. I analyzed long-term records of climate variables to determine whether changes in climate might be responsible for observed reductions in the flow of the Apalachicola River. I determined that changes in climate variables have not caused the long-term trends in streamflow that are observed at the Chattahoochee Gage.

22. **Temperature**: Annual average temperatures have not increased significantly within the ACF Basin during the last century (all data sets show a period of warming through about the 1930s, then cooling until about 1970; see Figure 4). Of the seven data sets that I analyzed, five showed temperatures unchanged post-1970, while two showed statistically significant increases of about 0.5° C. For the May-through-September growing season, two of the data sets showed statistically significant increases of about 0.5° C post-1970. In the August-through-October period, trends were mixed, and none were statistically significant.

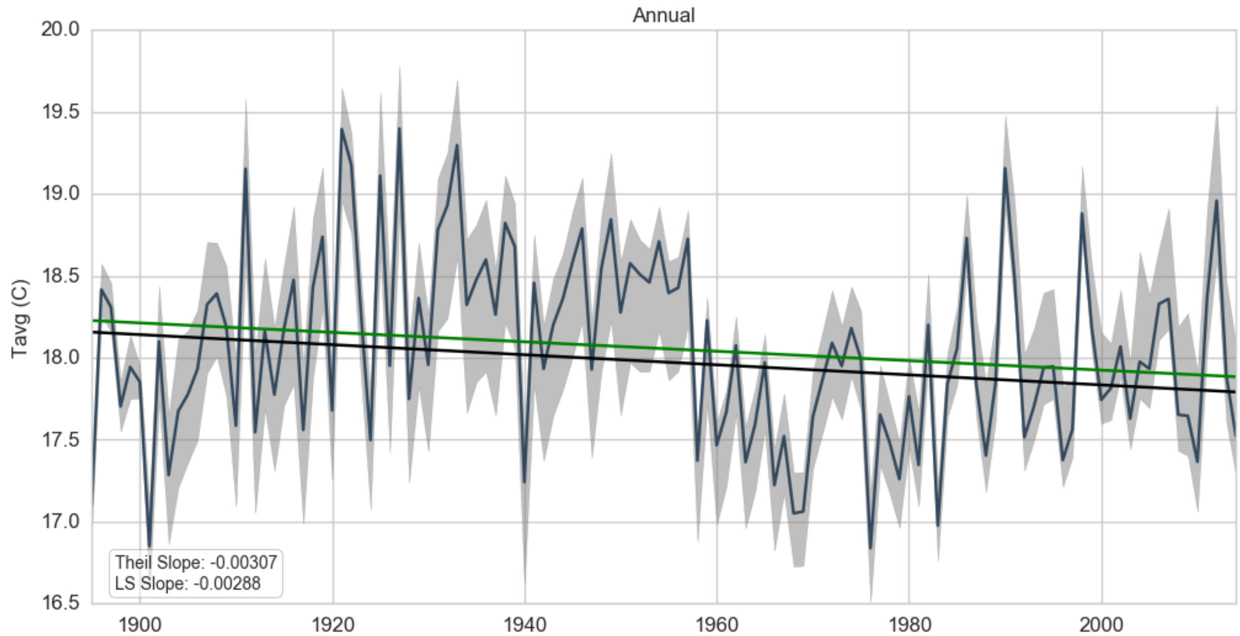

Figure 4: Average annual air temperature averaged over the ACF between 1895-2015. The spread between seven metrological datasets is shown in gray. The multi-dataset mean is shown in dark blue and is used to fit the Theil-Sen (black solid line) and Least-Squares (green solid line) slopes (the Theil-Sen and Least-Squares slope estimators are commonly used in the field of hydroclimatology to estimate statistical significance of trends). Neither slope is statistically different than zero. I created Figure 4 using generally accepted scientific principles and methods using the data in Figure 5.1.1-1 in my expert report (FX-793 at 18).

23. The general absence of warming, even as temperatures over much of the rest of the global land area have risen in recent decades, is consistent with the observed phenomenon of a "warming hole" over much of the central and southeastern United States. (*See* Lettenmaier Report, FX-793 at 18, 21 (citing NOAA Technical Report NESDIS 142-2: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 2, Climate of the Southeast U.S., 2013, at 24).) The National Climate Assessment, which I cited in my February 29, 2016 report, is a widely used source for regional climate data in my field; I obtained this report from

the NOAA website[1] and relied on it to form my opinions in my report and in this testimony. Such reports are typically relied upon by experts in my field. In Figure 5, below, note that the white area of the map, denoting that there has been no trend in annual air temperatures over this region during the period from 1950 to 2015, extends into the western and southwestern portions of Georgia, as well as over much of the Florida Panhandle, covering nearly all of the ACF Basin.

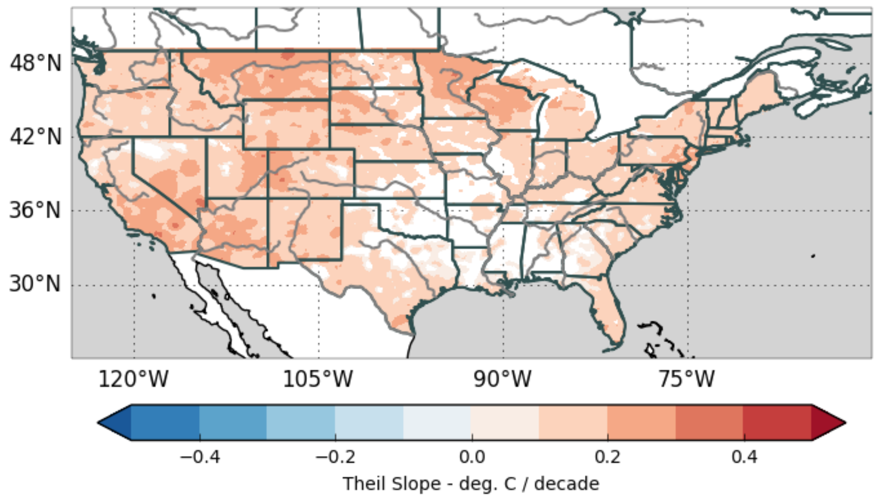

Figure 5: Trends in annual air temperature from 1950-2015 in the nClimGrid dataset across the conterminous United States. Trends were calculated using the Theil Sen slope method and are shown in Degrees Celsius per decade. I created Figure 5 using generally accepted scientific principles and methods. A lower-resolution version of this figure was presented in my expert report as Figure 5.1.1-4 (FX-793 at 21).

24. **Precipitation**: Over the last century, there has been no statistically significant trend in precipitation in any of the data sets (Figure 6). For the post-1970 period, all data sets show a slight, but not statistically significant, downtrend. Figure 6 shows several drought years over the last decade (although none as severe as the 1954 drought, which had the lowest annual precipitation of record).

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[1] *Available at* *h*ttp://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-2-Climate_of_the_Southeast_U.S.pdf.

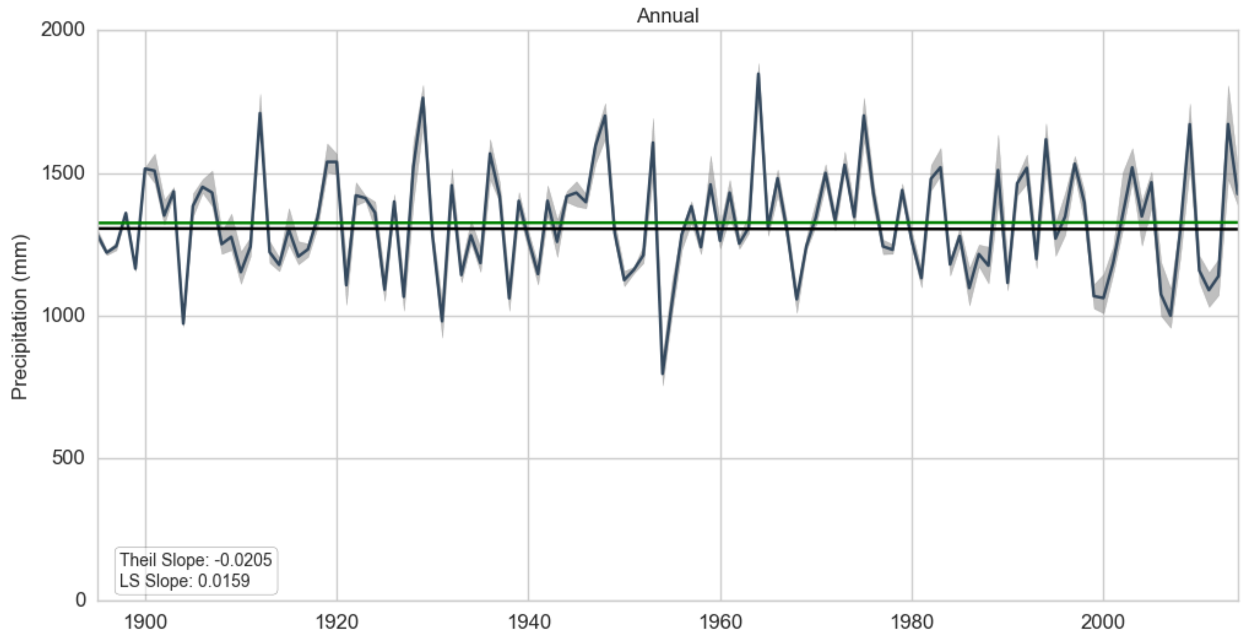

Figure 6: Total annual precipitation averaged over the ACF upstream of Sumatra between 1895-2015. The spread between seven metrological datasets is shown in gray. The multi-dataset mean is shown in dark blue and is used to fit the Theil-Sen (black solid line) and Least-Squares (green solid line) slopes. Neither slope is statistically different than zero. I created Figure 6 using generally accepted scientific principles and methods using the data in Figure 5.1.5-1 in my expert report (FX-793 at 31).

25. Figure 6 shows that although there have been several droughts in the ACF Basin since 2000, these droughts are not inconsistent with severe droughts earlier in 20th century. Furthermore, analyses of the regional paleoclimatic record, reconstructed using techniques such as tree-ring analysis, show that recent droughts are not unprecedented over the last 350 years, and that "the era in which local and state water supply decisions were developed . . . are amongst the wettest since at least 1665." (Pederson *et al.* 2012, JX-64 at 1.) I obtained this publication from the journal *Environmental Research Letters*, which is regularly read and relied upon by experts in my field, and I reviewed and relied on it to form my opinions in my report and in this testimony.

26. As I describe further in my expert report, other climate variables that affect runoff and streamflow, including evapotranspiration, have changed only slightly in the last century.

(Lettenmaier Report, FX-793 at 8.) Overall, there has not been a substantial change in naturalized runoff (unaffected by human consumption) in the ACF Basin that can be attributed to climate change either over the last century or since 1970. In other words, it is Georgia's water consumption, not changes in climate variables, that has caused streamflow depletions on the Apalachicola River.

IV. CLIMATE-MODEL PROJECTIONS INDICATE THAT CHANGES IN CLIMATE VARIABLES WILL HAVE NO MATERIAL EFFECT ON APALACHICOLA RIVER ANNUAL DISCHARGE THROUGH 2050

27. When assessing future climate projections, the most robust approach is to consider the averaged outputs of multiple global climate models. In my analysis, I used projections from 38 models for different climatic variables, including average temperature, maximum and minimum temperatures, precipitation, and evapotranspiration. I also generated my projections using two different future climate scenarios, and examining projections on an annualized basis, as well as for the growing season (May to September) and for low-flow periods (August to October).

28. The averaged results of these projections show that change in climate variables is unlikely to have any material effect on the Apalachicola River's annual discharge through at least 2050. While temperatures in the ACF are projected to increase by approximately 1.8°-3.0° C during that period, and evapotranspiration is projected to increase in parallel with temperature, these changes will mostly be offset by slight projected increases in precipitation. Because these countervailing factors should largely cancel one another out, the impacts of changing climate variables on Apalachicola River flows are likely to be minimal. These averaged projections through 2050 are shown below in Figure 7.

29. Not only is average annual river discharge unlikely to change substantially as a result of changes in climate variables, the averaged model projections indicate that, absent

Georgia's consumption, the Apalachicola's minimum flows, which typically occur during the dry months of late summer or early fall, are unlikely to change substantially through at least 2050. Indeed, the results indicate that average runoff for the August-to-October low-flow period and the May-to-September growing seasons are likely to increase slightly during this period. (Lettenmaier Report, FX-793 at 6, 43.)

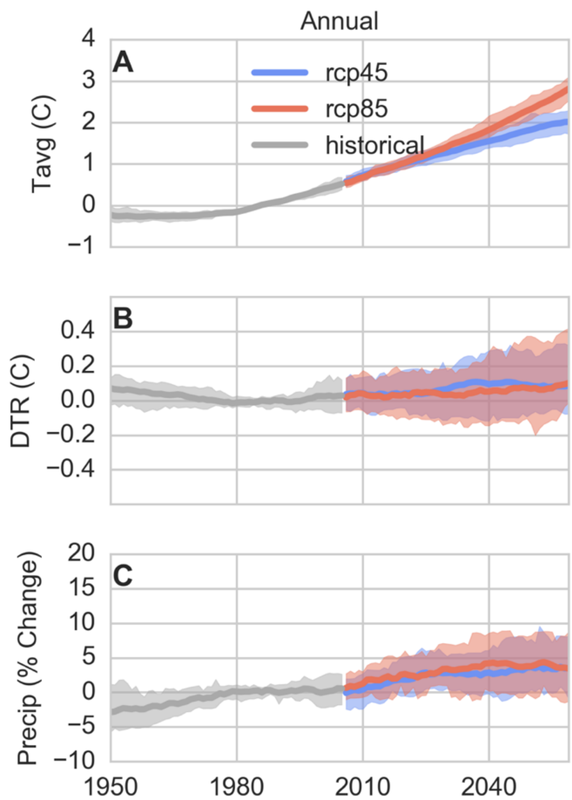

Figure 7: Projected changes in hydroclimate variables over the ACF Basin through the 21st Century, relative to mean climatology from the 1970-2000 period. The historical period is shown in gray, and the future period is shown in blue and red for two future global greenhouse gas emissions scenarios. The shading in both the historical and future periods represents the inter-quartile range among the 38 climate models. I created Figure 7 using generally accepted scientific principles and methods. This figure depicts a subset of the information in Figure 5.2.1-1 in my expert report (FX-793 at 44).

V. CHANGES IN INTRA-ANNUAL VARIABILITY OF RAINFALL HAVE NOT CAUSED THE STREAMFLOW DEPLETIONS IN THE APALACHICOLA RIVER

30. I also examined whether there has been a shift in precipitation from summer months to non-summer months that would account for the decreases in summer low flows in the Apalachicola River. I found that changes in annual rainfall patterns cannot explain the decreased flows in the Apalachicola River during summer months. (Lettenmaier Defensive Report, FX-809 at 5, 12-13.) I examined seven monthly precipitation data sets in the ACF Basin for periods of record before 1970 and after 1980. As is evident by comparing the blue line (pre-1970 data) and the red line (post-1980 data) in Figure 8, intra-annual precipitation patterns track one another quite closely across the two periods and in each of the different models. While there is a statistically significant increase in precipitation in the month of November across the entire ACF Basin, no statistically significant change occurred in any other month. Moreover, given the results of statistical tests performed for all twelve months, the apparent increase in November may well be attributable to chance.

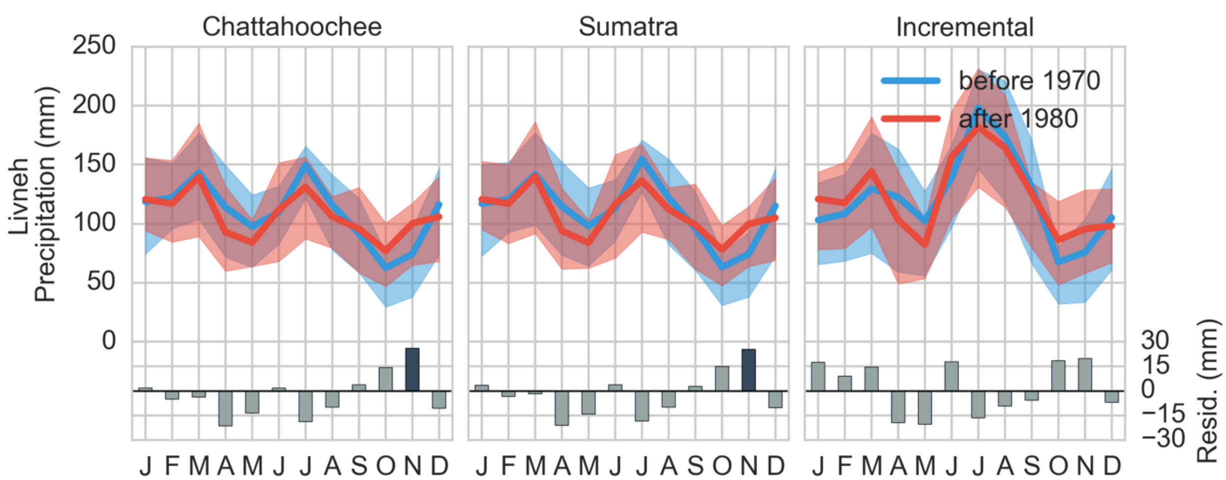

Figure 8: Intra-annual precipitation patterns over the ACF Basin comparing the period 1916-1970 and 1980-2011 for the ACF drainage basin upstream of Chattahoochee (left), upstream of Sumatra (center), and the difference between two (right). The bars at the bottom of the plot show the differences in the means of the two time periods with dark blue

bars representing statistically significant (p<0.05) changes. I created Figure 8 using generally accepted scientific principles and methods. This figure depicts a subset of the information in Figure 3 of my Defensive Report (FX-809 at 13).

VI. LONG-TERM TRENDS IN PRECIPITATION, RUNOFF, AND/OR EVAPOTRANSPIRATION IN THE INCREMENTAL AREA BETWEEN THE CHATTAHOOCHEE AND SUMATRA GAGES CANNOT EXPLAIN THE LOSS OF FLOW IN THIS REACH POSITED BY GEORGIA

31. Georgia has asserted that large quantities of water are lost in the incremental area between the Chattahoochee Gage, where the Apalachicola River begins at the Florida border (USGS 02358000), and the Sumatra Gage, about 20 miles above where the river flows into Apalachicola Bay (USGS 02359170), and that these losses of water have increased over time. In order for this to be true, however, some phenomenon, either natural or manmade, would have to explain the purported change. Figure 2 shows the entire ACF Basin and the incremental area—the portion of the ACF Basin between the Chattahoochee and Sumatra Gages.

32. I used seven observed gridded precipitation data sets, three modeled evapotranspiration data sets, modeled runoff, and observed incremental streamflow data to evaluate whether climate change or natural variability could explain the purported change in observed incremental flows over time. (Lettenmaier Defensive Report, FX-809 at 8.) I find that neither changes in climate nor natural variability can explain these purported changes between the Chattahoochee and Sumatra Gages. Precipitation in the incremental area has not changed in a statistically significant way since 1970 in any of the seven data sets. Similarly, there have been no statistically significant changes to actual evapotranspiration during this period in any of the three data sets, either annually or seasonally. Likewise, none of the data sets of modeled runoff showed a statistically significant trend between 1970 and the present.

33. While there have been some slight changes to climate variables in the incremental area between the gages during the relevant period, these changes are generally consistent with

the changes observed in the entire ACF Basin, including upstream. Moreover, changes to the climate in this relatively small area of only about 2,000 square miles cannot possibly explain the enormous purported losses.

34. Human water consumption cannot explain the apparent losses either. In one presentation of its "lost water" theory, Georgia suggested that between 1978 and 2014, approximately 5,000 cfs, or 3.6 million acre-feet, per year, of water has been lost. For this purported trend to be real, an extra 2.8 feet of water would have to have to be spread over every square inch of the incremental area, whether via irrigation or some other form of consumption, every year. There is no evidence of any such massive manmade diversions in this relatively natural area. Based on Georgia consumptive use numbers that Dr. Bedient provided in connection with his Defensive Expert Report, 5,000 cfs would be enough water to supply a population of approximately 19 million people or to irrigate nearly 4 million acres of agricultural land. (Ex. 75 to Deposition of Dr. Panday, August 3, 2016, FX-518.)

35. Based on my analysis, I conclude that any apparent trend in the uncorrected streamflow data between the Chattahoochee and Sumatra Gages is not the result of any real change in natural conditions, regional climatology, or consumptive uses. Rather, the purported trend that Georgia and its experts find of lost water in the Florida portion of the ACF Basin is likely attributable to systematic measurement error at the Sumatra Gage at high flows.

36. When I realized that there was no hydroclimatic explanation for the purported changes in flow that Georgia asserts, I contacted the USGS and asked if they had any information about the gages that might help me explain these differences in the flow records. I later learned, that in a letter to the Northwest Florida Water Management District dated July 25, 2016, the USGS confirmed that it had found problems in the Sumatra Gage record, stating that

its "team did find a problem with several discharge rating changes made during 1990–2002 when erroneous discharge measurements were made during out-of-bank flood flows. Non-standard methods were used during several high flow measurements that under-reported the flows, which in turn led to inaccurate rating changes." (USGS 2016, FX-515.) I received and evaluated a copy of this letter, and FX-515 is a true and accurate copy of the letter I reviewed. As a hydrologist, I routinely rely on information from USGS, as do other experts in my field, and this letter supports my conclusion. Georgia's disappearing-water theory has no plausible basis in hydrological principles.

VII. BASIC STATISTICAL ANALYSIS SHOWS THAT BOTH STREAMFLOWS AND THE RUNOFF RATIO HAVE DECLINED

37. I also used information provided by Dr. Bedient in connection with his May 20, 2016 Defensive Expert Report in an Excel worksheet titled, "Chatt (2)" and an Excel Workbook titled, "Annual_Ratio_Plots_FAK.xlsx." I broke the record into three periods—1929 to 2014, 1929 to 1969, and 1970 to 2014. When I analyzed either the entire 1929-2014 record (green line) or the earlier 1929-69 period (red line), I did not find any statistically significant trend. In contrast, when I analyzed 1970 to 2014, there is a statistically significant downward trend in stream flows on the Apalachicola River at the Chattahoochee gage. This analysis is shown in Figure 9, which was created at my direction using generally accepted scientific principles and methods. The Theil-Sen slope estimator, which I used to test for significance of trends, is commonly used in the fields of statistics and hydroclimatology to test for statistically significant trends. From 1970 to 2014, the magnitude of this decline is thousands of cfs.

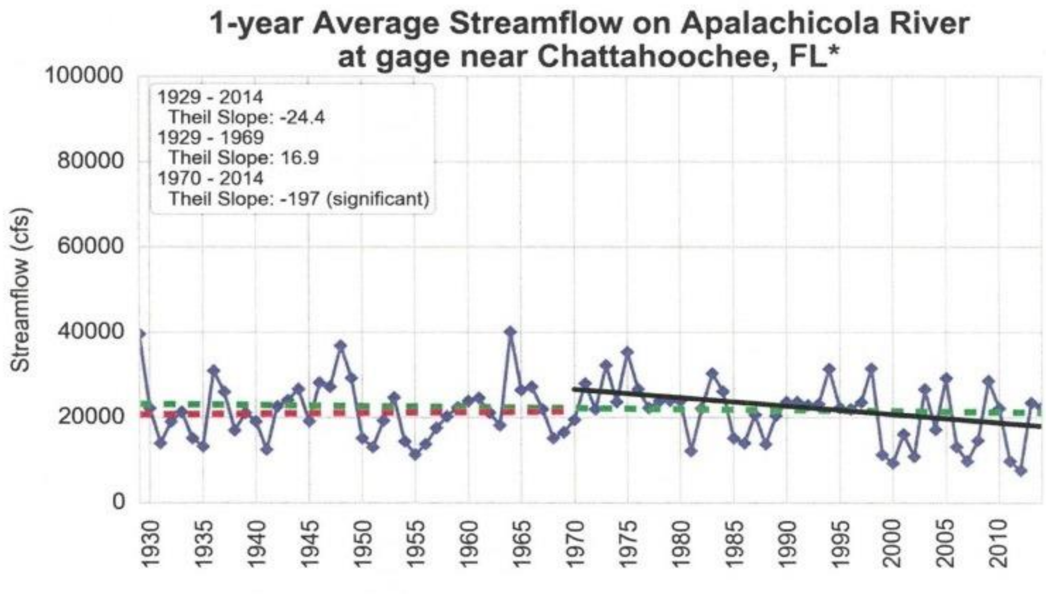

Figure 9. Annual streamflow trends at the Apalachicola River Chattahoochee Gage using the Theil Slope estimator (Exhibit F565).

38. There has been no statistically significant change in rainfall or temperature that would account for this streamflow decline. (Lettenmaier Report, FX-793 at 6, 8, 39-40.) I also analyzed the relationship between rainfall and runoff using precipitation information provided by Dr. Bedient (in his "Annual_Ratio_Plots_FAK.xlsx" Excel Workbook). Even when I use Dr. Bedient's precipitation data (which I consider less reliable than that used in my own analysis), there is a statistically significant decline in the runoff ratio from 1970 to 2014. In other words, since 1970, the proportion of precipitation that turns into stream flow has declined significantly (in contrast, the amount of precipitation that falls has not changed significantly). This is consistent with Dr. Hornberger's basin-yield analysis. (Hornberger 2016, FX-785 at 15-16.) This analysis is show in Figure 10, which was created at my direction using generally accepted scientific principles and methods.

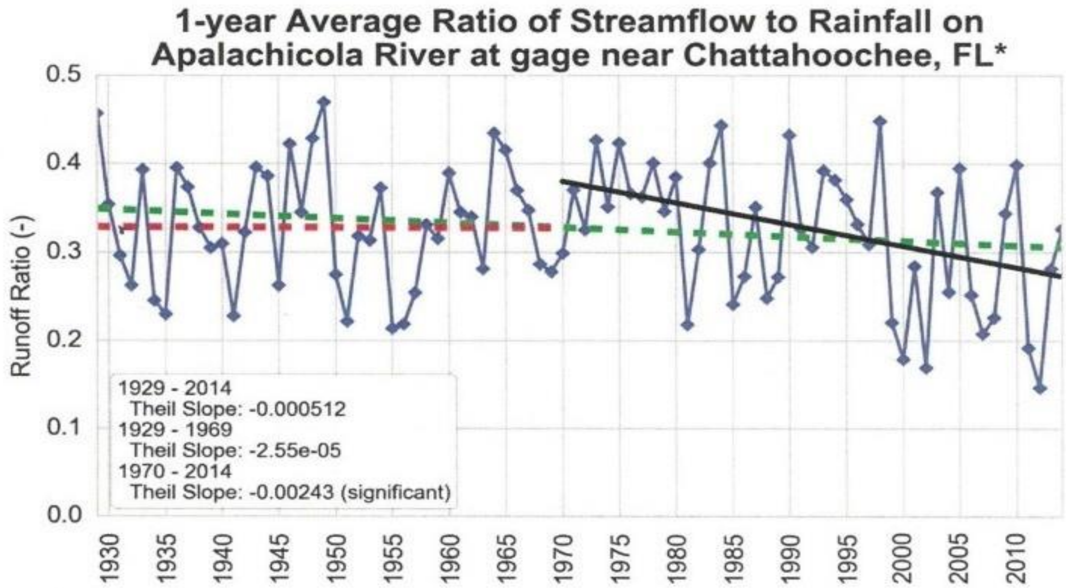

Figure 10. Annual runoff ratio and trends using Theil Slope estimator (Exhibit F562).

VIII. RESIDUALS ANALYSIS COMBINING HYDROCLIMATIC MODELS WITH OBSERVED STREAMFLOW DEMONSTRATE THAT LARGE REDUCTIONS HAVE OCCURRED IN STREAMFLOW IN THE APALACHICOLA RIVER THAT CAN BE ATTRIBUTED TO GEORGIA'S INCREASED WATER CONSUMPTION

39. I analyzed the differences (residuals) between modeled and observed streamflow in the Apalachicola River, as measured at the Chattahoochee Gage, for five different model output data sets. The modeled streamflow represents the flow that would have occurred under the climate conditions that actually occurred, absent human consumptive water use, streamflow regulation, or signatures of other long-term changes such as land use. The measured streamflow reflects actual climate conditions, but also includes the effects of consumptive water use, flow regulation, and possibly land cover change. Therefore, trends in the difference between the modeled streamflow and the observed streamflow provides an estimate of streamflow changes caused by human activity (and not changes in climate variables) in the ACF Basin. (Lettenmaier Report, FX-793 at 41, 42.) The difference between the modeled streamflow and the actual

streamflow is known as a "residual" in hydroclimatology, and this approach is known as a "residuals analysis."

40. Figure 11 below shows residuals calculated by subtracting the observed streamflow measured at the Chattahoochee Gage from the total (annual ACF Basin) modeled runoff from the five data sets I used. The positive trend in the center line on Figure 11 indicates that the effect of human activities on the ACF discharge has progressively increased since about 1950, and averaged over the five data sets now is about 3,800 cfs on annual average. My results using the VIC model are consistent with those that Dr. Hornberger observed using the PRMS model.

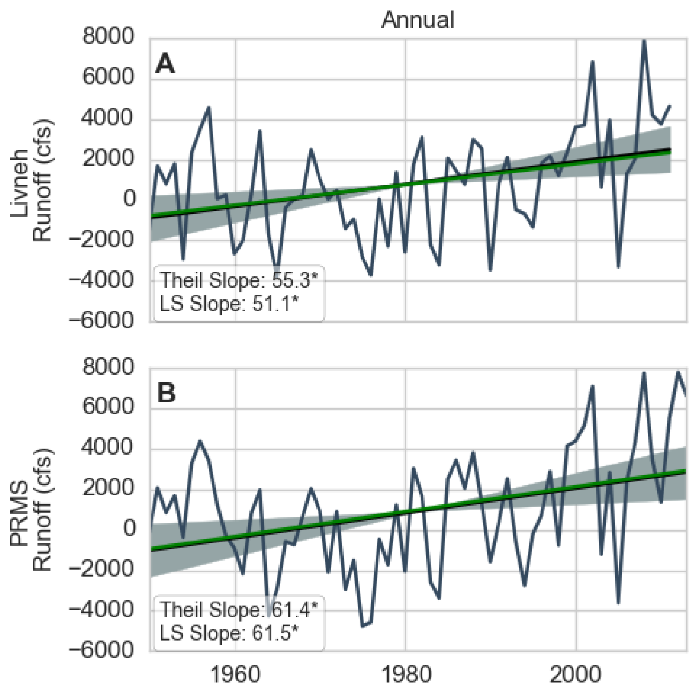

Figure 11: Residuals in annual streamflows between modeled (PRMS and VIC) and observed streamflow at the USGS Chattahoochee Gage (USGS 02358000). Slopes that are statistically significant at p<0.05 are denoted with an "*" symbol following the slope measure. I created Figure 11 using generally accepted scientific principles and methods. Figure 11 depicts a subset of the information in Figure 5.1.9-1 in my expert report (FX-793 at 42).

41. This residuals analysis is a powerful way to determine changes in consumptive use over time in the ACF Basin. The approach and the models it uses rely on physical first-principles of hydrology and capture all streamflow depletions from the entire Georgia portion of the ACF Basin by calculating water that is missing because of human consumptive use.

42. Certain land use changes, such as urbanization—which increases impervious surfaces like roofs and asphalt—can cause increased streamflow on an annual basis as well. But urbanization tends to increase runoff on an annual average (although by a relatively small amount over the entire ACF Basin). But if runoff from urban areas has increased, the increase would have cancelled part of the positive residual, implying that the contribution of Georgia's consumptive use to the residual was actually greater than 3,800 cfs. Furthermore, according to Loveland and Acevedo (2015), forest land cover over the ACF Basin has declined in recent decades, which likewise would cancel some of the positive residual (and would also imply that Georgia's consumptive use is greater than 3,800 cfs). (*See* Lettenmaier Report, FX-793 at 38, 41 (citing to Loveland, T.R. & Acevedo, W., "Land Cover Change in the Eastern United States", USGS, 2015).) USGS regional summary documents, such as the one referenced in my February 29, 2016 report, are widely accepted in my field as a source for land cover change data; I obtained this document from the USGS website[2] and reviewed and relied on it to form my opinions in my report and in this testimony.

43. In sum, land use changes are accounted for in the 3,800 cfs residual that I calculated. Changes in land use that increase runoff would mask the signal of Georgia's consumptive use, and 3,800 cfs can be considered a lower limit on Georgia's consumptive use.

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[2] *Available at* http://landcovertrends.usgs.gov/east/regionalSummary.html.

IX. THE METHODOLOGICAL APPROACHES THAT DR. IRMAK AND DR. PANDAY EMPLOYED TO QUANTIFY AND ANALYZE PRECIPITATION ARE NOT RELIABLE

44. Certain of Georgia's expert witnesses have employed unreliable methodological approaches for evaluating precipitation data. In my opinion, Dr. Irmak and Dr. Panday have inappropriately relied upon data from individual rain gages in large regions—*i.e.*, as opposed to gridded precipitation datasets—to determine precipitation conditions throughout those regions. For example, in his May 20 Expert Report, for the 2003 to 2013 time period, Dr. Irmak seeks to quantify daily precipitation volumes in five Georgia counties by relying upon only one monitoring station in each county.

45. As I discussed above, reliance on single rain gages for this purpose is inappropriate because precipitation measurements can vary considerably even within small spatial areas, let alone across entire counties as large as those that Dr. Irmak examined. Rather than using individual monitoring stations to quantify precipitation volumes in the five counties, Dr. Irmak would better have employed gridded precipitation datasets such as those that I rely upon in my expert reports and testimony.

46. Furthermore, Dr. Irmak used a method for filling gaps (missing data) in the precipitation records for the individual stations that is not scientifically defensible. Where those monitoring stations were missing precipitation data for particular days, Dr. Irmak filled in the missing data points with the last available precipitation values. For example, if no precipitation was recorded on Day 1 and precipitation values were unavailable for Days 2 through 10, Dr. Irmak assumed that Days 2 through 10 also had no precipitation. By doing so, Dr. Irmak underestimated precipitation, and introduced artificial trends. Had Dr. Irmak used gridded precipitation datasets such as those that I used in my analysis, he would not have encountered the

data-gap problem. Interpolated precipitation data from nearby monitoring stations would have been used to cover such gaps.

47. Dr. Panday committed similar methodological errors in Appendix C, Section C.1 of his May 20 Expert Report where he attempted to characterize precipitation trends in the ACF Basin—a large area of approximately 19,300 square miles—for the pre- and post-1992 periods by relying upon data from only 8 precipitation monitoring stations. (*See* Panday Expert Report, May 20, 2016, Figures C-1 and C-2 (identifying 8 NOAA monitoring stations in the Upper and Lower ACF River Basin: Station ID Nos. 098935, 090451, 092166, 093028, 090586, 089795, 081020, 080211); *see also* Panday Dep. Tr. (August 2, 2016), 405:4-9 ("Over those 19,300 square miles, I have analyzed data at eight rain gauges covering those 19,300 square miles, and those data points indicate to me that there is a declining [precipitation] trend from pre-'92 to post-'92 conditions.").) Dr. Panday should have used gridded precipitation data, which draw on a more robust data source and are less likely to produce spurious trends than relying on a handful of gages.

X. AUTHENTICATION OF OTHER TRIAL EXHIBITS

48. In the following paragraphs I identify and describe a number of exhibits relevant to my direct testimony:

49. Exhibit FX-252 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, comparing publicly available observed NOAA weather data (precipitation and temperature) and USGS streamflow data across four years: 1931, 1954, 2011 and 2012. Experts in my field regularly use these data sources to analyze hydrology and climate. The document was introduced as Ex. 8 during the August 2, 2016 deposition of Dr. Irmak.

50. Exhibit FX-542 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, identifying hundreds of NOAA precipitation monitoring stations in the Global Historical Climatology Network within and surrounding the ACF Basin. Experts in my field regularly use these data sources to analyze hydrology and climate. The document was introduced as Ex. 45 during the August 2, 2016 deposition of Dr. Panday.

51. Exhibit FX-543 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, identifying five rain gage stations located within 25 miles of the "baseline" precipitation gage ("098935") that Dr. Bedient describes in his Defensive Expert Report at Figure 3-3. This document provides the locations of the baseline station and the five neighboring stations that Dr. Panday analyzed in his report. It also shows that the 5 neighboring stations have complete data records. Experts in my field regularly use these data sources to analyze hydrology and climate. The document was introduced as Ex. 46 during the August 2, 2016 Deposition of Dr. Panday.

52. Exhibit FX 545 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting precipitation data from the "baseline" monitoring station that Dr. Panday selected (Station 098935), as well as precipitation data from five additional NOAA monitoring stations within 25 miles of Dr. Panday's "baseline" station. The precipitation data for Dr. Panday's "baseline" station was produced in support of his Defensive Expert Report. In addition to plotting precipitation data for the six stations, Theil slopes were added for the 1975-2015, 1975-1992, and 1992-2015 time periods to evaluate long-term precipitation trends at each of the stations for those time periods. Experts in my field regularly use these data sources and methods to analyze hydrology and

climate. The document was introduced as Ex. 49 during the August 2, 2016 deposition of Dr. Panday.

53. Exhibit FX-546 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting precipitation data from the “baseline” monitoring station that Dr. Panday selected (Station 098935), as well as precipitation data from five additional NOAA monitoring stations within 25 miles of Dr. Panday’s “baseline” station on double-mass curves. The precipitation data for Dr. Panday’s “baseline” station was produced in support of his Defensive Expert Report. Experts in my field regularly use these data sources and methods to analyze hydrology and climate. The document was introduced as Ex. 50 during the August 2, 2016 deposition of Dr. Panday.

54. Exhibit FX-554 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting precipitation data from the “baseline” monitoring station that Dr. Panday selected (Station 098935), as well as precipitation data from five additional NOAA monitoring stations within 25 miles of Dr. Panday’s “baseline” station. The precipitation data for Dr. Panday’s “baseline” station was produced in support of his Defensive Expert Report. In addition to plotting precipitation data for the six stations, Theil slopes were added for the 1975-1992 and 1992-2013 time periods to evaluate long-term precipitation trends at each of the stations for those time periods. Experts in my field regularly use these data sources and methods to analyze hydrology and climate. The document was introduced as Ex. 83 during the August 3, 2016 deposition of Dr. Panday.

55. Exhibit FX-562 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting the ratio of annual average streamflow to annual average rainfall (“runoff ratio”), using data measured by USGS at

the Chattahoochee Gage. The streamflow and rainfall data were produced in support of Dr. Bedient's Defensive Expert Report. Theil slopes were added to evaluate long-term trends in the 1-year average runoff ratio for three time periods: 1929-2014, 1929-1969, and 1970-2014. Experts in my field regularly use these data sources and methods to analyze hydrology and climate. The document was introduced as Ex. 65 during the June 29, 2016 deposition of Dr. Bedient.

56. Exhibit FX-563 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting rainfall data, produced in support of Dr. Bedient's Defensive Expert Report, on an annual-average basis and adding Theil slopes to evaluate long-term trends in annual-average precipitation for three time periods: 1929-2014, 1929-1969, and 1970-2014. Experts in my field regularly use these data sources and methods to analyze hydrology and climate. The document was introduced as Ex. 68 during the June 29, 2016 deposition of Dr. Bedient.

57. Exhibit FX-564 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting rainfall data, produced in support of Dr. Bedient's Defensive Expert Report, on a two-year average basis and adding Theil slopes to evaluate long-term trends in two-year average precipitation for three time periods: 1930-2014, 1930-1969, and 1970-2014. Experts in my field regularly use these data sources and methods to analyze hydrology and climate. The document was introduced as Ex. 69 during the June 29, 2016 deposition of Dr. Bedient.

58. Exhibit FX-566 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, plotting USGS streamflow data from the Chattahoochee Gage, produced in support of Dr. Bedient's Defensive Expert

Report, on an annual-average basis and adding Theil slopes to evaluate long-term trends in annual average streamflow for three time periods: 1929-2014, 1929-1969, and 1970-2014. Experts in my field regularly use these data sources and methods to analyze hydrology and climate. The document was introduced as Ex. 65 during the June 29, 2016 deposition of Dr. Bedient.

59. Exhibit FX-569 is a true and accurate copy of a document, prepared at my direction using generally accepted scientific principles and methods, comparing precipitation data produced in support of Dr. Bedient's Defensive Expert Report, with gridded precipitation datasets that I rely upon in my expert report and testimony. Experts in my field regularly use these data sources and methods to analyze hydrology and climate.

XI. CONCLUSION

60. It is Georgia's water consumption, not changes in climate variables, that has caused streamflow depletions on the Apalachicola River. Similarly, there is no climatological explanation for Georgia's theory that large amounts of water are being lost in Florida, and the most likely explanation is that the Sumatra gage has error at high flow. As to the future, results from standard models show that climate variables are not expected to significantly reduce streamflow on the Apalachicola River.