We put science to work.™

Savannah River National Laboratory™

OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

A U.S. DEPARTMENT OF ENERGY NATIONAL LABORATORY • SAVANNAH RIVER SITE • AIKEN, SC

2015 Assessment of Mercury in the Savannah River Site Environment and Responses to the Agency for Toxic Substances and Disease Registry 2012 Report on Assessment of Biota Exposure to Mercury Originating from the Savannah River Site

W. W. Kuhne
N.V. Halverson
D.G. Jackson
G.T. Jannik
B.B. Looney
M.H. Paller

August 2015

SRNL-STI-2015-00393, Revision 0

DISCLAIMER

Printed in the United States of America

Prepared for
U.S. Department of Energy

Keywords:
Water Quality
Fish
Air Deposition
Alligators
Mercury
Retention: *Permanent*

2015 Assessment of Mercury in the Savannah River Site Environment and Responses to the Agency for Toxic Substances and Disease Registry 2012 Report on Assessment of Biota Exposure to Mercury Originating from the Savannah River Site

W.W. Kuhne
N.V. Halverson
D.G. Jackson
G.T. Jannik
B.B. Looney
M.H. Paller

August 2015

Savannah River National Laboratory™

OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

Prepared for the U.S. Department of Energy under contract number DE-AC09-08SR22470.

EXECUTIVE SUMMARY

The purpose of this report is to 1) update previous Savannah River National Laboratory (SRNL) assessment reports (Kvartek et al. 1994 and Halverson et al. 2008) on the fate of mercury in the Savannah River Site (SRS) environment and 2) address comments and recommendations from the review of SRS by the Agency for Toxic Substances and Disease Registry (ATSDR) concerning the evaluation of exposures to contaminants in biota originating from the SRS. The ATSDR reviewed and evaluated data from SRS, South Carolina Department of Health & Environmental Control (SCDHEC) and the Georgia Department of Natural Resources (GDNR) concerning the non-radioactive contaminant mercury. This report will provide a response and update to conclusions and recommendations made by the ATSDR.

In an effort to address the implications of the ATSDR report, that mercury in biota of the Savannah River originated from SRS activities, a review of existing literature, monitoring data, and a comprehensive accounting of the mass balance of mercury usage and deposition from offsite sources to the SRS was conducted. A recent review by the U.S. Geological Survey in 2014 (USGS) was included in this report on mercury status and implications in our nation's streams. The USGS report highlights the unique environmental factors of forested wetlands, that are prominent features of the southeast, and the higher rainfall totals as primary keys to understanding the higher methylmercury tissue concentrations in higher trophic level fish as compared to the rest of the nation. Nearly 22% of the total land area of the SRS consists of forested wetlands which drain into five primary streams and ultimately to the Savannah River.

Little information was provided in the ATSDR report on the long historical inputs of mercury to the Savannah River from industries located upstream of Savannah River Site (i.e. Olin Corporation Chlor-Alkali Plant). It is documented that the Olin Corporation discharged 12 lbs per day into the Savannah River from August 1965 to August 1970. During this time period the Savannah River Site was pumping water directly from the Savannah River onto the site to cool reactors. The cooling water was pumped through the reactor cooling systems and then to holding ponds and subsequently to the site streams or directly to site streams. Reviews conducted by the Risk Assessment Corporation (RAC 2001) on behalf of the Centers for Disease Control and Prevention investigated mercury usage at SRS from 1954 to 1992 and concluded the mercury levels in sediment of creeks known to have mercury inputs from SRS activities have not resulted in appreciable mehrcury releases to the Savannah River. Additionally high mercury concentrations were measured in fish caught onsite in SRS streams and ponds that directly received reactor cooling effluent. Mercury would not have been used in or produced as a byproduct of reactor operations; therefore, the input of mercury originating from the Olin Corporation releases into the Savannah River Site is the likely source.

A comprehensive review of the mass balance of mercury inputs and deposition to the Savannah River Site and the Savannah River indicates that ~ 1.1 kg/yr of mercury enters the Savannah River from SRS stream outfalls. This value is small compared to the upstream sources of mercury that input ~12.0 kg/yr from known sources, and ~3.8 kg/yr from unknown sources, resulting in 16.9 kg/yr in the river effluent below the SRS.

Comparison of largemouth bass tissue concentrations for the SRS streams, the Savannah River and other streams in South Carolina showed that average concentrations were similar among all sites. Largemouth bass are known to bioaccumulate methylmercury and are a popular choice among sport fisherman so continued monitoring of this species is required.

A list of several projects describing efforts to mitigate impacts from residual mercury captured in bottom and bank sediments by employing a strategy to minimize mercury methylation through the use of stannous chloride, and projects initiated by SRS through the University of Georgia's, Savannah River Ecology Laboratory to address concerns of mercury uptake in biota are presented in the Appendix.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ATSDR	Agency for Toxic Substances and Disease Registry
CDC	Center for Disease Control and Prevention
DOE	Department of Energy
DNR	Department of Natural Resources
EPA	U.S. Environmental Protection Agency
GADNR	Georgia Department of Natural Resources
GWQCB	Georgia Water Quality Control Board
EPASWL	Environmental Protection Agency Southwest Water Laboratory
NADP	National Atmospheric Deposition Program
NPDES	National Pollutant Discharge Elimination System
NTN	National Trends Network
MDN	Mercury Deposition Network
ORNL	Oak Ridge National Laboratory
RK	River Kilometers
SCDHEC	South Carolina Department of Health & Environmental Control
SCDNR	South Carolina Department of Natural Resources
SREL	Savannah River Ecology Laboratory
SRNL	Savannah River National Laboratory
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site
USGS	U.S. Geological Survey

1.0 Introduction

In February 2012 the Agency for Toxic Substances and Disease Registry (ATSDR) issued a report of an evaluation of biota exposures to contaminants originating from the Savannah River Site (SRS) through a review of available monitoring data collected by the SRS, South Carolina Department of Health & Environmental Control (SCDHEC), and Georgia Department of Natural Resources (GADNR) for both on-site and off-site locations along the Savannah River. Monitoring data for both water and biota were collected during the years 1993 to 2008. Additionally, the ATSDR performed a scientific literature search to determine chemical contaminants measured in biota at or near SRS during the same time frame. Mercury, a non-radioactive contaminant, was identified as a chemical of concern based on records of measurement in the edible portions of biota.

Conclusions from the ATSDR regarding mercury and the potential exposure pathways evaluated are described below:

- *Mercury contamination in fish from the Savannah River, both upstream, along, and downstream of SRS, has been well documented by state agencies. However, the contribution of mercury from SRS-related activities to the river system is not known. Although mercury levels are elevated in some species of fish, these levels do not pose a public health hazard if the species-specific fish advisory guidance issued by South Carolina and Georgia are followed.*
- *If subsistence fishers do not follow the recommended consumption guidance, consuming large amounts of fish, especially species that typically accumulate mercury such as largemouth bass, bowfin, and catfish, from certain portions of the Savannah River might increase health risks associated with mercury exposure, especially to sensitive populations (e.g., fetuses and nursing infants whose mother ingests mercury-contaminated fish).*

Final recommendations from the ATSDR on the basis of information reviewed for the site included the following:

- *DOE should continue to monitor all types of biota consumed by humans both on and off the site until all remediation actions are completed and no old or new sources of contamination remain.*
- *DOE should keep informed of the types of biota consumed by humans and provide adequate monitoring for those types that may be contaminated by site activities. There were limited or no data available from 1993 to 2008 for review on some animals potentially consumed by humans, such as alligators, rabbits, squirrel, ducks, turtles, and other small animals. Migratory animals such as birds and ducks that frequent SRS's contaminated ponds and streams will continue to present a pathway for possible exposure to humans.*
- *DOE should periodically review potential differences in environmental monitoring results between all agencies and programs involved. This comparison should include the on-site field surveys performed on harvested animals and laboratory sampling results.*
- *Largemouth bass and bowfin have typically accumulated the highest concentrations of mercury. Currently, the state of South Carolina recommends not eating these two species if collected from portions of the Savannah River between Highway 119 in Jasper County U.S. to Highway 17 near Savannah, Georgia.*
- *DOE should consider routine environmental sampling of turtles for aquatic contaminants, especially for those chemical and radioactive contaminants found predominantly in pond and stream sediment.*

Based on the conclusions and recommendations of the ATSDR for mercury this follow up report has been prepared to 1) update the current status of mercury in the SRS environment and the current understanding of mercury in aquatic systems in the southeast and 2) specifically addresses the ATSDR recommendations.

This report is divided into three primary sections. Section 2.0 provides an overview of the current understanding of mercury in aquatic ecosystems as presented through reviews conducted by the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (EPA). The USGS report describes sources of mercury and environmental characteristics, such as high levels of rainfall and a predominance of forested wetlands, which promote the production and bioavailability of methylmercury in higher trophic level fish. The EPA conducted a review of average mercury concentrations in several species of fish across the nation. The data provide an opportunity to make comparisons of mercury concentrations between various geographic locations to determine if the southeast is markedly different versus other areas of the U.S. Section 3.0 of this report identifies sources of mercury specific to the SRS and to the Savannah River through atmospheric deposition, historical releases from industrial sources such as the Olin Corporation Chlor-alkali plant on the Savannah River, and the historical usage and release of mercury to the SRS from operational activities. Section 4.0 of this report introduces new information not included in the ATSDR report including: 1) Information collected through a risk assessment analysis for the Centers for Disease Control and Prevention for mercury in the environment; 2) an update to the mass balance inventory for mercury usage and release to the environment at SRS; 3) monitoring data from the Site's National Atmospheric Deposition Program monitoring station, and 4) introduction to various surveillance programs for mercury concentrations in biota including fish, sediment and new biota of interest, alligators.

Additionally, a list of projects is included in the Appendices to describe ongoing efforts to mitigate impacts from residual mercury captured in bottom and bank sediments by employing a strategy to minimize mercury methylation through the use of stannous chloride, and projects initiated by SRS through the University of Georgia's, Savannah River Ecology Laboratory to address concerns of mercury uptake in biota identified by the ATSDR as species of concern.

2.0 Current Understanding of Mercury in Aquatic Ecosystems

2.1 U.S. Geological Survey Report - Mercury in the Nation's Streams

Mercury, and specifically methylmercury, is one of the most widespread waterborne contaminants in the nation (USEPA 1997; USGS 2001; USGS 2014) and globally (UNEP 2002; 2013). Mercury in our nation's waters is from both natural and anthropogenic sources. Natural sources include such things as volcanoes, geologic deposits, geothermal springs and volatilization from the ocean. Anthropogenic sources are typically from activities including the burning of coal, mining (mercury, coal, gold), and the use of mercury in industrial processes and products. It is estimated that the amount of inorganic mercury in the global atmosphere has doubled since pre-industrial times, with the greatest increases occurring near urban locations (USGS 2014).

The U.S. Geological Survey recently completed a study of available scientific literature, datasets and monitoring data since the late 1990s and conducted an assessment of mercury in the nation's streams (USGS 2014). Findings of the report provide insights into the current status of mercury in the nation's streams and the importance of watershed characteristics relative to mercury inputs. It provides scientific explanations for higher mercury concentrations in water and fish in the southeast versus the rest of the country and explores current sources of mercury into the environment.

The major findings of the USGS assessment were that: 1) methylmercury concentrations in fish exceed the EPA criterion for protection of human health at about one in four streams across the U.S.; 2) wetlands increase the amount of inorganic mercury that is converted to methylmercury; 3) mercury emission reduction strategies need to consider global mercury sources in addition to domestic sources; and 4) existing mercury monitoring programs focus mostly on methylmercury concentrations in fish, and lack design elements and data to link these levels to mercury sources.

2.1.1 *Streams of Forested Wetlands Have the Highest Concentrations of Methylmercury in Fish*

In aquatic systems both total mercury and methylmercury are measured in water, sediment and biota. Methylmercury is a neurotoxin and can bioaccumulate through the aquatic food chain resulting in high concentrations in higher trophic level fish that are often caught by fishermen for food.

The highest concentrations of methylmercury in freshwater fish in the nation were measured primarily in forest or wetland-dominated coastal plain streams in the southeastern U.S. (Scudder et al. 2009) (Figure 2-1). Scudder et al. (2009) reported that during 1998-2005 methylmercury concentrations in largemouth bass were the highest for streams draining undeveloped basins and basins with mixed land use/land cover.

It is widely recognized that wetlands can possess water quality characteristics (low pH, high levels of carbon, and the presence of sulfate reducing bacteria) for efficient production of methylmercury from inorganic mercury inputs (Fitzgerald et al. 1998; Schroeder and Munthe 1998; Hall et al. 2008, cited in USGS 2014)

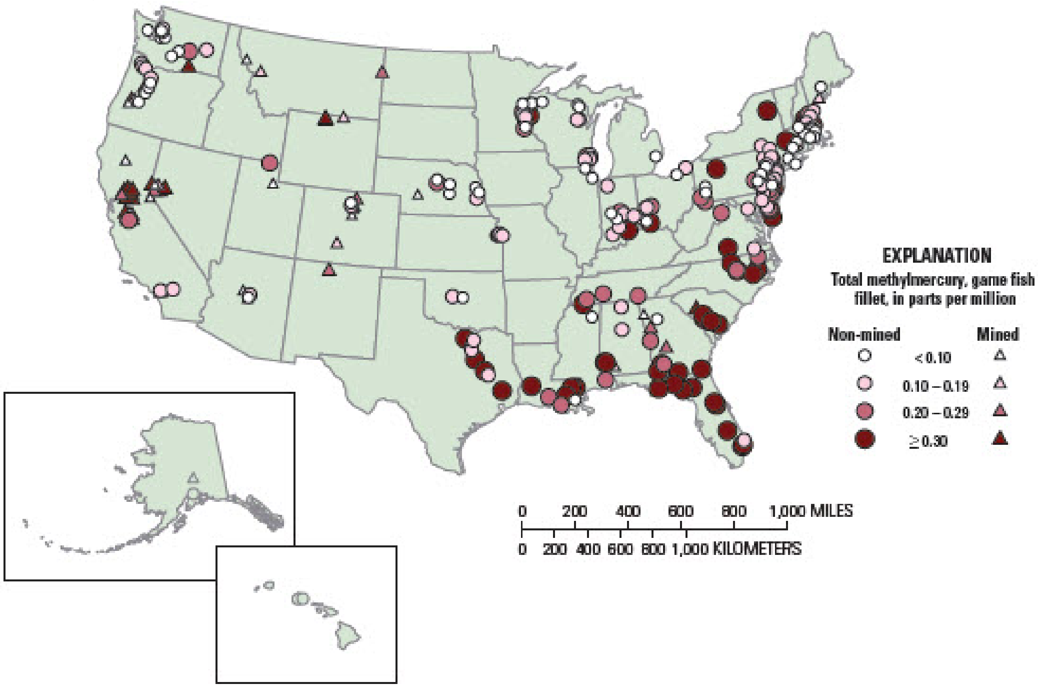

Figure 2-1 Methylmercury Concentrations in Fish across the U.S. (Image from USGS 2014 – modified from Scudder and others, 2009)

2.2 U.S. Environmental Protection Agency (EPA) Investigation of Mercury Concentrations in Fish

In 1999, the EPA compiled a report describing mercury in the nation's fish (EPA 1999). Data from 40 states and the District of Columbia were utilized to compare total mercury concentrations in fish tissue. Fish tissue samples were collected from 1990 to 1995 and were collected from numerous locations throughout the northeast, southeast, midwest and west. Analysis of the mean total mercury concentrations (ppm) measured in largemouth bass in states in these geographic regions showed no statistically significant difference by comparison using a single factor ANOVA ($p=0.14$), however, the general trend showed higher concentrations in fish from the southeast and the west (Figure 2-2).

Additional assessments of mercury datasets have been completed over the years with similar findings that: 1) southeastern U.S. had more upward mercury trends in fish than other regions; 2) upward mercury trends can be associated with increases in wet deposition and a greater influence of atmospheric mercury emissions; 3) ecoregion and water body type where the fish were collected played an important role in predicting mercury tissue levels; and 4) sampling locations associated with a high percentage of wetland area had fish with high levels of tissue mercury (Chalmers et al. 2011; Glover et al. 2010).

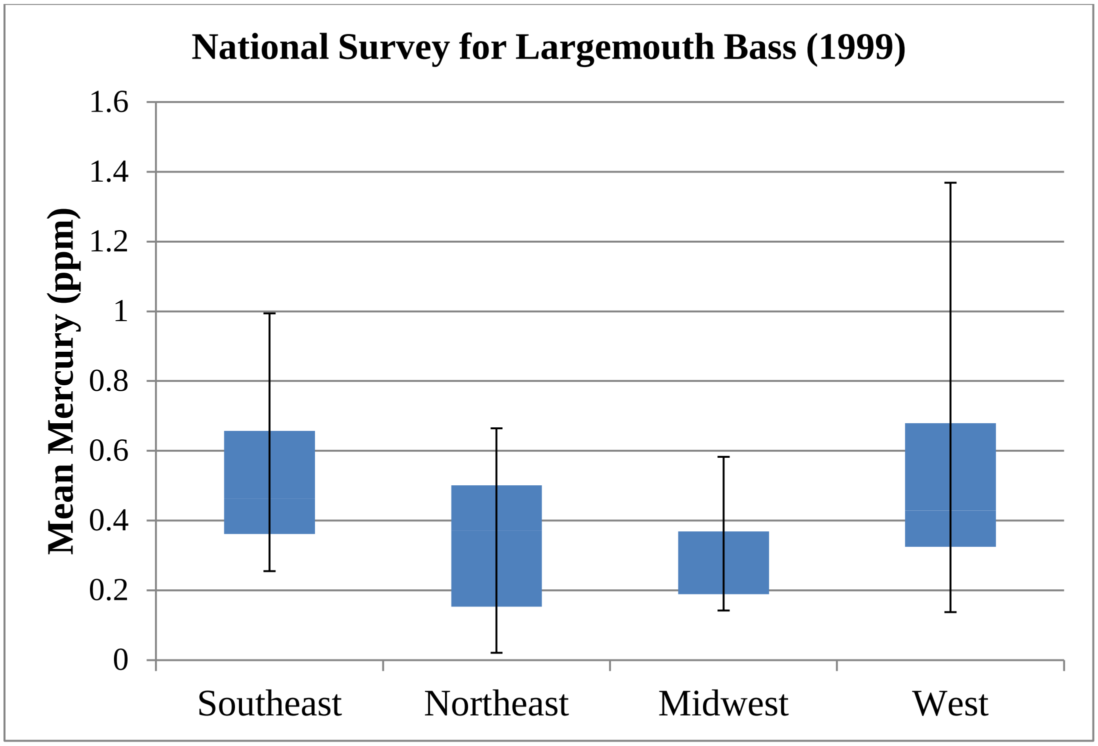

Figure 2-2 Mean Mercury Concentrations Measured in U.S. Geographic Regions

2.3 Predominance of Wetlands in the Southeast

Wetlands can be a sink for total inorganic mercury, deposited from legacy industrial point sources, wild land fires or atmospheric deposition, but can also be a primary producer of methylmercury given proper conditions often found in wetland environments. The inorganic mercury can be deposited in wetlands and reside in the upper layers of sediment where conditions are changing from aerobic to anaerobic (i.e. low oxygen). Sulfate reducing bacteria are ubiquitous organisms found in all wetlands and in these anaerobic environments, with proper amounts of carbon, they have the ability to methylate inorganic mercury to the form which is bioavailable and toxic to aquatic organisms and humans.

Recent studies on the status and trends of wetlands in the U.S. (Dahl 2011) indicated that there were an estimated 110.1 million acres of wetlands in the U.S. in 2009. Freshwater wetlands comprised 95% of all wetlands with the remaining 5% in marine or saltwater systems. Forested wetlands made up the largest category (~49.5%) of wetlands in the freshwater system.

States in the southeast have predominately wetland habitats (Figure 2-3) with Georgia and South Carolina, states which border the Savannah River, reported to have n 7.7 million and 4.6 million acres of wetlands respectively (USGS 1996).

In the state of South Carolina the majority of wetland systems occurs near the Piedmont/Coastal Plain fall line and extends to the coast of the Atlantic Ocean (Figure 2-4). SRS was established in 1950s and encompasses parts of Aiken, Barnwell and Allendale counties in South Carolina. The ecology and inventories of the wetlands of the site has been evaluated using aerial surveys (Mackey et al. 1985; Shields et al. 1982; Schalles et al. 1989).

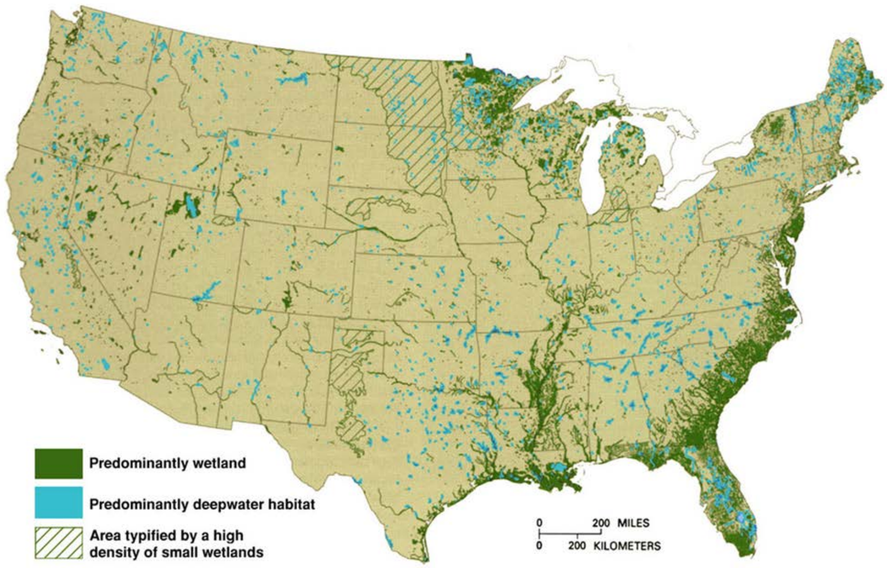

Figure 2-3 Locations of Wetland Ecosystems across the U.S. (Photo from USGS 1996)

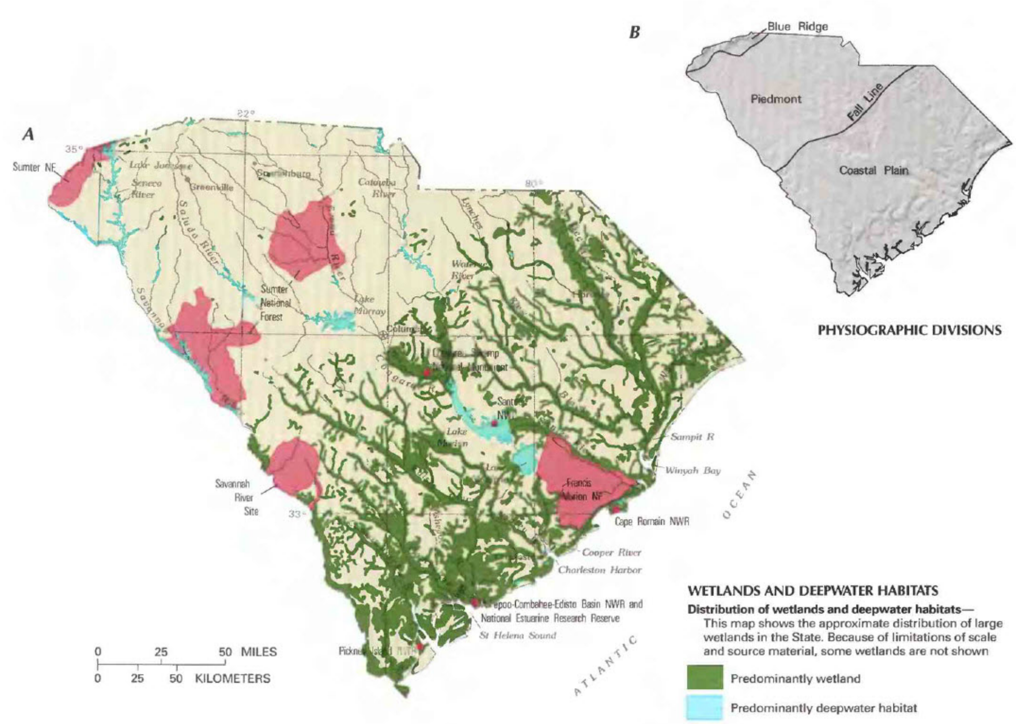

Figure 2-4 Wetland Distribution in South Carolina and Physiography of the State. A, Distribution of Wetlands and Deepwater Habitats, B, Physiology (Figures A and B taken from USGS 1996) (Sources: A, T.E. Dahl, U.S. Fish and Wildlife Service, unpub data, 1991. B, Physiographic divisions from Fenneman, 1946, landforms data from EROS data Center).

2.4 Wetlands on the SRS and Their Influence on Mercury in the Savannah River and in Biota

The SRS is 810 sq km of which 5% is developed industrial areas, 73% is forested (pine and mixed hardwoods) and the remaining 22% is made up of wetlands consisting of swamps, Carolina bays, streams and lakes (SRS 2005) (Figure 2-5). The Savannah River swamp borders 16 km (10 mi) of SRS on the southwest along the Savannah River. Additionally, six tributaries run across the site of which a few drain industrial areas and most drain forested wetlands before converging with the Savannah River. The main streams on the SRS are Upper Three Runs, Beaver Dam Creek, Fourmile Branch, Pen Branch, Steel Creek and Lower Three Runs.

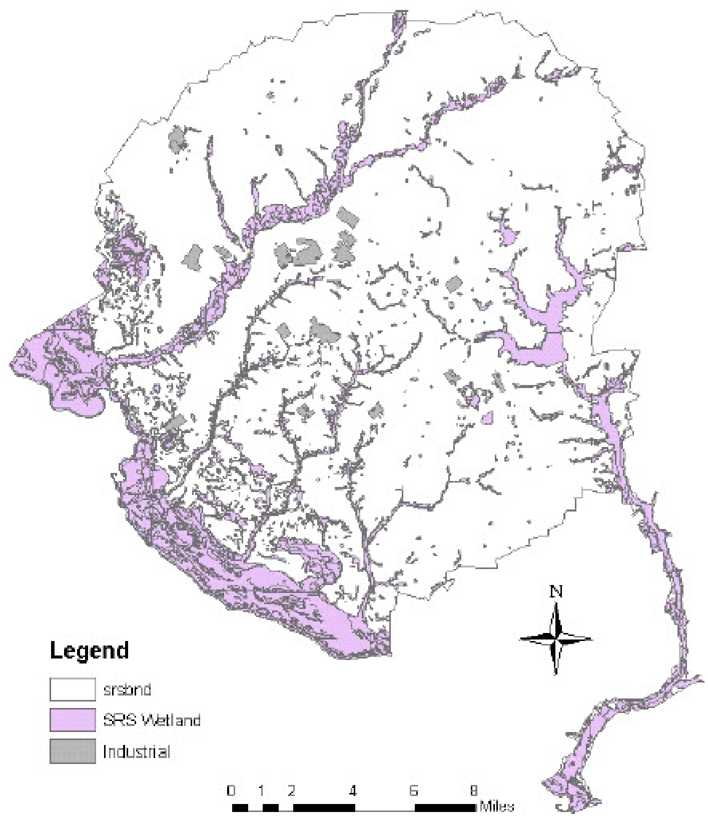

Figure 2-5 SRS Site Wide Wetlands map as of 2005 (Image from SRS 2005)

2.4.1 *Mercury Levels in Water and Tissues of Asiatic Clams*

A recent study evaluated methylmercury production in the SRS tributaries and their influence on methylmercury levels in the Savannah River by deploying Asiatic clams (*C. fluminea*), commonly known as *Corbicula,* to locations at the mouths of the discharge plumes to the Savannah River and to control locations just above the creek mouths in the Savannah River (Paller et al. 2004). Both water and tissue were analyzed for total mercury and methylmercury concentrations. Results showed that methylmercury concentrations in the creek mouths (0.170 ng/L) were nearly twice as high as in the river (0.085 ng/L). Average total mercury levels differed little between the creek mouths (2.98 ng/L) and the river (2.59 ng/L). Soft tissue methylmercury levels were approximately 2.5 times higher in *Corbicula* from the tributary discharge plumes than in *Corbicula* from the Savannah River upstream from the plumes. The elevated levels of methylmercury in the tributaries was hypothesized to be associated with the fact that the tributaries drain large surface areas of wetland habitats and possess water chemistry characteristics that favor methyl mercury production.

2.4.2 *Mercury Levels in Fish Collected at the Mouths of SRS Tributaries and the Savannah River*

Mercury levels in fish have been measured in the middle reaches of the Savannah River and several tributaries since 1971 as part of an environmental monitoring program conducted by SRS. Fish were collected in the middle reaches of the Savannah River near river kilometers (RKs) 193, 225 and 259 prior to 1992 and RKs 191, 208, 228, 243, 245, 253, and 302 thereafter. Collection sites were also located in four tributaries on the site including Upper Three Runs, Fourmile Branch, Steel Creek, and Lower Three Runs. Long term changes in mercury concentrations in fish from the middle Savannah River, including SRS tributaries was assessed by evaluating this long term data set (Paller and Littrell 2007).

Fourmile Branch may have received mercury contamination from industrial seepage basins located near its headwaters, and a small tributary of Upper Three Runs received water with low concentrations of mercury from a groundwater air stripping facility located approximately 6.5 km above its confluence with Upper Three Runs.

Sites were sampled yearly to every few years by fish traps, angling, and/or electrofishing. Largemouth bass (*Micropterus salmoides*), sunfish (*Lepomis* spp.), and catfish (*Ameiurus* spp. and *Ictalurus punctatus*) were collected for analysis because they are often consumed by anglers. Only fish of edible size were collected (~ $\geq$ 30 cm, 15 cm, and 30 cm total length).

Results of this work showed that persistently greater mercury bioavailability in the tributaries was indicated by the fish collection data, which showed that mercury concentrations were significantly higher ($p \leq 0.05$) in fish from the tributaries than in fish from the Savannah River, except for largemouth bass in Upper Three Runs and catfish in Fourmile Branch (Figure 2-6).

Additional variations observed within the data were the 1) reductions of concentration in Savannah River fish following the mandatory reductions of mercury inputs to the Savannah River from the chlor-alkali plant in Augusta, GA, and 2) influence of high- and low-water periods affecting fish concentrations.

Regression analysis of the long-term data indicated that for some species (sunfish and largemouth bass) both high- and low-water years affected total mercury and methylmercury concentrations in fish. High-water years showed more methylmercury in fish tissue indicating that more methylmercury produced in the tributaries was being transported in the Savannah River and became more bioavailable to biota.

These data coupled with the previous work on the mercury concentrations in water and Asiatic clams in the tributaries support the hypothesis that mercury deposited to the numerous wetlands on the SRS from atmospheric deposition is converted to methylmercury and is released to the tributaries and ultimately the Savannah River through natural watershed runoff.

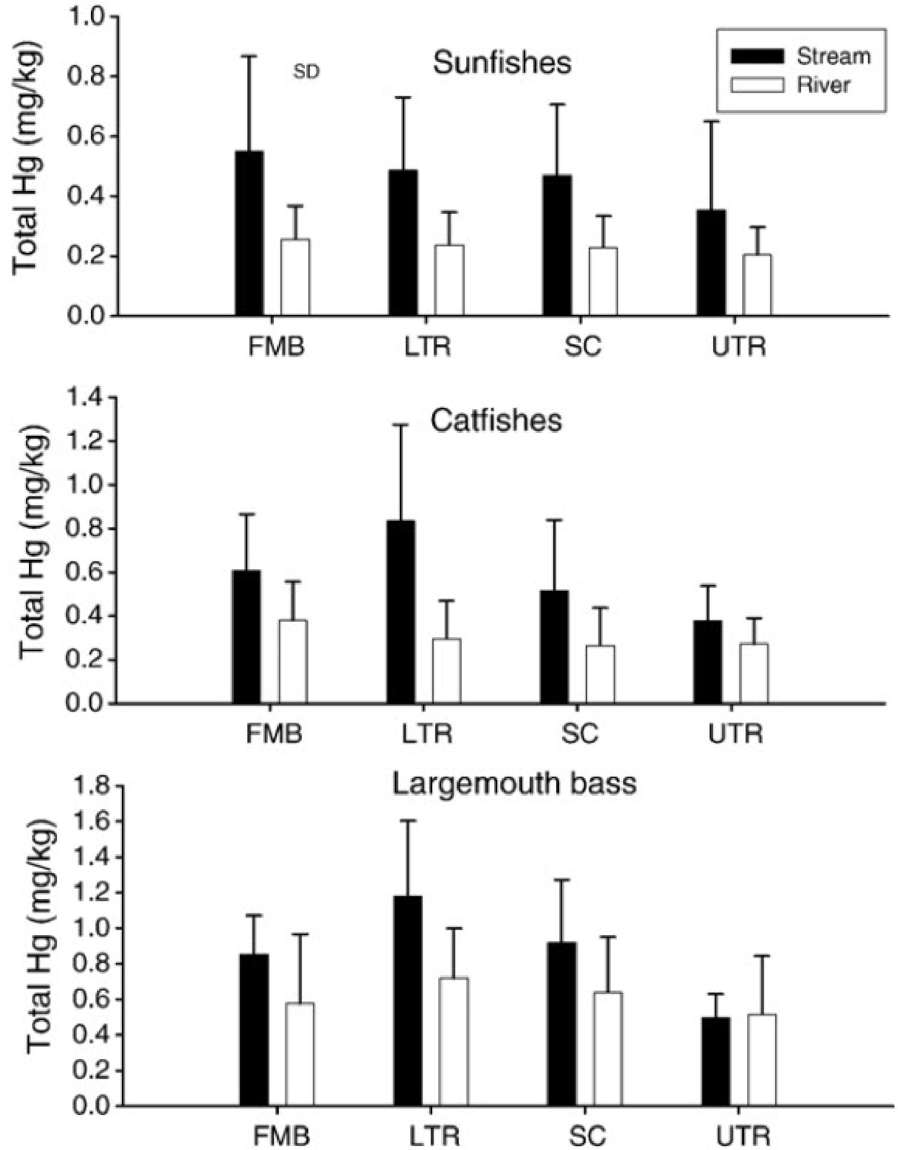

Figure 2-6 Total Mercury Concentrations in Fish from the Savannah River and Four Tributary Streams (Figure from Paller and Littrell, 2007)

3.0 Sources of Mercury to the SRS and Savannah River Environment

Sources of mercury to the SRS and the Savannah River are numerous, including point sources from the Olin Corporation’s chlor-alkali plant in Augusta, GA, operations at the SRS, and atmospheric deposition from rainfall and dry deposition events. This section provides insight into the current understanding of the amounts and roles of each of these known sources to current concentration levels on the SRS and the Savannah River.

3.1 Mercury in the Southeast and the Role of Atmospheric Deposition

Environmental monitoring of mercury in 1970s and 1980s showed that the primary cause of mercury contamination in ecosystems without direct anthropogenic sources of mercury in their watersheds was from atmospheric deposition.

Data from 2005 showed that U.S. anthropogenic mercury emissions were the third largest in the world with coal combustion accounting for about 55 percent of the total released (AMAP and UNEP 2008). Other sources of anthropogenic mercury release in the U.S. included metallurgical processes, waste incineration and numerous manufacturing sources. Most of the mercury emission sources were located in the eastern half of the nation.

Atmospheric transport and deposition constitute the predominant pathways of anthropogenic mercury to most aquatic ecosystems in the U.S., especially those in remote areas (Fitzgerald et al. 1998). Mercury in the atmosphere can be deposited onto the Earth's surface either as wet deposition (rain or snow) or dry deposition (gas phase or particulate). Average annual wet mercury deposition rates are typically higher in the East due to the larger annual rainfall levels (Fulkerson and Nnadi 2006). Today, it is anticipated that all of the Earth's aquatic ecosystems are contaminated by mercury from atmospheric emissions (USGS 2014). It is estimated that approximately 99% of the mercury loading to the Savannah River watershed is from atmospheric deposition or the erosion of the stream bank soils as opposed to industrial discharges or other point sources (EPA 2000).

3.2 Olin Corporation Chlor-alkali Plant, Augusta, GA

Chlor-alkali plants manufacture chlorine gas and lye, important intermediate chemicals in processes such as the production of paper and soap, from sodium chloride (salt or brine). The mercury-cell process was a method that was popular within this industry to use the mercury to conduct an electric current for the chemical reaction that splints the salt. Mercury cells are typically 50 foot long tanks and hold approximately 448,000 lbs (224 tons) of mercury.

The Olin Corporation operated along the Savannah River in Augusta, GA for nearly 47 years. From August 1965 through August 1970, the reported discharge rate of mercury from the Olin Corporation to the Savannah River was 12 lb/day (EPASWL 1971, cited in Tilly and Wilhite 1972). Before a study conducted by the Georgia Water Quality Control Board in 1970, discharge rates of 10 lb/day were reported (GWQCB 1971). Assuming a discharge rate of 10 lb per day for 5 years, more than 18,000 lb of mercury would have been discharged directly to the Savannah River between 1965 and 1970 (RAC 2001).

In 2006 high levels of mercury were measured in the canal discharging from the Olin Corporation into the Savannah River and prompted a decision by the Georgia Environmental Protection Division Hazardous Waste Branch to fill the canal with clean fill dirt in order to "cap" the mercury in place in 2008. The Olin Corporation plant in Augusta ran its mercury cell process until 2012 at which time operations were ceased.

3.3 Operational Activities Utilizing Mercury at the Savannah River Site

Mercury was used on the SRS for various applications including as a processing aid in aluminum dissolution and chloride precipitation; as part of the tritium facilities' gas handling system; from experimental, laboratory, or process support facilities; and as a waste from site operations. Extensive accountings of the use and release of mercury on the site has been performed along with assessments of mercury in the environment (Kvartek et al. 1994 and RAC 2001).

Mercury was used at the SRS as a processing aid in the F and H area separation areas. Effluents associated with the processes conducted at F and H area were discharged to the F-Area and H-Area seepage basins beginning in 1959. Between 1959 and 1981, approximately 3600 and 840 lb of mercury were released to F-Area and H-Area seepage basins, respectively (Horton 1974). Additional mercury releases to the SRS environment included air emissions from the coal burning power plants (Kvartek et al. 1994).

An important source of mercury to the SRS was from releases made by upriver point sources (i.e. Olin Corporation) along the Savannah River. Savannah River water was pumped directly from the river onto the site mainly as a source of reactor cooling water and to maintain PAR Pond and L-Lake's water levels. Much of this water was then released to cooling ponds and tributaries which drain back to the Savannah River.

4.0 Activities to Understand the Sources and Implications of Mercury in the SRS Environment and the Savannah River

4.1 Aquatic Mercury Assessment Study

A report issued by Halverson et al. 2008 discussed results of an aquatic mercury assessment study at SRS. One component of the report discussed total and methylmercury levels measured in SRS streams and swamps and in the Savannah River. The baseline water data covered the years 1999-2001. These data were organized into a graph and compared with available rainfall data collected during similar years at the SRS NADP collection station (Figure 4-1). Results of the data comparison showed that SRS surface water had generally lower total mercury concentrations and higher methylmercury concentrations than rainfall. The streams and swamps tended to have higher methylmercury levels than the Savannah River water. The higher concentration in the SRS streams and swamps was attributed to the predominance of wetlands draining into the streams and swamps that promote methylmercury production. Overall, very few SRS collected surface water samples exceeded the median values of total mercury and methylmercury measured in rainfall.

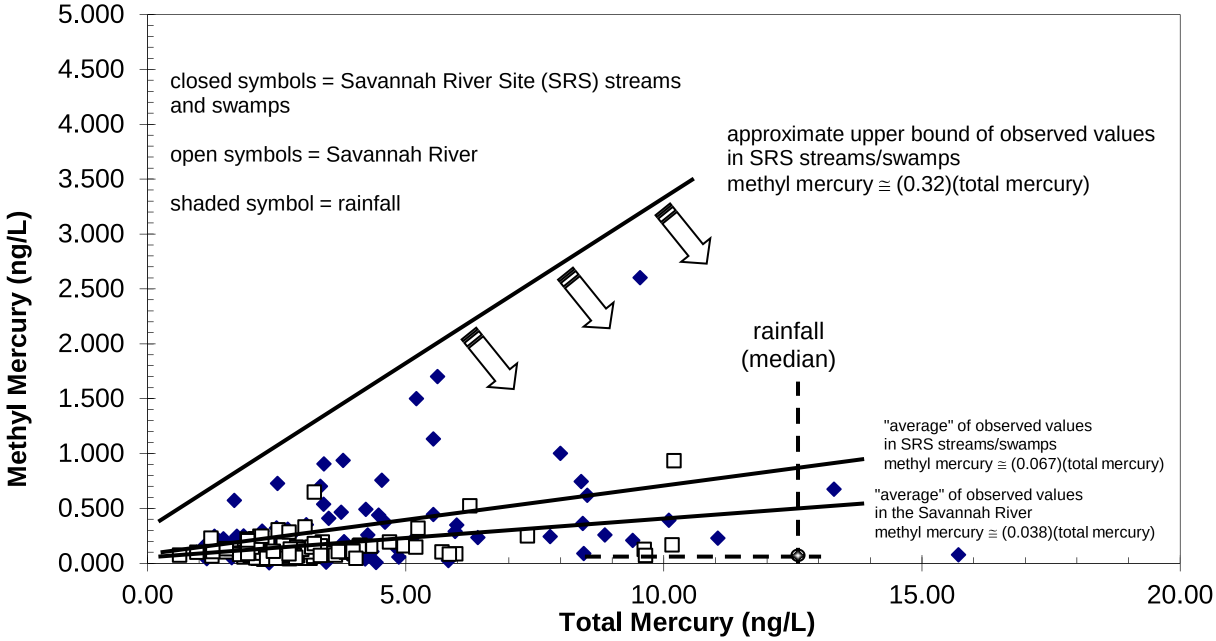

Figure 4-1 Example baseline (1999-2001) water data for mercury in surface waters and rainfall near Savannah River Site (figure from Looney et al. 2010)

The various solid lines in Figure 4-1indicate the relationship between methyl and total mercury for (from bottom to top) the Savannah River (median), on site streams (median) and on site stream (upper bound of the data). The dashed lines indicate median rainfall from the National Atmospheric Deposition Program (NADP) collection station located at the Savannah River Site.

4.2 Summary of Mass Balance for Total Mercury at SRS

A preliminary mass balance was performed for total mercury at the SRS and was reported in Halverson et al. 2008. The mass balance was based on the principle of conversion of mass: input must equal accumulation plus output. The amount of mercury entering the system should equal the sum of the mercury retained or chemically changed within the system and the mercury leaving the system.

For the SRS mercury mass balance, inputs included mercury discharged from SRS facilities to the environment through the National Pollutant Discharge Elimination System (NPDES) outfalls, mercury transported to the site in the Savannah River upstream of the site boundary, mercury entering the SRS via streams originating outside of the site boundaries, and atmospheric deposition. Outputs included mercury transported down the Savannah River at the downstream site boundary and re-volatilization. Accumulation locations include upland soils, the water column, sediments and biota. The preliminary mass balance calculated initial estimates of mass fluxes into the site, and the mass flux leaving the site via the Savannah River.

As reported in Halverson et al. (2008), influent mercury, comprised of influent from 1) the Savannah River and site streams, 2) mercury added by SRS operations via the NPDES outfalls, and 3) wet and dry atmospheric deposition, totaled ~ 33 kg/yr. Total effluent mercury in the Savannah River was ~ 16.9 kg/yr via site streams, upstream sources, unknown sources and an undetermined quantity re-volatilizing to the atmosphere. Assuming a balance, the sum of the mercury storage and re-volatilization within the SRS boundary drawn for this study was approximately 16.2 kg/yr. Atmospheric deposition alone (17 kg/yr) far exceeded mercury leaving the site via the SRS streams (1.1 kg/yr), indicating that approximately 95% of the deposited mercury was being retained in the soil, sediments, water bodies or vegetation, or was being re-emitted to the atmosphere. In addition, mercury released through the SRS outfalls was equivalent to approximately 1% of the total atmospheric deposition on the SRS, which aligns with the theory that atmospheric deposition is the major source of mercury to the SRS environment and supported EPA's determination that point source discharges contribute only 1% of the mercury loading to the watershed.

A figure depicting the influent and effluent based on the SRS site boundary has been updated with the results of the mass balance (Figure 4-2).

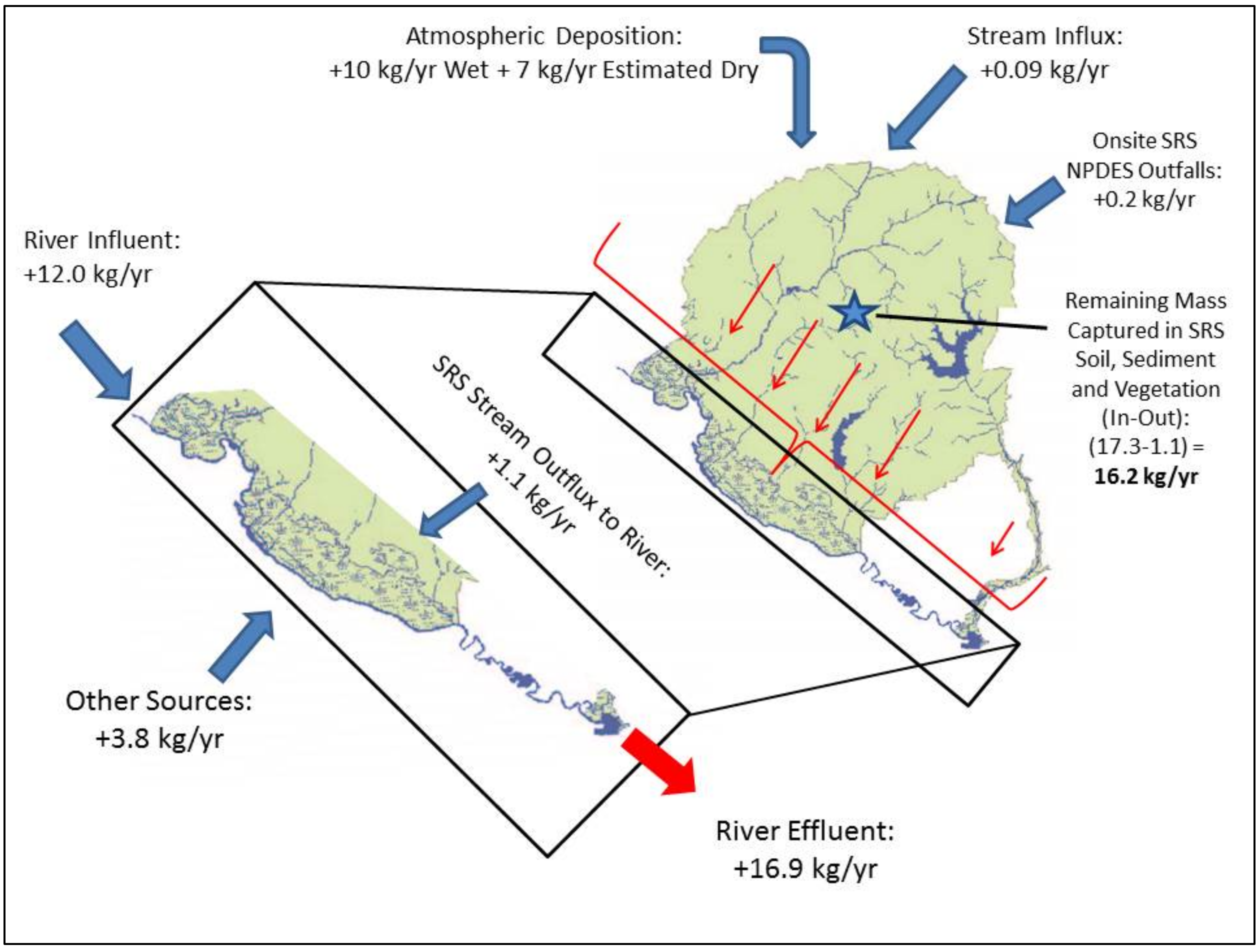

Figure 4-2 Summary of Mercury Mass Balance at Savannah River Site

4.3 National Atmospheric Deposition Program (NADP)

Savannah River National Laboratory (SRNL) sponsors a monitoring and collection station that is part of the National Atmospheric Deposition Program (NADP). The NADP provides fundamental measurements that support informed decisions on environmental issues such as atmospheric mercury and acid rain. NADP data are relevant to scientists, educators, policymakers, and the public. Additional information on this network is accessible via the following link: http://nadp.sws.uiuc.edu/mdn/.

Since 2001, SRS has operated a monitoring station within the program's Mercury Deposition Network (MDN). This network provides data on the geographic distributions and trends of mercury in precipitation. It is the only network providing a long-term record of mercury concentrations in North American precipitation. All monitoring sites follow standard procedures and have uniform precipitation collectors and gauges. Following equipment upgrades in 2010 and 2011, the mercury deposition station at SRS (SC03) is fully modernized and satisfies network collection requirements.

In 2012, an additional precipitation collector was added to the station as part of the National Trends Network (NTN). This network is also part of the NADP with the focus of monitoring major anions and cations that are present in precipitation. Weekly precipitation samples from this collector are sent to a central laboratory for analysis of free acidity, specific conductance, and calcium, magnesium, sodium, potassium, sulfate, nitrate, chloride, bromide, and ammonium ions.

4.3.1 *Precipitation Chemistry and Deposition for Mercury at SRS*

Maps generated from data collected from the NADP show consistent signatures of mercury wet deposition in the Midwest and Southeastern states higher than measured in Western states (Figure 4-3).

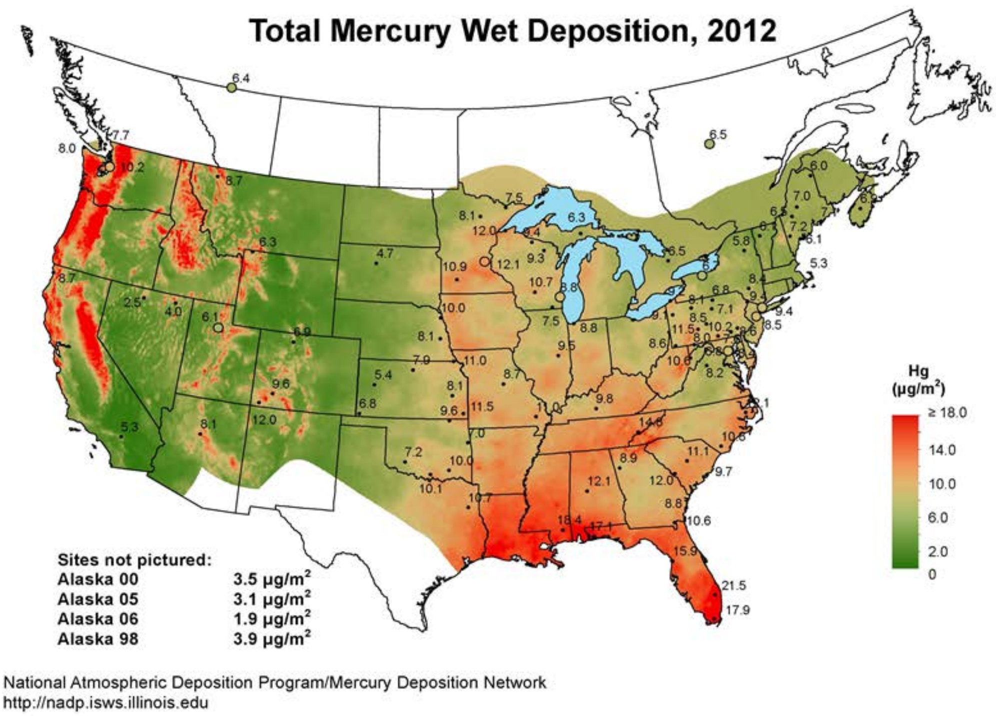

Figure 4-3 2012 Total Mercury in Rainfall Results from the National Atmospheric Deposition Program (NADP)

During calendar year 2011, the average (volume weighted) concentration of total mercury in precipitation at SRS was 10.6 ng/L and the wet deposition rate was 9.1 µg/m^2. During calendar year 2012 the average (volume weighted) concentration of total mercury in precipitation at SRS was 11.1 ng/L and the wet deposition rate was 12.0 µg/m^2. Comparing the 2012 SRS wet deposition rate to the rest of the nation the rate of 12.0 µg/m^2 was consistent with values measured in the southeast, but higher than those measured in the Northeast and West. Additional information on the MDN is accessible via the following link: http://nadp.sws.uiuc.edu/mdn/.

4.4 Fish Surveillance of Mercury in Fish Caught from the Savannah and Edisto Rivers

SRS collects and analyzes the flesh of fish caught from the Savannah and Edisto Rivers to determine concentrations of mercury. SRS compares the mercury tissue levels measured in the fish to trigger levels (Table 4-1) used by SCDHEC and South Carolina Department of Natural Resources (SCDNR) to issue fish advisories (SCDHEC 2010). The trigger levels have been established by SCDHEC from analysis of nearly 19,000 individual fish representing 55 species of freshwater, saltwater, and diadromous (fish that travel between salt and freshwater) fishes for mercury from 1993 to 2008. SRS fish mercury tissue values can be compared against the average values measured in the SCDHEC database (Table 4-2).

Table 4-1 South Carolina Fish Tissue Mercury Criteria in (µg/g)

Tissue Hg Levels	Advisory
0-0.24	No Restrictions
0.25-0.66	1 Meal Per Week
0.67-0.99	1 Meal Per Month
>= 1.0	Do Not Eat Any

Table 4-2 Average Tissue Mercury Values for South Carolina Fish Species From 1993 to 2008

Common Name	Average Tissue Hg (µg/g)	Type
Bowfin	0.92	Freshwater
Flathead Catfish	0.85	Freshwater
Largemouth Bass	0.58	Freshwater
Chain Pickerel	0.55	Freshwater
Warmouth	0.34	Freshwater
Spotted Bass	0.30	Freshwater
Yellow Perch	0.28	Freshwater
Blue Catfish	0.26	Freshwater
Black Crappie	0.25	Freshwater
Striped Bass	0.24	Diadromous
Redbreast Sunfish	0.23	Freshwater
Channel Catfish	0.22	Freshwater
Smallmouth Bass	0.21	Freshwater
Redear Sunfish	0.20	Freshwater
White Catfish	0.19	Freshwater
Bluegill	0.16	Freshwater
Spanish Mackerel	0.12	Saltwater
Striped Mullet	0.10	Saltwater
Spotted Seatrout	0.10	Saltwater
Spotted Weakfish	0.10	Saltwater

Red Drum	0.08	Saltwater
Spot	0.07	Saltwater

4.4.1 *Fish Surveillance Reported in the SRS Annual Environmental Report for 2012*

In 2012, SRS analyzed 476 fish at 11 locations including Site streams where they enter the Savannah River, the Savannah River and the Edisto River at West Bank Landing for mercury. The mercury results for fish in 2012 were below the 0.25 µg/g trigger level for the SCDHEC-issued fish species advisories for the Savannah River and Edisto River for catfish and panfish, but mean bass tissue concentrations did exceed the trigger level but remained within the range of 0.25 to 0.66 µg/g for a 1 meal per week advisory (SCDHEC 2012). The SRS mercury method detection limit for the fish analyses was 0.02 µg/g. The highest concentrations measured in individual fish were found in the Savannah River in the following species and locations: bass at Stokes Bluff Landing (1.08 µg/g), catfish at Stokes Bluff Landing (0.497 µg/g), and panfish at the Lower Three Runs Creek Mouth (0.664 µg/g).

The highest concentrations of mercury in individual saltwater fish, collected only at River Miles 0-8 near Savannah, Georgia, were 0.041 µg/g in red drum, 0.024 µg/g in mullet, and 0.172 µg/g in sea trout.

4.4.2 *Fish Surveillance Reported in the SRS Annual Environmental Report for 2013*

In 2013, SRS analyzed 190 fish at six locations on the Savannah River, including where SRS streams enter the Savannah River. The mercury results for fish in 2013 showed catfish and panfish tissue concentrations below the 0.25 µg/g trigger level for SCDHEC-issued fish species advisories for the Savannah River and Edisto River (SCDHEC 2014). The concentrations in bass tissue were below the trigger level in some locations and exceeded it in others. Overall the bass tissue concentrations remained in the range of the 0.25 to 0.66 µg/g for an advisory level of 1 meal per week. The SRS mercury method detection limit for the fish analyses was 0.02 µg/g. The highest concentrations measured in individual fish were found in the Savannah River in the following species and locations: bass at Four Mile Creek River Mouth (1.00 µg/g), catfish at Highway 301 Bridge (0.487 µg/g), and panfish at the Lower Three Runs Creek Mouth (0.562 µg/g).

The highest concentrations of mercury in individual saltwater fish, collected only at River Miles 0-8 near Savannah, Georgia, were 0.291 µg/g in red drum, 0.054 µg/g in mullet, and 0.241 µg/g in sea trout.

4.4.3 *Trends for Mercury in SRS Collected Fish Tissue*

Evaluating mean mercury concentrations measured in fish collected from above, along and below SRS the bass data shows the highest mercury concentrations as compared to catfish and panfish. Mean concentrations range from a minimum 0.162 (µg/g) measured in 2012 at Highway 17A to a maximum 0.726 (µg/g) at Stokes Bluff Landing in 2010 (Figure 4-4). Comparing the mean tissue concentrations collected by the SRS for all locations from 2008 to 2013 the values for bass are within the range of 0.25 – 0.66 µg/g triggering a fish consumption advisory of 1 meal per week, except for fish collected at Highway 301 in 2008 (0.711 µg/g) and Stokes Bluff in 2010 (0.726 µg/g) and 2011 (0.681 µg/g) where values are within the 1 meal per month advisory level.

Overall the mean tissue concentrations for bass collected by the SRS for all locations from 2008 to 2013 are comparable to or below those reported in SCDHEC 2010 for both the overall bass tissue concentration of 0.58 µg/g and for bass caught specifically in the Southeastern Plains ecoregion of 0.41 µg/g (SCDHEC 2010).

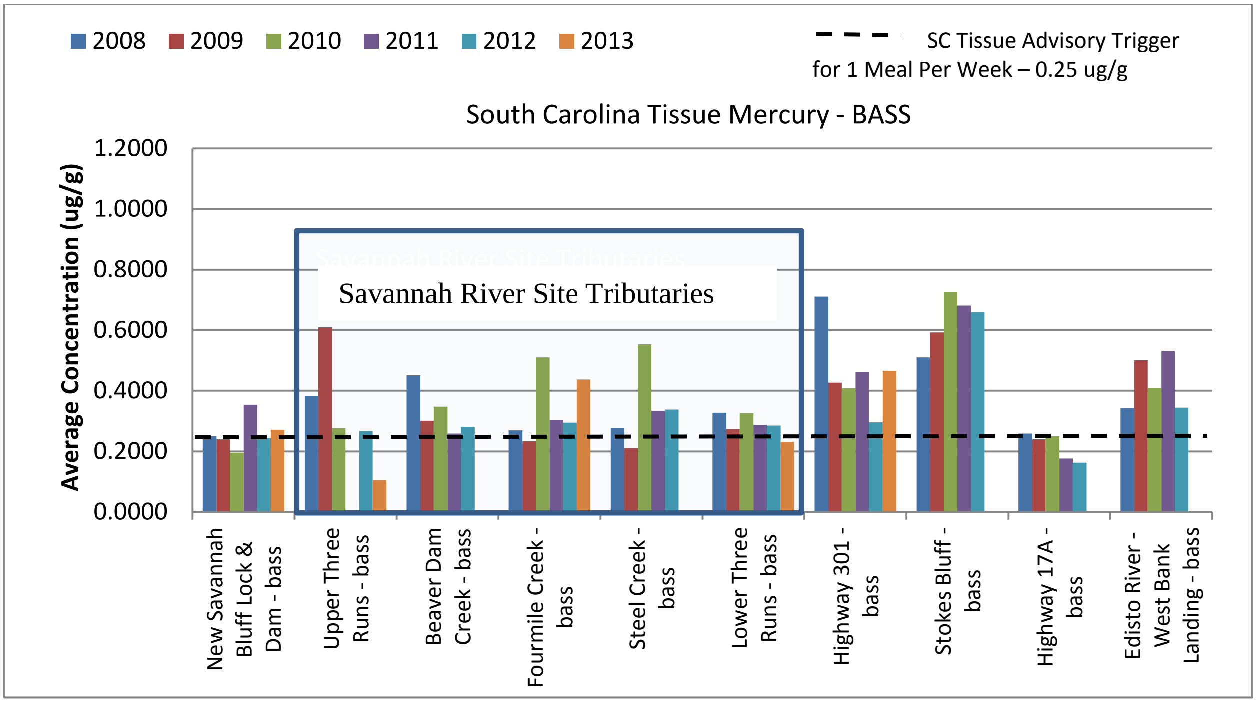

Figure 4-4 Mercury Concentrations in Bass by Location for the Period 2008 through 2013

Average concentration values for catfish collected at the mouths of the SRS streams were frequently below the SCDHEC trigger level of 0.25 µg/g. Downstream locations showed slightly higher concentrations with the highest concentration being measured in 2008 at Highway 301 at 0.452 (µg/g) and the minimum of 0.100 (µg/g) at Highway 301 in 2012 (Figure 4-5).

Average concentration values for panfish collected at the mouths of the SRS stream were frequently below the SCDHEC trigger level of 0.25 µg/g. The highest concentrations collected were in fish caught at the downstream location of the Edisto River near the West Bank Landing. Concentrations at this location ranged from a maximum of 0.480 µg/g in 2009 to a minimum of 0.265 µg/g in 2012 (Figure 4-6).

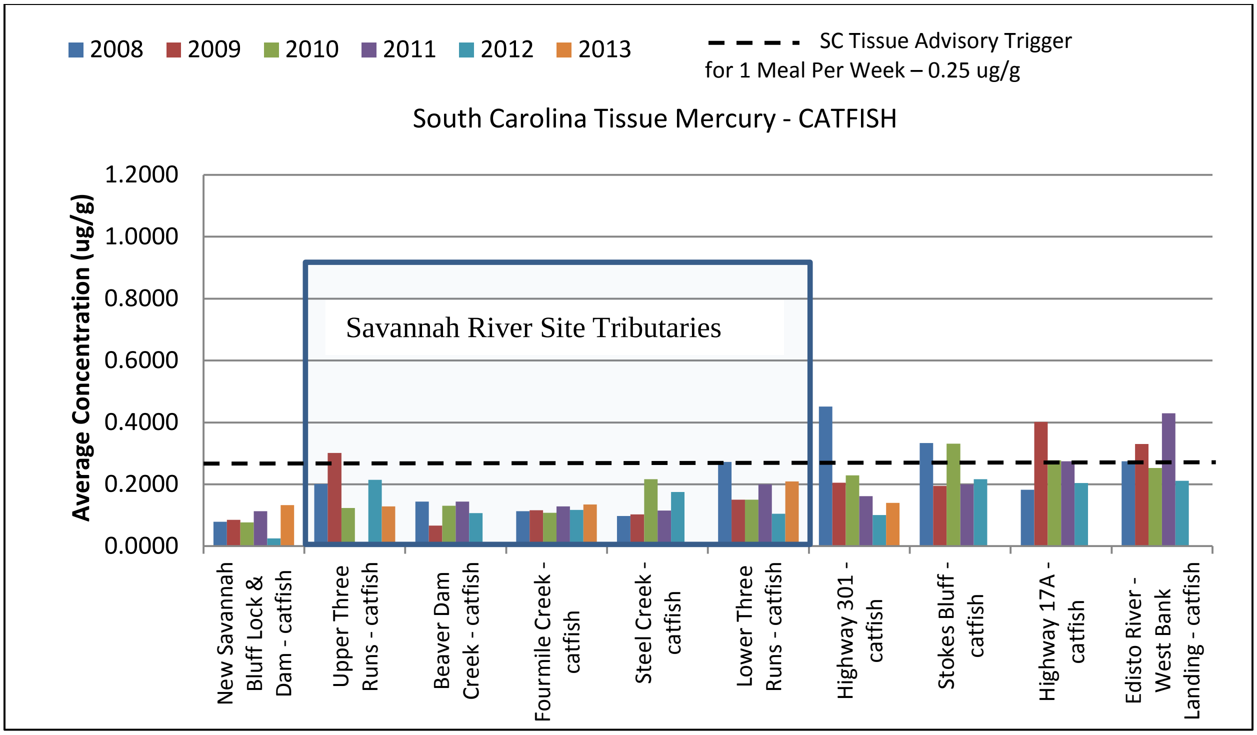

Figure 4-5 Mercury Concentrations in Catfish by Location for the Period of 2008 through 2013

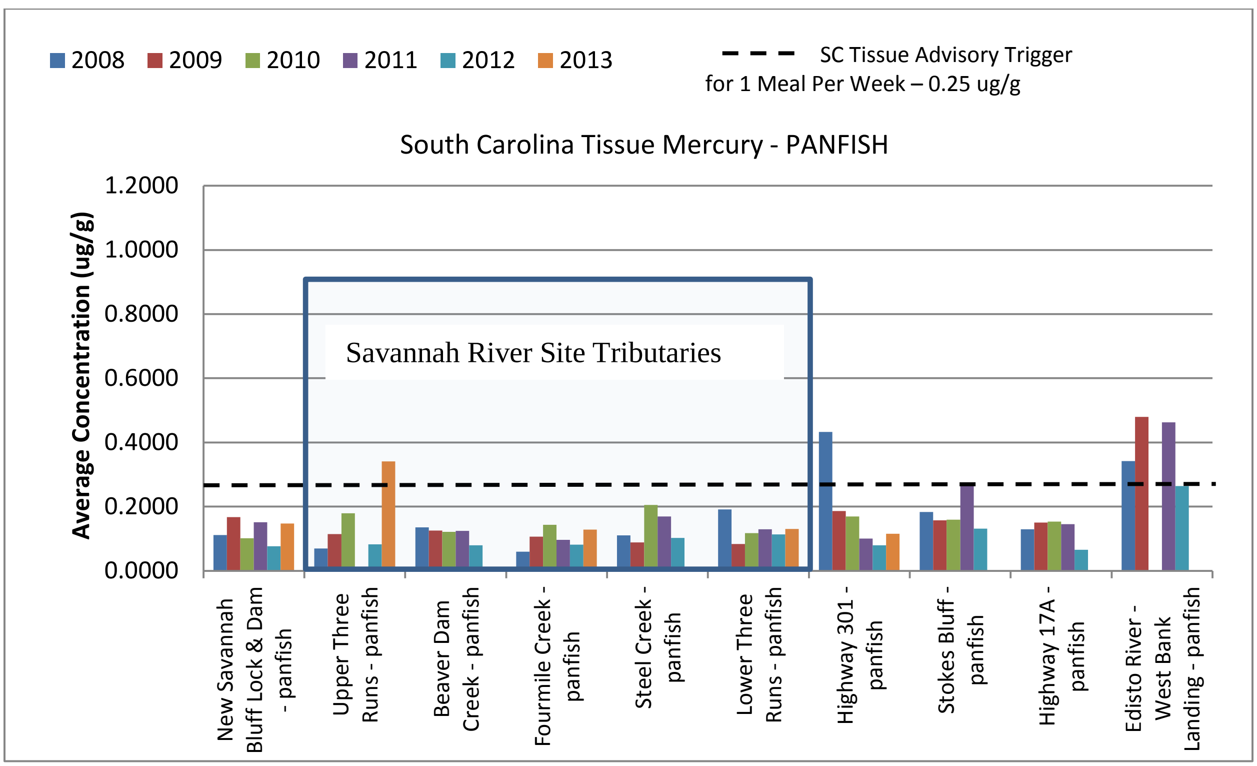

Figure 4-6 Mercury Concentrations in Panfish by Location for the Period of 2008 through 2013

4.4.4 *Comparison of SRS Largemouth Bass Tissue Concentrations with other South Carolina Rivers*

Largemouth bass are a species of concern for mercury contamination because their high trophic level and known ability to bioaccumulate methylmercury into their tissue. A comparison of known largemouth bass average tissue concentrations was conducted to determine if concentrations measured in fish from SRS streams were significantly different from other South Carolina rivers. Using average concentrations reported in the SCDHEC 2010 report, concentrations for largemouth bass collected from rivers found in the same ecoregion as SRS streams (Southeastern plains) were used for comparison. As shown in Section 2 a characteristic of the southeastern plains is the presence of forested wetlands (Figure 2-4).

Nine rivers were selected for comparison and showed that the maximum average tissue concentration was measured in the Little Pee Dee River at 1.43 µg/g and the minimum average concentration of 0.17 µg/g in the Santee River. The Savannah River average was 0.41 µg/g. Taking the average largemouth bass tissue concentrations collected at the mouths of the SRS streams for the last five years the maximum and minimum concentrations were measured at Upper Three Runs. The minimum concentration of 0.11 µg/g was measured in 2013 while the maximum of 0.61 µg/g was measured in 2009 (SRNS 2013) (Figure 4-7).

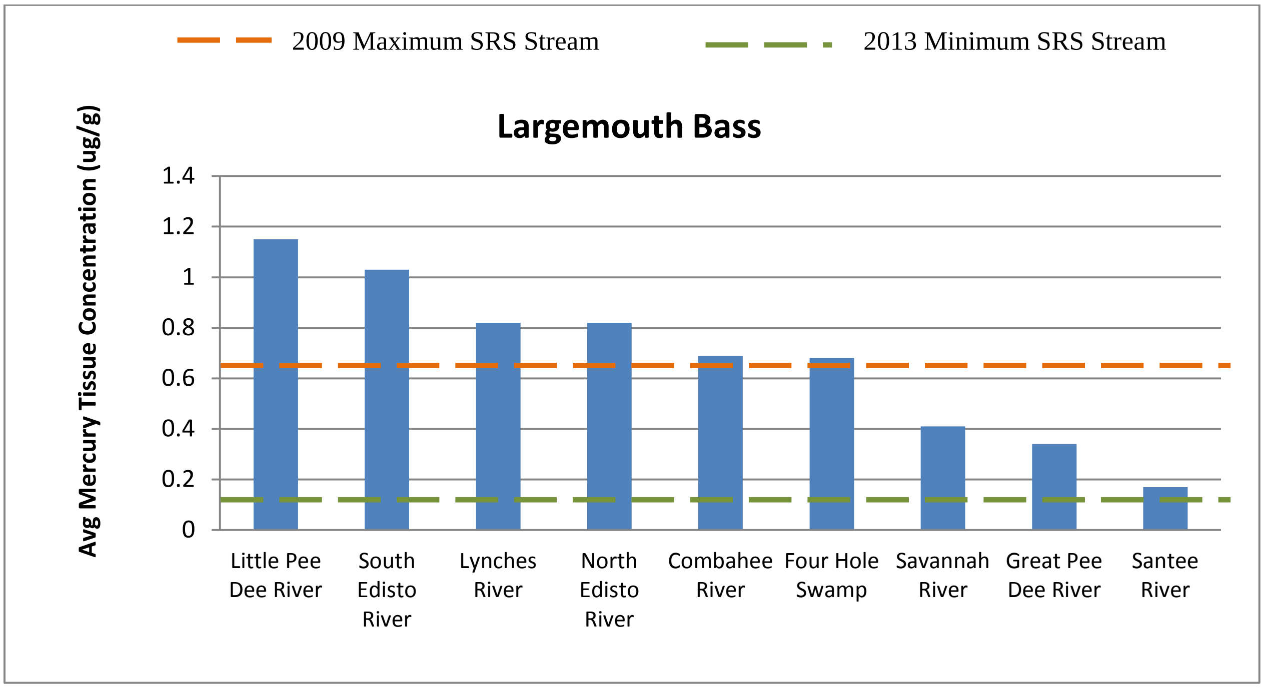

Figure 4-7 Comparison of Average Tissue Concentrations in SRS collected Largemouth Bass to other South Carolina Rivers in the Southeastern Plains

4.5 Sediment Surveillance for Mercury at SRS

SRS's non radiological sediment surveillance program collects sediment samples at eight onsite stream locations and three Savannah River locations. Collections are made by either Ponar sediment sampler or an Emery pipe dredge sampler. Samples are analyzed for mercury and duplicate sampling and analysis is performed by SCDHEC.

Results of sediment surveillance show that mercury concentrations are below detection or below practical quantitation limits for the last six years. Results from 2013 show a detection of mercury of 0.53 µg/g at

Beaver Dam Creek, but this value is within the range of background mercury levels measured in surface sediments that ranged as high as 1.00 µg/g (Kaplan et al. 2002) (Table 4-3).

Table 4-3 Sediment Surveillance for Mercury (µg/g)

Location	2008	2009	2010	2011	2012	2013
Upper Three Runs 4	ND	ND	ND	<0.26	<0.31	ND
Beaver Dam Creek	ND	ND	ND	<0.16	<0.13	0.53
Four Mile Creek at 125	ND	ND	ND	<0.15	<0.11	ND
Pen Branch	ND	ND	ND	<0.17	<0.17	ND
Steel Creek	ND	ND	ND	<0.12	<0.12	ND
Lower Three Runs	ND	ND	ND	<0.26	<0.14	ND
Upper Three Runs 1A	ND	ND	ND	<0.41	<0.54	ND
Tinker Creek	ND	ND	ND	<0.12	<0.12	ND
River Mile 160	ND	ND	ND	<0.13	<0.13	ND
Plant Vogtle Discharge	ND	14	11	<0.14	<0.12	ND
River Mile 118.7	ND	ND	ND	<0.16	<0.15	ND

4.6 Evolving Vectors for Exposure to Mercury – American Alligator

The American alligator (*Alligator mississippiensis*) lives in the Southeastern region of the United States. The historical range included the coastal plain portion of the Savannah River watershed, including SRS. Georgia and South Carolina have flourishing populations of alligators managed through a regulated hunting season. Georgia (GADNR 2013) and South Carolina (SCDNR 2013) control public hunting and monitor harvests using permits (tags) issued by each state's Department of Natural Resources (DNR).

On the SRS, alligators are abundant in the Savannah River, its swamp and tributaries, L-Lake, Par Pond, and other reservoirs on the site (Figure 4-8) (SREL 2012). Researchers at the Savannah River Ecology Laboratory (SREL) have extensively studied these alligators (Brisbin 1989, 1992, 1997; Jagoe et al. 1998). Long-term studies by SREL have been the foundation for the analysis and interpretation of the fate and effects of mercury and radioactive contaminants in these animals. Some individual alligators have accumulated muscle tissue levels of mercury and cesium-137 that would make human consumption of their meat an issue of potential concern. Even though the SRS is closed to public access and alligator hunting is prohibited, larger alligators can leave the Site's boundaries and move onto public lands where they could be harvested (Brisbin et al. 1992; 1997).

SRS is interested in understanding harvest rates of alligators that may have been associated with the Site to ensure that the public is not exposed to potentially harmful levels of Site-related contamination in alligator meat harvested in the vicinity of the Site.

Figure 4-8 Mature American Alligators Basking in the Sun on the Banks of L-Lake Public alligator hunting is prohibited on SRS (Photo from SRS 2012)

As part of the effort to answer questions about the potential for members of the public to harvest and consume contaminated alligators, SRS personnel researched harvest statistics for South Carolina and Georgia. Of particular interest are alligators harvested from Aiken, Allendale, and Barnwell counties since they border SRS. The annual harvest data (2008 to 2012) from these indicate an average of seven alligators was harvested from Aiken, Allendale, and Barnwell Counties between 2008 and 2012. SRS is working with Georgia DNR to obtain unpublished county specific harvest data for those Georgia counties that border SRS.

4.6.1 *Mercury Concentrations in Alligators Collected From 2010 to 2013*

Since mercury is known to bioaccumulate in alligators, SRS analyzed alligator samples donated by hunters who have harvested alligators from the Savannah River near the Site during the years 2010 to 2013.

In the summer of 2012, a local hunter donated a portion of meat from two alligators. One alligator was harvested in September of 2010 (GA-003766) and the second was harvested in September of 2011 (SC-12113). Both animals were harvested from the Savannah River near Little Hell Landing. Two alligator samples were collected during 2013. The mercury results for the 2013 samples in addition to the two samples collected in 2010 and 2011 were reported in the SRNS 2013 Annual Environmental Report (SRNS 2013).

Table 4-4 indicates the mercury concentrations measured in each alligator. These values were compared against mercury concentrations measured in fish collected as part of the surveillance program in the Savannah River. Figure 4-9 indicates the mercury results in the alligator samples are consistent with the ranges of mercury concentrations measured in the freshwater fish collected in the Savannah River.

Table 4-4 Mercury Concentrations in Alligators Collected From 2010 to 2013

Location	Collection Date	Mercury (µg/g)	MDL (µg/g)
GA-0003766	9/24/2010	0.70	0.02
SC-12113	9/25/2011	0.50	0.02
SC-10697	10/11/2013	0.59	0.02
GA-01100	9/18/2013	0.90	0.02

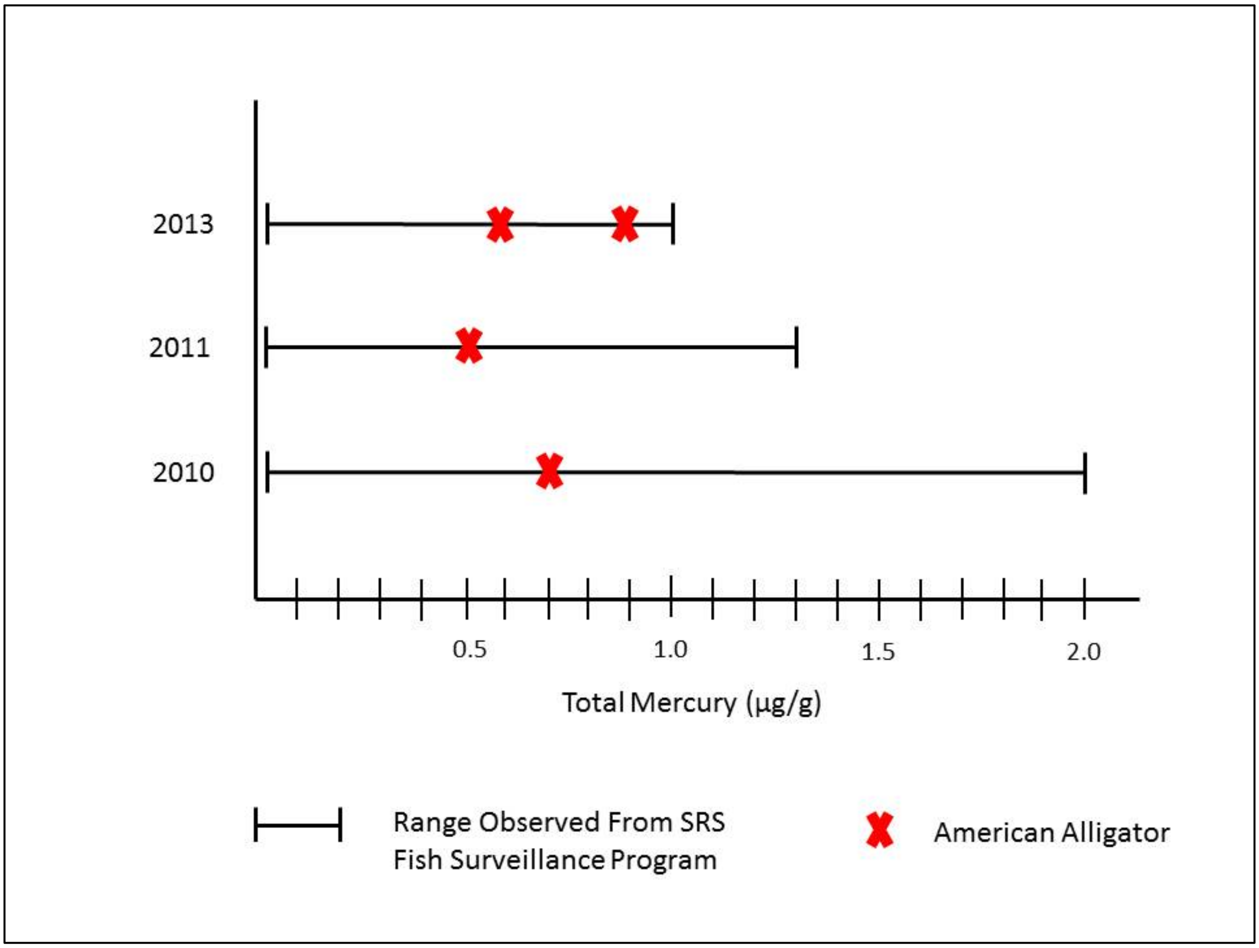

Figure 4-9 Comparison of Mercury Observed in American Alligator with Range Observed in Edible Wet Weight Fish from the Savannah River

4.7 <u>Centers for Disease Control and Prevention Investigates SRS Role in Mercury Releases to the Savannah River</u>

The Centers for Disease Control and Prevention (CDC) contracted with Risk Assessment Corporation (RAC) to conduct a "Dose Reconstruction" of past releases leading to human exposure and dose from chemicals and radioactive releases to the offsite environment from the SRS. Evaluations were conducted for the years 1951 through 1992 by thoroughly reviewing records and documents related to environmental releases in an attempt to determine whether SRS operations resulted in elevated mercury concentrations in the Savannah River.

4.7.1 *Mercury Released to F-Area and H-Area Seepage Basins*

Between 1959 and 1982, more than 3600 and 840 lb of mercury were released to H-Area and F-Area seepage basins, respectively (Horton 1974b, cited in RAC 2001). Use of the basins continued through 1988, after which they were capped and did not receive additional effluent. During 1972 several studies were conducted to identify mercury concentrations in the soil, seepline sediment, water and groundwater of the F- and H-Area seepage basins and Four Mile Creek sediment and water. Conclusions made by RAC in their report to the CDC from the review of available data indicated:

- "*Small amounts of mercury have migrated from F-Area and H-Area seepage basins into the groundwater;*
- *Mercury inventory for the F-Area and H-Area seepage basins (about 4500 lb) has remained in the environs of the basins, and the rate of mercury migration into Four Mile Creek (and the Savannah River) has been small relative to the rate of discharge from the Olin Corporation;*
- *Sediment samples collected from the swampy outcrop along the first sidestream into Four Mile Creek have indicated migration of mercury to this area. However, sediment samples taken from various locations in Four Mile Creek imply that the mercury has remained in rather localized areas.*
- *Based on mercury concentrations measured in Savannah River and Four Mile Creek sediment, SRS activities have not resulted in appreciable mercury releases to the Savannah River."*

4.7.2 *Concentrations of Mercury in Fish Caught On-Site at SRS Versus Off-Site in the Savannah River*

Fish data reported in the 1971 to 1991 annual environmental monitoring reports were evaluated and compared with fish collected from a control location upriver from the SRS (Thurmond Lake). Average mercury concentrations measured in fish from Thurmond Lake and the Savannah River at locations above, adjacent to, and below the SRS showed no statistically significant differences (RAC 2001). This was not consistent with the fact that Olin Corporation discharges to the Savannah River are well downriver from the Thurmond Reservoir, and concentrations of mercury in the fish from Thurmond Lake would not be expected to be the same as fish from the Savannah River. Fish evaluated in the study (Bream, Bass, Catfish and other) were of similar size and length (GWQCB 1971).

Conclusions made from the review of available data indicated:

- "*Evaluations of average mercury concentrations in fish for on-site and Savannah River locations from 1971 to 1991 showed that concentrations appear to be a factor of 2 greater in onsite fish;*
- *There is little evidence to suggest that mercury from F-Area and H-Area seepage basins has resulted in elevated fish concentration in Four Mile Creek or any other onsite stream.*
- *The highest concentrations appear to be in SRS streams and reservoirs that have received reactor cooling effluent. It is unlikely that cooling effluent would contain mercury resulting from reactor operations, and it appears that the primary source of mercury at the SRS has been the continuous pumping of Savannah River water for use as a reactor coolant.*
- *Several studies have reported elevated mercury concentrations in fish (approaching and exceeding concentrations measured in onsite fish) collected from South Carolina and Georgia reservoirs lacking a known mercury point source of contamination."*

5.0 Conclusions

Mercury in freshwater streams is a national and global issue. As referenced in the recent publication by the USGS on Mercury in the Nation's Streams (USGS 2014) the aquatic systems in the southeastern

United States have higher overall levels of mercury in water, sediment and biota due to factors including higher rainfall levels, increased inputs from atmospheric deposition, increased amounts of wetlands that promote methylmercury production and unique hydrological systems that make methylmercury more available to biota than other systems (USGS 2014; EPA 1999; USGS 2009). The southeastern U.S. is dominated by wetland systems. In South Carolina 1/4 of the state's land cover is wetlands and all major rivers have mercury fish advisories for 2014. SRS has a relatively undeveloped landscape, with nearly 22% of the area consisting of forested wetlands which are drained by five tributaries that run across the site.

Mercury in the Savannah River has numerous sources including atmospheric deposition (i.e. coal fired power plants, rainfall, forest fires), legacy industrial inputs (i.e. Olin Corporation, SRS), and, to a lesser extent, natural geologic deposits.

Recent comprehensive reviews of usage of mercury at the SRS and the dose reconstruction project conducted by RAC 2001 for the CDC concluded that:

- *"It appears likely that much of the F-Area and H-Area seepage basin mercury inventory (about 4500 lb) has remained in the environs of the basins, and the rate of mercury migration into Four Mile Creek (and certainly into the Savannah River) has been small relative to the rate of mercury from the Olin Corporation. At one time, the rate of discharge from the Olin plant was reported to be 12 lb per day. At this rate, Olin plant operations would result in an annual discharge of about 4400 lb of mercury directly to the Savannah River. For comparison, approximately the same amount was discharged by the SRS to F-Area and H-Area seepage basins between 1959 and 1982."*
- *"Based on mercury concentrations measured in Savannah River and Four Mile Creek sediment, however,* ***SRS activities have not resulted in an appreciable mercury releases to the Savannah River."***
- *"Based on concentrations of mercury measured in fish collected from the Savannah River at locations above, adjacent to, and below the SRS, which were very similar,* ***SRS activities have not resulted in measurable mercury releases to the Savannah River."***
- *"Mercury concentrations measured in fish collected from onsite ponds and streams have consistently been elevated (by about a factor of 2) relative to Savannah River fish concentration. However, concentration in fish from Four Mile Creek are similar to or lower than concentrations in fish from other onsite locations. There is little evidence to suggest that mercury from F-Area and H-Area seepage basins has resulted in elevated fish concentration Four Mile Creek or any other onsite stream. The highest concentrations appear to be in streams and reservoirs that have received reactor cooling effluent.* ***It is unlikely that cooling effluent would contain mercury resulting from reactor operations, and it appears that the primary source of mercury at the SRS has been the continuous pumping of Savannah River water for us as a reactor coolant"***.

Recent measurements of methylmercury concentrations in water, sediment and biota (fish and clams) from SRS tributaries and the Savannah River concluded that:

- On average the concentrations in the tributary water was twice as high as concentrations in the river;
- Concentrations in clams and fish in the tributaries was twice as high as for those in the Savannah River;
- Conditions associated with the wetlands that drain these tributaries are adequate to promote methylmercury production.

- Average tissue concentrations measured in largemouth bass at the mouths of the SRS streams into the Savannah River showed that the range of concentrations were within concentrations measured in other South Carolina rivers of the same ecoregion (Southeastern Plains).
- Analysis of sediment samples showed that mercury levels were within measured background levels.

SRS is continuing to conduct routine monitoring of biota, water, sediment and rainwater for analyses of mercury. Many activities have been initiated to address recommendations made by the ATSDR (ATSDR 2012) including the identification of biota consumed by humans residing near SRS and the monitoring of those biota including alligators, rabbits, squirrels, ducks, turtles and other small animals through SREL. SRNL personnel are continuing to address contributions of mercury to the site from atmospheric deposition pathways and identifying remediation strategies for contaminated locations like Tims Branch. Results of many of the initiated projects will be available in 2015-2016. Continued monitoring of sediment shows no accumulation of mercury in sediments of tributaries. Concentrations in freshwater fish show a downward trend in species starting from 2009 and continuing into 2013 with levels decreasing in catfish to panfish. Measurements in a small number of alligators indicate that mercury levels are consistent with those found in freshwater fish.

6.0 Recommendations

- More research is needed to better understand methylmercury production in the SRS tributaries, and the impact of tributary discharge on methylmercury level in the mainstem river and river biota.
- Additional research examining the relationship between flood events and aqueous mercury concentrations will be needed to fully understand and verify relationships between floodplain hydrology and mercury availability.
- A full inventory of Four Mile Creek and swampy outcrop along the first side stream for mercury is needed along with a multiyear study movement, if any, for mercury in this system.
- A review of Par Pond and L Lake sediment is needed to determine potential influxes of mercury from disturbed sediment to the SRS Mass Balance diagram.
- A review of sediment and fish concentrations from lesser studied reactor cooling ponds (Pond A, Pond B and Pond C).
- A review of mercury in litterfall found on SRS as well as South Carolina and Georgia.

7.0 References

ATSDR 2012. Agency for Toxic Substances and Disease Registry. (2012). Evaluation of Exposures to Contaminants in Biota Originating from the Savannah River Site (USDOE) Savannah River Site Aiken, South Carolina EPA Facility ID: SC1890008989 February 29,2012. Department of Health and Human Services, Springfield, Virginia.

AMAP and UNEP 2008. Arctic Monitoring and Assessment Programme and United Nations Environment Programme. (2008). Technical Background Report to the Global Atmospheric Mercury Assessment.

Brisbin et al. 1989. Brisbin, I.L., Jr. (1989). Radiocesium Levels in a Population of American Alligators: A Model for the Study of Environmental Contaminants in Free-Living Crocodilians. In Crocodiles: Proceedings of the 8th Working Meeting of the Crocodile Specialist Group of the Species Survival Commission of the International Union for Conservation of Nature and Natural Resources, IUCN. Quito, Ecuador.

Brisbin et al. 1992. Brisbin, I.L., Jr., J.M. Benner, L.A. Brandt, R.A. Kennamer, and T.M. Murphy. (1992). Long-Term Population Studies of American Alligators Inhabiting a Reservoir: Initial Responses to Water Level Drawdown. p. 53-76. In Crocodiles – Proceedings of the 11th Working Meeting of the Crocodile Specialist Group of the SSC of the IUCN - The World Conservation Union, Vol. 1. IUCN. Victoria Falls, Zimbabwe.

Brisbin et al. 1997. Brisbin, I.L., K.F. Gaines, C.H. Jagoe, and P.A. Consolie. (1997). Population Studies of A. Alligators (*Alligator mississippiensis*) Inhabiting a Reservoir: Responses to Long-Term Drawdown and Subsequent Refill. p. 446-477. In Proceedings of the 13th Working Meeting of the IUCN/SSC Crocodile Specialist Group, IUCN-The World Conservation Union. Gland, Switzerland.

Chalmers et al. 2011. Chalmers, A.T., Argue, D.M., Gay, D.A., Brigham, M.E., Schmitt, C.J. and D.L. Lorenz. (2011). Mercury Trends in Fish from Rivers and Lakes in the United States, 1969-2005. *Environmental Monitoring and Assessment.* 175(1):175-191.

Dahl 2011. Dahl, T.E. (2011). Status and Trends of Wetlands in the Conterminous United States 2004 to 2009. U.S. Department of the Interior. Fish and Wildlife Service, Washington, D.C. 108 pp.

EPA 1999. U.S. Environmental Protection Agency. (1999). The National Survey of Mercury Concentrations in Fish. Database summary 1990-1995. EPA-823-R-99-014.

EPA 2000. U.S. Environmental Protection Agency. (2000) Total Maximum Daily Load (TMDL) Development for Total Mercury in the Middle/Lower Savannah River, GA. USEPA Region 4, Atlanta, Georgia.

EPASWL 1971. Environmental Protection Agency Southeast Water Laboratory. (1971). A Report on Pollution in the Middle Reach of the Savannah River, Georgia-South Carolina. Technical Study Report No. TS03-71-208-003.

Fitzgerald et al. 1998. Fitzgerald, W.F., Engstrom, D.R., Mason, R.P., and E.A. Nater. (1998). The Case for Atmospheric Mercury Contamination in Remote Areas. *Environmental Science and Technology*. 32(1):1-7.

Fulkerson and Nnadi 2006. Fulkerson, M. and F.N. Nnadi. (2006). Predicting Mercury Wet Deposition in Florida – A Simple Approach. *Atmospheric Environment*. 40:3962-3968.

GADNR 2013. Georgia Department of Natural Resources. (2012) “Alligator Hunting Season for 2012.” Web site:http://www.georgiawildlife.com/Hunting/Alligator, Atlanta, Georgia.

GWCQB 1971. Georgia Water Control Quality Board. (1971). Mercury Pollution Investigation in Georgia 1970-1971. Georgia Water Quality Control Board, Atlanta Georgia.

Glover et al. 2010. Glover, J.B., Domino, M.E., Altman, K.C., Dillman, J.W., Castleberry, W.S., Eidson, J.P. and M. Mattocks. (2010) Mercury in South Carolina fishes, USA. *Ecotoxicology* 19:781–795.

Hall et al. 2008. Hall, B.D., Aiken, G.R., Krabbenhoft, D.P., Marvin-DiPasquale, M. and C.M. Swarzenski. (2008). Wetlands as Principal Zones of Methylmercury Production in Southern Louisiana and the Gulf of Mexico Region. *Environmental Pollution.* 154(1):124-134.

Halverson et al. 2008. Halverson, N.V., J.A. Bowers, M.H. Paller, D.G. Jackson, J.K. King, and D.L. Dunn. (2008) Final Report on the Aquatic Mercury Assessment Study. Savannah River National Laboratory. SRNS-STI- 2008-00106.

Horton 1974. Horton, J.H. (1974). *SRL-SRP Mercury Monitoring Program, DPST-74-389*, E.I. du Pont de Nemours & Co., Aiken, South Carolina.

Jagoe et al., 1998. Jagoe, C.H., B. Arnold-Hill, G.M. Yanochko, P.V. Winger, and I.L. Brisbin, Jr. “Mercury in alligators (*Alligator mississippiensis*) in the southeastern United States,” p. 255-262. In International Conference on Mercury as a Global Pollutant, *The Science of the Total Environment*. Hamburg, Germany.

Kaplan et al. 2002. Kaplan, D.I., Knox, A.S. and J. Myers. (2002). Mercury Geochemistry in a Wetland and its Implications for In-Situ Remediation. WSRC-MS-2002-00056.

Kvartek et al. 1994. Kvartek, E.J., W.H. Carlton, M. Denham, L. Eldridge, and M.C. Newman. (1994) Assessment of Mercury in the Savannah River Site Environment (U). WSRC-TR-94-0218ET

Looney et al. 2010. Looney B.B., Jackson, D.G., Peterson, M.J., Mathews, T.J., Southworth, G., Bryan, L., Paller, M. and C. Eddy-Dilek. (2010). Assessing Potential Impacts of Stannous Chloride Based Mercury Treatment on a Receiving Stream Using Real-World Data from Tims Branch, Savannah River Site. Technical Report SRNL-STI-2010-00393.

Looney et al. 2012. Looney, B., L. Bryan and T. Matthews. (2012) Interim Results from a Study of the Impacts of Tin(II) Based Mercury Treatment in a Small Stream Ecosystem: Tims Branch, Savannah River Site. Technical Report SRNL-STI-2012-00202. dx.doi.org/10.2172/1038050.

Mackey et al. 1985. Mackey, H.E., Jr., Jensen, J.R., Hodgson, M.E. and E.J. Christiansen. (1985) Savannah River Plant Wetlands Update. DPST-85-661. Savannah River Laboratory, E.I. du Pont de Nemours and Company, Aiken, South Carolina.

Paller et al. 2004. Paller, M.H., Jagoe, C.H., Bennett, H., Brant, H.A. and J.A. Bowers. (2004) Influence of Methylmercury from Tributary Streams on Mercury Levels in Savannah River Asiatic clams. *Science of the Total Environ*. 325:209-219.

Paller and Littrell 2007. Paller, M.H. and J.W. Littrell. (2007). Long-term changes in mercury concentrations in fish from the middle Savannah River. *Science of the Total Environment* 382:375-382.

RAC 2001. Risk Assessment Corporation. (2001) Savannah River Site Environmental Dose Reconstruction Project. Phase II: Source term calculation and ingestion pathway data retrieval evaluation of materials released from the Savannah River Site. Final Report. RAC Report No. 1-CDC-SRS-1999-Final.

SCDHEC 2010. South Carolina Department of Health and Environmental Control. (2010) "South Carolina Mercury Assessment and Reduction Initiative," Columbia, South Carolina.

SCDHEC 2012. South Carolina Department of Health and Environmental Control (SCDHEC). (2012) "South Carolina 2012 Fish Consumption Advisories," Columbia, South Carolina.

SCDHEC 2014. South Carolina Department of Health and Environmental Control (SCDHEC). (2014) "South Carolina 2014 Fish Consumption Advisories," Columbia, South Carolina.

SCDNR 2013. South Carolina Department of Natural Resources. (2013) Website: http://dnr.sc.gov/wild-life/alligator/ "Alligator Hunting Season Report 2012," Report 12-05. South Carolina Department of Natural Resources, Columbia, South Carolina.

Schalles et al. 1989. Schalles, J. F., Sharitz, R.R., Gibbons, J.W. and J. N. Knox. (1989). Carolina Bays of the Savannah River Plant. SRO-NERP-18. Savannah River Ecology Laboratory, Aiken, South Carolina.

Shields et al. 1982. Shields, J. D., Woody, N.D., Dicks, A.S., Hollod, G.J., Schalles, J. and G. J. Leversee. (1982). Locations and Areas of Ponds and Carolina Bays at the Savannah River Plant. Savannah River Laboratory, E. I. du Pont de Nemours and Company, Aiken, South Carolina.

SREL 2012. Savannah River Ecology Laboratory. (2012) "American Alligator," SREL Outreach Program Factsheet. http://www.srel.edu/outreach/factsheet/AlligatorBrochure.pdf, Savannah River Site, Aiken, South Carolina.

SRNS 2012. Savannah River Nuclear Solutions, LLC, (2012). Savannah River Site Environmental Report for 2012, SRNS-STI-2013-00024, Savannah River Nuclear Site, Aiken, South Carolina.

SRNS 2013. Savannah River Nuclear Solutions, LLC, (2013) Savannah River Site Environmental Report for 2013, SRNS-STI-2014-00006, Savannah River Nuclear Site, Aiken, South Carolina.

SRS 2005. Savannah River Site. (2005) Ecology, Environmental Information Document, WSRC-TR-2005-00201.

Schroeder and Munthe 1998. Schroeder, W.H. and J. Munthe. (1998) Atmospheric Mercury – An Overview. *Atmospheric Environment* 32(5):809-822

Scudder et al. 2009. Scudder, B.C., Chasar, L.C., Wentz, D.A., Bauch, N.J., Brigham, M.E., Moran, P.W. and D.P. Krabbenhoft. (2009). Mercury in Fish, Bed Sediment, and Water from Streams Across the United States, 1998-2005: U.S. Geological Survey Scientific Investigations Report 2009-5109, 74 p., http://pubs.usgs.gov/sir/2009/5109.

Selin 2009. Selin, N.E., (2009). Global Biogeochemical Cycling of Mercury – A Review. *Annual Review of Environment and Resources*. 34(1):43-63.

Tilly and Wilhite 1972. Tilly, L.J. and E.L. Wilhite. (1972). Mercury in the Par Pond System. Technical Division, Savannah River Laboratory, SRS Phase II Database PDM199710016.

UNEP 2002. United National Environmental Programme. (2002) Global Mercury Assessment. UNEP Chemicals Branch, Geneva, Switzerland.

UNEP 2013. United Nations Environment Programme. (2013). Global mercury assessment 2013: Sources, Emissions, Releases and Environmental Transport. UNEP Chemicals Branch, Geneva, Switzerland.

USGS, 1996. U.S. Geological Survey. (1996) Fretwell, J.D., Williams, J.S. and P.J. Redman. National Water Summary on Wetland Resources. Water Supply Paper 2425.

USGS 2001. U.S. Geological Survey (2001). A National Pilot Study of Mercury Contamination of Aquatic Ecosystems Along Multiple Gradients: Bioaccumulation in Fish. Biological Science Report, USGS/BRD/BSR-2001-009. 25 p.

USGS 2009. U.S. Geological Survey. (2009) Bradley, P.M., Chapelle, F.H. and C.A. Journey. Comparison of Methylmercury Production and Accumulation in Sediments of the Congaree and Edisto River Basins, South Carolina, 2004-2006. Scientific Investigations Report 2009-5021.

USGS 2014. U.S. Geological Survey. (2014) Wentz, D.A., M.E. Brigham, L.C. Chasar, M.A. Lutz and D.P. Krabbenhoft. Mercury in the Nation’s Streams – Levels, Trends, and Implications. Circular 1395. 90 p., http://dx.doi.org/10.3133/cir1395.

8.0 Appendix

8.1 SRNL Special Study for Removal and Treatment of Mercury and Tin in the Tims Branch Ecosystem

In 2012, a multi-organizational research team completed the initial phase of research in a special study of Tims Branch (Looney, et al., 2012). The project aimed to evaluate and quantify the impacts of an innovative, inexpensive treatment system that removes mercury from water. In this treatment, mercury reacts with stannous (tin) chloride and then air stripping removes the mercury from the water, a technology that treats volatile contaminants.

Starting in November 2007, this system operated continuously at full scale in M Area treating 400 to 500 gallons per minute (gpm) of water containing about 250 ng of mercury per liter (ng/L or parts per trillion). Figure 8-1 shows the air stripper. Mercury in the raw water is below the human drinking water standard of 2,000 ng/L, but higher than the ecological and recreational use-based water quality limits set for the outfall (51 ng/L). The long-term aim of implementing the outfall limits in 2007 was to lower mercury levels in downstream fish. Mercury levels in the treated water released to the environment have been reduced more than 95%, achieving the strict ecological and recreational use-based water quality limits.

Figure 8-1 SRS Modified the M-1 Stripper System in 2007 to Remove Mercury

Researchers from the Savannah River National Laboratory (SRNL), SREL, and Oak Ridge National Laboratory (ORNL), along with a student from Florida International University, contributed to the research (as shown in Figures 7-2 to 7-4). The research has generated a significant data set for two elements in the Tims Branch ecosystem, mercury and tin:

- Mercury bioaccumulates, or builds up in aquatic food chains. The research team measured mercury concentrations in several components of the aquatic ecosystem including water, sediment, biofilm, invertebrates, and fish.
- Confirming a significant reduction in mercury concentration in fish would provide an initial indication of the success of the treatment process in achieving the desired environmental benefits.
- Tin is released to the ecosystem as a byproduct of the mercury treatment. The anticipated form of tin (inorganic tin oxide particles) is not expected to impact the stream and the low concentrations of tin are below regulatory limits. Confirming the anticipated tin behavior in the ecosystem by measuring tin concentrations in the various ecosystem components would help assure that the treatment is not generating any unexpected adverse impacts.

All of the data from 2010 and later were compared to data from samples collected prior to the installation of the treatment system.

Figure 8-2 A SRNL Scientist Collects Water Samples From Tims Branch

Figure 8-4 Florida International University Student Marks a Sampling Location Along Tims Branch

Figure 8-3 Oak Ridge Scientists Collect Fish Samples in 2011 to Support Research on the Impacts of the Mercury Treatment in Tims Branch

Water treatment is having the desired impact on the primary ecological endpoint, fish concentrations, with mercury levels in fish decreasing as the element clears from the ecosystem. Initial mercury data indicate that the first few years of mercury treatment resulted in a significant decrease in mercury concentration in an upper trophic level fish—redfin pickerel—at all sampling locations in the impacted reach of Tims Branch. For example, the whole body mercury concentrations in redfin pickerel collected from the pond just downstream of the outfall decreased approximately 72% between 2006 (pre-treatment) and 2010 (post-treatment). Over this same period, mercury concentrations in the fillet of redfin pickerel in this pond decreased from approximately 1.45 μg/g (wet weight basis) to 0.45 μg/g. Initial data for tin confirmed that a majority of this element discharged into Tims Branch was “inert” tin oxide particles that should not accumulate in fish.

All of the data from the initial phase of work were reported in the Interim Results from a Study of the Impacts of Tin (II) Based Mercury Treatment in a Small Stream Ecosystem: Tims Branch, (Looney et al. 2012).

The initial results of this screening study indicated that the treatment process was performing as predicted. Importantly, the concentration of mercury in upper trophic level fish, as a surrogate for all of the underlying transport and transformation processes in a complex real-world ecosystem, declined as a direct result of the elimination of mercury inputs into Tims Branch. Inorganic tin released to the ecosystem was found in compartments where particles accumulate (such as sediment and biofilms).

8.2 Savannah River Ecology Laboratory, University of Georgia, Special Studies on Mercury in Biota

The Savannah River Ecology Laboratory (SREL), through funding by Savannah River Nuclear Solutions (SRNS) Area Completion Projects, is addressing mercury concerns in biota that could be consumed by humans living offsite of the SRS. The ATSDR report specifically addresses concerns for the monitoring of alligators, squirrels, rabbits, ducks, turtles, and other small animals.

In 2012 three separate projects were initiated to measure mercury in biota that could be harvested by humans as a food source.

8.2.1 *Preliminary Contaminant Analyses in Selected Game Species on the Savannah River Site*

PI and co-PI's: Larry Bryan, Dr. Jim Beasley, Bobby Kennamer and Dr. Gary Mills – SREL isconducting a preliminary study to document levels of radiocesium, mercury, and a suite of metals in tissues of gray squirrels (*Sciurus carolinensis*), waterfowl, and feral hogs (*Sus scrofa*) from various regions on the SRS, over a two-year period.

They will collect tissue samples from up to 80 individuals of each species over the two-year study. Squirrels will be captured in live traps and euthanized by established methods (UGA Animal Use Protocols; Sikes 2011). Waterfowl will be collected by shooting and/or trapping. Hog tissue will be collected at check stations from SRS hunters as well as from SRS contract hunters. To the extent possible, spatial data will be collected with each game sample to examine potential associations of contaminant concentration/prevalence with specific sites (e.g.; D-area).

Tissue samples collected will include muscle, liver, and hair/feathers although the primary analyses will focus on muscle as it is the typical tissue consumed by the public. Depending on the concentrations found in muscle, and if time and funding allow, SREL may also examine correlations between muscle and liver tissues and non-lethal/more easily attained tissues such as hair/feathers. If such correlations are strong, it would allow the estimation of contaminants in non-lethal samples collected during further studies and may allow the estimation of contaminants in off-site harvests (e.g., getting hair/feather samples from game harvested during off-site hunts which might be more feasible than collecting muscle or liver, etc.).

All contaminant analyses will be conducted at SREL. Radiocesium (Bq/g dry wt) will be determined with a Packard 5003 Cobra II Automated Gamma Counter. Mercury concentrations (ug/g dry wt) will be determined with a Milestone DMA 80 by cold vapor atomic absorption spectroscopy and metal/metalloid concentrations (ug/g dry wt for As, Cd, Cr, Cu, Ni, Pb, Se, Sr, U, & Zn) will be determined using ICPMS. For quality assurance, samples will be analyzed in batches containing a blank and standard reference material of known concentration.

This research has just begun, thus there are no conclusions at this time.

8.2.2 *Restoration of the MOX Stream (U8): Initial Efforts*

PI and co-PI's: Dr. J Vaun McArthur and Dean Fletcher – SREL has begun a systematic restoration of the MOX stream (U8). During this budget year SREL will obtain a more detailed profile of the hydrology during base and storm flows and begin collections and analysis of stream invertebrates to determine levels of bioaccumulation of toxic metals.

To date collections of crayfish and dragonfly nymphs have been successfully completed from the MOX stream (U8) as well as four other streams that will be used for comparisons. In addition SREL has collected sediment samples from each of these five streams. Mercury concentrations (µg/g dry wt) will be determined with a Milestone DMA 80 by cold vapor atomic absorption spectroscopy and metal/metaloid concentrations (µg/g dry wt for As, Cd, Cr, Cu, Ni, Pb, Se, Sr, U, & Zn) will be determined on an ICP-MS. For quality assurance, samples will be analyzed in batches containing a blank and standard reference material of known concentration.

This research has just begun, thus there are no conclusions at this time.

8.2.3 *Reptiles as Long-Lived Bioaccumulators of Contaminants & Potential Exposure Risk to Local Residents Through Consumption*

PI and co-PI's: Dr. Tracey D. Tuberville, David Scott and Dr. Stacey Lance – The objectives of this project are:
1) Assess body burdens of select metals and cesium-137 in alligators and aquatic turtles from SRS Integrated Operable Units where known contaminant issues occur and human trespassing is likely (i.e., Lower Three Runs, Savannah River and adjacent swamp, and Par Pond).
2) Survey / interview local hunters and fishermen in communities surrounding SRS with regard to harvesting and consumption of aquatic turtles and alligators. Consumption rate by individuals in vicinity of SRS is identified as a major knowledge gap in the ASTDR 2011 report.
3) Evaluate alternative fitness-related endpoints using standard veterinary diagnostic tools & health parameters for assessing the biological implications of contaminant exposure and bioaccumulation in alligators and aquatic turtles, thereby addressing the ecological risk of contaminants.

To date SREL has collected biological samples from alligators, turtles, and water snakes from contaminated and uncontaminated aquatic habitats on the SRS. In addition, they have identified a master's student's alligator project, which will focus on the effects of contaminants (both radiological and trace element) on stress and immunity in wild alligators by measuring long-term corticosterone (CORT) deposition in scute and nail tissue. They have collected the samples necessary to evaluate whether CORT in these tissues are likely to serve as a good metric for chronic stress. They are in the process of developing the questionnaire for hunters and fisherman and have discussed with our ACP contact expanding the questions, in collaboration with other SREL researchers funded by ACP, to include not just alligators and turtles but other game species. Finally, they are awaiting approval of the UGA IACUC committee to initiate an experiment examining the effects of dietary uptake of selenium on stress and immunity in captive alligators. This project will be conducted by a Ph.D. student at UGA.

Sample processing and data analysis is ongoing, so data is not available at this time to make any conclusions.

Major Impact(s) of Research
The primary objective is to identify and develop non-destructive metrics that can help us evaluate the biological effects of SRS contaminants on reptiles, an area of research that has received very little attention in the literature. The findings will help provide valuable information relevant to management of SRS contaminated habitats and will identify metrics that can be applied to contaminated systems elsewhere.

Products

- Thomas, P., M. Atkinson, B.S. Metts, and T.D. Tuberville. Terrestrial and aquatic performance of banded water snakes (*N. fasciata*) from contaminated wetlands. SREL Undergraduate Research Symposium, July 2013 (Oral Presentation).
- Atkinson, M., J.W. Finger, M. Hamilton, and T.D. Tuberville. Evaluating the use of PHA in testing the immunity of banded water snakes (*Nerodia fasciata*). SREL Undergraduate Research Symposium, July 2013 (Oral Presentation).