Request for Qualifications 2023-004

Permitting & Engineering Services for New Crooked Creek

ADDENDUM No. 1

ISSUE DATE: September 8, 2022

Responding Offerors on this project are hereby notified that this Addendum shall be made a part of the above named RFQ document.

The following items add to, modify, and/or clarify the RFQ documents and shall have the full force and effect of the original Documents. This Addendum shall be acknowledged by the Offeror in the RFQ document.

Question/Answer Section

1. Will the County allow 11x17 pages in the proposal submission? If so, will this count as one page or two in the page allowances?

   Answer: Yes, 11x17 pages are allowable and will count as one page.

2. May we use a 9 point font for graphics, captions, and tables?

   Answer: Yes, fonts smaller than 11 pt. may be used on graphics, captions, tables, etc.

3. Does the project include the conveyance infrastructure from the existing Crooked Creek WRF to the New Crooked Creek WRF?

   Answer: Yes, this project includes the conveyance infrastructure to direct flow from the Poplin Road Pump Station and from the existing Crooked Creek WRF to the new Crooked Creek WRF.

4. Can the documents (preliminary engineering report and/or technical memorandums) related to Site A be provided?

   Answer: Yes. See Attachment A.

5. Can the documents that supported the pursuit of the speculative limits from NCDEQ be provided?

   Answer: Yes. These documents were used to pursue speculative limits for this facility but in a different location. See Attachment A and Attachment B.

6. Can the documents (feasibility study and/or technical memorandums) for Site B be provided?

   Answer: Yes. The updated and approved service area for Site B is shown labelled as Twelve Mile (Poplin) in green. See Attachment C and Attachment D.

End of Question/Answer Section

Attachments

Attachment A – Engineer's Report (Pdf. Pages 3-82)
Attachment B – Speculative Limits (Pdf. 83-86 pages)
Attachment C – Sewer Service Area Maps (Pdf. Pages 87-93)
Attachment D – Site B Analysis (Pdf. Pages 94-106)

End of Addendum No. 1

Crooked Creek QUAL2K Model Development

Union County, North Carolina

June 8, 2017

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Pictured: North Fork Crooked Creek (Tetra Tech, 2016)

TETRA TECH

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EXECUTIVE SUMMARY

Union County, North Carolina is planning for the expansion of its wastewater treatment plant (WWTP) processing capacity in order to handle significant population growth projected for the county. There are three existing WWTP outfalls located along Crooked Creek in Union County with a maximum combined discharge capacity of 2.25 MGD. These three outfalls (Hemby Acres, Crooked Creek #2, and Grassy Branch) are anticipated to fall short of growing capacity needs for the county which are estimated to more than triple from existing levels by 2050. In order to meet demands, a new outfall is being considered for Crooked Creek located around Highway 601 which is geographically close to where growth is expected to be greatest (Error! Reference source not found.).

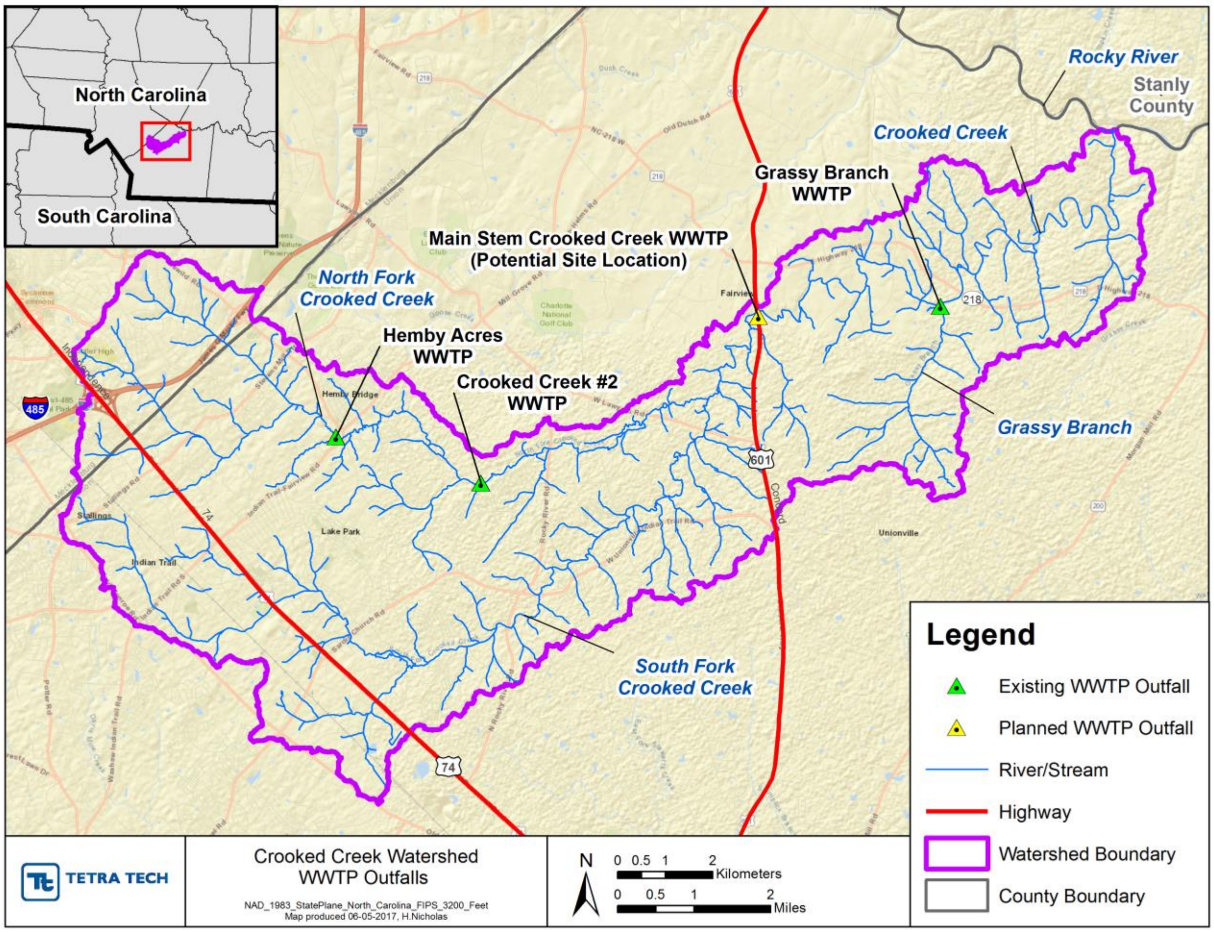

Figure 1. Crooked Creek watershed map: existing and projected WWTP outfalls

A QUAL2K model was developed to help evaluate the impacts of the new discharge on Crooked Creek. QUAL2K is a river water quality model that was used to develop a calibrated simulation of existing low flow critical conditions in Crooked Creek, as well as the impact of a new outfall on instream dissolved oxygen (DO). The baseline model of existing conditions along Crooked Creek was built, calibrated, and validated using monitoring data collected during the summer of 2016. Monitoring results and other criteria were used to break the modeled receiving stream into six model stream reaches (Error! Reference source not found.).

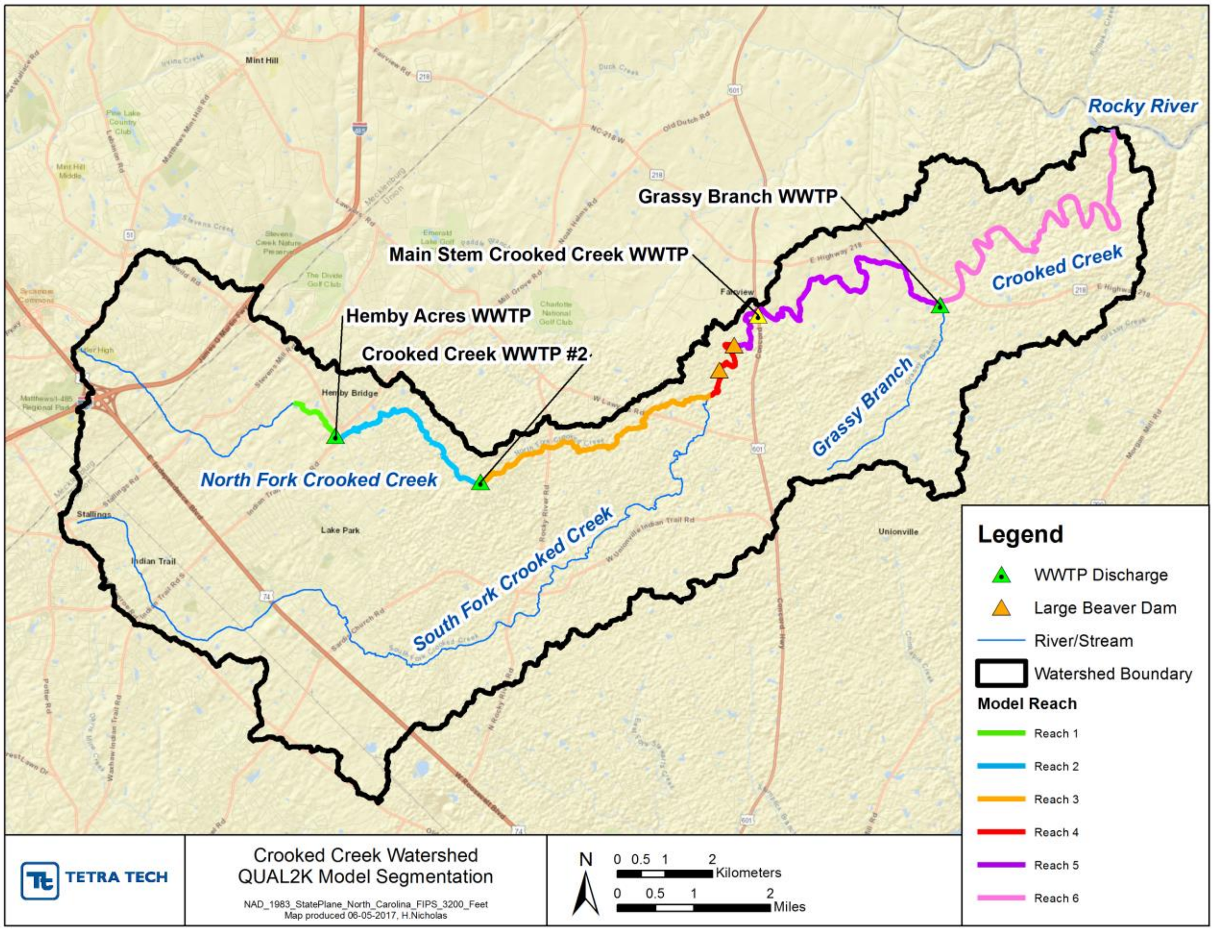

Figure 2. Crooked Creek QUAL2K model reach segmentation

A strong model calibration result was achieved for DO (**Error! Reference source not found.**). The model simulation of daily average DO captured key trends along the stream longitudinally, especially accounting for diurnal variation. A model validation run also demonstrated a similarly strong model performance (**Error! Reference source not found.**).

Sensitivity analyses revealed that the model was most sensitive to assumptions for sediment oxygen demand and reaeration, but results were relatively robust given strong assumptions based on good monitoring data. The model was applied to multiple scenarios both with and without effluent discharged to the stream. Under critical 7Q10 summer stream conditions, the model predicted DO concentrations to be considerably lower without the effluent of the permitted existing discharges (Figure 5). Well-treated and oxygenated effluent flow is expected to benefit the receiving stream during 7Q10 periods, increasing flow volume and velocity and thereby increasing reaeration and habitat quality.

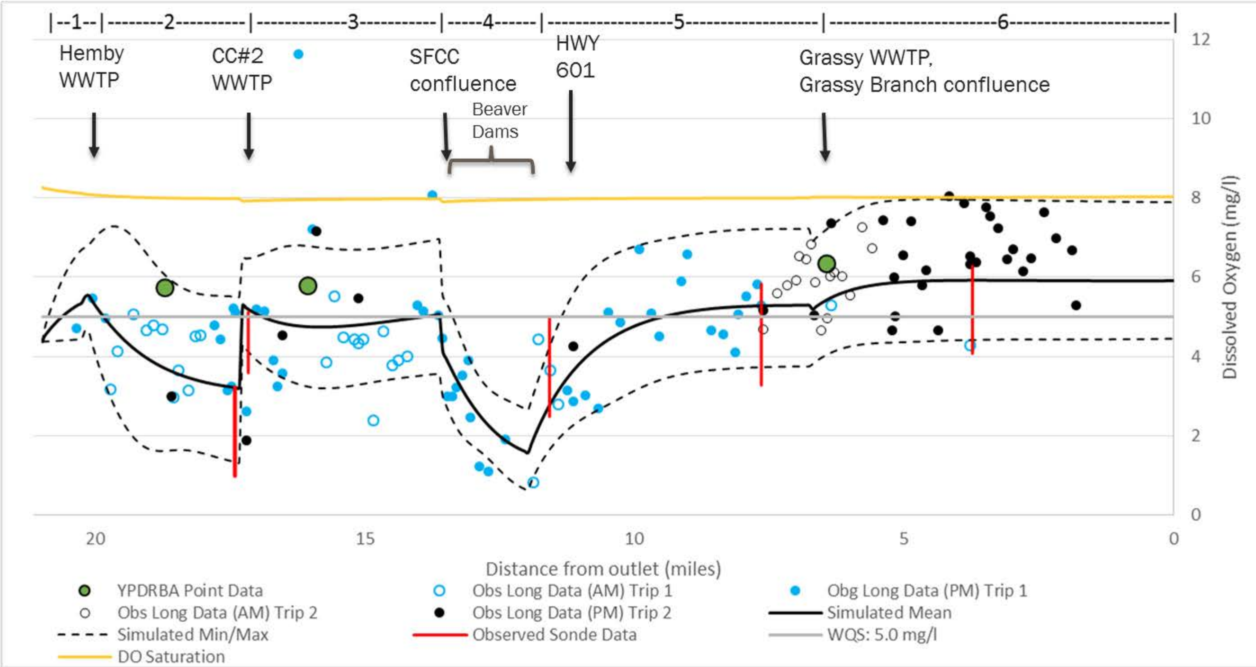

Figure 3. Simulated and observed DO along Crooked Creek (calibration)

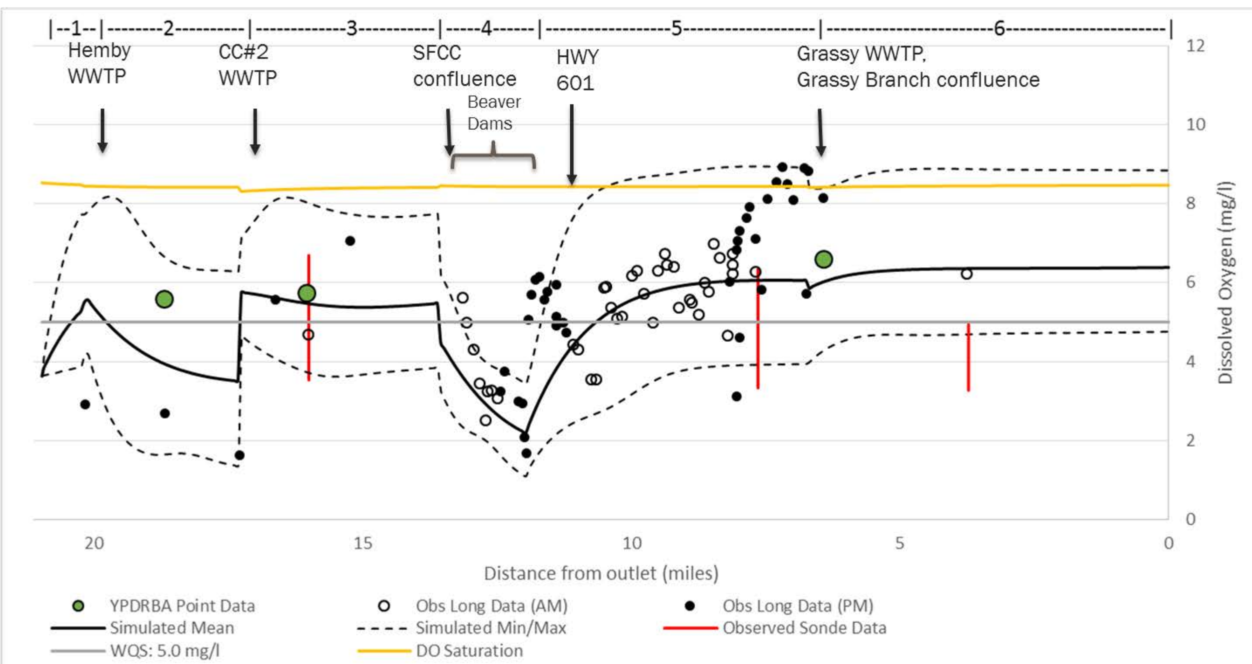

Figure 4. Simulated and observed DO along Crooked Creek (validation)

A new discharge from the MSCC WRF assuming effluent limits of 3 mg/L BOD_5, 1 mg/L NH_3N, and a minimum DO of either 6 mg/L or 7 mg/L would be expected to increase instream DO from existing permitted conditions below Highway 601 (**Error! Reference source not found.**).

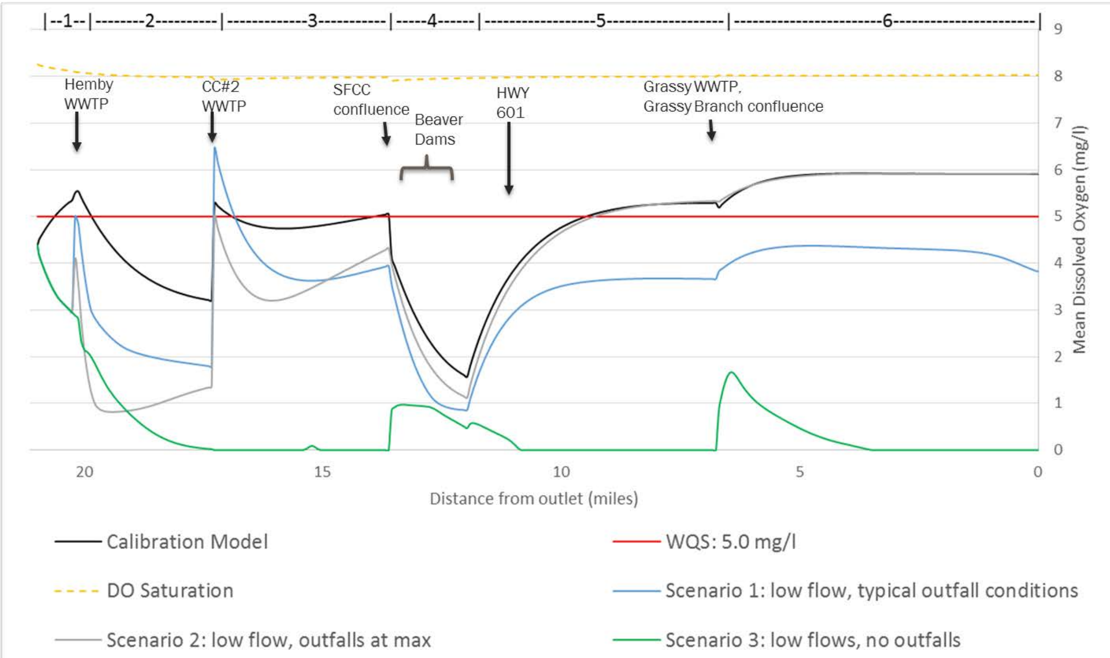

Figure 5. Mean DO model results for scenarios 1, 2, and 3.

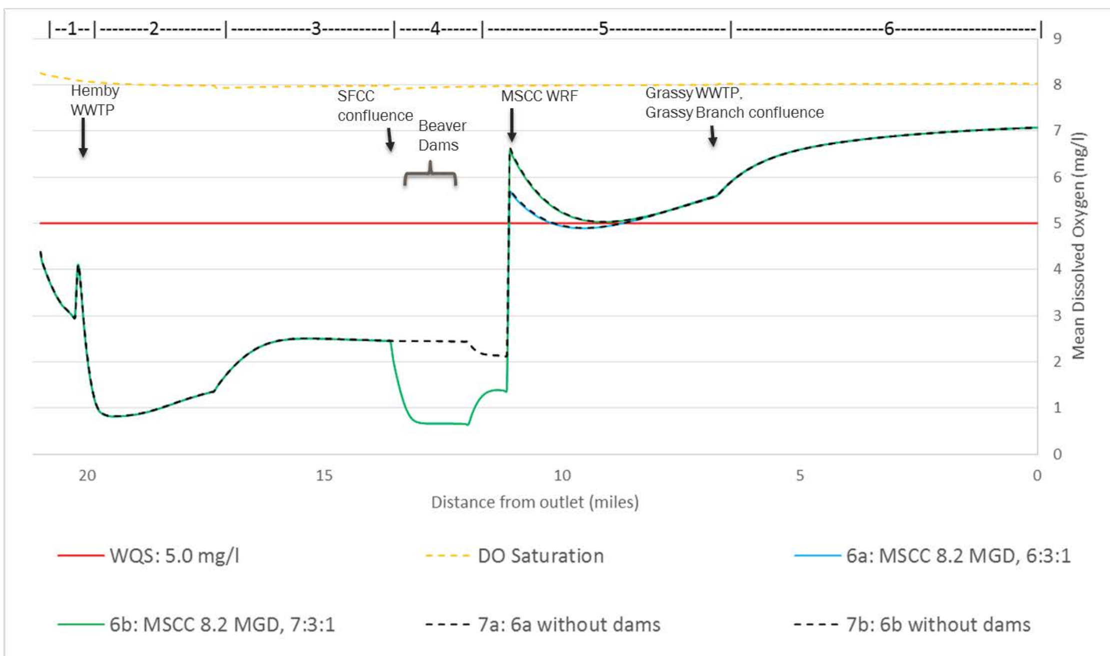

Figure 6. Mean DO model results for scenarios 6 and 7

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1.0 INTRODUCTION

The modeling analysis summarized in this report was performed to assess the assimilative capacity of the North Fork Crooked Creek and Crooked Creek (henceforth referred to as Crooked Creek together) to support NPDES permit decisions regarding additional effluent discharge to the receiving water. Crooked Creek is a Class C waterway, with the South Fork, North Fork, and Crooked Creek downstream of the confluence all listed as Category 5 impaired waterways for turbidity and ecological/biological integrity (NC DENR, 2016). Union County is exploring a potential new WWTP and associated discharge to Crooked Creek below the confluence of North Fork Crooked Creek and South Fork Crooked Creek. The North Carolina Division of Water Resources (DWR) has expressed concern about low dissolved oxygen (DO) levels along Crooked Creek and whether low DO conditions could be exacerbated by increased effluent discharge. DO is integral to aquatic biota in the water column.

The Crooked Creek watershed is located largely in Union County, North Carolina with a small fraction of land in the headwaters located in Mecklenburg County. The watershed is on the southeastern extent of the Charlotte metropolitan area, immediately east of the City of Matthews. The North Fork and South Forks of Crooked Creek join north of the City of Monroe, then flow eastward as Crooked Creek until the confluence with Rocky River in the Yadkin Pee Dee River Basin (Figure 7). The Crooked Creek drainage area is about 50 square miles, and the mainstem of the creek currently receives effluent from three permitted wastewater treatment plants (WWTPs): Hemby Bridge, Crooked Creek #2, and Grassy Branch.

Elevation across the watershed ranges from 406 – 794 feet (124 – 242 meters) (Figure 8). The North Fork Crooked Creek is approximately 11.6 miles long, South Fork Crooked Creek is 13.9 miles long, Crooked Creek south of the confluence is 12.2 miles long, and the Grassy Branch tributary is 3.0 miles long. There are also several small tributaries within the watershed.

In order to assess the assimilative capacity of Crooked Creek in regards to DO, a QUAL2K model was set up, calibrated and validated to simulate existing conditions as well as potential scenarios involving the new discharge. QUAL2K is a one-dimensional steady-state river water quality model frequently used for simulating DO (Chapra et al., 2012). QUAL2K assumes a well-mixed stream channel (both vertically and laterally), and employs a diel, or 24-hour period, heat budget which can be used to model DO on an hourly basis. Model calibration and validation used data collected during August and September 2016, along with supplemental data from other sources. This report details data sources, QUAL2K model setup, calibration, validation, sensitivity analysis and model application for evaluation of alternative discharge scenarios.

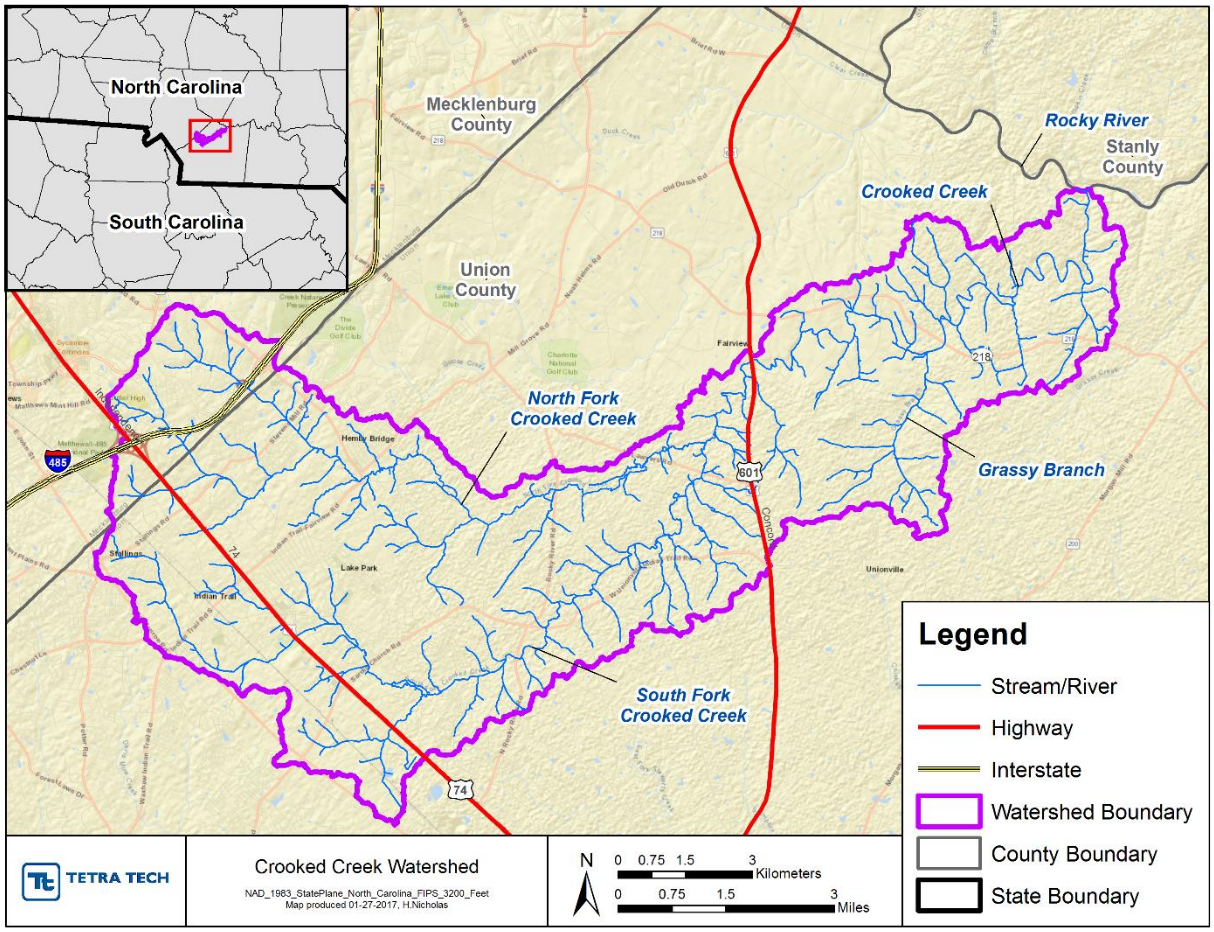

Figure 7. Crooked Creek watershed location map

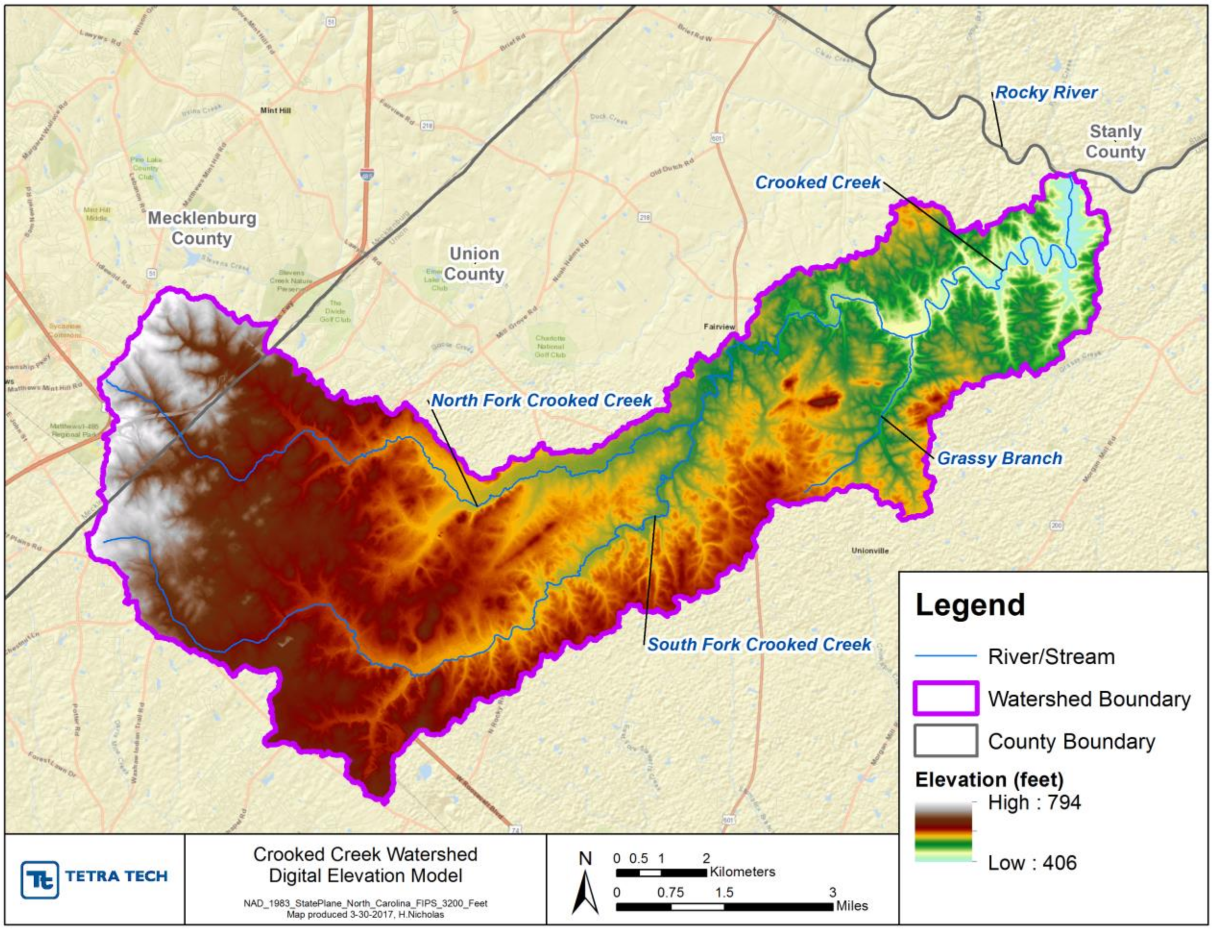

Figure 8. Crooked Creek watershed elevation and reach map

2.0 SUMMARY OF AVAILABLE DATA

The available data related to flow and water quality in the Crooked Creek watershed prior to the summer of 2016 was relatively limited, therefore field work was conducted by Tetra Tech to provide directly applicable data required for QUAL2K model setup, calibration, and validation. Note that there are no USGS or other flow gaging stations present within the Crooked Creek watershed. Available data for Crooked Creek which is relevant to QUAL2K model development is provided below.

2.1 GOOSE AND CROOKED CREEKS LWP

In 2008, the North Carolina Ecosystem Enhancement Program (NCEEP, now referred to as DMS which stands for Division of Mitigation Services) began development of a local watershed plan (LWP) for the Goose and Crooked Creek watersheds. The LWP involved preliminary characterization of the watersheds starting in 2008 and a more detailed watershed assessment starting in 2010. The LWP (Tetra Tech, 2012a) focused on:

- Determining the functional status of aquatic systems in the watershed.
- Identifying key stressors and their sources impacting water quality, habitat, and hydrology.
- Determining where management to address sources and stressors is most needed.
- Identifying potential management opportunities and key assets of the watershed.

Data collection and analysis associated with the LWP were used to inform channel characterization. For example, there was extensive documentation associated with the channel bed materials, presence of snags and logs in the streambed, and a number of anecdotal evidence which will inform decision making in the model such as the high instream Manning's n roughness values.

2.2 PERMITTED POINT SOURCE MONITORING

There are three point sources present within the Crooked Creek watershed which are permitted through the National Pollutant Discharge Elimination System (NPDES). Hemby Acres WWTP (NPDES ID: NC0035041, permitted discharge 0.3 MGD) and Grassy Branch WWTP (NPDES ID: NC0085812, permitted discharge 0.05 MGD) are minor point sources, whereas Crooked Creek #2 WWTP (NPDES ID: NC0069841, permitted discharge 1.9 MGD) is classified as a major point source (**Error! Reference source not found.**). Effluent discharge and instream monitoring data collected for these facilities was used to support model setup and calibration is presented in Appendix A.

Carolina Water Service Inc., which owns and operates the Hemby Acres WWTP located on the North Fork of Crooked Creek, conducts instream water quality sampling immediately upstream and downstream of the effluent discharge location. Sampling at these locations approximately 200 feet upstream and 200 feet downstream of the outfall has been collected on a weekly basis since 2014 and consists of temperature, DO, and fecal coliform bacteria. Carolina Water Service, Inc. also reports treated effluent flow and water quality data associated with their permitted discharge: flow reported daily, while water temperature, pH, five-day biochemical oxygen demand (BOD_5), ammonia (NH_3), DO, and total suspended solids (TSS) are reported weekly.

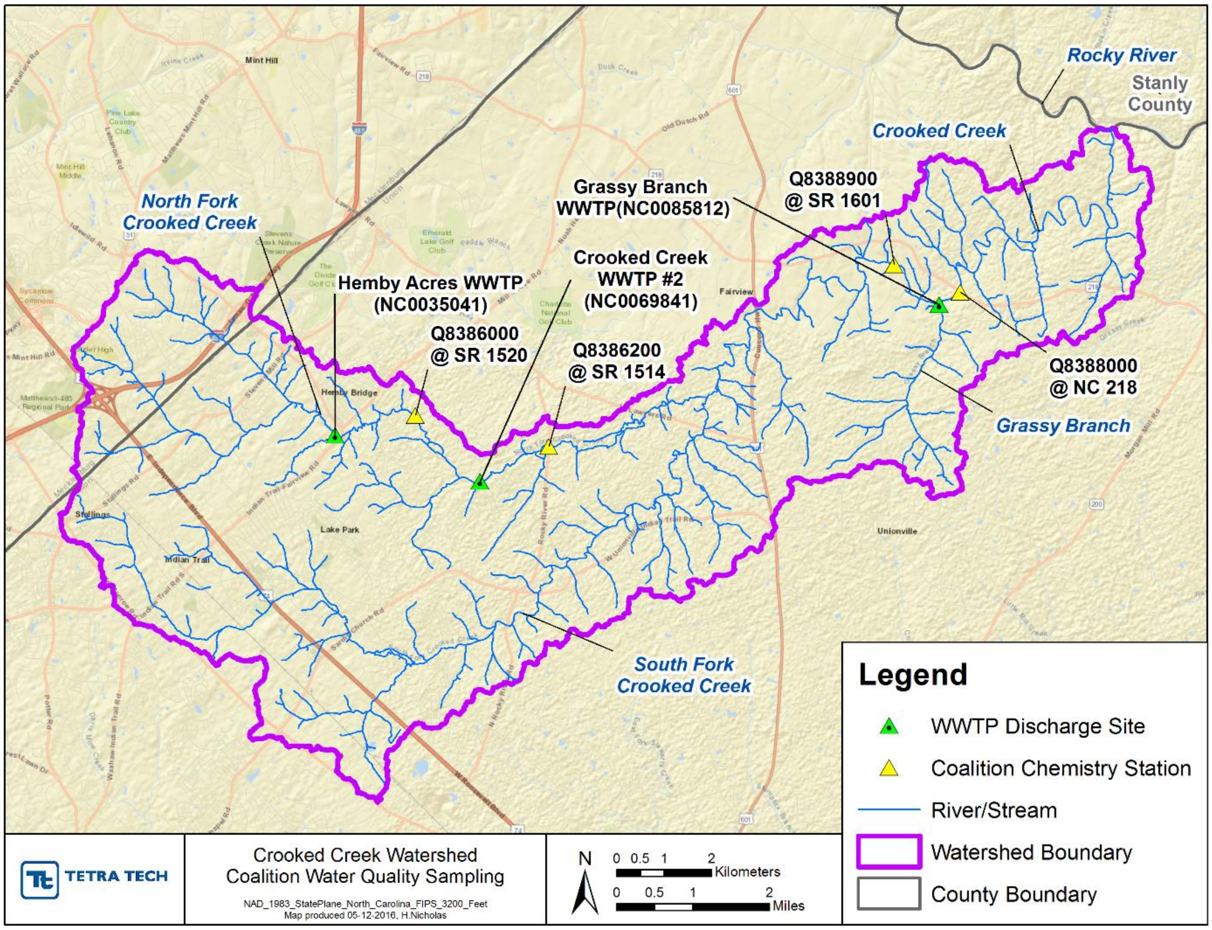

Figure 9. Crooked Creek point source discharge locations

Union County owns and operates the other two NPDES-permitted dischargers located along Crooked Creek: major discharger Crooked Creek #2 WWTP and minor discharger Grassy Branch WWTP. Treated effluent flow is reported daily for both dischargers. Water temperature and pH are reported daily for weekdays only at both sites. BOD_5, NH_3, DO, and TSS are reported weekly for Grassy Branch and daily on weekdays for Crooked Creek #2. Chemical oxygen demand (COD) is reported monthly for both sites, and total nitrogen (TN), total phosphorus (TP), and hardness are reported monthly for Crooked Creek #2. Note that effluent sampling for Crooked Creek #2 occurs prior to entering a pipe that carries the effluent from the plant to the discharge location. The distance between the plant sampling point and the pipe outfall is approximately 2.5 miles, which raised concerns that DO depletion could occur during transit through the closed system. Tetra Tech’s sampling of the effluent, however, showed that DO concentrations in the effluent leaving the pipe were similar to those recorded at the entrance to the pipe.

The NPDES permit limits for the existing outfalls within the Crooked Creek watershed are detailed in Table 1.

Table 1. Reach segmentation for Crooked Creek QUAL2K model

NPDES ID	Facility Name	Permitted Allowable Flows and Concentrations (Summer)				
		Flow (MGD)	BOD_5 (mg/l)	NH_3-N (mg/l)	DO (mg/l)	TSS (mg/l)
NC0035041	Hemby Acres	0.3	9.0	3.0	≥ 5.0	30.0
NC0069841	Crooked Creek #2	1.9	5.0	2.0	≥ 6.0	30.0
NC0085812	Grassy Branch	0.05	5.0	2.0	≥ 5.0	30.0

2.3 YPDRBA (COALITION) INSTREAM SAMPLING

There are four Coalition water quality sampling sites in the Crooked Creek watershed which are monitored by the Yadkin Pee Dee River Basin Association (YPDRBA). Of these four sites, two are located on the North Fork Crooked Creek (Q8386000, Q8386200), one is located on Crooked Creek below the confluence of the North and South Forks (Q8388900), and one is located below the confluence of Grassy Branch (Q8388000) (**Error! Reference source not found.**). All four sites monitor temperature (temp), pH, DO, and total nitrogen (TN) approximately monthly, and Site Q8388000 also measures other nutrient data on a monthly basis since 2013 including nitrate and nitrite (NOX), ammonia (NH_3), and total Kjeldahl nitrogen (TKN). These Coalition sites also monitor turbidity, fecal coliform bacteria, conductivity, and total suspended solids (TSS) on a monthly basis. These data are likely to be used during model calibration to instream conditions along Crooked Creek and is presented in Appendix B. Note that sampling at site Q8388900 was apparently discontinued during 2013.

2.4 TETRA TECH SAMPLING

During the late summer of 2016, hydraulic and water quality sampling was performed by Tetra Tech on three separate field trips: August 15-19, August 31-September 2, and September 13-16. Sampling efforts included surveying 20 cross sections along Crooked Creek, estimating flow velocity and discharge, and generating a log of hydraulic information related to the creek. Water quality sampling on all three trips involved longitudinal DO sampling by probe, deployment of multi-day sondes for diurnal DO and water temperature fluctuation measurements, and grab sampling for water quality analyses for oxygen-related and nutrient-related constituents. The longitudinal samples included direct sampling of the effluent discharges, and a few small tributaries. The 2016 summer sampling results provided key data for model parameterization and calibration (Appendix C).

2.5 CRITICAL LOW FLOW DATA AND RESEARCH

In North Carolina, critical low flow statistics are typically used to approximate stream conditions for NPDES wasteload allocation scenario analysis. A 7Q10 flow is the lowest seven-day average flow that occurs on average once every ten years. Although there are no flow gaging stations located along Crooked Creek, 7Q10 flows may be estimated based on historical flow conditions in an adjacent watershed as documented in Weaver and Fine (2003) and detailed in Appendix D.

2.6 HEC-RAS MODELING EFFORTS

Two flow models have been created for the Crooked Creek watershed using the Hydrologic Engineering Center River Analysis System (HEC-RAS) model developed by the US Army Corps of Engineers (USACE, 2016). HEC-RAS models are used by hydraulic engineers for channel flow and stage analysis for floodplain determination, typically using design storm events. The combined HEC-RAS models cover the full extent of Crooked Creek, Grassy Branch, and the North and South Forks. Although HEC-RAS models are largely developed and applied for high-flow flood condition modeling, certain components of the models may be useful for low flow steady-state analysis, such as calibration of reach hydraulic parameters and constraining hydraulic parameterization.

The HEC models in the Crooked Creek watershed covered all of the mainstem and major tributaries. Most of the HEC-RAS models were obtained from the NC Floodplain Mapping Program – Geospatial and Technology Management Dept. Several HEC-RAS models for portions of the Crooked Creek mainstem were provided by Union County. The HEC-RAS models comprise both “Limited Detail Study” and “Detailed Study” flood models. The “limited detail” models predict flood delineations for the 100-year storm event using cross section geometry developed from LIDAR data. The “detailed” models are much more rigorous than “limited detail” studies because they determine specific channel profiles, bridge and culvert opening geometry, and floodplain characteristics using traditional field surveys. The “detailed study” model also includes flood profiles for the 10-, 25-, and 50-year storm events.

2.7 GOOSE AND CROOKED CREEK LSPC MODEL

A model was developed to simulate hydrology and water quality in the Goose and Crooked Creek watersheds in support of watershed planning conducted by NCEEP, Centralina Council of Governments and North Carolina Division of Water Quality (Tetra Tech, 2012b). This effort involved simulating these two adjacent drainages using the Loading Simulation Program C++ (LSPC) watershed model to represent existing conditions (Tetra Tech, 2009a). The LSPC model, a continuous watershed model with a 1-D stream channel representation, was parameterized based on hydrologic soil groups, land slope characteristics, and land use/land cover across the two basins. Hydrology was calibrated to observed streamflow at multiple locations within the Goose Creek watershed. Although there are no flow monitoring stations within the Crooked Creek basin (and no direct hydrology calibration), the geology and soils of Crooked Creek are similar to Goose Creek. As a result, model hydrology predictions are likely reasonable across a range of flows. Water quality calibration was performed for both creeks by comparing simulated pollutant concentrations and loads to observed values.

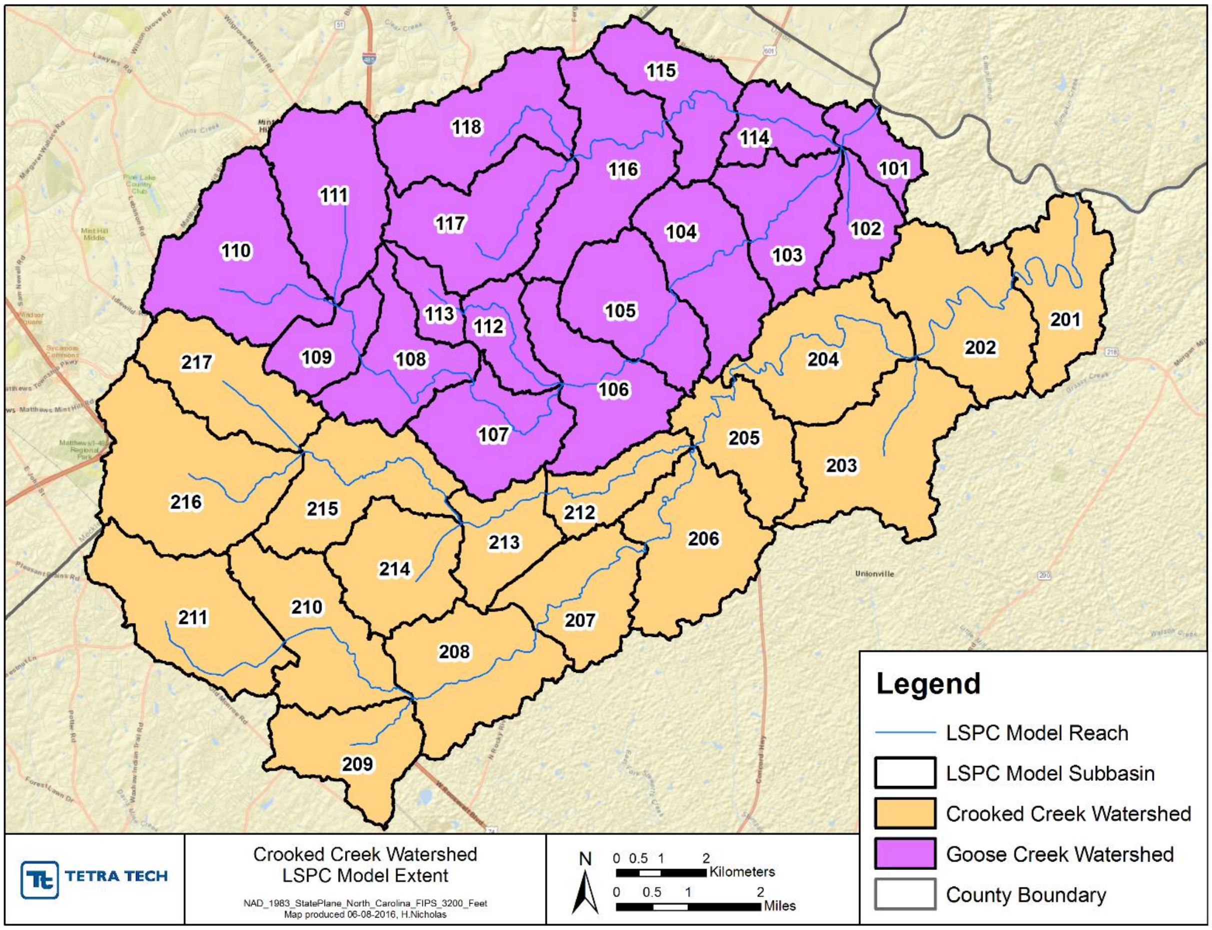

Figure 10. LSPC model extent and subbasins for the Goose and Crooked Creek watersheds

3.0 QUAL2K MODEL SETUP

3.1 MODEL DOCUMENTATION

The most recent version of the QUAL2K model available at the time of this report was used for modeling Crooked Creek: QUAL2K version 2.12b1. QUAL2K is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E model (Brown and Barnwell, 1987). QUAL2K was developed at Tufts University and has been funded partly by the United States Environmental Protection Agency (Chapra et al., 2012).

3.2 MODEL DATE SELECTION

The QUAL2K model is set up to run for a specific date, and information about latitude, longitude, and time zone are used to inform solar energy forcing. Based on the summer 2016 sampling effort conducted by Tetra Tech, the QUAL2K model for Crooked Creek was setup and calibrated to a date in August which best represented the first two sampling trips. The model was validated as well by comparing the simulated and observed results associated with the third sampling trip in September. The first and second trips to the Crooked Creek area for data collection were August 15 – 19, and August 31 – September 2. Grab samples were taken on those sampling efforts for the most part on August 16 and August 31 respectively. A date chosen approximately halfway between those two dates was identified to use as the model calibration date (August 24, 2016). The model validation date was chosen as the grab sampling date of September 14, 2016 during the third sampling field trip which was September 13 – September 16.

There is reasonable justification for combining the first and second field trips into a single calibration period based on known flow and atmospheric conditions. An analysis of flow gages in the adjacent watershed of Goose Creek, as well as an analysis of local air temperatures suggest that conditions on the August 16 and 31 were reasonably similar to suggest that combining data associated with those two trips for a single steady state model calibration run would be defensible. Average air temperature on 8/16 and 8/31 were 84.6 °F (29.2 °C) and 79.4 °F (26.3 °C) respectively. The two USGS flow gages along Goose Creek (0212467451 and 0212467595) both observed streamflow conditions between 0.4 and 0.9 cfs on August 16th and 31st. Flows at these gages experienced average annual flows in 2016 on the order of 7.0 and 4.4 cfs respectively, so conditions were considered sufficiently similar and relatively low during the two August dates compared to the annual statistics.

3.3 MODEL SEGMENTATION

The extent of the Crooked Creek QUAL2K model was identified as upstream of the Hemby Bridge WWTP on the North Fork, running 21.0 miles (33.8 kilometers) to the outlet at Rocky River. The total modeled distance was subdivided into “reaches” which themselves are made up of 0.1-kilometer computational “elements”. In general reach divisions represent areas of approximately similar hydraulic conditions. For Crooked Creek, the 6 segmented reaches largely reflect key points of interest in the watershed such as WWTP discharges or tributary inflows. The reach located downstream from the South Fork Crooked Creek (SFCC) confluence was segmented at a large beaver dam above Highway 601 because this stretch is particularly obstructed and sluggish due a series of large beaver/debris dams. This reach between SFCC and the end of the beaver dams above Highway 601 has significant hydrologic differences than downstream of the dams, reflected in channel geometry, flow velocity, and observed DO concentrations.

Hydraulic parameterization for each model reach was based on GIS-based spatial analyses of NHDPlusV2 flowlines, a 3-meter resolution digital elevation model (DEM) obtained from the USDA Data Gateway, and field data from surveys conducted in August and September, 2016. Table 2 and Figure 8 summarize the reach segmentation for the Crooked Creek QUAL2K model which were used for model setup and did not vary between calibration and validation model setups.

Table 2. Reach segmentation for Crooked Creek QUAL2K model

Reach	Description	Reach Length, mi (km)	Upstream Elevation, ft (m)	Downstream Elevation, ft (m)
1	Headwaters to Hemby Bridge WWTP	0.88 (1.42)	623 (190)	617 (188)
2	Hemby Bridge WWTP to Crooked Creek #2 WWTP	2.80 (4.50)	617 (188)	587 (179)
3	Crooked Creek #2 WWTP to South Fork Crooked Creek (SFCC) confluence	3.75 (6.03)	587 (179)	558 (170)
4	South Fork Crooked Creek (SFCC) to end of two large beaver dams	1.61 (2.59)	558 (170)	551 (168)
5	End of beaver dams, crossing Highway 601, to Grassy Branch WWTP	5.21 (8.39)	551 (168)	502 (153)
6	Grassy Branch WWTP to Rocky River	6.72 (10.82)	502 (153)	410 (125)

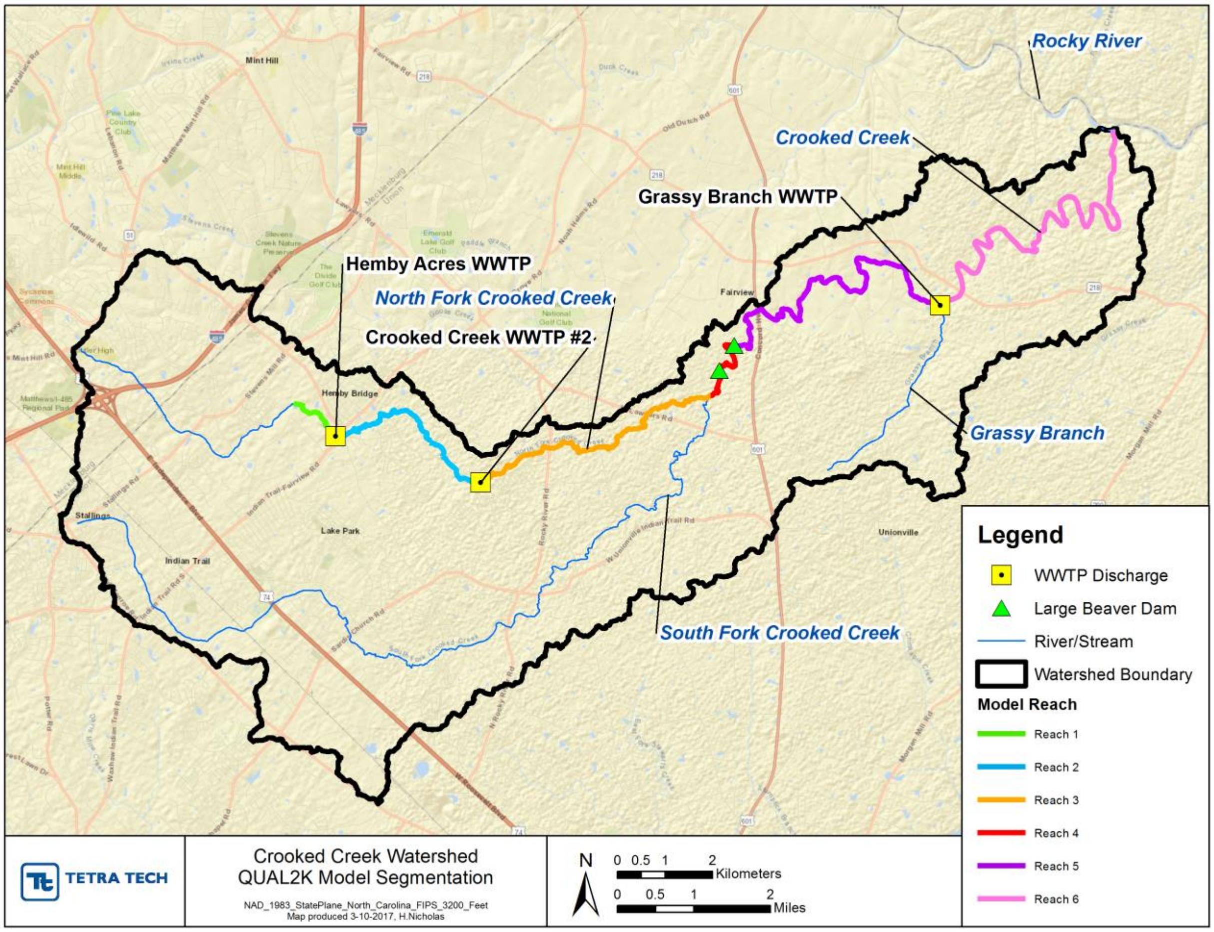

Figure 11. Crooked Creek QUAL2K model reach segmentation

3.4 REACH HYDRAULICS

Stream hydraulics were simulated using the Manning's Formula method within QUAL2K. Model inputs related to Manning's Formula may vary for each reach and are represented as average conditions based on the 2016 field survey cross sectional data (Figure 12). There were 20 locations surveyed during summer 2016, and channel geometry characteristics are used to approximate average conditions for each model reach. There is a strong relationship between increasing channel bottom width and distance from the headwaters, reflecting the corresponding increase in drainage area and flow; therefore, the average distance of each reach from the headwaters was used to approximate channel bottom width (Figure 13). Surface and bottom channel widths were used to estimate average channel side slopes for each reach by assuming trapezoidal area.

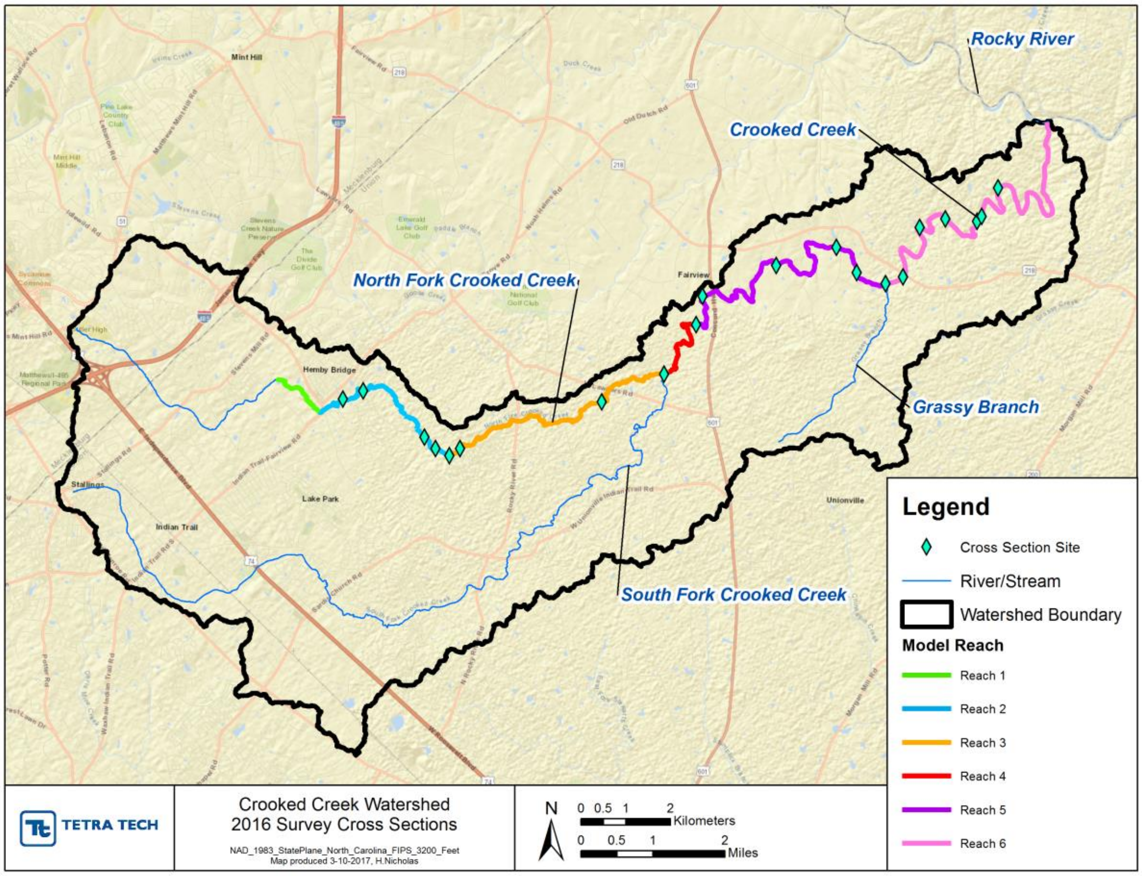

Figure 12. Crooked Creek summer 2016 cross sectional surveys by Tetra Tech

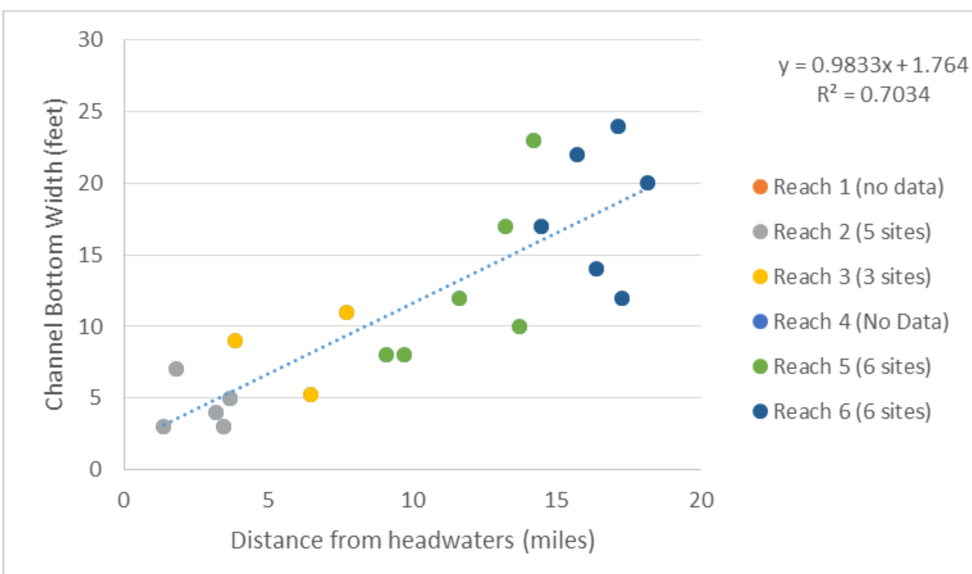

Figure 13. Crooked Creek channel bottom width measured from summer 2016 cross sections

For reach hydraulics, bottom channel widths were estimated based on the regression presented in Figure 13. Channel side slopes were estimated using surface and bottom channel widths and an average depth of 1 foot (0.32 meters). Bottom widths were generally small, and since water depths were shallow along the entire Crooked Creek, side slopes are high.

Channel bed slope is calculated as the difference in upstream and downstream elevation divided by the reach length (refer to Table 1 for raw data). Manning's n (roughness coefficient) can range from about 0.025 – 0.150 for natural streams (Chow, 1959). Manning's n may be subject to alteration during model calibration because channel roughness is heavily influenced by pool-riffle structures, debris, and obstructions (Beven et al., 1979). Manning's n was initialized for all reaches as 0.1 which indicates "mountain streams with boulders" since there is significant data suggesting high debris content and irregular channel bottoms along the entire stream (Chow, 1959). Manning's n was the only reach hydraulic parameter adjusted during model calibration.

Table 3. Reach hydraulic model setup inputs

Reach	Location Shorthand	Channel Bed Slope	Manning's n	Bottom Width, ft (m)	Side Slopes
1	HW to Hemby WWTP	0.0014	0.1	2.17 (0.66)	4.37
2	Hemby WWTP to CC#2 WWTP	0.0010	0.1	4.00 (1.22)	4.71
3	CC#2 WWTP to SFCC	0.0015	0.1	7.43 (2.26)	5.35
4	SFCC to Beaver Dams	0.0006	0.1	10.50 (3.20)	5.93
5	Beaver Dams to Grassy WWTP	0.0014	0.1	13.58 (4.14)	6.51
6	Grassy WWTP to outlet	0.0020	0.1	19.11 (5.83)	7.55

3.5 METEOROLOGICAL INPUTS, LIGHT AND HEAT

3.5.1 Hourly Inputs

Metrological inputs to the QUAL2K model include air temperature, dew point temperature, wind speed, cloud cover percentage, and percent of solar radiation blocked by stream shade. Hourly meteorological data are available through the Weather Underground (www.wunderground.com) for sites near Crooked Creek. The "Campobello Drive" site in Unionville, North Carolina (KNCUNION2) is located near Crooked Creek and was identified as the best source of hourly meteorological inputs for the QUAL2K model. For development of each meteorological input, see Table 4. Average air temperature as developed for model calibration was 83.1 °F (28.4 °C) with a daily range between minimum and maximum air temperatures of 15.95 °F (8.86 °C). Average air temperature as developed for model validation was 86.0 °F (24.6 °C) with a daily range between minimum and maximum air temperatures of 18.0 °F (10.0 °C).

Table 4. Meteorological inputs data source summary

Parameter	Processing Note
Air Temperature	Hourly air temperatures (dry bulb temperatures) were calculated as hourly averages of data from the KNCUNION2 site on 8/16/2016 and 8/31/2016 for the calibration model. Hourly air temperature from the same station was used from 9/14/2016 for the validation model. Inputs did not vary by reach.
Dew Point Temperature	Hourly dew point temperatures were calculated as hourly averages of data from the KNCUNION2 site on 8/16/2016 and 8/31/2016 for the calibration model. Hourly dew point temperatures from the same station was used from 9/14/2016 for the validation model. Inputs did not vary by reach.
Wind Speed	Hourly wind speed was available from the KNCUNION2 site, however the riparian vegetation and channel incision shelters the stream so significantly (as observed during field trips) that wind was assumed to be negligible to the stream for both calibration and validation models. Inputs were set to zero for all hours at all reaches.
Cloud Cover	Hourly cloud cover were calculated as hourly averages of data on 8/16/2016 and 8/31/2016 from the closest regional airport (Monroe Airport, station ID: KEQY). Hourly cloud cover from the same station was used from 9/14/2016 for the validation model. Inputs did not vary by reach.
Shade	A single shade percentage is applied to all hours and all reaches for initialization although inputs may vary hourly and by reach during calibration. Parameter initialized as 70%. Note that shade is very highly along Crooked Creek with much of the stream completely sheltered by vegetation such that the channel cannot be identified through aerial imagery. Shade was a calibration parameter because it has a large impact on average water temperature. Calibrated results for shade were used for the validation model setup.

Table 5. Hourly inputs for air temperature, dew point temperature, and cloud cover

Hour	Calibration Model			Validation Model		
	Air Temp (°F)	Dew Point Temp (°F)	Cloud Cover (%)	Air Temp (°F)	Dew Point Temp (°F)	Cloud Cover (%)
1	78.75	68.42	0.00%	72.67	66.00	0.00%
2	77.75	67.90	0.00%	71.33	65.00	0.00%
3	76.81	68.13	0.00%	70.17	64.17	0.00%
4	76.20	68.00	0.00%	69.33	64.00	41.67%
5	75.56	68.00	0.00%	69.00	63.50	45.83%
6	74.90	68.00	0.00%	68.00	63.00	50.00%
7	74.30	67.50	0.00%	68.00	63.00	93.75%
8	77.60	70.80	0.00%	68.17	63.33	100.00%
9	81.55	72.25	0.00%	70.00	65.50	100.00%
10	85.50	73.70	31.25%	72.67	68.33	100.00%
11	86.00	74.40	37.50%	75.83	71.33	91.67%
12	88.10	75.80	62.50%	78.00	72.67	25.00%
13	89.60	76.00	50.00%	79.83	73.00	0.00%
14	90.00	75.62	62.50%	81.60	72.40	0.00%
15	89.67	74.80	50.00%	84.00	70.83	0.00%
16	90.25	74.25	0.00%	85.50	70.00	0.00%
17	89.83	74.33	12.50%	86.00	70.00	0.00%
18	89.67	74.33	0.00%	86.00	68.00	50.00%
19	89.38	73.88	0.00%	84.40	69.00	0.00%
20	87.60	72.40	0.00%	82.20	68.20	0.00%
21	84.58	70.90	0.00%	79.33	67.00	0.00%
22	82.20	69.90	0.00%	77.25	67.00	0.00%
23	80.46	69.16	0.00%	75.60	67.00	0.00%
24	79.13	69.00	0.00%	74.60	66.40	0.00%

3.5.2 Light and Heat Inputs

A number of parameters related to light and heat functions may be adjusted for a given QUAL2K model. For model setup, solar inputs are calculated within the model based on latitude, time zone, and Julian day. Based on these inputs for Crooked Creek on 8/24/2016, sunrise and sunset were calculated within the model to be at 6:48 AM and 7:58 PM, which were externally verified through the North Carolina Wildlife Resources Commission, which publically documents sunrise and sunset times across North Carolina (www.NCWildLife.org). Sunrise and sunset times for the validation model on 9/14/2016 were calculated in the model as 7:04 AM and 7:29 PM respectively.

Most light and heat parameters were estimated based on suggested values from the QUAL2K manual. There are a number of options for modeling atmospheric attenuation of solar energy, atmospheric longwave emissivity, and wind speed function for evaporation and air convection/conduction, and sediment heat parameters (Table 6).

Table 6. Light and heat model setup inputs

Parameter (units)	Model Input	Note
Light Parameters		
Photosynthetically Available Radiation	0.47	Light parameters initialized based on QUAL2K example file.
Background light extinction (/m)	0.2	
Linear chlorophyll light extinction (/m)	0.0088	
Nonlinear chlorophyll light extinction (/m)	0.054	
ISS light extinction (/m)	0.052	
Detritus light extinction (/m)	0.174	
Model Parameters		
Atmospheric attenuation model for solar	Bras	Default atmospheric formula for QUAL2K
Atmospheric turbidity coefficient	2	Default value suggested by QUAL2K Manual
Atmospheric longwave emissivity model	Brutsaert	This equation tends to allow for warmer water temperatures to be achieved
Wind speed function for evaporation and air convention	Brady-Graves-Geyer	Default wind speed function for QUAL2K
Sediment Heat Parameters		
Sediment thermal thickness (cm)	20	Model default suggestions from QUAL2K manual. Default suggestion for sediment thermal thickness of 10 cm was modified to 20 cm given the observed presence of thicker sediment along the channel.
Sediment thermal diffusivity (cm^2/s)	0.005	
Sediment density (g/cm^3)	1.6	
Sediment heat capacity (cal/g °C)	0.4	

3.6 CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND SIMULATION

The QUAL2K model simulates instream chemical biological oxygen demand (CBOD) as two different pools: fast CBOD which is rapidly oxidized and labile in nature, and slow CBOD which is slowly oxidized and refractory in nature. For the QUAL2K model of Crooked Creek, fast CBOD was used to simulate the presence of oxygen-demanding substances in WWTP effluent, while slow CBOD was used to simulate the presence of instream background decay of organic matter such as leaf litter. The QUAL2K manual suggests that when modeling slow and fast CBOD separately, to keep the distinct pools apart by setting the CBOD hydrolysis rate to zero, so that choice was made for the Crooked Creek model.

Incubation time for BOD or CBOD measurements in laboratories is typically short-term for five days, reporting the results as BOD_5 or $CBOD_5$ respectively. These five-day concentrations of BOD and CBOD must be converted to the ultimate concentration of CBOD ($CBOD_{ultimate}$) for simulation in QUAL2K in order to approximate the slow or fast CBOD concentration after some fifty days of decomposition. For slow $CBOD_{ultimate}$ simulation in the model the Phelps equation below may be employed, as detailed in the QUAL2K manual (Chapra et al., 2012):

$$slow\ CBOD_{ultimate} = \frac{CBOD_5}{1 - e^{(-k_1 \times 5)}}$$

Note that for the equation above, k_1 is the rate of oxidation for CBOD which the QUAL2K manual suggests can range from 0.05 – 0.3 /d. For slow $CBOD_{ultimate}$ in the model, 0.05 /d will be used, and for fast $CBOD_{ultimate}$, 0.3 /d will be used in the model environment.

As mentioned above, WWTP effluent was modeled as fast $CBOD_{ultimate}$, which was based on Discharge Monitoring Report (DMR) data reported as BOD_5 concentrations. The original QUAL-II model (NCASI, 1985) internally converted 5-day BOD to ultimate CBOD using a ratio of 1.46 and was not user-specified (EPA, 1985). Studies have shown that rates can vary significantly from low ratios for domestic wastewater to very high ratios (e.g., 30) for pulp and paper waste (EPA, 1985). Leo, et al. (1984) summarized the results for numerous facilities that showed the ratios for secondary to advanced secondary averages from slightly below to slightly above 2. In the absence of specific lab studies on the existing County plant effluent BOD_5 to $CBOD_{ultimate}$ ratio, a factor of 2 was assumed:

$$fast\ CBOD_{ultimate} = 2 \times BOD_5$$

In summary, boundary conditions for headwaters and tributaries were simulated as slow CBOD pools estimated based on in-stream $CBOD_5$ sampling and Phelps first-order reaction equation, while boundary conditions for effluent point sources were simulated as fast CBOD pools estimated based on DMR BOD_5 sampling and a ratio of 2:1 for BOD_5:$CBOD_{ultimate}$.

3.7 BOUNDARY CONDITIONS

3.7.1 Headwaters

3.7.1.1 Headwater Flows

Of the twenty stream cross-sections surveyed during summer 2016, ten were paired with velocity measurements to estimate instantaneous streamflow. Stream velocity during each of three separate sampling trips was so low that a propeller-driven Global Water FP111 Flow Probe velocity meter with a lower measurement limit 0.3 ft/s (0.1 m/s) was not able to provide an estimate (i.e., velocity was too low to move the propeller to measure velocity). Therefore, at these ten sites, an orange was timed to float a specific distance—a crude but reasonable way to estimate average channel velocity. Stream discharge was subsequently approximated at these ten sites by multiplying the estimated flow velocity by cross-sectional area (Figure 14). This estimation was conducted using a linear regression of eight of the sites, as two were deemed to be probable outliers and may reflect error in methodology.

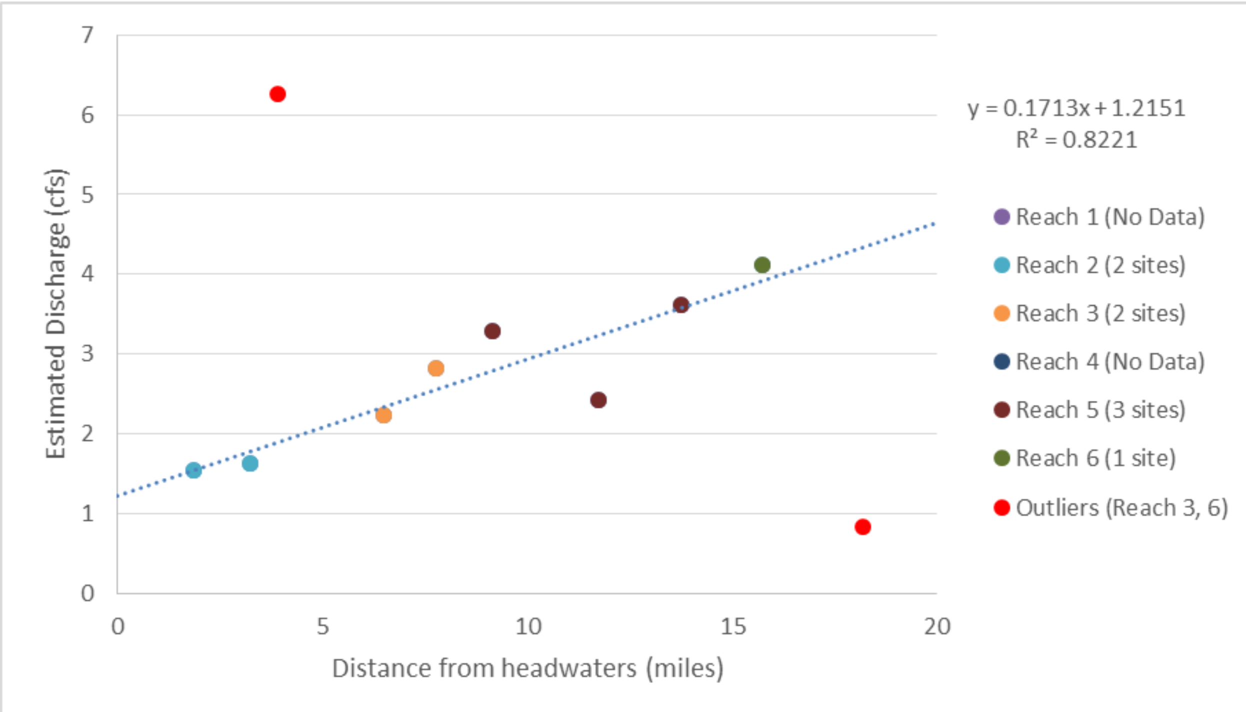

Figure 14. Crooked Creek stream discharge estimates

Although there are no flow gages located along Crooked Creek, flow gages in the adjacent Goose Creek watershed during the summer 2016 sampling period revealed that reasonably similar low-flow conditions were present during all three sampling trips. Streamflow conditions at USGS gages 0212467451 (Goose Creek at SR1524 near Indian Trail) and 0212467595 (Goose Creek at SR1525 near Indian Trail) were reported to be similarly low during all summer sampling trips in Crooked Creek (Table 7). Based on the limited flow data in-hand and the low-flow conditions in the adjacent Goose Creek, it is assumed that flow conditions were reasonably similar across all three sampling trips to use the same flow boundary conditions during calibration and validation model periods.

Table 7. USGS flow conditions in adjacent Goose Creek watershed (flows in cfs)

USGS gage	Minimum Flow, 2016	Maximum Flow, 2016	Average Flow, 2016	Flow on 8/16/2016	Flow on 8/31/2016	Flow on 8/14/2016
0212467451	0.38	98.44	4.46	0.61	0.38	0.48
0212467595	0.62	158.78	7.01	0.94	0.78	0.79

It is possible to use the relationship between discharge and distance from the headwaters to approximate flows at the headwaters. As seen in Figure 14 and using the linear regression, the best estimate of headwater flow conditions during the entire summer sampling period of 2016 is 1.215 cfs (0.034 cms).

3.7.1.2 Headwater Water Quality

Water quality conditions at the headwaters to be assumed for model calibration and validation periods were developed from the sampling sites located upstream of the Hemby Acres WWTP. Water temperature and DO were observed by Carolina Water Services Inc. upstream of the WWTP on a weekly basis. For the calibration period, the average of conditions from the weeks of the associated trips 1 and 2 were used to generate average headwater conditions for water temperature and DO, while grab sample site #1 results were averaged for trip 1 and trip 2 for all other applicable constituents. For the validation period, average conditions used during field trip 3 as sampled upstream of Hemby Acres WWTP were used in tandem with grab sampling at site #1. Headwater water quality inputs for model initialization for the calibration period and validation period are detailed in Table 8 and Table 9 respectively. Headwater boundary conditions specified for the calibration and validation periods are not subject to change although they vary between the two periods based on instream data. Within the model, the downstream extent was not a prescribed boundary.

For the simulation of $CBOD_{ultimate}$ at the headwaters, the entire pool was estimated to be slow CBOD because upstream of this point does not include any effluent sources. Modeled slow CBOD is approximated as a function of observed $CBOD_5$ at WQ Grab Site #1 and the slow decay rate detailed in Section 3.6 of 0.05 /d. Measurements of $CBOD_5$ at Site #1 on field trips 1, 2, and 3 were all non-detects (detection limit of 2 mg/l), therefore estimates of instream $CBOD_5$ were set to half the detection limit for the calculation of ultimate slow CBOD to use for model input for both calibration and validation:

$$CBOD_{ultimate} = \frac{CBOD_5}{1 - e^{(-k_1 \times 5)}}$$

$$\therefore \quad slow\ CBOD\ at\ headwaters = \frac{1\frac{mg}{l}}{1 - e^{(-0.05/d) \times 5)}} = 4.52\frac{mg}{l}$$

Table 8. Headwater water quality initial model inputs (calibration model)

Parameter	Model Input	Data Source
Water Temperature (°F)	74.8	Average of upstream of Hemby WWTP samples on 8/18/16 (76.3 °F) and 8/30/16 (73.4 °F)
Conductivity (µmhos)	252	Unknown at headwaters, set to average result of all downstream sondes from Trip 2 (no data from Trip 1)
Inorganic Solids (mg/L)	0	Unknown at headwaters, assume zero
Dissolved Oxygen (mg/L)	4.38	Average of upstream of Hemby WWTP samples on 8/18/16 (4.43 mg/l) and 8/30/16 (4.32 mg/l)
Slow CBOD (mg/L)	4.52	Refractory pool of CBOD calculated based on instream $CBOD_5$ measurements from WQ Grab Site #1 on Trips 1 and 2
Fast CBOD (mg/L)	0	
Organic Nitrogen (µg/L)	508	Calculated as the difference between Trip 1 and Trip 2 observed TKN and NH_3 for WQ Grab Site #1; non-detects set to half of the detection limit.
NH_4-Nitrogen (µg/L)	25	Ammonia was not detected in the headwaters from WQ Grab Site #1 from Trips 1 and 2, therefore the headwaters were set to half of the detection limit.
NO_3-Nitrogen (µg/L)	280	Average of observed NOX at WQ Grab Site #1, Trips 1 and 2.
Inorganic Phosphorus (µg/L)	95	Observed PO_4 from WQ Grab Site #1 was used from Trip 2. The observation from Trip 1 was not used as it was flagged for quality control exceedances.
Organic Phosphorus (µg/L)	16	Difference between Trip 1 and Trip 2 observed TP and PO4 for WQ Grab Site #1, excluding flagged PO_4 sample.
Alkalinity (mg/L)	100	Unknown at headwaters, use model default
Phytoplankton (mg/L)	0	Unknown at headwaters, assume zero
pH	7	Unknown at headwaters, use model default

Table 9. Headwater water quality initial model inputs (validation model)

Parameter	Model Input	Data Source
Water Temperature (°F)	71.8	Observed upstream of Hemby WWTP samples on 9/12/16
Conductivity (µmhos)	311	Unknown at headwaters, set to average result of all downstream sondes from Trip 3
Inorganic Solids (mg/L)	0	Unknown at headwaters, assume zero
Dissolved Oxygen (mg/L)	3.63	Observed upstream of Hemby WWTP samples on 9/12/16
Slow CBOD (mg/L)	4.52	Refractory pool of CBOD calculated based on instream $CBOD_5$ measurements from WQ Grab Site #1 on Trip 3
Fast CBOD (mg/L)	0	
Organic Nitrogen (µg/L)	680	Calculated as the difference between Trip 3 observed TKN and NH_3 for WQ Grab Site #1; non-detects set to half of the detection limit.
NH_4-Nitrogen (µg/L)	50	Ammonia was not detected in the headwaters from WQ Grab Site #1 from Trip 3, therefore the headwaters were set to half of the detection limit.
NO_3-Nitrogen (µg/L)	77	Observed NOX at WQ Grab Site #1 from Trip 3
Inorganic Phosphorus (µg/L)	51	Observed PO4 from WQ Grab Site #1 from Trip 3
Organic Phosphorus (µg/L)	69	Difference between Trip 3 observed TP and PO_4 for WQ Grab Site #1
Alkalinity (mg/L)	100	Unknown at headwaters, use model default
Phytoplankton (mg/L)	0	Unknown at headwaters, assume zero
pH	7	Unknown at headwaters, use model default

3.7.2 Point Source Flows and Water Quality

The three permitted wastewater treatment plant effluent dischargers along Crooked Creek were modeled explicitly: Hemby Acres WWTP which is operated by Carolina Water Services Inc., and Crooked Creek #2 WWTP and Grassy Branch WWTP which are both operated by Union County.

For the most part, point source model inputs for flow and water quality were based on average conditions for August (calibration model) and average conditions for September (validation model) based on Discharge Monitoring Report (DMR) data. For parameters not available through DMR monitoring, concentrations were estimated based on grab samples from the discharge pipe outfalls from trips 1, 2, and 3 (Table 10, Table 11). DMR reports show that discharge flows and water quality did not vary widely across August and September.

As detailed in Section 3.6, effluent fast CBOD pools estimated based on DMR BOD_5 sampling and a ratio of 2:1 for BOD_5:$CBOD_{ultimate}$. When DMR-reported concentrations for any given parameter were listed as below detection limit, the concentration was assumed to be half of the detection limit for the purposes of calculating average effluent concentrations.

Table 10. Point source flow and water quality inputs (calibration period)

Parameter	Hemby Acres WWTP	Crooked Creek #2 WWTP[1]	Grassy Branch WWTP
Discharge Information			
NPDES Permit ID	NC0035041	NC0069841	NC0085812
Permit Class	Minor	Major	Minor
NPDES Permitted Flow (MGD)	0.3	1.9	0.05
Model Inputs based on DMR data (August 2016 Averages)			
Location (km), distance from outlet	32.48	27.81	10.82
Inflow (m^3/s), [MGD]	0.0039 [0.09]	0.0364 [0.83]	0.0018 [0.04]
Water Temperature (°F)	78.1	79.9	78.3
Dissolved Oxygen (mg/L)	6.5	7.6	7.7
Slow CBOD (mg/L)	0	0	0
Fast CBOD[2] (mg/L)	8.36	2.38	3.60
Inorganic Suspended Solids (mg/L)	1.25	1.56	2.46
Ammonia Nitrogen (µgN/L)	50	940	640
pH	7.5	7.3	7.3
Model Inputs based on summer grab sampling data (Trips 1 and 2 Averages)			
Corresponding Grab Sample ID	#2	#4	#12
Organic Nitrogen (µgN/L)[3]	565	1,100	825
Nitrate+ Nitrite Nitrogen (µgN/L)	38,000	28,450	39,000
Organic Phosphorus (µgP/L)[4]	800	2,000	1,150
Inorganic Phosphorus (µgP/L)	3,300	2,700	1,850
Specific Conductance (µmhos)[6]	641	628	837
Phytoplankton (ug/L)	No Data, assume 0		
Alkalinity (mg/L)	86.0[5]	73.4	98.6

[1]Measurements were observed at the entrance of the pipe. DO measurements at the end of the pipe suggest that water quality does not change significantly through the pipe.

[2]Measured and reported BOD_5 was converted to fast $CBOD_{ultimate}$ as described in the text with 1:2 ratio.

[3]Organic nitrogen was not measured directly, but calculated as the difference between measured TKN and NH_3

[4]Organic phosphorus was not measured directly, but calculated as the difference between measured TP and PO_4

[5]Alkalinity was not measured at Hemby Acres, so it was approximated as the average the other two dischargers

[6]Conductance measured from Trip 3 (used for calibration and validation models)

Table 11. Point source flow and water quality inputs (validation period)

Parameter	Hemby Acres WWTP	Crooked Creek #2 WWTP[1]	Grassy Branch WWTP
Model Inputs based on DMR Data (September 2016 Averages)			
Location (km), distance from outlet	32.48	27.81	10.82
Inflow (m^3/s), [MGD]	0.0039 [0.09]	0.0381 [0.87]	0.0018 [0.04]
Water Temperature (°F)	75.6	75.6	76.3
Dissolved Oxygen (mg/L)	6.8	8.0	7.6
Slow CBOD (mg/L)	0	0	0
Fast CBOD[2] (mg/L)	11.80	4.08	2.00
Inorganic Suspended Solids (mg/L)	1.25	4.71	1.27
Ammonia Nitrogen (µgN/L)	50.00	57.06	255.56
pH	7.3	7.1	7.1
Model Inputs based on summer grab sampling data (Trip 3)			
Corresponding Grab Sample ID	#2	#4	#12
Organic Nitrogen (µgN/L)[3]	1075	1875	100
Nitrate+ Nitrite Nitrogen (µgN/L)	25100	33900	53300
Organic Phosphorus (µgP/L)[4]	1600	1300	200
Inorganic Phosphorus (µgP/L)	4000	4800	4500
Specific Conductance (µmhos)	641	628	837
Phytoplankton (ug/L)	No Data, assume 0		
Alkalinity (mg/L)	64.6[5]	37.7	91.4

[1]Measurements were observed at the entrance of the pipe. DO measurements at the end of the pipe suggest that water quality does not change significantly through the pipe.

[2]Measured and reported BOD_5 was converted to fast $CBOD_{ultimate}$ as described in the text with 1:2 ratio.

[3]Organic nitrogen was not measured directly, but calculated as the difference between measured TKN and NH_3

[4]Organic phosphorus was not measured directly, but calculated as the difference between measured TP and PO_4

[5]Alkalinity was not measured at Hemby Acres, so it was approximated as the average the other two dischargers

3.7.3 Tributary Flows and Water Quality

Model inputs for flow and water quality for the South Fork Crooked Creek and Grassy Branch tributaries contributing to the Crooked Creek mainstem were developed based on a combination of observed data, water balance calculations, and best professional judgement. Streamflow was estimated at several points along Crooked Creek based on cross-section surveys paired with velocity measurements. By combining the observed streamflow information with the reported point source discharge data, the relative contributions of each modeled tributary can be estimated using a water balance assuming no other losses due to evaporation and groundwater seepage. For tributary inflows, CBOD is modeled as slow $CBOD_{ultimate}$ and estimated the same way as the headwaters.

Table 12. Tributary flow and water quality inputs (calibration model)

Parameter	SFCC	Grassy Branch	Data Source Information
Inflow, ft^3/s (m^3/s)	1.06 (0.03)	0.32 (0.009)	Estimated by water balance as the difference between instream flow estimates which are not accounted for by point source flows.
Water Temperature, (°F)	81.86	74.48	Water temperature is based on probe sampling conducted on Trip 1 for SFCC and Grassy Branch. Note that Grassy Branch is cooler because it is largely groundwater-fed.
Conductivity (µmhos)	252	252	No available data, assumed same as headwaters
ISS (mg/L)	0	0	No available data, assumed zero
Dissolved Oxygen (mg/L)	2.47	2.67	DO estimates are based on probe sampling conducted on Trip 1 for SFCC and Grassy Branch.
Alkalinity (mg/l)	100	100	No available data, assume model default
Phytoplankton (ug/l)	0	0	No available data, assumed zero
pH	7.35	6.23	pH estimates are based on probe sampling conducted on Trip 1 for SFCC and Grassy Branch.
Slow CBOD (mg/L)	4.52	23.73	Average measured $CBOD_5$ from Trips 1 and 2 was used to approximate slow CBOD as described in the text. Observed $CBOD_5$ along Grassy Branch was noticeably high.
Fast CBOD (mg/L)	0	0	
Ammonia N (µgN/L)	478	25	NH_3 and NOX data are averages of observed data from Trips 1 and 2 at WQ Site #9 (SFCC) and WQ Site #13 (Grassy Branch). Organic N was calculated as the difference between observed TKN and NH_3 data.
Organic N (µgN/L)	1,073	435	
Nitrate+Nitrite N (µgN/L)	2,865	1,600	
Organic P (µgP/L)	380	98	Organic P was calculated as the difference between observed TP and PO_4 during Trips 1 and 2 for SFCC (WQ Site #9). Model inputs for Grassy Branch are from Trip 3 only because of a lab issue with P-species data from Trips 1 and 2 (WQ Site #13).
Inorganic P (µgP/L)	245	72	

Table 13. Tributary flow and water quality inputs (validation model)

Parameter	SFCC	Grassy Branch	Data Source Information
Inflow, ft^3/s (m^3/s)	1.06 (0.03)	0.32 (0.009)	Estimated to be the same as during the calibration period.
Water Temperature (°F)	71.6	76.8	Water temperature is based on probe sampling conducted on Trip 3 for SFCC and Grassy Branch.
Conductivity (µmhos)	102	263	Estimates are based on probe sampling conducted on Trip 3 for SFCC and Grassy Branch.
ISS (mg/L)	0	0	No available data, assumed zero
Dissolved Oxygen (mg/L)	2.47	2.67	DO estimates are based on probe sampling conducted on Trip 1 for SFCC and Grassy Branch.
Alkalinity (mg/l)	100	100	No available data, assume model default
Phytoplankton (ug/l)	0	0	No available data, assumed zero
pH	5.95	7.51	pH estimates are based on probe sampling conducted on Trip 3 for SFCC and Grassy Branch.
Slow CBOD (mg/L)	9.49	4.52	Measured $CBOD_5$ from Trip 3 was used to approximate slow CBOD as described in the text.
Fast CBOD (mg/L)	0	0	
Ammonia N (µgN/L)	110	25	NH_3 and NOX data are observed data from Trip 3 at WQ Site #9 (SFCC) and WQ Site #13 (Grassy Branch). Organic N was calculated as the difference between observed TKN and NH_3 data.
Organic N (µgN/L)	630	705	
Nitrate+Nitrite N (µgN/L)	5	610	
Organic P (µgP/L)	98	98	Organic P was calculated as the difference between observed TP and PO_4 from Trip 3.
Inorganic P (µgP/L)	92	72	

3.8 REACH WATER QUALITY PARAMETERS

Modeled water quality parameters that can vary by reach include sediment oxygen demand (SOD) rates; prescribed nutrient flux rates from sediment; channel reaeration rates; nutrient hydrolysis and settling rates; phytoplankton growth, respiration, and death rates; and bottom algae coverage, growth, respiration, and death rates. If not otherwise specified for a given reach, water quality parameterization was tabulated using default values and suggested ranges of model inputs.

Model inputs related to reaeration, SOD, bottom algae, and phytoplankton can have large influence on average DO and the diurnal range of DO. The DO sondes were used to identify the diurnal variation in DO observed at specific points along Crooked Creek. DO sondes were used to identify the relative impact of bottom algae (surrogate for macrophyte growth) along Crooked Creek based on observed diel DO variation. During the first field sampling trip, DO sondes were placed upstream and downstream of the Crooked Creek #2 discharge and near the crossing of Highway 601. During the second trip, DO sondes were placed at the Highway 601 crossing, at the Brief Road crossing, and at the State Road 1601 crossing. All six sondes experienced a diurnal DO variation between 1.18 and 2.53 mg/l. Diurnal DO fluctuations are due to photosynthetic processes of biota which are light and temperature dependent. The relatively low diurnal fluctuations in DO observed along Crooked Creek suggest that algae play a relatively minor role in the system. Bed coverage of algae was initialized for the calibration model as 50% for all reaches, and 75% for all reaches during the validation period based on generalized field observations.

Average instream DO concentrations are sensitive to SOD, which is the consumption of DO at the soil-water interface. SOD is simulated in QUAL2K as both a rate of oxygen consumption as well as a percent coverage of the channel bottom. SOD was not measured along Crooked Creek, so the model was initialized based on the observed range measured in another North Carolina Piedmont-area stream: Rich Fork Creek near High Point (Tetra Tech, 2009b). SOD estimates associated with Rich Fork Creek were also used in the modeling effort associated with Twelve Mile Creek in Union County (Tetra Tech, 2009c). SOD was measured with in situ chambers at a number of locations along Rich Fork Creek, both upstream and downstream of an existing WWTP. The observed range of SOD along Rich Fork Creek was 0.067 – 0.213 g/ft^2/d (0.721 – 2.293 g/m^2/d), with the lowest values generally being recorded upstream of the WWTP discharge. The Crooked Creek model was initialized with instream SOD coverage set to 100% at a rate of 0.067 g/ft^2/d (0.721 g/m^2/d) for all reaches. This SOD rate was adjusted during calibration adjust simulated DO concentrations to mimic longitudinal profiles. Note that the North Carolina Division of Water Quality has measured SOD across the state periodically and the observed range for the Upper Cape Fear River watershed was approximately 0.4 – 2.5 g/m^2/d, which provided a constraining range during model calibration.

Channel reaeration is the natural input of oxygen to a waterbody through the transfer of atmospheric oxygen into the water column at the air-water interface. Rates of reaeration are typically higher for shallow, fast moving streams, and lower for slow, deep streams. Although reaeration was not measured directly in Crooked Creek, anecdotal evidence and observed reaeration from the Rich Fork Creek project was used to confine and inform the Crooked Creek model setup. Rich Fork Creek had observed reaeration rates of 0.32/d in low-velocity pooled areas of the stream, and 1.85 /d in free-flowing sections of the stream with observed flows on the order of 27 cfs. The Tsivoglou-Neal reaeration formula was identified as likely appropriate for Crooked Creek as it computes reaeration based on mean water velocity and channel slope, and is appropriate for low flow streams where flow ranges 1 – 15 cfs, and the average field-estimated flow along Crooked Creek is about 2.5 cfs (Tsivoglou and Neal, 1976).

For model setup, initial assumptions for reach parameters related to nutrient processing, settling rates, and decay were held at model default values and were adjusted during calibration as-needed.

4.0 MODEL CALIBRATION AND VALIDATION

Model calibration involves comparing how well model simulations match observed data. Model calibration is designed to ensure that the model is adequately and appropriately representing the system in order to answer the study questions. The model must be able to provide credible representations of the movement of water, and the DO and BOD interactions within the stream representing steady state conditions. Validation is applied using a different time period to confirm that model calibration is robust, provide additional evaluation of model performance, and to guard against over-fitting to the calibration data.

The QUAL2K model for Crooked Creek will be calibrated to an average of data collected during the first two sampling trips in August 2016. The validation period for the model will be focused on the middle of September during the third and final summer sampling trip. Physical properties related to stream flow and atmospheric inputs may be subject to change during the model validation period. The model will be set up for these conditions using available data and calibrated to reproduce observed DO.

4.1 HYDROLOGY CALIBRATION

Reach hydraulics were calibrated in order to approximate observed and estimated conditions of flow, depth, and velocity along Crooked Creek during the summer sampling trips. Manning’s n was the key calibration parameter that was adjusted to capture site-estimated flow dynamics since the measured cross-sections were considered reasonable enough to approximate channel shapes. The calibrated reach hydraulic inputs were to alter Manning’s n to 0.3 for all reaches except Reach 4 (sluggish, pooled beaver dam reach) which had a roughness coefficient of 0.6.

Travel time for the full extent of Crooked Creek was estimated by the model to be just over six days, and model results of flow along the mainstem compared to observations may be seen in Figure 15. Along the entire reach, simulated stream velocity ranged from 0.07 – 0.16 ft/s (0.02 – 0.05 m/s) (observed range was 0.13 – 0.39 ft/s [0.04 – 0.12 m/s]), and simulated water depth ranged from 0.89 – 2.13 ft (0.27 – 0.65 m) (observed range was 0.49 – 2.10 ft [0.15 – 0.64 m]). Upstream and downstream streamflow along Crooked Creek were simulated to be 1.06 and 4.24 cfs (0.03 and 0.12 cms) respectively.

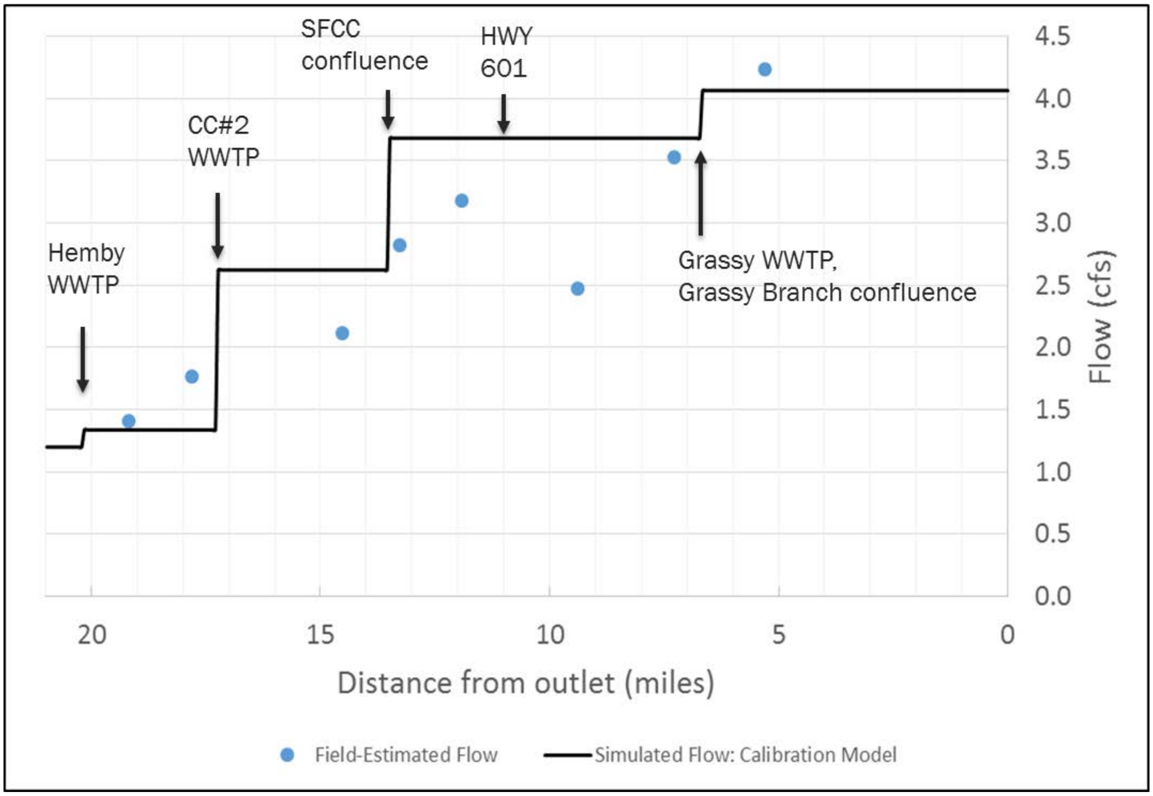

Figure 15. Simulated and site-estimated flows for Crooked Creek model extent (calibration)

4.2 WATER TEMPERATURE CALIBRATION

In general the parameters which control water temperature are channel geometry, meteorological inputs, stream shading, atmospheric heat models, and sediment heat parameters. Initialized parameterization related to sediment thermal properties, stream shading, and heat models captured the observed water temperature data reasonably well.

The simulated minimum, maximum, and average water temperature are shown in Figure 16 in comparison with observed water temperature from the YPDRBA in August, longitudinal sampling along the entire extent from sampling trips 1 and 2, and the range of temperatures observed at the sonde locations from trips 1 and 2 as well (Figure 16). Moving from upstream to downstream, it is possible to see that the majority of morning sampling (open circles) fall below the mean simulated water temperature line, while the majority of afternoon sampling (closed circles) fall above the mean simulated water temperature line. The spread of observed temperature data is largely captured by the diel range simulated by the model as seen in the dashed lines below. In general the sonde data which represents the observed range of data over several days at a given point (red vertical lines) are skewed low relative to the longitudinal sampling (points) due to the fact that these sondes were submerged along the stream bed which is anticipated to be cooler and more well-insulated to daily fluctuations than the water closer to the surface.

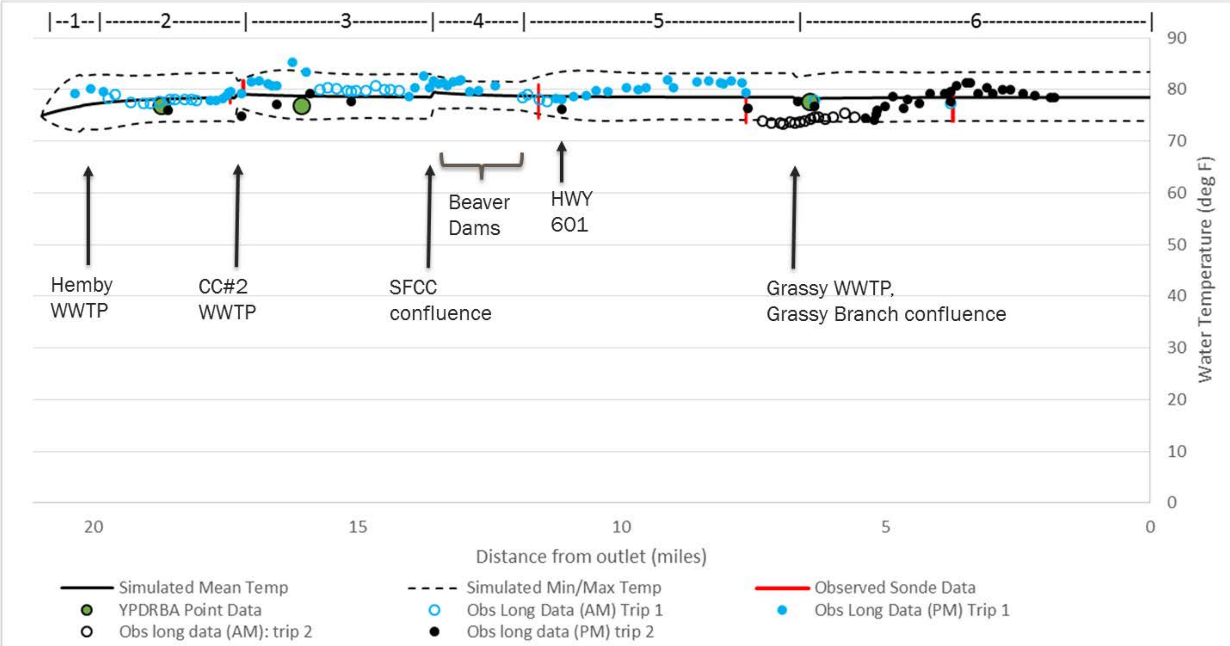

Figure 16. Simulated and observed water temperature along Crooked Creek (calibration)

4.3 WATER QUALITY CALIBRATION

The primary focus of water quality calibration was related to DO concentrations along Crooked Creek. The key parameters which control average DO concentrations were identified to be SOD rate and channel reaeration. The magnitude of daily minimum and maximum DO are controlled by the streambed coverage of bottom algae as an aggregate term for all macrophyte growth exerting photosynthetic processes within the water column. Reaeration rates were simulated using the Tsivoglou-Neal model, and were estimated as 0.4 – 3.3 /d, with an average reaeration rate of 2.3 /d. The lowest reaeration rate occurred in the model along the sluggish beaver-dammed Reach 4.

SOD rates were used as a calibration parameter, constrained by the range of observed SOD in the Upper Cape Fear River basin from NC DWQ of 0.4 – 2.5 g/m^2/d. Calibrated SOD rates ranged from 1.0 – 2.2 g/m^2/d in the calibrated model (Table 14). In order to simulate the observed minimum and maximum DO, the bottom algae coverage was calibrated on the order of 25% to 50% coverage.

Table 14. Reach calibration parameters

Reach	SOD rate (g/m^2/d)	Bottom Algae Coverage
1	1.0	25%
2	2.2	50%
3	2.2	50%
4	2.2	50%
5	2.2	50%
6	2.2	50%

The simulated minimum, maximum, and average DO are shown in Figure 17 in comparison with observed DO from the YPDRBA in August, longitudinal sampling along the entire extent from sampling trips 1 and 2, and the range of DO observed at the sonde locations from trips 1 and 2 as well. Annotations on the plot below reveal key features along the mainstem such as point source and tributary inflows which may have significant impacts on in-stream DO concentration. From upstream to downstream, it is possible to the see the increase in DO due to the Hemby WWTP discharge, then a decline in DO downstream due to the BOD decay from the effluent. The DO spike at the end of Reach 2 is due to the CC#2 outfall, and the DO decline downstream is smaller downstream relative to downstream of Hemby because of the difference in BOD loading to the stream. The SFCC tributary has low DO, and the DO along the sluggish and dammed Reach 4 causes a precipitous drop in oxygen along that reach. The recovery in DO downstream of the beaver dams and Highway 601 is due to the combined impacts of higher slopes, less in-stream BOD, and the impact of the Grassy Branch WWTP is relatively small as Crooked Creek flows down to Rocky River. The range of daily DO concentrations observed along Crooked Creek is captured reasonably well by the calibration model, with DO at the downstream end estimated to be about 6 mg/l at the Rocky River confluence.

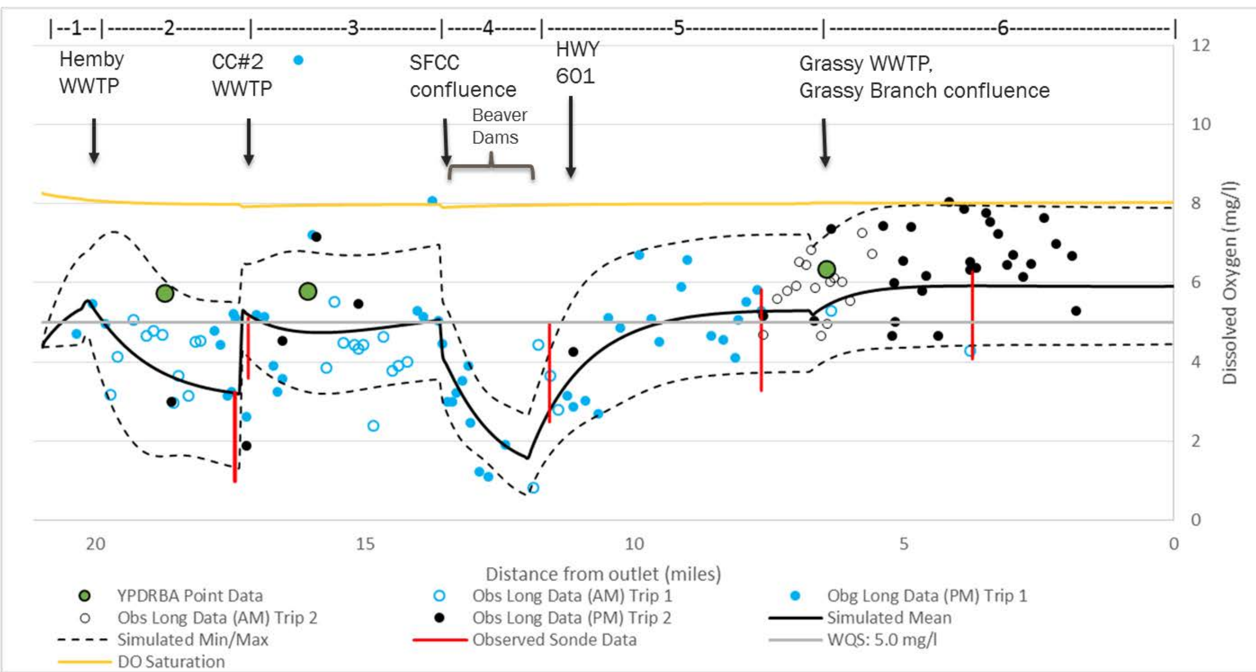

Figure 17. Simulated and observed DO along Crooked Creek (calibration)

4.4 MODEL VALIDATION RESULTS

Model validation is conducted in order to verify the simulation and parameterization achieved during model calibration reasonably approximates stream conditions during different stream conditions. Although overall stream hydrology is held constant between the calibration and validation periods, significant model changes were made for the validation regarding the following parameters: model run date, meteorological inputs (air temperature, dew point temperature, and cloud coverage), tributary and headwater chemistry, and point source flow and water chemistry. All other model parameters related to channel geometry, flows, shading, SOD, and reaeration were held constant for the validation model run.

4.4.1 Water Temperature Validation

In general, the water temperature was reasonably well simulated during the model validation period. The downstream water temperature from near the end of Reach 5 and into Reach 6 was observed much warmer than the model predicted, but the water temperatures are reasonably well approximated for Reaches 1 through most of Reach 5.

The simulated minimum, maximum, and average water temperature are shown in Figure 18 in comparison with observed water temperature from the YPDRBA in September, longitudinal sampling along the entire extent from sampling trip 3, and the range of temperatures observed at the sonde locations from trips 3 as well.

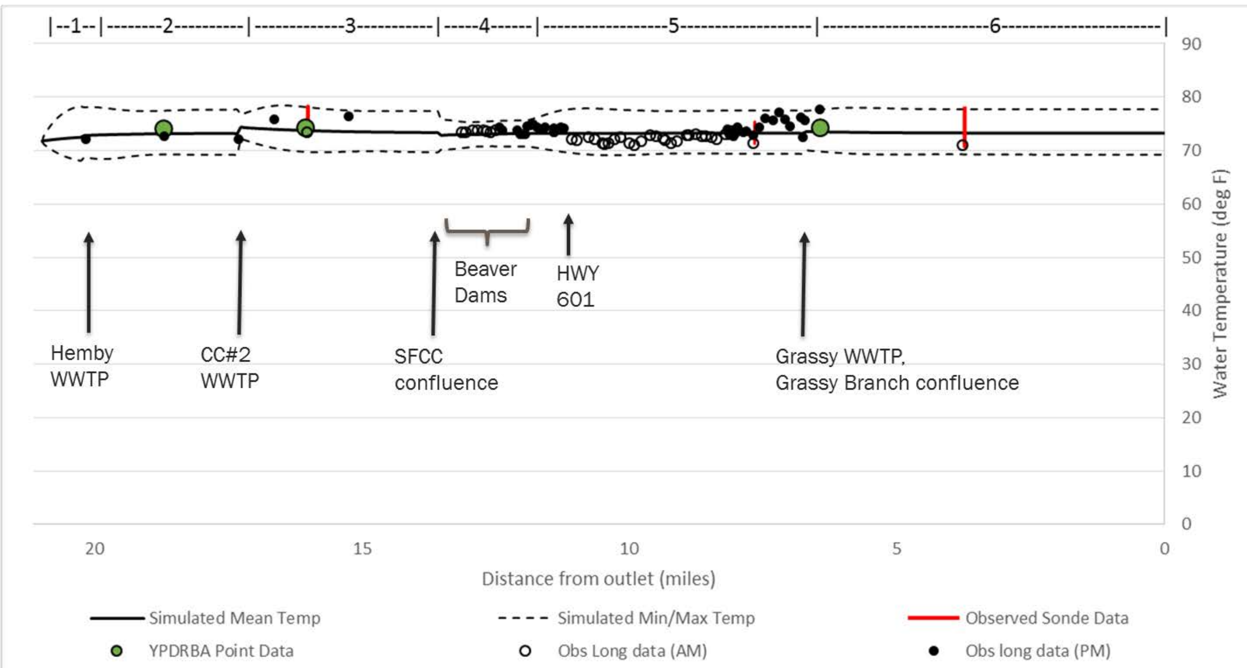

Figure 18. Simulated and observed water temperature along Crooked Creek (validation)

4.4.2 Water Quality Validation

The validation model for Crooked Creek reasonably approximates the observed DO along the model extent. Bottom algae coverage was increased for the validation run based on field observations and observed DO fluctuations along the stream. In the validation model bottom algae coverage was increased by 25% for all reaches with the exception of Reach 5 which was set to 95% algae coverage due to the very high fluctuation of diel DO along that reach resulting in observed DO greater than saturation. Average DO is reasonably approximated in the validation model relative to observations.

The simulated minimum, maximum, and average DO are shown in Figure 19 in comparison with observed DO from the YPDRBA in September, longitudinal sampling along the entire extent from sampling trip 3, and the range of DO observed at the sonde locations from trip 3 as well.

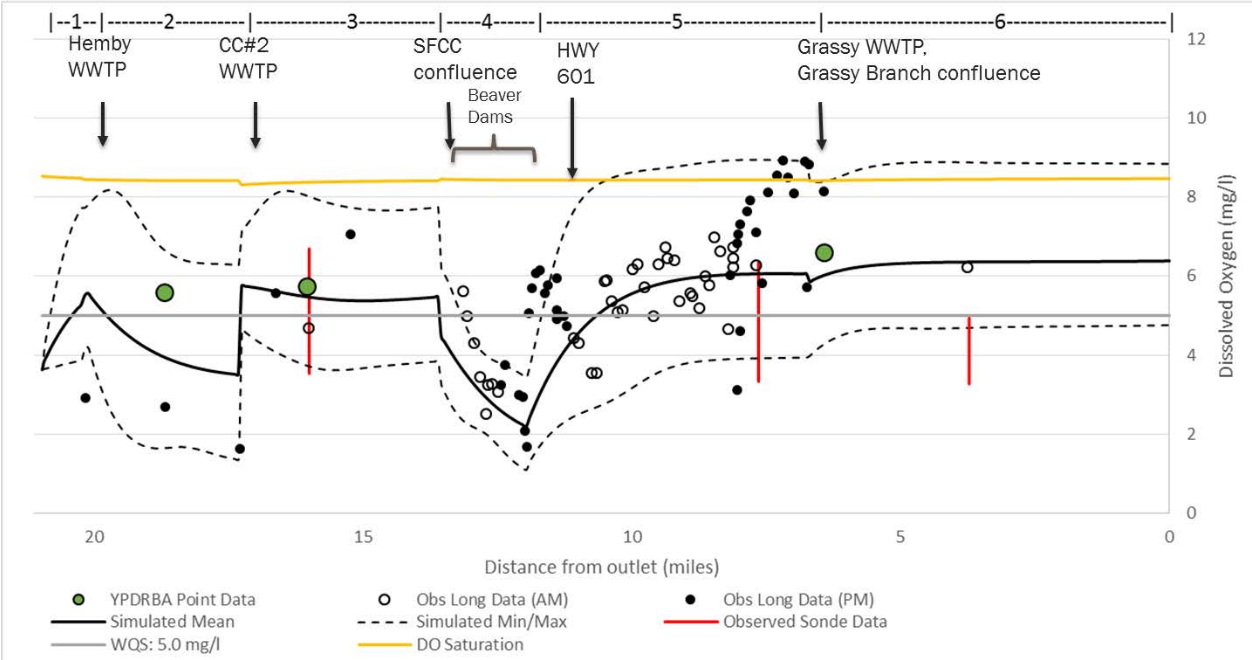

Figure 19. Simulated and observed DO along Crooked Creek (validation)

5.0 MODEL SENSITIVITY AND APPLICATION

5.1 MODEL SENSITIVITY

A series of sensitivity analyses were conducted in order to provide an increased understanding of uncertainty associated with key model parameters. The relative impact of several model parameters were gauged in order to test the model sensitivity to changes in: bottom algae coverage, SOD rate, Manning's n, percent shade, headwater flow rate, and the selected reaeration model (Table 15). Each parameter was tweaked by +25% and -25% with the exception of the reaeration model, for which other formulas were selected in each successive run.

Table 15. Crooked Creek QUAL2K model sensitivity test runs

Model Run	Details
Calibration	Representative summer conditions for setting up sensitivity analyses
Sensitivity 1	Bottom Algae +/- 25%
Sensitivity 2	SOD Rate +/- 25%
Sensitivity 3	Manning's n +/- 25%
Sensitivity 4	Shade +/- 25%
Sensitivity 5	Headwater Flow +/- 25%
Sensitivity 6	Reaeration Models: O'Connor-Dobbins, Churchill, Owens-Gibbs, Thackston-Dawson

The results from the six sensitivity tests reveal the relative impact each of the tested parameters has on the simulated mean dissolved oxygen concentrations along the extent of the Crooked Creek QUAL2K model. Sensitivity tests 1 and 2 involve a 25% change in bottom algae coverage and SOD rate respectively. These scenarios reveal that the model is more sensitive to SOD rate than bottom algae coverage by impacting mean DO on the order of 16% and 5% respectively (Figure 20). Sensitivity tests 3, 4, and 5 involve a 25% change in Manning's n, shade, and headwater flow respectively. These scenarios reveal the impact to mean DO to be relatively small, on the order of 4-5% for these three tests (Figure 21). Sensitivity test 6 involved testing model sensitivity to reaeration model selection (Figure 22). Of the four reaeration models selected, the impact on mean DO was as follows, from greatest to least: Owens-Gibbs (35%), O'Connor-Dobbins (31%), Churchill (19%), and Thackston-Dawson (11%). Both Owens-Gibbs and O'Connor-Dobbins reaeration models predicted a positive impact on mean DO, while Churchill and Thackston-Dawson reaeration models predicted a negative impact on mean DO relative to the calibration model which used the reaeration model of Tsivoglou-Neal. In general, both Churchill and O'Connor-Dobbins models are only appropriate for streams with depths greater than 1.6 feet (0.5 meters) which is greater than the observed depths in Crooked Creek. The Owens-Gibbs formula overestimates reaeration significantly (similar to O'Connor-Dobbins), likely because Owens-Gibbs assumes high reaeration with low depth, even when velocities are small, but as seen visually along Crooked Creek, low velocities can lead to pooling and stagnation with limited reaeration occurring. The Thackston-Dawson formula responds similarly to the selected model of Tsivoglou-Neal, however it consistently underpredicts instream DO by about 0.5 mg/l. The Tsivoglou-Neal formula remains the best fit to the observed data during both the calibration and validation periods (Thackston and Dawson, 2001). The overall results are summarized in Table 16.

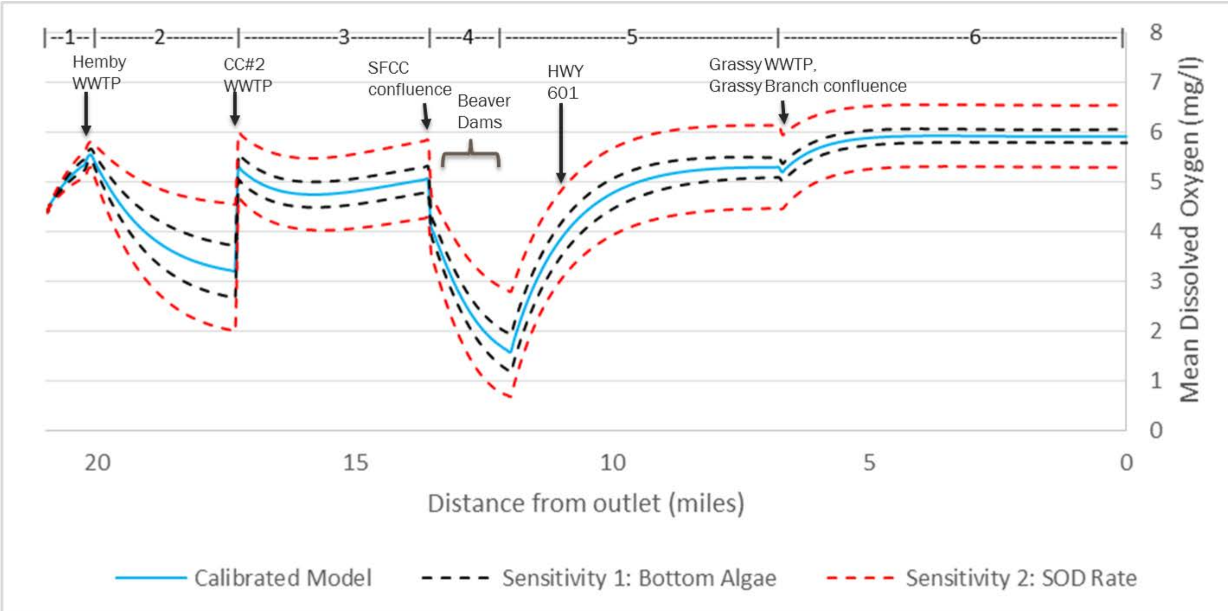

Figure 20. Sensitivity test results (runs 1 and 2)

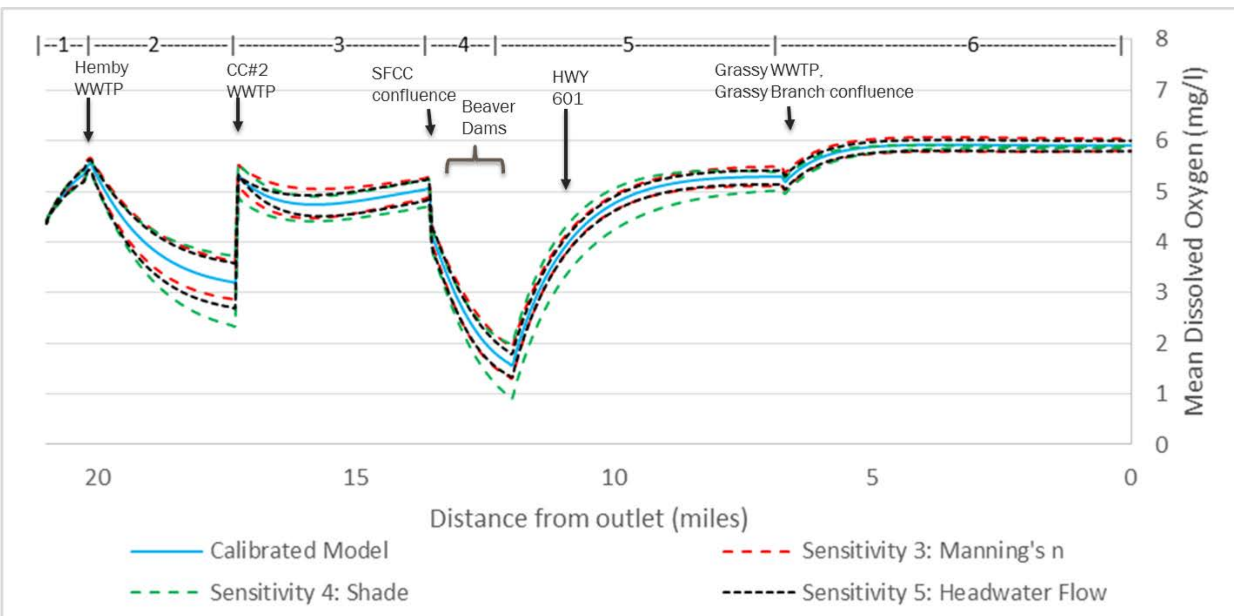

Figure 21. Sensitivity test results (runs 3, 4, and 5)

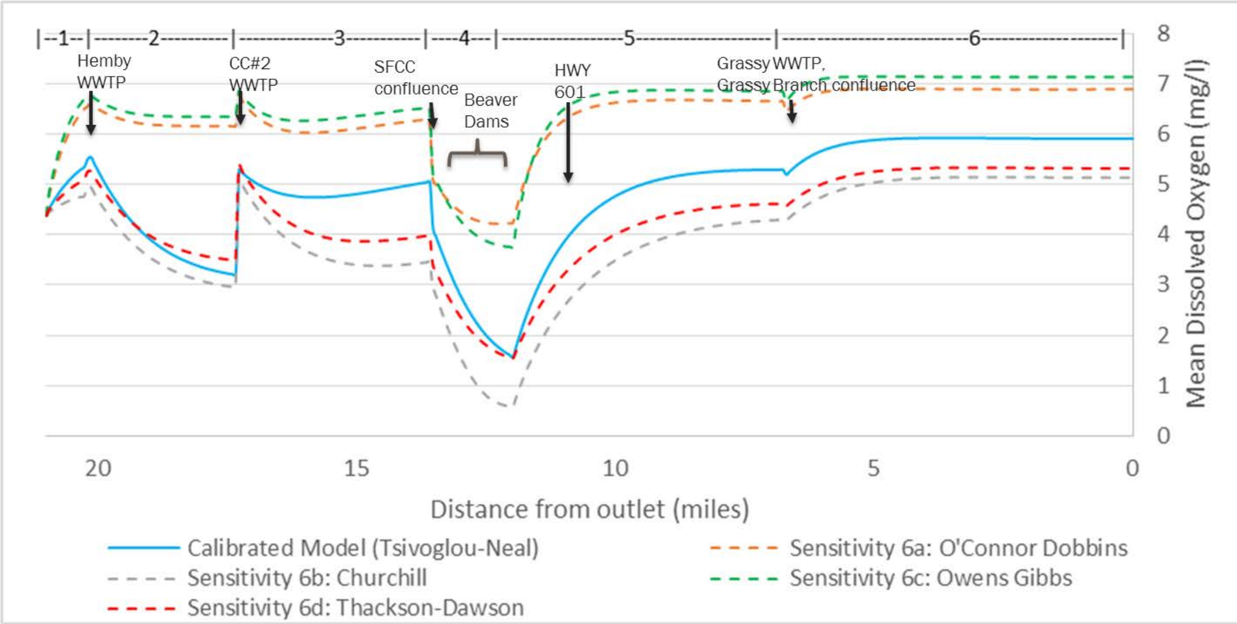

Figure 22. Sensitivity test results (run 6)

Table 16. Crooked Creek QUAL2K model sensitivity test run results

Model Run	Details	Average Absolute Difference in Mean DO (mg/l)	Average Absolute Relative Percent Difference on Mean DO
Calibration	Baseline	N/A	N/A
Sensitivity 1	Bottom Algae +/- 25%	0.2	5%
Sensitivity 2	SOD Rate +/- 25%	0.8	16%
Sensitivity 3	Manning's n +/- 25%	0.2	4%
Sensitivity 4	Shade +/- 25%	0.2	5%
Sensitivity 5	Headwater Flow +/- 25%	0.2	4%
Sensitivity 6	Reaeration Model Variations	1.1	24%

The selection of the reaeration formula can result in the largest single absolute error, however there is reasonably good knowledge that the selected model of Tsivoglou-Neal is the most appropriate choice. The next parameter which the model is quite sensitive to is SOD, which had an average absolute relative percent difference on mean DO of 16%. Since neither reaeration nor SOD were measured directly along Crooked Creek, the interaction between those two parameters are likely the greatest source of uncertainty within the model environment, although estimates for both were established based on reasonable approximations.

5.2 MODEL APPLICATION

A number of modeling scenarios were developed to simulate Crooked Creek under low flow conditions, and the impact of a proposed new WWTP outfall to be located in the vicinity of Highway 601. The new outfall, referred to hereafter as the Main Stem Crooked Creek Wastewater Reclamation Facility (MSCC WRF), was simulated in the model near the upstream end of model Reach 5, 11.1 miles (17.8 km) from the Crooked Creek outlet. The effluent limitations and permit maximums associated with MSCC WRF were assumed to be those achievable through advanced secondary treatment, as BOD_5:NH_3 at 3:1 (mg/l). Dissolved oxygen concentration of the MSCC WRF outfall were assumed as either 6.0 or 7.0 mg/l as indicated in the summaries below. The list of scenarios is presented in Table 17. **Crooked Creek QUAL2K model scenarios and downstream DO sag resultsError! Reference source not found.**.

Table 17. Crooked Creek QUAL2K model scenarios and downstream DO sag results

Scenario	Details	Trial	DO sag location downstream of MSCC WTF (miles)	DO sag downstream of MSCC WTF (mg/l)
Calibration	Representative summer conditions for setting up scenarios	N/A	N/A	N/A
1	Critical low flow, permitted outfalls at calibration levels	N/A	N/A	N/A
2	Critical low flow, permitted outfalls at maximum permitted allowances	N/A	N/A	N/A
3	Critical low flow, all WWTP outfalls removed	N/A	N/A	N/A
4	Critical low flow, MSCC WRF at 4.6 MGD, CC#2 removed	A: DO 6 mg/l	1.5	4.4
		B: DO 7 mg/l	1.8	4.6
5	Critical low flow, MSCC WRF at 4.6 MGD, CC#2 removed, dams removed	A: DO 6 mg/l	1.6	4.5
		B: DO 7 mg/l	1.6	4.6
6	Critical low flow, MSCC WRF at 8.2 MGD, CC#2 removed	A: DO 6 mg/l	1.6	4.9
		B: DO 7 mg/l	1.9	5.0
7	Critical low flow, MSCC WRF at 8.2 MGD, CC#2 removed, dams removed	A: DO 6 mg/l	1.6	4.9
		B: DO 7 mg/l	2.0	5.0

Calibrated model rates, constants and kinetics were applied to f the scenarios under the conditions of an assumed “critical low flow”. As detailed in Section 2.5 and Appendix D, critical low flows for this system were defined as 7Q10 or the lowest seven-day average flow that occurs on average once every ten years, per DEQ procedures for establishing NPDES permit effluent limitations. The 7Q10 flow estimates for Crooked Creek were developed by the USGS.

Scenario 1 was developed to simulate stream conditions that would be present if existing outfalls maintained average discharge flows and water quality during critical low flows. Relative to the calibration model, the predicted DO concentration instream for Scenario 1 (see Figure 23) is lower by as much as 2 mg/L in some reaches. This makes intuitive sense because the influence of the existing outfalls and algae presence is greater when there is less stream baseflow for dilution, and the lower streamflows decrease estimated velocity and reaeration.

Scenario 2 simulates predicted stream conditions with the existing NPDES permitted outfalls set to maximum permitted flow and effluent limitations. The results of Scenario 2 (see Figure 23) are quite similar to Scenario 1, except that predicted DO sags are deeper downstream of outfalls due to the impact of higher effluent pollutant concentrations entering the stream (i.e., existing effluent conditions are lower than permitted conditions). Note that the recovery downstream of the beaver dams mirrors the calibration model setup because the existing flow downstream of that point is similar calibration flows at that point.

Scenario 3 represents a background condition for Crooked Creek for which flows are critically low and there are no outfalls shown. Under these conditions, the model predicts that there would be significant ponding along the stream, increased algae proliferation due to extremely low velocities and standing water, and average daily DO is simulated to bottom out along large stretches of the stream due to the high oxygen demand of decaying algae and in-stream SOD (see Figure 23). Scenarios 1 through 3 illustrate that the presence of the existing effluent outfalls is predicted to provide flow and DO augmentation during critical low flow conditions, subsequently increasing DO concentration profiles below the outfalls compared with no effluent at all.

Scenarios 4 and 5 include the addition of the MSCC WRF outfall at Highway 601 assuming an effluent volume of 4.6 MGD (see Figure 24). Scenarios 4a and 4b include MSCC WRF effluent limits for DO:BOD_5:NH_3 as 6:3:1 and 7:3:1 mg/L respectively. Scenarios 5a and 5b are identical to Scenarios 4a and 4b, although the dams in Reach 4 were removed, for which the model predicts to have relatively little impact downstream of MSCC WRF. Scenarios 4a and 4b reveal predicted DO sags of 4.4 and 4.6 mg/l approximately 1.5 and 1.8 miles downstream of the outfall respectively. When effluent DO is increased, the sag minimum improves slightly, and the length of stream for which DO is below 5 mg/L is predicted to decrease by roughly a quarter mile.

Scenarios 6 and 7 include the MSCC WRF outfall at Highway 601 assuming an effluent flow of 8.2 MGD representative of projected 2050 population growth for the district (see Figure 25). Scenarios 6a and 6b include MSCC WRF effluent limits of DO:BOD_5:NH_3 as 6:3:1 and 7:3:1 mg/L respectively. Scenarios 7a and 7b are identical to Scenarios 6a and 6b, although the dams in Reach 4 were removed, which (as seen in Scenarios 5a and 5b) results in little predicted impact downstream of the proposed MSCC WRF outfall. Scenarios 6a and 6b reveal predicted DO sags of 4.9 and 5.0 mg/l approximately 1.6 and 1.9 miles downstream of the outfall respectively. Thus, when effluent DO is increased from 6 to 7 mg/L, the length of stream where DO is predicted to fall below the daily average standard of 5 mg/L decreases from roughly 1.5 miles to zero miles.

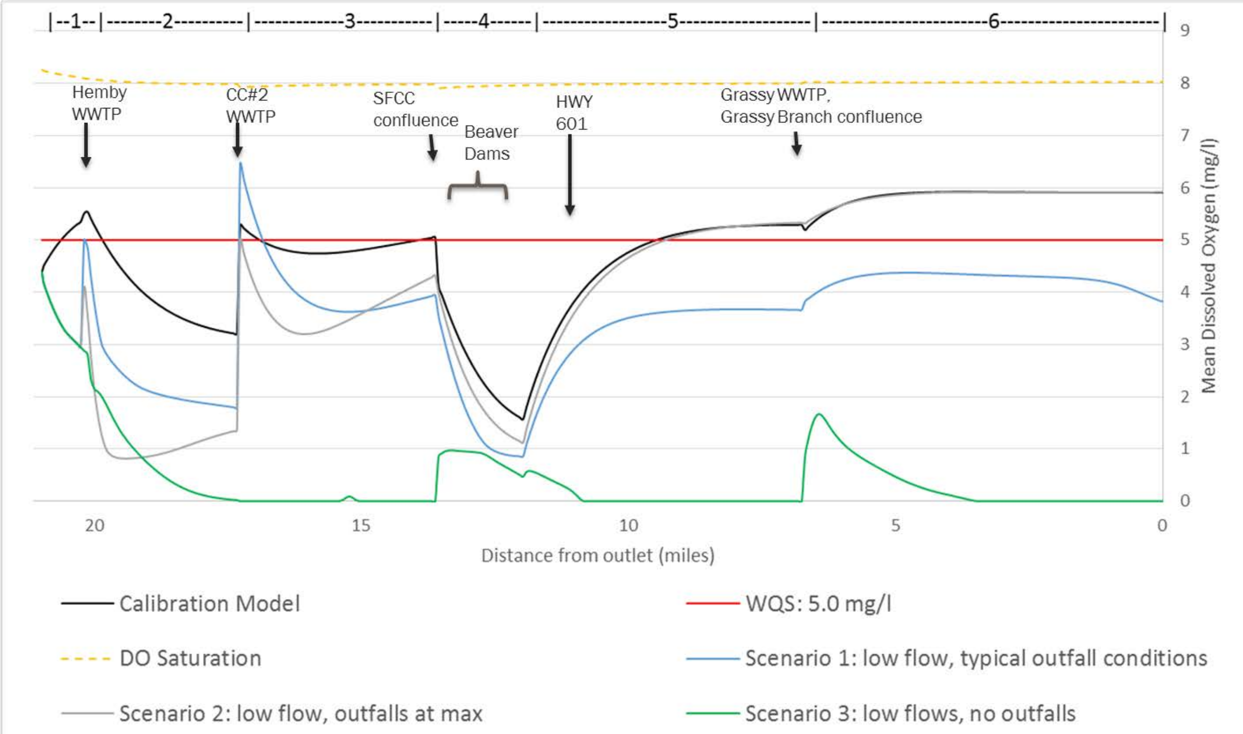

Figure 23. Model results for scenarios 1, 2, and 3: average DO concentration along Crooked Creek

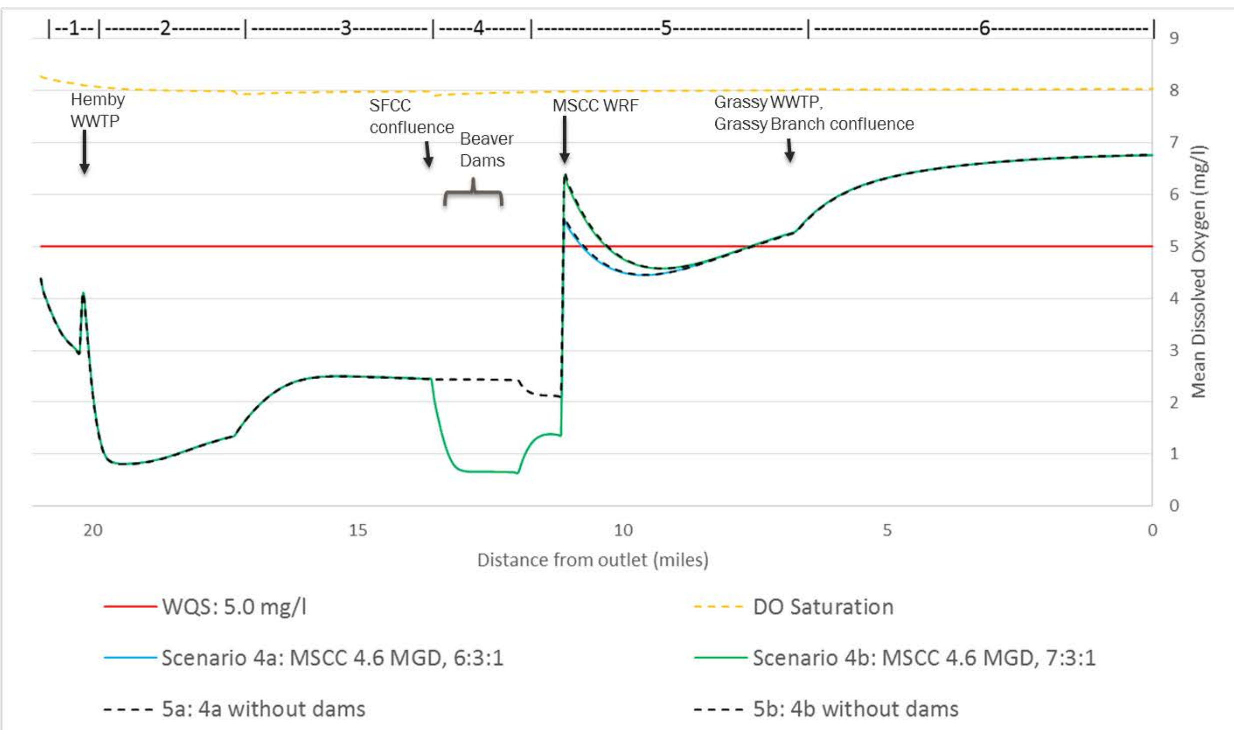

Figure 24. Model results for scenarios 4 and 5: average DO concentration along Crooked Creek

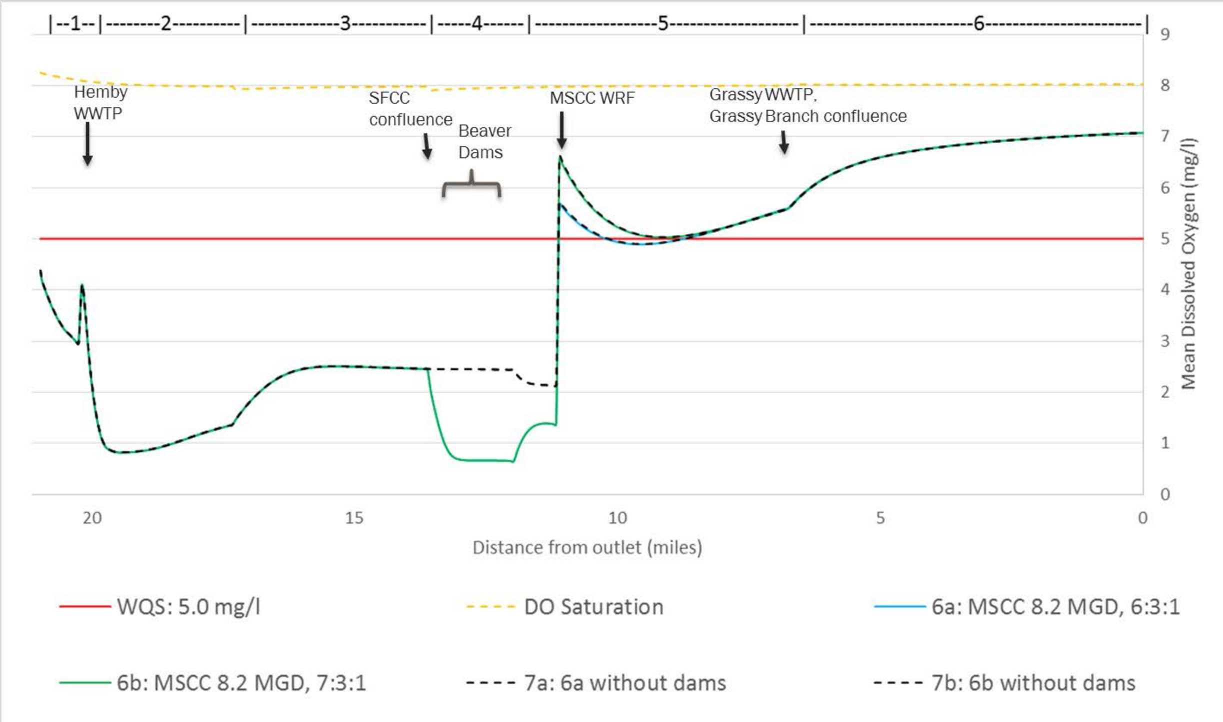

Figure 25. Model results for scenarios 6 and 7: average DO concentration along Crooked Creek

In summary, model application indicates that although DO in Crooked Creek is not expected to meet the water quality standard under critical low flow summer conditions assuming that existing permitted facilities are discharging at maximum allowed limits, the conditions without the permitted flows are predicted to be considerably worse. Limited natural base flow during the summer results in slower stream velocity and the longer residence time allows for background levels of carbonaceous and nitrogenous pollutants to oxidize more fully in slow moving stream segments. This includes the buildup of algae in slower moving waters which generates carbonaceous BOD. As the algae respires, oxygen is rapidly depleted as is evident from observing diurnal DO variation. Additionally, slower velocities reduce reaeration rates further exacerbating low DO concentrations.

Therefore, discharge of well-treated and oxygenated effluent is predicted to improve DO and biological habitat during critical low flow conditions. The additional flow volume supports increased velocity and reaeration. The additional oxygenated water helps raise background DO concentrations instream. The proposed new discharge from the MSCC WRF is being designed to routinely meet effluent concentrations lower than the maximum allowed 3:1 mg/L of BOD5 and ammonia nitrogen respectively. Thus, the impact of the discharge on oxygen demand in Crooked Creek would be expected to be even lower than predicted while the flow volume would be expected to provide benefits of higher reaeration and greater aquatic habitat quality than Crooked Creek would likely exhibit without the effluent.

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APPENDIX A: PERMITTED POINT SOURCE DATA

Included here are the treated effluent flow and water quality data associated with the permitted point sources in the Crooked Creek watershed for August and September 2016 (Table A-1, Table A-2, and Table A-3). Note that parameters such as chemical oxygen demand (COD), TN, TP, and Hardness were measured only once per month at some sites. Also reported by Carolina Water Services, Inc. are instream water quality conditions immediately upstream and downstream of the Hemby Acres WWTP which were used for headwater conditions parameterization as well as instream water quality calibration (Table A-4).

Table A-1. DMR data from August and September 2016: Crooked Creek #2 WWTP (NC0069841)

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	Hardness (mg/l)	Alkalinity (mg/l)
8/1/16	0.71	80.4	7.5	<2	<.1	<2.5	7.8					
8/2/16	0.86	78.8	7.3	<2	0.91	<2.5	7.8					
8/3/16	0.85	78.8	7.4	<2	0.92	<2.5	7.6					88
8/4/16	0.79	78.8	7.4	<2	1.0	<2.5	7.7					
8/5/16	0.80	77.4	7.3	<2	0.87	<2.6	5.5					
8/6/16	0.92											
8/7/16	0.81											
8/8/16	0.89	79.7	7.3	<2	3.3	<2.5	7.6					
8/9/16	0.95	79.3	7.3	<2	4.7	<2.5	7.6					
8/10/16	0.91	80.2	7.2	<2	3.5	<2.6	7.4	33	6.4	3.3	74	91
8/11/16	1.11	80.2	7.4		2.2		7.6					
8/12/16	0.87	82.4	7.2				6.8					
8/13/16	0.26											
8/14/16	0.75											
8/15/16	0.79	82.0	7.5	2.9	<.1	2.5	7.7					
8/16/16	0.82	81.5	7.6	<2	<.1	<2.5	7.9					
8/17/16	0.80	81.1	7.5	<2	<.1	<2.5	8.0					85
8/18/16	0.85	80.8	7.3				7.8					
8/19/16	0.95	80.6	7.0				7.4					
8/20/16	0.89											
8/21/16	0.84											
8/22/16	0.80	80.6	7.3	<2	<.1	<2.5	7.9					

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	Hardness (mg/l)	Alkalinity (mg/l)
8/23/16	0.82	78.8	7.3	<2	<.1	<2.5	7.9					
8/24/16	0.76	77.9	7.3	<2	<.1	<2.5	8.0					65
8/25/16	0.77	77.5	7.3	<2	<.1	<2.5	8.1					
8/26/16	0.81	80.6	6.7			<2.5	7.2					
8/27/16	0.81											
8/28/16	0.94											
8/29/16	0.90	79.0	7.1	2.5	<.1	4.3	80					
8/30/16	0.81	78.8	7.1	<2	<.1	2.7	8.0					
8/31/16	0.77	80.1	7.1	<2	<.1	<2.6	7.9					38
9/1/16	0.78	78.4	7.2	<2	<.1	<2.5	8.0					
9/2/16	0.86	80.6	6.8				7.8					
9/3/16	1.85											
9/4/16	0.91											
9/5/16	0.75	77.0	6.9				7.3					
9/6/16	0.79	76.1	7.3	<2	<.1	<2.5	8.2					
9/7/16	0.89	76.6	7.2	<2	<.1	3.9	8.0					
9/8/16	0.81	77.4	7.2	2.7	<.1	6.5	7.9	27	30.35	4.8	150	52
9/9/16	0.78	77.7	7.2	5.2	<.1	10.4	8.0					
9/10/16	0.78											
9/11/16	0.78											
9/12/16	0.80	77.7	7.1	6.8	0.11	19	8.0					
9/13/16	0.89	76.8	7.1	2.4	<.1	8.4	8.1					
9/14/16	0.79	77.5	7.0	2.0	<.1	7.6	7.9					34
9/15/16	0.79	77.5	7.0				8.0					
9/16/16	0.78	78.8	6.4	2.6	<.1	6.6	7.9					
9/17/16	0.76											
9/18/16	0.80											
9/19/16	0.81	78.6	6.4	<2	0.11	4.6	7.9					
9/20/16	0.81	77.5	6.8	<2	<.1	3.0	8.0					
9/21/16	0.82	75.4	7.2	<2	<.1	<2.6	8.2					27

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	Hardness (mg/l)	Alkalinity (mg/l)
9/22/16	0.88	75.2	7.2	<2	<.1	<2.6	8.3					
9/23/16	1.07	75.9	6.4				7.9					
9/24/16	0.89											
9/25/16	0.86											
9/26/16	0.96	76.6	7.4	<2	<.1	<2.6	8.2					
9/27/16	0.89	75.9	7.6				8.3					
9/28/16	0.95	76.8	7.3	3	<.1	<2.5	8.1					
9/29/16	0.84	76.1	7.3	<2	<.1	<2.5	8.2					
9/30/16	0.87	77.0	7.3	<2	<.1	<2.5	7.7					

Table A-2. DMR data from August and September 2016: Grassy Branch WWTP (NC0085812)

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)	COD (mg/l)	Alkalinity (mg/l)
8/1/16	0.01	80.6	7.1						
8/2/16	0.05	75.2	7.3	2.4	0.32	2.7	7.75	30	59
8/3/16	0.03	75.2	7.1						
8/4/16	0.03	77.0	7.5						
8/5/16	0.02	77.0	7.5						
8/6/16	0.32								
8/7/16	0.02								
8/8/16	0.07	77.0	7.8						
8/9/16	0.11	77.0	7.8						
8/10/16	0.04	78.8	7.8						
8/11/16	0.03	78.8	7.2	<2	<.1	<2.6	7.95		87
8/12/16	0.03	78.8	7.7						
8/13/16	0.18								
8/14/16	0.02								
8/15/16	0.02	82.4	7.7						
8/16/16	0.02	80.6	7.6	<2	<.1	<2.6	7.04		96
8/17/16	0.02	80.6	7.2						
8/18/16	0.02	82.4	7.3						

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)	COD (mg/l)	Alkalinity (mg/l)
8/19/16	0.04	78.8	7.5						
8/20/16	0.03								
8/21/16	0.02								
8/22/16	0.02	78.8	7.2						
8/23/16	0.02	77.0	7.0	<2	<.1	2.6	8.25		131
8/24/16	0.02	77.0	7.0						
8/25/16	0.03	77.0	7.0	2	<.1	<2.5	7.3		120
8/26/16	0.03	78.8	7.3						
8/27/16	0.02								
8/28/16	0.03								
8/29/16	0.03	78.8	7.0						
8/30/16	0.03	77.0	6.9	3.4	3.3	5.6	7.88		
8/31/16	0.03	77.0	6.6						
9/1/16	0.04	78.8	6.9	<2	1.2	<2.5	7.52		59
9/2/16	0.03	78.8	7.1						
9/3/16	0.10								
9/4/16	0.03								
9/5/16	0.02	77.0	7.4						
9/6/16	0.04	78.8	7.4						
9/7/16	0.03	77.0	6.8	<2	<.1	<2.6	7.98		74
9/8/16	0.04	75.2	6.7	<2	<.1	<2.5	7.38		67
9/9/16	0.03	77.0	6.9						
9/10/16	0.03								
9/11/16	0.02								
9/12/16	0.02	78.8	7.0						
9/13/16	0.03	77.0	6.3	<2	0.34	<2.5	7.19	19	38
9/14/16	0.03	77.0	6.6	<2	0.46	<2.5	7.16		62
9/15/16	0.04	75.2	6.8						
9/16/16	0.04	77.0	7.3						
9/17/16	0.03								

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)	COD (mg/l)	Alkalinity (mg/l)
9/18/16	0.02								
9/19/16	0.02	77.0	7.7						
9/20/16	0.04	75.2	7.6						
9/21/16	0.03	73.4	7.1	<2	<.1	<2.5	8.35		164
9/22/16	0.04	73.4	7.1	<2	<.1	<2.6	7.49		176
9/23/16	0.05	75.2	7.0						
9/24/16	0.05								
9/25/16	0.02								
9/26/16	0.04	77.0	7.7						
9/27/16	0.05	73.4	6.7						
9/28/16	0.10	77.5	7.8						
9/29/16	0.03	74.5	7.2	<2	<.1	<2.5	8.34		
9/30/16	0.04	74.5	7.3	<2	<.1	<2.6	7.35		

Table A-3. DMR data from August and September 2016: Hemby Acres WWTP (NC0035041)

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)
8/1/16	0.06	80.4	7.0				6.72
8/2/16	0.08						
8/3/16	0.09	79.0	7.3	2.3	<0.1	<2.5	7.38
8/4/16	0.09						
8/5/16	0.08						
8/6/16	0.13						
8/7/16	0.08						
8/8/16	0.07						
8/9/16	0.10						
8/10/16	0.10	79.5	8.0				
8/11/16	0.10	78.6	7.6	4.6	<0.1	<2.5	6.73
8/12/16	0.09						
8/13/16	0.10						

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)
8/14/16	0.10						
8/15/16	0.06						
8/16/16	0.09	76.8	6.8				5.84
8/17/16	0.09						
8/18/16	0.08	80.2	7.7	<2	<0.1	<2.5	6.5
8/19/16	0.10						
8/20/16	0.08						
8/21/16	0.09						
8/22/16	0.12						
8/23/16	0.07	76.3	7.8				5.31
8/24/16	0.09						
8/25/16	0.07	75.6	7.3	<2	<0.1	<2.5	6.65
8/26/16	0.09						
8/27/16	0.14						
8/28/16	0.06						
8/29/16	0.09						
8/30/16	0.09	75.6	8.1	12	<0.1	<2.5	6.62
8/31/16	0.11						
9/1/16	0.07	76.8	7.6				6.2
9/2/16	0.10						
9/3/16	0.18						
9/4/16	0.08						
9/5/16	0.09						
9/6/16	0.06	73.9	7.0				6.55
9/7/16	0.09						
9/8/16	0.08	74.5	7.0	11	<0.1	<2.5	6.1
9/9/16	0.08						
9/10/16	0.11						
9/11/16	0.08	75.2	7.2				7.01
9/12/16	0.07	76.1	8.2	4.9	<0.1	<2.5	7.21

Date	Flow (MGD)	Temp (°F)	pH	BOD_5 (mg/l)	NH_3 (mg/l)	TSS (mg/l)	DO (mg/l)
9/13/16	0.09						
9/14/16	0.10						
9/15/16	0.07						
9/16/16	0.09						
9/17/16	0.09						
9/18/16	0.08						
9/19/16	0.11						
9/20/16	0.09	75.9	7.4				6.61
9/21/16	0.08						
9/22/16	0.10	76.6	7.3	3.2	<0.1	<2.5	6.87
9/23/16	0.10						
9/24/16	0.08						
9/25/16	0.08						
9/26/16	0.08						
9/27/16	0.04	75.7	7.1				7.33
9/28/16	0.20	75.4	7.2	4.5	<0.1	<2.5	7.12
9/29/16	0.07						
9/30/16	0.09						

Table A-4. Instream DMR water quality data upstream and downstream of Hemby Acres WWTP, August and September 2016

Date	Temperature (°F)		Dissolved Oxygen (mg/l)	
	Upstream	Downstream	Upstream	Downstream
8/3/16	74.8	75.4	4.72	5.03
8/11/16	73.8	75.2	4.57	5.03
8/18/16	76.3	76.8	4.43	4.96
8/25/16	73.6	75.0	3.33	4.01
8/30/16	73.4	75.0	4.32	4.91
9/8/16	71.6	73.2	4.01	4.59
9/12/16	71.8	73.2	3.63	4.97

Date	Temperature (°F)		Dissolved Oxygen (mg/l)	
	Upstream	Downstream	Upstream	Downstream
9/22/16	73.9	76.3	3.65	4.01
9/28/16	68.2	69.8	4.22	4.98

APPENDIX B: YPDRBA COALITION DATA

Water quality sampling conducted by the Yadkin Pee Dee River Basin Association (Coalition) during August and September of 2016 may be relevant to use for model calibration and validation (Table).

Table B-1. Coalition water quality data of-interest from August and September 2016

Parameter	Date*	Sampling Site		
		Q8386000 (NFCC at SR 1520)	Q8386200 (NFCC at SR1514)	Q8388000 (CC at NC 218)
Water Temperature (°F)	8/9/2016	77.2	77.2	78.8
	8/30/2016	76.6	76.8	76.5
	9/13/2016	73.6	73.8	74.8
Dissolved Oxygen (mg/l)	8/9/2016	5.8	5.8	6.3
	8/30/2016	5.7	5.8	6.4
	9/13/2016	5.5	5.7	6.5
pH (s.u.)	8/9/2016	6.6	6.6	6.8
	8/30/2016	6.6	6.6	6.9
	9/13/2016	6.6	6.6	6.8
Conductivity (umhos/cm)	8/9/2016	263	289	162
	8/30/2016	393	372	219
	9/13/2016	248	229	179
Fecal Coliform (#/100ml)	8/9/2016	310	270	166
	9/13/2016	300	250	162
Suspended Residue (mg/l)	8/9/2016	No Data	No Data	9.1
	9/13/2016	No Data	No Data	20
Turbidity (NTU)	8/9/2016	16	20	16
	9/13/2016	21	11	11
Ammonia as N (mg/l)	8/9/2016	No Data	No Data	0.1
	9/13/2016	No Data	No Data	0.08
TKN as N (mg/l)	9/13/2016	No Data	No Data	0.8
NOX as N (mg/l)	8/9/2016	No Data	No Data	1.74
	9/13/2016	No Data	No Data	2.49
TP (mg/l)	9/13/2016	No Data	No Data	0.76

*Note: some samples were taken 1 day before or after the reported date listed in this table

APPENDIX C: TETRA TECH 2016 SAMPLING DATA

C.1 STREAM HYDROLOGY MEASUREMENTS

Twenty cross-sections were measured during the 2016 summer sampling effort (Table C-1).

Table C-1. Measured reach properties, summer 2016

Distance from headwaters (km)	Sample Point ID	Width (ft)	Velocity (ft/s)	Maximum Depth (ft)	Site-Estimated Flow (cfs)
2.21	8	16	No Data	1.1	No Data
2.92	13	13	0.30	0.5	1.54
5.15	26	18	0.15	0.9	1.63
5.58	33	10	No Data	0.6	No Data
5.93	3	No Data	No Data	No Data	No Data
6.20	35	19	0.22	2.1	6.25
10.43	61	14	0.26	1.1	2.23
12.45	75	17	0.30	0.8	2.83
14.63	87	23	0.40	0.5	3.29
15.68	1	27	No Data	0.2	No Data
18.71	252	16.5	0.28	0.8	2.42
21.26	117	41.5	No Data	0.6	No Data
22.09	138	24	0.33	1.0	3.61
22.90	118	40.6	No Data	1.6	No Data
23.33	119	38	No Data	1.1	No Data
25.28	160	38.5	0.18	1.0	4.11
26.34	120	28.5	No Data	1.1	No Data
27.59	121	26.5	No Data	1.2	No Data
27.79	122	30	No Data	1.8	No Data
29.23	182	35	0.03	1.1	0.84

C.2 NUTRIENT SAMPLING

Grab samples were analyzed for water quality constituents along Crooked Creek during each sampling effort. Fifteen samples were taken from the main stem, tributaries, and wastewater treatment plant discharge sites during each sampling trip (Figure C-1). Water quality analyses were conducted by Pace Analytical laboratory for the following parameters: 5-day biochemical oxygen demand (BOD_5), 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), ammonia (NH_3), nitrate and nitrite (NO_2+NO_3), phosphate (PO_4), total Kjeldahl nitrogen (TKN), total nitrogen (TN), and total phosphorus (TP).

For a number of laboratory samples, the measured parameter was found to be below the level of detection (LOD). The laboratory equipment did produce a numerical result below the LOD which has been included and flagged as such. Although these results are below the LOD, the numbers seem reasonable and may be relevant to include in modeling efforts with an increased level of uncertainty associated with the exact concentrations. The results from all grab samples have been compiled by sampling location, parameter, and trip (Table C-1, Table C-2, and Table C-3**)**.

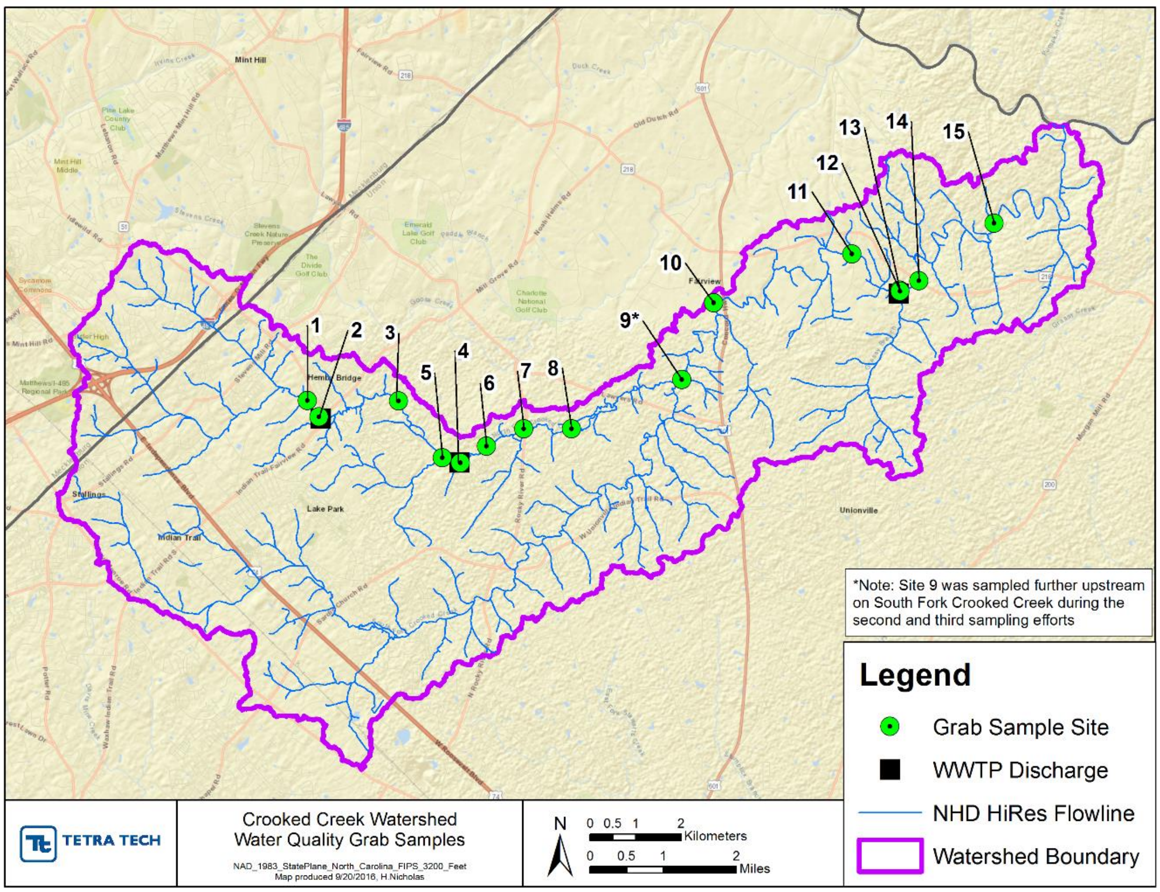


Figure C-1. Water quality grab sample locations

Table C-2. BOD/CBOD results (units mg/l)

ID	Location Note	BOD_5			$CBOD_5$		
		1	2	3	1	2	3
1	US of Hemby discharge	1.40*	1.20*	4.10	1.10*	1.20*	0.60*
2	Hemby WWTP discharge	0.70*	2.60	1.40*	0.70*	3.20	2.10
3	Indian Trail Fairview Rd	1.30*	2.00*	1.50*	0.80*	1.60*	1.60*
4	Crooked Creek #2 discharge	1.50*	0.70*	2.20	0.80*	0.50*	1.50*
5	US of CC#2 WWTP discharge	1.50*	1.30*	1.40*	1.00*	1.20*	1.90*
6	Old Farm Bridge crossing	1.60*	1.00*	0.90*	1.40*	0.60*	0.30*
7	DS of Rocky River Rd	1.50*	0.50*	1.20*	1.00*	0.95*	0.50*
8	Ridge Road crossing	1.50*	0.60*	3.50	0.80*	0.90*	0.90*
9	SF Crooked Creek	1.40*	2.00	0.80*	0.90*	1.20*	2.10
10	DS of debris dams	1.40*	0.70*	0.90*	1.10*	0.90*	0.30*
11	Brief Rd crossing	1.40*	1.30*	0.70*	0.90*	1.20*	0.50*
12	Grassy Branch WWTP discharge	0.70*	1.10*	1.70*	0.20*	1.10*	0.10*
13	Grassy Branch Tributary	9.00	8.10	0.90*	3.00	7.50	1.10*
14	Hwy 218 crossing	1.10*	0.60*	0.90*	0.00*	0.80*	0.60*
15	US of Brief Rd	1.00*	0.70*	1.10*	0.50*	0.70*	0.40*

*reflects the numerical result reported from lab analysis although result is below reporting limit.

Report limit for BOD_5: 2.0 mg/l, $CBOD_5$: 2.0 mg/l

Table C-3. Nitrogen species results (units mg/l)

ID	Location Note	NH_3-N			NO_2+NO_3-N			TKN			TN		
		1	2	3	1	2	3	1	2	3	1	2	3
1	US of Hemby discharge	0.08*	0.03*	0.02*	0.34	0.22	0.08	0.46*	0.94	0.73	0.81	1.20	0.80
2	Hemby WWTP discharge	0.02*	0.05*	0.02*	33.70	42.30	25.10	0.98	0.00*	1.10	34.70	42.30	26.30

3	Indian Trail Fairview Rd	0.00*	0.07*	0.08*	6.50	3.20	5.40	0.79	0.54	0.98	7.30	3.70	6.30
4	Crooked Creek #2 discharge	0.00*	0.02*	0.00*	24.00	32.90	33.90	1.20	1.10	1.90	25.10	33.90	35.80
5	US of CC#2 WWTP discharge	0.09*	0.08*	0.15	2.30	0.51	0.70	0.53	0.69	1.40	2.80	1.20	2.10
6	Old Farm Bridge crossing	0.12	0.05*	0.04*	10.80	20.50	28.90	1.00	1.30	1.50	11.80	21.80	30.50
7	DS of Rocky River Rd	0.02*	0.05*	0.04*	11.70	23.30	24.10	1.20	0.63	1.50	12.90	23.90	25.50
8	Ridge Road crossing	0.03*	0.05*	0.03*	10.30	16.40	33.20	1.20	1.10	1.10	11.40	17.40	34.30
9	SF Crooked Creek	0.07*	0.93	0.11	5.60	0.13	0.00*	1.50	1.60	0.74	7.10	1.70	0.74
10	DS of debris dams	0.08*	0.07*	0.13	0.46	1.50	8.40	0.92	0.56	1.20	1.40	2.00	9.60
11	Brief Rd crossing	0.00*	0.02*	0.01*	0.34	2.90	0.67	0.67	0.73	0.75	1.00	3.70	1.40
12	Grassy Branch WWTP discharge	0.01*	0.44	0.03*	34.00	44.00	53.30	1.30	0.84	0.00*	35.30	44.80	53.30
13	Grassy Branch Tributary	0.00*	0.02*	0.02*	1.50	1.70	0.61	0.79	0.25*	0.73	2.30	1.90	1.30
14	Hwy 218 crossing	0.02*	0.07*	0.02*	1.20	3.80	2.50	0.44*	0.70	0.56	1.60	4.50	3.10
15	US of Brief Rd	0.01*	0.03*	0.00*	0.55	13.80	0.89	0.47*	0.72	0.46*	1.00	14.50	1.30

*reflects non-detect, numerical result reported

Reporting limit for NH_3-N: 0.10 mg/l, NO_2+NO_3-N: 0.020 mg/l, TKN: 0.50 mg/l, TN: 0.12 mg/l.

Table C-4. Phosphorus species results (units mg/l)

ID	Location Note	PO_4-P			TP		
		1	2	3	1	2	3
1	US of Hemby discharge	0.13	0.10	0.05	0.06	0.16	0.12
2	Hemby WWTP discharge	1.80	4.80	4.00	3.20	5.00	5.60
3	Indian Trail Fairview Rd	0.54	2.10	0.50	0.47	0.47	0.57

ID	Location Note	PO_4-P			TP		
		1	2	3	1	2	3
4	Crooked Creek #2 discharge	2.90	4.60	4.80	2.50	4.80	6.10
5	US of CC#2 WWTP discharge	0.31	1.10	0.16	0.24	0.23	0.36
6	Old Farm Bridge crossing	1.20	2.90	4.10	1.20	2.70	4.50
7	DS of Rocky River Rd	1.30	3.30	3.60	1.20	3.00	3.90
8	Ridge Road crossing	0.32	2.40	3.60	1.10	2.20	4.00
9	SF Crooked Creek	0.34	0.15	0.09	1.10	0.15	0.19
10	DS of debris dams	0.23	2.10	1.10	0.84	0.53	1.10
11	Brief Rd crossing	0.86	2.70	0.43	0.72	0.66	0.65
12	Grassy Branch WWTP discharge	0.30	3.40	4.50	2.70	3.30	4.70
13	Grassy Branch Tributary	0.20	0.26	0.07	0.19	0.12	0.17
14	Hwy 218 crossing	0.16	1.00	0.74	0.75	0.86	0.80
15	US of Brief Rd	0.14	1.90	0.75	0.66	1.60	0.61

Reporting limit for PO_4-P: 0.050 mg/l, TP: 0.050 mg/l.

C.3 LONGITUDINAL DISSOLVED OXYGEN

Dissolved Oxygen was monitored using a hand-held probe every several hundred meters along the extent of Crooked Creek on each sampling effort to some degree. The results of the raw DO readings at each location sampled from each trip are seen below (Figure C-2, Figure C-3**,** Figure C-4, Table C-5, Table C-6, Table C-7). Note that these results have not been temperature-corrected. Frequently sampled alongside dissolved oxygen concentration were: pH, dissolved oxygen saturation, water temperature, turbidity, and specific conductivity.

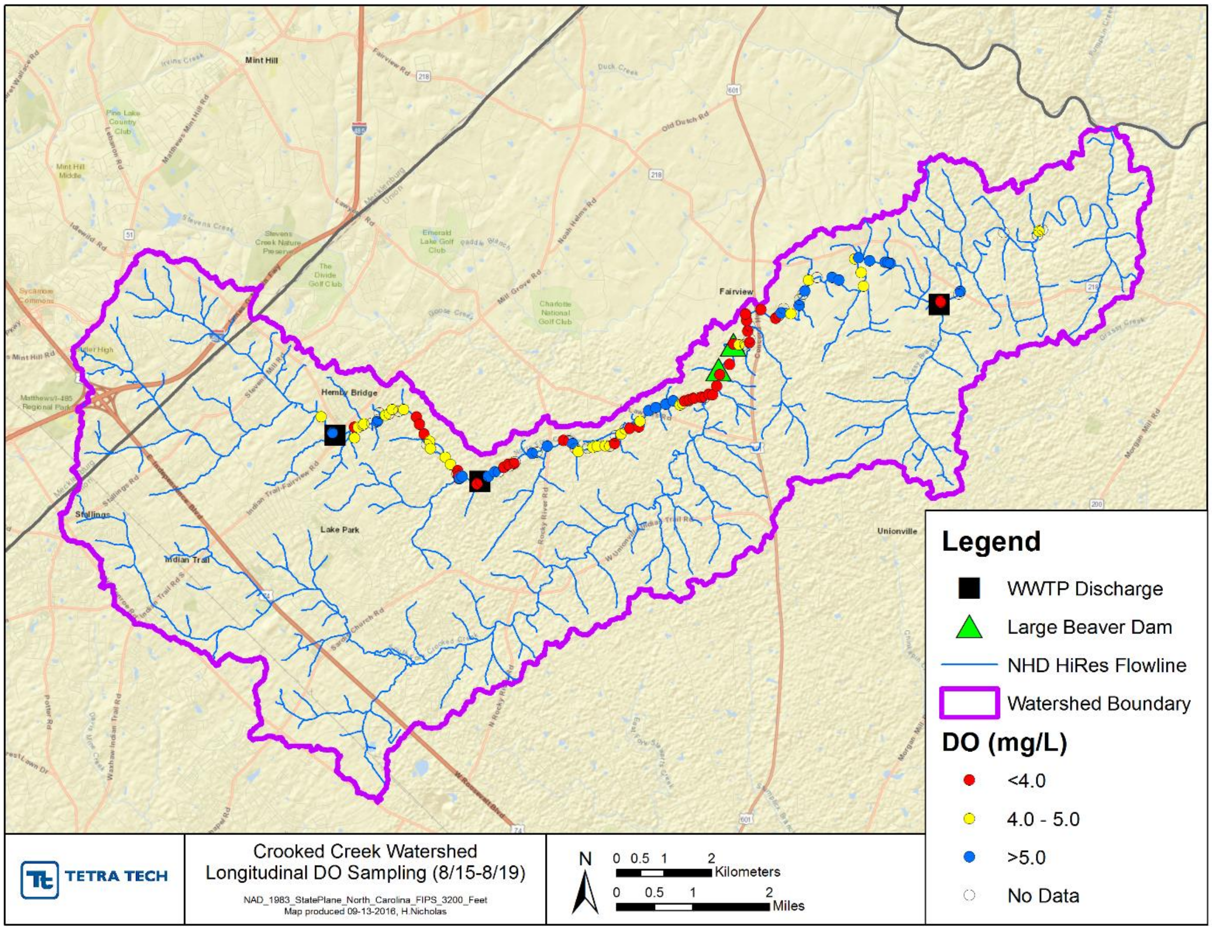


Figure C-2. Instream longitudinal dissolved oxygen measurements (8/15/16-8/19/16)

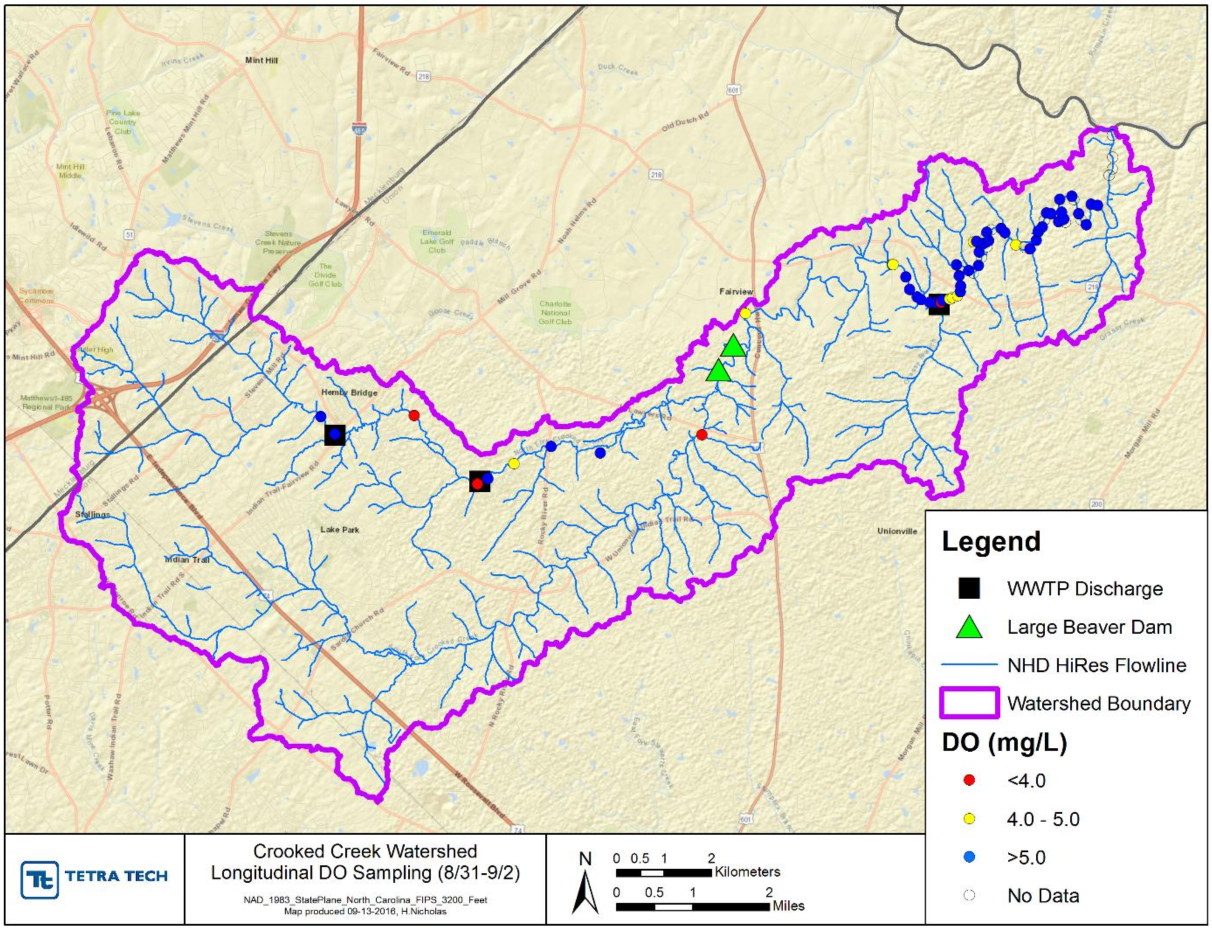


Figure C-3. Instream longitudinal dissolved oxygen measurements (8/31/16-9/2/16)

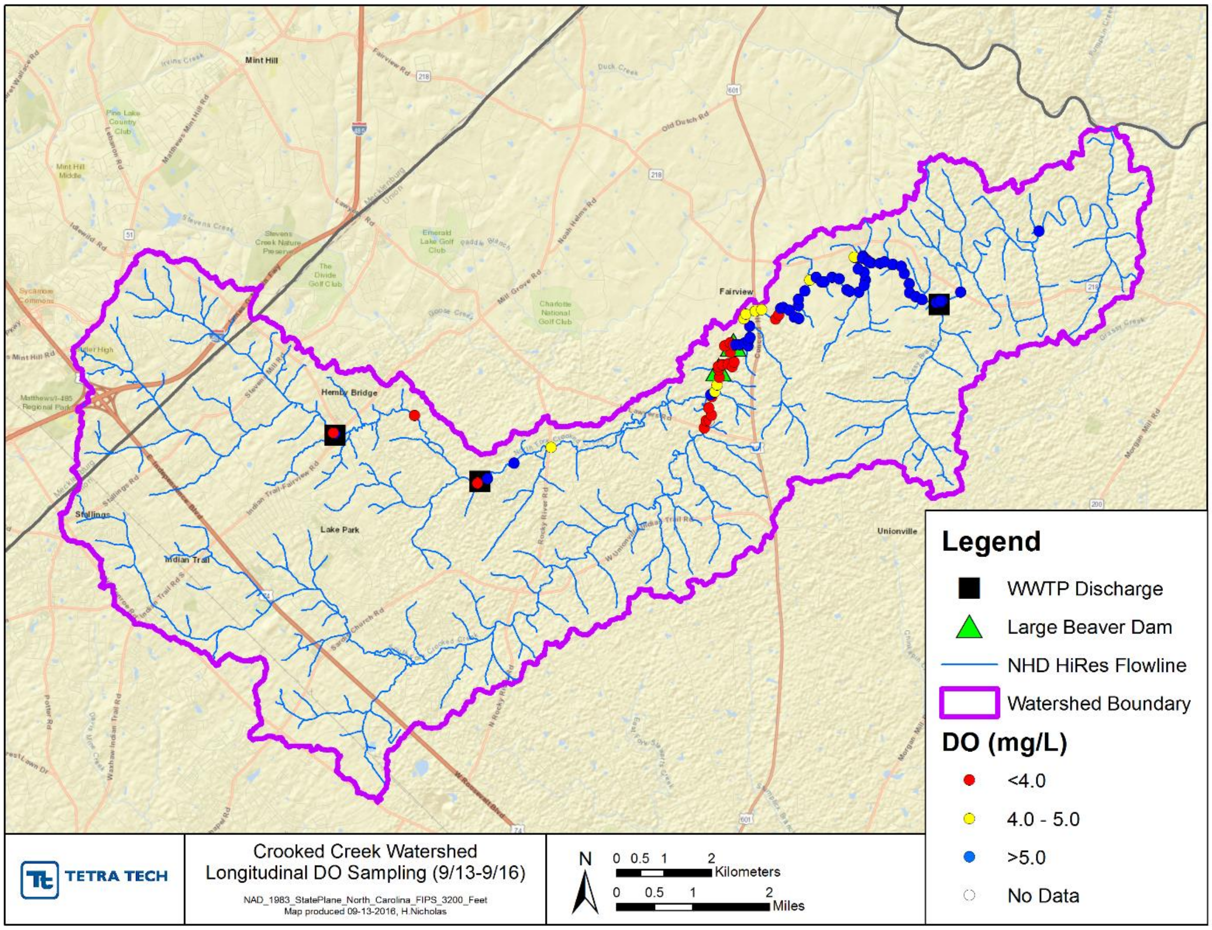


Figure C-4. Instream longitudinal dissolved oxygen measurements (9/13/16-9/16/16)

Table C-5. Longitudinal data from trip 1 (August 15-19, 2016)

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
1	35.1074	80.63715	8/15	17:48	6.29		58.9	79.2
2	35.10429	80.63447	8/15	18:18	6.84		68.8	80.1
4	35.10346	80.62941	8/15	18:30	6.91		62	79.5
5	35.10547	80.62941	8/16	8:02	6.95	3.18	39.2	78.3
6	35.10545	80.62855	8/16	8:22	6.99	4.13	51.2	79.0
8	35.10617	80.6272	8/16	8:40	7.14	4.03	49.1	78.3
10	35.10659	80.62418	8/16	9:14	7.13	5.07	61.6	77.5
13	35.10786	80.62229	8/16	9:34	7.1	4.67	55.9	77.4
15	35.10893	80.62077	8/16	10:06	7.18	4.79	58.3	77.4
18	35.109	80.61813	8/16	10:40	7.21	4.68	57.5	77.7
19	35.1076	80.61507	8/16	11:01	7.04	2.97	36.3	78.1
20	35.10626	80.6144	8/16	11:13	7.12	3.65	44.7	78.1
21	35.1044	80.61324	8/16	11:27	7.22	3.15	38.8	78.1
22	35.10303	80.61198	8/16	11:41	7.09	4.5	55.1	78.1
24	35.10164	80.61172	8/16	11:51	7.12	4.53	55.3	77.9
25	35.10003	80.6083	8/16	12:11	7.09	4.78	58.4	77.9
26	35.09868	80.60705	8/16	12:25	7.17	4.43	54.2	77.9
28	35.0975	80.60536	8/16	12:58	7.12	3.13	38.4	78.3
30	35.09652	80.60519	8/16	13:05	7.1	3.24	39.9	78.8
31	35.09602	80.60497	8/16	1:13	6.81	2.29	29.4	80.8
32	35.0961	80.60487	8/16	1:19	7.24	5.22	64.5	79.3
33	35.09645	80.6043	8/16	13:32	7.09	5.11	63.4	79.5
34	35.09502	80.60084	8/16	14:02	7.02	2.62	32.3	79.2
35	35.09652	80.59822	8/16	14:38	7.38	5.2	66.2	81.5

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
36	35.09743	80.59677	8/16	15:16	7.31	5.13	64.9	81.7
38	35.09833	80.59464	8/16	15:33	7.37	3.89	49.1	81.1
39	35.0989	80.59364	8/16	15:47	7.28	3.25	39.9	80.8
41	35.09908	80.59235	8/16	16:00	7.27	3.57	44.9	80.8
43	35.10103	80.58817	8/16	16:22	8.66	11.64	152.3	85.3
45	35.10244	80.58469	8/16	16:48	7.93	7.2	90.4	83.3
46	35.10362	80.58096	8/17	8:28	7.29	3.85	48.2	79.9
48	35.10303	80.57883	8/17	8:43	7.48	5.53	69.8	80.2
50	35.10158	80.57745	8/17	9:00	7.47	4.48	56.8	80.1
52	35.10235	80.57418	8/17	9:14	7.44	4.42	55.1	79.7
53	35.10264	80.57316	8/17	9:32	7.38	4.34	54.3	79.5
54	35.10268	80.57128	8/17	9:53	7.28	4.44	55.3	79.7
56	35.10316	80.56911	8/17	10:15	7.31	2.39	29.9	79.7
58	35.10502	80.56769	8/17	10:36	7.31	4.64	58.5	80.8
60	35.10611	80.56563	8/17	10:54	7.38	3.77	46.1	79.9
61	35.10641	80.56356	8/17	11:32	7.33	3.91	48.8	79.9
62	35.1075	80.56329	8/17	11:48	7.4	4.01	50.2	79.7
63	35.10954	80.56135	8/17	12:13	7.28	5.28	65	78.6
64	35.11013	80.55966	8/17	12:28	7.41	5.13	64.4	80.4
65	35.1108	80.55741	8/17	12:42	7.77	8.08	102.9	82.6
66	35.11146	80.55566	8/17	12:55	7.63	5.03	63	80.4
67	35.11067	80.55408	8/17	13:10	7.4	4.46	56.8	81.7
69	35.11141	80.55309	8/17	13:27	7.36	2.99	37.8	81.1
71	35.11172	80.5519	8/17	13:41	7.33	3	38	81.3
72	35.11196	80.55107	8/17	13:56	7.34	3.21	40.3	80.8

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
74	35.11223	80.54912	8/17	14:23	7.34	3.52	45	81.5
76	35.11278	80.54745	8/17	14:57	7.33	3.9	49.5	81.7
77	35.11274	80.54661	8/17	15:08	7.35	2.47	31.5	81.9
78	35.11441	80.54568	8/17	15:35	7.16	1.22	15.1	79.5
79	35.11661	80.54506	8/17	15:55	7.14	1.1	13.7	79.7
80	35.11855	80.54276	8/17	16:16	7.11	1.9	23.3	80.8
82	35.14477	80.4716	8/18	8:34	7.15	4.27	51.9	77.4
83	35.1331	80.48961	8/18	8:49	7.26	5.3	54.7	77.9
84	35.13116	80.49425	8/18	9:07	7.34	3.7	44.8	76.6
85	35.13099	80.49411	8/18	9:14	6.68	2.78	32.9	74.5
86	35.12245	80.54194	8/18	10:59	6.95	0.82	10.2	78.4
87	35.12229	80.54069	8/18	11:21	7.04	4.43	54.5	79.0
90	35.12278	80.53825	8/18	11:38	7.12	3.64	43.2	78.1
92	35.12492	80.53868	8/18	11:57	7.07	2.78	34	77.7
94	35.12695	80.53902	8/18	12:13	7.06	3.13	38.7	78.3
95	35.12815	80.53928	8/18	12:23	7.02	2.87	35.2	78.1
96	35.12911	80.53567	8/18	12:38	7.05	3.02	37.3	78.6
97	35.12745	80.53224	8/18	13:02	7.05	2.69	32.9	78.8
99	35.12849	80.53107	8/18	13:14	7.2	5.12	63.7	79.7
101	35.12836	80.52878	8/18	13:48	7.3	4.86	60.3	79.5
102	35.12998	80.5269	8/18	14:00	7.35	6.7	83.9	80.4
105	35.13273	80.52562	8/18	14:21	7.48	5.1	63.7	79.9
106	35.1348	80.5248	8/18	14:42	7.29	4.51	56.6	80.2
108	35.13543	80.51939	8/18	15:06	7.62	5.9	76	81.9
109	35.13492	80.51781	8/18	15:37	7.45	6.58	82.5	80.4

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
110	35.13382	80.51204	8/18	15:58	7.49	4.65	59	81.5
111	35.13643	80.5126	8/18	16:12	7.69	4.56	58	81.7
112	35.13899	80.51417	8/18	16:24	7.55	4.09	51.7	81.3
113	35.13919	80.51332	8/18	16:34	7.45	5.07	65.2	81.1
114	35.13871	80.51076	8/18	16:42	7.61	5.52	69.8	81.7
115	35.13842	80.50713	8/18	16:50	7.68	5.81	73.4	81.3
116	35.13825	80.50588	8/18	16:56	7.35	5.3	66.5	79.3

Table C-6. Longitudinal data from trip 2 (August 31-September 2, 2016)

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
120	35.14462	80.47173	8/31	15:02	7.57	6.33	77.4	77.7
121	35.13301	80.4896	8/31	15:26	7.5	7.37	89.1	76.6
122	35.13091	80.49409	8/31	15:49	6.78	7.87	95	76.6
123	35.13112	80.49418	8/31	16:06	7.28	7.29	87.9	76.5
124	35.13121	80.49426	8/31	16:12	7.79	5.03	61.2	77.7
125	35.13803	80.50548	8/31	17:14	7.46	5.17	61.8	76.3
126	35.12832	80.53928	8/31	17:39	6.9	4.26	51.1	76.1
127	no data	no data	8/31	18:00	6.62	0.82	9.7	74.3
128	35.10136	80.57244	8/31	18:19	7.07	5.47	66.7	77.7
129	35.10238	80.5838	8/31	18:32	7.18	7.17	88.7	79.2
130	35.09903	80.59232	8/31	18:50	6.98	4.52	54.8	77.2
131	35.0961	80.59836	8/31	19:10	7.27	7.67	95.4	79.2
132	35.09506	80.60077	8/31	19:26	6.78	1.87	22.2	74.8
133	35.10788	80.61561	8/31	19:46	6.8	3	35.9	75.9
134	no data	no data	8/31	20:10	7.63	8	98	78.1
135	no data	no data	8/31	20:13	7.55	5.9	70.2	75.4

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
136	35.13803	80.50533	9/1	8:13	7.29	4.66	55	74.1
137	35.13571	80.5023	9/1	8:30	7.42	5.59	65.4	73.9
138	35.13332	80.50132	9/1	8:42	7.33	5.79	67.8	73.6
139	35.13187	80.49962	9/1	9:15	7.45	5.9	68.3	73.6
140	35.13139	80.49867	9/1	9:23	7.39	6.51	76.1	73.4
141	35.13094	80.49665	9/1	9:41	7.47	6.45	75.5	73.8
142	35.13089	80.49506	9/1	9:50	7.43	6.81	79.7	73.6
143	35.13116	80.49414	9/1	9:57	7.31	7.35	87.5	75.2
144	35.13094	80.49404	9/1	10:01	6.23	2.67	30.7	71.1
145	35.13134	80.49369	9/1	10:05	7.34	5.87	68.7	73.8
146	35.13165	80.49204	9/1	10:14	7.28	4.65	54.6	73.9
148	35.13233	80.4902	9/1	10:26	7.34	4.96	58.7	74.3
149	35.13306	80.48958	9/1	10:35	7.38	6	70.8	74.7
150	35.1341	80.48951	9/1	10:41	7.47	6.12	72.3	74.7
151	35.13606	80.48993	9/1	10:50	7.35	6.02	70.9	74.3
152	35.13813	80.49062	9/1	11:00	7.45	5.52	65.3	74.7
154	35.13709	80.48772	9/1	11:20	7.63	7.24	86.2	75.4
156	35.13804	80.4855	9/1	11:36	7.6	6.72	79.5	74.7
158	35.14062	80.48538	9/1	12:00	7.54	7.43	87.6	74.5
159	35.14259	80.48672	9/1	12:09	7.44	4.66	54.8	74.1
160	35.14266	80.48602	9/1	12:18	7.42	5.99	71.3	75.2
161	35.14226	80.48444	9/1	12:49	7.23	5.01	60.1	75.9
163	35.14281	80.4832	9/1	13:20	7.26	6.56	79.3	76.8
165	35.1444	80.48367	9/1	13:39	7.47	7.42	91.7	78.6
167	35.14518	80.48033	9/1	13:50	7.24	5.8	69.7	76.3

ID	Latitude (N)	Longitude (W)	Date	Time	pH	DO (mg/l)	DO (%Sat)	Temp (°F)
168	35.14437	80.47944	9/1	14:00	7.4	6.17	75.5	78.1
169	35.14214	80.47688	9/1	14:12	7.3	4.67	56.3	77.4
171	35.14138	80.47367	9/1	14:30	7.57	8.05	99.7	79.2
172	35.14304	80.47221	9/1	14:37	7.71	7.87	97.5	79.2
173	35.14477	80.47175	9/1	14:50	7.71	6.54	81.3	79.5
174	35.14561	80.4708	9/1	16:04	7.85	6.37	80.2	80.8
176	35.14824	80.46992	9/1	16:15	7.54	7.77	98.4	81.3
177	35.14809	80.46889	9/1	16:23	7.62	7.55	95.5	81.3
178	35.1466	80.46709	9/1	4:32	7.6	7.23	89.5	79.2
180	35.14716	80.46584	9/1	16:44	7.66	6.45	80.8	80.4
181	35.14845	80.46641	9/1	16:48	7.6	6.7	83	79.2
182	35.15091	80.46693	9/1	16:57	7.66	6.14	76.5	79.9
183	35.15145	80.46413	9/1	17:23	7.75	6.47	80.7	79.9
185	35.14817	80.46246	9/1	17:35	7.85	7.65	94.8	79.2
187	35.14616	80.46063	9/1	17:46	7.8	6.98	86	78.8
188	35.15005	80.45959	9/1	17:57	7.91	6.67	82	78.4
189	35.14981	80.45807	9/1	18:10	7.89	5.28	64.9	78.4

Table C-7. Longitudinal data from trip 3 (September 13-16, 2016)

ID	Latitude (N)	Longitude (W)	Date	Time	Turbidity (NTU)	pH	DO (mg/l)	DO (%Sat)	Specific Conductivity (uS/cm)	Temp (°F)
194	35.14474	80.47161	9/14	7:20	6.4	6.53	6.23	71	159	71.1
195	35.13801	80.50545	9/14	7:46	7.4	6.07	6.27	71.6	169.1	71.4
196	35.10223	80.58383	9/14	8:20	10.1	6.48	4.69	54.7	531	73.4
197	35.10636	80.54846	9/14	9:20	11.8	5.95	0.57	6.5	102.2	71.6
198	35.10777	80.548	9/14	9:26	65	6.39	0.09	1.1	103	71.8

ID	Latitude (N)	Longitude (W)	Date	Time	Turbidity (NTU)	pH	DO (mg/l)	DO (%Sat)	Specific Conductivity (uS/cm)	Temp (°F)
199	35.10886	80.54678	9/14	9:40	13.3	6.61	0.28	3.3	105.1	71.2
200	35.11024	80.54744	9/14	10:02	43	6.59	0.05	0.6	136	71.6
201	35.11235	80.54677	9/14	10:19	10.3	6.79	0.29	3.4	102	71.1
203	35.11274	80.54707	9/14	10:36	12.6	7.09	5.62	65.6	498	73.4
204	35.11332	80.54606	9/14	10:50	11.7	7.16	4.99	58.3	499	73.4
205	35.11466	80.54564	9/14	11:03	15.9	7.17	4.3	50.4	489	73.8
206	35.11606	80.54512	9/14	11:20	19.9	7.07	3.44	40.4	459	73.8
207	35.11754	80.54533	9/14	11:29	33.1	7.02	2.51	29.4	420	73.8
208	35.11809	80.54537	9/14	11:38	28.2	7.02	3.25	37.9	398	73.6
209	35.11847	80.54442	9/14	11:47	14.5	7.05	3.27	38.2	406	73.4
210	35.11859	80.5431	9/14	11:58	12.7	7.05	3.07	36	402	73.8
211	35.11815	80.54212	9/14	12:13	25.4	7.03	3.25	38.6	396	74.3
212	35.11897	80.54178	9/14	12:22	17.4	7.15	3.76	44.1	391	73.8
213	35.12085	80.54262	9/14	12:56	11.2	7.09	2.95	34.3	384	73.0
214	35.12205	80.54395	9/14	13:05	12	7.01	2.98	35	379	73.8
215	35.12263	80.54272	9/14	13:10	39.9	6.98	2.07	24.3	353	73.0
216	35.1223	80.542	9/14	13:14	42.6	6.91	1.67	19.5	337	73.0
217	35.12228	80.54147	9/14	13:23	90	7.02	5.07	59.7	334	74.5
218	35.12233	80.54047	9/14	13:29	29	7.16	5.7	67.5	332	74.8
219	35.1226	80.53941	9/14	13:35	20.9	7.21	6.08	72.2	331	75.0
220	35.12211	80.5386	9/14	13:40	48	7.25	6.14	72.3	331	74.3
221	35.12314	80.5385	9/14	13:50	12.4	7.2	5.58	65.6	333	73.9
222	35.1237	80.53819	9/14	13:57	25.5	7.23	5.76	67.9	335	74.3
223	35.12588	80.53824	9/14	14:08	21.5	7.19	5.15	60.1	344	73.4
224	35.12732	80.53961	9/14	14:18	17.8	7.28	4.98	58.6	339	74.3

ID	Latitude (N)	Longitude (W)	Date	Time	Turbidity (NTU)	pH	DO (mg/l)	DO (%Sat)	Specific Conductivity (uS/cm)	Temp (°F)
225	35.12815	80.53922	9/14	14:24	21.4	7.31	4.73	55.7	333	74.1
226	35.12886	80.53698	9/14	14:30	26.4	7.28	4.61	54.1	314	74.1
227	35.13293	80.48951	9/14	15:12	4.5	7.71	8.14	99.3	188	77.7
228	35.13092	80.49402	9/14	15:24	0.1	7.51	18.9	229	263	76.8
229	35.13119	80.49428	9/14	15:31	0.8	7.56	7.8	94.3	837	76.6
230	no data	no data	9/14	16:02	6.9	7.54	7.05	85.1	575	76.5
231	35.09909	80.59237	9/14	16:17	5.6	7.14	5.58	66.8	5.79	75.9
232	35.09612	80.59837	9/14	16:42	3	7.18	7.75	94.7	628	77.7
233	35.09518	80.60079	9/14	16:51	49	7.28	1.63	18.7	198	72.1
234	35.10787	80.61551	9/14	17:07	43.3	7.22	2.68	31.1	274	72.7
235	35.1042	80.63397	9/14	17:19	0.4	7.06	8.16	98.1	641	76.1
236	35.10434	80.63426	9/14	17:24	54.4	7.29	2.92	33.6	125	72.1
237	35.1288	80.537	9/15	7:30	14.9	7.47	4.44	51.2	330	72.1
238	35.12906	80.53555	9/15	7:38	11.6	7.29	4.31	49.6	332	72.0
239	35.12732	80.53225	9/15	7:48	12.2	7.2	3.54	41	313	72.5
240	35.12809	80.53156	9/15	7:56	8.5	7.19	3.55	40.9	299	72.1
241	35.12933	80.5312	9/15	8:04	4.5	7.33	5.86	67	294	71.4
242	35.1295	80.53051	9/15	8:09	23.4	7.37	5.89	67.2	293	71.2
243	35.12904	80.52917	9/15	8:15	16.9	7.35	5.36	61.2	291	71.4
244	35.1277	80.52801	9/15	8:24	8.5	7.35	5.09	58.6	291	72.1
245	35.12745	80.52695	9/15	8:34	8.5	7.34	5.14	59.3	279	72.5
246	35.1299	80.52703	9/15	8:48	10.1	7.41	6.18	70.6	274	71.4
247	35.13115	80.52707	9/15	8:56	5.1	7.44	6.29	71.7	271	71.1
248	35.13271	80.5256	9/15	9:03	4.8	7.43	5.71	65.6	266	71.8
249	35.13482	80.52454	9/15	9:10	10.2	7.33	4.98	57.7	238	72.9

ID	Latitude (N)	Longitude (W)	Date	Time	Turbidity (NTU)	pH	DO (mg/l)	DO (%Sat)	Specific Conductivity (uS/cm)	Temp (°F)
250	35.13532	80.523	9/15	9:30	22.5	7.38	6.29	72.8	237	72.7
251	35.13454	80.52183	9/15	9:41	18.3	7.47	6.72	77.4	234	72.3
252	35.13451	80.52116	9/15	10:00	10.6	7.46	6.45	74.1	233	72.0
253	35.13541	80.51936	9/15	10:20	5	7.55	6.41	73.2	231	71.4
254	35.13516	80.51765	9/15	10:25	14.1	7.43	5.36	61.6	229	71.8
255	35.13304	80.51588	9/15	10:35	11.9	7.5	5.56	64.6	213	72.9
256	35.13282	80.51525	9/15	10:40	10.4	7.41	5.48	63.5	210	72.9
257	35.1327	80.51311	9/15	10:52	9.7	7.4	5.2	60.4	206	73.0
258	no data	no data	9/15	10:58	7.9	7.67	6.01	69.6	205	72.7
259	35.13502	80.51162	9/15	11:17	10.9	7.34	5.77	66.8	199	72.7
260	35.13643	80.51194	9/15	11:23	no data	7.73	6.99	80.7	198	72.5
261	35.13703	80.51332	9/15	11:31	10.2	7.48	6.62	76.2	197	72.1
262	35.13924	80.51406	9/15	11:43	10.3	7.33	4.65	54	185	73.0
263	35.13919	80.5123	9/15	11:53	8.5	7.52	6.23	72.5	185	73.2
264	no data	no data	9/15	11:55	7.4	7.45	6.45	75.1	186	73.0
265	no data	no data	9/15	11:58	14.9	7.43	6.74	78.8	183	73.6
266	35.13913	80.51331	9/15	12:02	16.8	7.29	6.03	70.7	183	73.9
267	35.13929	80.51405	9/15	12:06	43.1	7.36	5.96	70.1	184	74.1
268	35.13933	80.51427	9/15	12:09	12.5	7.3	4.92	57.4	185	73.4
269	35.13878	80.51134	9/15	12:40	10.9	7.89	6.82	79.8	183	73.8
270	35.13878	80.51134	9/15	12:45	4.8	7.28	3.12	36.3	154	72.7
271	no data	no data	9/15	12:52	4	7.57	7.05	82.2	175	73.2
272	35.13826	80.51035	9/15	12:54	5.9	7.6	7.31	86.2	183	74.3
273	35.13817	80.50831	9/15	13:06	17.2	7.63	7.65	89.2	180	73.4
274	35.13847	80.50727	9/15	13:11	6.5	7.66	7.93	92.6	180	73.6

ID	Latitude (N)	Longitude (W)	Date	Time	Turbidity (NTU)	pH	DO (mg/l)	DO (%Sat)	Specific Conductivity (uS/cm)	Temp (°F)
275	no data	no data	9/15	13:22	11.9	7.52	7.1	82.4	178	72.9
276	no data	no data	9/15	13:28	7.1	7.39	5.82	68.6	174	74.3
277	35.13634	80.5026	9/15	13:39	10.7	7.82	8.13	97.4	171	76.1
278	35.13442	80.5015	9/15	13:46	13.1	7.84	8.56	102.1	169	75.7
279	35.13269	80.50138	9/15	13:57	7.1	7.88	8.94	108.3	167	77.2
280	35.13197	80.49989	9/15	14:02	6.6	7.89	8.5	101.7	166	75.9
281	35.13145	80.4984	9/15	14:10	9.3	7.7	8.1	95.6	166	74.5
282	35.1309	80.49506	9/15	14:19	8.6	7.87	8.91	107.1	164	76.3
283	35.13115	80.49435	9/15	14:23	11.9	7.58	5.73	65.8	166	72.5
284	35.13125	80.4938	9/15	14:26	16	7.72	8.82	105.4	253	75.7
285	35.13105	80.49401	9/15	14:29	0.1	7.63	16.7	197	269	74.7
286	35.13116	80.4942	9/15	14:32	1.9	7.54	7.84	94.5	790	76.3

C.4 DIURNAL DISSOLVED OXYGEN

Daily cycles of dissolved oxygen concentration can vary due to temperature, macrophyte productivity, and changes in point sources. Diurnal DO was measured using long-term sondes for multiple days at a number of locations along Crooked Creek at ten-minute intervals. The sampling locations for each trip are shown in Figure C-5, with overall statistics reported in Table C-8. Timeseries results of all results for all sites (not temperature-corrected) are seen in Figure C-6, Figure C-7, and Figure C-8.

Table C-8. Dissolved oxygen sonde result statistics (units are mg/L)

Trip	Site	Average DO	Minimum DO	Maximum DO	DO Range
1 (8/13-8/19)	DS of CC#2	4.46	3.60	5.12	1.52
	HWY 601	3.15	2.54	3.72	1.18
	US of CC#2	2.03	1.01	3.25	2.24
2 (8/31-9/2)	Brief Rd	4.97	4.11	6.28	2.17
	SR 1601	4.52	3.30	5.83	2.53

Trip	Site	Average DO	Minimum DO	Maximum DO	DO Range
	HWY 601	3.47	2.82	5.01	2.19
3 (9/13-9/16)	Brief Rd	3.93	3.30	4.94	1.64
	N Rocky River Rd	4.89	3.54	6.70	3.16
	SR 1601	4.67	3.33	6.33	3.00

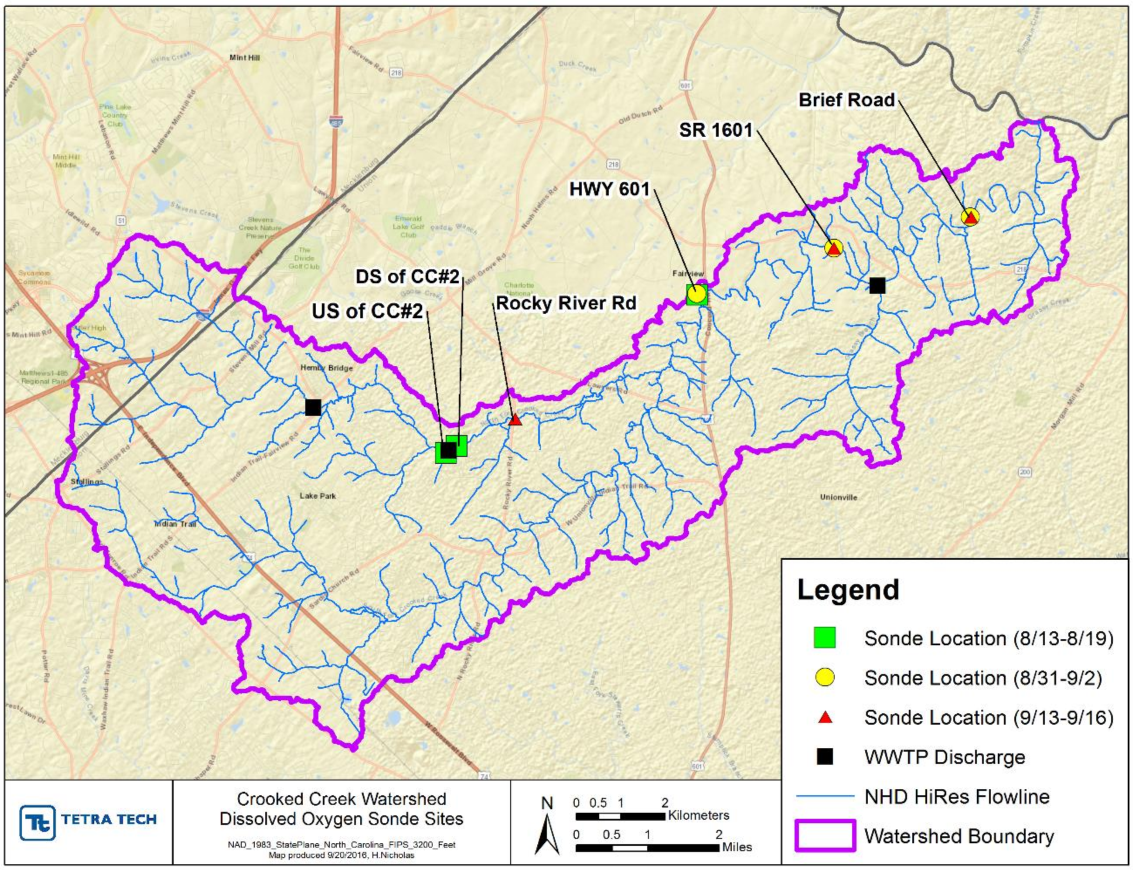


Figure C-5. Dissolved oxygen monitoring sonde sites (all trips)

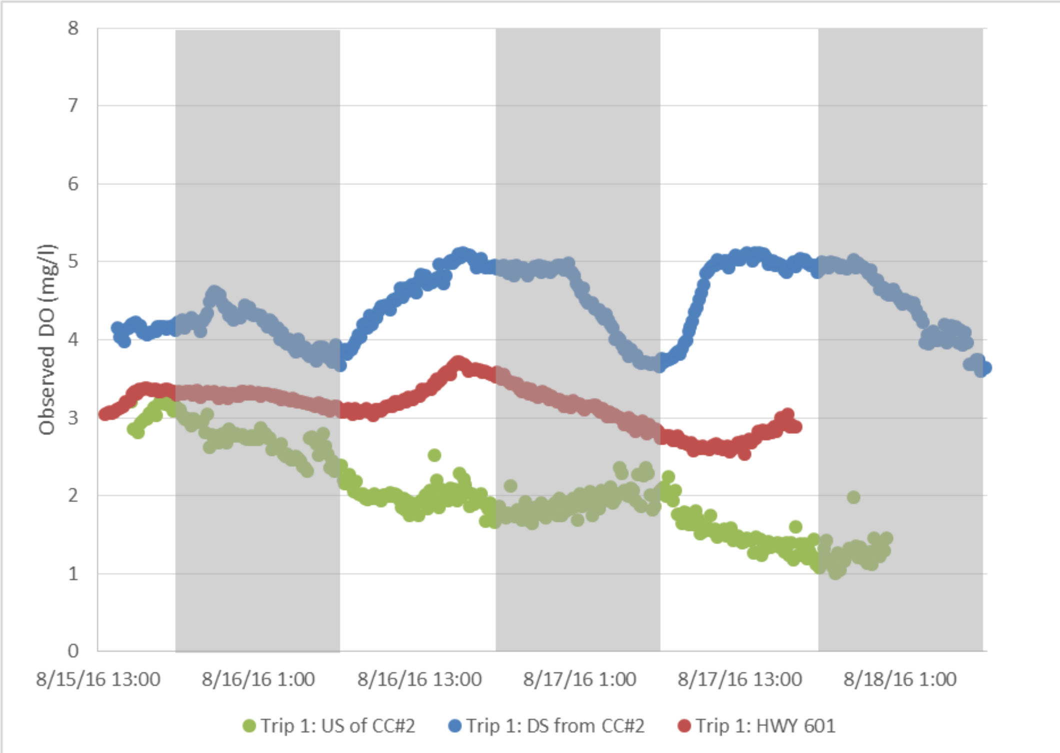


Figure C-6. Diurnal dissolved oxygen concentrations (8/15-8/19), gray areas are night (7pm-7am)

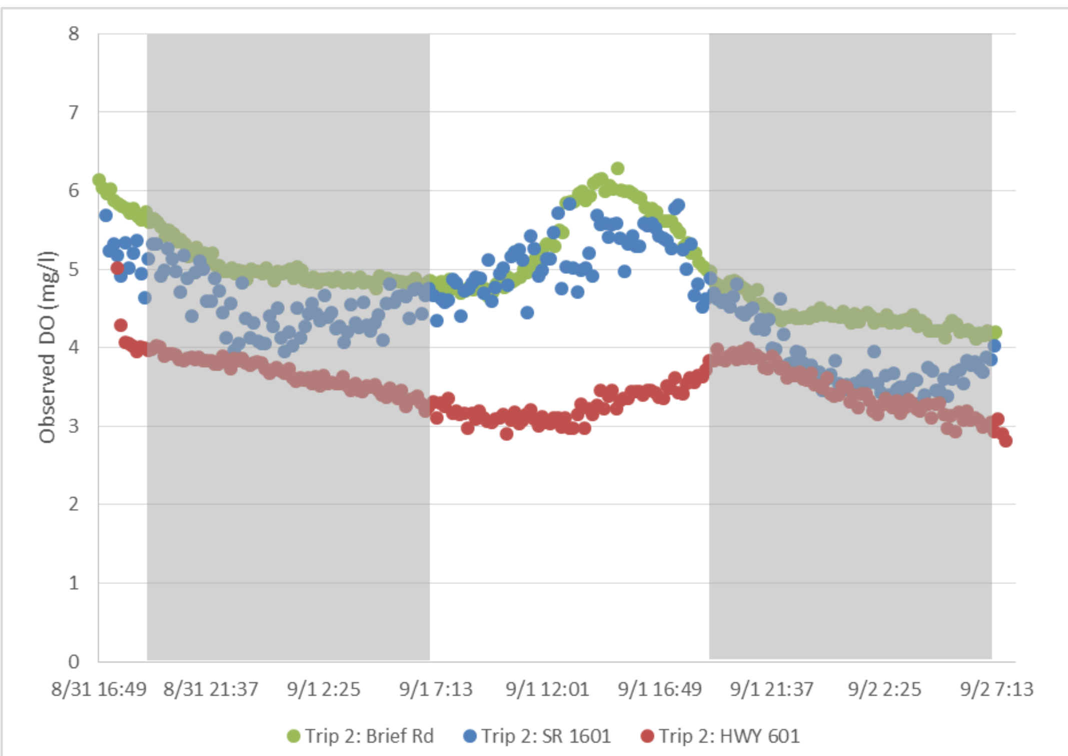


Figure C-7. Diurnal dissolved oxygen concentrations (8/31-9/2), gray areas are night (7pm-7am)

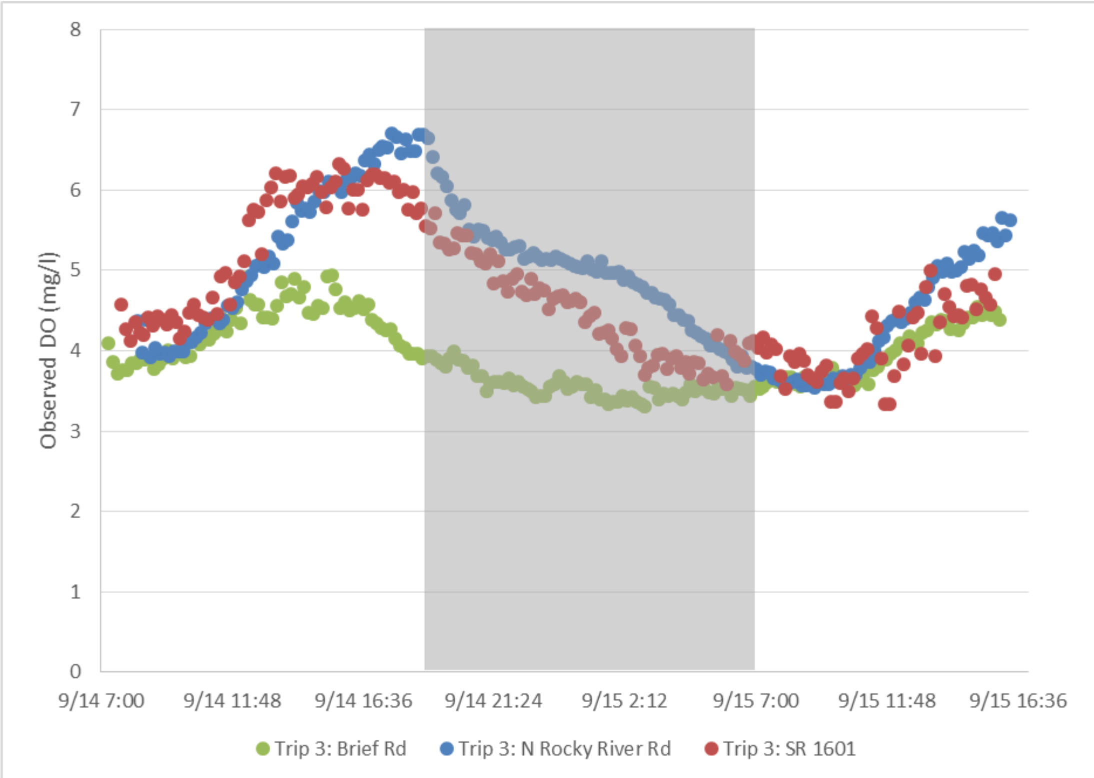


Figure C-8. Diurnal dissolved oxygen concentrations (9/13-9/16), gray areas are night (7pm-7am)

APPENDIX D: CRITICAL LOW FLOW DATA AND RESEARCH

Curtis Weaver from the USGS suggested that 7Q10 flows be estimated in Crooked Creek using low-flow estimates from Richardson Creek which is immediately adjacent to the watershed, due south. A USGS report entitled "Low-flow characteristics and profiles for the Rocky River in the Yadkin-Pee Dee River Basin, North Carolina, through 2002" provides 7Q10 estimates for Richardson Creek, which is underlain by the same key geologic zone as Crooked Creek, the Carolina Slate Belt (Weaver and Fine, 2003). The Carolina Slate Belt is associated with high groundwater infiltration and low flow conditions for many overlying small streams to be zero. Richardson Creek 7Q10 flow data from the USGS report are as follows (Table D-1)

Table D-1. Richardson Creek low flow estimates (Weaver and Fine, 2003)

USGS Gage	Gage Record	Drainage Area (mi^2)	7Q10 Flow (cfs)
02125500	Continuous	163	0.5
02125557	Continuous	8.75	0
0212514705	Partial	3.22	0
02125223	Partial	54.6	0.3
02125310	Partial	89	0.9
02125482	Partial	153	4.2[1]
02125591	Partial	234	0.8
02125462	Partial	4.62	0
02125464	Partial	6.7	0

[1]Flows at this gage were monitored after the addition of a large local WWTP, therefore they are not representative of the same conditions as the other gages.

Excluding the 7Q10 flow associated with gage 02125482 which is not representative of the same period of monitoring, Curtis Weaver proposed using the linear relationship between drainage area and 7Q10 flows in Richardson Creek to approximate low flows in Crooked Creek:

$$7Q10\ Flow\ (cfs) = 0.0036 \times Drainage\ Area\ (mi^2) + 0.0594$$

ROY COOPER
Governor

ELIZABETH S. BISER
Secretary

S. DANIEL SMITH
Director

NORTH CAROLINA
Environmental Quality

July 13, 2021

Andrew Neff, P.E.
Water and Wastewater Division Director
Union County Public Works
4600 Goldmine Rd
Monroe, NC 28112

Subject: Speculative Effluent Limits
New Lower Crooked Creek WRF
Union County
Yadkin-Pee Dee River Basin

Dear Mr. Neff:

First, we appreciate the time and effort by our organization during this process. Based upon data and information provided by you, NCDEQ conducted a review and assessment utilizing the QUAL2K model and subsequent revisions from TetraTech which resulted in the required speculative limits evaluation. We want to note that NCDEQ is not in agreement in the interpretation of the application of the rules for less restrictive winter limits. It is NCDEQ's position that rule 15A NCAC 2B .0404(b) allows for seasonal limits for existing facilities that are meeting the limits in summer but not consistently in winter, this precludes the application of the rule to new facilities. As the Lower Crooked Creek plant is a new facility, the clause for existing discharges in 15A NCAC 2B .0206(d) would not apply as well.

With that said as requested this letter provides speculative effluent limits for 4.6 MGD and 8.2 MGD at a proposed new Lower Crooked Creek WRF. Please recognize that speculative limits may change based on future water quality initiatives, and it is highly recommended that the applicant verify the speculative limits with the Division's NPDES Unit prior to expending time and resources towards any engineering design work.

<u>Receiving Stream.</u> Crooked Creek is located within the Yadkin-Pee Dee River Basin. Crooked Creek has a stream classification of C, and waters with this classification have a best usage for aquatic life propagation and maintenance of biological integrity, wildlife, secondary recreation and agriculture. Crooked Creek has a summer 7Q10 flow of 0.0 cfs, a winter 7Q10 flow of 0.4 cfs, a 30Q2 flow of 1.4 cfs, and an annual average flow of 24.0 cfs.

Based upon an initial review of information available from the North Carolina Natural Heritage Program Online Map Viewer, there are not any Federally Listed threatened or endangered aquatic species identified within a 5-mile radius of the proposed discharge location. If there are any identified threatened/endangered species, it is recommended that the applicant discuss the proposed project with the US Fish and Wildlife Service to determine whether the proposed discharge location might impact such species.

Speculative Effluent Limits. Based on Division review of receiving stream conditions and water quality modeling results, speculative limits for the proposed expansion to 4.6 MGD and 8.2 MGD are presented in Tables 1 and 2, respectively. A complete evaluation of these limits and monitoring requirements for metals and other toxicants, as well as potential instream monitoring requirements, will be addressed upon receipt of a formal NPDES permit application. Some features of the speculative limit development include the following:

- BOD/NH3 Limits. These limits are provided with the understanding that the Grassy Branch (NC0085812) and Crooked Creek #2 (NC0069841) plants will be decommissioned and their permits rescinded upon completion of each of the new plant's flow tiers respectively. Modeling used to support these speculative limits indicated potential for high pH stream values. The actual permit may use site-specific criteria to determine ammonia-nitrogen toxicity limits which may be lower than those in these tables. The EAA requirement listed below will need to include discussion of the removal of the existing plants and their effects on water quality parameters in the stream.

TABLE 1. Speculative Limits for Lower Crooked Creek WRF (Proposed New at 4.6 MGD)

Effluent Characteristic	Effluent Limitations		
	Monthly Average	Weekly Average	Daily Maximum
Flow	4.6MGD		
BODs	5.0 mg/L	7.5 mg/L	
NH3 as N (summer)	1.0 mg/L	3.0 mg/L	
NH3 as N (winter)	1.9 mg/L	5.7 mg/L	
Dissolved Oxygen (daily average)	2: 6.0 mg/L		
TSS	30 mg/L	45 mg/L	
TRC			17 ug/1
Fecal coliform (geometric mean)	200/100 ml	400/100 ml	
Chronic Toxicity Pass/Fail (Quarterly test)	90%		

TABLE 2. Speculative Limits for Lower Crooked Creek WRF (Proposed New at 8.2 MGD)

Effluent Characteristic	Effluent Limitations		
	Monthly Average	Weekly Average	Daily Maximum
Flow	8.2 MGD		
BODs	5.0 mg/L	7.5 mg/L	
NH3 as N (summer)	1.0 mg/L	3.0 mg/L	
NH3 as N (winter)	1.9 mg/L	5.7 mg/L	

Dissolved Oxygen (daily average)	≥ 6.0 mg/L		
TSS	30 mg/L	45 mg/L	
TRC			17 ug/l
Fecal coliform (geometric mean)	200/100 ml	400/100 ml	
Chronic Toxicity Pass/Fail (Quarterly test)	90%		

Engineering Alternatives Analysis *(EAA).* Please note that the Division cannot guarantee that an NPDES permit for a new or expanding discharge will be issued with these speculative limits. Final decisions can only be made after the Division receives and evaluates a formal permit application with all supporting data for the new/expanded discharge. In accordance with North Carolina Administrative Code 15A NCAC 2H.0105(c), the most environmentally sound alternative should be selected from all reasonably cost-effective options. Therefore, as a component of all NPDES permit applications for new or expanding flow, a detailed engineering alternatives analysis (EAA) must be prepared. The EAA must justify requested flows and provide an analysis of potential wastewater treatment alternatives. EAA guidance can be found at:
https://files.nc.gov/ncdeq/Surface%20Water%20Protection/NPDES/permits/eaa-guidance-20140501-dwr-swp-npdes_13.pdf.

State Environmental Policy Act (SEPA) EA/EIS Requirements. A SEPA EA/EIS document may be required for projects that: 1) involve $10 Million or more of state funds; or 2) will significantly and permanently impact 10 or more acres of public lands. Please check with the DWR SEPA coordinator (David Wainwright, 919-707-9045) as to whether your project requires SEPA review. For projects that are subject to SEPA, the EAA requirements discussed above will need to be folded into the SEPA document. Additionally, if subject to SEPA, the NPDES Unit will not accept an NPDES permit application for a new/expanding discharge until the Division has approved the SEPA document and sent a Finding of No Significant Impact (FONSI) to the State Clearinghouse for review and comment.

If you would like to discuss the contents of this letter or any other aspect of the project, please feel to reach out to David Hill at david.hill@ncdenr.gov or (919) 707-3612 at any time. At your request, David will coordinate a Teams meeting with all relevant players. All we will need from you is some proposed dates and times to set up a meeting.

Respectfully,

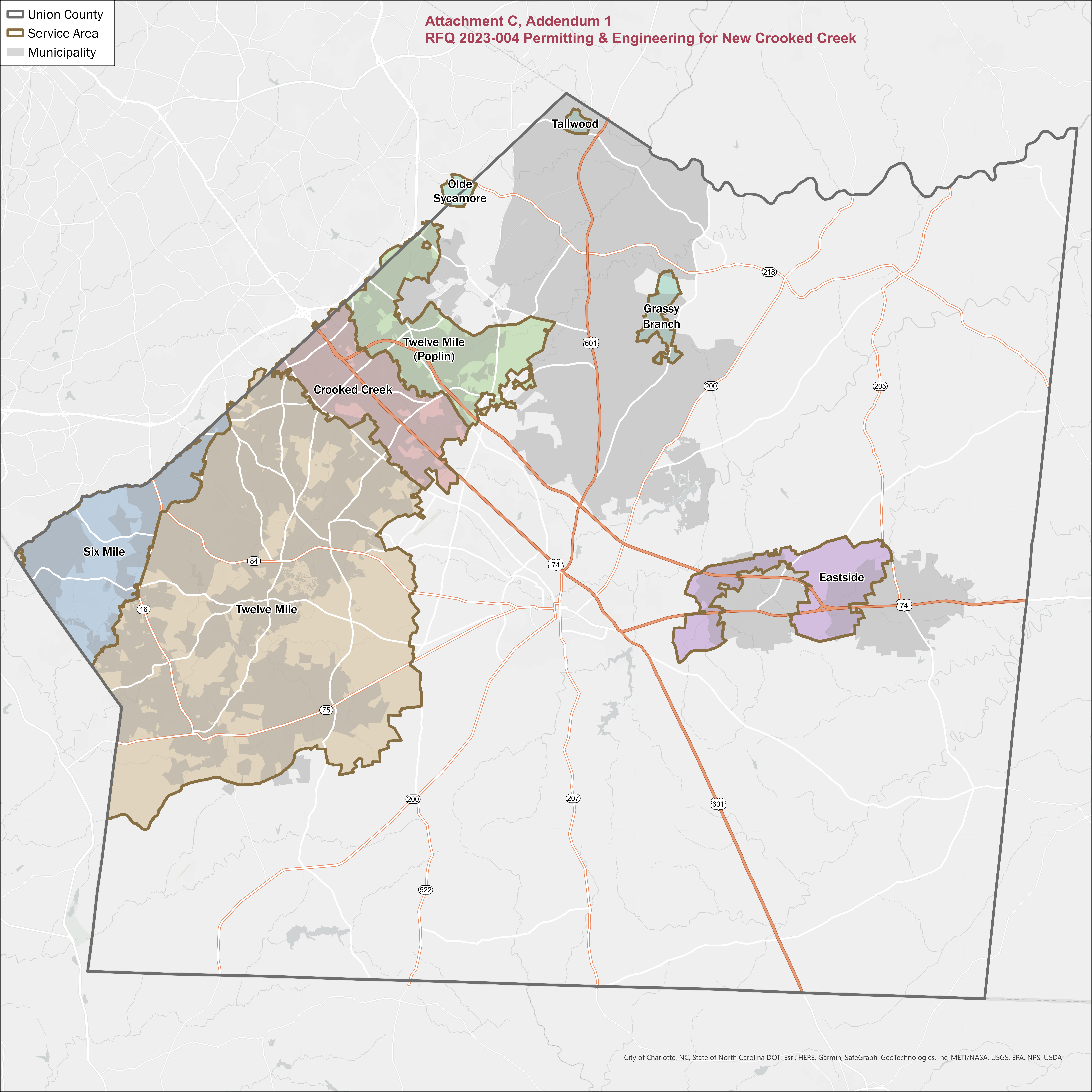
DocuSigned by:

Michael Montebello
Supervisor, NPDES Municipal Permitting Unit

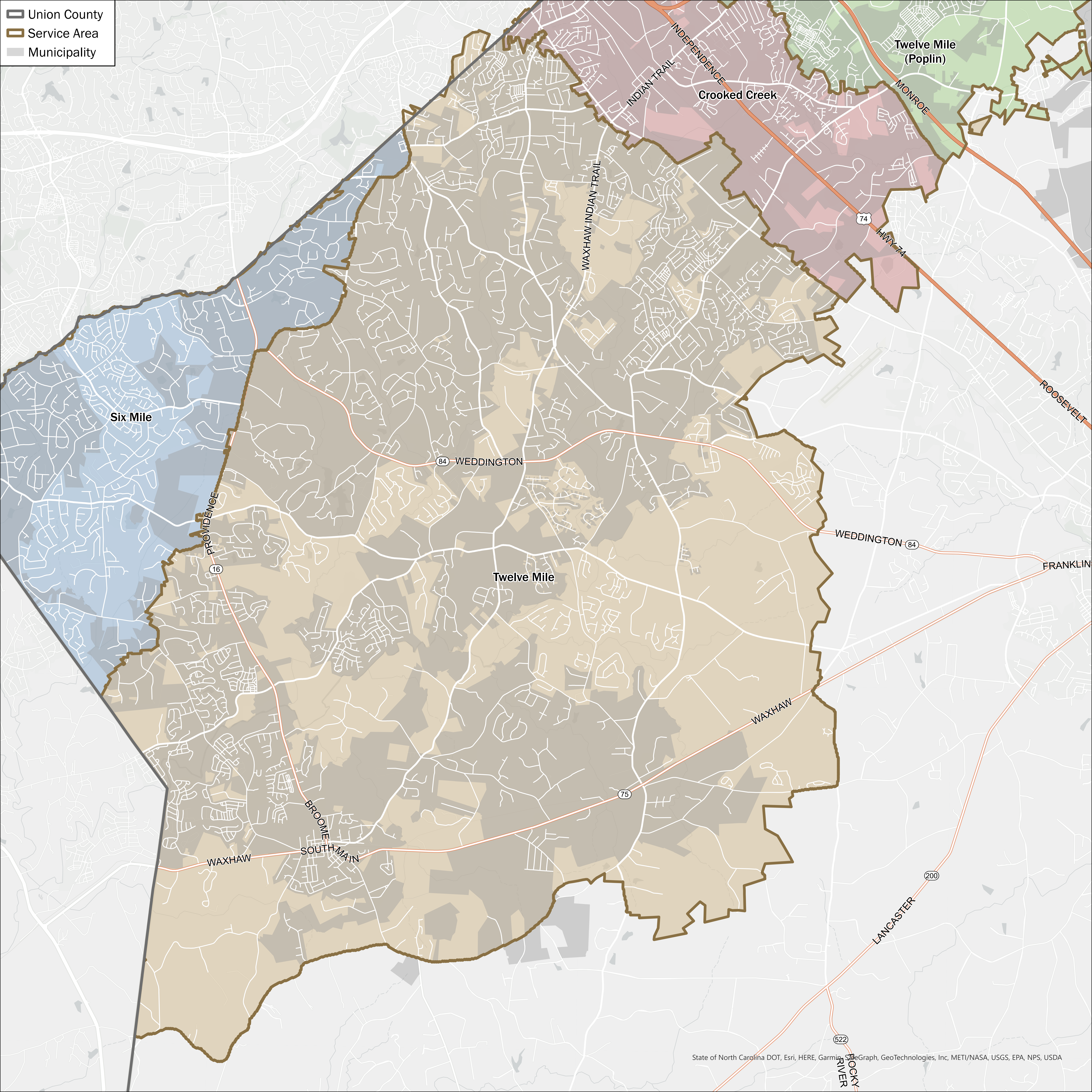
Electronic Copy:

NCDWR Laserfiche
NC WRC, Inland Fisheries, shannon.deaton@ncwildlife.org
US Fish and Wildlife Service, Sarah_mcrae@fws.gov
DWR/Water Quality Regional Office

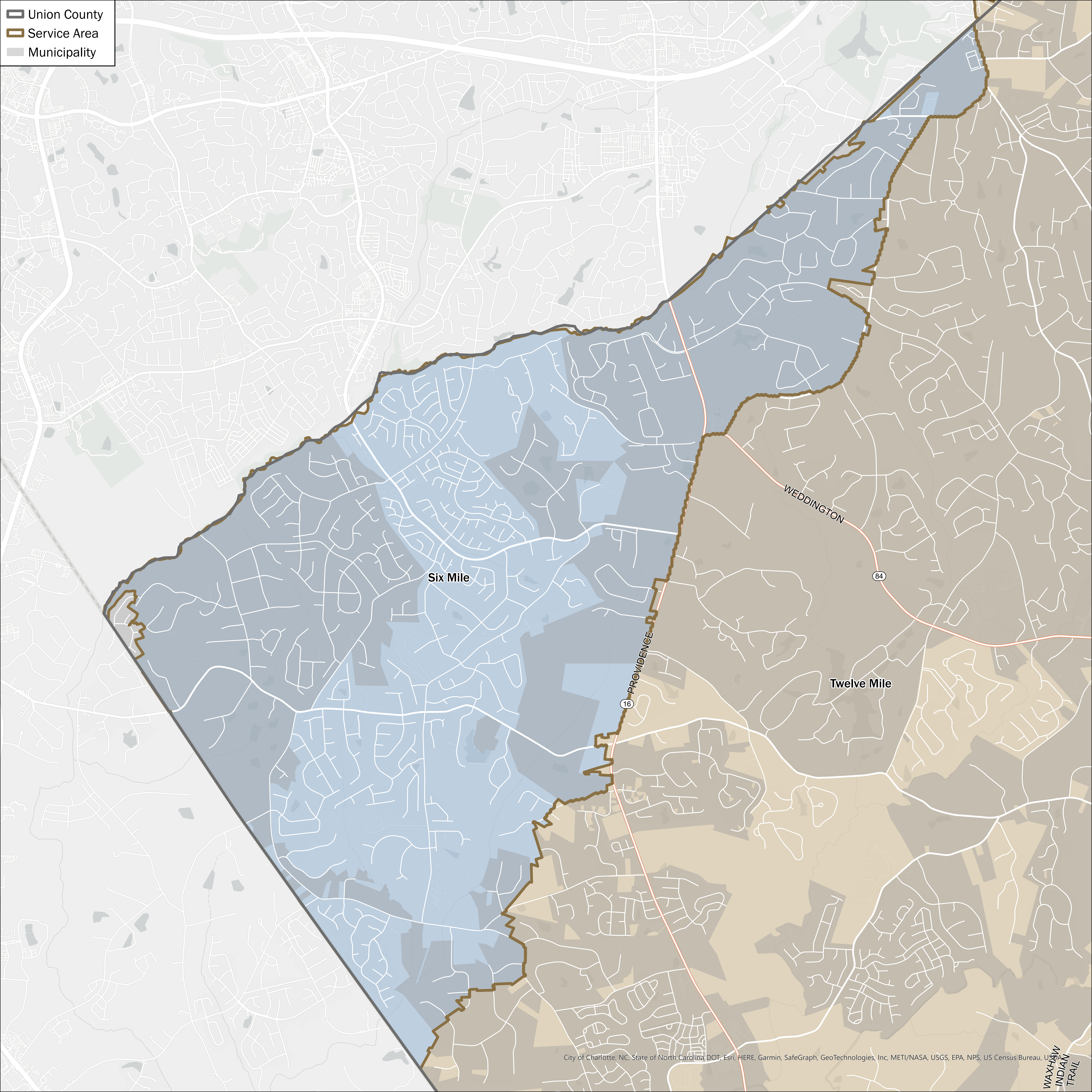
DWR/Modeling, Pam Behm
DWR/Basinwide Planning, Ian McMillan
DWR/NPDES Server>Specs



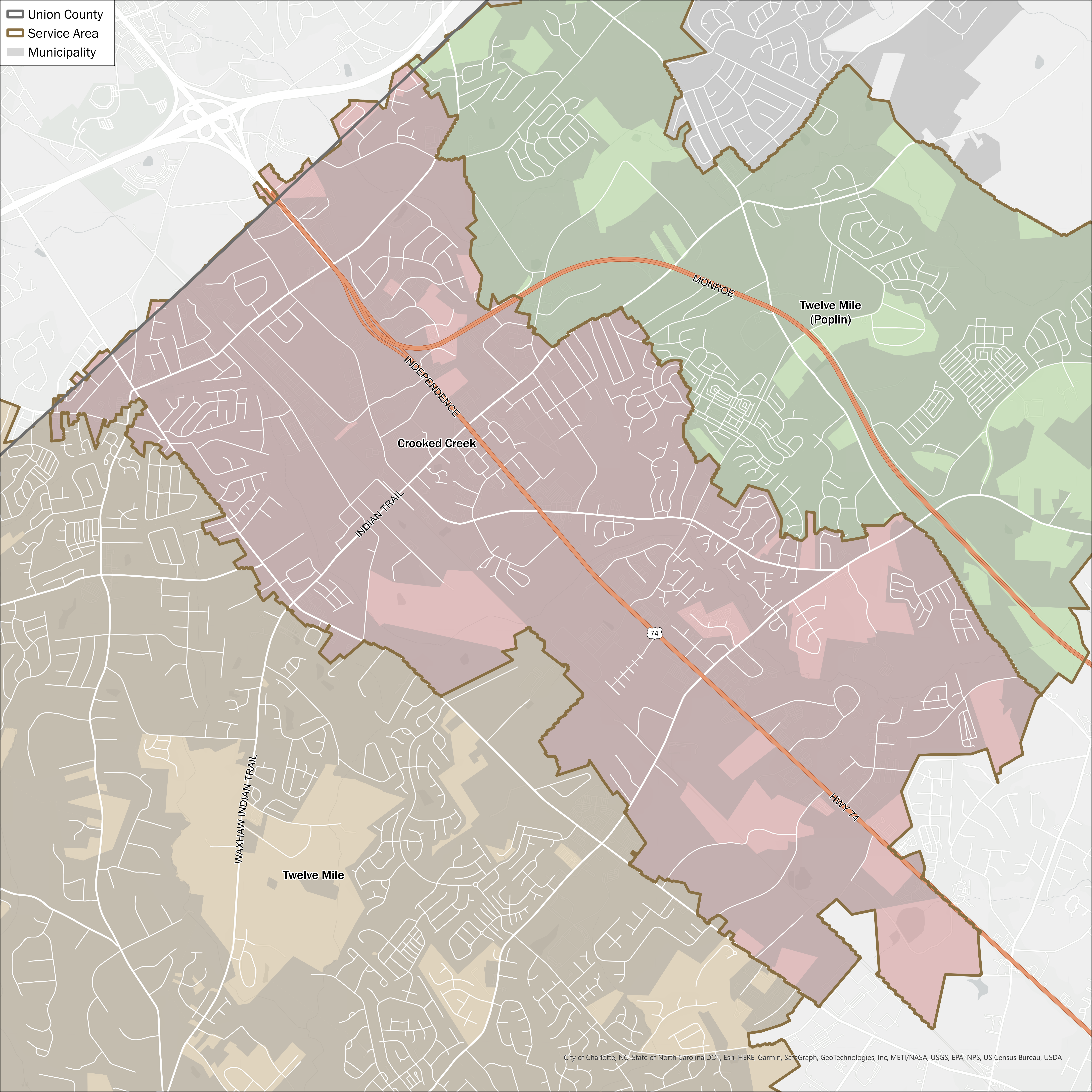
Union County
Service Area
Municipality
Attachment C, Addendum 1
RFQ 2023-004 Permitting & Engineering for New Crooked Creek
Tallwood
Olde Sycamore
Grassy Branch
Twelve Mile (Poplin)
Crooked Creek
Six Mile
Twelve Mile
Eastside
218
601
200
205
74
84
16
75
207
522
City of Charlotte, NC, State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA



Union County
Service Area
Municipality
Twelve Mile (Poplin)
Crooked Creek
INDEPENDENCE
INDIAN TRAIL
MONROE
74
HWY 74
WAXHAW INDIAN TRAIL
ROOSEVELT
Six Mile
84 WEDDINGTON
WEDDINGTON 84
FRANKLIN
PROVIDENCE
16
Twelve Mile
WAXHAW
75
BROOME
SOUTH MAIN
200
LANCASTER
522
ROCKY RIVER
State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA



Union County
Service Area
Municipality
Six Mile
Twelve Mile
WEDDINGTON
84
PROVIDENCE
16
WAXHAW INDIAN TRAIL
City of Charlotte, NC, State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA


Union County
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Municipality
MONROE
Twelve Mile
(Poplin)
INDEPENDENCE
Crooked Creek
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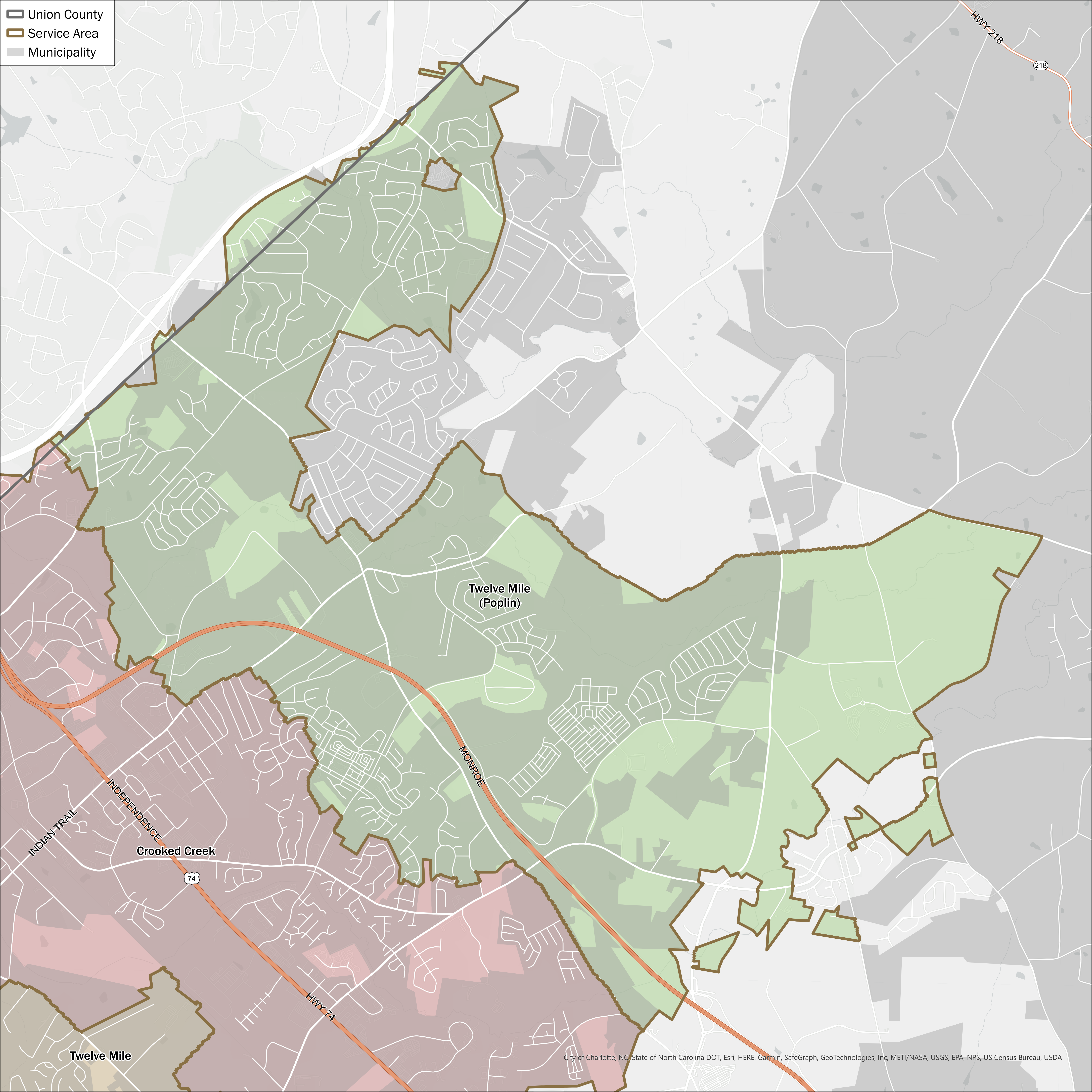
HWY 74
WAXHAW INDIAN TRAIL
Twelve Mile
City of Charlotte, NC, State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA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Municipality
HWY 218
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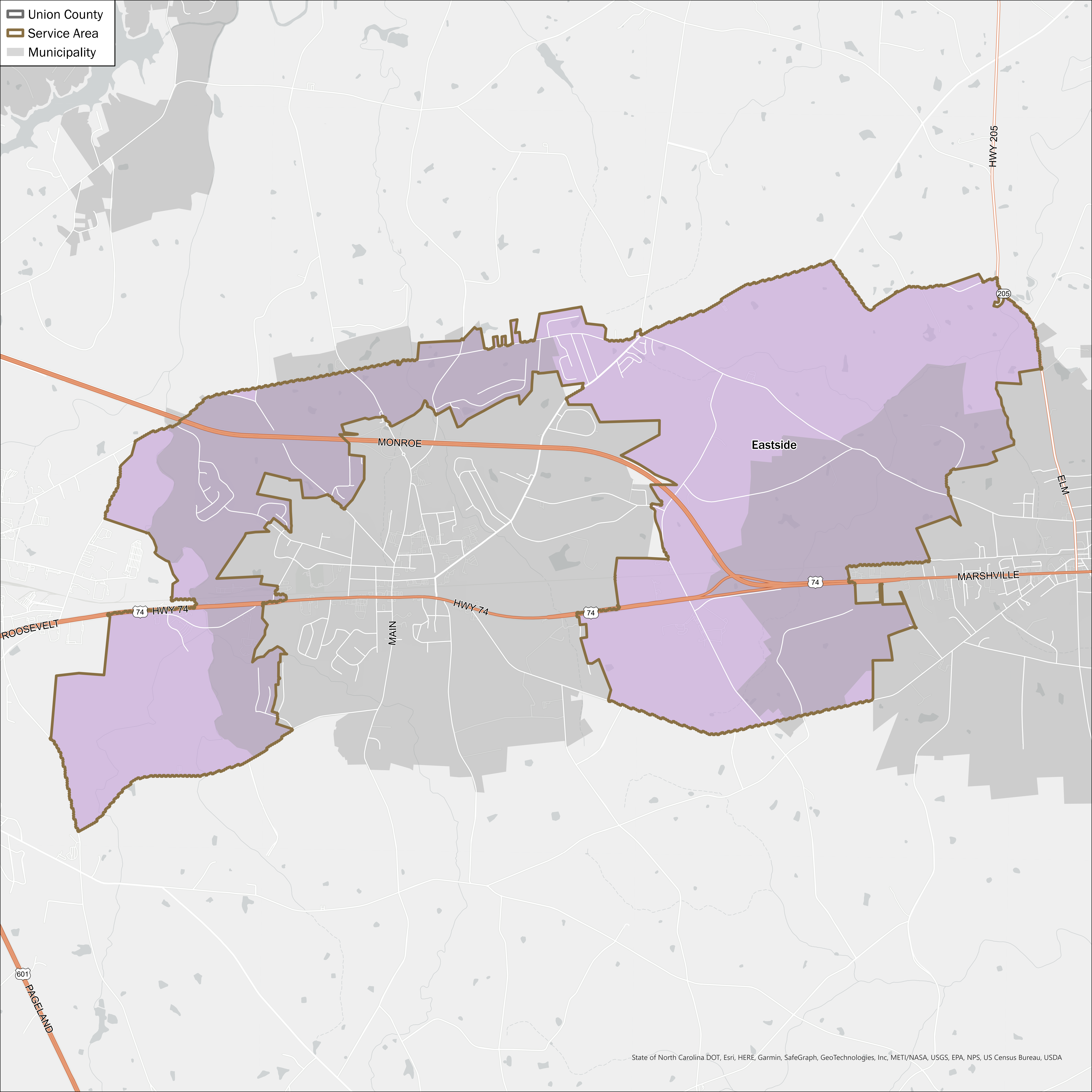
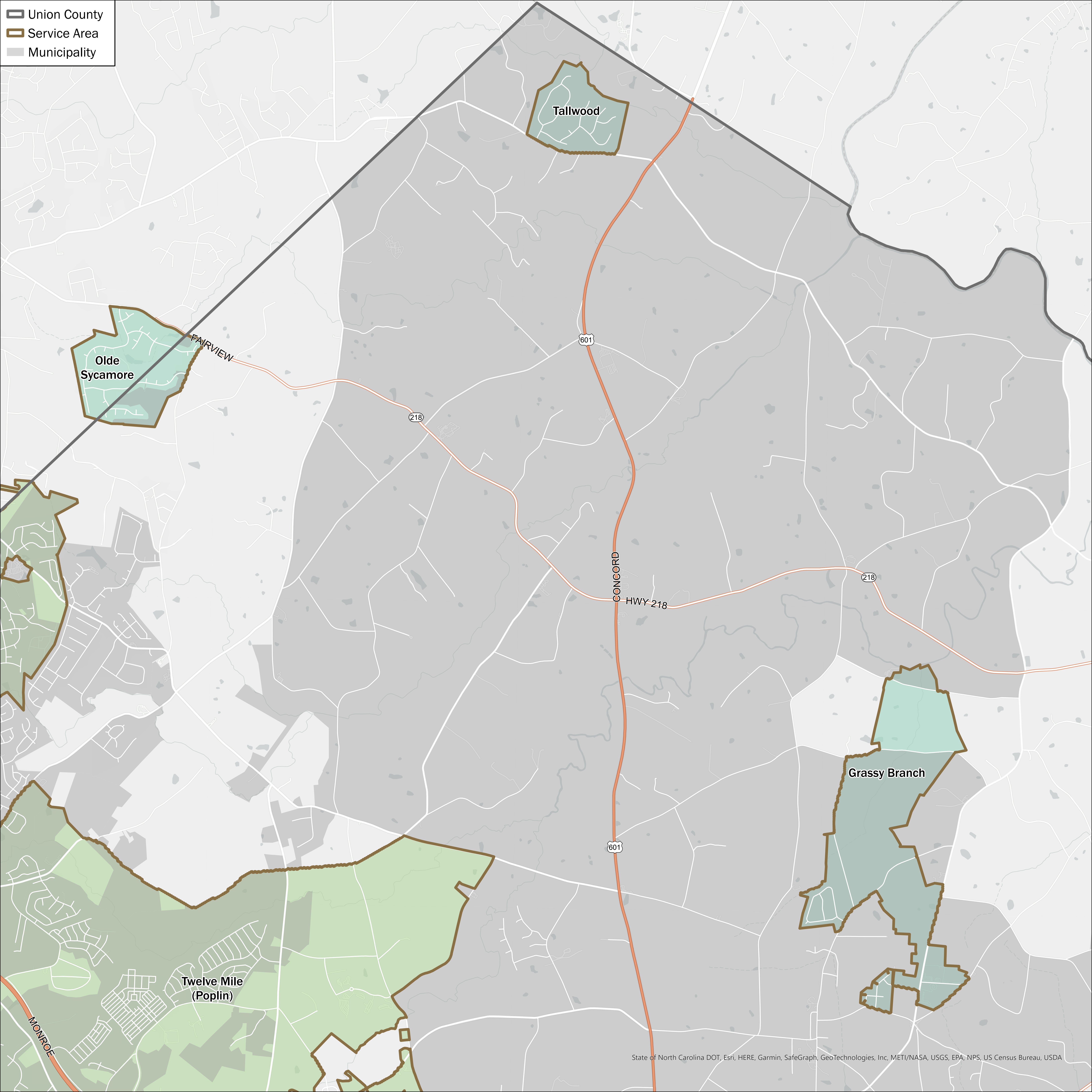
Twelve Mile
(Poplin)
MONROE
INDEPENDENCE
INDIAN TRAIL
Crooked Creek
74
HWY 74
Twelve Mile
City of Charlotte, NC, State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA



Union County
Service Area
Municipality
HWY 205
205
Eastside
MONROE
ELM
MARSHVILLE
74
HWY 74
ROOSEVELT
MAIN
601
PAGELAND
State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA


Union County
Service Area
Municipality
Tallwood
Olde Sycamore
FAIRVIEW
218
601
CONCORD
HWY 218
Grassy Branch
Twelve Mile (Poplin)
MONROE
State of North Carolina DOT, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA

BLACK & VEATCH

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MEMORANDUM

Union County Water
New Crooked Creek WRF
Implementation Plan

B&V Project: 409249
B&V File: 41.5000
20 August 2021

To: John Shutak, UCWUCW Engineering

From: Kent Lackey, B&V Project Manager

Subject: Crooked Creek Site B Analysis

The purpose of this memorandum is to evaluate Site B for construction of the New Crooked Creek Water Reclamation Facility (CCWRF) and conveyance projects to deliver flows to the Site B location.

INTRODUCTION

Union County Water (UCW) is planning the construction of the new CCWRF to meet the projected 2050 flows in their growing service area. The need for a new facility was identified in the *Wastewater Treatment Planning Update* prepared by Black & Veatch in June 2016 and included in the CIP as project CC-T-02. The new CCWRF is expected to be located at "Site B" located where North Fork Crooked Creek crosses Ridge Rd. An evaluation of the infrastructure needed to convey wastewater flows to the new plant is also included.

FLOW AND LOADS ANALYSIS

Flow data from the existing CCWRF and the Poplin Rd Pump Station was received for 2018-2021. The recent data were compared to the projections from the 2016 Wastewater Treatment Planning Update (2016 Update). The average annual flow for the existing CCWRF basin ranged from 1.04 MGD to 1.3 MGD. The average annual to max month peaking factor for Crooked Creek from the 2016 Master Plan was 1.3. Using the master plan peaking factor, the estimated max month flow was about 1.66 MGD. For projection purposes, the 2020 flow was neglected due to the impacts of the coronavirus pandemic on commercial water users. The 2016 projections were greater than the actual flows during 2018-2021 time period. The 2016 Update projected significant growth on the North side of Highway 74 after the completion of the Monroe Bypass. After reviewing the recent data from the basin, the projections for 2020 and 2030 were revised to align with the more moderate rate of growth observed over the last 5 years. Figure 1 shows the 2016 Update projections and the revised projections based on the more recent data. It is expected future flow projections will be updated with the ongoing wastewater system master plan and the resulting future flows will be used for plant sizing and permitting of the new CCWRF moving forward.

NORTH CAROLINA PROFESSIONAL ENGINEER Seal 023997 KENT A. LACKEY 9-16-24

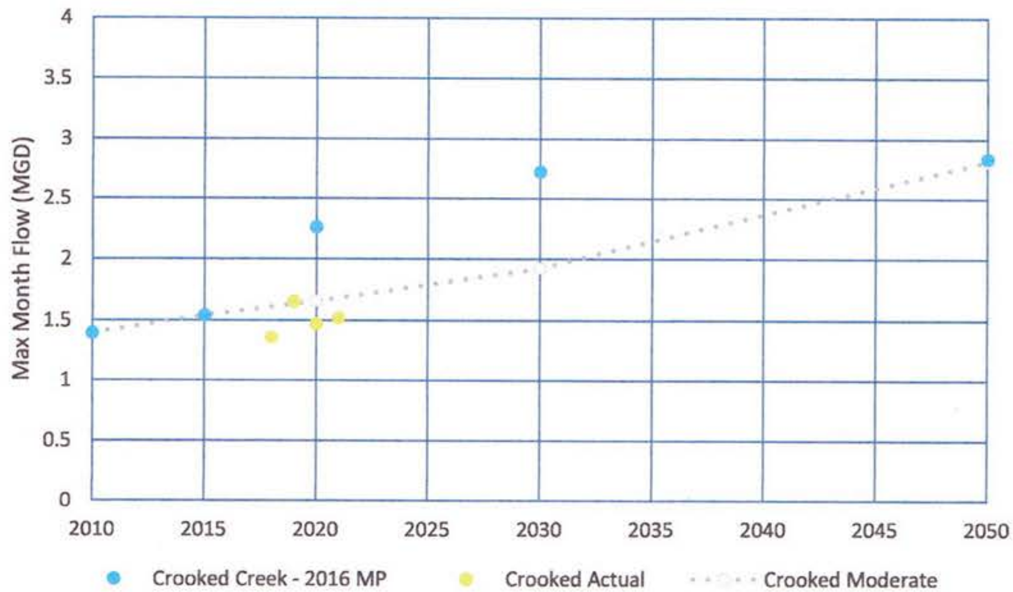

Figure 1 Existing Crooked Creek WRF Basin Flows

The flows in the Poplin basin showed similar trends to the Crooked Creek basin. The 2020 projections were revised to match the 2020 observed flows and a similar growth rate was applied through 2030. Figure 2 shows the Poplin basin flows.

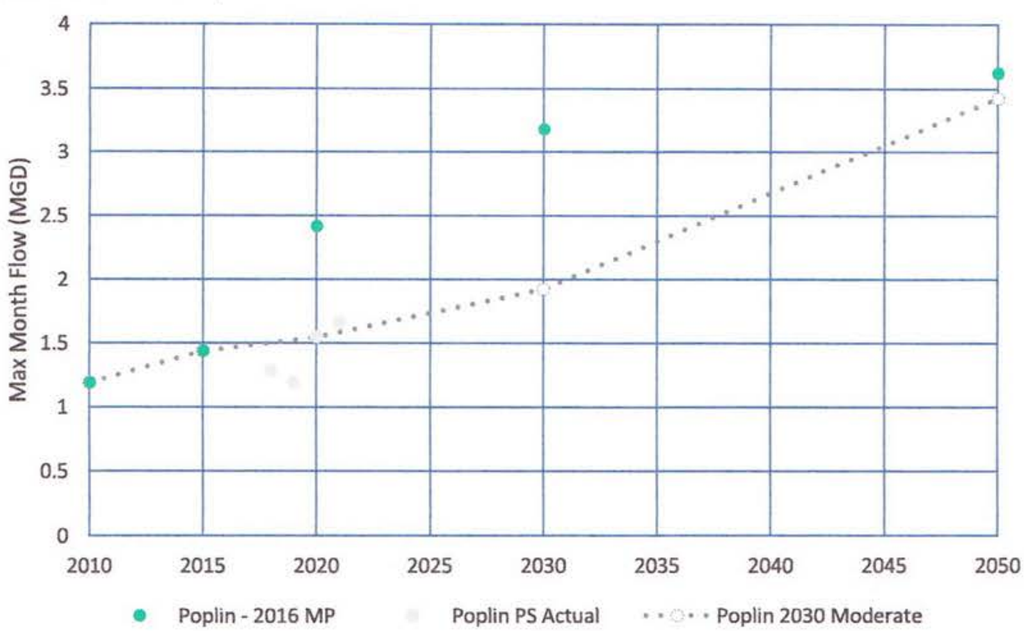

Figure 2 Poplin Pump Station Basin Flows

The 2050 projections in the *Wastewater Treatment Planning Update* were calculated based on available land area and assumptions on future land use. The service area for the new WRF was revised following selection of the Site B location for the New CCWRF. Figure 3 shows the assumed service area used in the 2016 Update and the revised service area for the Site B location (gray).

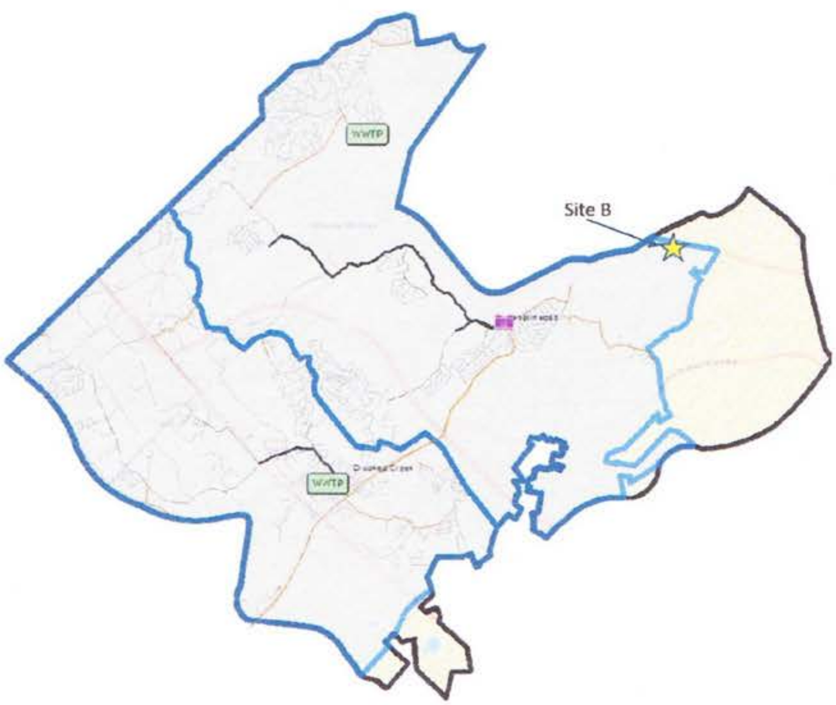

Figure 3 New CCWRF Service Area

The 2016 Update projections for the planning level flow (2050) were revised to align with the new service area. The impact to the flows in the Crooked Creek basin was minimal as much of the trimmed land area was occupied by a quarry and already deemed "non-developable". All future flows assigned to the Poplin Basin outside of the revised service area were removed from the 2050 projection. The revised maximum month flow projections are listed in Table 1. Note: flow projections for the new service areas assumes a septic to sewer conversion rate of 25% by 2050.

Table 1 Revised Maximum Month Flow Projections (MGD) for New CCWRF Service Area

YEAR	EXISTING CCWRF BASIN	POPLIN RD PS BASIN	TOTAL
2015	1.54	1.44	2.98
2020	1.66	1.55	3.21
2030	1.93	1.93	3.85
2050	2.81	3.43	6.24

A preliminary evaluation of the existing CCWRF data was performed to develop wastewater characteristics for the New CCWRF. This information was used to develop preliminary unit process sizing that could form the basis for estimating construction costs.

Based on the 2016 Update and the revised maximum month flow projections shown in Table 1, the new CCWRF is sized for a maximum month (MM) permitted flow of 6 mgd. The annual average daily flow (AA), maximum month average flow (MM), and peak day flow (PD) for the CCWRF were determined based on the existing CCWRF data and service area flow projections (Table 2).

Peak hour flows as high as 27.5 mgd were projected for the new CCWRF Site B service area in 2050 without the use of flow equalization. However, the existing and planned flow equalization tanks at the existing Crooked Creek WRF and at Poplin Pump Station will provide a total volume of 7 million gallons which can be used to reduce flows to a peak day average of lower than 12 mgd. For planning purposes, the new CCWRF was sized for a nominal peak flow capacity of 12 mgd which is consistent with peaking factors observed in the most recent plant influent flow data (PD/AA factor of approximately 2.7).

Using the flow equalization tanks to reduce peak hour flows that are pumped to the new CCWRF Site B helps reduce the size of facilities needed at the plant. There are a number of treatment plant facilities that are typically sized to accommodate the peak hydraulic flow, including influent pumping, screens, grit removal, secondary clarifiers, effluent filters, and disinfection. Sizing these units for a firm capacity of 12 mgd represents significant savings compared to passing the peak hydraulic flow of 27.5 mgd through the plant and/or eliminates the need to construct equalization tanks at the new CCWRF Site B. As these equalization tanks are located in the collection system, there is also an opportunity to reduce pumping rates.

Table 2 Anticipated New CCWRF Flows

FLOW CONDITION	UNITS	VALUE	PEAKING FACTOR	BASIS
Annual Average	mgd	4.6		
Maximum Month	mgd	6.0	1.3	MM/AA
Peak Day	mgd	12.42	2.7	PD/AA

CCWRF influent data from January 2011 to January 2015 were evaluated previously to establish the influent loads to the LCCWRF. Data from that time period suggested that Biological oxygen demand (BOD) and total suspended solids (TSS) concentrations of approximately 200 mg/L would be representative. One additional year of plant influent data from May 2020 through April 2021 was evaluated and found to be similar. Influent load projections should be periodically updated so that any changes and patterns resulting from development are captured in the final plant design criteria at the beginning of the design phase.

Table 3 New CCWRF Influent Wastewater Characteristics

PARAMETER	ANNUAL AVERAGE	MAXIMUM MONTH
Flow, mgd	4.6	6.0
BOD5, mg/L	210	200
TSS, mg/L	250	240
NH3-N, mg/L	23	20

NEW CROOKED CREEK WRF

For the purposes of developing the planning level costs, the new CCWRF was sized for 6 mgd maximum month flow as described earlier. The unit processes included in this scenario were selected to meet the Speculative Limits recently provided by the State for the Site A location (refer to Table 8), and to be consistent with the types of processes UCW is currently operating at its existing CCWRF and 12-Mile Creek WRF. Effluent limits that significantly impact the facilities requirements are the ammonia limits (NH_3-N) which require the biological treatment system to be designed for consistent nitrification to low levels, and the monthly BOD_5 limit of 5 mg/L which would be difficult to achieve without effluent filters.

The preliminary facilities are listed in Table 4 and a schematic is provided in Figure 4. More detailed discussions and evaluation of alternatives would be performed during a later stage to develop more detail and tailor the proposed solution to Union County Water's goals.

Table 4 Proposed New Crooked Creek WRF Facilities

LOCATION	DESCRIPTION	NOTES
Influent Pumps and Preliminary Treatment	Influent Pumps	Sized for 12 mgd firm capacity
	Bar screens and Grit removal	
	Odor Control	
Secondary Treatment	Activated Sludge Basins with anoxic zones	Nitrifying Activated Sludge with solids retention time (SRT) of 10 days under maximum month winter conditions. Fine bubble diffusers and mixers.
	Blower Building	Activated sludge system blowers and aerobic digester blowers
	Secondary Clarifiers	Sized for Class I Redundancy
	Return Activated Sludge and Waste Activated Sludge (RAS and WAS) Pump Station	RAS, WAS, Scum Pumps

LOCATION	DESCRIPTION	NOTES
Tertiary Treatment	Effluent Filters	Disk filters sized for Class I Redundancy
	Ultraviolet (UV) Disinfection	Ultraviolet – Low Pressure, High Intensity
	Reaeration	Cascade Aeration Steps
	Recycled Plant Effluent Pumps	Plant service water uses inside plant
Solids Treatment	Solids Thickening and Dewatering Building	
	Rotary Drum Thickeners	
	Thickened Sludge pumps	
	Aerobic digesters (including option for compositing)	Diffused air
	Belt Filter Presses, Feed Pumps, and Cake Conveyors	
	Truck Loadout	
	Polymer Batching and Feed Systems	Thickening and Dewatering
Support Facilities	Administration Building	Offices, training room, locker rooms, etc.
	Maintenance Building	To support onsite maintenance needs.

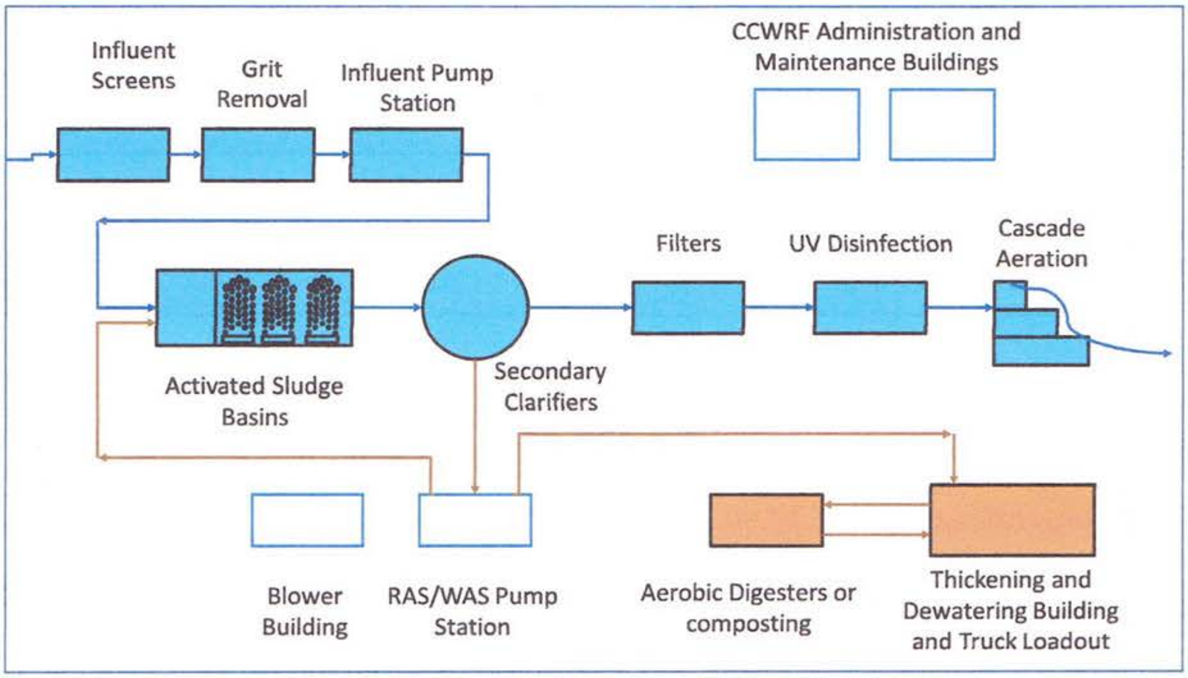

Figure 4 Schematic of New CCWRF

CONVEYANCE INFRASTRUCTURE

New conveyance infrastructure is required to transfer flows from the existing infrastructure in the Crooked Creek and Poplin basins to the new treatment facility at Site B. In planning for the new treatment plant, as much of the existing infrastructure as possible was repurposed. The new conveyance plan includes the existing equalization basins at the old CCWRF site and at the Poplin Pump Station site and well as reusing pumping stations, screening and force mains where available. The project will also allow flow to be pumped to the 12-mile WRF either through the Poplin Road Pump Station or from the existing Crooked Creek WRF. A summary list of the projects relating to conveyance to the new treatment facility are listed below. Detailed evaluation of conveyance options will be performed during the conceptual design phase to determine the most cost-effective solution. The future projects are shown on the map in Figure 5.

- New Infrastructure
  - 48-inch Gravity Interceptor from the Poplin Rd Pump Station to the new Crooked Creek WRF at Site B
- Repurpose
  - Reconfigure existing CCWRF site into a transfer pump station site
  - Re-use the CCWRF 20-inch effluent force main. Condition of this force main will be evaluated during the conceptual design phase to confirm this approach.
- Decommission
  - Existing CCWRF treatment facilities (except influent pump station, headworks, equalization tank, and transfer pump station which will remain in service to pump wastewater to New CCWRF Site B).
  - Fieldstone Pump Station and force main
- The Poplin Rd Pump Station and force main will remain in service for redundancy and potential use in balancing Inter-basin transfer limits.

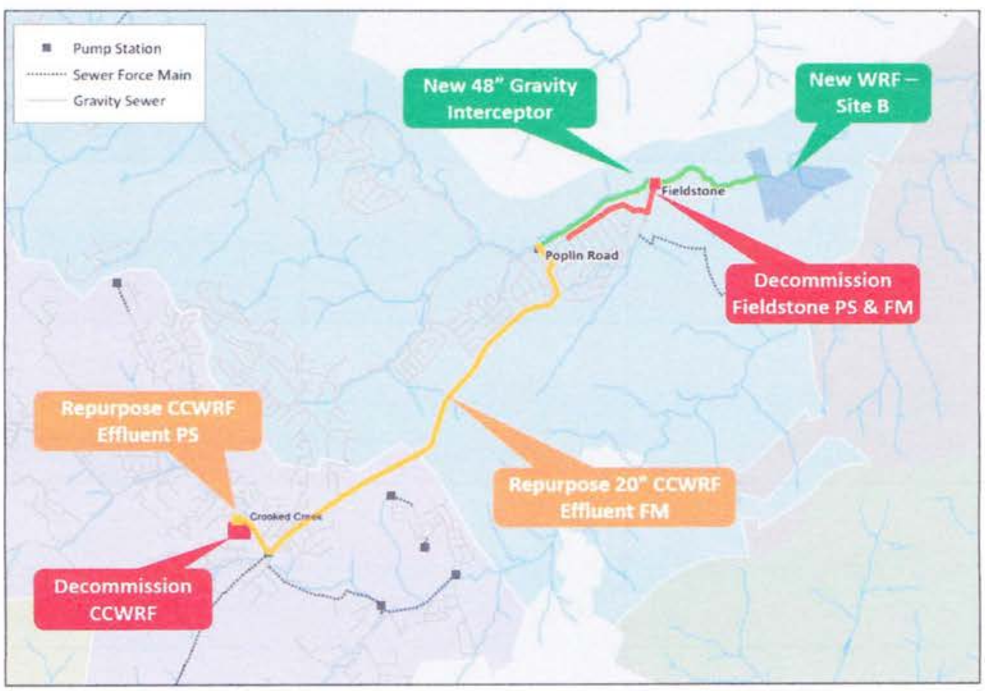

Figure 5 Conveyance Infrastructure to Site B

Crooked Creek Transfer Pump Station

All wastewater flows in the Crooked Creek basin are routed to the existing CCWRF site. From that location, flows will be transferred to the North Fork basin to be treated at the new CCWRF at Site B. The existing infrastructure was assessed to capitalize on reusing facilities to lower the potential cost of new infrastructure.

Recent upgrades to the existing CCWRF include a new 3 MG equalization (EQ) tank new influent pump station, and new screening and grit facilities. The influent pump station pumps raw wastewater up to the screening and grit removal systems. It is recommended that raw wastewater be screened and go through grit removal prior to using the EQ basin. The new configuration of the facilities will be designed to allow flow to bypass the treatment basins. After screening and grit removal, flow will be routed directly to either the effluent pump station or the EQ basin. The EQ basin will be configured to drain directly to the effluent pump station, which pumps the existing facility discharge to North Fork Crooked Creek. The 20-inch effluent force main parallels the Poplin Rd force main and discharges to North Fork Crooked Creek adjacent to the Poplin Rd pump station site.

The transfer capacity at the effluent pump station needs to be able to convey average flows between the South Fork and North Fork basins as well as be able to drain the EQ tanks following a storm event. The hydraulic model calibrated in 2011 showed high infiltration and inflow rates for the Crooked Creek basin with wet weather peaking factors as high as 7.8 during a 1-year storm event. Much of the wet weather volume can be stored in the EQ tank until after a rainfall event. A transfer capacity of 4.6 MGD was selected to allow diurnal peaks and small wet weather events to be transferred without using any EQ volume and also allow for the ability to drain the tank in less than 18 hours even at the future flow condition. At 4.6 MGD, the velocity in the 20-inch force main will be 3.3 ft/s to promote scour of deposited solids. The transfer pump station capacity could be increased to reduce the number of events that are diverted to EQ storage. It is recommended to refine the pump station sizing after completion of the current Master Plan update. The update includes a recalibration of the collection system wet weather flows and updated flow projections that could impact the recommended sizing. The 20-inch force main has sufficient capacity for 9-10 MGD.

Poplin Road Interceptor

A new sewer interceptor is required to move wastewater flows from the existing Poplin Road pump station location to the new CCWRF site. The effluent force main from the old CCWRF will discharge to the new interceptor as well. The interceptor route will follow the North Fork Crooked Creek route 11,000 feet from Poplin Pump Station to Site B located just east of Ridge Road. The alignment of the interceptor will pass within a couple hundred feet of the Fieldstone pump station, allowing for the abandonment of the station and force main and conversion to gravity sewer. Figure 6 shows the interceptor route.

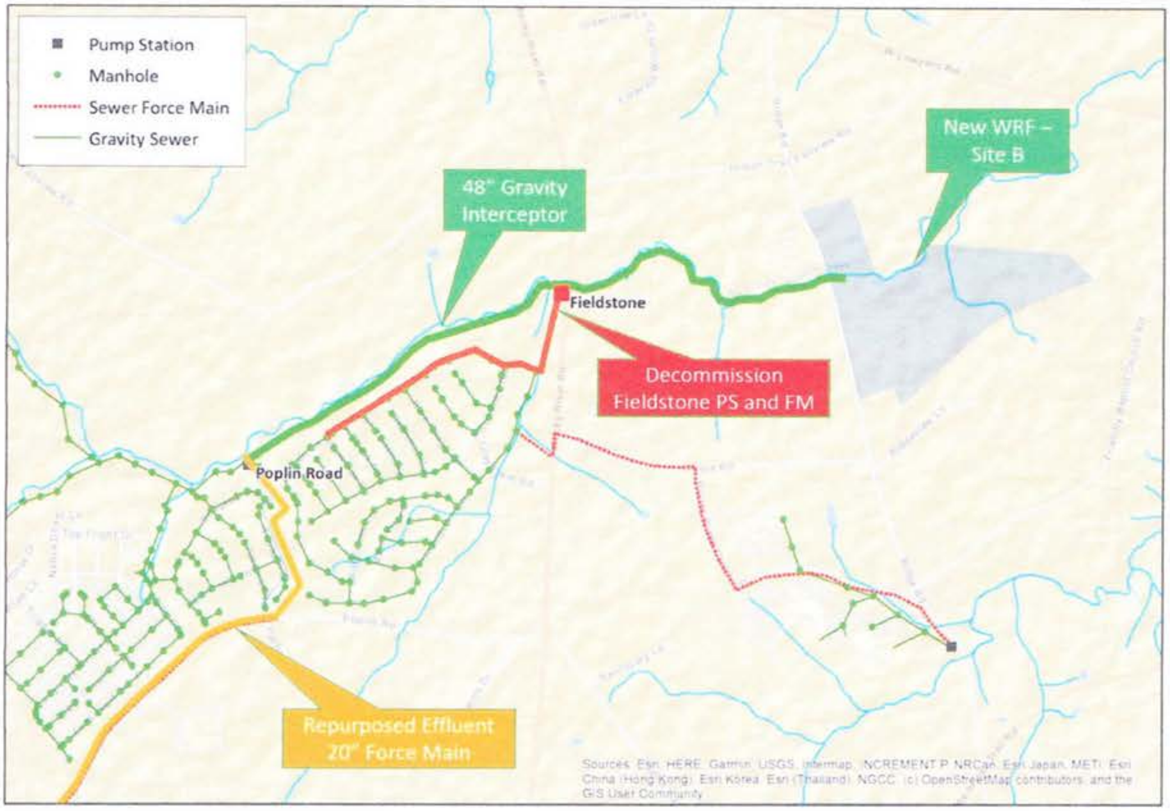

Figure 6 Poplin 48-inch interceptor

Table 5 lists the required diameter size for each planning year assuming the average slope of 0.153%. The significant volume of equalization storage at both Poplin (4 MG) and the old CCWRF site (3 MG) impacts the peak flows expected in the new interceptor. The estimated future flows should be refined once projections are updated in the current master plan. For costing, the 48-inch size was selected. The 48-inch will allow for operational redundancy for the EQ tanks and reduce the number of events per year when both tanks will be used. Reducing the frequency of filling and draining the EQ tanks will reduce maintenance associated with cleaning and odor.

Table 5 Required Interceptor Diameter (in)

YEAR	USING EQ AT POPLIN AND OLD CCWRF	WITHOUT USING EQ
2030	30 in	42 in
2050	36 in	48 in

ESTIMATION OF PROJECT COSTS

A Level 5 Cost Opinion (conceptual level estimate with range of -30% to +50% of the base estimate) was prepared for construction of each infrastructure project as summarized in Table 6.

Table 6 Construction Cost Summary - Level 5 Cost Opinion

PROJECT	BASE COST SCENARIO
New Site B WRF	94,600,000
New Gravity Interceptor	9,400,000
Reconfigure Existing CCWRF into Transfer Pump Station	500,000
Modify Existing CCWRF Force Main for Effluent Transfer to New Plant	1,300,000
Demolish Unused Existing CC WRF Facilities	1,600,000
Demolish Fieldstone Pump Station and connect to new gravity sewer	120,000
TOTAL CONSTRUCTION COST (2021 $)	107,520,000

The estimated construction costs for the program were carried forward into an overall program budget including construction; program contingency; escalation; planning, engineering and construction oversight; easements and land acquisition; and miscellaneous costs as shown in Table 7. Key assumptions included the following:

- Construction estimates for the plant and infrastructure improvements were developed in 2021 dollars.
- A program scope contingency is included in the construction cost total to account for additional components that may be identified once concept planning proceeds in more detail.
- The total construction costs were escalated to the midpoint of construction using an escalation factor of 4.5%. A total of 5.5 years of escalation is included to bring the costs to 2027 dollars.
- Planning, engineering, and construction oversight is included as 15% of construction cost.
- The cost for easements is based on $14,300 per acre for an average 25 ft wide easement along a 2-mile corridor.
- Land acquisition costs for the CCWRF Site B is under development (to be determined).
- An allowance of $1 million is included to cover legal and other related costs.

Table 7 Estimated Budget Summary

PROJECT	LOW (-30%)	BASE COST	HIGH (+50%)
Plant + Infrastructure	75,264,000	107,520,000	161,280,000
Program Scope Contingency	11,290,000	16,128,000	24,192,000
2021 Construction Subtotal	86,554,000	123,648,000	185,472,000
Escalation to 2026 (4.5%, 5.5 years)	24,255,000	34,649,000	51,974,000
Future Construction Subtotal (2026)	110,808,000	158,298,000	237,446,000
Planning, Engineering, and Construction Oversight	16,621,000	23,745,000	35,617,000
Easements	87,000	87,000	87,000
Land Acquisition (Plant Site)	TBD	TBD	TBD
Miscellaneous	1,000,000	1,000,000	1,000,000
ESTIMATED PROJECT BUDGET	128,516,000	183,129,000	274,150,000

Under the current market conditions, it is unlikely that the program could be completed for less than the base cost. Further investigation and comparison with other plants shows that the base cost of $107.5M for the new CCWRF is comparable to that of other projects. For example, the anticipated costs for a new 6 mgd plant in Clayton, NC is $117M based on 2021 actual bid pricing. The Clayton plant has many similarities to that of the New CCWRF but does include some additional facilities that are needed to meet more stringent nitrogen and phosphorus limits. The Clayton program also includes some collection system infrastructure modifications and decommissioning of an existing WRF, for a total budget of approximately $172 million (includes contingencies, 1.5 years escalation to mid-point of construction, and engineering costs). Considering this information, a program budget of approximately $200M for the new CCWRF program seems consistent with these costs.

REGULATORY CONSIDERATIONS

Union County Water received Speculative Effluent Limits for the New CCWRF Site A discharge location on July 13, 2021. The limits were provided for an initial 4.6 mgd capacity and a future phase expansion to 8.2 mgd and are based on Grassy Branch and the existing CCWRF being decommissioned and their permits rescinded.

Although water quality modeling results seemed to support seasonal BOD limits, NC DEQ interprets rules 15A NCAC 2B .0404(b) and 15A NCAC 2B. 0206(d) as applying to existing discharges only and not to new facilities. The speculative limits are summarized in Table 8.

Table 8 Speculative Limits for New Crooked Creek WRF (Site A Location, July 13, 2021)

EFFLUENT CHARACTERISTIC	MONTHLY AVERAGE	WEEKLY AVERAGE	DAILY MAXIMUM
Flow	4.6 mgd and 8.2 mgd		
Biochemical Oxygen Demand (BOD_5)	5.0 mg/L	7.5 mg/L	
Ammonia (NH_3 as N) (summer)	1.0 mg/L	3.0 mg/L	
Ammonia (NH_3 as N) (winter)	1.9 mg/L	5.7 mg/L	
Dissolved Oxygen (daily average)		>/= 6.0 mg/L	
Total Suspended Solids (TSS)	30 mg/L	45 mg/L	
Total Residual Chlorine (TRC)			17 ug/L
Fecal Coliform (geometric mean)	200/100 mL	400/100 mL	
Chronic Toxicity Pass/Fail (Quarterly Test)		90%	

The Site B location for the New CCWRF is upstream from the original Site A location that was the focus of the permitting work to date. To support a Speculative Limits request for Site B, the following tasks are proceeding:

- Validation of the previously modeling stream characteristics with actual steam conditions.
- Assessment of the 7Q10 and 30Q2 flows at the Site B discharge location. If these flows are positive, a request can be initiated to transfer the Site A Speculative Limits to Site B. (The 7Q10 flow is the lowest 7-day average stream flow in a 10-year period while the 30Q2 flow is the lowest 30-day average stream flow in a 2-year period).
- If the flows for these geologic conditions do not meet the minimum criteria, detailed modeling of the new discharge may be needed to support the Site B discharge location.
- As a fallback option, final effluent from the New CCWRF at Site B could be pumped downstream as needed to achieve positive stream flow requirements.
- Speculative Limits request for Site B would need to include continued operation of the Grassy Branch facility which was originally planned for decommissioning. This facility is downstream from Site B and would need to remain in service.
- Once Speculative Limits for Site B are obtained, NPDES permitting can begin.
- It is noted that when conceptual development of the New CCWRF begins, consideration should be made toward future phosphorus, nitrogen, and other limitations to ensure there is a workable pathway for upgrades if needed.

As outlined in the letter from NC DEQ, a SEPA EA/EIS document may be needed prior to submittal of the NPDES permit application. This determination would be made during the next phase of planning and permitting. The overall permitting effort is expected to take 3 to 4 years.