Technical Memorandum

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

From: *CDM Smith*

Date: *July 2016*

Subject: *Unimpaired Flow Methodology and Dataset for the Catawba-Wateree 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 Catawba-Wateree River Basin. The TM references the electronic database which houses the completed UIF dataset for the Catawba-Wateree 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 Catawba-Wateree Basin

The Catawba-Wateree River basin covers 5,620 square miles, 2,320 of which falls within South Carolina. The South Carolina portion covers eight percent of the land area of the State and lies primarily within the Piedmont and Upper Coastal Plain physiographic provinces (**Figure 2-1**). The main watercourse has two names: the Catawba River and the Wateree River. The Catawba River originates in the Blue Ridge Mountains of North Carolina in McDowell County and is heavily-regulated as it passes through a series of large reservoirs in North Carolina. The Catawba River then flows through Lake Wylie, which forms approximately 10 miles of the North and South Carolina border. The watercourse changes to the Wateree River downstream of Lake Wateree. Major tributaries include Sugar Creek, Fishing Creek, and Rocky Creek. About 25 miles southeast of Columbia, the Wateree River merges with the Congaree River upstream of Lake Marion and forms the Santee River.

Twelve active Unites States Geological Survey (USGS) gaging stations monitor streamflow in the basin including three on the Catawba and Wateree rivers, one on Sugar Creek, one on Rocky Creek, and the remaining on smaller tributaries. The Wateree River station near Camden (02148000) offers the earliest period of record, starting from October 1929 and the Rocky Creek gage at Great Falls (02147500) offers the second earliest, starting from March 1951 (see **Section 3.2.1**). Average streamflow[1] varies from 3,970 cubic feet per second (cfs) on the Catawba River near Rock Hill (02146000) to 5,900 cfs on the Wateree River near Camden.

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 explained and presented in the Catawba Framework Memorandum (CDM Smith, 2015). 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. The former users and dischargers are summarized below in **Tables 2-1 and 2-2** as they needed to be accounted for in the UIF development. Individual withdrawal and discharges less than 3 million gallons per month (MG/m) are generally not included in UIF calculations or in the water quantity models.

Table 2-1. Formerly permitted or registered surface water users in the Catawba-Wateree Basin

Intake ID	Facility Name	Withdrawal Tributary
Water Supply		
28WS001S02	Camden City of	Big Pine Tree Creek
29WS001S01	Lancaster County Water & Sewer Plant	Bear Creek
29WS001S02	Lancaster County Water & Sewer Plant	Bear Creek
29WS003S01	Springs-Grace Bleachery	Catawba River
29WS003S02	Springs-Grace Bleachery	Catawba River
46WS004S01	Fort Mill Town of	Catawba River
Industrial Users		
12IN005S01	Clariant Corp Lando Water Plant	Fishing Creek
28IN003S01	Whibco Blaney Plant	Gillies Creek
28IN005S01	Weylchem Us Inc Elgin Site	Spears Creek
46IN003S01	Rock Hill Printing & Finishing Co	Catawba River
46IN004S01	Cinergy Solutions Of Rock Hill, LLC	Catawba River
46IN008S01	Stablex South Carolina	Wildcat Creek

[1] Restricted to overlapping calendar years of 1942-2013 between the two gages.

Table 2-2. Formerly Permitted NPDES Discharges in the Catawba-Wateree Basin

NPDES Pipe ID	Facility Name	Discharge Tributary
SC0001015-005	BOWATER INC/COATED PAPER DIV	Catawba River
SC0020303-001	CLOVER/CALABASH CREEK PLANT	Allison Creek
SC0026298-001	CWS/RIVER HILLS WWTP	Catawba River
SC0001783-001	GREENS OF ROCK HILL	Catawba River
SC0001783-002	GREENS OF ROCK HILL	Catawba River
SC0001783-003	GREENS OF ROCK HILL	Catawba River
SC0002585-002	INVISTA S.A.R.L./CAMDEN	Wateree River
SC0023264-001	KAWASHIMA TEXTILE USA INC	Gillies Creek
SC0023264-002	KAWASHIMA TEXTILE USA INC	Wateree River
SC0023264-02B	KAWASHIMA TEXTILE USA INC	Wateree River
SC0041378-03C	KENNECOTT/RIDGEWAY GOLD MINE	Twentyfive Mile Creek
SC0022080-001	LANCASTER, TOWN OF	Bear Creek
SC0043494-001	PALMETTO UTILS/VALHALLA WWTP	Spears Creek
SC0024970-001	USAF/SHAW AIR FORCE BASE	Beech Creek
SC0024970-01A	USAF/SHAW AIR FORCE BASE	Beech Creek
SC0022705-001	YORK COUNTY/NEW HERITAGE	Sugar Creek

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. An alternate method sometimes employed utilizes rainfall-runoff modeling to estimate natural runoff tendencies, but this technique is often uncertain, and its only sure footing is in calibration to measured (and frequently impaired) streamflow records. For the Catawba-Wateree River Basin, UIFs were calculated at most 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 1951-2010 (coinciding with the *second* longest recorded streamflow in the basin, 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

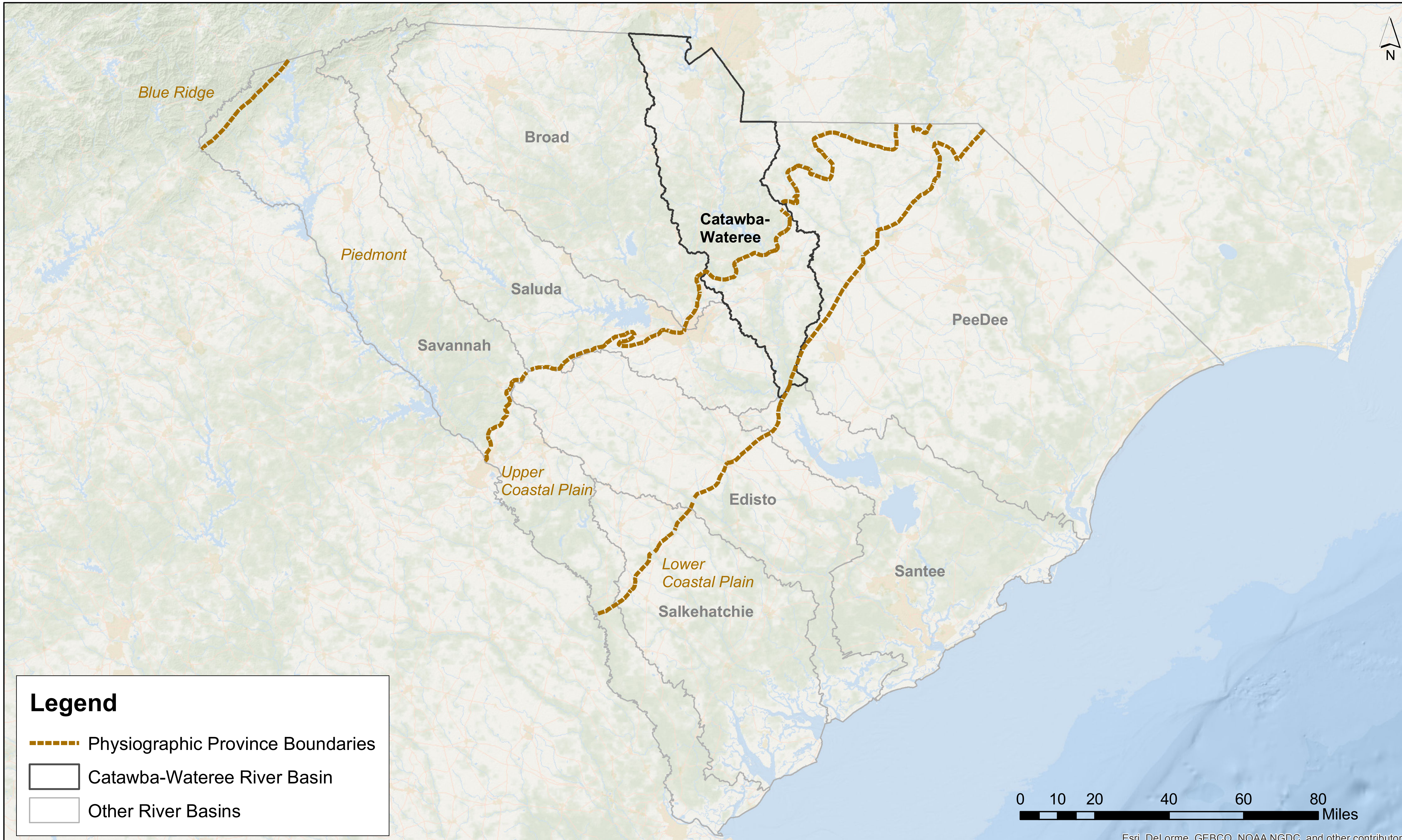

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Figure 2-1
South Carolina's Catawba-Wateree River Basin and Other Major River Basins

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 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, and Pee Dee River Basins was also used in the Catawba. 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:

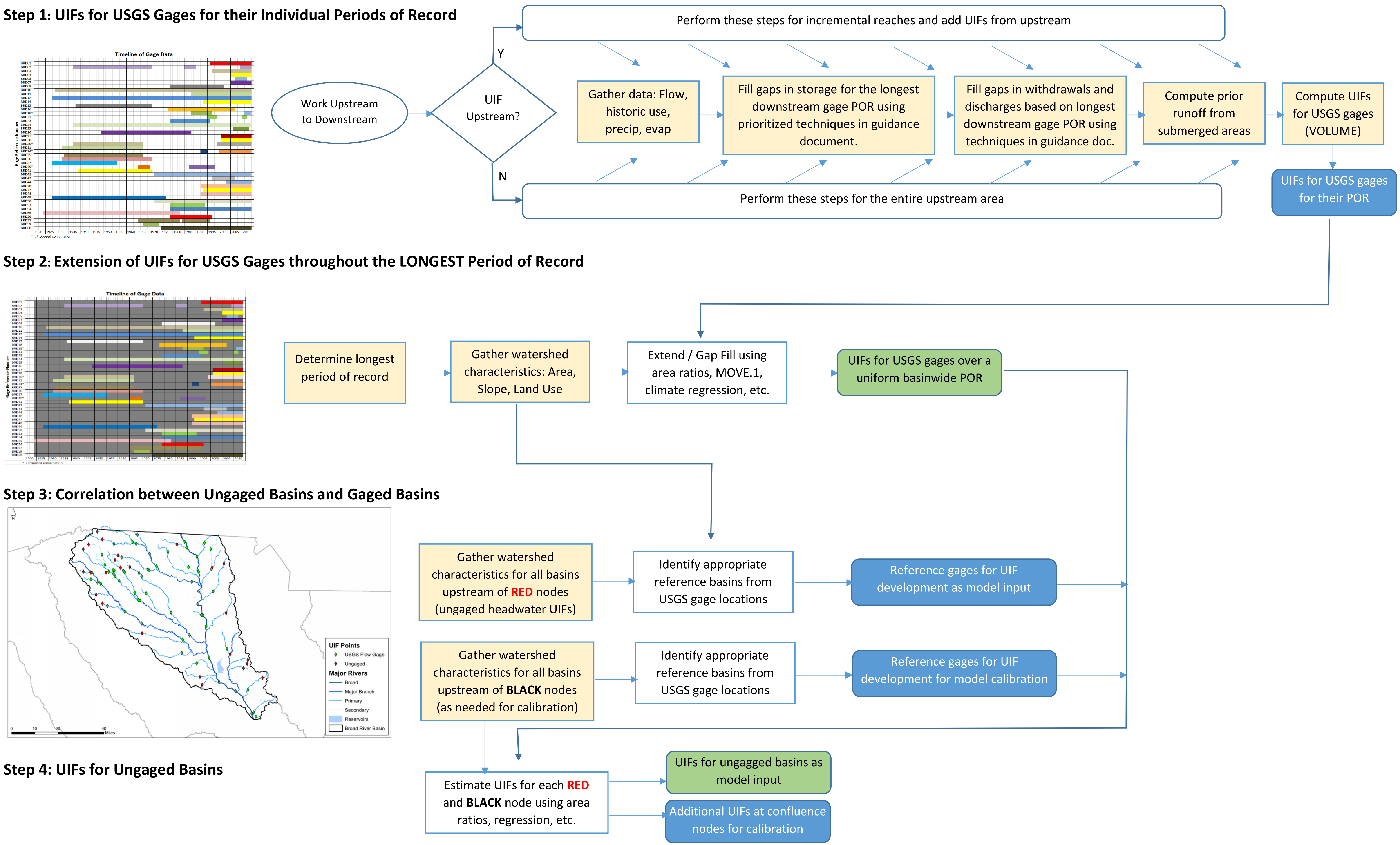
- *Guidelines for Standardizing and Simplifying Operational Record Extension (CDM Smith, March 2015)* – Included as **Attachment A** of this report. This includes guidelines for various techniques for operational gap filling and record extension, and which techniques are most appropriate for various circumstances.
- *Guidelines for Identifying Reference Basins for UIF Extension or Synthesis (CDM Smith, April 2015)* – Included as **Attachment B** 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 Catawba-Wateree River Basin. The five black points identified by a "CH" and a number refer to UIFs that were previously calculated by HDR Inc., on behalf of the Catawba-Wateree Water Management Group (CWWMG). Given these existing UIFs, three UIFs on the Catawba River were not calculated from USGS gages (gray). Two other UIFs, CAT01 and CAT02, have become gray as well; these two are on tributaries that drain into Lake Wylie, which is no longer in the model. The ungaged UIF locations are computed via area transposition and serve as headwater flows for explicit model tributaries or confluence flows for implicit tributaries. **Attachment G** contains a simplified schematic of the USGS streamflow gages, existing UIFs, and reservoirs. The existing UIFs, as developed by HDR Inc., are further discussed in **Section 3.2.1**.

3.1 Period of Record

While UIF estimates begin in 1951 for the Catawba-Wateree River Basin, more than half of the stream gages began operation in the 1980s or later. The records for all gages that began tracking flow after 1951 were extended using gap filling techniques. Therefore, much of the UIFs are based on estimated flows, but the value of a lengthy record, even if approximate, is that DNR, DHEC, and other users can evaluate results over a large range of hydrologic and climate conditions. **Figure 3-3** depicts the length and timing of records available for all USGS gages in the Catawba-Wateree River Basin.

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



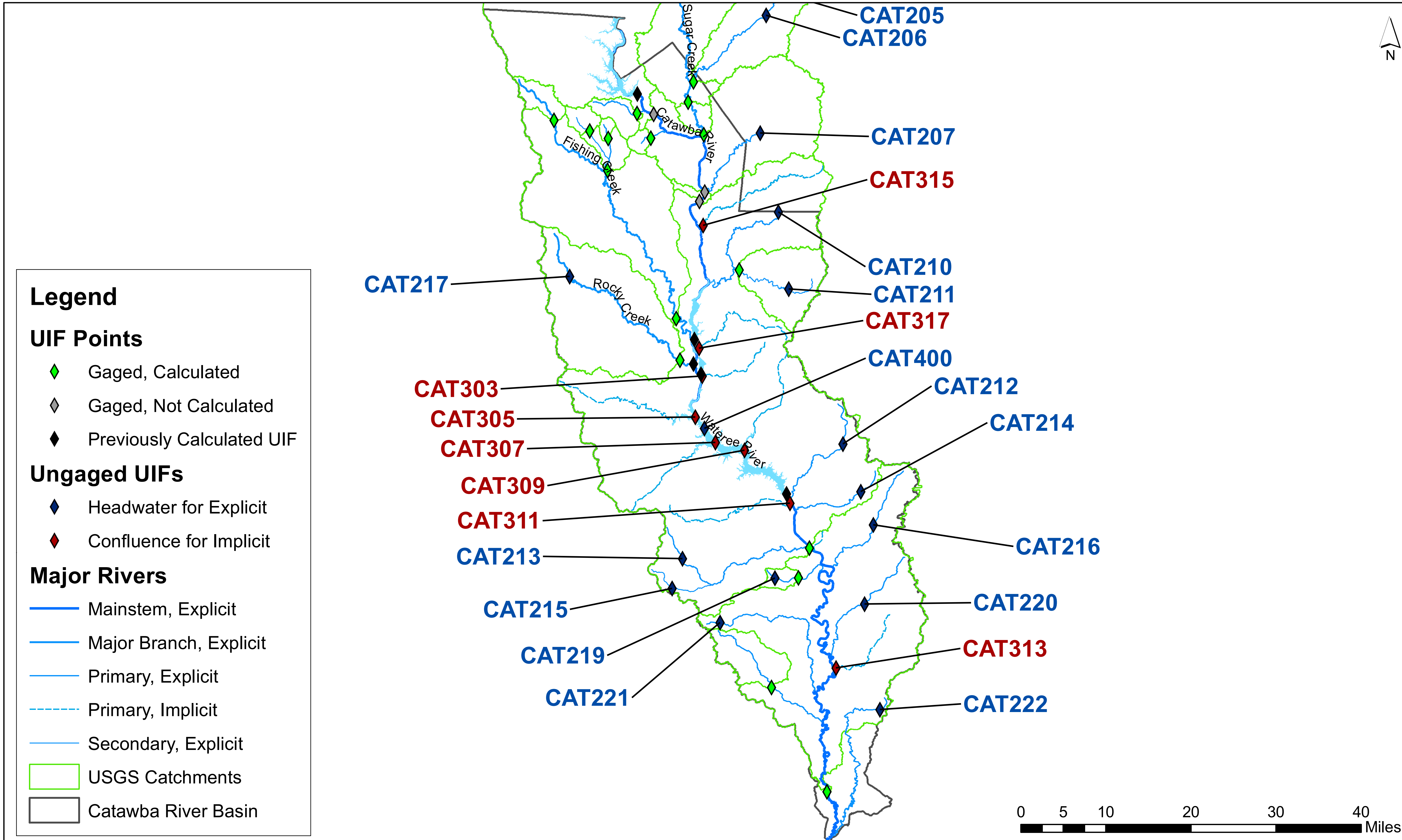


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Figure 3-2
Unimpaired Flow Locations in the Catawba River Basin

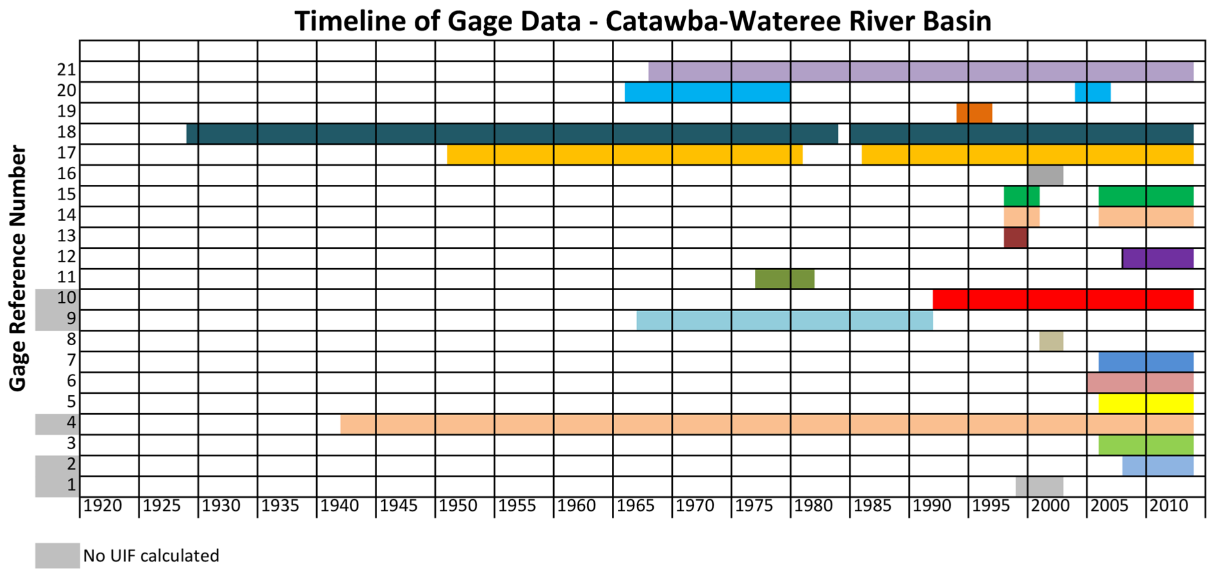


Figure 3-3. Period of record for USGS gages in the Catawba-Wateree River Basin

3.2 Issues Specific to the Catawba-Wateree River Basin

3.2.1 Existing Catawba River UIFs in North and South Carolina

UIFs flowing through the Catawba-Wateree River Basin from North Carolina and South Carolina were previously developed by HDR Engineering under contract to Duke Energy Carolinas, LLC, as reported in the *Catawba-Wateree Hydroelectric Project Operations Model – Model Logic and Verification Report* (HDR, 2014). The UIFs were developed for use in the CHEOPS model, a model that principally simulates hydropower operations in river networks. In support of such a tool, the UIFs were developed to help predict expected flow conditions on the main stem of the Catawba River, at points representing inflow to hydropower reservoirs.

The previously-developed UIFs only extend to Lake Wateree, leaving two USGS gages on the main watercourse before the confluence with the Congaree River: CAT18 (02148000) and CAT21 (02148315). As outlined in **Figure 3-1**, the standardized process adopted for calculating a UIF in this study depends on whether a site is the most upstream gage on the river, or is incremental, which takes into account the previous upstream UIF and impairments in the incremental reach. In addition to calculated upstream UIFs, corresponding upstream managed flows are also used for calculating a UIF. To calculate the UIFs for CAT18, both the Lake Wateree UIFs at CH11 and simulated managed flows were used, the difference between the two representing the total impairments upstream of Lake Wateree.

Unfortunately, the simulated managed flows from the CHEOPS model appeared unsuitable for unimpairing daily gage flow at CAT18. The modeled flows demonstrate sudden changes and jumps typical of reservoir operating rules, particularly from a hydropower model, but which are not observed in the downstream flow record, suggesting that such management may not have been constant throughout the historical time period. Usage of such flows would require post-processing such as n-day smoothing, which can be appropriate if a better method is not available, but which also introduces some uncertainty. For comparative purposes, two different UIFs for CAT18 were computed: one using the UIFs and managed flows for CH11 along with the impairments of CAT18's incremental area, and another by simply prorating the CHEOPS UIF for CH11. The prorated UIFs resulted in less daily uncertainty while maintaining reasonable time-step hydrograph patterns. With either method, the uncertainty embedded in the UIF at CAT18 results in it not being used when evaluating potential reference gages for UIF extension or synthesis elsewhere in the basin. Given these complications, the start year of the UIF dataset is determined by the next-earliest gage, CAT17 on Rocky Creek at 1951.

Additionally, two USGS gages frequently are missing values above a certain threshold: CAT06 (0214676115) on McAlpine Creek and CAT21 (02148315) on the Wateree River. CAT06 is affected by backwater conditions at high flows. Since values are not recorded during these conditions, these dates remain blank and are filled during the UIF extension process. For CAT21, values above 10,000 cfs exceed bankfull capacity and are not reported. Additionally, values near 10,000 cfs have questionable behavior. Given this, and because the upstream gage CAT18 is estimated via prorated CH11 UIFs, CAT21 UIFs are not based off of unimpaired gage flow, but instead prorated CH11 UIFs.

3.2.2 Groundwater

Registered and permitted (both active and inactive) groundwater withdrawal locations are shown in **Figure 3-4**. 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 C**.

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 C**.

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. A summary of hindcasting methods used for withdrawals and discharges are presented in **Table 5.1** and **Table 5.2**, respectively. The following tables also only contain hindcasting as needed for unimpairing downstream USGS gages. Many withdrawals and discharges did not require hindcasting given the locations of previously-calculated UIFs or the period of record for tributary gages. Reference **Attachment A** for details on the listed methodologies.

Hindcasting of agricultural withdrawals in the Catawba-Wateree River Basin was also required for the UIF calculations. Withdrawal data reported to DHEC from 2002 and 2014 was used directly, and prior to that, values from 1950 through 2001 were hindcasted using irrigated acreage estimation techniques. These estimation techniques are described in the memorandum entitled, *Methodology for Developing Historical Surface Water Withdrawals for Agriculture Irrigation* (CDM Smith, July 2015).

Table 5.1: Summary of Methods Used for Hindcasting Withdrawals

Project Gage ID	USGS Number	Stream	Withdrawal Hindcasting			
			User ID	User Name	Time Periods	Method Used
CAT11	02147240	BEAR CREEK AT LANCASTER, SC	29WS001S01	Lancaster County Water & Sewer	9/1978 – 1/1983	Monthly pattern and extrapolation

Table 5.2: Summary of Methods Used for Hindcasting Discharges

Project Gage ID	USGS Number	Stream	Discharge Hindcasting			
			ID	Facility Name	Time Periods	Method Used
CAT02	021457492	ALLISON CREEK AT RD 114 NEAR YORK, SC	SC0020303-001	CLOVER/CALABASH CREEK PLANT	11/1974 - 1/1989	Hindcasted to known start date
CAT17	02147500	ROCKY CREEK AT GREAT FALLS, SC	SC0036056-001	CHESTER/ROCKY CREEK PLANT	3/1988 - 1/1989	Correlated with municipal withdrawal (Chester)
CAT18	02148000	WATEREE RIVER NR. CAMDEN, SC	SCG646020-001	LUGOFF-ELGIN WTR AUTH/WATER TP	1/1983 - 12/2013	Permit estimate of Lugoff-Elgin
			SCG646025-001	CAMDEN, CITY OF/ WTR TTMT PLT	1/1983 - 12/2013	Permit estimate of Camden
CAT21	02148315	WATEREE R. BL EASTOVER, SC	SC0002518-001	DEROYAL TEXTILES	2/1978 - 1/1989	Hindcasted to known start date
			SC0021032-001	CAMDEN WWTF	2/1983 - 1/1989	Correlated with municipal withdrawal (Camden)
			SC0023264-002	KAWASHIMA TEXTILE USA INC	7/1975 - 1/1989	Hindcasted to known start date
			SC0023264-02B			Combined with pipe 002
			SC0024970-001	USAF/SHAW AIR FORCE BASE	4/1985 - 1/1989	Hindcasted to known start date
			SC0024970-002			Combined with pipe 001
			SC0024970-01A			Combined with pipe 001

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 B.** See **Attachment D** for details pertaining to the decision-making process and **Attachment F** for notes associated with each individual decision.

Section 3.2.1 outlined the previously-calculated mainstem UIFs and the situation leading to CAT18 not having gage-based UIFs. CAT18 would have been the gage with the longest POR, starting in October 1929; however, now the UIF dataset begins in 1951 as defined by CAT17's earliest record. Additionally, because the previously developed 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.

As MOVE.1 without an initial log transform may produce negative or near-zero values, area proration (which is strictly linear and cannot produce negative flows from non-negative reference flows) replaces values below a site-specific minimum threshold determined by the overlapping period between the partial and reference gages. For example, in the overlap between CAT07 and

CAT15, the lowest flow is 89 cfs. Thus, when MOVE.1 is calculated using CAT07's untransformed flows, any days below 89 cfs are replaced with the corresponding flows of that day found from area proration. Note that if a reference gage registers a flow of zero, the extended flow for the partial gage will also be estimated as zero.

Two relatively-unimpaired North Carolina Catawba Basin gages were implemented as reference gages as well: 02143500 on Indian Creek near Laboratory, NC (NC01) and 02146750 on McAlpine Creek near Pineville, NC (NC02). Additionally, gages from the nearby Broad 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

<table>
<tr><th colspan="5">USGS Gage with Partial Record</th><th colspan="3">USGS Reference Gage(s)</th><th rowspan="2">Method of Extension</th></tr>
<tr><th>Project Gage ID</th><th>USGS Number</th><th>Stream</th><th>Periods of Record</th><th>Basin Area (mi²)</th><th>Project Gage ID</th><th>Stream</th><th>Basin Area (mi²)</th></tr>
<tr><td rowspan="3">CAT03</td><td rowspan="3">021459367</td><td rowspan="3">BIG DUTCHMAN CREEK AT ROCK HILL, SC</td><td rowspan="3">9/2006 - 12/2010</td><td rowspan="3">17</td><td>CAT15</td><td>WILDCAT CREEK BELOW ROCK HILL, SC</td><td>30</td><td>Area Ratio</td></tr>
<tr><td>NC02</td><td>MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC</td><td>92</td><td>MOVE.1 (log transform)</td></tr>
<tr><td>CAT17</td><td>ROCKY CREEK AT GREAT FALLS, SC</td><td>196</td><td>MOVE.1 (log transform)</td></tr>
<tr><td rowspan="3">CAT05</td><td rowspan="3">02146110</td><td rowspan="3">MANCHESTER CREEK AT ROCK HILL, SC</td><td rowspan="3">12/2006 - 12/2010</td><td rowspan="3">6</td><td>CAT15</td><td>WILDCAT CREEK BELOW ROCK HILL, SC</td><td>30</td><td>Area Ratio</td></tr>
<tr><td>NC02</td><td>MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC</td><td>92</td><td>MOVE.1 (log transform)</td></tr>
<tr><td>CAT17</td><td>ROCKY CREEK AT GREAT FALLS, SC</td><td>196</td><td>MOVE.1 (log transform)</td></tr>
<tr><td rowspan="2">CAT06</td><td rowspan="2">0214676115</td><td rowspan="2">MCALPINE CREEK AT SR2964 NR CAMP COX, SC</td><td rowspan="2">10/2005 - 12/2010</td><td rowspan="2">95</td><td>NC02</td><td>MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC</td><td>92</td><td>MOVE.1 (log transform)</td></tr>
<tr><td>CAT17</td><td>ROCKY CREEK AT GREAT FALLS, SC</td><td>196</td><td>MOVE.1 (log transform)</td></tr>
</table>

CAT07	02146800	SUGAR CREEK NEAR FORT MILL, SC	4/2006 - 12/2010	263	NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)
					CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1: no transform, Area Ratio if MOVE.1 < 89 cfs
CAT08	02146820	SUGAR CR. NR FT. MILL, S.C.	5/2001 - 9/2002	275	CAT01	CROWDERS CREEK (RD 1104) NEAR CLOVER, SC	89	Area Ratio
					NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	Area Ratio
					CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
CAT11	02147240	BEAR CREEK AT LANCASTER S. C.	9/1978 - 5/1982	66	CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
					NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)
CAT12	021473415	FISHING CREEK @ HWY 5 BELOW YORK, SC	4/2008 - 12/2010	16	CAT15	WILDCAT CREEK BELOW ROCK HILL, SC	30	MOVE.1 (log transform)
					CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
					NC01	INDIAN CREEK NEAR LABORATORY, NC	69	MOVE.1 (log transform)
CAT13	021473423	WILDCAT CREEK NEAR ROCK HILL, SC	8/1998 - 5/2000	4	CAT15	WILDCAT CREEK BELOW ROCK HILL, SC	30	MOVE.1 (log transform)
					NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)
					CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
CAT14	021473426	TOOLS FORK CREEK NEAR ROCK HILL, SC	8/1998 - 6/2001 4/2006 - 12/2010	10	CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
					NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)

CAT15	021473428	WILDCAT CREEK BELOW ROCK HILL, SC	8/1998 - 6/2001 1/2006 - 12/2010	30	NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)
					CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
CAT16	02147403	FISHING CREEK BELOW FORT LAWN, SC	2/2001 - 10/2003	280	CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	Area Ratio
					NC01	INDIAN CREEK NEAR LABORATORY, NC	69	MOVE.1 (log transform)
CAT17	02147500	ROCKY CREEK AT GREAT FALLS, SC	3/1951 - 9/1981 8/1986 - 12/2010	196	NC01	INDIAN CREEK NEAR LABORATORY, NC	69	MOVE.1 (log transform)
CAT19	02148071	GILLIES CREEK NEAR LUGOFF, SC	4/1994 - 9/1997	8	CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
					NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)
CAT20	02148300	COLONELS CREEK NEAR LEESBURG,S.C.	9/1966 - 9/1980 2/2004 - 10/2007	40	CAT03	BIG DUTCHMAN CREEK AT ROCK HILL, SC	17	MOVE.1 (log transform)
					CAT17	ROCKY CREEK AT GREAT FALLS, SC	196	MOVE.1 (log transform)
					NC02	MCALPINE CR BELOW MCMULLEN CR NR PINEVILLE, NC	92	MOVE.1 (log transform)

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 CAT19 is shown in **Figure 6-1**.

Validation graphs are available for each USGS gage. Each validation graph show 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 B**. **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, *Catawba-Wateree River Basin SWAM Model Framework.*

CDM Smith, July 2015, *Methodology for Developing Historical Surface Water Withdrawals for* Agriculture *Irrigation*

HDR Engineering Inc. 2014. *Catawba-Wateree Hydroelectric Project Operations Model – Model Logic and Verification Report.*

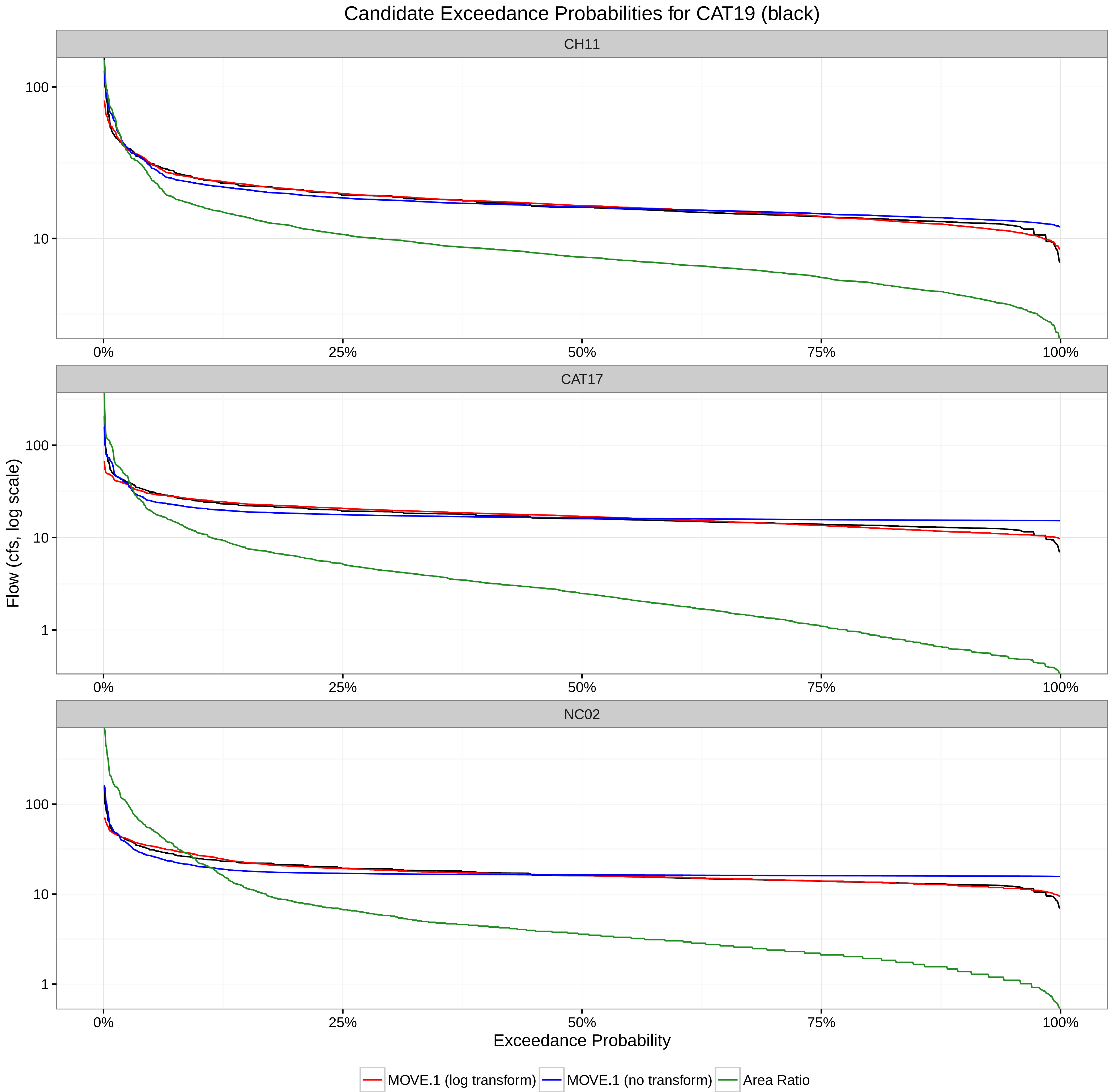


Figure 6-1: Comparison of Exceedance Probabilities for the Computed UIF and Extension Methods

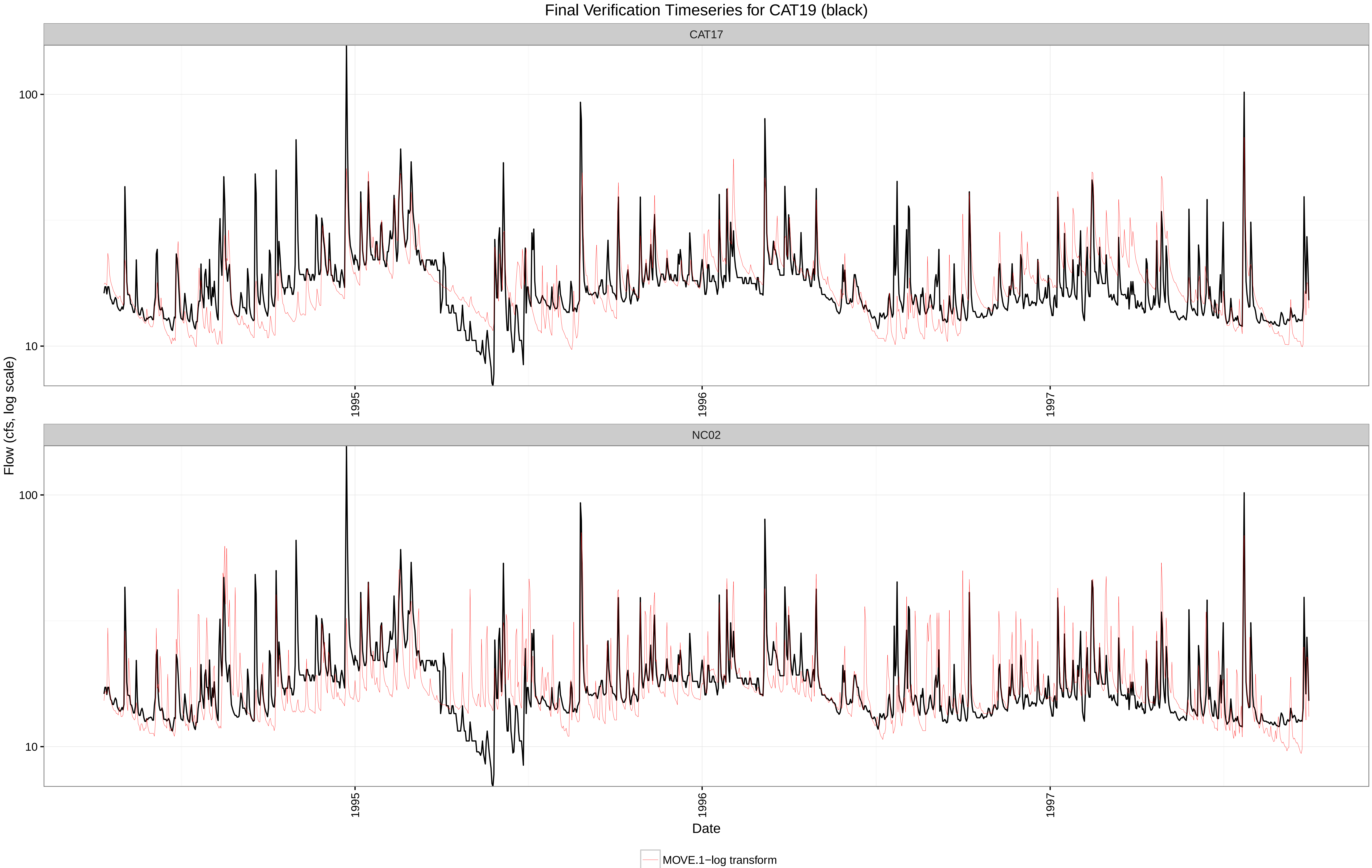


Figure 6-2: Validation Graphs for CAT19 with Predicted Flows from Reference Gages CAT17 and NC02

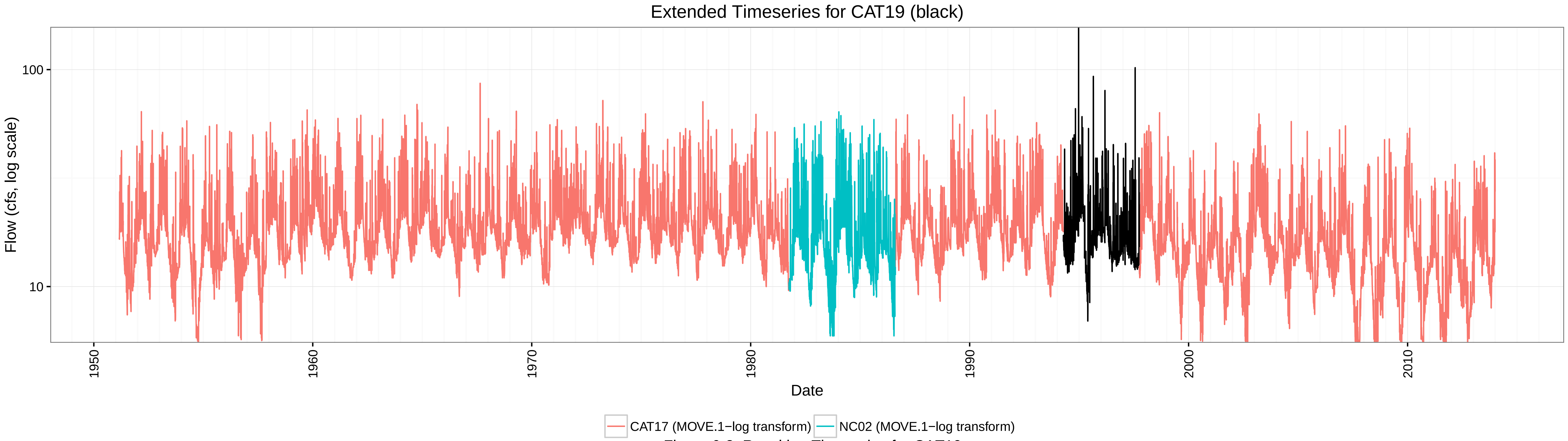


Figure 6-3: Resulting Timeseries for CAT19

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

	Ungaged Basin				USGS Reference Gage[2]				
Project ID	**SWAM Usage**	**Stream**	**Basin Area (mi^2)**	**% Developed / % Forest**	**Project Gage ID**	**USGS Number**	**Stream**	**Basin Area (mi^2)**	**% Developed / % Forest**
CAT206	Headwater Flow	McAlpine Creek	16.3	89 / 9.6	CAT06	0214676115	MCALPINE CREEK AT SR2964 NR CAMP COX, SC	94.8	83.7 / 14
CAT207	Headwater Flow	Twelvemile Creek	53.7	21.5 / 44.6					
CAT205	Headwater Flow	Sugar Creek	12.7	83.2 / 12.4	CAT07	02146800	SUGAR CREEK NEAR FORT MILL, SC	262.7	79.4 / 15.7
CAT210	Headwater Flow	Cane Creek	21.4	4.3 / 57.4	CAT11	02147240	BEAR CREEK AT LANCASTER S. C.	66.4	20.4 / 46.8
CAT211	Headwater Flow	Bear Creek	13.0	5.4 / 50.8					
CAT212	Headwater Flow	Grannies Quarter Creek	10.3	8.6 / 48.4	CAT17	02147500	ROCKY CREEK AT GREAT FALLS, SC	196.0	6.7 / 67.7
CAT217	Headwater Flow	Rocky Creek	15.5	18.8 / 53.2					
CAT303	Confluence Flow	Cedar Creek	32.5	2.2 / 79.5					
CAT305	Confluence Flow	Big Wateree Creek	67.4	3.5 / 76					
CAT307	Confluence Flow	Dutchmans Creek	42.7	3.6 / 75.2					
CAT309	Confluence Flow	Beaver Creek	52.1	2.7 / 81.4					
CAT311	Confluence Flow	Sawneys Creek	58.2	3.3 / 73.5					
CAT315	Confluence Flow	Waxhaw Creek	52.5	5.5 / 66.8					
CAT317	Confluence Flow	Camp Creek	41.1	4.4 / 71.6					
CAT400	Headwater Flow	Lake Wateree Local Inflow	100.3	3.6 / 82.6					

[2] Ungaged flows are synthesized from UIFs; not original USGS gage flows.

	Ungaged Basin				USGS Reference Gage[2]				
Project ID	**SWAM Usage**	**Stream**	**Basin Area (mi^2)**	**% Developed / % Forest**	**Project Gage ID**	**USGS Number**	**Stream**	**Basin Area (mi^2)**	**% Developed / % Forest**
CAT219	Headwater Flow	Gillies Creek	1.3	20.8 / 46.4	CAT19	02148071	GILLIES CREEK NEAR LUGOFF, SC	8.5	18.6 / 34.6
CAT213	Headwater Flow	Twentyfive Mile Creek	8.3	4.6 / 80.5	CAT20	02148300	COLONELS CREEK NEAR LEESBURG,S.C.	40.2	5.1 / 63.5
CAT214	Headwater Flow	Sanders Creek	8.1	3.2 / 52.7					
CAT215	Headwater Flow	Rice Creek	5.2	50.3 / 29.7					
CAT216	Headwater Flow	Big Pine Tree Creek	31.4	5.9 / 51					
CAT220	Headwater Flow	Swift Creek	34.7	4.2 / 54.1					
CAT221	Headwater Flow	Spears Creek	3.7	79.7 / 9.9					
CAT222	Headwater Flow	Beech Creek	2.0	23 / 54.6					
CAT313	Confluence Flow	Rafting Creek	54.9	3.5 / 59.6					
CAT18	None	Wateree River	5057.2	19.1 / 53.3	CH11	None	WATEREE RIVER BELOW LAKE WATEREE, SC	4740	-
CAT21	None	Wateree River	5554.3	18.1 / 53.9	CH11	None			

List of Attachments

A. *Guidelines for Standardizing and Simplifying Operational Record Extension* (CDM Smith, March 2015)

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

C. *Quality Assurance Guidelines: Unimpaired Flow Calculations (UIFs) for the South Carolina Surface Water Quantity Models* (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 Catawba-Wateree River Basin

ATTACHMENT A

Guidelines for Standardizing and Simplifying Operational Record Extension

(CDM Smith, March 2015)

Guidelines for Standardizing and Simplifying Operational Record Extension

South Carolina Surface Water Quantity Models – Unimpaired Flow Development

CDM Smith, March 2015

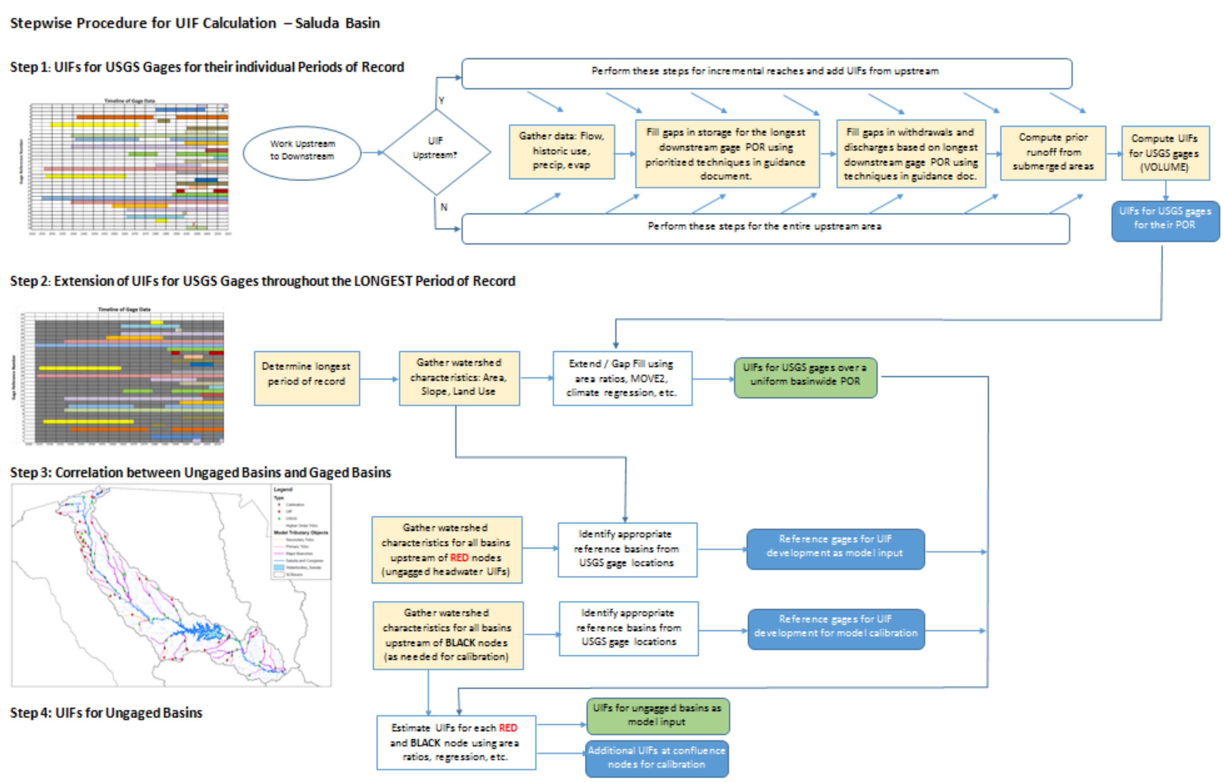
Objective:

This set of guidelines is intended to help simplify and standardize the process of extending and filling gaps in operational records of water **withdrawals, discharges,** and **storage impacts** as part of the process of developing Unimpaired Flows (UIFs) for the South Carolina water quantity models. It is based on the following principles of large-scale water planning:

a) De-emphasize the nuances of specific undocumented local issues (such as matching population trends with service area changes, etc.) and generalize water use trends regionally, and

b) Provide a consistent framework for filling data gaps and extending records

Summary text appears in blue. Note that the recommendations in this document apply only to the synthetic extension of operational records, and not to the extension of the UIFs themselves (the alternative procedures for which are described in the UIF Methodology TM). That is, the guidelines in this document apply to the gap-filling boxes in Step 1 of the overall UIF process below:



While the ultimate UIF data sets in any given basin are required to extend all the way back to the earliest USGS record in the basin, IT IS ONLY NECESSARY TO SYNTHESIZE OPERATIONAL DATA FOR EACH SPECIFIC USE BACK TO THE DATE OF THE EARLIEST **DOWNSTREAM** USGS GAGE RECORD, either on the tributary of use, or downstream on the mainstem. This is because the downstream gages will be the basis for UIFs using upstream impairments, but once each UIF is developed for the period of gaged record at each gage, the UIFs themselves will be statistically extended using other techniques that do not rely on historic use (Step 2 in the diagram above). In other words, if there are no streamflow records for which a given use would be used in unimpairment calculations, we do not need the use record.

> **GENERAL SIMPLIFICATION:** Only extend use data back to the date of the earliest <u>downstream</u> USGS flow record <u>within the basin</u> that would use the data in unimpairment calculations over its period of record.

Specific Guidelines for Water Withdrawals

Water withdrawals may need to be disaggregated into annual and then monthly values (monthly values would be spread evenly across the days in the month). To estimate undocumented water withdrawals on an <u>**ANNUAL**</u> basis (as an example, consider a documented withdrawal from 1990-2013, which requires extension back to 1950):

- **First Priority - Anecdotal Information:** If anectodal information about dates and volumes is available via direct communication from water users, this should be used and interpolated/extrapolated to the greatest extent possible. In the example above, if the water user informs us that the intake came on line in 1962 and started at 2mgd, linearly interpolate usage from 2 mgd in 1962 to the documented value in 1990. *Note: Do not synthesize water use prior to any known date of initiation (in this example, 1962).*

- **Second Priority – Regional Population Trends:** In the example above, if there is a correlation between population and withdrawals from 1990-2013, this correlation can be applied going back in time. Note that the correlation could be as simple as a per capita use rate. DO NOT attempt to fully reconcile local population, county population, and service area, as the relationship between all of these will change over time and would consume too much time to document in every case. Rather, use judgment on whether local, county, or service area estimates (based on availability of data and applicability to the case at hand) will serve as a reasonable indicator of trends in the service area. Note that correlation relationships should be simple – linear if possible, unless there are obvious nonlinearities in the observed trends. In no case should we use anything more than a second order polynomial (because these can exaggerate conditions at the ends of the time spectrum, and sometimes reverse directions inappropriately).

- **Short-Term Gap Filling**: For short-duration periods of missing information between documented periods (up to ~5 years), values may be linearly interpolated between dates of available data. Refer also to the guidelines for monthly estimation below.

To superimpose <u>**SEASONAL OR MONTHLY**</u> withdrawal patterns on these annual averages, compute average monthly multipliers for the documented period of record, and apply these for the period of record extension. Ensure that they average 100%. Do not adjust for the variability in the number of days per month.

Specific Guidelines for Water Discharges

To estimate undocumented discharges, first determine if there is a repeatable monthly pattern of discharge. If not, hindcast using annual values using the guidelines below and apply the discharge as a constant rate throughout the year per below. If there is an observable monthly pattern, refer to the monthly guidelines below the annual guidelines, and choose an option based on the data.

FOR ANNUAL AVERAGE DISCHARGE VALUES:

- **First Priority – Anecdotal Information:** If anectodal information about dates and volumes is available via direct communication from water users, this should be used and interpolated/extrapolated to the greatest extent possible.

- **Second Priority – Correlation with Withdrawal**: If documented discharges can be correlated with documented withdrawals, the correlation can be extended back in time. This actually matches the SWAM model construct, in which discharges are usually specified in terms of corresponding withdrawal percentages.

- **Third Priority – Permit Estimates**: In some cases, discharge permits estimate the discharge volume as a percentage of withdrawal. In such cases, this can be a simple approximation of the historical discharge volumes.

- **Fourth Priority – Regional Population Trends**: If there is a correlation between population and withdrawals during the documented period, this correlation can be applied going back in time. DO NOT attempt to reconcile local population, county population, and service area, as the relationship between all of these will change over time and would consume too much time to trace and document in every case. Rather, assume that either local or county level population (based on availability of data and applicability to the case at hand) will serve as a reasonable indicator of trends in the service area (especially if good correlation exists for the period of documented discharge). Note that correlation relationships should be simple – linear if possible, unless there are obvious nonlinearities in the observed trends. In no case should we use anything more than a second order polynomial (because these can exaggerate conditions at the ends of the time spectrum, and sometimes reverse directions inappropriately).

- **Short-Term Gap Filling**: For short-duration periods of missing information between documented periods (up to ~5 years), values may be linearly interpolated between dates of available data. Refer also to the guidelines for monthly estimation below.

If there is an observable monthly pattern to withdrawals, then use the following guidelines and choose the approach that best matches the situation or available data:

FOR MONTHLY DISCHARGE VALUES (if observed patterns exist):

- **Option 1 – Correlate with Monthly Withdrawal**: If monthly discharge can be well correlated to monthly withdrawal, then it may not be necessary to estimate annual discharge. Rather, develop ratios between observed monthly withdrawal and observed monthly discharge for a period over which records overlap. The ratios would most likely be average values for each month, provided there is not too much scatter. Then apply these ratios to the full (possibly extended) record of withdrawals. Note: Do not use synthesized withdrawal data to establish the ratios – use only documented values. However, it is acceptable to use synthesized withdrawals as the basis for extending the discharge by applying the ratios from the documented values.

- **Option 2 – Apply observed trends to annual discharge estimates**: If the periods of observed withdrawals and observed discharges do not overlap, or there is poor correlation between withdrawal and discharge, then annual average values will need to be determined per the above procedures, and monthly multipliers applied. Determine average monthly multipliers of discharge, using <u>documented</u> (not extended) annual average as a basis. Ensure that the multipliers average 100%. Then, apply these multipliers to annual average discharge estimates from the procedures above.

FOR INDUSTRIAL DISCHARGES:

For industrial discharges with no withdrawal (groundwater use, for example), simply extrapolate observed data back to the known or estimated date at which operations commenced. This would apply on an annual and/or monthly basis, as deemed appropriate based on the available data.

Specific Guidelines for Storage Impacts

There will be cases in which we need to synthesize the impacts of reservoirs in the absence of documented fluctuations in storage and/or elevation. The presence of reservoirs affects both the timing of flow and the volume of water in the river system. The following guidelines may be applied:

- **Surface Evaporation (volume impact):** Assume full reservoir area for computing surface evaporation in the absence of records of reservoir fluctuations.

- **Surface Precipitation (volume impact):** Assume full reservoir area for computing surface precipitation in the absence of records of reservoir fluctuations.

- **Change in Storage (timing impact)**: Knowing the historic fluctuation in storage is useful because by impounding water, drawing down, and recovering, the timing of when water is released can be affected. Impoundment does not, however, affect the total volume of water in the system, only the distribution of that water as flow over time. To estimate historical water level fluctuations accurately, a calibrated hydrologic and operations model would be needed. This is not always practical, so several alternatives are offered for hind-casting historical reservoir elevation/storage:

    - **First Priority – Published Estimates from Other Modeling Studies**: Many of the basins in South Carolina have been simulated with reservoir operations models (CHEOPS, for example, or HEC-ResSim). As available (without re-running the models), published values from these models can be used to help extend or fill reservoir records.

- **Second Priority – Extrapolation and Correlation with Precipitation**: There are three proposed approaches that can be applied in various conditions. The decision of which method to use should account for the availability and credibility of data, as well as the overall dynamics of the reservoir, per the guidelines below. The 2nd and 3rd methods are described in more detail on the pages that follow, but summarized here. Note that in many cases, it may simply be best to see which of these methods reproduces observed data the best, and rely upon that method purely on its predictive basis. It should be emphasized, though, that hindcasting reservoir storage *does not* account for detailed operational practices, but rather the observed patterns of drawdown, and the apparent dependence the drawdown may have on prior rainfall levels. The graphs that follow the detailed descriptions of the two regression methods illustrate how the two methods may be appropriate for different types of reservoir response patterns. Additionally, following the graphs, a procedure is outlined for adjusting the hindcast timeseries for the potential impacts of variable historical withdrawal rates (if such data are available).

    a) **METHOD 1: Simplest: Monthly Averages*****: [To be used only if there is a clear and consistent pattern of drawdown and refill that does not vary significantly from year-to-year].*** Monthly average elevation/storage can be computed for the period of documented record, and these can be applied as estimated hindcasts. Daily values can be interpolated between monthly values. It should be noted with our UIF records that if this method is employed for reservoirs with a great deal of year-to-year variability in water levels, that this is a very approximate technique.

    b) **METHOD 2: Next Simplest: (REGRESSION METHOD A) Correlation Between Daily Elevation and Cumulative Historic Precipitation**: ***[To be used if the reservoir is frequently full, but exhibits irregular drawdown during droughts] – SEE FULL PROCEDURAL DESCRIPTION BELOW FOR REGRESSION METHOD A.***

    c) **METHOD 3: More Complex: (REGRESSION METHOD B) Scaling the Monthly/Daily Averages from (a) above to expected min annual elevation based on historic precip**: ***[To be used if the reservoir experiences significant multi-year or irregular drawdowns during droughts, and is not frequently observed to be full.] - SEE FULL PROCEDURAL DESCRIPTION BELOW FOR REGRESSION METHOD B.***

- **Third Priority – Iteration:** If either of the two methods above are employed for the UIFs, they can be validated or refined once the SWAM models are constructed. This would be a time-consuming process, likely involving iteration between UIFs and model runs, so it should be employed with discretion, and only if truly needed for reservoirs that have pronounced impacts in a basin or a great deal of uncertainty in the hind-casting.

Full Procedure – METHOD 2 - REGRESSION METHOD A:
Hindcasting Reservoir Elevation Using Daily Precipitation Sums
Note: Example spreadsheets are available to assist as reference or templates for this procedure.

This method for developing a historical time series of elevation data for a specific reservoir uses available observed reservoir elevations and daily precipitation records. The precipitation records must cover the entire period of hindcasting and/or gap filling, as they will serve as the independent variable in a regression model. The observed reservoir elevations are needed to develop the regression model, and should cover a multi-year period. The observed reservoir elevations do not need to be continuous, but they must cover an overlapping period with available precipitation data. This procedure may be modified if only average monthly reservoir elevations are available, but will then only be able to hindcast average monthly elevations (or weekly, etc.). The following procedure assumes that daily precipitation data are available for the full hindcast period, and that there is a sufficient multi-year overlap between observed daily reservoir elevations and daily precipitation data.

Step 1: Compile daily observed data. The suggested format for the daily observed data is a continuous time series of dates that span from the 3 years before the earliest reservoir elevation observation to the latest daily reservoir elevation observation, with column headings: Date, Observed Elevation, Daily Precipitation. For example, if the reservoir elevations start on 1/1/2000 and end on 12/31/2010, the time series should span 1/1/1998 to 12/31/2010, and the first 2 years of reservoir observations will be blank.

Step 2: Check linear correlation between preceding daily precipitation sums and reservoir elevation. This step involves calculating the sum of precipitation for the previous X number of days, for each day in the observed data time series. The resulting time series of X-days previous precipitation sum should then be checked for correlation with the reservoir elevation using the RSQ()[1] function in Excel (or similar function to find the linear R-squared correlation in another software). If the table includes precipitation data for 3 years prior to the first reservoir observation, the precipitation sums can go up to the preceding 1,095 days (3 years). The process of computing the preceding X-day precipitation sum and linear correlation value may need to be repeated multiple times to find the best fit precipitation time series. The suggested procedure is to start with the 30-day sum and repeat in 30-day increments until a maximum linear R-squared value is found. For example, the table described in Step 1 is expanded to include the time series of preceding 30-day precipitation total, preceding 60-day precipitation total, preceding 90-day precipitation total, and so on.

Step 3: Use the best-correlated precipitation sums to develop regression equation. The ideal R-squared value is 1.0. If the best linear correlation of all incremental 30-day precipitation sums going back 3 years is not greater than 0.5, this may not be the best method to use to hindcast reservoir elevations. Once the best-linear-fit precipitation sums time series is established, additional regression functions should be explored that relate precipitation sums to reservoir elevation. For example, a logarithmic regression relationship between the 240-day precipitation and observed reservoir elevation may provide a slightly higher R-squared value than the linear regression. Generally, the function types should be limited to linear, logarithmic, exponential, and power. The final hindcast model formula, which uses the X-day preceding precipitation sum to estimate the reservoir elevation, will take the following form:

Elev = min(Max, F(Psum))
Psum: Sum of daily precipitation totals for the X-day period discovered in Step 2
Max: Maximum possible reservoir elevation
Elev: Calculated reservoir elevation
F(Psum): Regression function that produces highest R-squared correlation between Psum and Elev
An example of this model function is:
Elev = min(1230, 32*LN(Psum)+1078)

---

[1] If the precipitation sum time series is in column A, and the reservoir elevation time series is column B, the format for this formula is: RSQ(column B, column A); or more generally: RSQ(known Ys, known Xs)

Where:
Max = 1230, and
F(Psum) = 32*LN(Psum)+1078

Step 4: Check the agreement between observed and modeled reservoir elevations. This step is qualitative. Does the model capture the times when the reservoir is full? Does the model adequately reproduce significant drawdowns? Is the model biased high or low throughout the overlap time period? This step will determine if this method is appropriate for hindcasting elevations for this reservoir. For example, if significant annual drawdowns are not represented by the modeled elevations, another method for hindcasting should be explored.

Step 5: Hindcast the reservoir elevations using the regression model and historic precipitation data. The final step is to calculate estimated reservoir elevation for each day in the full hindcast time series for which there are no observations. This will be done using the X-day precipitation sum time series for the full period, and the model equation developed in Step 3. The suggested format for this step is a daily time series table covering the full hindcast period (e.g. 1/1/1925 to 12/31/2013) with the following columns: Date, Observed Precipitation, X-day precipitation sum, Observed Elevation, Modeled Elevation. The Observed Elevation rows will be blank for days with no reservoir observations. The modeled Elevation rows will be blank for days with reservoir observations. The combination of these time series will be used for the unimpaired flow development.

Full Procedure – METHOD 3 - REGRESSION METHOD B:
Scaling Monthly/Daily Average Elevation to Expected Minimum Annual Elevation Based on Historic Precipitation
Note: Example spreadsheets are available to assist as reference or templates for this procedure. See "Reservoir Hindcasting – Method 2 Example.xlsx"

Like Method 2 above, this method for synthesizing a historical time series of elevation data for a specific reservoir uses available observed daily or monthly reservoir elevations and annual precipitation records. The precipitation records must cover the entire period of hindcasting and/or gap filling, as they will serve as the independent variable in a regression model. The observed reservoir elevations are needed to develop the regression model, and should cover a multi-year period. The observed reservoir elevations do not need to be continuous, but they must cover an overlapping period with available precipitation data. At a minimum, the data should cover a significant drawdown and full recovery of the reservoir to a full condition. This procedure may be applied with either daily or monthly reservoir elevation data, and any form of precipitation data that can be aggregated into annual totals. The following procedure assumes that there is a sufficient multi-year overlap between observed reservoir elevations and precipitation data.

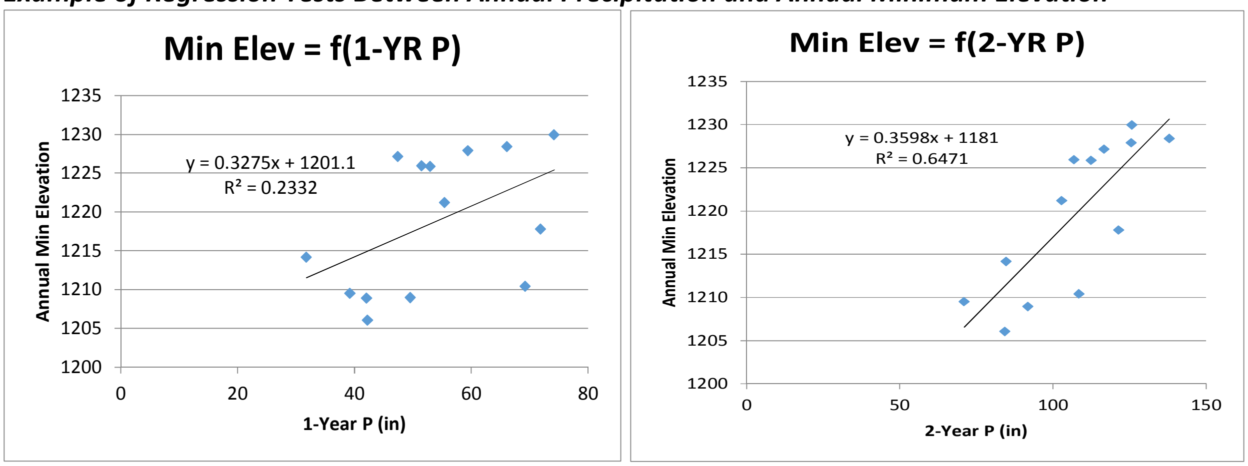
Step 1 - Collect Data: Gather all available information on precipitation and reservoir elevation. Precipitation may be daily, monthly, or annual. Reservoir elevation may be daily or monthly.

Step 2 - Compute Daily Average Elevation: Over the reservoir period of record, compute a *one-year timeseries* of daily average elevation for each day of the year. For example, the elevation for January 1 would be the average values of all records from January 1 in the period of record. If reservoir elevation is reported monthly, interpolate linearly to approximate daily values. (This is the same as Method 1, above, but it will serve as an interim step in Method 3, here).

Step 3 – Annualize Data from Step 1: Using pivot tables or other means, summarize the recorded data from Step 1 in the form of **Total** Annual Precipitation (summation) and **Minimum** Annual Elevation. For each year in the reservoir's period of record, then, there will be a value of annual precipitation that can be correlated in the next step with the minimum elevation (maximum drawdown) for that year.

Step 4 – Regression Relationship Between Annual Precipitation and Annual Minimum Elevation: Develop a relationship (preferably linear) between Annual Precipitation and Annual Minimum Elevation. In some cases, a relationship may not develop until the past 2 or 3 years of precipitation are added together, so multiple regression tests may be needed to find a good relationship between antecedent rainfall totals and minimum reservoir elevation in a given year. *If a good relationship cannot be clearly developed for the period of record, or if the record does not include a good example of significant drawdown and full recovery, this method may not be appropriate.* The example below shows poor correlation using 1-year total rainfall, but reasonably good correlation using 2-year total rainfall:

Example of Regression Tests Between Annual Precipitation and Annual Minimum Elevation



Step 5 – Extend Minimum Annual Elevation Record: Using the regression relationship from Step 4, extend the annual timeseries of minimum annual elevation over the entire period of record for the basin (defined by the earliest recorded USGS streamflow) using the precipitation statistics as the predictive variable. Also validate the relationship over the period of record for reservoir elevation.

Step 6 – Develop Annual Scaling Factors: For each year in the period for which no reservoir elevation data exist, develop a single annual scaling factor that relates the estimated minimum annual elevation (from Step 5) with the minimum elevation of the Average Year pattern from Step 2. However, before computing these values, convert the minimum elevation into Maximum Drawdown in order to properly scale the relativity of the two values (Full Reservoir Elevation – Minimum Elevation). For example, for a reservoir with a maximum elevation of 1230 feet, if the estimated minimum elevation from Step 5 for year X is 1210 feet, and the minimum elevation of the average year pattern from Step 2 is 1225 feet, the scaling factor would be:

$$Scale\ Factor_{Year\ X} = \frac{Max\ Drawdown_{Year\ X}}{Max\ Drawdown_{Avg\ Year}} \frac{(Full\ Elev - Min\ Elev_{Year\ X})}{(Full\ Elev - Min\ Elev_{Avg\ Year})} = \frac{(1230 - 1210)}{(1230 - 1225)} = \frac{20}{5} = 4$$

The end product of this step will be a timeseries of ANNUAL scaling factors for each year in which no reservoir records exist. It is conceivable that some scale factors could be negative, depending on the regression relationship from Step 4. Consider these carefully, and possibly apply a lower bound of 0 for the scaling factors.

Step 7 – Develop Synthetic Timeseries of Reservoir Drawdown: This is the final step in this procedure, and will result in a DAILY timeseries of estimated reservoir elevation for the entire period of record for the basin.

7a) First, convert the average daily elevations from Step 2 into daily drawdown by subtracting each value from the full reservoir elevation.

7b) Then, copy this annual pattern for every year for which the reservoir record is to be extended or filled.

7c) Next, multiply each value of daily drawdown by the scale factor computed for the corresponding year. *Caution: Do not multiply the actual elevation by the scale factor – rather, multiply the DRAWDOWN (Full Elevation – Daily Elevation) by the scale factor, and then recompute the resulting elevation in 7d.*

7d) Lastly, convert the drawdown values into reservoir elevation values by subtracting them from the full reservoir elevation.

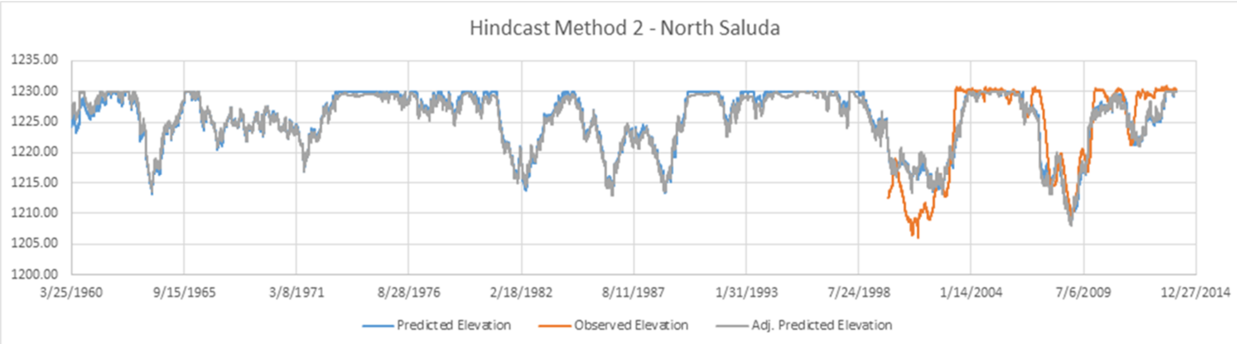
7e) Validate the approach by comparing estimated daily elevation with observed daily or monthly elevation for the period in which the reservoir records exist.

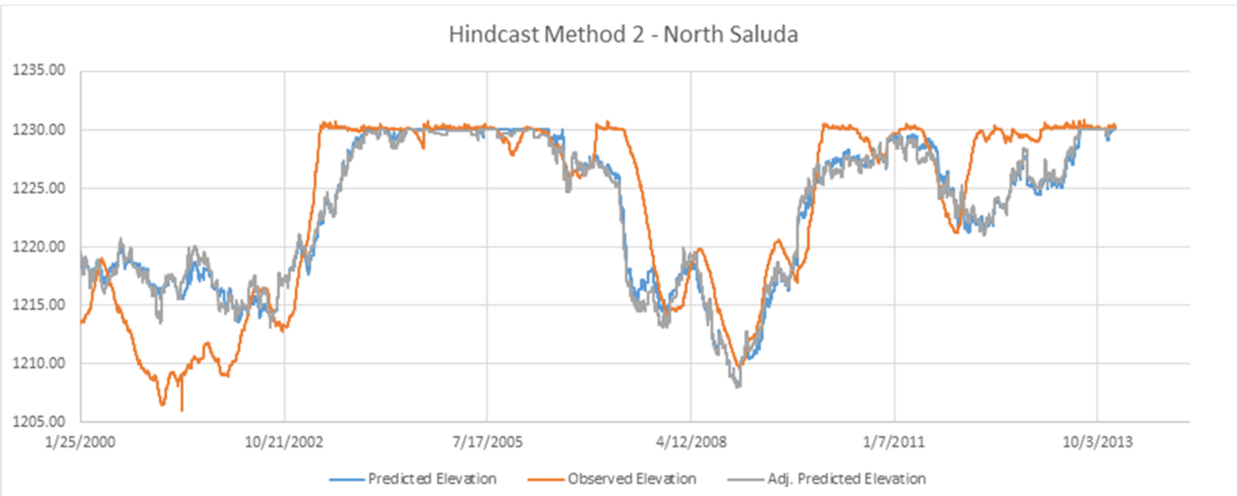
Examples of the Regression Methods:

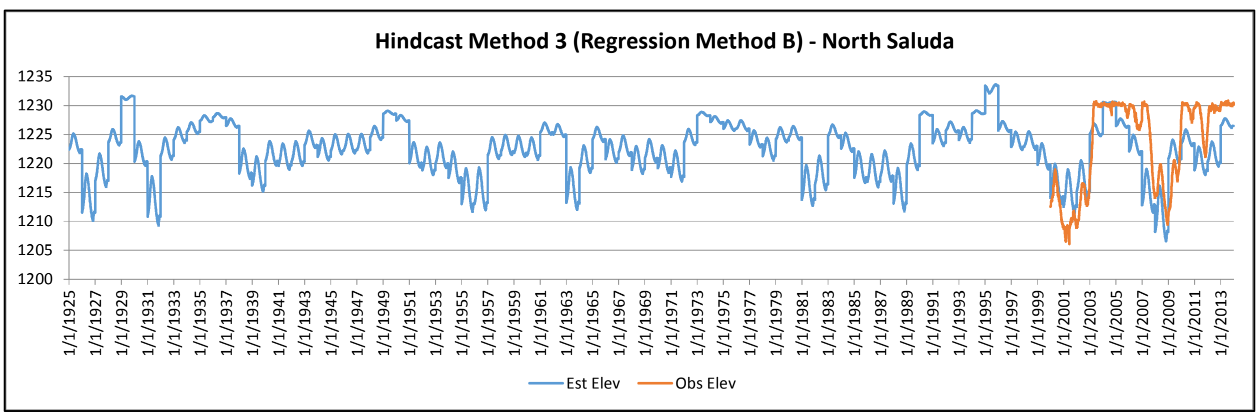
Examples of using these two regression techniques: The two techniques are applied to two reservoirs in the Saluda Basin, and demonstrated below. As noted, this example demonstrates that the best approach may simply be the one with the most obvious predictive ability, but there are some distinguishing features about these two reservoirs that may be important.

In the first example, the two methods are applied to the North Saluda Reservoir. The data suggest that there are extended periods of time over which the reservoir is full, or nearly full, but that it can draw down somewhat irregularly during droughts. **METHOD 2 (Regression Method A) is preferred in this example** because it appears to preserve the full condition more realistically than Method 3, and also simply because it provides a more credible reproduction of the historical drawdown pattern.

First Example: North Saluda Lake

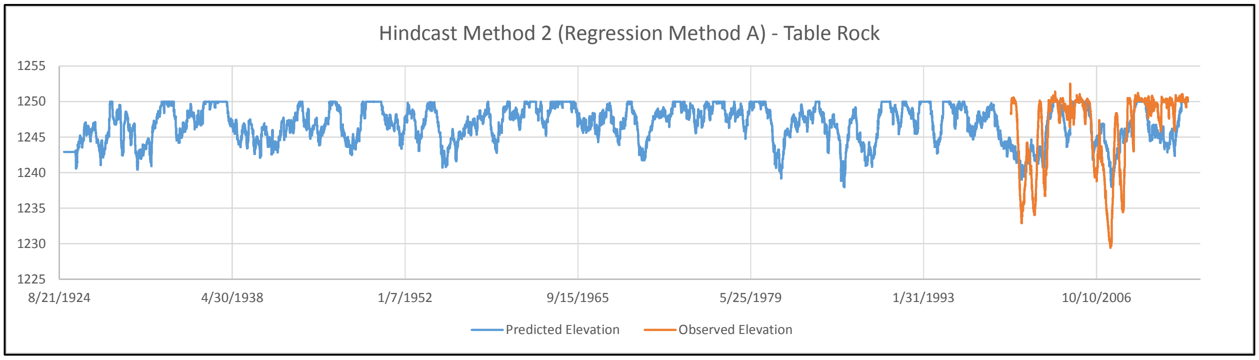


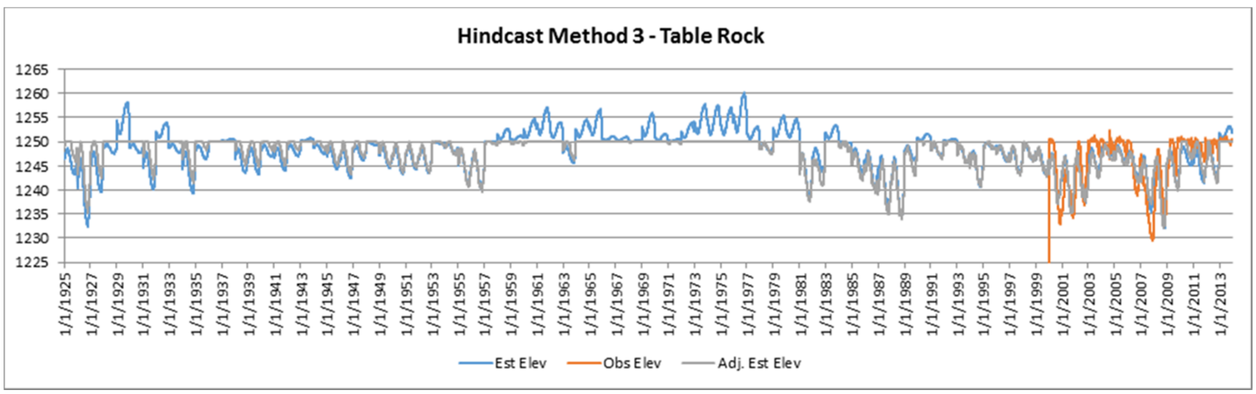


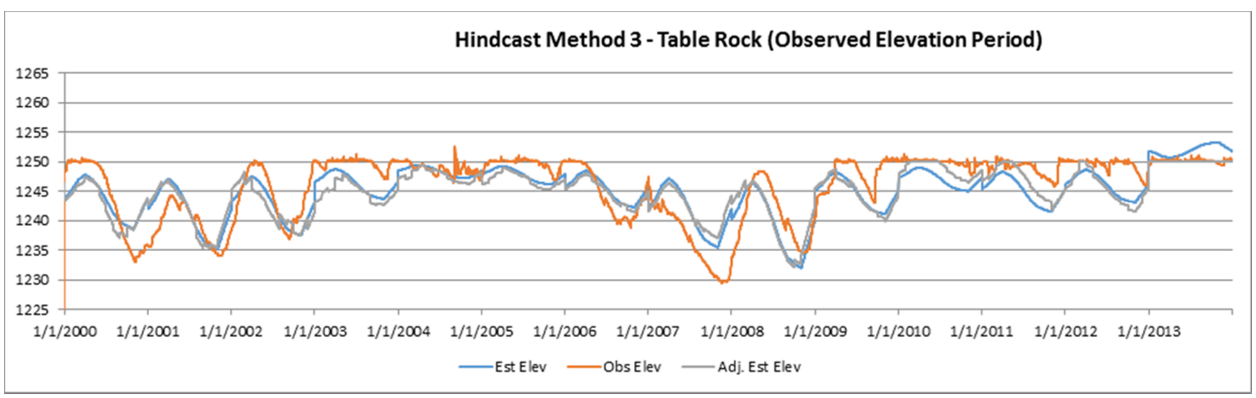


In the second example, the two methods are applied to Table Rock Reservoir. The data suggest that the reservoir draws down irregularly, and is not usually completely full. **METHOD 3 is preferred in this example** because it appears to better match the magnitude of severe drawdown, the reservoir is not usually full, and because the method provides a more credible reproduction of the overall historical pattern.

Second Example: Table Rock Reservoir







Adjustment for Variable Historic Withdrawal Rates

If data for reservoir withdrawals extend back beyond the available data of reservoir water level, adjustments can be made to the hindcast timeseries of reservoir elevation. This is because the elevation hindcasting assumes an average withdrawal pattern equal to the average withdrawals over the period of elevation records, and is aimed principally at distinguishing drawdown due to severe drought from drawdown due to normal reservoir use and operations. It does not explicitly account for drawdown due to variations in reservoir withdrawals.

In such situations, the following approach may be applied (as a supplement to Method 1, 2, or 3 above):

1. Proceed with the full reservoir hindcast procedures as specified above (Method 1, 2, or 3).

2. Compute the average monthly withdrawal over the period of ELEVATION record for each month (the average of all Januaries, the average of all Februaries, etc.)

3. Convert hindcast elevation into hindcast volume for each month using the storage-elevation relationship for the reservoir.

4. Add or subtract volume for each hindcast month based on the difference between <u>recorded</u> withdrawal for that specific month and average withdrawal for the corresponding months over the period of ELEVATION record (computed in Step 2).

5. Convert the adjusted volume back to elevation (but keep both timeseries, as volume is used in the UIF equation, but elevation is used for validation).

Note that this method should NOT be applied with hindcast withdrawal data. Only apply this adjustment step when there are actual operational records of withdrawals that extend back further than the records of reservoir elevation.

Also note that if the period of elevation record suggests that the reservoir does not exceed spillway elevation for extended periods of time, hindcast elevations should be capped at the spillway elevation as a maximum, with the assumption that spills happen quickly. If the period of elevation record demonstrates extended periods of time above the spillway elevation, then the hindcasting can reflect this as well, but it should not exceed the documented maximum elevation.

ATTACHMENT B

Guidelines for Identifying Reference Basins for UIF Extension or Synthesis

(CDM Smith, April 2015)

CDM Smith

Technical Memorandum

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

From: *CDM Smith*

Date: *April 2015*

Subject: *Guidelines for Identifying Reference Basins for UIF Extension or Synthesis South Carolina Surface Water Quantity Modeling – Unimpaired Flow Development*

1.0 Introduction

These guidelines are developed to help provide a consistent thought process for selecting reference basins (gaged basins) to estimate flow in ungagged or incompletely gaged basins. This applies to the extension of UIFs at USGS gages, and also to the transposition of UIFs into ungaged basins. Naturally, finding a representative basin with similar hydrologic dynamics is partly objective and largely subjective, and many factors can be considered. The following list can be used as a guideline, with the importance of each factor usually decreasing from top to bottom.

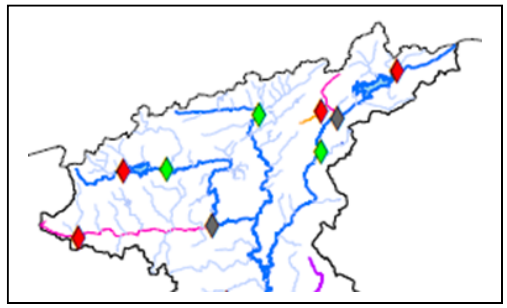
For clarity, we shall refer to ungaged and undergaged sites (needing either full synthesis or gap filling/extension, respectively) all as “ungaged” basins, as opposed to the reference basins, whose gage records will be used for hydrologic transposition.

Consider these factors as guidelines with decreasing importance moving down the list, and refer to the general guidance at the end – There will be cases in which these priorities may need to be adjusted when dealing with certain extreme situations.

2.0 Guidelines

Factor 1: Correlated Overlapping Record: If a candidate reference gage and a basin that has a partial gage requiring extension have overlapping periods of record, test the DAILY correlation between the UIFs (UIFs will be a better indicator of hydrologic similarity than the actual gage records). Note that monthly correlation may be a good indicator of overall water budget characteristics (runoff vs. evap and infiltration), but may not necessarily suggest similar daily hydrologic response patterns, which are important for the UIFs.

Factor 2: **Same Basin**: If the ungaged basin is tributary to a gaged basin (or vice versa) and the area ratios are within a factor of 2x to 4x (approximately), the flows should be highly correlated because one is part of the other. Several examples are shown to the right, where the red nodes indicate ungaged basins, and the green nodes are candidate reference basins. The green nodes downstream of the red nodes should be the first candidates as reference gages.



Factor 3: Measured vs. Estimated Reference Data: In some cases, if a basin would otherwise be a very good candidate as a reference basin but a large percentage of its data have already been synthesized (operational data for UIFs, or a UIF itself synthetically extended), preference should be given to basins with lower amounts of estimated data in the record that would be used for extension.

Factor 4: Basin Area: Because of our daily timestep, this is a critical factor – Large watersheds will exhibit very different daily hydrographs than will small ones in response to the same rain event. It is important that reference basins be comparable in size (generally, within a factor of 2 or 3, if possible).

Factor 5: Land Use: The relative amounts of common land use, and certainly the dominant land use, should be reasonably similar between the reference basin and the ungaged basin to help provide confidence that hydrologic tendencies of the ungaged basin (runoff, infiltration, and evapotranspiration) are well represented by the reference gage.

Factor 6: Basin Slope: The average slope of the basin as determined with DEM's and the stream length in actual river miles can help indicate runoff propensity.

Factor 7: Runoff Curve Number: If the factors above are not sufficient to distinguish several candidate basins, the Soil Conservation Service (SCS) Runoff Curve Number (CN) may be used as a "tie breaker." It can also be used to help determine how adequate the land use similarity (Factor 5) really is as an indicator of runoff propensity.

3.0 General Application of Guidelines

It is not recommended that the six factors above be weighted numerically, nor applied with the exact same priorities in every case. Rather, the determination of a good reference gage is largely subjective, and the factors above should be considered in the selection, but the relative importance may vary depending on certain extremes. For example, if a basin is extremely steep, it would not make sense to choose a reference basin that is nearly flat, even if all the other criteria indicate a good match. Likewise, if a basin is well forested, it would not be wise to use a well-developed basin as a reference, even if all the other criteria indicate a good match. In other words, **while the list**

above provides some general priorities for consideration, we should try to avoid extreme mismatches in any of the criteria.

It is not essential that an ungaged basin use just one reference gage. In fact, it would be impossible to do so unless only the longest gage in the basin were to be used for each ungaged basin. For example, if Basin A is ungaged and must be synthesized back to 1925, and Basin B and C are good candidates for reference basins, we might encounter the following: Basin B is preferred as a reference, but only extends back to 1950, while Basin C is less preferred but extends back to 1925. In this case, use Basin B back to 1950, then Basin C from 1925-1949.

ATTACHMENT C

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

(CDM Smith, April 2015)

Quality Assurance Guidelines

Unimpaired Flow Calculations (UIFs) for the South Carolina Surface Water Quantity Models

Prepared by CDM Smith, April 2015, Adjusted September 2015

Procedural Review

What to Review	How Many UIF Workbooks	How Much Within Each UIF Workbook
Operational Hindcasting and Gap Filling – Appropriate Method?	All	N/A
Approach for negative flow resulting from storage calculations – Major or Minor impact, and Appropriate?	All	Review all UIF entries and required conversions
Overall UIF Equation Correct and Complete	~25%	N/A

Detailed Review

What to Review	How Many UIF Workbooks	How Much Within Each UIF Workbook
All uses included (active and inactive)?	All	N/A
Operational Hindcasting calculations – check math	~50%	Spot check
Operational Hindcasting calculations – visual timeseries evaluation	All	N/A
Hindcast data color-coded through all workbooks and worksheets?	All	Entire workbook
Upstream UIFs (if applicable) accounted for accurately?	All	N/A
Units consistent and accurate?	~25%	Spot check
Overall Mass Balance for reservoirs, if applicable (per example in SLD01 and SLD19)	All	Each Reservoir
Visual comparison of UIF timeseries vs. Gage timeseries	All	N/A

Extension Review

What to Review	R Output Per UIF
DNR recommendations for reference gages applied or justification provided for use of others?	All
All graphs created, labeled correctly, contain correct methods?	All
Any issues regarding noise or minimum values?	All
Selection of UIF Extension Method – Appropriate and Documented?	All
Visual check of final flows graph	All

ATTACHMENT D

Refinements to the UIF Extension Process, with an Example

(CDM Smith, September 2015)

Refinements to the UIF Extension Process, with an Example

South Carolina Surface Water Quantity Modeling

September 2015

The following demonstrates an update to the previously-submitted UIF extension process. Previously, all calculations were performed in Excel, but given a need to accelerate the decision process (e.g. reduce time spent making plots by hand), R codes now automate calculations and plot creation. To demonstrate the reliability of the R code, we present an example of the full UIF extension process via Excel for comparison. For the example, we chose SLD15 on North Rabon Creek (USGS gage 2165280). SLD15 provides a solid example as 1) the gage flows required no unimpairing, 2) the best candidate for extension, SLD14, also required no unimpairing, and 3) it has the same overlapping period of record for all candidate extension gages.

Three methods of extension are considered:

1) Standard MOVE.1 – Flow data is transformed into log (base 10) space, mean and standard deviation are determined from this, and the MOVE.1 equation is applied.
2) Untransformed MOVE.1 – Flow data remains untransformed, mean and standard deviation are determined from this, and the MOVE.1 equation is applied.
3) Area proration – Flow is estimated using a simple ratio of areas.

Two main questions arose in prior investigations: 1) Whether mean and standard deviation should be strictly contained to the overlapping record only and 2) Whether flows should be transformed into log space. To adhere to the strict definition of MOVE.1, for current purposes mean and standard deviation are held to the overlapping record. As the choice of using a log transform or not can produce appreciable differences in estimated flows, both options are still considered. In the table below, the first nine rows (excluding overlapping minimum) represent the necessary distributional statistics for performing MOVE.1 in transformed and untransformed space. The following two rows demonstrate initial suitability of candidacy through correlation. To fulfill assumptions of linearity, candidate flows are first transformed into log space before calculating Pearson's correlation coefficient. The rank-based Kendall's Tau is performed on untransformed flows and can provide a more robust standard of correlation given no assumptions of linearity. However, both coefficients typically trend in the same direction in assessing suitability of candidate reference gages.

	SLD14	SLD18	SLD26
Overlapping Mean (Gage)	27.63	27.63	27.63
Overlapping Log Mean (Gage)	1.18	1.18	1.18
Overlapping St. Dev (Gage)	48.99	48.99	48.99
Overlapping Log St. Dev (Gage)	0.47	0.47	0.47
Overlapping Minimum (Gage)	0	0	0
Overlapping Mean (Ref)	21.90	1514.91	2707.93
Overlapping Log Mean (Ref)	1.08	3.03	3.29

Overlapping St. Dev (Ref)	35.79	1687.60	3034.92
Overlapping Log St. Dev (Ref)	0.46	0.35	0.32
Flow Correlation (Kendall's Tau)	0.83	0.61	0.54
Log Flow Correlation (Pearson)	0.94	0.77	0.71
RMSE (MOVE.1-log transform)	15.78	28.10	38.35
RMSE (MOVE.1-no transform)	16.07	27.78	30.32
RMSE (Area Ratio)	16.07	30.66	31.86
PRESS (MOVE.1-log transform)	1.81	16.93	12.15
PRESS (MOVE-no transform)	0.83	12.53	6.14
PRESS (Area Ratio)	0.72	42.37	28.34

A valid concern arising from untransformed MOVE.1 is the possible existence of negative or unrealistically-low flows. In the previous UIF dataset, we offered a hybrid approach where values from area proration substitute these negative values or values below a certain threshold. In Excel, these thresholds were found through trial and error. This threshold is now strictly defined by the overlapping minimum between the partial gage and candidate gage. As SLD15 naturally runs dry, in this example, all untransformed MOVE.1 values that fall below zero are replaced with those from area proration.

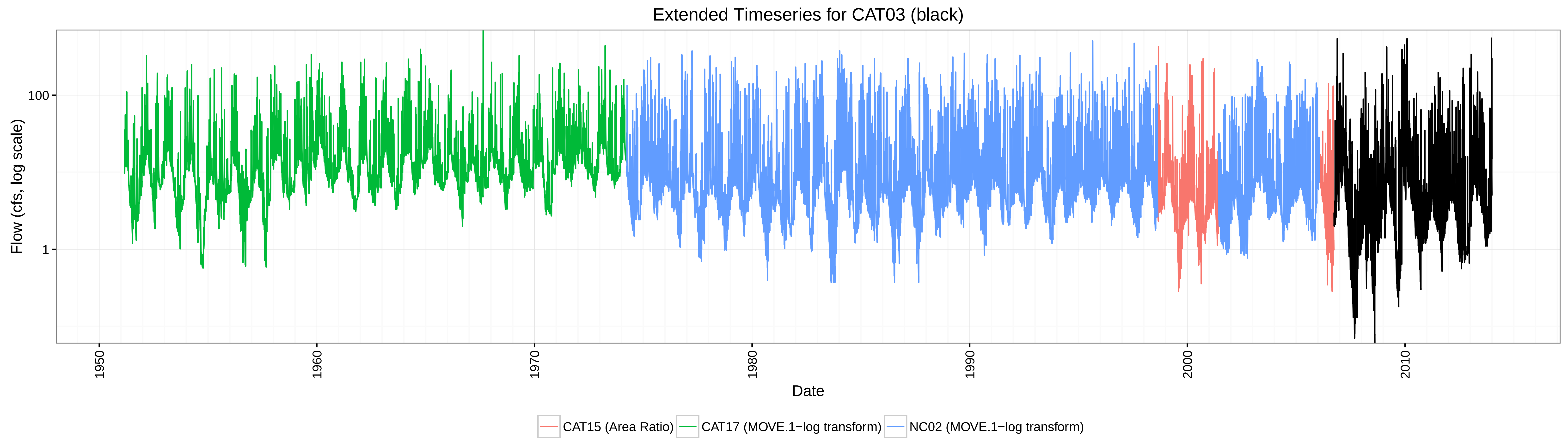
Two quantitative metrics aid the selection of reference gages and methods: root mean square error (RMSE) and predicted residual sum of squares (PRESS). RMSE compares estimated daily values and must be interpreted cautiously as this can be skewed by under or over-predicted flows. As an additional standard, the PRESS metric evaluates *yearly* error. To perform this statistic, one year is iteratively dropped, mean and standard deviation are found from the remaining years, and the dropped year is evaluated from the resulting extension. The values in the table above correspond to total yearly squared error of total volume of water in 1000 acre-ft. While dropping years does not affect the performance of area proration, the final PRESS value is useful in the overall comparison between methods as part of the decision process.

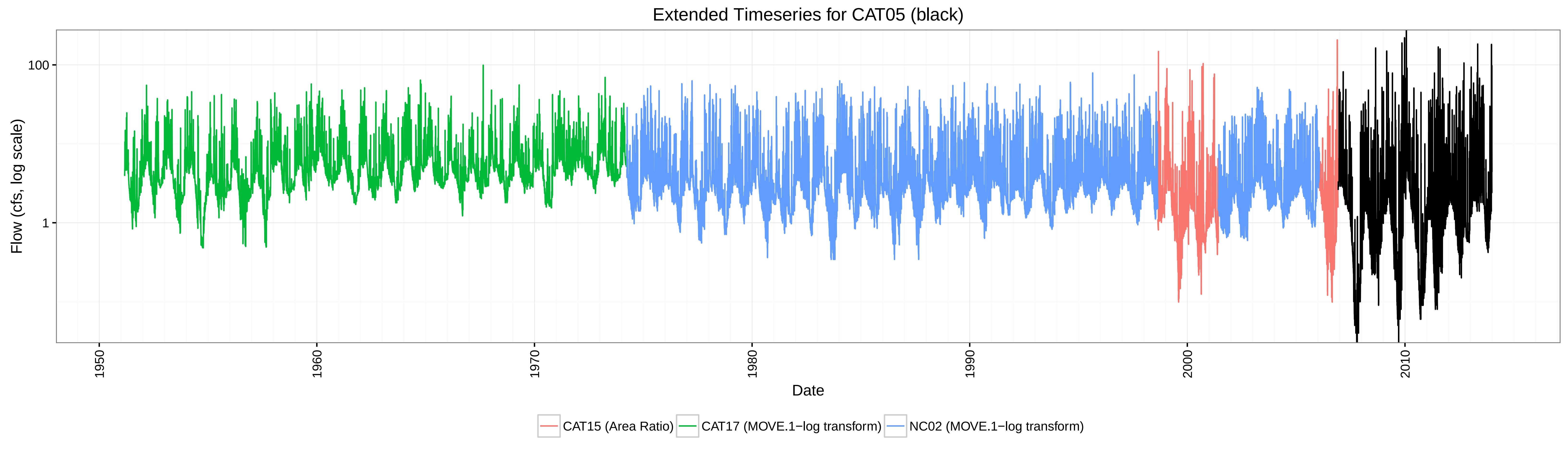
In addition to summary statistics, there are four plots to support to decision-making process: 1) an initial comparison of the original timeseries, 2) timeseries plots of the overlapping record for all methods, 3) scatterplots of the observed versus estimated flows and 4) exceedance frequency curves of the observed and estimated flows. After the first plot, with the y-axis in log-scale, the remaining plots have alternate versions in square root scale. This scale allows for examining low flows without diminishing too much the behavior of higher flows.

After examining the table and these performance plots, a final decision table is created and fed into another R script that creates the fully-extended record and makes two more plots: 5) verification showing the estimated values for the overlapping record and 6) final flows timeseries for the entire period of record with the use of each reference gage indicated by color. However, this may be an iterative process. The final flow timeseries is still examined and if problems, such as an obvious bias, are evident, the decision table is changed to explore alternate options for problem areas. Lastly, there are timeseries plots contrasting the behavior of immediate upstream/downstream gages.

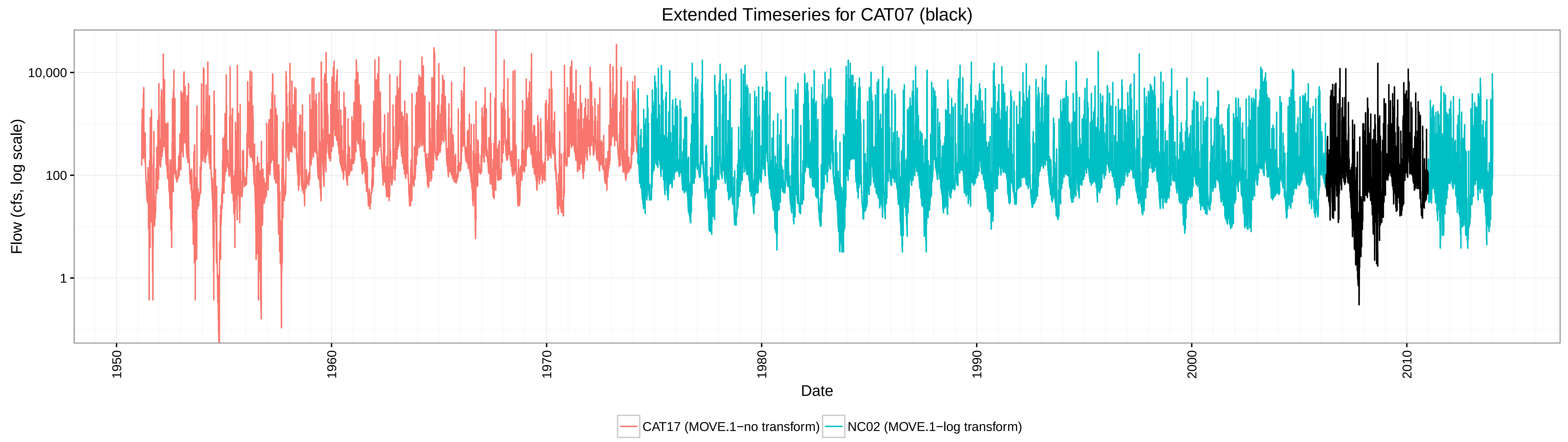
ATTACHMENT E

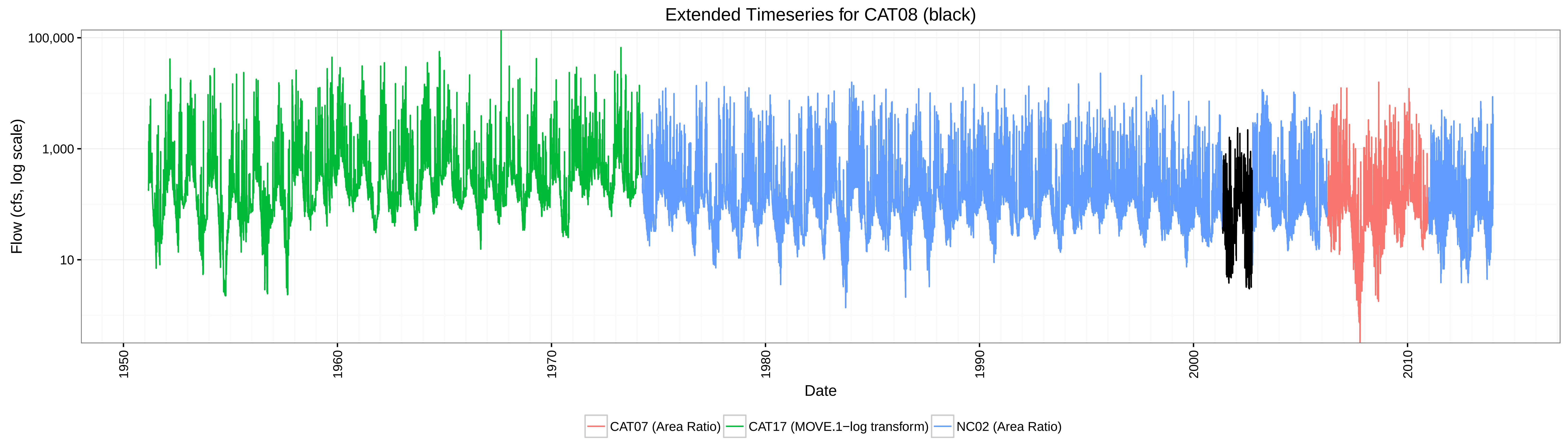
UIF Timeseries Graphs at USGS Gage Locations

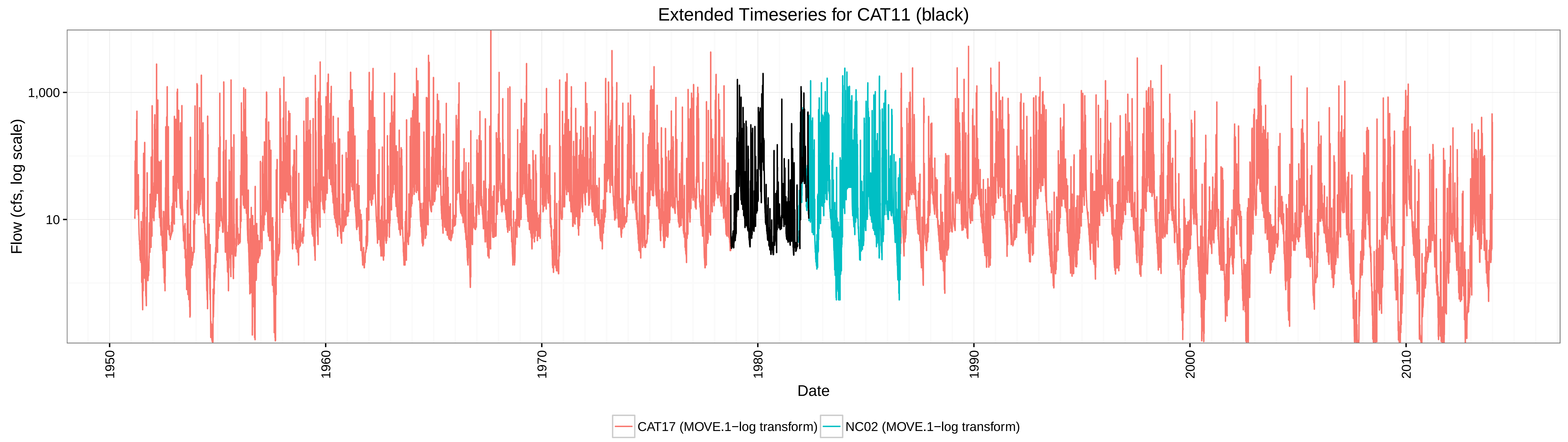

Extended Timeseries for CAT03 (black)
Flow (cfs, log scale)
100
1
1950
1960
1970
1980
1990
2000
2010
Date
CAT15 (Area Ratio)
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)

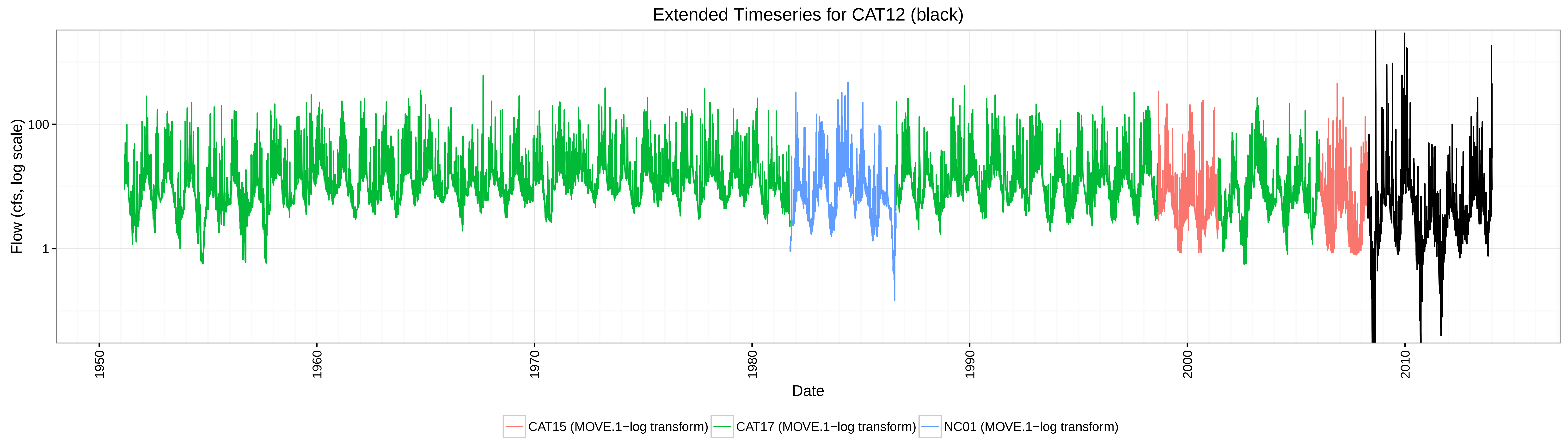

Extended Timeseries for CAT05 (black)
Flow (cfs, log scale)
100
1
1950
1960
1970
1980
1990
2000
2010
Date
CAT15 (Area Ratio)
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)

Extended Timeseries for CAT06 (black)
Flow (cfs, log scale)
1,000
10
1950
1960
1970
1980
1990
2000
2010
Date
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)

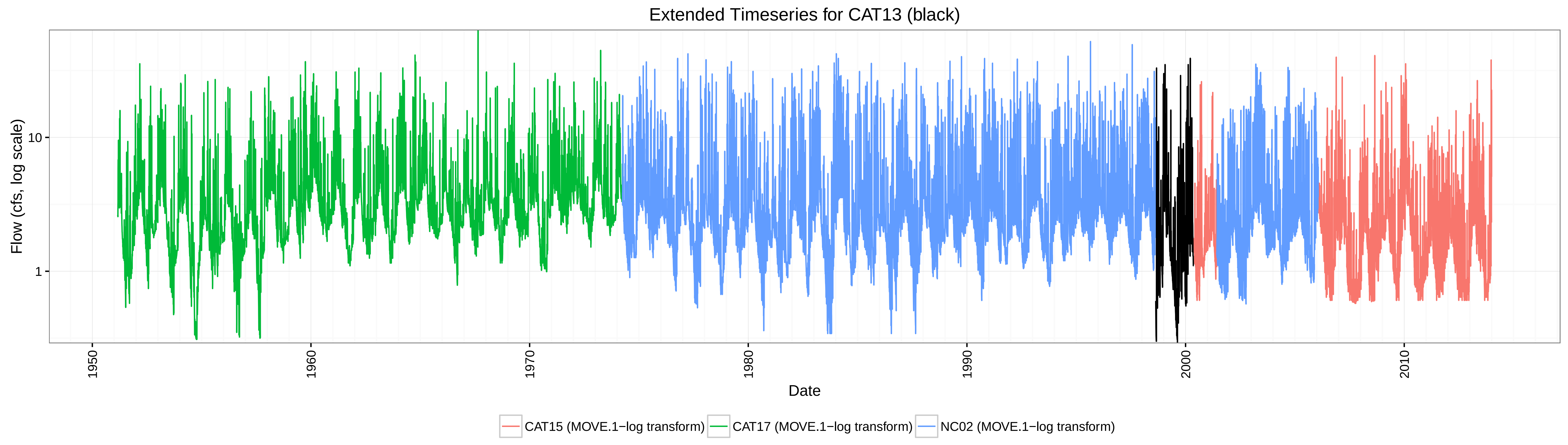

Extended Timeseries for CAT07 (black)
Flow (cfs, log scale)
10,000
100
1
1950
1960
1970
1980
1990
2000
2010
Date
CAT17 (MOVE.1−no transform)
NC02 (MOVE.1−log transform)

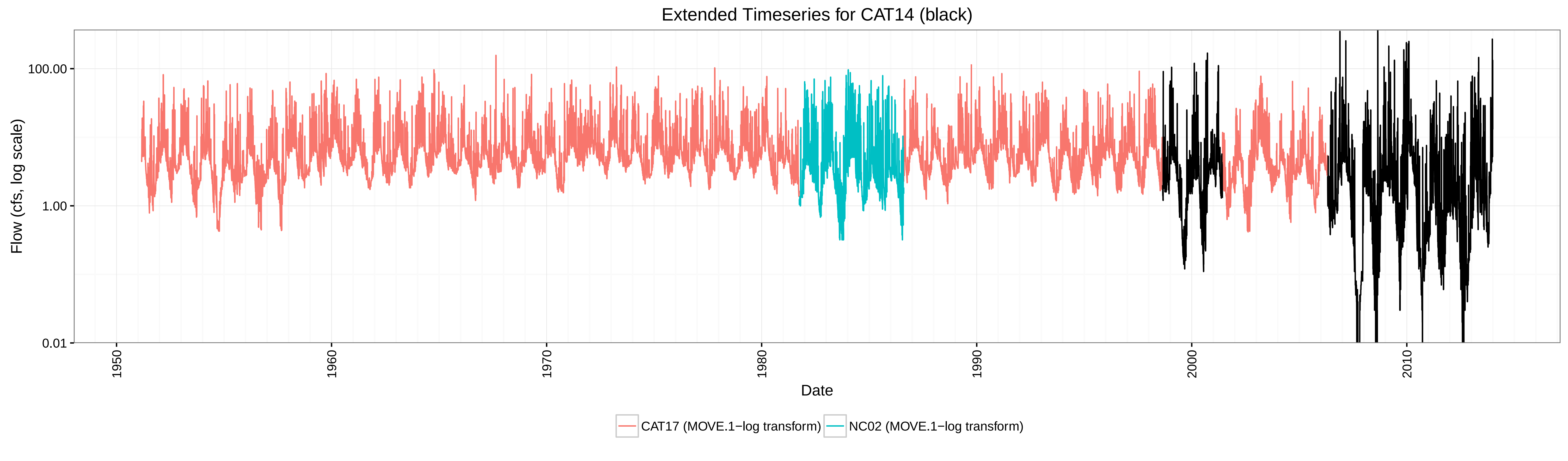

Extended Timeseries for CAT08 (black)
Flow (cfs, log scale)
100,000
1,000
10
1950
1960
1970
1980
1990
2000
2010
Date
CAT07 (Area Ratio)
CAT17 (MOVE.1−log transform)
NC02 (Area Ratio)

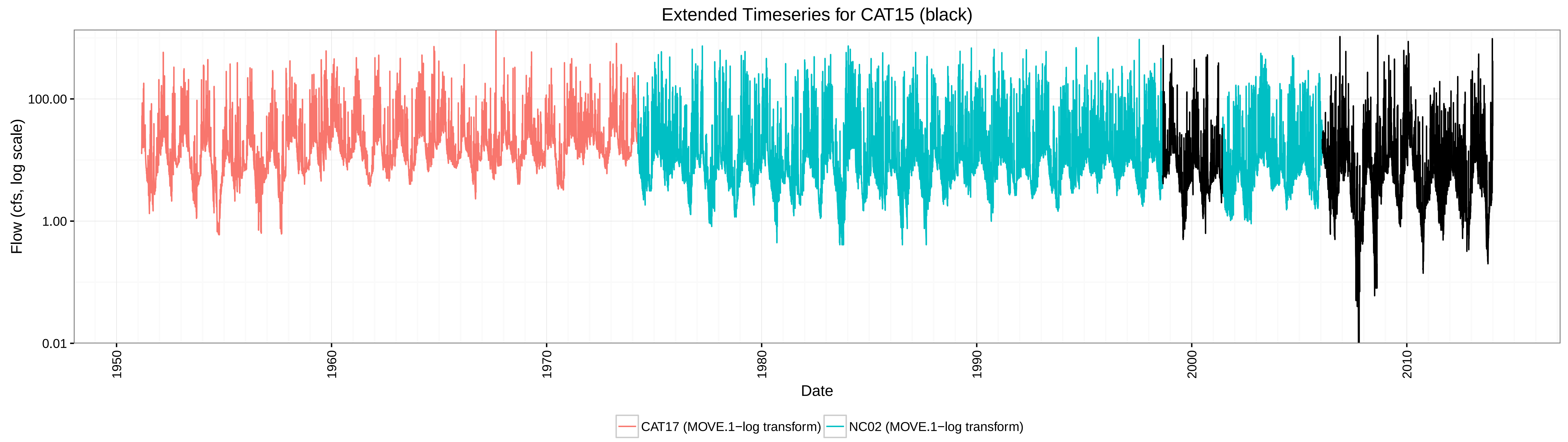

Extended Timeseries for CAT11 (black)
Flow (cfs, log scale)
1,000
10
1950
1960
1970
1980
1990
2000
2010
Date
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)



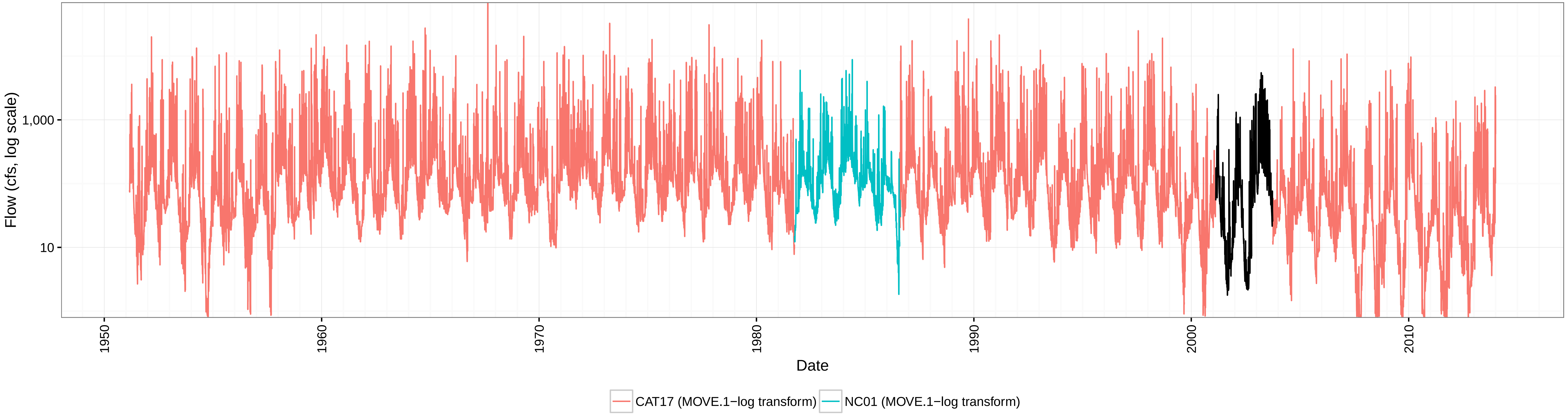
Extended Timeseries for CAT12 (black)
Flow (cfs, log scale)
100
1
1950
1960
1970
1980
1990
2000
2010
Date
CAT15 (MOVE.1−log transform)
CAT17 (MOVE.1−log transform)
NC01 (MOVE.1−log transform)

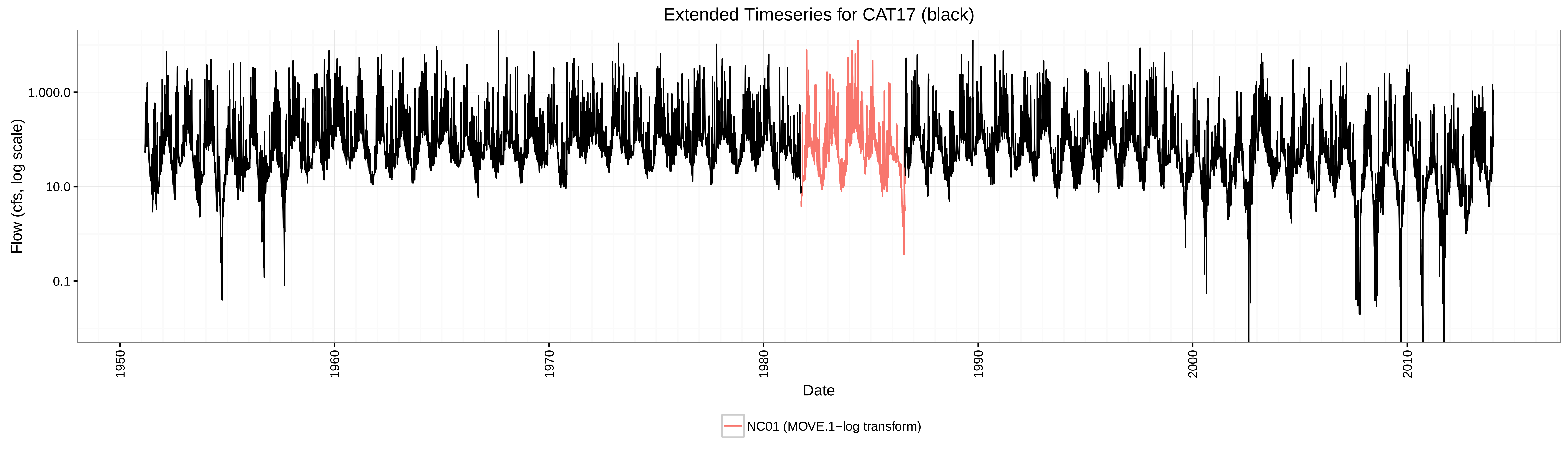

Extended Timeseries for CAT13 (black)
Flow (cfs, log scale)
10
1
1950
1960
1970
1980
1990
2000
2010
Date
CAT15 (MOVE.1−log transform)
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)

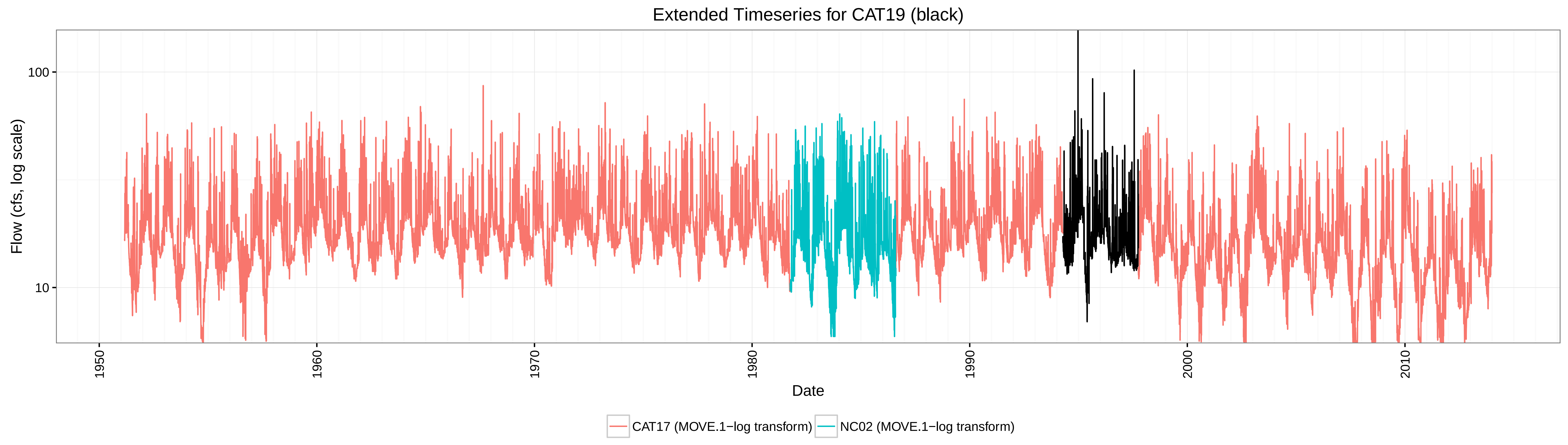

Extended Timeseries for CAT14 (black)
Flow (cfs, log scale)
100.00
1.00
0.01
1950
1960
1970
1980
1990
2000
2010
Date
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)

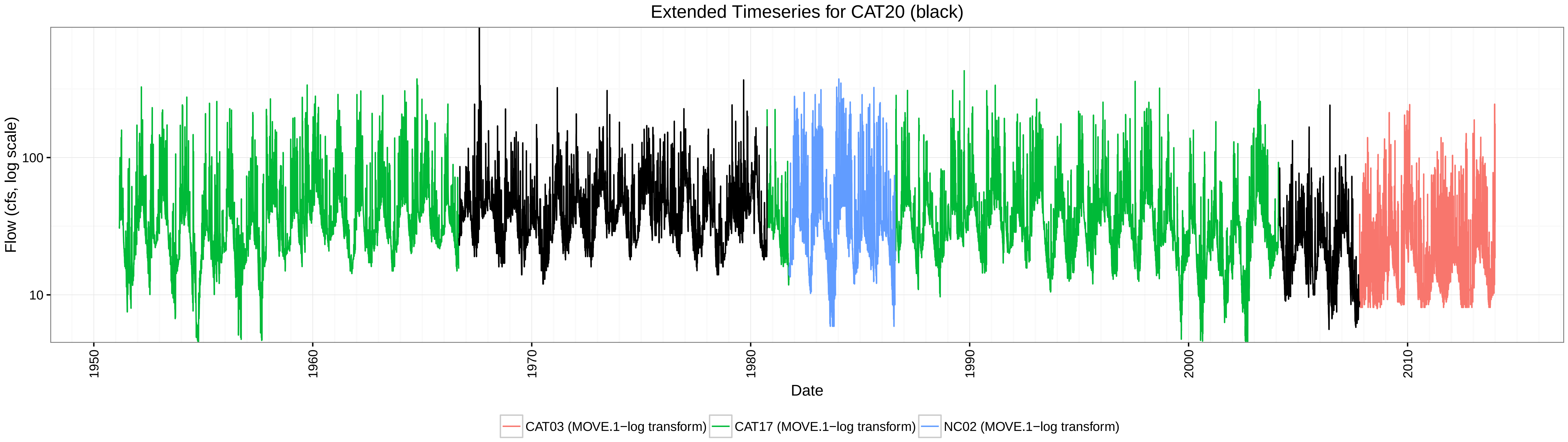

Extended Timeseries for CAT15 (black)
Flow (cfs, log scale)
100.00
1.00
0.01
1950
1960
1970
1980
1990
2000
2010
Date
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)

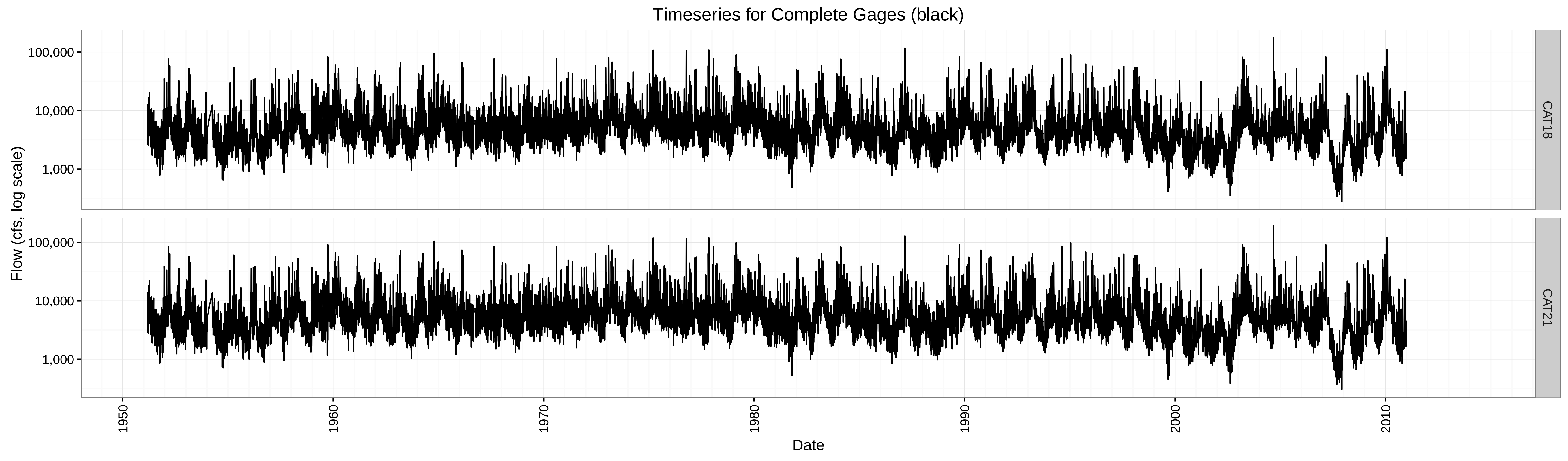
Extended Timeseries for CAT16 (black)




Extended Timeseries for CAT17 (black)
Flow (cfs, log scale)
1,000.0
10.0
0.1
1950
1960
1970
1980
1990
2000
2010
Date
NC01 (MOVE.1−log transform)


Extended Timeseries for CAT19 (black)
Flow (cfs, log scale)
100
10
1950
1960
1970
1980
1990
2000
2010
Date
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)


Extended Timeseries for CAT20 (black)
Flow (cfs, log scale)
100
10
1950
1960
1970
1980
1990
2000
2010
Date
CAT03 (MOVE.1−log transform)
CAT17 (MOVE.1−log transform)
NC02 (MOVE.1−log transform)


Timeseries for Complete Gages (black)
Flow (cfs, log scale)
100,000
10,000
1,000
CAT18
CAT21
1950
1960
1970
1980
1990
2000
2010
Date

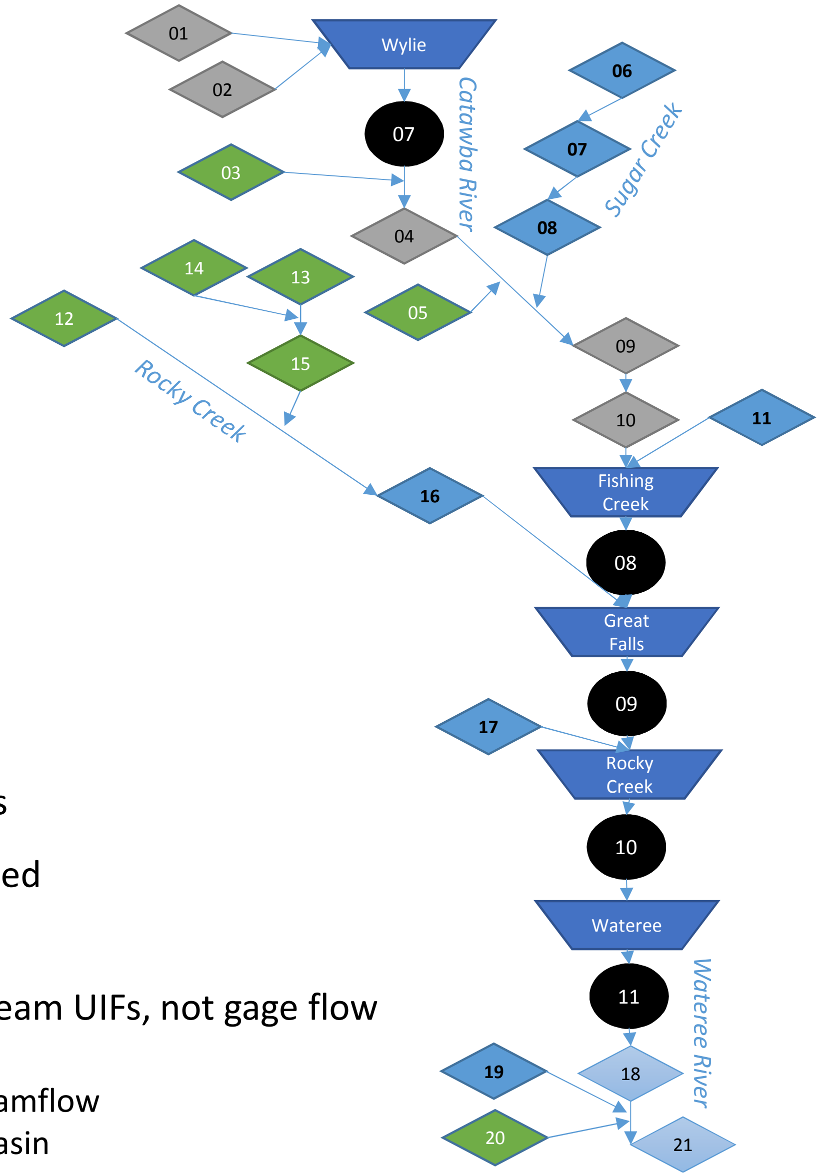
ATTACHMENT F

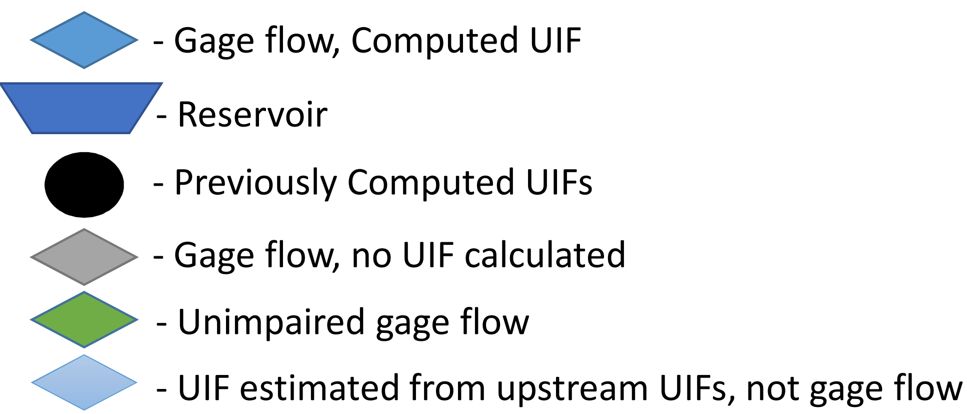
Discussion on Reference Gage and Method Selection

Gage	Reference	Method	Notes
CAT02	NC01	MOVE.1-log transform	Fills remaining record.
CAT03	CAT15	Area Ratio	Best across most plots and statistics.
CAT03	NC02	MOVE.1-log transform	Best across most plots and statistics.
CAT03	CAT17	MOVE.1-log transform	Also tried CAT20 as a preference over this one, but final timeseries yielded unrealistically-high peaks.
CAT05	CAT15	Area Ratio	Best across most plots and statistics.
CAT05	NC02	MOVE.1-log transform	Best across most plots and statistics.
CAT05	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT06	NC02	MOVE.1-log transform	Best across most plots and statistics.
CAT06	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT07	NC02	MOVE.1-log transform	Only supplies one more year of record.
CAT07	CAT17	MOVE.1-no transform	Same as with CAT15.
CAT08	CAT07	Area Ratio	No overlap to test, inspection done through final timeseries.
CAT08	NC02	Area Ratio	Choice of MOVE.1 debatable given length of record.
CAT08	CAT17	MOVE.1-log transform	Has questionable high flows.
CAT11	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT11	NC02	MOVE.1-log transform	Fills remaining record.
CAT12	CAT15	MOVE.1-log transform	Best across most plots and statistics.
CAT12	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT12	NC01	MOVE.1-log transform	Fills remaining record.
CAT13	CAT15	MOVE.1-log transform	Best across most plots and statistics.
CAT13	NC02	MOVE.1-log transform	Best across most plots and statistics.
CAT13	CAT17	MOVE.1-log transform	Fills remaining record.
CAT14	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT14	NC02	MOVE.1-log transform	Fills remaining record.
CAT15	NC02	MOVE.1-log transform	Best across most plots and statistics.
CAT15	CAT17	MOVE.1-log transform	Fills remaining record.
CAT16	CAT17	MOVE.1-log transform	Length of record calls into question using MOVE.1 and has worrisome high flows.
CAT16	NC01	MOVE.1-log transform	Length of record calls into question using MOVE.1 and has worrisome high flows.
CAT17	NC01	MOVE.1-log transform	Argument could be made for not using transform.
CAT19	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT19	NC02	MOVE.1-log transform	Fills remaining record.
CAT20	CAT03	MOVE.1-log transform	Best across most plots and statistics.
CAT20	CAT17	MOVE.1-log transform	Best across most plots and statistics.
CAT20	NC02	MOVE.1-log transform	Fills remaining record.

ATTACHMENT G

Schematic of USGS Streamflow Gages in the Catawba-Wateree River Basin





Attachment G: Schematic of USGS Streamflow Gages in the Catawba-Wateree River Basin