

TOTAL MAXIMUM DAILY LOAD (TMDL)

**For
Total Mercury Fish Tissue
in the
Canoochee River
(Canoochee Watershed)**

Including Listed Segments

Canoochee River – GA Highway 192 to Fifteen Mile Creek

Canoochee River – Fifteen Mile Creek to Cedar Creek

Canoochee River – Cedar Creek to Lotts Creek

Canoochee River – Lotts Creek to Confluence with Ogeechee River



In compliance with the provisions of the Federal Clean Water Act, 33 U.S.C §1251 et.seq., as amended by the Water Quality Act of 1987, P.L. 400-4, the U.S Environmental Protection Agency is hereby establishing a Total Maximum Daily Load (TMDL) for total mercury in fish tissue for the Canoochee River in the Ogeechee River Basin. Subsequent actions must be consistent with this TMDL.

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Date

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TOTAL MAXIMUM DAILY LOAD (TMDL)
Total Mercury in Fish Tissue Residue
In the
In the Canoochee Watersheds

Under the authority of Section 303(d) of the Clean Water Act, 33 U.S.C. 1251 *et seq.*, as amended by the Water Quality Act of 1987, P.L. 100-4, the U.S. Environmental Protection Agency is hereby establishing a TMDL for total mercury for the protection of public health associated with the consumption of fish taken from the following segments of the Canoochee River in the Ogeechee River basin, Georgia:

Canoochee River – GA Highway 192 to Fifteen Mile Creek

Canoochee River – Fifteen Mile Creek to Cedar Creek

Canoochee River – Cedar Creek to Lotts Creek

Canoochee River – Lotts Creek to Confluence with Ogeechee River

The calculated allowable load of mercury that may come into the identified segments of the Canoochee River without exceeding the applicable water quality standard is 9.8 ng/l and 5.52 kilograms per year respectively. The applicable water quality standard is the State of Georgia's numeric interpretation of their narrative water quality standard for protection of human health from toxic substances. The applicable water quality standard provides that total mercury in the Canoochee River shall not exceed the level that will result in more than 0.3 mg/kg mercury in fish tissue residue.

1. Introduction

The U.S. Environmental Protection Agency (EPA) Region 4 is establishing this Total Maximum Daily Load (TMDL) for total mercury for the Canoochee River. The listed segments are as follows:

- Canoochee River – GA Highway 192 to Fifteen Mile Creek
- Canoochee River – Fifteen Mile Creek to Cedar Creek
- Canoochee River – Cedar Creek to Lotts Creek
- Canoochee River – Lotts Creek to Confluence with Ogeechee River

These segments are listed on the State of Georgia's 2004 Section 303(d) list of impaired waters because mercury in certain species of fish tissue exceeds the Georgia Department of Natural Resources (GDNR) Fish Consumption Guidelines State's guidelines.

TMDLs are required for waters on a state's Section 303(d) list by Section 303(d) of the Clean Water Act (CWA) and the associated regulations at 40 CFR Part 130. A TMDL proposes the maximum amount of a pollutant a waterbody can assimilate without exceeding the applicable water quality standard. The TMDL allocates the total allowable pollutant load to individual sources or categories of pollution sources through wasteload allocations (WLAs) for point sources regulated by the National Pollutant Discharge Elimination System (NPDES) program and through load allocations (LAs) for all other sources. The WLAs and LAs in the TMDL provide a basis for states to reduce pollution from both point and nonpoint sources that will lead to restoration of the quality of the impaired waterbody. The purpose of this TMDL is to identify the allowable load of mercury that will result in attainment of the applicable water quality standard, and the unrestricted use of the identified segments for fish consumption.

This TMDL satisfies a consent decree obligation established in *Sierra Club, et. al. v. EPA*, Civil Action: 94-CV-2501-MHS. The Consent Decree requires TMDLs to be developed for all waters on Georgia's current Section 303 (d) list consistent with the schedule established by Georgia for its rotating basin management approach. The State of Georgia requested EPA to develop this TMDL, and as such, EPA is establishing this TMDL for Georgia for the listed segments in the Canoochee watershed.

2. Phased Approach to the TMDL

EPA recognizes that it may be appropriate to revise this TMDL in the future. With such possible revisions in mind, this TMDL is characterized as a phased TMDL. In a phased TMDL, EPA or the State uses the best information available at the time to propose the TMDL at levels necessary to implement applicable water quality standards and to make the allocations to the pollution sources. However, the phased TMDL approach recognizes that additional data and information may be necessary to validate the assumptions of the TMDL and to provide greater certainty that the TMDL will achieve the applicable water quality standard. Thus, the Phase 1 TMDL identifies data and information to be collected after the first phase TMDL is established that would then be assessed and would form the basis for a

Phase 2 TMDL. The Phase 2 TMDL may revise the needed load reductions or the allocation of the allowable load or both. EPA intends to gather new information and perform new analyses so as to produce a revised or Phase 2 TMDL for mercury for the identified segments of the Canoochee River, if necessary, in 2014. The phased approach is appropriate for this TMDL because information on the actual contributions of mercury to the Canoochee River Basin from both point and nonpoint sources will be much better characterized in the future.

2.1. Phased Approach to Atmospheric Sources

The impairment of the Canoochee River is by mercury, largely due to the deposition of mercury from the atmosphere. This TMDL estimates that over 99 percent of the pollutant loads to the waterbodies come from the atmosphere (Section 6.1). Mercury is emitted into the atmosphere by a large number of different sources. The mercury that reaches the Canoochee watershed comes from nearby sources (local sources) as well as sources much farther away, both within the United States (national sources) and outside of the United States (international sources). Only a small part, less than 1 percent, of the mercury loading into Canoochee River is due to discharges from water point sources (e.g., pipes) into the Canoochee River or its tributaries.

EPA has made its best attempt to characterize the air sources of mercury to surrounding watersheds (Savannah/Altamaha/Oconee/Ocmulgee), given the time available to the Agency for proposing the TMDL. The analysis of deposition of mercury from the atmosphere to the Canoochee watershed depends heavily on modeling conducted for the Mercury Study Report to Congress (EPA, 1997). This Study was based on the Regional Lagrangian Model of Air Pollution (RELMAP) modeling, which has several areas of uncertainty, and assumptions that could affect the level of reductions projected by the analysis. Many of these uncertainties are not unique to the analysis of atmospheric deposition prepared for the Canoochee River Creek Mercury TMDL. Some of these uncertainties include the estimates of the amount of the chemical form or species of mercury emitted by each source category; the projected level of reductions from each source category subject to the Clean Air Act (CAA) Section 129 or 111 or MACT; the definition of local sources contributing deposition to the watershed; the contribution from global sources; and other aspects of the modeling. While it is not possible to quantify the net effect of these factors, EPA believes the assumptions made to address these uncertainties are reasonable and consistent with the state-of-the art mercury modeling available at the time this TMDL was prepared. Also, EPA is currently developing legislation to establish additional controls on multiple air pollutants, including mercury, from electric utilities. EPA anticipates that this process will produce reductions in the atmospheric deposition of mercury that will enable achievement of water quality standards.

2.2. Phased Approach to Water Point Sources

At this time, there is relatively little data on the actual loading of mercury from NPDES point sources in the basin. Because, until recently, EPA's published method for the analysis of mercury was not sensitive enough to measure mercury at low trace level concentrations, most NPDES facilities have not detected mercury during their required priority pollutant

monitoring. EPA assumes, however, that all facilities discharge some mercury into the River with their effluent because mercury is pervasive in the environment and is present in rainwater.

Recently, in 1998, EPA adopted a new analytical procedure that detects mercury at low trace level concentrations (0.5 nanograms/liter) (See EPA Method 1631, Revision B, 40 C.F.R. 136.3(a)). A sampling by EPA of a small subset of the NPDES dischargers in Middle Georgia using the trace level Method 1631 analytical technique verifies EPA's assumption that all facilities are discharging some mercury. As NPDES permits are reissued, dischargers will be required to use the version of Method 1631 then in effect for analyzing mercury. (Georgia Rules and Regulations for Water Quality Control, Chapter 391-3-6-.06). Therefore, in the Phase 2 TMDL, data on the concentration of mercury in point source discharges using the more sensitive analytical technique will be available to characterize the actual loading of mercury into the Canoochee River. This will allow EPA, as appropriate, to refine wasteload allocations provided in the TMDL.

Because the impairment of the Canoochee River by mercury is due predominantly to air deposition, the complete elimination or significant reduction of mercury from water point source discharges would produce little benefit in the quality of the waterbodies. In addition, the elimination or significant reduction of mercury would likely be expensive and possibly technically infeasible for point sources to implement. Since many of the NPDES facilities in the basin affected by this TMDL are municipal wastewater treatment plants that are funded through the taxpayers, EPA chooses to move cautiously before implementing wasteload allocations that may cause significant economic hardship in a situation where, as here, EPA expects most of the needed mercury reductions to be achieved through Clean Air Act reductions in mercury emissions from air sources. In this Phase 1 TMDL, EPA expects point source loadings of mercury will be reduced primarily through mercury minimization programs developed and implemented by some point sources.

In summary, during implementation of the Phase 1 TMDL, EPA expects the following activities to occur:

- Where appropriate, NPDES point sources will develop and implement mercury minimization plans;
- Air point sources will continue to reduce emissions of mercury through implementation of the Clean Air Act Section 112 MACT requirements and Section 129 Solid Waste Combustion requirements;
- EPA and the regulated community will improve the mercury air emissions inventory;
- EPA will refine and revise the mercury air deposition modeling to better characterize sources of mercury; and
- EPA and the states will collect additional ambient data on mercury concentrations in water, sediment and fish.
- EPA expects Georgia to adopt a numeric water quality criterion for methylmercury for the protection of human health that is based on EPA's recent criteria guidance, either as published or as modified to reflect site-specific conditions, or that are based on other scientifically defensible

methods. (See 40 C.F.R. 131.11(b))

EPA intends to use the data and information collected and developed during the next ten years to revise the Phase 1 TMDL, as necessary, to assure that the allowable load will be achieved by implementation of the TMDL. EPA's intention to revise the TMDL is consistent with the State of Georgia's Rotating Basin Management Program (RBMP) schedule. Therefore, EPA intends to revise the TMDL one year prior to reissuance of permits in the Canoochee River.

3. Problem Definition

The Canoochee River is on the State of Georgia's 2002 Section 303(d) list. The Canoochee River was listed because mercury in the tissue of largemouth bass, channel; catfish and red breasted sunfish exceeded the Fish Consumption Guidelines (FCG) established by the State of Georgia. (See Georgia Department of Natural Resources, 2000.) The Fish Consumption Guidelines establish limits on the amount of fish that should be consumed over a given time frame (a week or a month) in order to protect human health.

The Georgia Department of Natural Resources (DNR) uses a risk-based approach to determine how often contaminated fish may be consumed at different levels of fish tissue contamination. Table 1 provides the frequency of consumption for three different levels of fish tissue contamination with mercury.

Table 1 Georgia Department of Natural Resources Fish Consumption Guideline

Mercury Fish Tissue Threshold (mg/kg)	Frequency of Consumption
0.23	Once a Week
0.70	Once a Month
2.3	Do Not Eat

If fish tissue contains 0.23 mg/kg (parts per million) or more of mercury, the State's FCG indicates that the fish should not be consumed more than once a week. If fish tissue contains 0.70 mg/kg (parts per million) or more of mercury, the State's FCG indicates the fish should not be consumed more than once a month, and if the fish tissue contains 2.30 mg/kg (parts per million) or greater of mercury, the State issues a "Do Not Eat" guideline. The following FCG are in place for the Canoochee River: largemouth bass, channel; catfish and red breasted sunfish.

The methodology used by the State of Georgia in the development of the fish consumption guidelines targets specific species and size of fish, and uses a conservative risk-based approach in determining whether consumption guidance is warranted for a particular waterbody. EPA supports the State of Georgia's approach to establishing consumption guidelines as an appropriate way to inform the public of the potential risks in eating certain size and species fish.

4. Applicable Water Quality Standard

TMDLs are established at levels necessary to attain and maintain the applicable narrative and numerical water quality standards. (See 40 CFR Section 130.7(c)(1).) In December 2002, Georgia adopted a numeric human health standard for total mercury in fish tissue in the Rules and Regulations for Water Quality Control Chapter 391-3-6. The numeric standard is as follows:

Rule 391-3-6.03, (5)(e)(vii) Mercury: For the protection of human health, total mercury concentrations bioaccumulating in a waterbody, in a representative population of fish, shellfish and/or other seafood representing different trophic levels, shall not exceed a total mercury concentration in edible tissues of 0.3 mg/kg wet weight. This standard is in accord with the USEPA Water Quality Criterion for the Protection of Human Health: Methylmercury, (January 2001, EPA-823-R-01-001), and because nearly 100% of the mercury in fish tissue is methylmercury, adoption of the standard as total mercury is an additional conservative measure. The representative fish tissue total mercury concentration for a waterbody is determined by calculating a Trophic-Weighted Residue Value, as described by the Georgia EPD Protocol (October 19, 2001).

Using this methodology, a waterbody is determined to be impaired when the weighted fish consumption concentration is greater than 0.30 mg/kg. This is based on the assumption that the general population is consuming greater than 17.5 grams of fish per day. The methodology uses a “weighted consumption” approach that assumes that 9.91 grams per day (58.4%) of the total fish consumption is trophic level 3 fish (e.g., catfish and sunfish), and 7.60 grams per day (41.6%) are trophic level 4 fish (e.g., largemouth bass). See Equation 4-1 below.

Equation 4-1 Weight Fish Tissue Calculation to Determine Impairment

Weighted Fish Tissue Concentration = (Geomean Trophic 4 Conc. * 41.6%) + (Geomean Trophic 3 * 58.4%)
where:

Geomean Trophic 4 Concentration = 0.56 mg/kg

Geomean Trophic 3 Concentration = 0.26 mg/kg

EPA collected site-specific data in the listed segment for ambient mercury in fish tissue and in the water column in September 2003 at 2 locations in the Canoochee River and 2 locations on the Canoochee River. Using Equation 4-1, site-specific fish tissue concentration in the Canoochee River yields a weighted fish tissue concentration of 0.38 mg/kg which is greater than the State’s current, applicable water quality criterion of 0.3 mg/kg.

5. TMDL Target

In order to establish the TMDL, the maximum allowable concentration of total mercury in

the ambient water must be determined that will prevent accumulation of methylmercury in fish tissue above the applicable water quality standard of 0.3 mg/kg level. To determine this allowable ambient water concentration, EPA referred to the “Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health” (EPA 2000). The methodology is expressed below (Equation 5-1):

Equation 5-1 Water Quality Standard Calculation

$$WQS = \frac{((ReferenceDose - RSC) * BodyWeight * UnitsConversion)}{(ConsumptionRate * Weighted BAF * FractionMeHg)}$$

where:

WQS = 1.8 ng/l

Reference Dose = 0.0001 mg/kg/day MeHg

RSC = 0.000027mg/kg/day MeHg (Relative Source Contribution from Saltwater Species)

Body Weight = 70 kg

Units Conversion = 1.0E6

Consumption Rate = 0.0175 kg/day Fish

Weighted Bioaccumulation Factor = 235,874

Fraction of the Total Mercury as Methylmercury = 0.13 as measured

In the determination of the allowable ambient water concentration, EPA used the recommended national values from the Human Health Methodology, including the reference dose of 0.0001-mg/k/day methylmercury; a standard average adult body weight of 70 kg; and the consumption rate for the general population of 17.5 grams per day. (Note that a recent report by the National Academy of Sciences confirms that methylmercury is a potent toxin, and concludes that EPA’s reference dose of 0.0001 mg/kg/day is appropriate. (See NAS, Toxicological Effects of Methylmercury, July 2000). For the other factors in the calculation, bioaccumulation and fraction methylmercury, EPA used site-specific data from the Canoochee River collected in June/July 2002. (See Section 6.3.) From this site-specific data, EPA determined a representative “weighted” bioaccumulation factor (BAF). This BAF was calculated by taking the average calculated BAF from each of the two trophic levels to determine a “weighted” BAF based upon the different consumption rates for trophic levels, and the measured fraction methylmercury of 0.10. Using this approach, an allowable concentration of total mercury in the ambient water of Canoochee River for the protection of human health is 1.8 nanograms per liter (parts per trillion). This concentration or less in the ambient water will prevent the bioaccumulation of mercury in fish tissue above 0.3 mg/kg. The site-specific data for total mercury in the water column collected during the monitoring in 2002 was 14 to 12 ng/l.

6. Background

The Canoochee River consists of one watershed: Canoochee. This watershed is located in southeastern Georgia. The USGS Hydrologic Unit Codes (HUCs) for this watershed is: 03060203. The Canoochee watershed is presented in Figure 1.

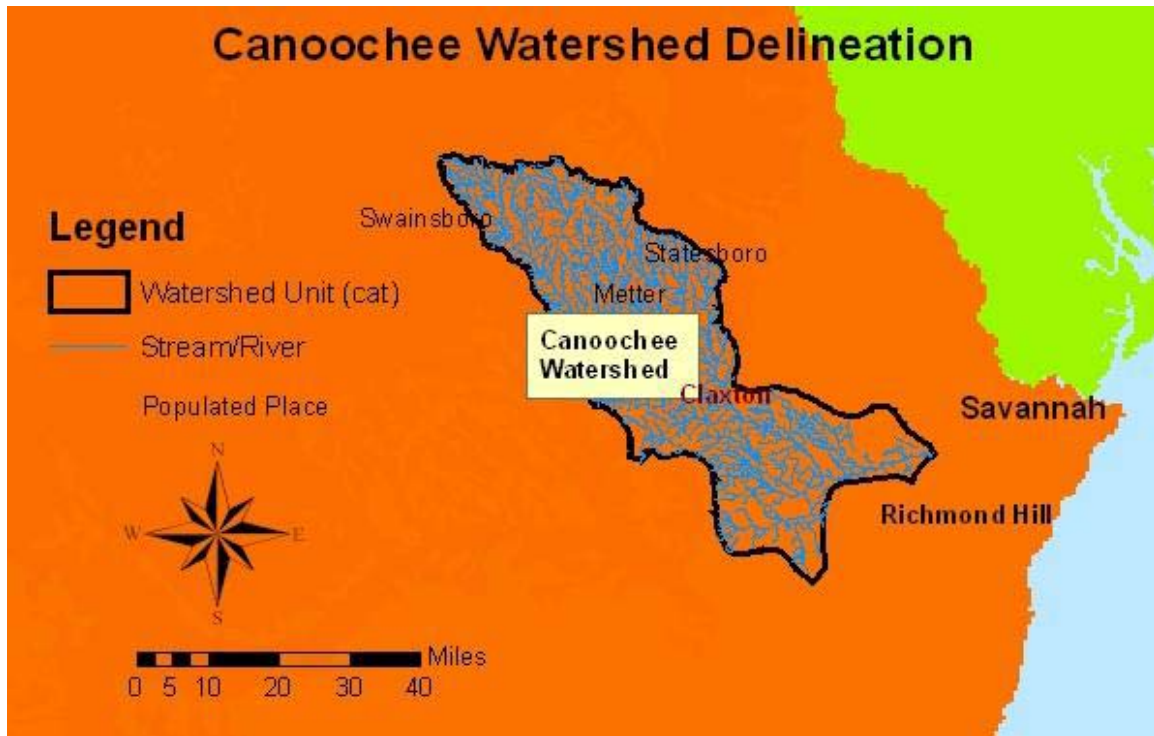


Figure 1 Canoochee River Watershed

The Canoochee watershed has been divided into 6 subwatersheds (Figure 2) for this TMDL, representing all of the major tributaries to the Canoochee River. A total mercury load will be determined for each of these subwatersheds to determine the impact of atmospheric deposition on the Canoochee River.

Canoochee River Sub Watersheds

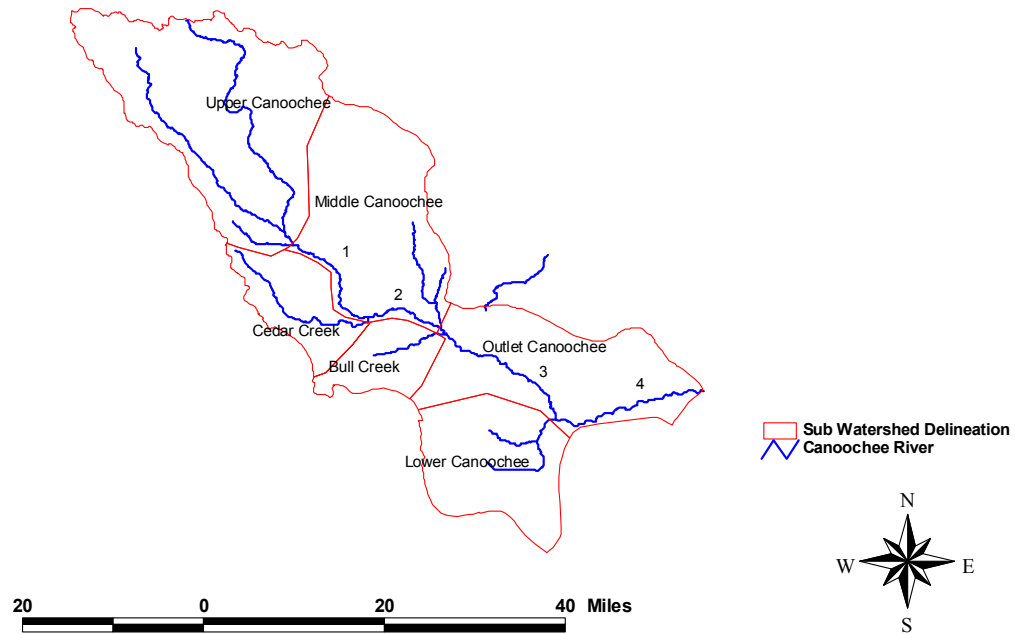


Figure 2 Canoochee River Watershed Delineation

The watershed contains several different types of landuses. The landuses for the Canoochee watershed are given in Figure 3. Different landuses collect and distribute mercury at different rates as a function of runoff and erosion.

Canoochee Watershed Landuses

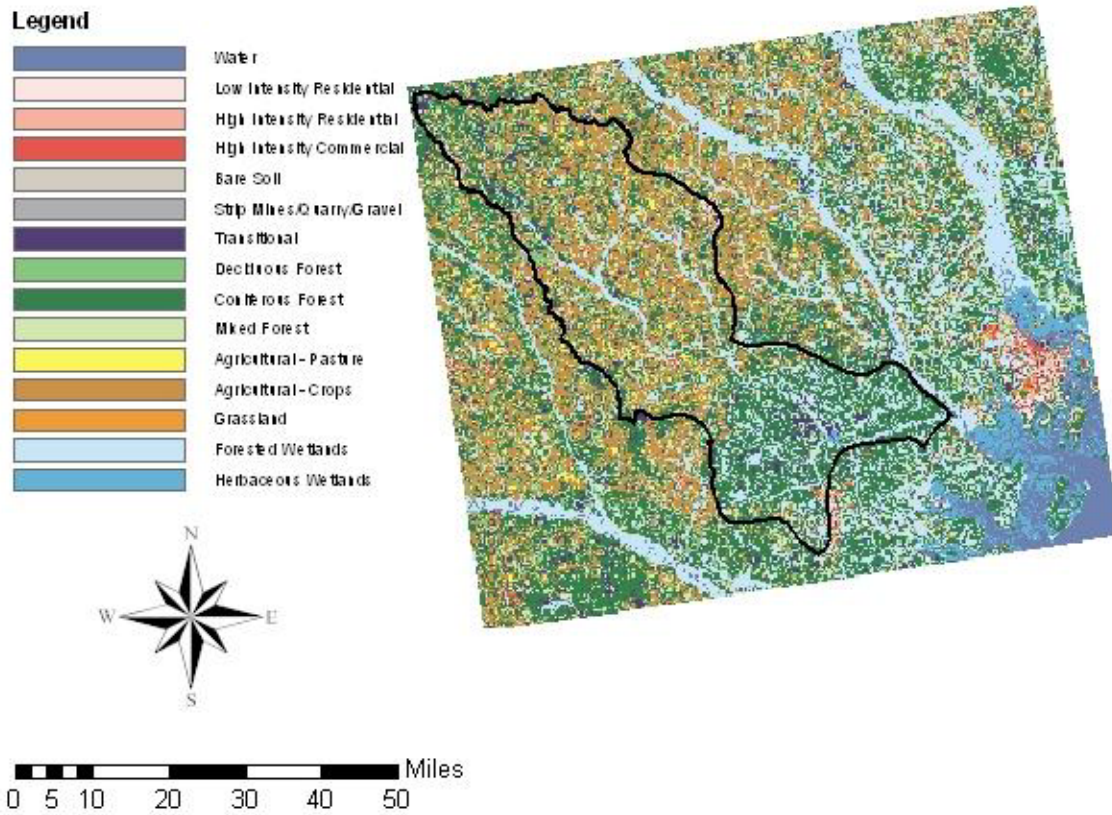


Figure 3 Canoochee Watershed Landuses

This TMDL covers all waterbodies in the Canoochee River watershed. Because the spatial distribution of mercury contamination is not completely known in the streams and creeks throughout the watershed, and fish move throughout the watershed, this TMDL is developed to protect all streams and creeks in the entire watershed from unacceptable accumulations of mercury in fish tissue. As discussed in previous sections of this document, the State of Georgia has issued a Fish Consumption Guideline for various segments of the Canoochee River and tributaries. This guideline was issued due to elevated levels of mercury found in fish flesh collected in the watershed.

6.1. Source Assessment

A TMDL evaluation must examine all known potential sources of the pollutant in the watershed, including point sources, nonpoint sources, and background levels. The source assessment is used as the basis of development of a model and the analysis of TMDL allocation options. This TMDL analysis includes contributions from point sources, nonpoint sources and background levels. The point sources in the Canoochee watershed, which could potentially have mercury in their discharge, are listed in Table 2.

Table 2 Permitted Facilities in the Canoochee

Facility	NPDES #	Receiving Water
Hinesville	GA0047180	Unnamed Trib
Pembroke	GA0033588	Unnamed Trib
Statesboro	GA0023108	Little Lotts Creek
Swainsboro	GA0020346	Crooked Creek
Claxton Polutry	GA0003689	Canoochee River
Swainsboro WPC	GA0020346	Crooked Creek
Metter Waste	GA0025534	Caney Brook
Claxton STP	GA0025551	Canoochee River
Hinesville-Evergreen	GA0033502	Mill Creek

6.2. Watershed Background Load

Significant atmospheric sources of mercury often cause locally elevated areas of atmospheric deposition downwind. Mercury emitted from man-made sources usually contains both gaseous elemental mercury (Hg (0)) and divalent mercury (Hg(II)). Hg (II) forms, because of their solubility and their tendency to attach to particles, redeposit relatively close to their source (probably within a few hundred miles) whereas Hg (0) remains in the atmosphere much longer.

Based on a review of the Mercury Study Report to Congress, significant potential point sources of airborne mercury include coal-fired power plants, waste incinerators, cement and limekilns, smelters, pulp and paper mills, and chlor-alkali factories (USEPA, 1997).

Atmospheric deposition is a major source of mercury in many parts of the country. In a study of trace metal contamination in reservoirs in New Mexico, it was found that 80 percent of mercury found in surface waters was coming from atmospheric deposition (Popp et al., 1996). In other remote areas (Wisconsin, Sweden, and Canada) atmospheric deposition has been identified as the primary (or possibly only) contributor of mercury to the waterbodies (Watras et al., 1994; Burke et al., 1995; Keeler et al., 1994).

6.2.1. Mercury Deposition Network

The objective of the Mercury Deposition Network (MDN) is to develop a national database of weekly concentrations of total mercury in precipitation and the seasonal and annual flux of total mercury in wet deposition. The data will be used to develop information on spatial and seasonal trends in mercury deposited to surface waters, forested watersheds, and other

sensitive receptors. Locations of the MDN sampling stations are shown on Figure 4.

The EPA Region 4 Air Program reviewed the MDN data for a series of sampling stations around the state of Georgia. The sampling stations with the average mercury concentration in precipitation and mercury deposition are presented in Table 3.

Table 3 Average MDN Hg Concentrations and Deposition Rates

Station Number	Station Name	Hg Conc in Precipitation (ng/L)	Hg Dry Deposition (ug/m ² /yr)
GA09	Okefenokee National Wildlife Refuge	14.47	13.25
GA22	Jefferson Street	15.7	13.15
GA40	Yorkville	15.37	10.49
SC03	Savannah River	13.63	12.07
SC19	Congaree Swamp	14.46	11.35
	Average	14.73	12.06

This data is substantially higher than the RELMAP deposition predictions. Using the MDN data, the average annual wet deposition rate was determined to be 14.7 ug/sq. meter and the dry deposition rate was determined to be 12.1 ug/sq. meter/year.

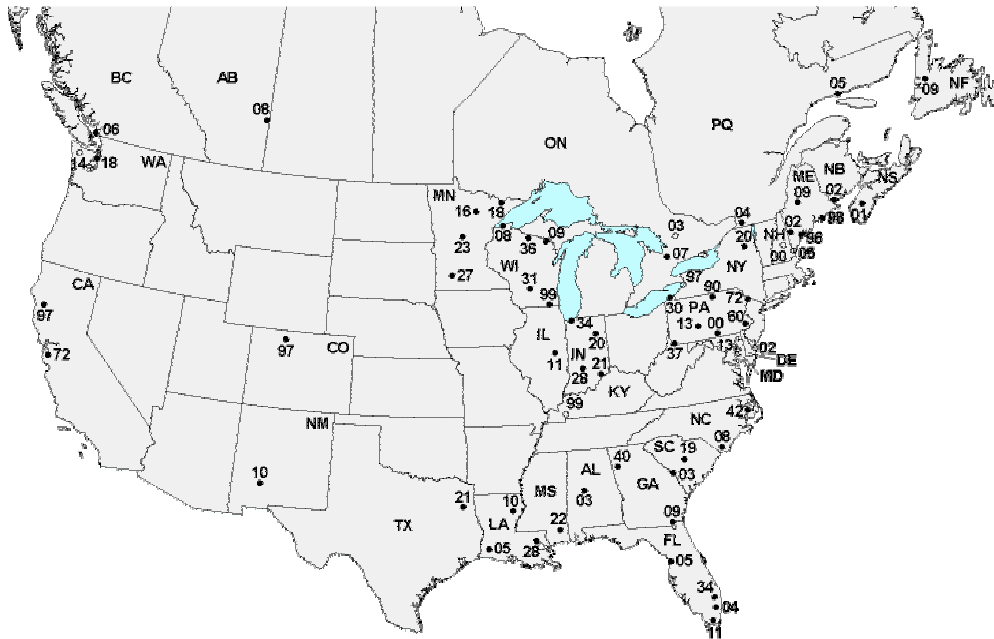


Figure 4 Mercury Deposition Network Sampling Locations

6.3. Available Monitoring Data

The State of Georgia's Environmental Protection Division and the Wildlife Resources Division routinely monitor water and fish tissue in State waters. Focused monitoring work for the Canoochee River, in accordance with the Georgia river basin planning cycle, was conducted in 1998. The metals sampling and analysis work is done by contract with the United States Geologic Survey (USGS). Water samples were collected and analyzed for metals including mercury by the USGS in the Canoochee River basin. Mercury analysis methodology for water samples at that time had a detection limit of 200 ng./l (parts per trillion). This methodology is used by EPA, the USGS and the states in the environmental monitoring programs. Mercury was not detected in water samples from the Canoochee in 1998.

In June of 1998 EPA promulgated Method 1631 for mercury in water for data gathering and compliance monitoring under the Clean Water Act and Safe Drinking Water Act. (See 64 CFR 30417.) This method has a detection limit of 0.5 ng/l (parts per trillion). The availability of this methodology has made detection of mercury in the water column possible. Since low concentrations of mercury in water can lead to significant accumulation of mercury in fish tissue, it was necessary for EPA to sample the Canoochee River using Method 1631 to determine the ambient concentration in the River.

6.3.1. EPA Region 4 Data

Because little ambient mercury data exists for the Canoochee watershed, EPA Region 4 sampled the Canoochee River watershed in July 2003. The purpose of this data collection effort was to collect data needed for the development of this mercury TMDL. The sample locations for the Canoochee River watershed are illustrated in Figure 5. Water column, sediment and fish tissue samples were taken from the mainstem of the Canoochee River. The following sections provide the results of the field sampling for mercury.

Canoochee Sampling Locations

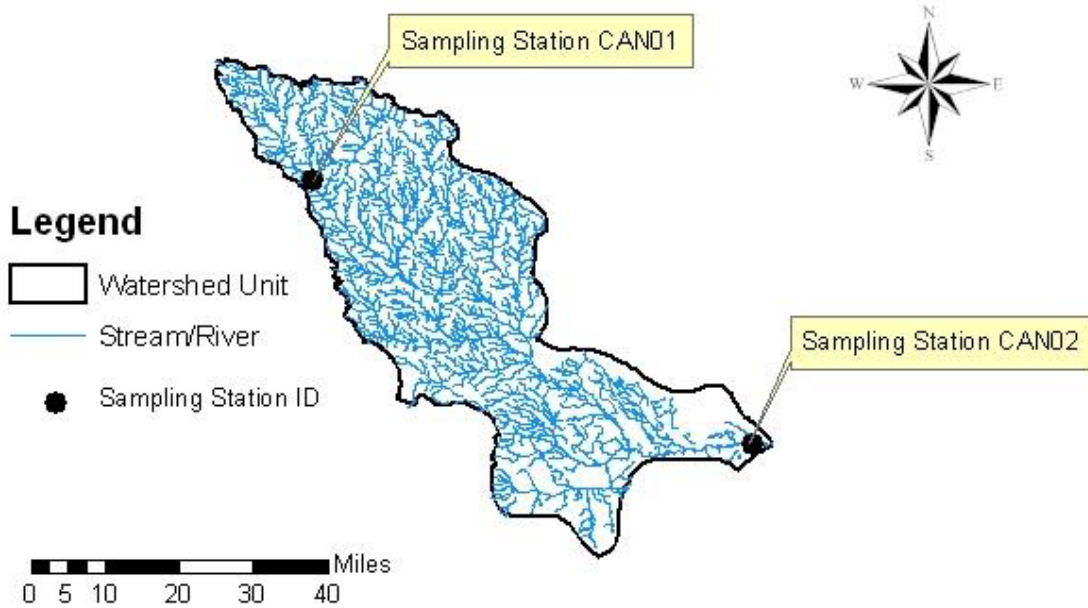


Figure 5 Canoochee River Watershed Sample Locations

6.3.2. *Water Column Data*

Water column samples were taken to determine the ambient concentration of mercury in the water column using Method 1631, an ultra-trace level clean sampling and analytical technique with a detection limit of 0.5 ng/l. The water column samples were analyzed for both total mercury and methylmercury. Because methylmercury is the primary form of mercury taken up in the food chain, it was important to quantify the fraction of the total mercury in the methyl form. Table 4 provides the measured mercury concentrations in the water column in the receiving waterbodies of the Canoochee watershed.

Table 4 Water Column Mercury Concentrations Canoochee River

Station	Total Mercury (ng/L)	Methyl Mercury (ng/L)	Percent MeHg
CAN01	12	1.7	14%
CAN02	14	1.6	11%

6.3.3. *Sediment/Soil Data*

Samples of river sediments were gathered at the same locations as the water samples to determine the amount of mercury associated with the sediments and porewater. This data provides important information that can be used to parameterize the water quality model by providing evidence of the effects of mercury in the sediments on the total mercury water column concentration. Soil samples were collected from the surrounding watershed where the other samples were taken. EPA collected the soil samples to be used in the calibration of the watershed model. . Table 5 provides the mercury concentrations associated with soils collected during the July 2003.

Table 5 Sediment/Soil Mercury Concentrations Canoochee River

Station	THg ($\mu\text{g}/\text{kg}$)		MeHg ($\mu\text{g}/\text{kg}$)	
	Sediment	Soil	Sediment	Soil
CAN01	48	32	3.4	1.8
CAN02	66	71	1.4	0.01

6.3.4. *Fish Tissue Data*

Samples of fish were taken from the Canoochee River within the same area as the water column and sediment samples. Trophic level four fish (largemouth bass) and trophic level 3 (sunfish) were targeted in the collection. The fish fillets obtained during EPA's sampling effort were analyzed for total mercury. Table 6 provides the individual fish data. The fish tissue mercury concentration will be used to determine a site-specific weighted bioaccumulation factor (BAF) for trophic level 3 and 4, and to determine the appropriate target for the TMDL.

Table 6 Fish Tissue Mercury Data Canoochee River

Station	Trophic Level	Species	Total Length (mm)	Whole Weight (g)	Filet Weight (g)	Total Mercury (mg/kg, wet wt.)
CAN01	4	largemouth bass	380	833	290	1.2
		largemouth bass	320	510	179	1.5
		largemouth bass	295	403	154	0.75
		largemouth bass	195	88	33	0.69
		largemouth bass	175	80	26	0.65
	3	redbreast sunfish	240	361	139	0.24

		redbreast sunfish	230	311	117	0.23
		redbreast sunfish	220	276	88	0.70
		redbreast sunfish	195	222	97	0.17
		redbreast sunfish	200	208	87	0.24
CAN02	4	largemouth bass	285	382	138	0.34
		largemouth bass	285	398	145	0.34
		striped bass	325	387	156	0.28
		striped bass	295	281	112	0.29
	3	white catfish	395	1021	287	0.10
		white catfish	390	875	248	0.20
		white catfish	375	763	195	0.34
		white catfish	305	383	99	0.51
		white catfish	275	336	74	0.31

7. Numeric Targets and Sources - Model Development

The link between the fish tissue end-point and the identified sources of mercury is the basis for the development of the TMDL. The linkage is defined as the cause and effect relationship between the selected indicators, the fish tissue end-point and identified sources. This provides the basis for estimating total assimilative capacity of the river and any needed load reductions. In this TMDL, models of watershed loading of mercury are combined with a model of mercury cycling and bioaccumulation in the water. This enables a translation between the end-point for the TMDL (expressed as a fish tissue concentration of mercury) and the mercury loads to the water. The loading capacity is then determined by the linkage analysis as a mercury-loading rate that is consistent with meeting the end-point fish tissue concentration.

7.1. Watershed Hydrologic and Sediment Loading Model

An analysis of watershed loading could be conducted at various levels of complexity, ranging from a simplistic gross estimate to a dynamic model that captures the detailed runoff from the watershed to the receiving waterbody. Because of the limited amount of data available for the Canoochee River watershed to calibrate a detailed dynamic watershed runoff model, a more simplistic approach is taken to determine the mercury contributions to the Canoochee River from the surrounding watershed and atmospheric components. Therefore, a scoping-level analysis of the watershed mercury load, based on an annual mass

balance of water and sediment loading from the watershed is used for the TMDL development.

Watershed-scale loading of water and sediment was simulated using the Watershed Characterization System (WCS). The complexity of this loading function model falls between that of a detailed simulation model, which attempts a mechanistic, time-dependent representation of pollutant load generation and transport, and simple export coefficient models, which do not represent temporal variability. The WCS provides a mechanistic, simplified simulation of precipitation-driven runoff and sediment delivery yet is intended to be applicable without calibration. Solids load, runoff, can then be used to estimate pollutant delivery to the receiving waterbody from the watershed. This estimate is based on pollutant concentrations in wet and dry deposition and processed by soils in the watershed and ultimately delivered to the receiving waterbody by runoff, erosion and direct deposition.

7.2. Water Quality Fate and Transport Model

WASP (Ambrose, et al., 1993) was chosen to simulate mercury fate in the Canoochee River. WASP is a general dynamic mass balance framework for modeling contaminant fate and transport in surface waters. Based on the flexible compartment modeling approach, WASP can be applied in one, two, or three dimensions with advective and dispersive transport between discrete physical compartments, or segments. A body of water is represented in WASP as a series of discrete computational elements or segments. Environmental properties and chemical concentrations are modeled as spatially constant within segments. Each variable is advected and dispersed among water segments, and exchanged with surficial benthic segments by diffusive mixing. Sorbed or particulate fractions may settle through water column segments and deposit to or erode from surficial benthic segments. Within the bed, dissolved variables may migrate downward or upward through percolation and pore water diffusion. Sorbed variables may migrate downward or upward through net sedimentation or erosion.

Two WASP models are provided with WASP. The toxics WASP model, combines a kinetic structure adapted from EXAMS2 with the WASP transport structure and simple sediment balance algorithms to predict dissolved and sorbed chemical concentrations in the bed and overlying waters. WASP simulates the transport and transformation of one to three chemicals and one to three types of particulate material. The three chemicals may be independent, such as isomers of PCB, or they may be linked with reaction yields, such as a parent compound-daughter product sequence. Each chemical exists as a neutral compound and up to four ionic species. The neutral and ionic species can exist in five phases: dissolved, sorbed to dissolved organic carbon (DOC), and sorbed to each of the up to three types of solids. Local equilibrium is assumed so that the distribution of the chemical between each of the species and phases is defined by distribution or partition coefficients. The model, then, is composed of up to six systems, three chemical and three solids, for which the general WASP mass balance equation is solved.

The WASP model was parameterized to simulate the fate and transport of mercury for the development of this TMDL. Site specific and literature values were used to predict water

column concentrations as a function of flow.

8. Total Maximum Daily Load (TMDL)

The TMDL is the total amount of a pollutant that can be assimilated by the receiving waterbody while achieving the water quality target protective of human health through fish consumption. This TMDL determines the maximum load of total mercury that can enter the Canoochee River watershed within a year and still achieve a water column concentration for total mercury at or below the 9.8 ng/l target concentration as determined in the Target Identification Section.

8.1. Critical Condition Determination

EPA's derivations of human health criteria assume that effects of mercury are a long-term exposure to water column concentrations that lead to the accumulation of mercury in the fish tissue. The TMDL utilizes an average annual flow to determine the TMDL. Furthermore, the period of record for climate data stations in the watershed are used to calculate an annual average load of mercury to the system.

8.2. Seasonal Variation

Wet deposition is greatest in the winter and spring seasons. Mercury is expected to fluctuate based on the amount and distribution of rainfall, and variability of localized and distant atmospheric sources. While a maximum daily load is established in this TMDL, the average annual load is of greatest significance since mercury bioaccumulation and the resulting risk to human health that results from mercury consumption is a long-term process. Thus, daily or weekly inputs are less meaningful than total annual loads over many years. The use of an annual load allows for integration of short-term or seasonal variability.

Methylation of mercury is expected to be highest during the summer. High temperatures and static conditions result in hypoxic and/or conditions that promote methylation. Based on this enhanced methylation and high predator feeding activity during the summer, mercury bioaccumulation is expected to be greatest during the summer. However, based on the refractory nature of mercury, seasonal changes in body burden would be expected to be slight. Inherent variability of mercury concentrations between individual fish of the same and/or different size categories is expected to be greater than seasonal variability.

Because the water quality target was determined using data from a one-time sampling event under a single condition, the water quality target calculation could be re-visited when more data is available to determine the annual average condition.

8.3. Margin of Safety

A Margin of Safety (MOS) is a required component of a TMDL that accounts for the uncertainty about the relationship between the pollutant loads and the quality of the receiving waterbody. The MOS is typically incorporated into the conservative assumptions

used to develop the TMDL. A MOS is incorporated into this TMDL in a variety of ways. These include:

- Selecting the highest predicted water column concentration of mercury in the entire stretch of river to determine the load reduction needed to achieve Georgia's water quality standard. This approach conservatively assumes that fish are exposed to the highest water column concentration and accounts for uncertainties associated with identifying the precise locations where the fish take in mercury.
- Assigning a load reduction to point sources. While EPA believes that such reductions, considered together with reductions from air sources, are necessary to achieve water quality standards, EPA also recognizes that future studies of mercury emissions from air sources may indicate that water quality standards can be achieved solely by controlling air sources. By assigning this load reduction to point sources, EPA accounts for the possibility that air source reductions are insufficient. Thus, in addition to reflecting what EPA believes today are necessary load reductions from point sources, these reductions help account for EPA's lack of precise knowledge concerning the relationship between the effects of Clean Air Act controls and water quality.
- Incorporating a number of conservative assumptions in deriving the estimate of anticipated reductions in emissions to the air. These are described in the Analysis of Atmospheric Deposition of Mercury to the Canoochee River Watershed (2000). In addition, the resulting estimate does not take into account reductions resulting from voluntary control measures or new regulations. Therefore, reductions from air sources may possibly be greater than presently estimated.

9. TMDL Development

The TMDL development will integrate the watershed loading with receiving water fate and transport of mercury. Annual average loads and flows will be used to evaluate current loading conditions and to determine what the loads would have to be to achieve the water quality target.

9.1. Model Results

Both the nonpoint source runoff model and the receiving waterbody model were used to determine the maximum load that could occur and protect fish from accumulating mercury to unacceptable levels. This section provides detailed information on how the models were applied, how the watershed and waterbody were broken down into segments (computational boxes) and how the mercury was transported throughout the watershed.

9.1.1. Nonpoint Source

The main driving force for the WCS mercury model is the input of the appropriate wet and dry deposition rates for mercury. The wet and dry deposition rates that were used in the watershed model were determined by a comparison between the RELMAP model results as reported in the Mercury Report to Congress and the Mercury Deposition Network sample

collection site located in the Okefenokee Swamp. Yearly average dry deposition rates of 6.2 $\mu\text{g}/\text{sqm}$ and wet deposition rates of 12.4 $\mu\text{g}/\text{sqm}$ are used in the model. These deposition rates were interpreted from the MDN data. The WCS model was used to calculate the total load of mercury entering the mainstem portion of the Canoochee River from the sub basins delineated in Figure 2. The predicted annual loads are given in Table 7.

Table 7 Annual Average Total Mercury Load from each Sub Basin

Watershed Name	Area (ha)	Fr. Atm. (mg)	Total Hg Load (mg)	Load (mg) /ha	Fr. Imp. Surface (mg)	Fr. Sediment (mg)	Fr. Runoff (mg)	Fr. Dep. on Water (mg)
Upper Canoochee	113770	29603341	2872359	25	734783	885248	933987	318240
Cedar Creek	27592	7186140	880779	32	143629	408412	246837	81900
Bull Creek	20544	5358600	655599	32	125471	250818	197410	81900
Middle Canoochee	79834	20744100	2285199	29	482087	847171	639941	315900
Lower Canoochee	51683	13429259	808609	16	329823	51800	344986	81900
Outlet Canoochee	71783	18680220	953261	13	335018	61112	468110	88920

For each of the sub basins, the total load is presented in mg/yr, and the percentage of the contribution of mercury from soil/erosion, runoff, direct deposition and impervious soil are presented. The loads from each of the sub basins are passed onto the water quality model as an annual load.

9.1.2. *Water Quality Model*

The WASP toxic chemical program was set up to simulate mercury in the mainstem of the Canoochee River. The mainstem of the river was divided into 6 reaches. Each reach was further divided into 2 vertical compartments representing surface water and surficial sediment. The 2 cm deep surficial sediment layer actively exchanges silt and clay-sized solids as well as chemicals within the water column. In addition, this layer is the site for active microbial transformation reactions. Sediment-water column diffusion coefficients were set at $10^{-5} \text{ cm}^2/\text{sec}$.

Two solids classes were simulated sand and silt. Sand makes up most of the benthic sediment compartments, which have a dry bulk density of 0.5 g/ml. Given a particle density of 2.7 g/ml, the sediment porosity is about 0.8 and the bulk density is 1.3 g/ml. Silt is found both suspended in the water column and in the sediment. These simulations assumed that 10 mg/L of silt enters the mainstem from the subwatersheds, settling out at an assumed velocity of 0.3 m/day. Silt in the surficial sediment compartments is assumed to resuspend at a velocity of 0.006 m/day, giving a concentration of about 0.005 g/ml, or about 1% of the surficial sediment. The exchanging silt carries sorbed mercury between the water column and surficial sediment.

Mercury was simulated as 3 components: elemental mercury, Hg^0 ; inorganic divalent mercury, Hg(II) ; and monomethylmercury, MeHg . Hg(II) and MeHg partition to solids and dissolved organic carbon (DOC). These are represented as equilibrium reactions governed by specified partition coefficients. The three mercury components are also subject to several transformation reactions, including oxidation of Hg^0 in the water column, reduction and methylation of Hg(II) in the water column and sediment layer, and demethylation of MeHg in the water column and sediment layer. These are represented as first-order reactions governed by specified rate constants. Reduction and demethylation are driven by sunlight, and the specified surface rate constants are averaged through the water column assuming a light extinction coefficient (here, 0.5 m^{-1}). In addition to these transformations, Hg^0 is subject to volatile loss from the water column. This reaction is governed by a transfer rate calculated from velocity and depth, and by Henry's Law constant, which was set to $7.1 \text{ H } 10^{-3} \text{ L-atm/mole-K}$. Under average flow conditions, velocity ranges from 0.2 to 0.3 m/sec, while depth ranges from 0.37 to 0.69 m. The specified and calculated reaction coefficients used here are summarized in Table 8.

Table 8 Specified and Calculated Reaction Rates and Coefficients

Component	Reaction	Compartment	Coefficient Value
Hg^0	Volatilization	Water	$1.0 - 3.9 \text{ day}^{-1}$ (calc)
	Oxidation	Water	0.001 day^{-1}
Hg(II)	Reduction	Water	0.05 day^{-1} $0.074 - 0.090$ (calc)
	Methylation	Water	0.001 day^{-1}
	Methylation	Sediment	0.00002 day^{-1}
	Partitioning to silt	Water, Sediment	$2 \text{ H } 10^5 \text{ L/kg}$
	Partitioning to sand	Water, Sediment	$4.8 \text{ H } 10^4 \text{ L/kg}$
	Partitioning to DOC	Water, Sediment	$2 \text{ H } 10^4 \text{ L/kg}$
MeHg	Demethylation to Hg(II)	Sediment	0.0001 day^{-1}
	Demethylation to Hg^0	Water	0.1 day^{-1} $0.074 - 0.090$
	Partitioning to silt	Water, Sediment	$2 \text{ H } 10^5 \text{ L/kg}$
	Partitioning to sand	Water, Sediment	$1 \text{ H } 10^3 \text{ L/kg}$
	Partitioning to DOC	Water, Sediment	$2 \text{ H } 10^5 \text{ L/kg}$

The Canoochee River simulation was conducted using annual average flow and load. The average flow simulation was run for 20 years, so that steady-state conditions are achieved in the water and surficial sediment. The flows, depths, velocities, and volumes used for annual average conditions are summarized in Table 9.

Table 9 Flows, Depths, Velocities and Volumes used in WASP Model

	Segment	Length	Width	Depth	Volume	Flow
1	Canoochee	42872.84031	279.176	2.6854	3.2E+07	4193.23
2	Upper Canoochee	24030.9729	40.2201	0.3655	353276	387.9
3	Cedar Creek	16501.85156	52.409	0.5297	458118	549.93
4	Lotts Creek	30714.01482	83.5626	0.9332	2394970	971.71
5	Lower Canoochee	32636.86223	100.941	1.098	3617248	1257.89

The Watershed Characterization System calculates mercury loadings to each reach. These values are specified as constant Hg(II) and MeHg loadings for each surface water compartment. Loadings for average flow conditions reflect both wet and dry deposition throughout the watershed, followed by runoff and erosion to the tributary stream network. These loadings to the tributary network are subject to reduction and volatilization losses in transport to the mainstem.

The highest predicted water column concentration is used in the TMDL calculation to determine the maximum annual average load that could occur and still achieve the target.

9.2. TMDL Determination

To determine the total maximum load that can come into the Canoochee River the current loading conditions are evaluated and instream concentration is determined using the modeling approach described above. This allows the development of a relationship between load and instream mercury concentrations. Using this developed relationship, the total maximum load can be determined. Because the water column mercury concentration response is linear with respect to changes in load a proportion can be developed to calculate the total maximum mercury load from the watershed that would achieve the derived water quality target of 9.8 ng/l. The TMDL is calculated as given below:

$$\frac{\text{HighestSegmentConcentration}}{\text{CurrentAnnualAverageLoad}} = \frac{\text{WaterQualityTarget}}{\text{TMDLLoad}}$$

where:

Highest Segment Concentration = 15 mg/l

Current Annual Average Load = 8.45 kg/year

Water Quality Target = 9.8 ng/l

TMDL Load is calculated as 5.52 kg/year total mercury.

The estimated current loading of mercury to the Canoochee River basin is 8.45 kg/year.

The percent reduction from atmospheric sources is calculated using the following equation:

$$\% \text{Reduction} = \frac{TMDL}{\text{Current Loadings}} * 100$$

where:

TMDL = Total allowable Annual Load derived in TMDL Calculation

Current Loadings = Sum of all loads from the Watershed

In order to achieve this TMDL, a 35% reduction of mercury from all sources is needed.

10. Allocation of Loads

In a TMDL assessment, the total allowable load is divided and allocated to the various pollutant sources. This allocation is provided as a Load Allocation (LA) to the nonpoint sources, defined in this TMDL as the air sources, and as a Wasteload Allocation (WLA) to the point-source facilities in Georgia with a NPDES permit. The difference between the current load and the allowable load is the amount of pollutant reduction the sources need to achieve in order for the waterbody to ultimately achieve the applicable water quality target of 9.8 ng/l.

The calculated allowable load of mercury that can come into the Canoochee River without exceeding the applicable water quality target of 9.8 ng/l is 5.52 kilograms/year. This assessment indicates that over 99% of the current loading of mercury is from atmospheric sources; therefore a 35% reduction from the current atmospheric loading is applied in deriving the LA and WLA. In the future when air deposition has been reduced by 35% to 5.52 kg/year, the contribution of the load from water point sources will be less than 5%. Therefore, the Load Allocation and Wasteload Allocation for the Canoochee River is:

Load Allocation (atmospheric sources) = 5.32 kilograms/year

Wasteload Allocation (NPDES sources) = 0.20 kilograms/year

The estimated current loading of mercury to the Canoochee River from the surrounding watershed is 8.45 kilograms/year. This load was determined by adding the predicted mercury load for each of the subwatersheds taking into account delivery times and volatilization that occurs in the tributaries. The difference between the estimated current mercury load (8.45 kg/year) and the calculated allowable load (9.52 kg/year) is 2.93 kilograms/year. Since 9.52 kg/year is 65% of the estimated current loading of mercury, it is estimated that a 35% reduction in total mercury loading is needed for the Canoochee River to achieve a water column concentration of 9.8 ng/l.

10.1. Atmospheric Reductions

EPA estimates that over 99% of current mercury loadings to the River are from atmospheric deposition; therefore, significant reductions in atmospheric deposition will be necessary if the applicable water quality standard is to be attained. Based on the total allowable load of

9.52 kilograms per year, a 42% reduction of mercury loading is needed to achieve the applicable water quality standard. EPA is currently developing legislation to establish additional controls on multiple air pollutants, including mercury, from electric utilities. EPA anticipates that this process will produce reductions in the atmospheric deposition of mercury that will enable achievement of water quality standards.

It is anticipated that additional data and information collected during implementation of this Phase 1 TMDL will allow a more certain analysis of attainable air reductions to be accomplished in the Phase 2 TMDL. EPA will determine at that time whether it is appropriate to revise the load allocation, or the wasteload allocation, to assure that the applicable water quality standard will be achieved.

10.2. Allocation to NPDES Point Sources

During EPA's sampling effort in Canoochee River, three NPDES facilities that discharge to the impaired segment were monitored for mercury. These sources are considered to be "minor" dischargers since the effluent flow for each source is less than 1 MGD. Table 10 provides the results of the EPA sampling. Based on this sampling, this TMDL estimates that these sources contribute, in the aggregate, less than 1% of the current total mercury loadings to the watershed. When the TMDL is fully implemented, these sources will contribute less than 1%, in the aggregate, of the allowable load to the watershed. None of these sources have been designated as significant minor sources by the State of Georgia.

Table 10 NPDES Effluent Concentrations

Facility Name	NPDES ID	Total Hg (ng/l)	MeHg (ng/l)
Swainsboro WPCP	GA0020346	1.9	0.03
USA Fort Stewart	GA0004308	4.8	0.29
Hinesville/Fort Stewart WPCP	GA0047180	3.5	0.18

EPA has assigned to this NPDES point source a wasteload allocation equal to its current effluent discharge, subject to mercury characterization or minimization conditions as set out more fully below. EPA recognizes that this point source contributes only a minute share of the total mercury contributions to the watershed. However, EPA also recognizes that mercury is a highly persistent toxic pollutant that can bioaccumulate in fish tissue at levels harmful to human health. Therefore, EPA has determined, as a matter of policy, that NPDES point sources known to discharge mercury at levels above the amount present in their source water should reduce their loadings using appropriate, cost-effective mercury minimization measures. In particular, wastewater treatment plants can attain significant mercury reductions through source reduction efforts.

This TMDL assumes that the State of Georgia, as the permitting authority, will determine the necessary elements of a mercury characterization/minimization study plan, considering the size and nature of the affected WWCP.

No data or information was available to determine if mercury was present in the effluent of the dischargers identified in Table 11. For these facilities, EPD will use its reasonable potential procedure to determine the appropriate effluent limitations necessary to ensure that the TMDL of 9.8 ng/l is 5.52 kilograms/year is achieved

Table 11 NPDES Discharges

Facility	NPDES #	Receiving Water
Pembroke	GA0033588	Unnamed Trib
Statesboro	GA0023108	Little Lotts Creek
Claxton Polutry	GA0003689	Canoochee River
Swainsboro WPC	GA0020346	Crooked Creek
Metter Waste	GA0025534	Caney Brook
Claxton STP	GA0025551	Canoochee River
Hinesville-Evergreen	GA0033502	Mill Creek

11. References

- Ambrose Jr R.B., Wool, T.A., Connolly J.P. and Schanz R.W. (1988) *WASP4, A Hydrodynamic and Water Quality Model – Model Theory, User's Manual, and Programmer's Guide*. U.S. Environmental Protection Agency. Environmental Research Laboratory, Athens, Georgia. EPA/600/3-87/039.
- Hudson, R. J. M., S. A. Gherini, c. J. Watras, et al. 1994. Modeling the biogeochemical cycle of mercury in lakes: The mercury cycling model (MCM) and its application to the MTL study lakes. In "Mercury as a global pollutant". Watras C. J. and J. W. Juckabee (Eds.). Lewis Publishers. Pp 473-523.
- Mason, R. P. and W. F. Fitzgerald. 1990. Alkylmercury species in the equatorial Pacific. *Nature*. 347:457-459.
- Tremblay, A., L. Cloutier, and M. Lucotte. 1998. Total mercury and methylmercury fluxes via emerging insects in recently flooded hydroelectric reservoirs and a natural lake. *Sci.Total Environ*. 219:209-221.
- USEPA. 1997. Mercury study report to congress. EPA-452/R-97-003. Office of Air Quality, Planning and Standards. Office of Research and Development. Washington, DC.
- USEPA. 1998. Better Assessment Science Integrating Point and Nonpoint Sources, *BASINS, Version 2.0 User's Manual*. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.
- USEPA. 1986. *Quality Criteria for Water 1986*. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.
- USEPA. Region 6. 2000. *Mercury TMDLs for Segments within Mermentau and Vermilion-TecheRiver Basins*. U.S. Environmental Protection Agency, Region 6, Dallas Texas.
- Watras, C.J., K. A. Morrison, and R. C. Back. 1996. Mass balance studies of mercury and methylmercury in small, temperate/boreal lakes of the Northern Hemisphere. In "Baeyens, E., R. Ebinghaus, O. Vasiliev. (ed.) Regional and global mercury cycles: sources, fluxes and mass balances. Kluwer Academic Publ. Netherlands. Pp. 329-358.
- Zillioux, E.J., D. B. Porcella, J. M. Benoit. 1993. Mercury cycling and effects in freshwater wetland ecosystems. *Environ. Toxicol. Chem.* 12:2245-2264.