DRAFT

Technical Memorandum

To: *South Carolina Department of Natural Resources (DNR)*
South Carolina Department of Health and Environmental Control (DHEC)

From: *CDM Smith*

Date: *November 2016*

Subject: *Unimpaired Flow Methodology and Dataset for the Santee River Basin (Prepared as part of the South Carolina Surface Water Quantity Modeling Program)*

1.0 Introduction

Unimpaired Flows (UIFs) represent the theoretical historical rate of flow at a location in the absence of all human activity in the river channel, such as water withdrawals, discharges, and impoundments. They will be used as boundary conditions and calibration targets for natural hydrology in the computer simulation models of the eight major river basins in South Carolina. As such, they represent an important step in the South Carolina Surface Water Quantity Modeling project.

This technical memorandum (TM) summarizes the methodology and completion of the draft UIF dataset for the Santee River Basin. The TM references the electronic database which houses the completed UIF dataset for the Santee River Basin, and summarizes the techniques and decisions pertaining to synthesis of data where it is unavailable, which may be specific to individual locations.

2.0 Overview of the Santee Basin

The Santee River is the second largest river on the eastern coast of the United States, and before the construction of Santee Dam in 1941, had the fourth-largest average flow. Formed by the confluence of the Congaree River and Wateree River, the full drainage of the Santee River Basin is over 67,000 square miles. Including the drainage from the coastal Ashley and Cooper Rivers, the drainage downstream of the Congaree-Wateree confluence is approximately 3,000 square miles and contains two large lakes: Lake Marion and Lake Moultrie, with surface areas of 166 square miles and of 94 square miles, respectively. Both reservoirs were created in conjunction with each other to provide hydropower, recreation and water supply. Their construction dramatically changed the character of the basin. Between 1941 and 1985, most water passed from Lake Marion to Lake Moultrie then onto the Cooper River with only a small amount back to the Santee River. After 1985, operations began on a rediversion canal to return flows from Lake Moultrie back to the Santee River. The basin lies primarily within the Lower Coastal Plain physiographic province, with a small section in the Upper Coastal Plain (**Figure 2-1**).

Chapter 6 of The South Carolina State Water Assessment (SCDNR, 2009) describes the basin's surface water and groundwater hydrology and hydrogeology, water development and use, and water quality. A summary is also provided in An Overview of the Eight Major River Basins of South Carolina (SCDNR, 2013).

A detailed discussion of water users and dischargers is presented in the Santee Framework Memorandum (CDM Smith, 2016). The South Carolina DHEC has provided information and data regarding current (active) and former (inactive) water users and dischargers throughout the state. The Framework Memorandum summarizes the current water users and dischargers for the purposes of the model. For reasons discussed later in **Section 3.2.1**, no users or dischargers were needed for UIF calculations.

3.0 Overview of UIF Methodology

Fundamentally, UIFs are calculated by removing known impacts from measured streamflow values at places in which flow has been measured historically. For the Santee River Basin, UIFs were created at only a selection of locations in which a USGS gage has recorded historical flow measurements.

Measured and estimated impacts of withdrawals, discharges, and impoundments were included as linear "debits" or "credits," and the measured flow was adjusted accordingly. Where historical data on river operations did not exist, values were hindcasted using various estimation techniques. Once the UIFs were developed for each USGS gage, the Period of Record (POR) for each gage was statistically extended (if necessary) to cover the range of 1942-2010 (coinciding with the *second* longest recorded streamflow in the basin and limitations from upstream UIFs, see **Section 3.2.1**). As a final step, the UIFs in ungaged basins were estimated from UIFs in gaged basins with similar size, land use, and topography.

UIFs are intended to be used for the following purposes:

a) Headwater input to the SWAM models

b) Incremental flow inputs along the mainstem in the SWAM models

c) SWAM model calibration

d) Comparison of simulated managed flows to natural flows

e) Other uses by DNR/DHEC outside of the SWAM models

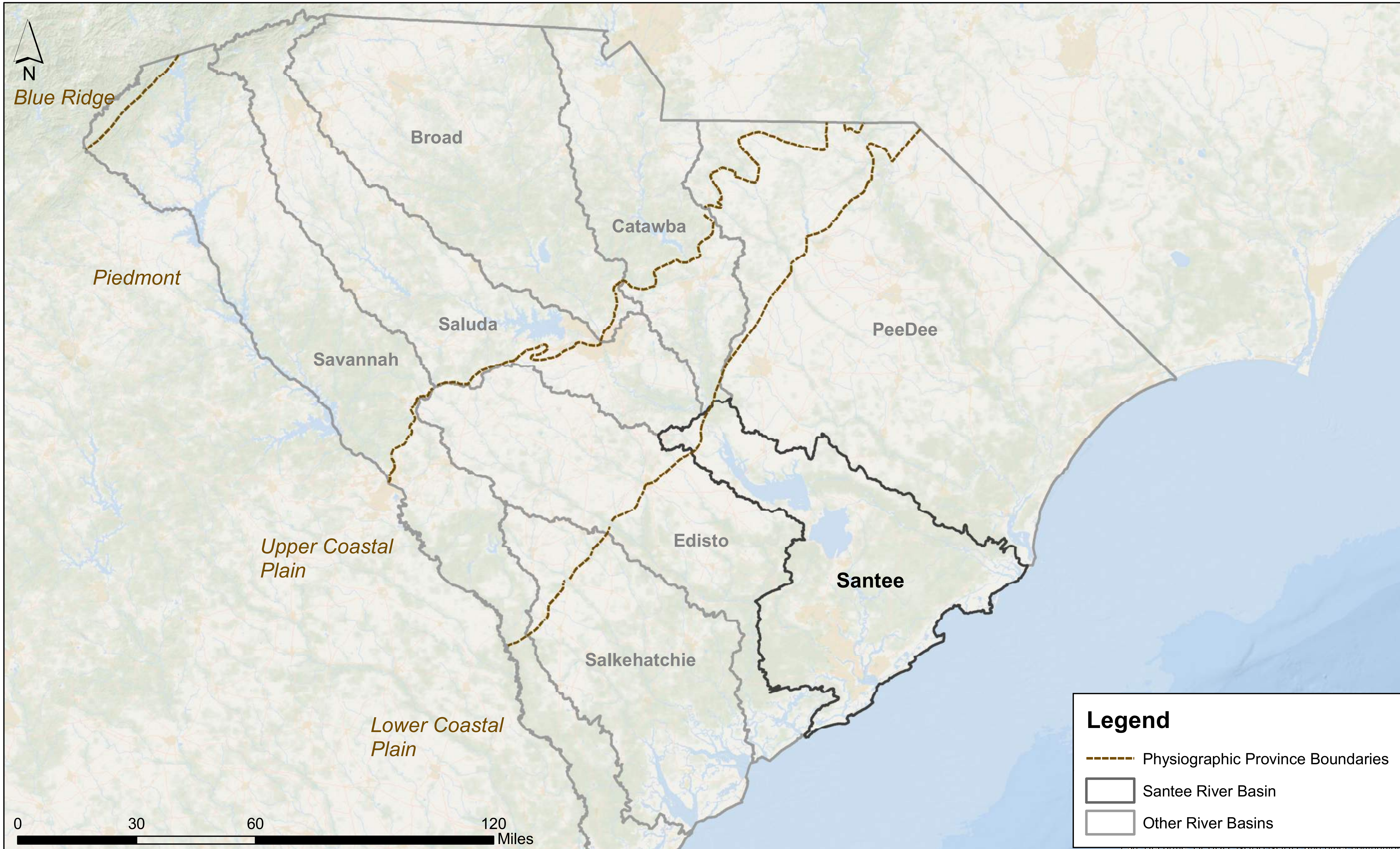


Figure 2-1
South Carolina's Santee River Basin and Other Major River Basins

Figure 3.1 illustrates the step-by-step methodology for computing UIFs. The same general methodology that has been previously used in the Saluda, Edisto, Broad, Catawba-Wateree, Salkehatchie, and Pee Dee River Basins was also used in the Santee. Please refer to the *Methodology for Unimpaired Flow Development* documents prepared for these basins. The methodology is also supported by the following technical memoranda, which specifically outline the steps and guidelines for UIF computation and decision-making:

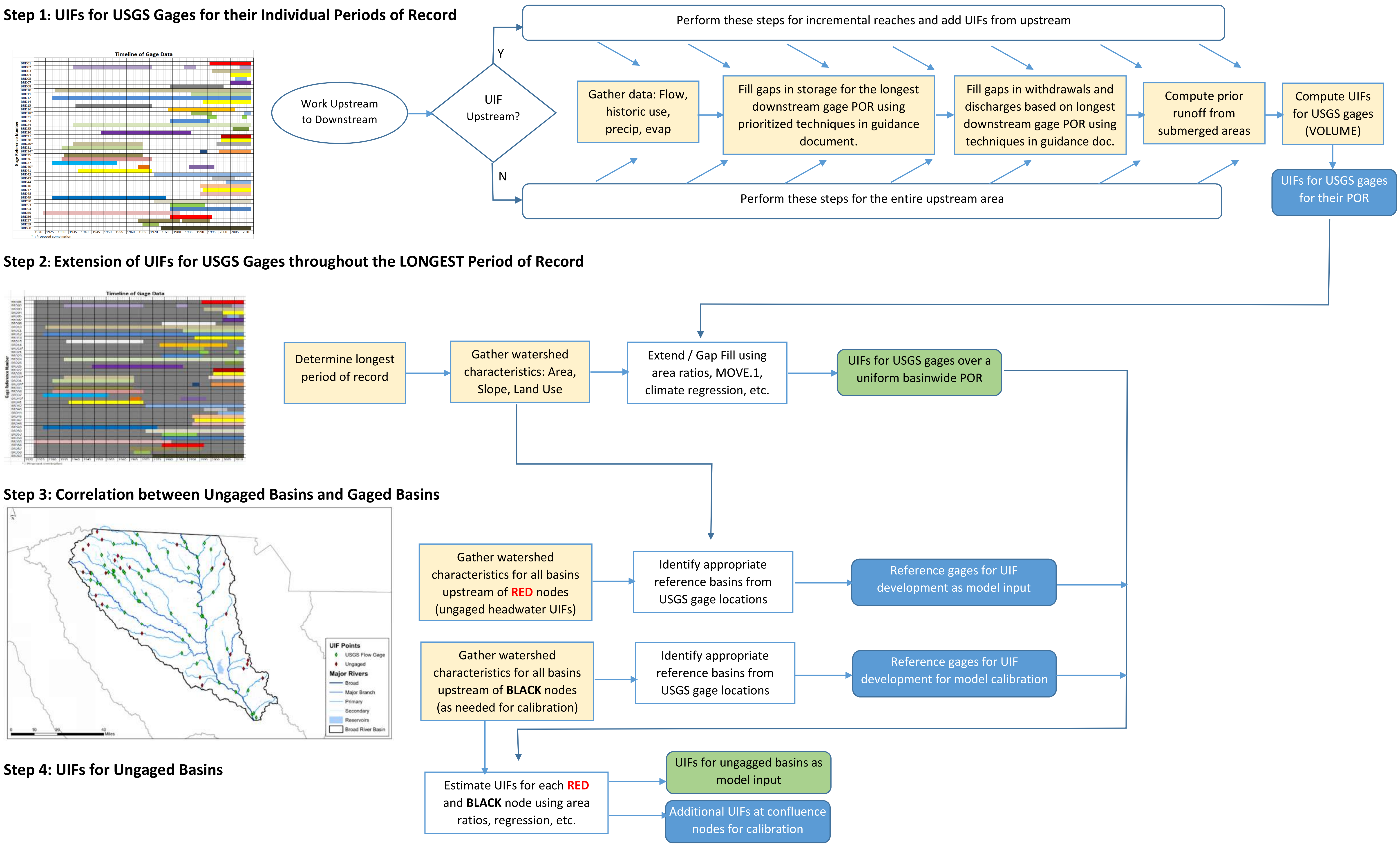
- *Methodology for Unimpaired Flow Development, Santee River Basin, South Carolina (CDM Smith, May 2016)* – Included as **Attachment A** of this report. This includes a list of all USGS gages in the basin and provides recommendations on where UIF development may occur.
- *Guidelines for Identifying Reference Basins for UIF Extension or Synthesis (CDM Smith, April 2015)* – Included as **Attachment C** of this report.
- Refinements to the UIF Extension Process, with an Example – Included as **Attachment D.**

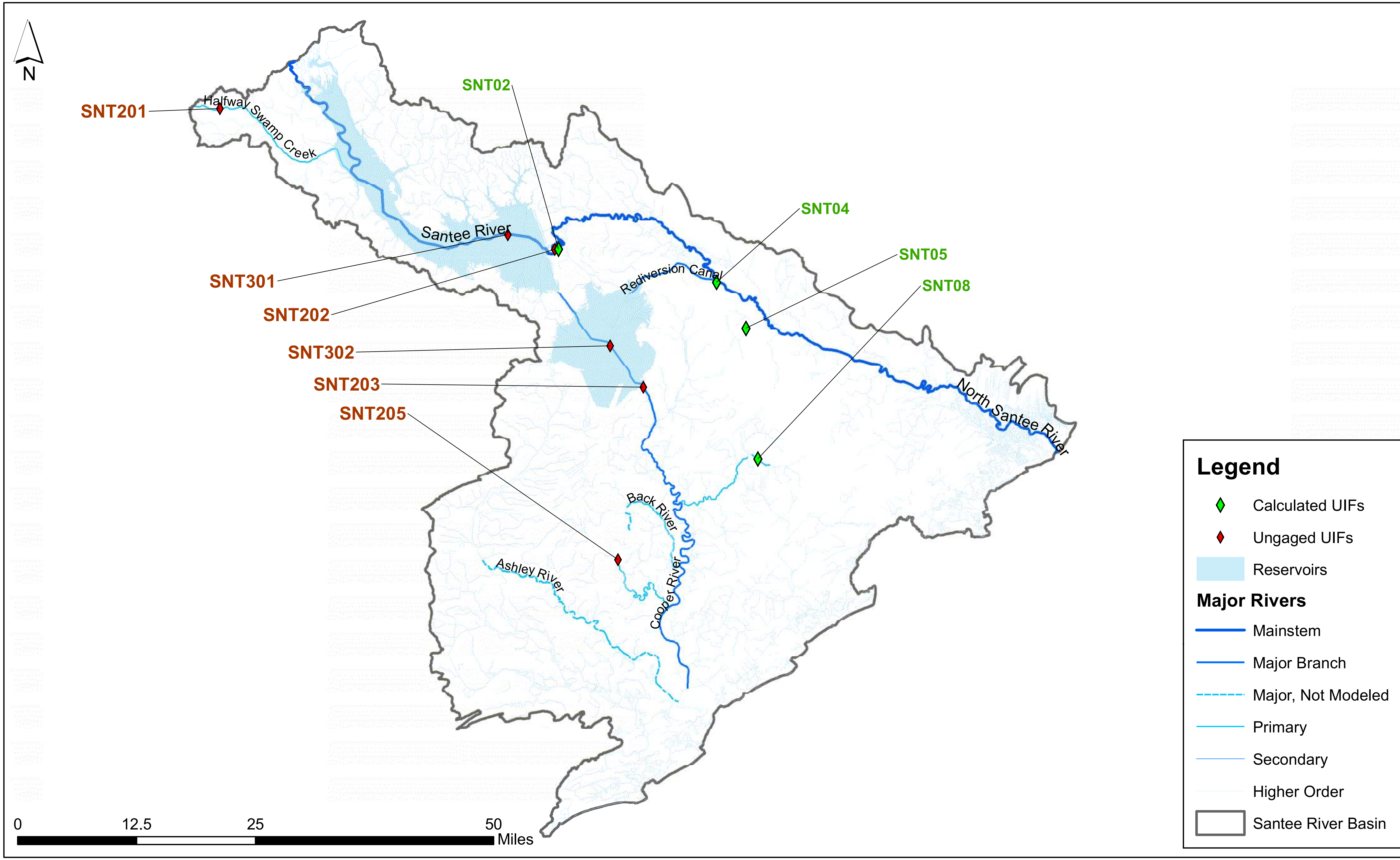
Figure 3-2 illustrates the locations of all UIFs developed for the Santee River Basin. **Attachment G** contains a simplified schematic of the USGS streamflow gages and reservoirs. The existing UIFs from upstream basins and selection of gages are further discussed in **Section 3.2.1**.

3.1 Period of Record

Attachment A contains information for the length and timing of records available for all USGS gages in the Santee River Basin. Following the recommendations in **Attachment A**, four gages were selected for the UIF dataset: SNT02, SNT04, SNT05, and SNT08. SNT07 was not included as it is tidally-influenced during low-to-medium flows. SNT02 provides the earliest record, dating back to 1942. Since UIFs in this basin rely on PORs from UIFs upstream, the Santee UIFs are capped to the upstream available records. Because UIFs in the Catawba-Wateree Basin end in 2010, so do the UIFs for the Santee Basin.

Figure 3-1: Stepwise Procedure for UIF Calculation – Santee Basin





CDM Smith

Figure 3-2
Unimpaired Flow Locations in the Santee River Basin

3.2 Issues Specific to the Santee River Basin

3.2.1 Accounting for Lake Marion and Lake Moultrie

SNT02 proved a troublesome gage for which to create estimates of unimpaired flow. It is downstream of Lake Marion, an almost 500,000 MG reservoir supplied by the combined drainage of the Saluda, Broad, Congaree and Catawba-Wateree River Basins. **Figure 3-3** highlights the characteristics of SNT02's flow and how the majority of water is not released back to the Santee River, with the exception of infrequent high flow events. In the established style of UIF calculations, changes in storage, net evaporation, and submerged runoff are added/subtracted from this gage flow timeseries to unimpair the influence of a reservoir. For a reservoir the size of Lake Marion, the slightest changes in elevation yield changes of flow in thousands and sometimes tens of thousands of cfs. Thus, when starting from a gage flow that is so low, the resulting UIF can have wildly-negative numbers. For other basins, it became standard practice to enforce an n-day smoothing to produce more realistic flows. However, because this reservoir is so large and the gage flow so low, any streak of consecutive days of negative storage change results in a need for multi-week smoothing.

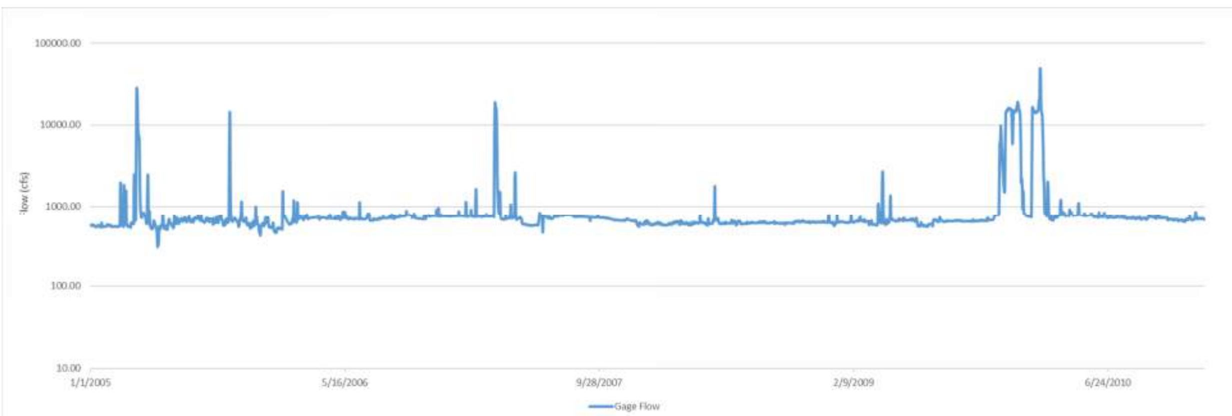


Figure 3-3: SNT02 Gage Flow

Another challenge in calculating the unimpaired flow at SNT02 involved quantifying the flow from Lake Marion to Lake Moultrie through the diversion canal. No direct record of flows through the diversion canal was available, so instead a water balance around Lake Moultrie was utilized to back calculate the flows entering through the diversion canal. However, data was also not available for the St. Stephen hydropower plant on the rediversion canal from Lake Moultrie back to the Santee, thus estimates had to be made. After this exercise and incorporating the calculated flows through the diversion canal into the UIF, the resulting UIF improved, but even with 11-day smoothing the final hydrograph had many unrealistic dips.

Because of the noted issues calculating the SNT02 UIF with the standard methodology, an alternate methodology was considered using area-prorated flows from upstream UIFs. Substituting area-prorated flows for calculated UIFs had been implemented in both the Broad and Catawba-Wateree Basins, where both had unique and complicated situations arising for gages downstream of reservoirs. Both SLD27 from the Congaree River and CAT18 from the Wateree River were viable candidates, representing almost the entire drainage of their respective basins. Since natural Santee River flows would be a combination of those two large basins, an area-weighted area proration was developed, as follows:

$$Q_{SNT02} = A_{SNT02}/(A_{SLD27} + A_{CAT18}) \times (Q_{SLD27} + Q_{CAT18})$$

Figure 3-4 compares the results of a calculated UIF for SNT02, which also has 11-day smoothing, and area-prorated results. The calculated UIF shows that further smoothing would be needed, possibly rendering the timeseries useful for only monthly or even seasonal patterns. However, the general shape of the calculated hydrograph does support the validity of the area-prorated hydrograph in terms of seasonality and magnitude.

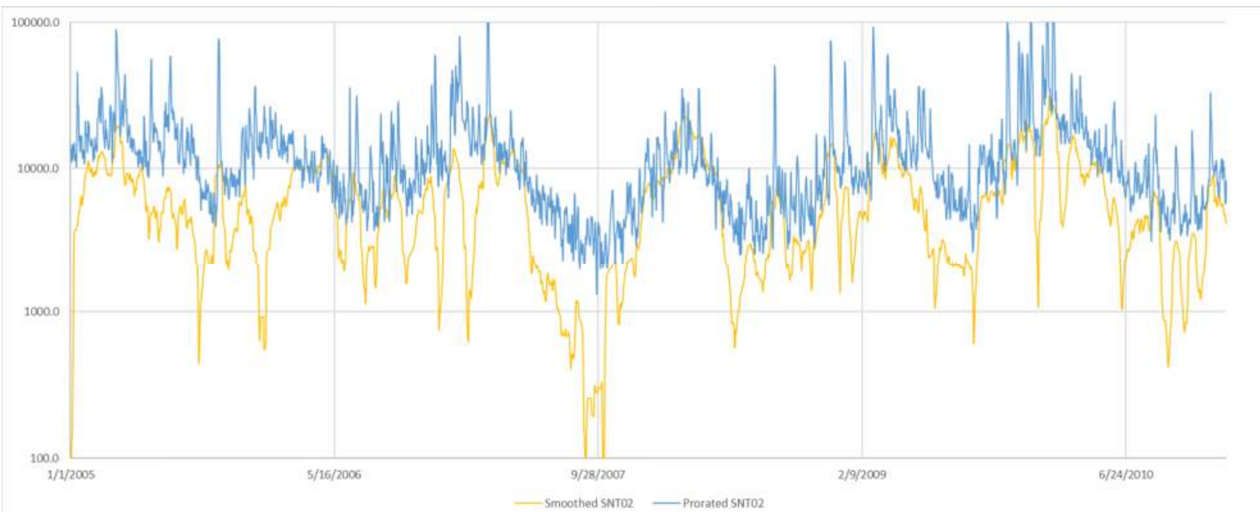


Figure 3-4: Calculated with 11-day Smoothing and Area-Prorated UIFs for SNT02

After developing a reasonable estimate for SNT02's UIFs, the remaining gage on the Santee River to resolve was SNT04, which is downstream of the rediversion canal. Because of the lack of data for flows through the rediversion canal, SNT04's UIFs were estimated in similar fashion to SNT02 with the combined area proration. The last two remaining UIFs in the basin, SNT05 and SNT08, are on small tributaries and are not affected by upstream impairments. Because SNT02 and SNT04 were developed from existing UIFs, and SNT05 and SNT08 only require extension to fill out their records, no current or former users, discharges, or reservoir elevation records ended up being used in the UIF process. Some were accounted for in the SNT02 calculation exercise, but as only recent years were used for comparative purposes, no operational hindcasting was needed.

3.2.2 Groundwater

Registered and permitted (both active and inactive) groundwater withdrawal locations are shown in **Figure 3-5** Groundwater withdrawals may lower streamflow to a point that they potentially influence UIF estimates in a significant manner if the following conditions are met:

- The withdrawal occurs in an aquifer that contributes baseflow to a stream via direct groundwater discharge.
- The withdrawals are greater than 100,000 gpd.
- A significant portion of the withdrawal is not returned to the stream as a wastewater discharge or to the surficial aquifer via onsite wastewater treatment systems (septic tanks). For example, groundwater withdrawals for irrigation of golf courses or agriculture are expected to be mostly lost to evapotranspiration. Very little is returned to the stream via direct or indirect runoff.

The combined net amount of groundwater withdrawals from private wells (individual wells not permitted or registered) that is not returned to the surficial aquifer system via onsite wastewater systems is not expected to significantly lower stream baseflow in any area of the basin, such that consideration of these withdrawals is not necessary in calculating UIFs.

4.0 Quality Assurance Reviews

Quality Assurance guidelines were developed in an internal CDM Smith memorandum dated April 2015, entitled *"Quality Assurance Guidelines: Unimpaired Flow Calculations (UIFs) for the South Carolina Surface Water Quantity Models."* The document is included in this report as **Attachment B**.

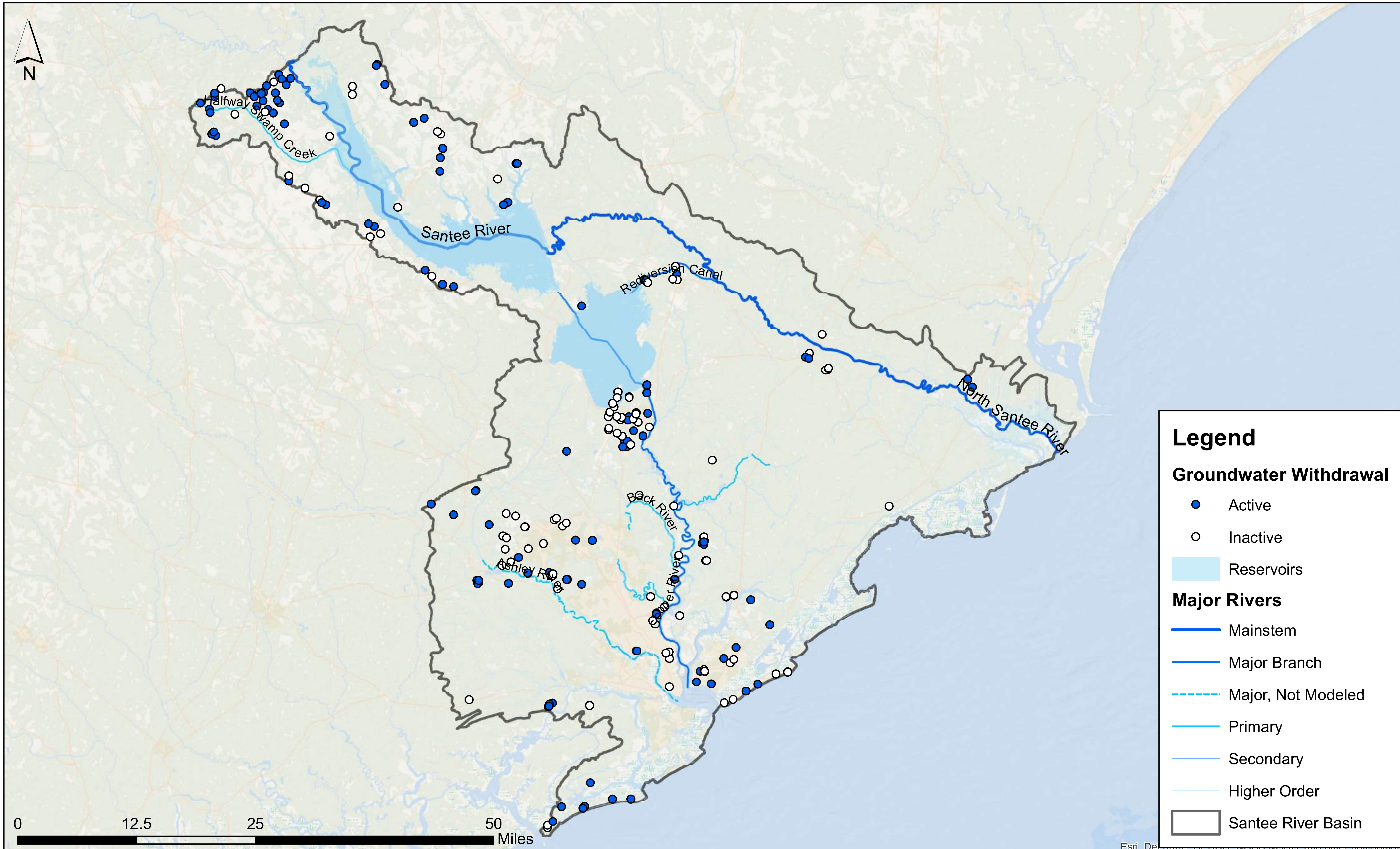
The Quality Assurance results are documented in each UIF workbook in the "QAQC" worksheet. Documentation includes the name of the reviewer, requested changes, and changes made. Some review items pertaining to the UIF extension calculations exist separately from the individual UIF workbooks, but are still listed in **Attachment B**.

5.0 Summary of Operational Hindcasting

Unique circumstances involving data availability, observable trends, etc. required decisions about how to develop representative hindcast values for each individual user. No withdrawals and discharges required hindcasting for the reasons discussed in **Section 3.2.1**.

6.0 Summary of Gaged UIF Flow Record Extension

A summary of the reference gages and methods used to extend the UIFs with partial periods of record is provided in **Table 6.1**. Initial candidates of reference gages are selected following guidelines outlined in **Attachment C.** See **Attachment D** for details pertaining to the decision-making process and **Attachment F** for notes associated with each individual decision.



CDM Smith

Figure 3-5
Active and Inactive Groundwater Withdrawal Locations

Section 3.2.1 outlined the situation leading to SNT02 and SNT04 not having gage-based UIFs. Additionally, because the Catawba-Wateree UIFs end in December 2010, the decision was made to also end this UIF dataset in December 2010, which is three years earlier than the Saluda, Edisto, Broad and Pee Dee river basins. Though SNT02 and SNT04 were created via area proration, which is technically an extension method, they were wholly created from area proration and not involved in the actual record extension workflow. Therefore, they do not appear in **Table 6.1**.

Two UIFs from outside the basin were implemented as reference gages as well: 02174250 on the Cow Castle Creek near Bowman, SC (EDO12) from the Edisto River Basin and 02136000 on the Black River at Kingstree, SC (PDE26) from the Pee Dee River Basin. Several other gages from the Pee Dee, as well as one from the Saluda River Basin were evaluated as potential reference gages but none were found to be suitable.

Table 6.1: Summary of Extending UIFs with Partial Periods of Record

USGS Gage with Partial Record					USGS Reference Gage(s)			Method of Extension
Project Gage ID	USGS Number	Stream	Periods of Record	Basin Area (mi^2)	Project Gage ID	Stream	Basin Area (mi^2)	
SNT05	02171680	WEDBOO CREEK NEAR JAMESTOWN, S.C.	9/1966 - 2/1972 2/1973 - 9/1992	15	SNT08	TURKEY CREEK ABOVE HUGER, SC	23	Area Ratio
					EDO12	COW CASTLE CREEK NEAR BOWMAN, SC	24	Area Ratio
					PDE26	BLACK RIVER AT KINGSTREE, SC	1213	Area Ratio
SNT08	02172035	TURKEY CREEK ABOVE HUGER, SC	10/2005 - 12/2010	23	SNT05	WEDBOO CREEK NEAR JAMESTOWN,S.C.	15	Area Ratio
					EDO12	COW CASTLE CREEK NEAR BOWMAN, SC	24	Area Ratio
					PDE26	BLACK RIVER AT KINGSTREE, SC	1213	Area Ratio

One way to evaluate the selection of an extension method is comparing frequency curves with flows from the partial record needing extending. A sample plot for SNT05 is shown in **Figure 6-1**. Validation graphs are available for each USGS gage. Each validation graph shows the period of record for a computed UIF and the predicted flows from reference gages during that same period. A sample validation graph is shown in **Figure 6-2**. The usage of each reference gage over different ungaged periods for the target gage (prioritized by hydrologic similarity and available record) is illustrated in **Figure 6-3**. Graphs for each UIF timeseries developed at a USGS gage site are presented in **Attachment E**.

7.0 Summary of Ungaged UIF Transposition

Area proration was used to transpose the UIF timeseries from gaged basins to ungaged basins. Selection of reference gages follows guidelines established in **Attachment C**. **Table 7.1** summarizes the information for the ungaged basins and the gaged basins used as reference. Headwater flows are used as input for each explicitly modeled tributary in SWAM whereas confluence flows are used for implicit tributaries needed for model calibration.

8.0 References

CDM Smith, October 2015, *Santee River Basin SWAM Model Framework.*

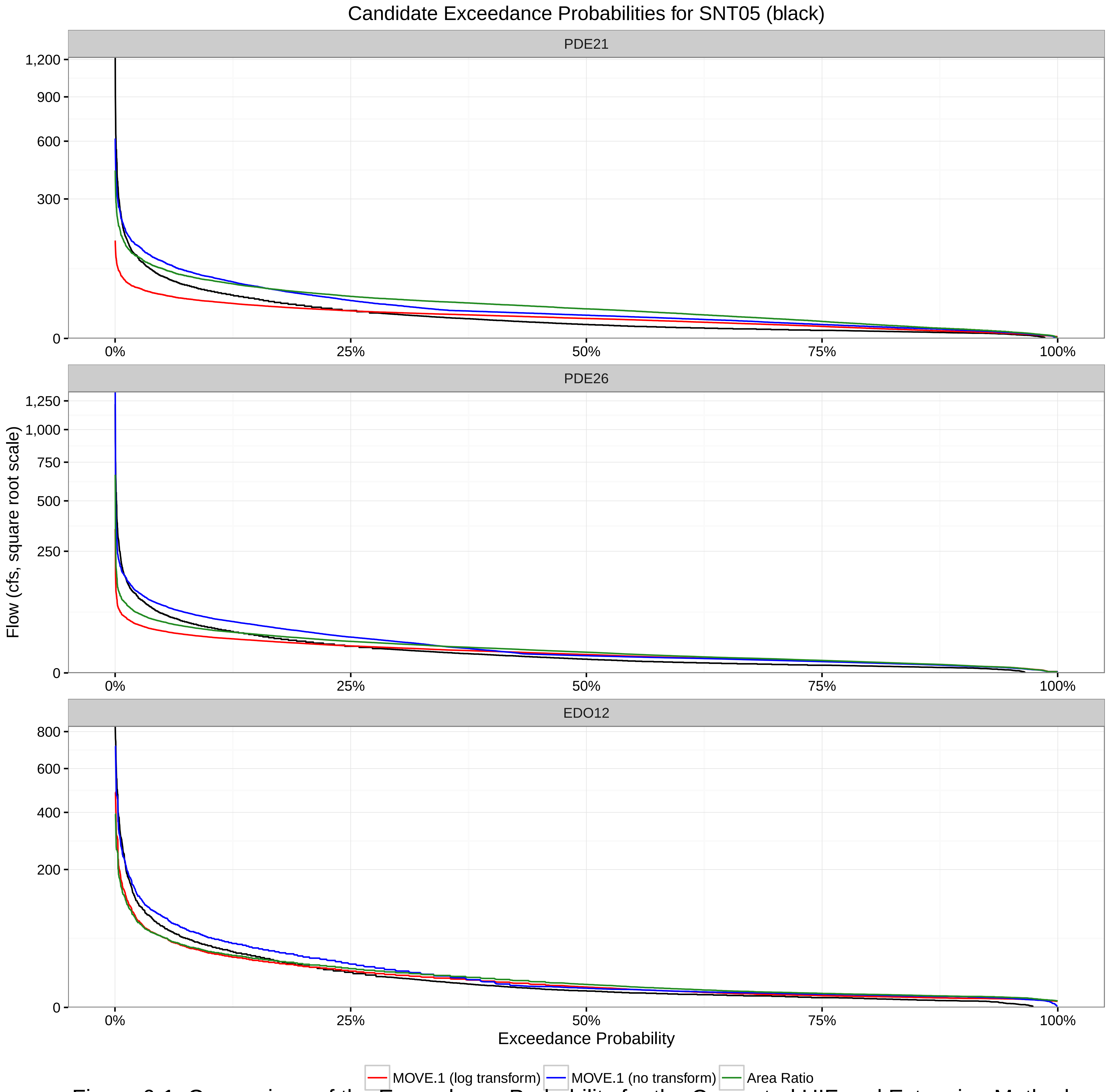


Figure 6-1: Comparison of the Exceedance Probability for the Computed UIF and Extension Methods

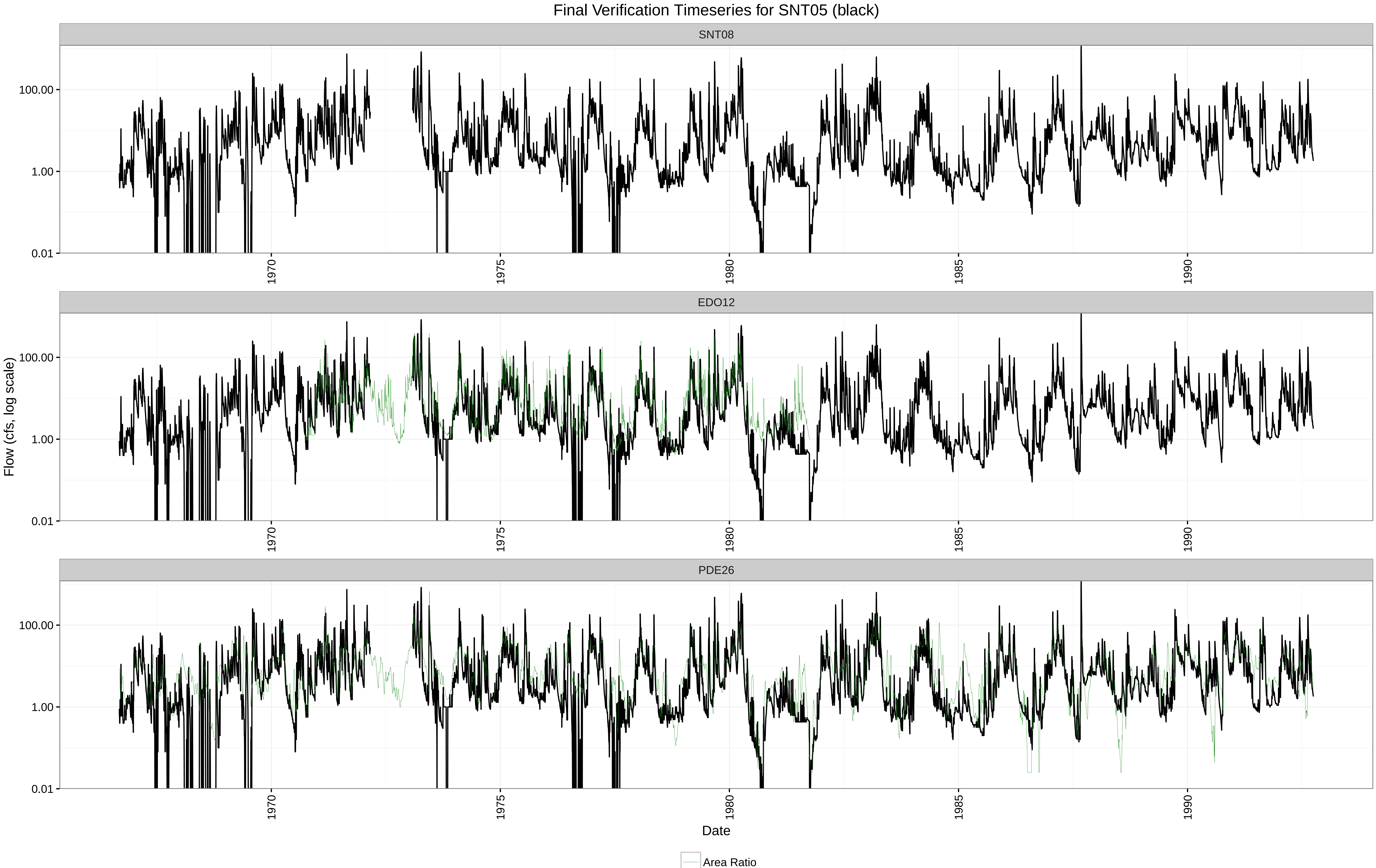


Figure 6-2: Validation Graphs for SNT05 with Predicted Flows from Reference Gages EDO12 and PDE26

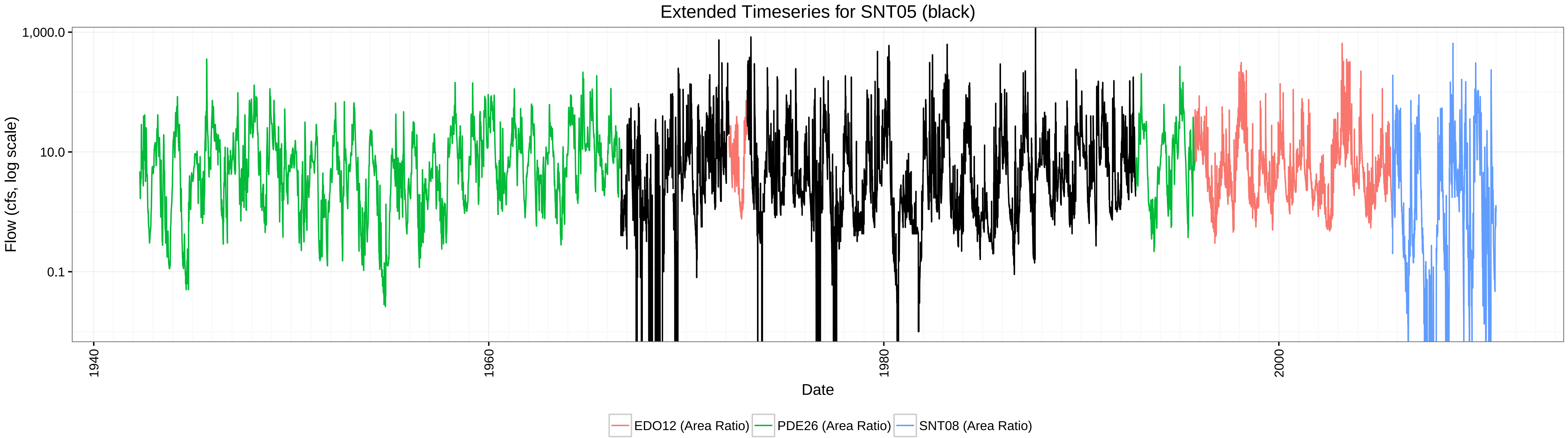


Figure 6-3: Resulting UIF Timeseries for SNT05

Table 7.1 UIFs in Ungaged Basins (Area Ratio Method Only)

	Ungaged Basin			USGS Reference Gage[1]			
Project ID	**SWAM Usage**	**Stream**	**Basin Area (mi^2)**	**Project Gage ID**	**USGS Number**	**Stream**	**Basin Area (mi^2)**
SNT202	Headwater Flow	Santee River	3.6	SNT02	02171500	SANTEE RIVER NEAR PINEVILLE, SC	14568.5
SNT201	Headwater Flow	Halfway Swamp Creek	3.6	SNT05	02171680	WEDBOO CREEK NEAR JAMESTOWN,S.C.	15.2
SNT205	Headwater Flow	Goose Creek	31.6				
SNT301	Headwater Flow	Marion Local Inflow	382.0				
SNT302	Headwater Flow	Moultrie Local Inflow	29.3				
SNT203	Headwater Flow	Cooper River	3.9	SNT08	02172035	TURKEY CREEK ABOVE HUGER, SC	23.0

[1] Ungaged flows are synthesized from UIFs, not original USGS gage flows.

List of Attachments

A. *Methodology for Unimpaired Flow Development, Santee River Basin, South Carolina* (CDM Smith, May 2016)

B. *Quality Assurance Guidelines: Unimpaired Flow Calculations (UIFs) for the South Carolina Surface Water Quantity Models* (CDM Smith, April 2015)

C. *Guidelines for Identifying Reference Basins for UIF Extension or Synthesis* (CDM Smith, April 2015)

D. *Refinements to the UIF Extension Process, with an Example* (CDM Smith, September 2015)

E. UIF Timeseries Graphs at USGS Gage Locations

F. Discussion on Reference Gage and Method Selection

G. Schematic of USGS Streamflow Gages in the Santee River Basin

ATTACHMENT A

Methodology for Unimpaired Flow Development, Santee River Basin, South Carolina
(CDM Smith, May 2016)

Technical Memorandum

To: *South Carolina Department of Natural Resources (DNR)*
South Carolina Department of Health and Environmental Control (DHEC)

From: *CDM Smith*

Date: *May 2, 2016*

Subject: *Unimpaired Flow Development*
Santee River Basin, South Carolina

1.0 Background and Objectives for Unimpaired Flows

Unimpaired Flow (UIF) describes the natural hydrology of a river basin. UIFs quantify streamflows throughout a river basin in the absence of human intervention in the river channel, such as storage, withdrawals, discharges, and return flows. From this basis, modeling and decision making can be compared with pristine conditions.

This memorandum identifies the active and inactive flow gages the Santee River basin and provides recommendations on where UIF development may occur.

2.0 Overview of the Santee Basin USGS Gages

Eighteen Unites States Geological Survey (USGS) gaging stations monitor streamflow in the Santee River Basin. Of these, only eight are not located in tidally influenced areas, including three on the Santee River, one on the Cooper River, two on tributary streams, and two on diversion canals. Only four of the non-tidally influenced gages are currently active.

An overview map of the USGS streamflow gages in the Santee River Basin are shown in **Figure 1. Figure 2** depicts the length and timing of records available for the non-tidally influenced USGS gages in the Santee River basin.

Figure 1. Santee River Basin USGS Streamflow Gages (with project IDs)

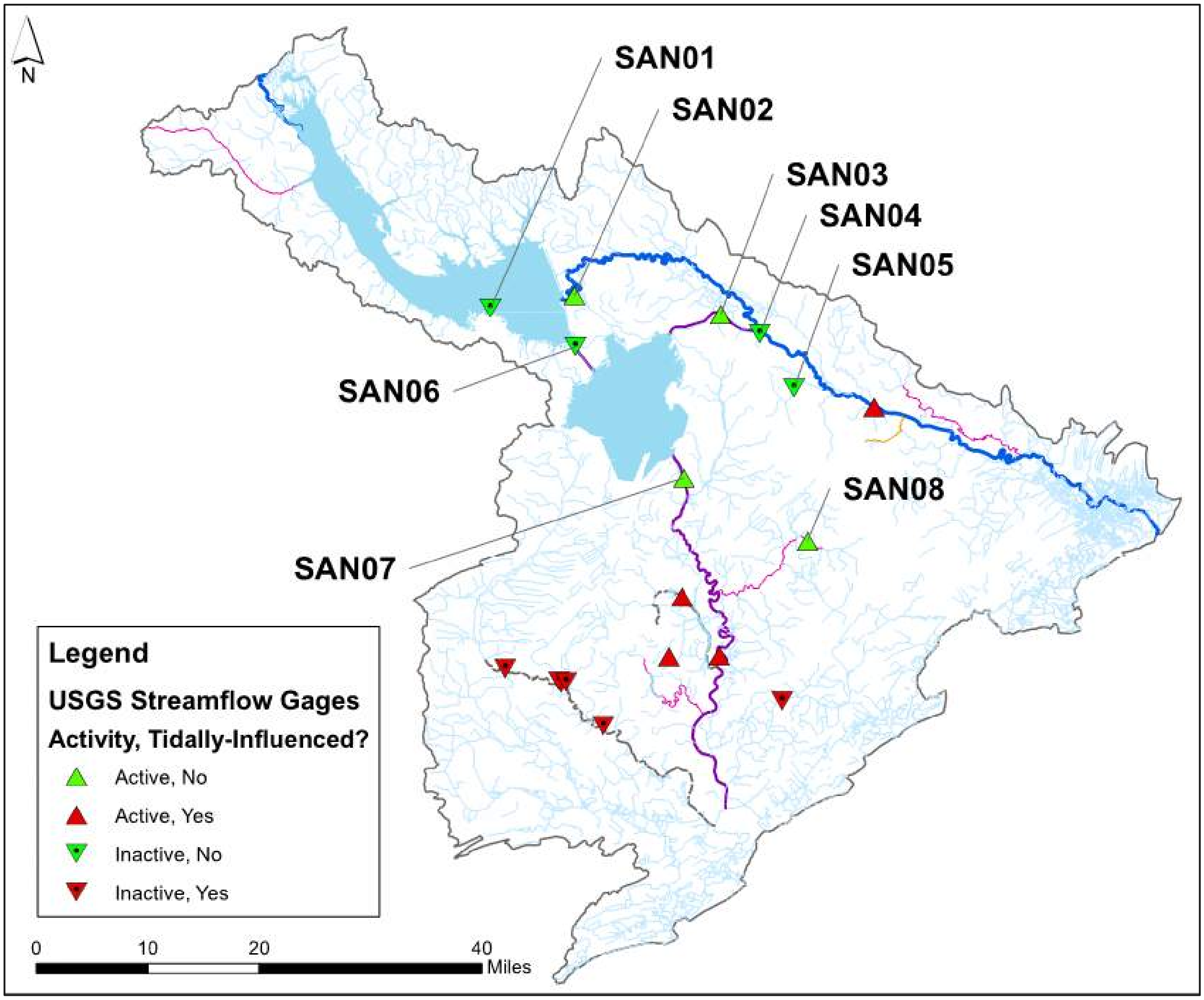
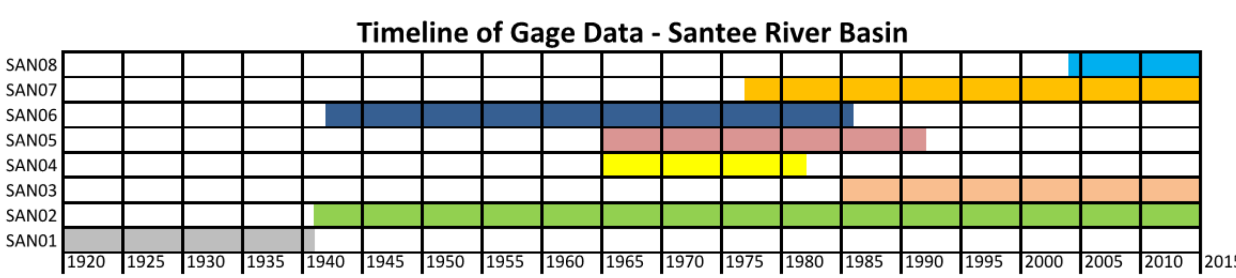


Figure 2. Period of record for USGS gages in the Santee Basin



3.0 Recommendations for UIF Development

The eight non-tidally influenced USGS gages are candidates for UIF development. A detailed explanation for each of these gages is listed below:

SAN01 (USGS 0217000): This gage has been inactive since 1941, since the construction of Lake Marion. Its original location now places it in the middle of Lake Marion, six miles upstream of the current dam. UIF development at this gage is not recommended since it is now within Lake Marion. However, the hydrologic patterns of SAN01 can still serve as validation tools for the SAN02 UIFs for comparing seasonal fluctuation, annual average flow, and low flow statistics.

SAN02 (USGS 02171500): This active gage (1941-2015) is located just downstream of Lake Marion dam on the Santee River. This is the replacement gage to SAN01, becoming active the year SAN01 became inactive. Although the unimpairment of Lake Marion and its multiple diversion canals may be complex, SAN02 is a candidate for UIF development. SAN02 is recommended as the primary gage for this basin's period of record.

SAN03 (USGS 02171645): This gage is located on the rediversion canal from Lake Moultrie to the Santee River. UIF development is not recommended since it does not reflect a location where natural (unimpaired) flow once occurred.

SAN04 (USGS 02171650): This inactive gage (1966-1982) is located on the Santee River downstream of a confluence with the rediversion canal from Lake Moultrie. This gage is a candidate for UIF development.

SAN05 (USGS 02171580): This inactive gage (1966-1992) is located on Wedboo Creek, tributary to the Santee River. This gage is a candidate for UIF development.

SAN06 (USGS 02170500): This gage is located on the diversion canal from Lake Marion to Lake Moultrie. UIF development is not recommended since it does not reflect a location where natural (unimpaired) flow once occurred.

SAN07 (USGS 02172002): This gage is located on the Cooper River just below the outlet from Lake Moultrie. Unimpairment of this gage requires removing the effects of Lake Moultrie and the input of flow from Lake Marion. This gage is a candidate for UIF development.

SAN08 (USGS 02172035): This gage is maintained and used by the Francis Marion National Forest parks service. This gage is a candidate for UIF development.

4.0 Summary

Five of the eight USGS gaging stations are candidates for UIF development. The three exceptions are SAN01, which is currently inundated, and the two diversion canals, SAN03 and SAN06. Although SAN01 is not a candidate for UIF development, its original record will still be used to check patterns in the UIF for SAN02. UIF development is not recommended for gages located on diversion canals since they do not reflect a location where natural (unimpaired) flow once occurred.

ATTACHMENT B

Quality Assurance Guidelines: UIFs for the South Carolina Surface Water Quantity Models

(CDM Smith, April 2015) ***- To be Included in Final Memo***

ATTACHMENT C

Guidelines for Identifying Reference Basins for UIF Extension or Synthesis

(CDM Smith, April 2015) ***- To be Included in Final Memo***

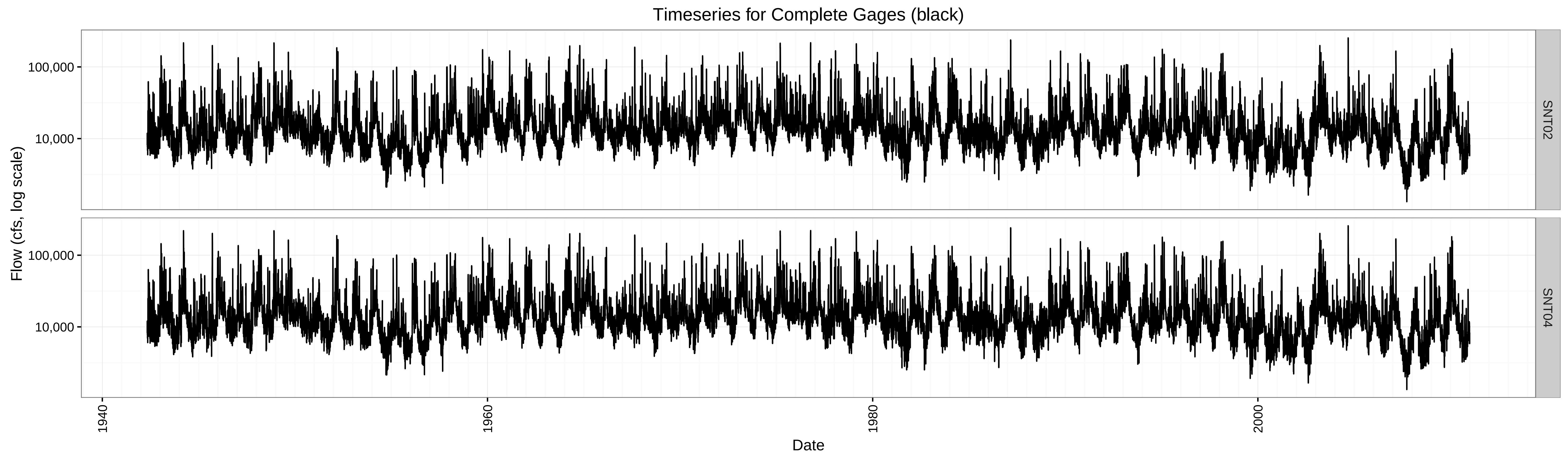
ATTACHMENT D

Refinements to the UIF Extension Process, with an Example

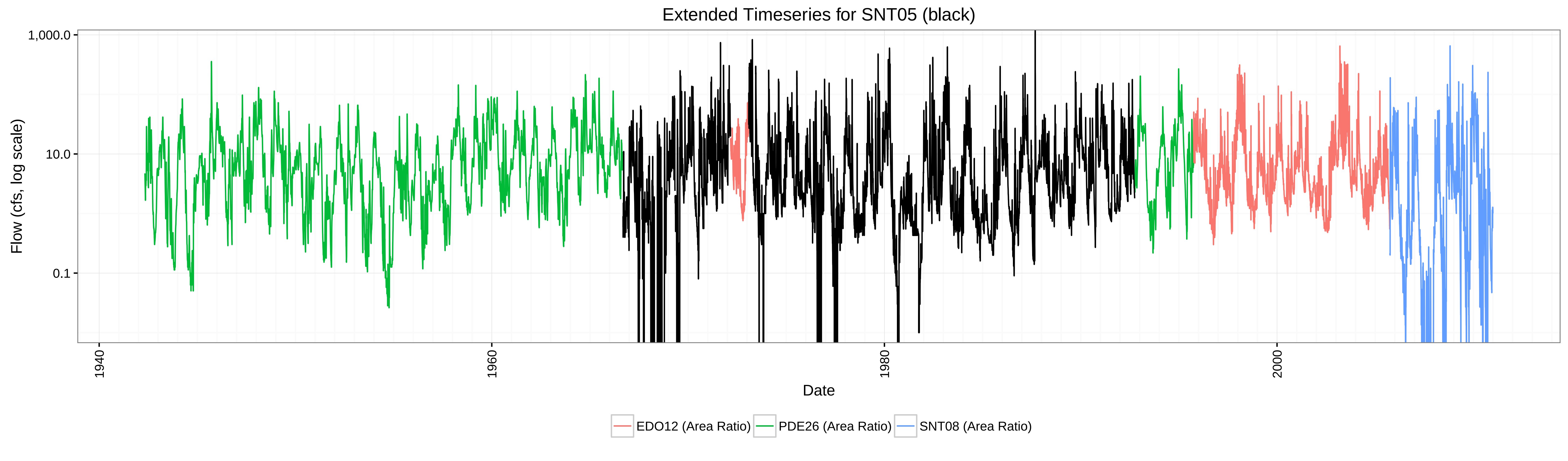
(CDM Smith, September 2015) - To be Included in Final Memo

ATTACHMENT E

UIF Timeseries Graphs at USGS Gage Locations



Timeseries for Complete Gages (black)
Flow (cfs, log scale)
100,000
10,000
SNT02
SNT04
1940
1960
1980
2000
Date



Extended Timeseries for SNT05 (black)
1,000.0
10.0
0.1
Flow (cfs, log scale)
1940
1960
1980
2000
Date
EDO12 (Area Ratio)
PDE26 (Area Ratio)
SNT08 (Area Ratio)


Extended Timeseries for SNT08 (black)
Flow (cfs, log scale)
100.00
1.00
0.01
1940
1960
1980
2000
Date
EDO12 (Area Ratio)
PDE26 (Area Ratio)
SNT05 (Area Ratio)

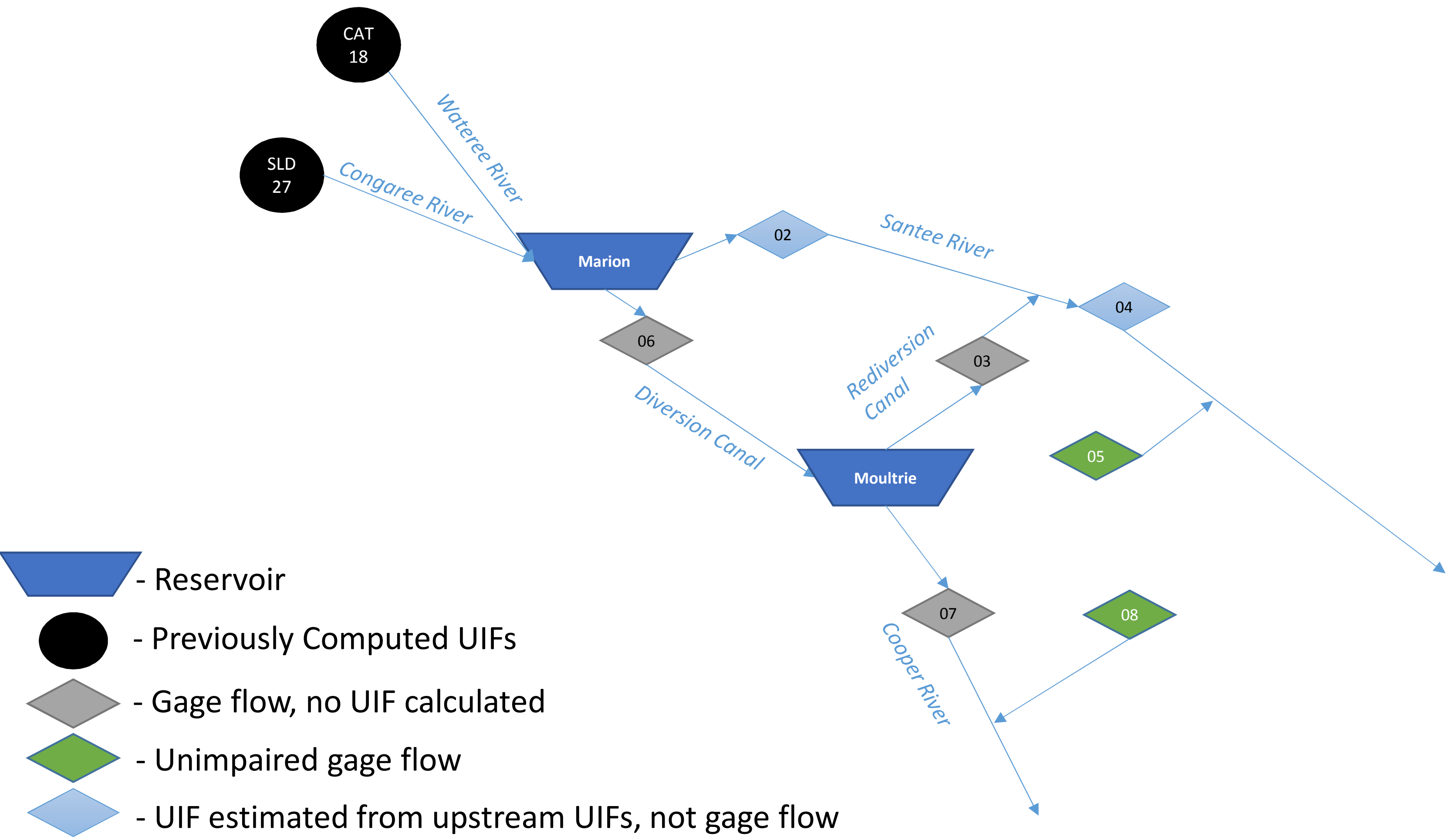
ATTACHMENT F

Discussion on Reference Gage and Method Selection

Gage	Reference	Method	Notes
SNT05	SNT08	Area Ratio	No overlap to test, but behavior in final timeseries was examined.
SNT05	EDO12	Area Ratio	Is debatable which method is most appropriate; area ratio appears slightly more suitable from summary statistics and most plots. Additionally, the existence of zeroes in gage flow adds some questionability to using MOVE.1
SNT05	PDE26	Area Ratio	Similar reasoning as with above, but with particular emphasis on how area ratio performs in cumulative flow versus the MOVE.1 methods.
SNT08	SNT05	Area Ratio	No overlap to test, but behavior in final timeseries was examined.
SNT08	EDO12	Area Ratio	No method really can represent characteristics for both low and high flows. Like with SNT05, the presence of zeroes in gage data leads to question MOVE results.
SNT08	PDE26	Area Ratio	Similar reasoning as with above.

ATTACHMENT G

Schematic of USGS Streamflow Gages in the Santee River Basin



Attachment G: Schematic of Selected USGS Streamflow Gages in the Santee River Basin