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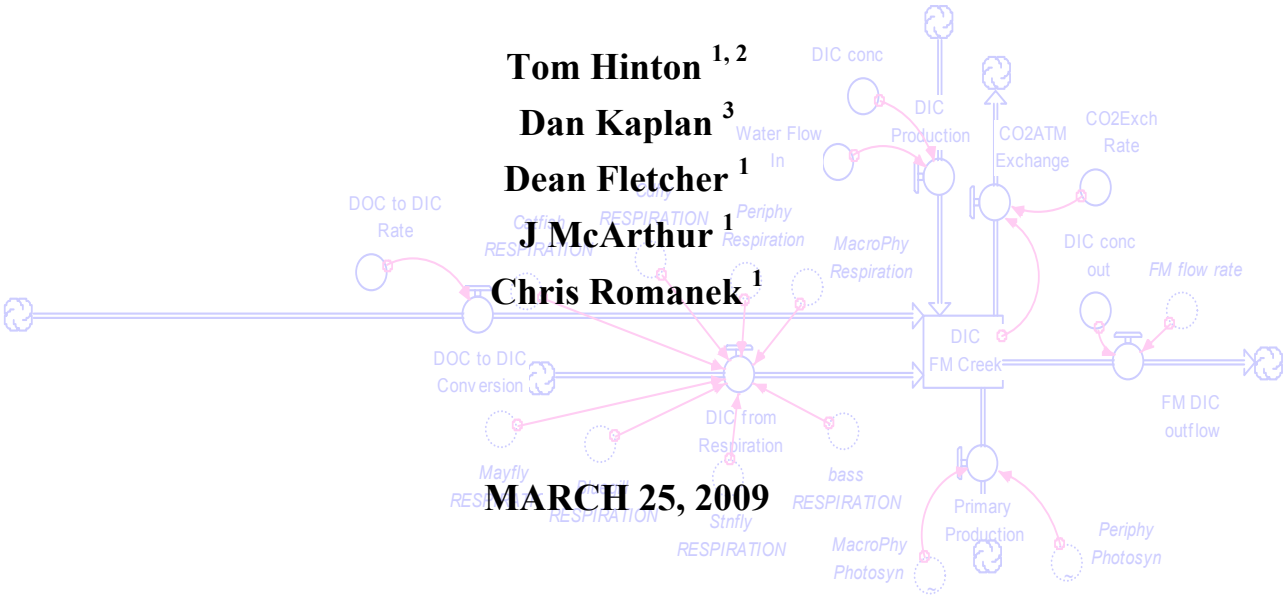
SYSTEMS MODEL of CARBON DYNAMICS in FOUR MILE BRANCH on the SAVANNAH RIVER SITE



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MARCH 25, 2009

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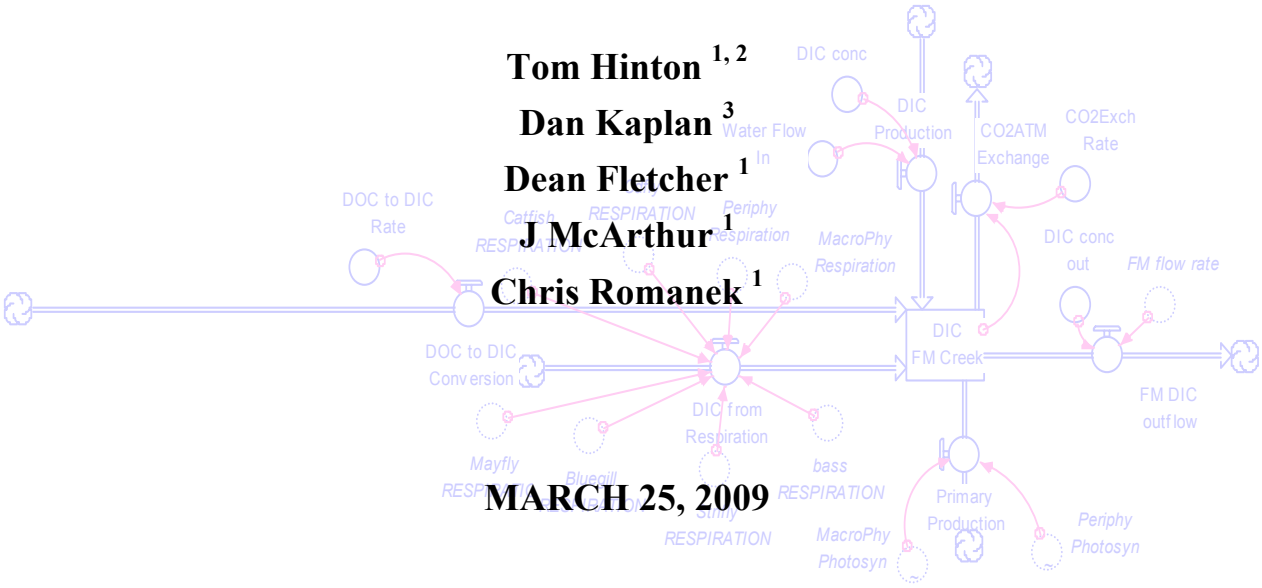

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Thomas G. Hinton, Co-author, Institute of Radiation and Nuclear Safety Date

Daniel I. Kaplan 4/16/2009

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1.0 EXECUTIVE SUMMARY

Past modeling efforts by the SRS to estimate the risks of ^{14}C to humans via the consumption of contaminated food have used a bioconcentration factor (BCF) to estimate contaminant levels in fish. BCFs are easy to use in modeling because concentrations of the contaminant in the water can be multiplied by a BCF (4500 L/kg in the case of ^{14}C, NCRP 1985) to obtain an estimate of the ^{14}C concentrations in fish. However, BCFs have several disadvantages, particularly for radioisotopes for which a high abundance of stable analogous isotopes exist in nature. Carbon is such an element, in that approximately 40 to 50% dry weight of all living components are comprised of stable carbon. A failure to account for the abundance of stable carbon may bias the BCF, and thus, over-predict the contaminant concentrations in fish.

The objective of this work was to produce an ecosystem model of the contaminated system and to estimate the ^{14}C activity concentrations in fish without using BCFs and after accounting for concentrations of stable carbon in the environment. Ecosystem modeling is much more robust than BCRs. This model allows for the dilution of stable isotopes as mentioned above, but equally important, allows for modification and scaling of model parameters and functions due to predicted changes in conditions. Thus, giving risk managers the possibility of assessing risks far into the future, a requirement for calculations involving long-lived radionuclides and nuclear waste repositories.

This modeling effort was possible because of the availability of rich, abundant, relevant field data specific to stable carbon dynamics in a ^{14}C-containing stream on the Savannah River Site (Four Mile Branch, 4MB). Field data exist for dissolved organic carbon, particulate organic carbon, dissolved inorganic carbon, biomass of primary producers (plants), biomass of invertebrates and the biomass of fish within a 1.5 km stretch of 4MB. Model simulations of stable C were within a factor of three of these field measurements.

The same parameters and assumptions used in the stable carbon model were then used to model ^{14}C activity dynamics, assuming a hypothetical, continuous release of 1 kBq L^{-1} of ^{14}C from the groundwater (a groundwater concentration that is 27 times greater than the Drinking Water Limit of 37 Bq L^{-1} (1 pCi L^{-1})) into 4MB. The simulation accounted for the stable carbon within 4MB and reduced the BCF of ^{14}C in the top predatory fish from 4500 L kg^{-1} (NCRP, 1985) to 3 L kg^{-1}. The 1000-fold reduction in the BCF is directly transferable to a similar reduction in risk calculations to humans that might consume ^{14}C-contaminated bass. Validation of the model was attempted by measuring ^{14}C concentrations in fish collected from 4MB; however, all results were below detection limit (<~4 dpm g^{-1} fish). It is recommended that future work validates the proposed model by either attempting to use more sensitive analytical means to detect ^{14}C or collecting larger masses of 4MB fish and stream water for subsequent ^{14}C analyses.

2.0 INTRODUCTION

Carbon-14 is a groundwater contaminant on the U.S. Department of Energy's (DOE) Savannah River Site (SRS) (several scientific terms and abbreviations are defined in Appendix A). The primary source of the contaminant is leaching from seepage basins and a low-level waste depository associated with the nuclear complex that is adjacent to an onsite natural stream, Four Mile Branch (4MB). Carbon-14 enters 4MB via effluent leaching from these sources (Carlton et al., 1993). Within the waste depository are ion exchange resins that contain ^{14}C as carbonates ($H^{14}CO_3^-/H_2{}^{14}CO_3^0$). An estimated 1.7E18 Bq of ^{14}C have been buried in the waste depository (Cook, 1989). Additionally, four nearby seepage basins in F- and H-Areas, covering an area of 42,700 m^2, received liquid discharges that contained radioactivity from a nuclear separations facility from 1955 to 1988. Following microbial metabolism, ^{14}C can be released as a gas or dissolved in groundwater solution. In addition to ^{14}C, the effluents to these basins contained metals (including mercury and cadmium), radionuclides (including $^{239/240}Pu$, ^{241}Am, ^{244}Cm, ^{3}H, ^{90}Sr, and ^{235}U), nitrate and NaOH. The basins were closed in 1988 and have since been capped.

Data from monitoring wells between 4MB and the seepage basins, sampled in the early 1990s, indicate a contaminant plume with concentrations of ^{14}C in the shallow groundwater reaching 55 Bq L^{-1} (Carlton et al. 1993). The patterns of ^{14}C in the wells suggest that low levels are discharging to 4MB (Carlton et al. 1993). ^{14}C is believed to be fairly mobile within the SRS. McIntyre (1988) determined that the ^{14}C distribution coefficient (Kd) within SRS soils was a relatively low 55 mL g^{-1}. Thus, carbon is not strongly bound to the sediment.

Although no measurements of ^{14}C concentrations within the creek water were found in the literature associated with the SRS, it is not surprising that ^{14}C is a contaminant of the SRS nuclear complex. ^{14}C is often found in large quantities within nuclear low-level wastes (Liepins and Thomas, 1988) and is of considerable interest because of its high environmental mobility and relatively long half-life (5730 years). It is common for modeling studies of low-level waste disposal facilities to indicate that ^{14}C is the major contributor to radiation dose (Bandrowski, 1988; IUR, 2006).

Carbon-14 is easily incorporated into food webs via photosynthesis by primary producing organisms (Cook, et al. 1998), and human exposure to ^{14}C is greatest via the ingestion pathway versus inhalation or external irradiation (IAEA, 2001). The contribution from all other pathways is < 1% of the total effective dose from ingestion (IAEA, 2001). The intake of ^{14}C by fish consumption is often found to be an important exposure pathway. This conclusion arises because of the assumption that the specific activity of carbon in fish is equal to the specific activity in the surrounding water, which is not often the case (Sheppard et al. 2006a&b).

Past modeling efforts by the SRS to estimate the risks of ^{14}C to humans via consumption of contaminated food have used a simple bioconcentration factor (BCF) to estimate the ^{14}C concentration in fish, based on estimates of the ^{14}C concentration in water. BCFs are often criticized in the literature, but nevertheless continue to be widely used in assessment models (e.g. NCRP, 1985; IAEA, 1994). The use of BCFs is motivated by the simplicity of the approach and because large amounts of relevant data have been collected and reported in the literature. Indeed, it is the wide range of generalized BCFs for ^{14}C contamination of fish [4,500 L kg^{-1} (NCRP, 1985) and 50,000 L kg^{-1} (NCRP, 1991; IAEA, 1994; CSA, 1987)] upon which this report intends

to improve. Although BCFs are easy to use in modeling because concentrations of the contaminant in the water can be multiplied by a BCF to obtain an estimate of the concentration in fish, BCFs have several disadvantages, as highlighted by Kumblad et al. (2006):

- BCFs do not invoke an understanding of the processes that influence radionuclide movement in environments.
- BCFs assume equilibrium conditions (Whicker et al. 1999); however, such equilibrium conditions are rarely tested.
- BCFs assume a linear relationship between radionuclide concentrations in the environment and concentrations in the organism of interest; such linearity may not exist (Brown et al. 2003), and the degree of non-linearity is seldom tested prior to the use of the BCF.
- Site-specific BCFs may not exist, and the use of generic ones may be inappropriate because of differences between the BCF test environment and the environment of interest; use of generic values introduce considerable uncertainty into model predictions.
- BCFs for a given radionuclide and organism can range over several orders of magnitude (IAEA, 1985) because they are influenced by a myriad of physical, biological and environmental processes (Whicker and Schultz, 1982).

Although BCFs are adequate for many radionuclides, they are especially questioned when used for ^{3}H and ^{14}C because of the large amount of naturally occurring stable hydrogen and carbon within ecosystems (IUR, 2006). The enormous dilution of the contaminant by the vast amount of corresponding stable element that occurs is not accounted for when BCFs are used. Sheppard et al. (2006a) have stated that it is probably essential to model ^{14}C by taking into account the dilution from stable carbon.

The use of BCFs to describe ^{14}C transfer is not recommended (IUR, 2006) because they do not adequately address the fluxes of ^{14}C through foodchains. Instead, several authors have recommended that alternative approaches, such as specific activity and dynamic ecosystem models, be given preference (Kumblad et al., 2003; IUR, 2006; Kumblad et al. 2006; Sheppard et al., 2006a&b; Andersson and Kumblad 2006).

The use of BCFs and distribution coefficients versus more ecosystem process-oriented models has been evaluated (Kumbald et al. 2006). Ecosystem modeling allows for the dilution of stable elements as mentioned above, but equally important, allows for modification and scaling of model parameters and functions due to predicted changes in conditions. Thus, ecosystem models provide risk managers the possibility of assessing risks under a wide range of environmental conditions far into the future, a requirement for calculations involving long-lived radionuclides and nuclear waste repositories. One study of ^{14}C releases from nuclear power plants in Sweden found an order-of-magnitude difference in dose estimates when dynamic modeling was used and full accounting of local conditions was taken into consideration (Aquilonius and Hallberg, 2005). Models based on fundamental ecological principles (Odum, 1983) are mechanistic in construction and allow analyses to determine the influence of individual environmental processes on contaminant uptake and transport (Bartell et al. 1999). With ecosystem modeling it is possible to explore how the fate of contaminants is altered by changes in environmental variables (Bartell et al. 1999; Kumblad and Kautsky, 2004; Kumblad et al. 2006).

However, a major drawback of ecosystem models is that they require a huge amount of ecological knowledge and site-specific data. This drawback has been diminished in our case because of the robust data sets specific to 4MB that have been provided by the Savannah River Laboratory (presently the Savannah River National Laboratory, SRNL) and the University of Georgia's Savannah River Ecology Laboratory (SREL). Indeed, these data collections from the mid-1980s make the ecosystem approach presented below possible.

2.1 OBJECTIVES

Using an approach similar to Kumblad et al. (2003; **Figure 1**), we use the rich data sets from 4MB and Meyers Branch to:

1) compile pertinent site-specific data on the 4MB ecosystem,
2) develop a stable carbon inventory for the reach of interest in 4MB,
3) develop a dynamic stable carbon model using data from the carbon inventory, and
4) develop a ^{14}C contaminant model, by assuming 4MB has an influx of contaminants from groundwater and that ^{14}C follows the flow of stable carbon on a specific activity basis. The activity of ^{14}C (A^{14C}) is dependent on the concentration of ^{14}C (C^{14C}), as well as the concentration of stable carbon ($C^{Cstable}$) within ecosystem components:

$$\frac{dA^{14C}}{dt} = \frac{dC^{14C}}{dt}\frac{1}{C^{Cstable}} \qquad \textit{(Eq. 1)}$$

5) determine if the ^{14}C systems modeling approach alters the prediction of ^{14}C uptake in fish when compared to a bioconcentration factor of 4500 (NCRP 1985).

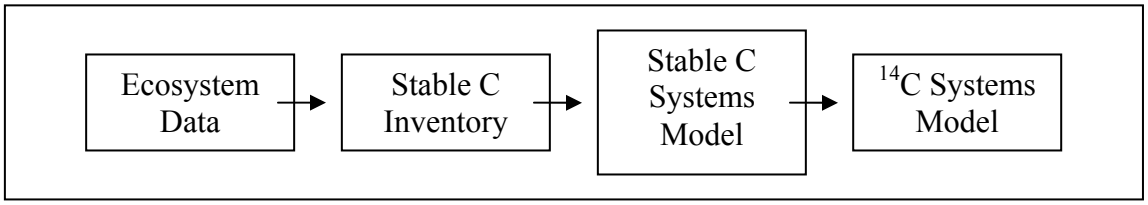

Figure 1. Steps in developing a dynamic model of ^{14}C kinetics in Four Mile Branch.

3.0 AVAILABLE SITE-SPECIFIC DATA

This modeling effort was generated because of the availability of rich, abundant, relevant data specific to the ^{14}C contaminated stream (4MB). During the mid-1980s, a large, multi-disciplinary aquatic ecology program was undertaken by the onsite laboratory, known as the

Savannah River Laboratory at that time, and SREL. The objective of the aquatic ecology program (termed the Comprehensive Cooling Water Study) was to provide monitoring data for the assessment of effects from current and proposed DOE activities relative to the quality of waters used for cooling five nuclear production reactors on the SRS. Water from the Savannah River was used as a secondary coolant in these nuclear reactors. After a single pass through the secondary cooling system, the heated water was discharged into local streams to eventually make its way back to the Savannah River, some 15 km away. The increased water flows and elevated water temperatures had large impacts on the receiving streams (Gibbons and Sharitz, 1974). Included in the aquatic ecology program were several streams that were receiving effluents, others that were in a state of recovery from prior releases, and other streams that were un-impacted controls.

This scenario was ideal for scientific investigations, and the aquatic ecology program utilized 34 sampling locations among the various streams, with each location sampled for 55 variables during 46 biweekly samplings between 1 November 1983 and 21 August 1985 (Newman, 1986) Numerous other specialized projects acquired data in addition to the 55 routinely sampled variables (Sprecht, 1986). These data were used to develop a robust, site-specific, stable carbon-inventory and ecosystem model of ^{14}C dynamics in these aquatic systems.

3.1 DESCRIPTION OF FOUR MILE BRANCH (4MB)

Four Mile Branch is a 2nd order stream which drains a 14.8 km^2 watershed in the Sandhill region of the upper Atlantic Coastal Plain of the United States. It is a low gradient, sandy bottom, blackwater stream with a mean width of 3.5 m and a mean depth of 30 cm in the reach of interest. Precipitation averages 1.2 m per year, with no distinct wet and dry seasons. The soils in the upland areas of the watershed have sand surface horizons over clay subsoils (Williams and Pinder, 1990). The soils allow rapid infiltration and percolation of rainwater; runoff events are uncommon even on steeper slopes (Williams and Pinder, 1990). Some key parameters that characterize the stream are presented in **Table 1**. Additionally, median phosphorus concentrations were 0.015 to 0.18 mg P L^{-1}; and extraordinarily high concentrations of nitrate (2.3 ± 0.9 mg NO_3-N L^{-1}; range 0.6 - 3.9) were measured in 4MB due to the outcropping from industrial waste seepage basins.

Upland soils of the area are of a sandy texture with low organic matter content (< 2%; Dosskey and Bertsch, 1994). The soils support pine (longleaf, *Pinus palustris*; loblolly, *P. taeda* and slash, *P. elliottii*), as well as southern mixed hardwood forests (oaks, *Querus spp*.; hickorys, *Carya spp*.; and sweetgum, *Liquidambar spp*.). Riparian wetlands are associated with the streams and run the full length of the stream valley. As described by Dosskey and Bertsch (1994), the wetlands are low, flat, floodplains 50 to 100 m wide and contain dense forest of sweetgum, tupelos (*Nyssa sylvatica*), oaks, red maple (*Acer rubrum*) and cypress (*Taxodium distichum*). Tree canopies generally cover the stream, limiting sunlight and resultant plant growth, but also providing an important source of carbon to the stream in the form of leaf and litter-fall. As streams widen and become more open, they receive more direct sunlight, resulting in greater primary productivity and less dependence on allochthonous inputs.

Table 1. Characterization parameters for Four Mile Branch (4MB; Newman 1986).

Parameter	Mean	SD	Med.	Range	N	Skewness
Air Temp. (ºC).	23.5	8.4	24.1	1.7 -45	44	-0.06
Water Temp. (ºC)	16.8	7.4	17.6	1.3 – 28.5	46	-0.26
Max. Depth (cm)	48	20	43	19 – 119	33	1.81
Velocity (cm s^{-1})	73	52	72	7 – 250	41	1.02
pH	6.32	0.76	6.09	5.1 – 8.1	46	0.75
Dissolved O_2 (mg L^{-1})	6.79	2.61	6.40	2.3 – 11.6	46	0.23
% Sat. Dis. O_2	66.1	17.0	67.0	28.7 – 98.1	46	-0.16
Total Alkalinity (mg L^{-1} $CaC0_3$)	4.3	3.3	3.5	.5 – 11.9	45	0.91
Calcium (mg/L)	1.60	1.41	1.05	0.69 – 8.81	39	3.75
Total Organic C (mg C L^{-1})	7.98	3.7	7.2	2.4 – 18.5	26	0.81
Dissolved Org. C (mg C L^{-1})	4.57	2.59	4.04	1.97 – 11.6	11	2.29
Particulate Org. C (mg C L^{-1})	1.92	1.5	1.4	0.3 – 4.7	11	0.82

Within the Comprehensive Cooling Water Study, the upper reaches of 4MB, as well as a very similar stream within the same watershed (Meyers Branch), were selected as control sites. Data from both 4MB and Meyers Branch have been used to develop the carbon inventory and dynamic model presented herein.

4.0 CARBON'S IMPORTANCE IN AQUATIC ECOSYSTEMS

Carbon is of great importance in aquatic systems, largely because some 40 to 50% of the dry weight of all biotic tissues is made up of stable C. Additionally, the reduced carbon atom incorporated within an organic molecule is an exploitable energy resource that enters and leaves different components of the stream ecosystem until it is eventually oxidized or is exported from the system (Hauer, 1985).

Carbon takes many different forms. In aquatic systems, predominate forms are generally, particulate organic carbon (POC), sometimes referred to as particulate organic matter (POM), dissolved organic carbon or matter (DOC or DOM), and dissolved inorganic carbon (DIC). The distinction between DOC and POC is generally made on the basis of whether or not it passes through a 0.45 μm filter (Thurman, 1985). The greatest concentration of non-living organic matter in streams is within the dissolved fraction, and is largely unavailable to macroinvertebrates as a direct food source. DOM enters streams from (1) groundwater, (2) leachate from leaves that have fallen into the water; (3) leachate from leaves that have fallen onto the flood plain and subsequently washed into the stream during high water, (4) leachate from

woody debris within the stream, (5) extracellular exudates of stream autotrophs and microbes (Hauer, 1985). DOM exists in a variety of carbohydrates and proteins, forms that are readily taken up by stream microorganisms, as well as 50-75% humic and fulvic acids (Thurman, 1985) that are resistant to microbial uptake. Humic compounds are also responsible for much of the color seen in many river waters.

There are two major sources of organic matter in a stream environment. Autochthonous organic matter is produced within a stream ecosystem by primary producers such as algae and macrophytes. Allochthonous organic matter is produced outside the stream ecosystem (leaf litter) and enters the system from the adjacent landscape. Detrital, non-living, organic matter is an important food source for organisms low on the food web. Detritus consists of POM that includes leaves, fasces, dead animal tissues, and decomposed plant material.

The size distribution of particulate organic matter changes as a function of stream size. Large POM concentration decreases and fine POM concentration increases as waters move downstream. The size classes of POM reflect differing sources of input, physical retention and extent of processing. POM dynamics and changes in physical stream features influence insect species diversity, stream ecosystem stability and biotic-abiotic interactions (Hope et al. 1993).

DIC occurs in ionic form as $H_2CO_3^0$, HCO_3^-, CO_3^{2-}, or as dissolved free CO_2. The major sources of carbon to riverine DIC loads are dissolution of carbonate minerals, soil CO_2 derived from root respiration and from microbial decomposition of organic matter (often mainly of terrestrial origin but also including aquatic production), and exchange with atmospheric CO_2 (Hope et al. 1993). The major processes removing riverine DIC are carbonate mineral precipitation, CO_2 degassing from the water surface, and aquatic photosynthesis. Organic matter production (photosynthesis) and utilization (respiration) affect the riverine DIC pool. Carbon dioxide is used by plants during photosynthesis[1] to make sugars which may either be consumed again in respiration or used as the raw material to produce polysaccharides such as starch and cellulose, proteins and the wide variety of other organic compounds required for plant growth and development. CO_2 is produced during respiration by plants, and by all animals, fungi and microorganisms that depend on living and decaying plants for food, either directly or indirectly. It is, therefore, a major component of the carbon cycle.

The primary pathway for C to transfer from abiotic (CO_2) to biotic components within the environment is through photosynthesis. Once stable CO_2 or $^{14}CO_2$ is incorporated within plants it can become part of plant tissues, or respired as CO_2 or $^{14}CO_2$. Herbivores can then ingest organic ^{14}C and dispersal commences throughout the food-web. Turnover times of ^{14}C vary by tissues and organisms based on metabolic rates. Highest uptake rates are known to occur in rapidly growing organisms that are incorporating much stable C.

All organic matter in a stream is continually subject to water movement. Thus, downstream transport of organic matter is an important component of stream ecosystem dynamics. The retardation of transport is important to the biota dependent on its processing.

[1] Only in electronic versions of this report are many of the terms used in the report defined using internet links to Wikipedia. These blue-font and underline linked terms appear as regular text font in hard copy version of report.

5.0 CARBON INVENTORY IN FOUR MILE BRANCH

An annual inventory of stable C within the 1.5 km reach of 4MB was derived from site-specific data of carbon in water, sediment, aquatic plants, aquatic invertebrates, and fish. Details on data sources, field methods and necessary assumptions are presented below.

5.1 WATER FLOW RATES

The quantity, seasonality and sources of water flow were determined for two segments of 4MB using hydrograph separation, stream flow partitioning, and ^{3}H tracer methods (Williams and Pinder, 1990). Mean daily discharge data were obtained from USGS sampling stations for the period from 1973 through 1986. The stream was analyzed as four subunits (**Figure 2**):

(1) the upstream segment prior to 4MB's confluence with H-area Creek (USGS station 34, Fig.2);

(2) the H-Area tributary;

(3) the F-Area tributary; and

(4) a downstream segment represented by the catchment area between USGS station 34 and the confluence of F-Area creek (Williams and Pinder, 1990).

Water flow rates in both F-and H-Area tributaries have major contributions from process waters associated with industrial operations, as well as, inflow from enhanced runoff due to storm drain systems. The existing data do not allow the natural flows in the F-and H-Area tributaries to be separated from their anthropogenic influences. However, the primary interest is in the downstream section, as it is the portion of the stream that directly receives ^{14}C effluent from groundwater seepage due to H-area industrial processes. The downstream section between Road 4 and Road C is 1.5 km in length, with a mean stream width ~ 3.5 m.

Groundwaters discharging into 4MB are labeled with ^{3}H due to releases from the F-and H-Area seepage basins and wastes in the burial grounds. Travel times for the ^{3}H to flow from the basins to 4MB are 3.75 to 14 years, but areas of channelized and more rapid subsurface flow have been identified (Williams and Pinder, 1990). The area of effluent input to 4MB can be easily discerned by ^{3}H concentrations (**Table 2**) at the various sampling points depicted in **Figure 2**.

Table 2. Mean (±SD) Tritium concentrations in Four Mile Branch (Williams and Pinder, 1990); USGS sampling stations are referenced on Figure 2.

Station	kBq L^{-1}
34	5 ± 22
36	39 ± 12
39	47 ± 15
40	37 ± 12

Williams and Pinder (1990) determined that greater than 90 % of the water flows in the upstream portion of 4MB were due to groundwater-driven base flow (**TABLE 3**). They observed periods when contributions from H-Area industrial process waters constituted the only flow into the downstream reach of 4MB. That is, the upstream segments went through periods of no natural flow during periods of drought.

Table 3. Components of mean (±SD) flow in Four Mile Branch (Williams and Pinder, 1990), station locations are depicted on Figure 2.

Location/Component	Flow ($m^3 s^{-1}$)	Flow (GL y^{-1})	% of total flow
Station 34			
Process flow from H-Area	0.085 ± 0.037	2.68 ±1.16	24
Natural flow from upstream	0.129 ± 0.175	4.07 ± 5.52	35
Total flow at station 34	0.217 ± 0.203	6.84 ± 6.40	
Station 40			
Flow from Station 34	0.217 ± 0.230	6.84 ± 6.40	
Process flow from F-Area	0.075 ± 0.032	2.36 ±1.01	21
Inflow to downstream segment	0.071 ± 0.105	2.23 ± 3.31	20
Total flow at Station 40	0.367 ± 0.251	11.43 ± 7.92	

Conversion for creek flows from $m^3\ s^{-1}$ to GL y^{-1} [where G (giga) = $1x10^9$]

$$\frac{1\,m^3}{s} x \frac{1000\,L}{m^3} x \frac{31{,}536{,}000\,s}{y} = 31.5\,GL/y \qquad (Eq:2)$$

- Annual mean water flow from upstream reach of 4MB (0.13 ± 0.18 $m^3\ s^{-1}$) = 4.1 ± 5.7 GL y^{-1}
- Annual mean surface flow from F- and H-Area creeks (0.16 ± 0.07 $m^3\ s^{-1}$) = 5.0 ± 2.2 GL y^{-1}
- Annual mean groundwater influx (0.07 ± 0.1 $m^3\ s^{-1}$) = 2.2 ± 3.1 GL y^{-1}; includes some unknown fraction from industrial seepage basins in F and H Areas. ***It is from this component that ^{14}C is presumed to contaminate 4MB***.
- Annual mean outflow from modeled reach (0.37 ± 0.25 $m^3\ s^{-1}$) = 11.4 ± 7.8 GL y^{-1}

5.2 CARBON INFLUX FROM SURFACE WATERS

Relying on the data of Williams and Pinder (1990), Dosskey and Bertsch (1997) composed an organic matter budget for the upstream section of 4MB by quantifying the export of organic matter and partitioning the export among base flow and runoff. These data, when combined with that provided by the Comprehensive Cooling Water Report, provide critical information for our modeling of carbon flux in the downstream section. The stable carbon influx was calculated as median C concentrations of various forms of C in water (Dosseky and Bertsch 1997) times mean annual water flow (Williams and Pinder, 1990) as follows:

- **DOC**
- From upstream reach of 4MB ($DOC_{upstreamFMC}$)

$$DOC_{upstreamFMC} = \frac{5.3\,mg\,C}{L} x \ \frac{4.1E9\,L}{y} x \frac{kg}{1E6\,mg} == \frac{21{,}730\,kg\,C}{year} \qquad (Eq.\ 3)$$

- From surface flow of F-and H-Area creeks ($DOC_{F\&Hcreeks}$); assumed DOC concentration was the same as the upstream reach of 4MB

$$DOC_{Fcreek} = \frac{5.3\,mg\,C}{L} x \ \frac{2.36E9\,L}{y} x \frac{kg}{1E6\,mg} = \frac{12{,}508\,kgC}{y} \qquad (Eq:4)$$

$$DOC_{Hcreek} = \frac{5.3\,mg\,C}{L} x \ \frac{2.7E9\,L}{y} x \frac{kg}{1E6\,mg} = \frac{14{,}310\,kgC}{y}$$

- **POC**

  Calculated as median POC concentration in water (Dosseky and Bertsch 1997) times mean annual water flow (Williams and Pinder, 1990)

- From upstream reach of 4MB ($POC_{upstreamFMC}$)

$$POC_{upstreamFMC} = \frac{1.8\,mg\,C}{L} x \ \frac{4.1E9\,L}{y} x \frac{kg}{1E6\,mg} \qquad (Eq:5)$$

$$POC_{upstreamFMC} = 7{,}380 \frac{kg\,C}{y}$$

- From surface flow of F-& H-Area creeks ($POC_{F\&Hcreeks}$); assumed POC concentration was the same as the upstream reach of 4MB

$$POC_{Hcreek} = \frac{1.8\,mg\,C}{L}\,x\;\frac{2.7\,x\,E9\,L}{y}\,x\,\frac{kg}{1E6\,mg} = 4{,}860\,\frac{kg\,C}{y} \qquad (Eq:6)$$

$$POC_{Fcreek} = \frac{1.8\,mg\,C}{L}\,x\;\frac{2.36\,x\,E9\,L}{y}\,x\,\frac{kg}{1E6\,mg} = 4{,}248\,\frac{kg\,C}{y}$$

5.3 CARBON INFLUX FROM GROUNDWATERS ($DOC_{GROUNDWATER}$)

Calculated from 2.2 ± 3.1 GL y^{-1} influx from F-and H-Area seepage (Williams and Pinder; 0.071 ± 0.105 $m^3\ s^{-1}$) and median groundwater DOC concentrations of 0.5 mg L^{-1} (Dosskey and Bertsch, 1997).

$$DOC_{groundwater} = \frac{0.5\,mg\,C}{L}\,x\;\frac{2.2E9\,L}{y}\,x\,\frac{kg}{1E6\,mg} \qquad (Eq:7)$$

$$DOC_{groundwater} = 1{,}100\,\frac{kg\,C}{y}$$

5.4 CARBON STORED AS POC IN SEDIMENTS (POC_{SED})

- Based on 5 cm diameter X 30 cm long sediment cores (core volume = 589 cm^3; core surface area = 19.6 cm^2) collected by Hauer (1985) in Meyers Branch.
- Benthic Storage of POM = 10 to 40% of substrate (Hauer, 1985); 15% used below
- Density of sediment cores assumed to be 1.1 g DW cm^{-3}
- Assumed 0.5 g C per g dry weight (Sheppard et al. 2006)
- Calculated for the 1,500 m reach of 4MB, with average stream width of 3.5 m (5250 m^2)

$$POC_{sed} = \frac{1.1\,g\;DW}{cm^3}\,x\,0.15\,POM\;x\,\frac{0.5\,g\;C}{g\;DW\;POM}\,x\,\frac{589\,cm^3}{core}\;x\,\frac{core}{19.6\,cm^2}\,x$$

$$\frac{5250\,m^2}{reach}\,x\,\frac{10{,}000\,cm^2}{m^2}\;x\,\frac{kg}{1000\,g} \qquad (Eq:8)$$

POC_{sed} = 130,160 kg C per stream reach

5.5 POC FROM GROUNDWATER

No carbon was assumed to enter groundwater as POC (Dosskey and Bertsch, 1997).

5.6 INORGANIC CARBON (DIC)

The fraction of DIC present in the water as dissolved CO_2 is almost always at concentrations much greater than the atmosphere (Baker et al. 2008). The major sources of carbon to riverine DIC loads are dissolution of carbonate minerals, soil CO_2 derived from root respiration and from microbial decomposition of organic matter, and exchange with atmospheric CO_2. The major processes removing riverine DIC are carbonate mineral precipitation, CO_2 degassing, and aquatic photosynthesis (Kanduc et al. 2007).

Dissolved CO_2 provides an indication of the CO_2 transfers from the water column to the atmosphere (CO_2 degassing). Because actual field measurements of dissolved CO_2 are rarely collected, this information is not available for 4MB. However, excess CO_2 partial pressures can be estimated from pH and alkalinity measurements of stream waters with errors typically less than 15% (Neal et al. 1998). Alkalinity, measured in 4MB at 35 mg $CaCO_3$ L^{-1}, was first multiplied by 20 to convert to units of µEq L^{-1} (Neal, 2001). Then the excess CO_2 partial pressure (EpCO2) was calculated (Neal et al. 1998) as follows:

$$EpCO_2 = \frac{(0.95 * ALK + 10^{6-pH}) * 10^{6-pH}}{6.46 - 0.0636 * T°C} \qquad \textit{(Eq. 9)}$$

where $EpCO_2$ is the dissolved CO_2 concentration in a water sample divided by the dissolved CO_2 concentration in pure water in equilibrium with the atmosphere at the same temperature and pressure. ALK is the Gran alkalinity in µEq L^{-1}, and T° C is the water temperature in degrees Celsius. Using median measurements taken in 4MB for alkalinity (35 mg $CaCO_3$ L^{-1} X 20 = 700 µEq L^{-1}), pH (6.1), and temperature (17.6 °C), the $EpCO_2$ was calculated from *Eq. 9* as 99 (unitless). Total dissolved CO_2 concentration for the pCO_2 is 0.002067 moles CO_2 L^{-1}, equaling 0.0248 g C L^{-1} in the stream from DIC.

Multiplying this concentration by the annual stream flow (0.367 m^{-3} s^{-1}) gives an estimate of the annual kg of C in the stream from DIC:

$$DIC_{water} = \frac{0.0248\ g\,C}{L} x \frac{0.367\,m^3}{s} x \frac{1000\,L}{m^3} x \frac{31{,}536{,}000\,s}{y} x \frac{kg}{10^3\,g} = 287{,}028\ \frac{kg\,C}{y} \qquad \textit{(Eq. 10)}$$

When compared with the other carbon sources in the stream, DIC is by far the largest contributor to the carbon mass balance.

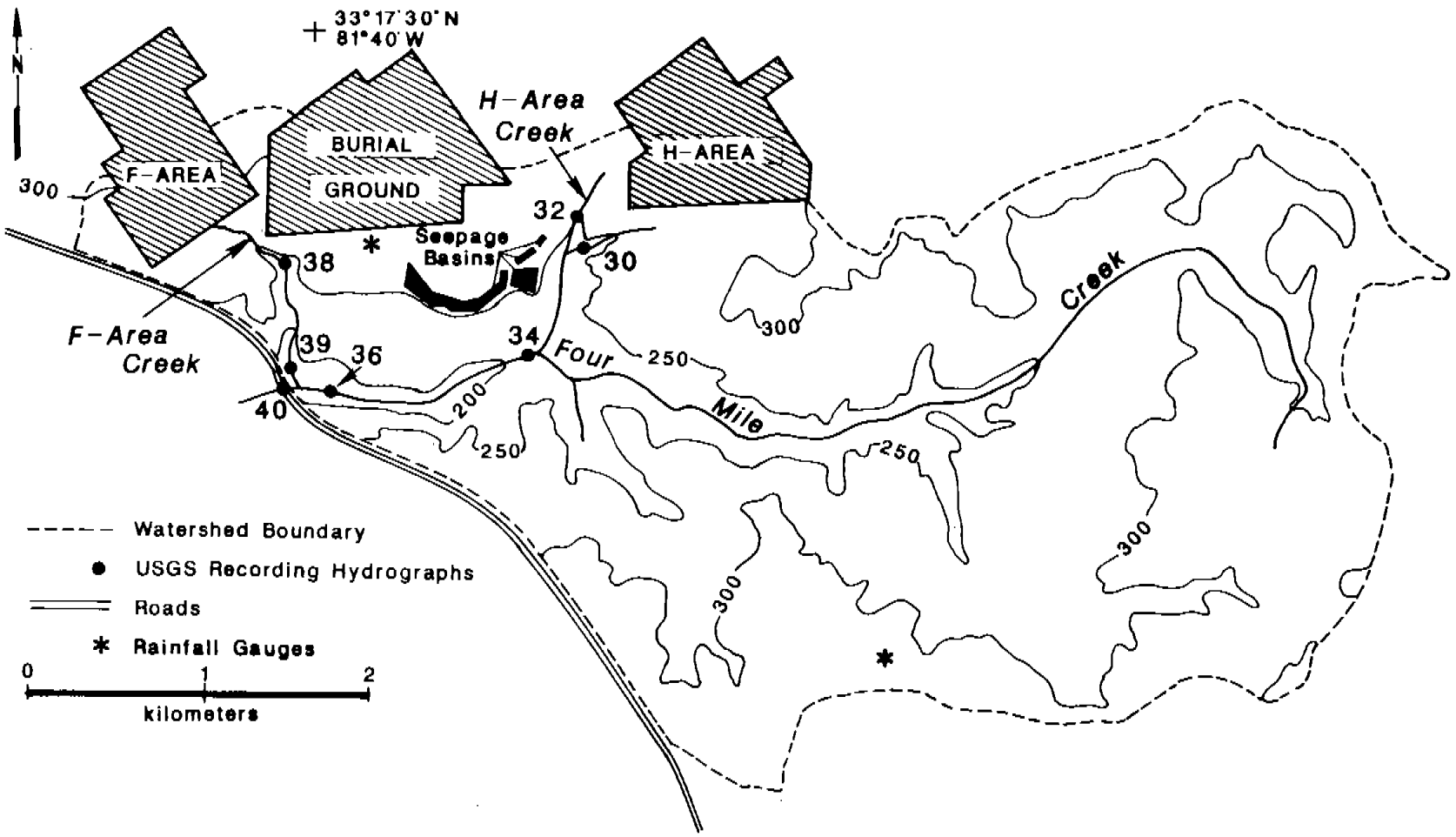

Figure 2. Map of study area showing Four Mile Branch, F-and H-Area tributaries, USGS Gauging Stations (#30, 32, 36, 38, 39 and 40), and major Savannah River Site installations (from Williams and Pinder, 1990).

5.7 CARBON FROM PERIPHYTON BIOMASS ($C_{PERIPHYTON}$)

Periphyton are primary producers attached to submerged material in water, and include diatoms, algae, fungi, bacteria, and protozoa. They readily take up carbon, some via photosynthesis, and they are an easily digestible food for macroinvertebrates. Estimates of $C_{periphyton}$ were made using the annual mean ash-free-dry-weight (AFDW) of periphyton scraped from natural substrates in Meyers Branch (Specht, 1986). Samples were taken from 45 randomly selected locations during three seasons. Data used for the carbon model were from Stations 39 and 40 on Meyers Branch. The annual mean organic standing crop biomass (periphyton biomass plus associated non-living organic material) at both locations was averaged over three seasons (**Table 4**), resulting in an overall mean of 486 ± 241 g AFDW m^{-2}, and was used to estimate carbon in periphyton. The g C derived in this manner was multiplied by the mean debris area within the creek as mapped for stream structure by Firth et al. (1986; cited within Specht, 1986), described below, to obtain an estimate of the total carbon produced annually by periphyton within the downstream section of 4MB.

To estimate stream structure Firth et al. (1986; cited within Specht, 1986) marked five 25-m longitudinal reaches along the stream channel considered representative of the site. All material greater than or equal to 1 cm was measured and drawn to scale, in accurate positions, on a map of the stream reach. Area measurements were also recorded of terrestrial vegetation and leaf packs within the stream. Volume measurements were taken of roots, logs, and sticks, stumps, cypress knees, trees and macrophyte beds in the channel. For Station 39 on Meyers Branch the following stream structure data were measured (n=20; total number of 25 m reaches mapped during sampling year):

- mean (± sd) total wood volume = 0.019 ± 0.016 m^3 m^{-2}
- mean (± sd) log volume > 10 cm diameter = 0.014 ± 0.014 m^3 m^{-2}
- mean (± sd) stick volume < 10 cm diameter = 0.005 ± 0.009 m^3 m^{-2}
- mean (± sd) percent volume due to logs = 69.5 ± 26.9 m^3 m^{-2}.
- mean (± sd) trailing vegetation area = 0.004 ± 0.008 m^2 m^{-2}
- mean (± sd) trailing root volume = 0.004 ± 0.006 m^3 m^{-2}
- mean (± sd) debris area = 0.039 ± 0.046 m^2 m^{-2}

Table 4. Organic standing crop (g AFDW m^{-2}) on natural substrate materials in Meyers Branch (stations 39 and 40 in 1984; Specht, 1986).

Season/ Station	Mean	Range	n	CV
WINTER				
39	321	17 - 1119	16	97.8
40	474	0 – 1081	28	62.2
SPRING				
39	382	18 -2411	30	159.9
40	920	135 - 2475	30	72.3
SUMMER				
39	250	32 - 722	6	113.7
40	572	44 - 2667	30	113.3
Mean	**486**			

When combined, these data allow an estimate of the mass of carbon within periphyton residing in the 5,250 m^2 reach of 4MB.

$$C_{periphyton} = \frac{486 g\ AFDW}{m^2\ substrate - y} x \frac{0.5\, gC}{g\ AFDW} x \frac{0.04\, m^2\ debris\ substrate}{m^2\ stream} x \frac{5{,}250\ m^2\ stream}{reach} x \frac{kg}{1000 g} \quad (Eq:11)$$

$C_{periphyton}$ = 51.0 kg C in 1.5 km reach of stream

The stream structure data of Firth et al. (1985) presented above also allows an estimate of the standing wood biomass in the stream (i.e., channel debris load) to be calculated from the mean total wood volume combined with the trailing root volume. A dry weight density of wood of 500 kg m^{-3} was used.

$$C_{DebrisLoad} = \frac{0.023\, m^3\ channel\ debris}{m^2} x \frac{500\, kg\ DW}{m^3} x \frac{5{,}250\, m^2}{reach} x \frac{0.5\, kgC}{kgDW} = 30{,}187\ kg\, C \quad (Eq.:12)$$

5.8 CARBON FROM AQUATIC MACROPHYTES ($C_{MACROPHYTES}$)

In mapping stream structure, Firth et al. (1985; cited within Specht, 1986) estimated the area, volume, biomass and percent cover of aquatic macrophytes (aquatic vascular plants) in several of the SRS streams, including two locations on Myers Branch (**Table 5**). These data were used to calculate the contribution of macrophytes to the total carbon mass balance of 4MB. Because the section of 4MB being modeled has been impacted by nitrate levels leaching from H-Area operations, some tree death has occurred, and that portion of the stream is no longer a closed canopy like Myers Branch. Floating aquatic vegetation can be readily seen in 4MB from the

bridge at Road 4. Therefore, we opted to use the upper biomass values (0.011 g DW vegetation m^{-2}) that Firth et al. (1985; cited within Specht, 1986) reported for Myers Branch to calculate the carbon concentrations in macrophytes of 4MB. Carbon content per g DW of macrophyte was based on conversion factors in Andersson and Kumblad (2006; **Table 6**).

Table 5. Annual mean (± SD) for vegetation parameters on a per m^2 basis during 1984-1985. Aquatic Vascular Plant (AVP) area (m^2 m^{-2}); AVP volume (m^3 m^{-2}), AVP biomass (g m^{-2}) and AVP percent cover (Firth et al. 1986; cited within Specht, 1986).

Station	AVP Area	AVP Volume	AVP Biomass	Percent Cover	N
39	0.0001 ± 0.0002	< 0.0001 ± < 0.0001	0.0002 ± 0.0007	0.005 ± 0.017	20
40	0.0009 ± 0.003	0.0002 ± 0.0005	0.011 ± 0.033	0.09 ± 0.3	20
40 (NU)[1]	0.0001 ±0.0003	<0.0001 ±<0.0001	0.0003 ± 0.0014	0.008 ±0.034	20
40 (VAL)[1]	0.0008 ± 0.003	0.0002 ± 0.0005	0.011 ± 0.033	0.08 ± 0.30	20

1 NU= *Nuphar luteum*; VAL = *Vallisneria americana* and/or *Sparangium sp*.

$$C_{macrophytes} = \frac{0.011\,g\,DW}{m^2\,y}\ x\ \frac{0.395\,g\,C}{g\,DW}\ x\ \frac{5250\,m^2}{reach}\ x\ \frac{kg}{1000g} = 0.023\frac{kg\,C}{y-reach} \quad (Eq:13)$$

5.9 CARBON FROM LITTER-FALL ($C_{LITTERFALL}$)

Leaf litter was collected weekly during the fall season and monthly during the rest of the year at 25 sites. Litter was averaged by month for each station (g m^{-2} $month^{-1}$), as well as expressed as grams per linear reach of stream per month (Firth et al. 1986). Values in **Table 7** are means of two stations on Meyers Branch (reported as sum of yearly litter inputs at each site; 3 litter traps per site at 16 collection times). Conversion of litter biomass to g C was based on Mulholland (1981; **Table 8**).

$$C_{litterfall} = \frac{470\,g\,DW}{m^2\,y}\ x\ 0.475\frac{g\,C}{g\,DW}x\ \frac{5{,}250\,m^2}{reach}\ x\frac{kg}{1000g} \quad (Eq:14)$$

$$C_{litterfall} = 1{,}177\ \frac{kg\,C}{y}$$

Table 6. Factors used to convert biomass (g ww) into biomass (g dw and g C) and into respiration rates for various organism groups. The respiration conversion factors are valid for a temperature of 20 C (Andersson and Kumblad, 2006).

Function Group	Biomass ($g\ dw\ g^{-1}\ ww$)	Biomass ($gC\ g^{-1}\ dw$)	Respiration ($gC\ gC^{-1} \cdot d^{-1}$)
Pelagic habitat			
Zooplankton	-	-	0.115
Fish	0.200	0.492	0.033
Benthic Habitat			
Bacteria	-	-	0.069
Filter feeders	0.222	0.196	0.028
Detrivores	0.204	0.300	0.032
Herbivores	0.154	0.251	0.029
Carnivores	0.197	0.430	0.033
Littoral Habitat			
Macrophytes	-	0.395	-
Epiphytic fauna	-	0.400	0.030

Table 7. Rates of litterfall per surface area of stream (dry weight (DW); $g\ m^{-2}\ y^{-1}$), as well as per linear meter of stream for Meyers Branch during October 1984 to September 1985 (Firth et al. 1986).

Station	Total DW[(a)]	Mean DW ($g\ m^{-2}\ y^{-1}$)	N	SE	CV ($g\ linear\ m^{-1}\ month^{-1}$)	Min.	Max.
39	598	150	36	9.9	119	12	805
40	343	164	36	6.7	141	1	722

[(a)]) DW = dry weight; N = sample size; SE = standard error; Min. = minimum; Max. = maximum.

Table 8. Conversion factors derived from Mulholland 1981; (based on litter fall comprised of 78% leaves, 14% wood, and 8% fruit).

Year	Mean Annual Leaflitter fall (g DW m^{-2})	g C m^{-2}	Conversion factor
1975	604	285	0.472
1976	638	305	0.478
1977	572	272	0.475

Mean dry weight (g) per linear meter of stream per month from Oct 1984 - Sept. 1985. Mean for two stations on Meyers Branch and station 12 on 4MB was 168.6 ± 21.4 g m^{-1}-month.

$$C_{litterfall} = \frac{168.6\,g\,DW}{m-month}\ x\ 0.475\frac{g\,C}{g\,DW}\ x\ \frac{12\,month}{year}\ x\frac{1500\,m}{reach}\ x\frac{kg}{1000g} \quad (Eq:15)$$

$C_{litterfall}$ = 1,441 kg C y^{-1}

The two methods of estimating litter fall gave similar results, we opted to use the larger of the two (1,441 kg C y^{-1}) in the carbon mass balance.

5.10 CARBON FROM MACROINVERTEBRATES ($C_{MACROINVERTS}$)

Macroinvertebrates are key components in the food web of streams, and considerable effort was spent identifying their niche during the Comprehensive Cooling Water Study (Specht, 1986). Macroinvertebrates were defined as aquatic invertebrate organisms retained by a 600 µm sieve. They are both consumers and prey. Community structure of macroinvertebrates within a stream depends primarily on the source and size of organic matter (Minshall 1978).

Macroinvertebrates were sampled quarterly using leaf bags and by sampling macrophyte beds, and stream sediments. Leaf bags (43 cm X 17 cm plastic mesh) were filled with 5 g each of sycamore and sweetgum leaves that had been collected at leaf abscission and air dried. The weighted bags were sunk to the bottom of the stream and colonization occurred over a four week period.

Stream sediments were also sampled quarterly for macroinvertebrates by coring with a 7.5 cm diameter steel tube. Typical core depths were about 14 cm. The volume of sediment sampled was 666.8 cm^3 and covered a surface area of 0.004 m^2.

Artificial snags were made from two 3 x 20 cm twigs of freshly cut alder (*Alnus rubra*) that were tied together at right angles and suspended in the water 4 to 6 cm above the sediments. Each snag had an approximate surface area of 0.04 m^2. During the 4-week sampling period much

organic debris accumulated on the snags. Most of the invertebrates were found in the debris when the artificial snags were collected.

Macrophyte beds were sampled quarterly for macroinvertebrates by using stainless steel cylinders (90 cm long x 25.5 cm diameter) to isolate a known area (0.05 m^2) of plant material. The cylinder was pushed into the stream bottom and all plant material (including roots and associated debris) was removed with a hand cultivator and small aquarium net. The remaining water and detritus in the cylinder were subsequently pumped through a 124-µm mesh net bag that trapped the suspended organisms.

Modified Hester Dendy multiplate samplers (Hester and Dendy, 1962) were deployed for four-week intervals and used to quantitatively characterize macroinvertebrate communities on a monthly basis. Samples were taken January 1984 through April 1984, June 1984 through August 1984, and October 1984 through September 1985. The Hestor-Dendy data from October 1984 through September 1985 were sufficiently robust that estimates were made of the mean macroinvertebrate density, biomass, biomass per individual, and average number of taxa collected (**Table 9**). Annual biomass was estimated by multiplying the monthly mean value for the three collection sites (two sites on Meyers Branch and one site on 4MB; **Table 9**) by 12, to yield 2.21 g AFDW m^{-2} (AFDW = ash free dry weight)

Macroinvertebrates were sorted by their modes of feeding (Merritt and Cummins, 1978; **Table 10**). The primary taxa associated with the functional groups and collected in Meyers Branch are shown in **Table 11**. Monthly mean biomass (g AFDW m^{-2}) values of invertebrate functional groups collected from 4MB (Station ID = FM) and at two locations in Meyers Branch (Station ID = MB) are shown in **Table 12**. Macroinvertebrate of the collector guild comprised about 75% of the invertebrate mass and predatory invertebrates comprised the remaining 25%.

Table 9. Density, biomass, biomass per individual, and average number of macroinvertebrate taxa collected on Hester-Dendy multiplate samplers. Data are averages of monthly samples collected from October 1984 through September 1985. HD samplers were deployed for 4-week intervals during each month (Specht, 1986).

Station sampler^{-1}	Avg # m^{-2}	Avg g AFDW m^{-2}	Avg mg AFDW ind.$^{-1}$	Avg # of taxa
FM-12	2109	0.351	0.166	19.0
MB-39	565	0.073	0.129	13.5
MB-40	876	0.129	0.147	17.9
mean	1183	0.184	0.147	16.8

Table 10. Classification of macroinvertebrates based on functional groups (Merritt and Cummins, 1978).

Functional Group	Feeding Mode
Scrapers	shear off attached awfwuchs from under water substrates
Collector-gatherers	glean sedimented organic deposits from the substrate
Collector-filterers	filter suspended particulate organic matter from the water column
Shredders	skeletonize whole leaves and leaf fragments
Piercers-herbivores	pierce plant tissues or cells and suck fluids
Predators-engulfers	capture and ingest animals

Table 11. Abundant macroinvertebrate taxa and their associated function group collected from Meyers Branch (Firth et al. 1986).

Abundant Taxa	Function Group
mayflies (*Ephemeroptera*)	Collectors
Oligochaetes	Collectors
hydropsychid caddisflies (*Trichoptera: Hydropsychidae*)	Collectors
blackflies (*Diptera: Simulidae*)	Collectors
stoneflies (*Plecoptera*)	Shredders and Predators
chironomids (*Diptera: Chironomidae*)	Collectors and Predators
water mites (*Hydracarina*)	Predators

Table 12. Monthly mean biomass (g AFDW m^{-2}) of invertebrate functional groups collected from Four Mile Branch (Station ID = FM) and at two locations in Meyers Branch (Station ID = MB) using multi-plate HD samplers during October 1984 through September 1985 (Firth et al. 1986).

Station	CG[1]	CF	SC	PR	PH	SH	Total
FM-12	0.065	0.215	0.001	0.068	0.000	0.002	0.351
MB-39	0.044	0.006	0.001	0.021	0.000	0.000	0.071
MB-40	0.060	0.010	0.002	0.048	0.000	0.010	0.129
mean	0.056	0.079	0.001	0.046	0.000	0.004	0.184

[1]Functional Groups: CG = collector-gatherer; CF = collector-filterer; SC = scrapers; PR = predators-engulfers, PH = piercer-herbivores; SH = shredder.

The total numbers of macroinvertebrates collected using the various methods are shown in **Table 13**. Based on the ratio of number of individuals to biomass collected on HD samplers (**Table 9**), biomass was also estimated for the invertebrates collected using the other methods (**Table 13**).

Table 13. Total number of macroinvertebrate taxa and mean density collected quarterly on leaf bags, artificial snags, plant material, multiplate Hester-Dendy samplers (HD), and sediment cores taken from Meyers Branch. Based on the ratio of number of individuals to biomass measured for invertebrates collected on the HD samplers, the biomass was estimated for the invertebrates collected using the other methods.

Station	Total Taxa	# leaf bag^{-1}	# m^{-2} snag	# g^{-1} DW plant	# m^{-2} HD	# m^{-2} sediment
39	71	609	7,830	50	2,604	8,886
40	86	1,114	9,704	240	5,448	7,051
mean #	78	861	8,767	145	4,026	7,968
monthly mean biomass [(a)] (g AFDW)		0.13	1.29	0.02	0.59	1.17

[a] average mass per individual (0.147 mg indiv^{-1}), measured from samples collected with HD samplers (**Table 9**), was used to derive the biomass for the macroinvertebrates collected using the other methods. AFDW = ash free dry weight

The monthly mean biomass numbers (**Table 13**) were then scaled to a yearly biomass (x12), and used to calculate the contribution of macroinvertebrates collected on snags, plants, leaf bags and within the stream sediments, to the total carbon budget of 4MB.

$$C_{macroinvert} = C_{macroinvet\ SNAGS} + C_{macroinvert\ PLANT} + C_{macroinvert\ SEDIMENTS} + C_{macroinverts\ LEAFBAGS} \qquad (Eq:16)$$

$$C_{macroinverts\ SNAGS} = \frac{15.48\,g\ AFDW}{m^2\ snag - y} x \frac{0.5\,g\,C}{g\ AFDW} x \frac{0.039\,m^2\ snag}{m^2\ stream} x \frac{5250\,m^2\ stream}{reach}$$
$$x \frac{kg}{1000\,g} = 1.58 \frac{kg\,C}{reach}$$

$$C_{macroinverts\ PLANT} = \frac{0.24\,g\ AFDW}{g\ DW\ plant - y} x \frac{0.5\,g\,C}{g\ AFDW} x \frac{0.011\,g\ DW\ plant}{m^2\ stream} x \frac{5250\,m^2\ stream}{reach}$$
$$x \frac{kg}{1000\,g} = 0.007 \frac{kg\,C}{reach}$$

$$C_{macroinverts\ SEDIMENT} = \frac{14.04\,g\ AFDW}{m^2\ sediment - y} x \frac{0.5\,g\,C}{g\ AFDW} x \frac{5250\,m^2}{reach} x \frac{kg}{1000\,g} = 36.8 \frac{kg\,C}{reach}$$

$$C_{macroinvets\ LEAFBAGS} = \frac{0.13\,g\ AFDW}{10\,g\ DW\ leafbag} x \frac{470\,g\ DW\ litterfall}{m^2\ y} x \frac{0.5\,g\,C}{g\ AFDW} x \frac{5250\,m^2}{reach} x \frac{kg}{1000\,g} = 15.9 \frac{kg\,C}{reach}$$

$C_{macroinvert}$ = 54.3 kg C of macroinvertebrates in the 1.5 km reach of stream (25% predatory, 75% prey)

5.11 CARBON FROM FISH (C_{FISH})

Fish assemblages properties were determined at 44 sites in 1 to 3 order streams located on the Savannah River Site of South Carolina (Meffe and Sheldon 1988; Sheldon and Meffe 1995). Collections were made from 15 October – 19 November 1985 when young-of the-year fish were large enough to be identified. Sample sites were 4 to 15 m long (n = 44) and selected visually to be representative of homogeneous single habitats (e.g., pool, sandy run). Sites were isolated with 6-mm mesh block seines and fished 5-7 times with 500 -700 V electroshocker. Preserved collections (10% Formalin) were stored, measured, and weighed in the laboratory. Thirty fish species in 11 families were collected (Table 14). The median sample contained seven species (range 2 -17) at a density of 1.5 individuals m^{-2} (range 0.2 - 9.5), and individual mass of 2.8 g (range 0.4 – 22.2) and a biomass of 4.0 g m^{-2} (range 0.1 – 42.1).

Fish diets were categorized as carnivorous, primarily carnivorous, or omnivorous based on published reports as well as our data and experience. The diet of species listed as primarily carnivorous feed largely on animal material, but some individuals have been reported to contain varying amounts of plant material in their gut. Assimilation of plant material has not been noted and seems unlikely in species such as the Notropis spp. with relatively short guts. Exceptions within this category may exist. Sheldon and Meffe (1993) found only animal material in the diet yellow bullhead from SRS streams, but more extensive ingestion of plant material has been reported. These data, along with conversion factors from Andersson and Kimbald (2006; **Table 6**), were used to estimate the kg C, as fish, in the stream reach.

$$C_{fish} = \frac{4.0\,g\,ww}{m^2} x \frac{0.2\,g\,dw}{ww} x \frac{0.492\,g\,C}{g\,dw} x \frac{5250\,m^2}{reach} x \frac{kg}{1000g} = 2.1 \frac{kg\,C}{reach} \qquad (Eq:17)$$

Table 14. Species captured by electrofishing from 44 sites. A total of 2500 fish weighing 12.027 kg were collected.

Species	Number	% Total	Biomass (g)	% Total	Biomass Rank	Diet	Location in Water Column
Notropis lutipinnis	985	39.4	812.6	6.8	7	primarily carnivorous	mid-water
Aphredoderus sayanus	235	9.4	1005.7	8.4	6	carnivorous	mid-water
Notropis cummingsae	231	9.3	53.7	0.5	21	primarily carnivorous	mid-water
Lepomis auritus	152	6.1	1279.9	10.6	3	carnivorous	mid-water
Nocomis leptocephalus	148	5.9	621.6	5.2	8	omnivorous	moderately benthic
Noturus leptacanthus	98	3.9	212.9	1.8	12	carnivorous	benthic
Gambusia holbrooki	90	3.6	23.6	0.2	25	primarily carnivorous	surface
Erimyzon oblongus	81	3.2	1111.1	9.2	5	omnivorous	moderately benthic
Etheostoma olmstedi	77	3.1	99.9	0.8	16	carnivorous	benthic
Lepomis punctatus	70	2.8	1243.1	10.3	4	carnivorous	mid-water
Anguilla rostrata	54	2.2	2203.6	18.3	1	carnivorous	benthic
Percina nigrofasciata	45	1.8	73.8	0.6	19	carnivorous	benthic
Semotilus atromaculatus	40	1.6	199.5	1.7	13	primarily carnivorous	mid-water
Ameiurus natalis	34	1.4	1412.2	11.7	2	primarily carnivorous	benthic
Noturus insignis	31	1.2	343.1	2.9	10	carnivorous	benthic
Notropis chalybaeus	27	1.1	14.6	0.1	27	primarily carnivorous	mid-water
Etheostoma fricksium	25	1	30.4	0.3	23	carnivorous	benthic
Noturus gyrinus	23	0.9	94.6	0.8	17	carnivorous	benthic
Esox americanus	12	0.5	399.2	3.3	9	carnivorous	mid-water
Hypentelium nigricans	12	0.5	155.4	1.3	14	omnivorous	benthic
Lepomis marginatus	11	0.4	94.5	0.8	18	carnivorous	mid-water
Erimyzon sucetta	5	0.2	144	1.2	15	omnivorous	moderately benthic
Micropterus salmoides	4	0.2	58.5	0.5	20	carnivorous	mid-water
Ameiurus platycephalus	3	0.1	249	2.1	11	primarily carnivorous	benthic
Acantharchus pomotis	2	0.1	39.2	0.3	22	carnivorous	mid-water
Umbra pygmea	1	0.04	2.6	0.02	28	primarily carnivorous	mid-water
Esox niger	1	0.04	26.7	0.2	24	carnivorous	mid-water
Notemigonus crysoleucas	1	0.04	2.6	0.02	29	omnivorous	mid-water
Lepomis gulosus	1	0.04	17.1	0.1	26	carnivorous	mid-water
Fundulus lineolatus	1	0.04	2	0.02	30	omnivorous	surface

5.12 STABLE CARBON INVENTORY; CUMULATIVE RESULTS WITHIN REACH OF FOUR MILE BRANCH

The culmination of data presented above allows a carbon inventory to be made of the entire 1.5 km reach of 4MB. The annual inventory (**Table 15**), or standing stock, shows the distribution of stable carbon within numerous ecosystem components. Abiotic (non-living) forms of C far exceed the mass of living carbon within the creek. DOC within the water is the largest constituent, comprising some 287,000 kg, an amount that is over 50% of the entire carbon balance. POC within the stream sediments comprised the next largest fraction (130,000 kg; 25% of total). POC within the water column was much less abundant (16,500 kg; 3% of total), and as has been reported in the literature (Hope, 1993) was about 1/3 the amount of DOC within the river water (50,000 kg; 10% of total). Logs, limbs, twigs, leaves and other organic debris are critical components within streams. They provide cover for biota, slow water movement, and provide structure for algae to colonize. Such debris within the 1.5 km reach accounted for 30,000 kg of C (6% of the total).

Of the living components of C, primary producers (periphyton and macrophytes) comprised a very small percentage of the total C inventory (0.01 %); a mere 50 kg of C within the reach. This mass of C within the periphyton and macrophytes was essentially the same as that of the aquatic invertebrates. Further up the food chain, two kg of C in the form of fish accounted for less than 0.0003 % of the total inventory within the stream reach.

Indeed, it is this very small percentage of "fish carbon" (0.0003 %) relative to the total carbon in the stream that has caused some scientists to question the use of bioconcentration factors within ^{14}C risk assessments (IUR, 2006; Kumblad et al. 2006; Sheppard et al. 2006a&b). As mentioned in the introduction, BCFs do not account for isotopic dilution of the stable element relative to the radioactive contaminant. Systems modeling, the next stage of this work, presented below, accounts for the abundance of the stable carbon.

Table 15. Carbon – Inventory of 1.5 km stretch of upper 4MB.

Component	Annual Biomass *(kg C in 1.5 km reach)*	Annual Biomass *(kg C m^{-3})*	% of Total (%)
DIC	287,028	279	55.7
POC_{sed}	130,160	126	25.3
$C_{channel\ debris\ load}$	30,187	29	5.8
$DOC_{upstreamFMC}$	21,730	21	4.2
DOC_{Hcreek}	14,310	14	2.8
DOC_{Fcreek}	12,508	12	2.4
$POC_{upstreamFMC}$	7,380	7	1.4
POC_{Hcreek}	4,860	5	0.9
POC_{Fcreek}	4,248	4	0.8
$DOC_{groundwater}$	1,100	1	0.2
$C_{litterfall}$	1,441	1	0.3
$DOC_{sedimentPOM}$	189	0.20	0.03
$C_{periphyton}$	51.0	0.05	0.01
$C_{macroinver\ (PREY)}$	40.7	0.04	0.008
$C_{macroinver(PREDATOR)}$	13.5	0.01	0.003
$C_{fish(OMNIVORE)}$	1.6	0.002	0.0003
$C_{fish(PREDATOR)}$	0.5	0.0005	0.00009
$C_{marcophytes}$	0.02	0.00002	0.000004
TOTAL	515,248	500	

6.0 STABLE CARBON MODEL

In the previous section, a C inventory of major abiotic and biotic components was developed for a 1.5 km reach of 4MB. The inventory is a distribution of the annual C loading among the various environmental components within the stream reach. The robust data sets specific to 4MB and the adjacent Meyers Branch, provided by the Savannah River Laboratory (presently SRNL) and SREL from data collections in the mid-1980s, make the inventory possible.

Using data from the C inventory, a dynamic stable C model was developed as the third step in the procedure highlighted in **Figure 1** of the Introduction. A model was constructed of stable carbon dynamics within 4MB using STELLA Systems software (ISEE Systems; http://www.iseesystems.com). Data obtained during the Comprehensive Cooling Water Program formed the core of the carbon model. Additional data were obtained from the U.S. Environmental Protection Agency (EPA) model AQUATOX (Park and Clough, 2004). AQUATOX is an EPA model designed to simulate the environmental fate and ecological effects of contaminants within aquatic ecosystems. AQUATOX is a food-web based model. Much of the metabolic information (e.g., rates of respiration, food consumption, digestion, etc.) for the biotic components used in the carbon model was obtained from the AQUATOX databases and adapted to conditions on the SRS. Adaptation of metabolic parameters often involved using site-specific water chemistry data for the several processes that are temperature dependent.

A fourth-order Runge-Kutta integration method was used in STELLA to solve the differential equations that depict the transfer of carbon among systems components. Eleven state variables were modeled as kg C m^{-3} within the 1.5 km reach of 4MB:

- Particulate organic carbon
- Dissolved organic carbon
- Dissolved inorganic carbon
- Biomass of periphyton
- Biomass of macrophytes
- Biomass of three invertebrates that represent different ecological niches
    - Stonefly
    - Caddisfly
    - Mayfly
- Biomass of three fish species that represent different ecological niches
    - Bluegill
    - Catfish
    - Bass

Carbon is a very dynamic component in aquatic systems and exhibits strong daily fluctuations due to variation in photosynthesis, as well as strong seasonal dynamics due largely to variation in temperatures that ultimately govern many chemical, physical and biological processes that influence the carbon balance. Modeling such variation was not required for the steady-state conditions sought to explain the long-term dynamics of ^{14}C in 4MB. Instead, a much simpler annual time step was used with input data based largely on annual means or annual medians from the carbon inventory.

An annual time step is rational because of the long physical half-life of ^{14}C (5240 y) and because the carbon dynamics were modeled under the assumption of continuous input of ^{14}C via groundwater. An annual time step is also conducive to our objective of predicting ^{14}C concentrations in fish under steady state conditions. Such an approach is typical for models that estimate ^{14}C from nuclear installations, and allows for predictions to be made based on

calculations that extend dozens to hundreds of years into the future (IUR, 2006). (Although an annual time step was used; the current model could be adapted to a seasonal model should short term dynamics of carbon be of interest).

Fluxes of carbon into and out of the state variables are described in general terms below. Input parameters and model flux rates were adjusted to fulfill two primary modeling goals:

1. The stable carbon model should produce rational results that mimic a sustainable ecosystem under steady state conditions. The test of this objective is if all ecosystem components are functional within the model. The biomass of dysfunctional components is not sustainable and goes to zero shortly after the start of model simulation.
2. The model predictions for the 11 state variables listed above should have steady state values similar to those actually quantified by field measurements and from which the stable carbon inventory was derived (Chapter IV).

6.1 FOOD WEB DYNAMICS

The living biota within 4MB were modeled as two main groups: plants and aquatic animals. Each main group was subdivided into representative species that broadly depicted different ecological niches. Two plant niches, three aquatic invertebrate species and three fish species were simulated within the model. The species separation was done by altering process-level equations whose niche-specific input values were obtained from field measurements during the Comprehensive Cooling Water Study or by using more generic data from the EPA AQUATOX model (Park et al. 2008; Park and Clough, 2004). Plants, differentiated into periphyton and macrophytes, are primary consumers of carbon via photosynthesis and form the base of the food web. Aquatic invertebrates and fish consume prey items within a food web matrix and thereby take up carbon. These groups are represented by different parameter values and by variations in the equations as described below.

A relatively simple food web was established for the carbon model (**Figure 3**). The dynamics of food consumption are depicted in the food web as pathways, with each path representing a dietary preference of prey for the predatory organism. Each path has an associated fraction that quantifies the portion of the predator's diet composed of by that prey item. For example, the bass diet was modeled as being comprised of 50% bluegill; 10% catfish and 40% invertebrate stonefly (**Figure 3**). The dietary preferences were derived from data within the EPA AQUATOX model (Park and Clough, 2004). Food consumption preferences were purposely biased to include a greater abundance of periphyton and macrophytes within the higher organisms' diets, as well as consumption of particulate organic matter by some organisms. This biasing was done to increase the critical pathways of ^{14}C uptake. It is the ^{14}C contamination of primary producers and their subsequent consumption by higher level organisms that eventually leads to the contamination of bass. This injected bias of enhanced consumption of primary producers within the food web is conservative in that it increases the probability that bass will become contaminated as ^{14}C traverses up the food web.

A brief description of the eleven state variable sub-models follows.

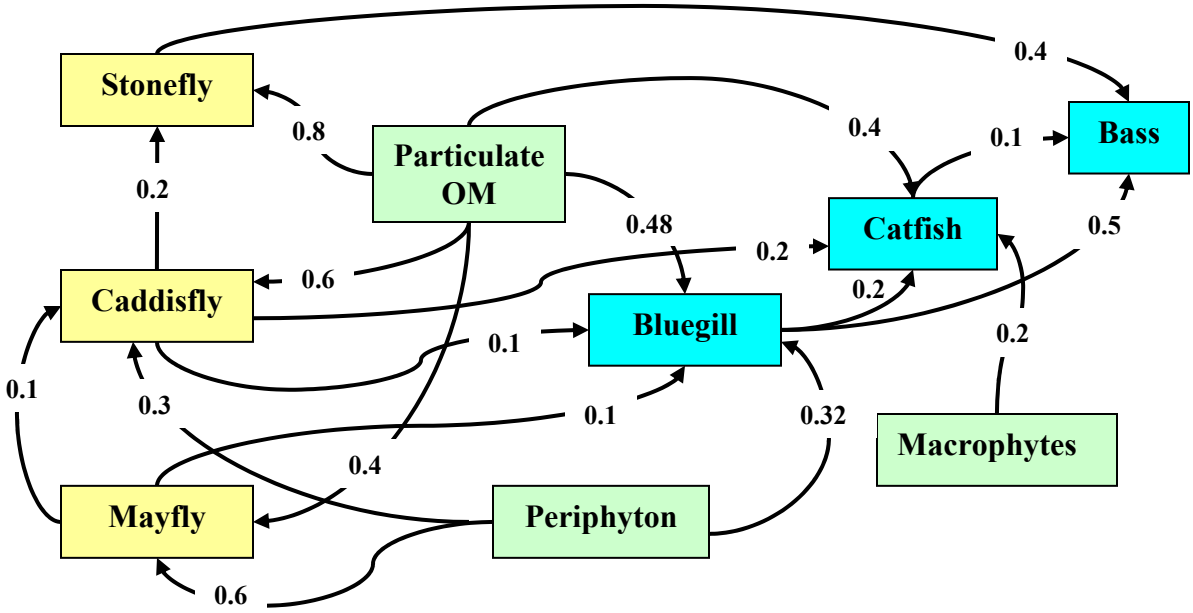

Figure 3. Depicts a simple food web and shows the dietary preferences of organisms within the carbon systems model. Numbers represent the fraction of that prey item within the respective consumer's diet.

6.2 PARTICULATE ORGANIC CARBON (POC)

The POC state variable (coded in the model as *POC_FM_Creek*; see model equation below) was modeled as kg C m^{-3}, largely from the data of Williams and Pinder (1990) and Dosskey and Bertsch (1997). Inputs to the 1.5 km reach of interest were simulated based on water flows multiplied by concentrations of POC, and included contributions from Upstream (coded as *UpStrrm*;), F-area (*F_Creek*), and H-area tributaries (*H_Creek*). A groundwater component (*GrndH20*) was included in the model for POC, but only so that the volume of groundwater could be added to the stream reach. POC contribution from groundwater was assumed to be zero (Dosskey and Bertsch 1997). Litterfall (*Biotic_Input*) into the reach was modeled as an annual biotic input to POC, based on the data collected by Firth et al. (1986) for Meyers Branch (*Eq. 15*). All non-predatory mortality, defecation and excretion by biota was summed and added to the POC pool (*biota_to_POC*), thus providing a recirculation mechanism of carbon in the model. Outflows of POC were also modeled on the basis of water flow rates and POC concentrations (*FM_POC__outflow*). A POC to DOC conversion factor of 0.29 (Futter et al. 2007) was used to convert a fraction of the POC in the water column to DOC (*POC_to_DOC*). Conversion of sediment POC to DOC and transfer to the water column was also modeled at 0.2 kg C m^{-3}. The equations, as well as a graphical depiction (**Figure 4**) of the POC portion of the carbon model follow.

POC Model Equations

POC_FM_Creek(t) = POC_FM_Creek(t - dt) + (UpStrm__POC_in + H_Creek__POC_in + F_Creek__POC_in + Biotic_INput + GrndH20_POC + biota_to_POC - FM_POC__outflow - POC_to_DOC) * dt.

POC INFLOWS:

UpStrm__POC_in = POC_conc_upstream * UpStrm__flow_rate/1030 m^3

H_Creek__POC_in = H_Creek__flow_rate * POC_conc_HC/1030 m^3

F_Creek__POC_in = F_Creek__flow_rate * POC_conc_FC/1030 m^3

Biotic_INput = litter_fall/1030 m^3

GrndH20_POC = GH20__flow_rate * POC_Conc__GrdH2O/1030m^3

Biota_to_POC = bass_DEFECATION + bass_EXCRETION + bass_MORTALITY + Bluegill_DEFECATION + Bluegill_EXCRETION + Bluegill_MORTALITY + Caddisfly_DEFECATION + Catfish_DEFECATION + Catfish_EXCRETION + Catfish_MORTALITY + Cdfly_EXCRETION + Cdfly_MORTALITY + MacroPhy_Excretion + MacroPhy_Mortality + Mayfly_DEFECATION + Mayfly_EXCRETION + Mayfly_MORTALITY + Periphy_Excretion + Periphy_Mortality + Stnfly_DEFECATION + Stnfly_EXCRETION + Stnfly_MORTALITY)

POC OUTFLOWS:

FM_POC__outflow = FM_flow_rate * POC__conc__out/1030

POC_to_DOC = (POC_to_DOC_Rate *POC_FM_Creek) + DOC_from__Sediment_POC

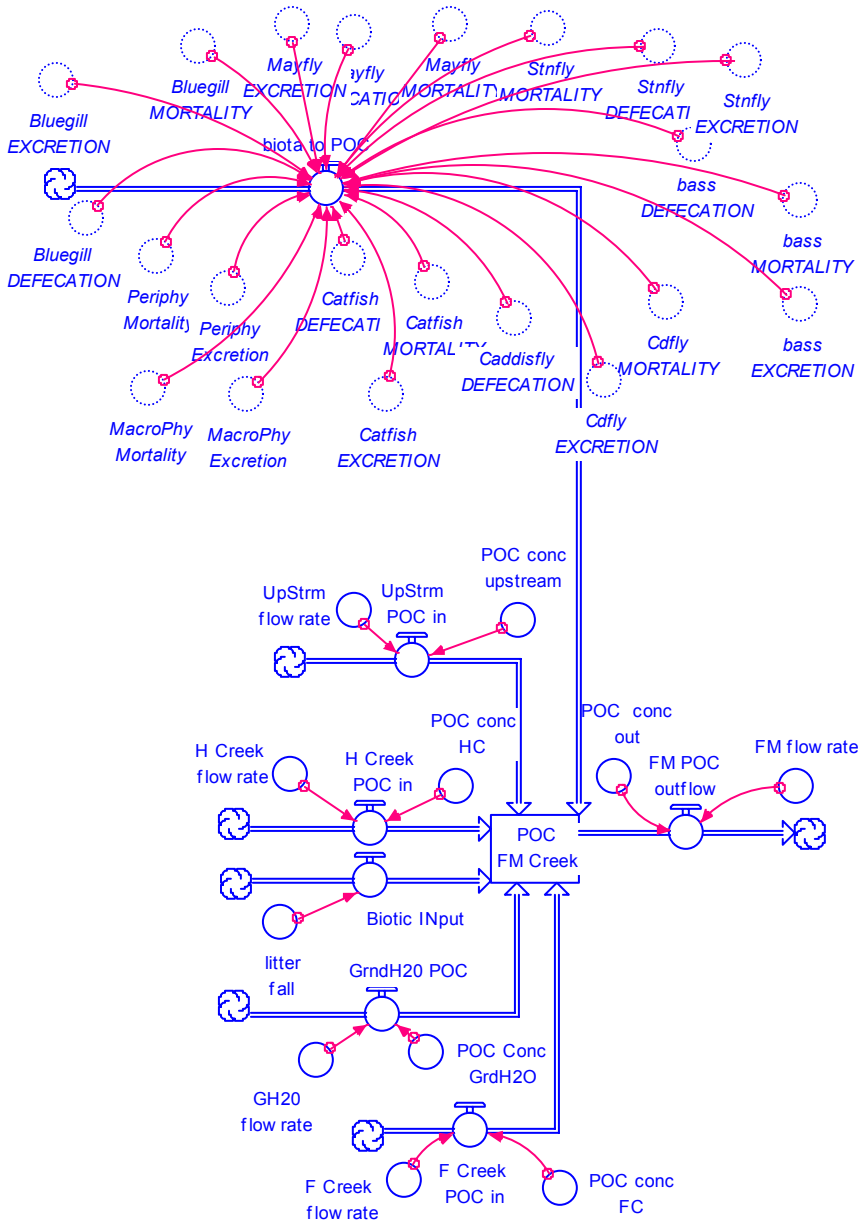

Figure 4. Graphical depiction of particulate organic portion (POC) of the carbon model. Outflows are connected to inflow of DOC portion of model.

6.3 DISSOLVED ORGANIC CARBON (DOC)

Inflows and outflow of DOC were modeled similarly to POC (i.e., water flow rates time concentrations; **Figure 5**). Groundwater contributed DOC at concentrations that were a factor of 10 less than the concentrations in surface waters (Dosskey and Bertsch, 1997). Other source terms of DOC included leaching from POC within the sediments (*DOC_from__Sediment_POC*), leaching of DOC from litterfall (*DOC_leach_from_litterfall*); and a POC to DOC conversion factor. Outflow of DOC included a conversion rate to DIC of 0.16 (*DOC_to_DIC_Rate*) from Futter et al. (2007).

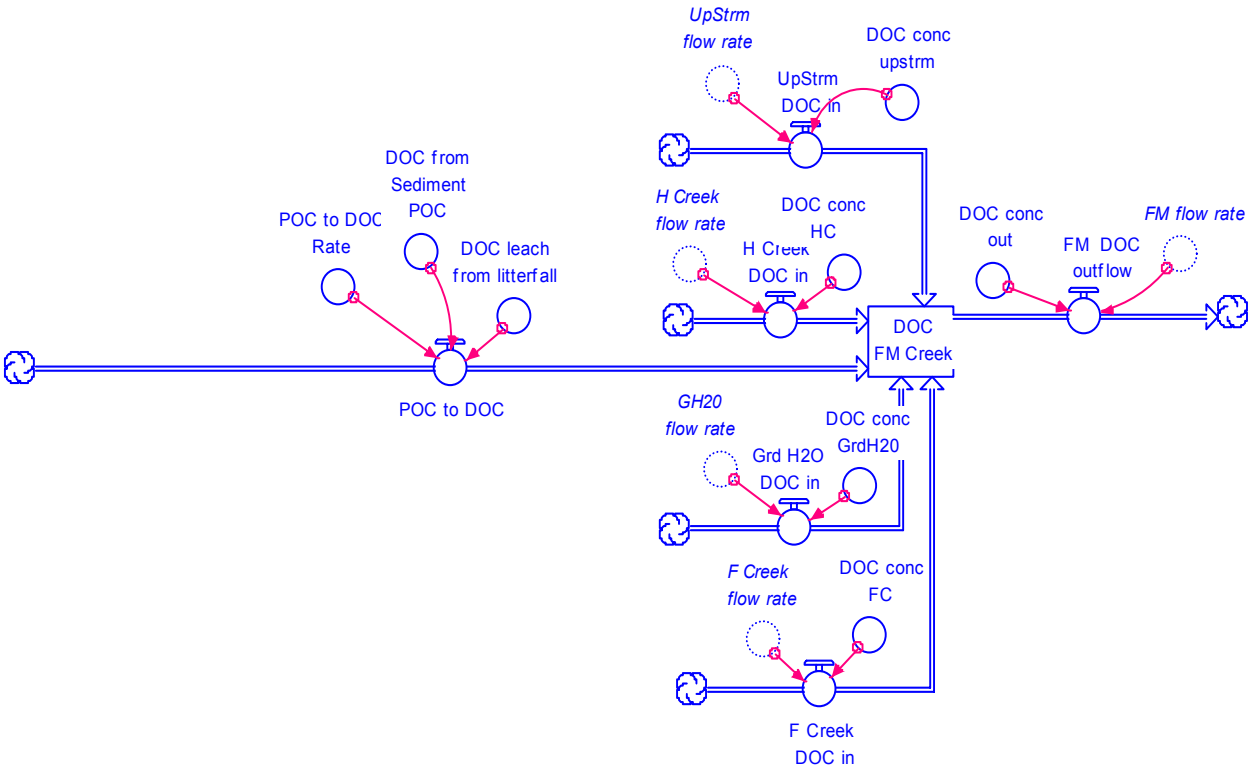

Figure 5. Graphical depiction of dissolved organic portion of the carbon model. Inflows are connected to POC portion of the carbon model and outflows are connected the DIC portion of model.

DOC Model Equations:

DOC_FM_Creek(t) = DOC_FM_Creek(t - dt) + (UpStrm__DOC_in + H_Creek__DOC_in + F_Creek__DOC_in + Grd_H2O__DOC_in + POC_to_DOC - FM__DOC__outflow - DOC_to_DIC_Conversion) * dt

DOC INFLOWS:

UpStrm__DOC_in = DOC_conc_upstrm * UpStrm__flow_rate/1030 m^3

H_Creek__DOC_in = H_Creek__flow_rate * DOC_conc_HC/1030 m^3

F_Creek__DOC_in = F_Creek__flow_rate * DOC_conc_FC/1030 m^3

Grd_H2O__DOC_in = GH20__flow_rate * DOC_conc_GrdH20/1030 m^3

POC_to_DOC = (POC_to_DOC_Rate * POC_FM_Creek) + DOC_leach_from_litterfall + DOC_from__Sediment_POC

DOC OUTFLOWS:

FM__DOC__outflow = DOC_conc_out * FM_flow_rate/1030 m^3

DOC_to_DIC_Conversion = DOC_to_DIC_Rate * DOC_FM_Creek

6.4 DISSOLVED INORGANIC CARBON (DIC)

Inputs of DIC included the transformation of DOC to DIC; based on a transfer rate of 0.16 (Futter et al. 2007). All respiration from biotic components in the model was added as input to the DIC state variable (**Figure 6**), providing another recirculation mechanism of carbon in the model. Concentration of DIC in stream water was based on annual median measurements of pH, alkalinity and stream temperature (*Eq 10*). In addition to washout of DIC from the outflow of the stream reach, loss of DIC included its uptake for photosynthesis by periphyton and macrophytes. DIC as CO_2 and its exchange with the atmosphere (*CO2Exch_Rate* = 0.29) was modeled using Henry's constant and the CO_2 partial pressure.

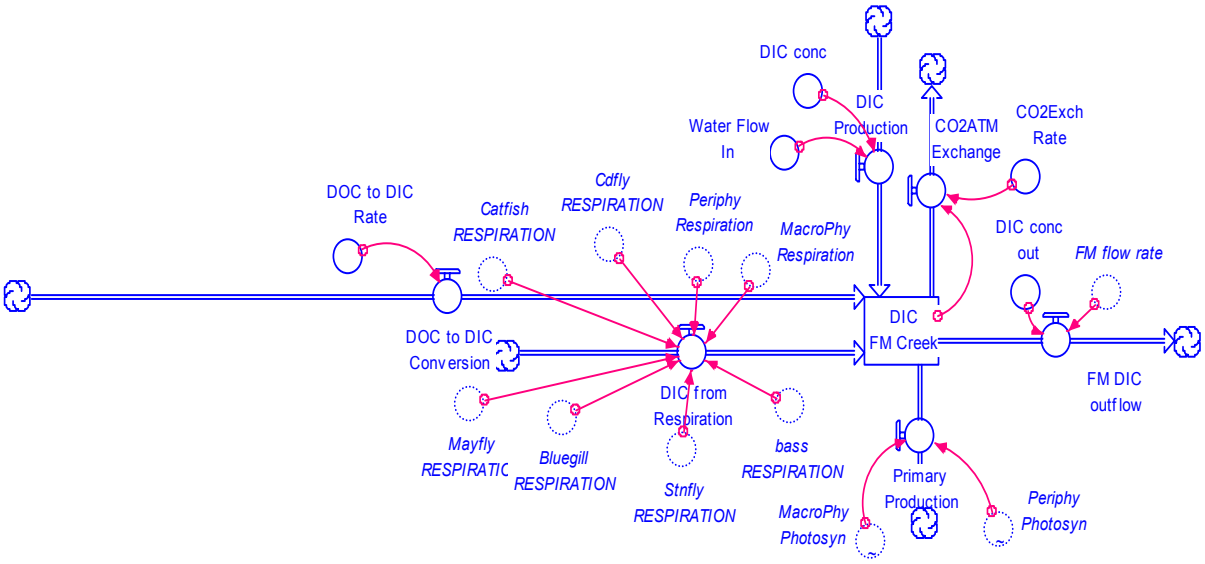

Figure 6. Graphical depiction of dissolved inorganic portion of the carbon model. Inflows are connected to DOC portion of the carbon model.

DOC Model Equations:

DIC__FM_Creek(t) = DIC__FM_Creek(t - dt) + (DIC_from_Respiration + DOC_to_DIC_Conversion + DIC_Production - CO2ATM_Exchange - FM_DIC__outflow - Primary__Production) * dt

DIC INFLOWS:

DIC_from_Respiration = 0.526 * (bass_RESPIRATION + Bluegill_RESPIRATION + Catfish_RESPIRATION + Cdfly_RESPIRATION + MacroPhy_Respiration + Mayfly_RESPIRATION + Periphy_Respiration + Stnfly_RESPIRATION)

DOC_to_DIC_Conversion = DOC_to_DIC_Rate * DOC_FM_Creek

DIC_Production = DIC_conc * Water_Flow_In/1030 m^3

DIC OUTFLOWS:

CO2ATM_Exchange = CO2Exch_Rate * DIC__FM_Creek

FM_DIC__outflow = FM_flow_rate * DIC_conc_out/1030 m^3

Primary__Production = MacroPhy_Photosyn + Periphy_Photosyn

All POC, DOC and DIC data were ultimately transformed from concentrations based on volume (kg C m^{-3}) to total kg C within the 1.5 km reach of 4MB. This was done by multiplying the concentrations per volume, by the total volume of water in the reach. The latter was estimated based on water depth, flow rate, channel roughness, slope, and channel width using Manning's equation (Gregory and Walling 1973): mc

$$ManningVOL = Y * CLength * Width \qquad (Eq.\ 18)$$

where:

Y = dynamic mean depth (m),

CLength = length of reach (m); and

Width = width of channel (m).

$$Y = \left(\frac{Q * Manning}{\sqrt{slope} * Width} \right)^{3/5} \qquad (Eq.\ 19)$$

where:

Q = flow rate (0.367 m^3 s^{-1});

Manning = roughness coefficient (default coefficient for a natural channel = 0.040);

Slope = slope of channel (0.004 m/m based on data from topographical maps);

Width = mean channel width (3.5 m).

The resultant ManningVol calculates to be 1030 m^3.

6.5 PERIPHYTON

The change in periphyton biomass, expressed kg C m^{-3} , was modeled as a function of the initial loading, photosynthesis, respiration, excretion or photorespiration, nonpredatory mortality, and predation (periphyton consumption by other biota).

$$\frac{d\ Biomass_{Periphy}}{dt} = Loading + Photosynthesis - \mathrm{Re}spiration - Excertion - Mortality - \mathrm{Pr}edation$$

where:

$d\ Biomass_{Periphy}/dt$ = change in biomass of periphyton with respect to time (kg C m^{-3});

Loading = initial loading of algal group (0.05 kg C m^{-3}; from *Eq 10* (51 kg C / 1030 m^3 volume of reach);

Photosynthesis = rate of photosynthesis (kg C m^{-3}); max. photosynthetic rate (2.06; from AQUATOX) * $Biomass_{Periphy}$ (kg C m^{-3}); this is a conservative number that maximizes

photosynthesis, does not account for reduction due to tree canopy shading of stream, seasonal shift in light intensity, or temperature dependent production. Indeed, this equation resulted in exponential growth of periphyton. Therefore, a damping function was graphed and added so that periphyton biomass was similar to what was measured during the Comprehensive Cooling Water Study. Graphed data are given below.

Respiration = respiratory loss (kg C m^{-3}); ideal respiration at 20 C = 0.08; from AQUATOX) * $1.045^{(Temperature-20)}$ * $Biomass_{Periphy}$ (kg C m^{-3}); annual mean stream temperature of 17 C was used for Temperature, suggesting a respiration value of 0.070. A respiration value of 0.05 was ultimately used in order to stabilize the periphyton population. The 0.05 value was determined by trial and error.

Excretion = excretion or photorespiration (kg C m^{-3}), = KResp (coefficient of proportionality between excretion and photosynthesis at optimal levels; 0.026 unitless; from AQUATOX) * photosynthesis (kg C m^{-3}). KResp was eventually lowered to 0.002 to stabilize the periphyton dynamics.

Mortality = nonpredatory mortality (kg C m^{-3}) = 0.001 (default from AQUATOX) * $Biomass_{Periphy}$ (kg C m^{-3}). Mortality was increased to 0.005 to reduce tendency for exponential growth of periphyton.

Predation = herbivory (kg C m^{-3}) = Σ ingestion by consumers (kg C m^{-3})

Consumption of periphyton was based on dietary preferences within the foodweb depicted in **Figure 3**, multiplied by a species-specific maximum consumption rate of the consumer (**Table 16**) and the biomass of the consumer compartment (Park and Clough 2004). Daily rate constants were converted to annual ones via a conversion factor of 365. Thus the model equations for consumption of periphyton by bluegill, caddisfly and mayfly were:

- bluegil_consump = 0.068 * 0.32 * 365 * BLUEGILL_BIOMASS
- cadfly_consump = 0.25 * 0.3 * 365 * CADDISFLY_BIOMASS
- mayfly_consump = 0.23 * 0.6 * 365 * MAYFLY_BIOMASS

The model equations for periphyton, as coded in the model and corresponding to **Figure 7**, are:

Periphyton Model Equations

Periphyton_BIOMASS(t) = Periphyton_BIOMASS(t - dt) + (Periphy_Photosyn - Periphy_Respiration - Periphy_Excretion - Periphy_Mortality - Periph_Consumption) * dt

PERIPHYTON INFLOWS:

Periphy_Photosyn = GRAPH (Periphy_Photosyn_Rate * Periphyton_BIOMASS) ; (0.00, 0.478), (0.07, 0.546), (0.14, 0.588), (0.21, 0.614), (0.28, 0.624), (0.35, 0.627), (0.42, 0.631), (0.49, 0.631), (0.56, 0.634), (0.63, 0.631), (0.7, 0.631)

PERIPHYTON OUTFLOWS:

Periphy_Respiration = Periphyton_BIOMASS * Periphy_Resp_rate

Periphy_Excretion = KResp * Periphy_Photosyn

Periphy_Mortality = Periphy_Mort_Rate * Periphyton_BIOMASS

Periph_Consumption = bluegil_consump + cadfly_consump + mayfly_consump

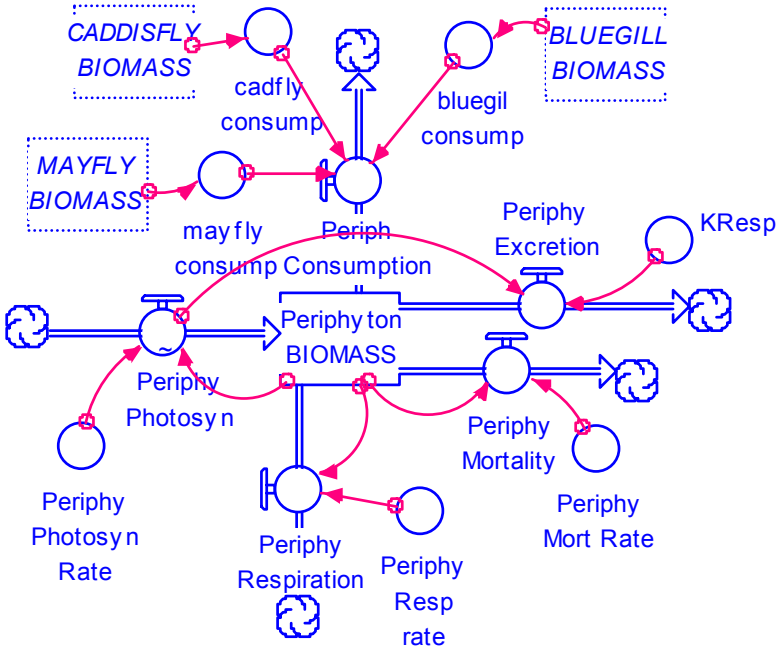

Figure 7. Graphical depiction of periphyton variable within the carbon model. Dotted boxes represent connections to other state variables.

Table 16. Maximum consumption rate, non-predatory mortality rate, respiration rate and mean mass of biota simulated within the carbon systems model.

Organism	Maximum consumption rate (g/g-d)	Consumption intercept and slope [1]	Mortality coefficient (1/d)	Respiration rate (1/d)	Respiration intercept and slope [a]	Mean mass (g-wet)
Bass *	0.043 *	0.33 & -0.32	0.0004	0.0046 *	0.003 & -0.35	500
Bluegill *	0.068 *	0.18 & -0.27	0.0045	0.0075 *	0.015 & -0.20	36
Catfish *	0.025 *	0.15 & -0.36	0.004	0.0048 *	0.027 & -0.35	150
Caddisfly	0.25	not applicable	0.004	0.013	not applicable	0.06
Mayfly	0.23	not applicable	0.02	0.02	not applicable	0.024
Stonefly	0.09	not applicable	0.002	0.013	not applicable	0.03

[a] Maximum consumption and respiration rates of fish were based on mass- and species-specific allometric equations in AQUATOX; with rate = intercept * mass $^{(slope)}$.

6.6 MACROPHYTES

Macrophyte biomass was modeled in a manner similar to that of the periphyton state variable, but with specific input parameters and rate constants. A graphical depiction of the macrophtye sub-model (**Figure 8**) and the equations used follow:

$dBiomass_{MACRO}\ dt$ = Loading + Photosynthesis - Respiration - Excretion- Mortality - Predation

where:

$dBiomass_{MACRO}/dt$ = change in biomass with respect to time (kg C m^{-3});

Loading = initial loading of macrophytes model compartment);

Photosynthesis = rate of photosynthesis (kg C m^{-3}); max. photosynthetic rate (1.2; from AQUATOX) * *$Biomass_{MACRO}$* (kg C m^{-3}); this is a conservative number that maximizes photosynthesis, does not account for reduction due to tree canopy shading of stream, seasonal shift in light intensity, reduced water quality or suboptimal temperature. As with periphyton, this idealized equation resulted in exponential growth of macrophytes. Therefore, a damping function was graphed and added so that macrophyte biomass was similar to what was measured during the Comprehensive Cooling Water Study.

Respiration = respiratory loss (kg C m^{-3}); ideal respiration at 20 C = 0.024; from AQUATOX) * $1.045^{(Temperature-20)}$ * *$Biomass_{MACRO}$* (kg C m^{-3}); annual mean stream temperature of 17C was used for Temperature, resulting in respiration value of 0.021.

Excretion = excretion or photorespiration (kg C m^{-3}), = KResp (coefficient of proportionality between excretion and photosynthesis at optimal levels; 0.25 unitless; from AQUATOX) * photosynthesis (kg C m^{-3})

Mortality = nonpredatory mortality (kg C m^{-3}) = 0.001 (default from AQUATOX) * *$Biomass_{MACRO}$* (kg C m^{-3})

Predation = herbivory (kg C m^{-3}) = Σ ingestion by consumers (kg C m^{-3})

Macrophyte Model Equations:

MacroPhy_BIOMASS(t) = MacroPhy_BIOMASS(t - dt) + (MacroPhy_Photosyn - MacroPhy_Respiration - MacroPhy_Excretion - MacroPhy_Mortality - MacroPhy_Consumption) * dt

MACROPHYTE INFLOWS:

MacroPhy_Photosyn = GRAPH(MacroPhy_Photsyn_Rate*MacroPhy_BIOMASS) : (0.00, 0.000305), (0.04, 0.0003), (0.08, 0.000285), (0.12, 0.00028), (0.16, 0.00029), (0.2, 0.0003), (0.24, 0.000305), (0.28, 0.0003), (0.32, 0.000285), (0.36, 0.000255), (0.4, 0.00021)

MACROPHYTE OUTFLOWS:

MacroPhy_Respiration = MacroPhy_Respir_rate (0.021) * MacroPhy_BIOMASS

MacroPhy_Excretion = MacroPhy_Photosyn * MacroPhy_KResp (0.25)

MacroPhy_Mortality = MacroPhy_Mort_Rate (0.001) * MacroPhy_BIOMASS

MacroPhy_Consumption = Catfish__consum_Macrophy * CATFFISH_BIOMASS (0.026 * 0.2 * 365)

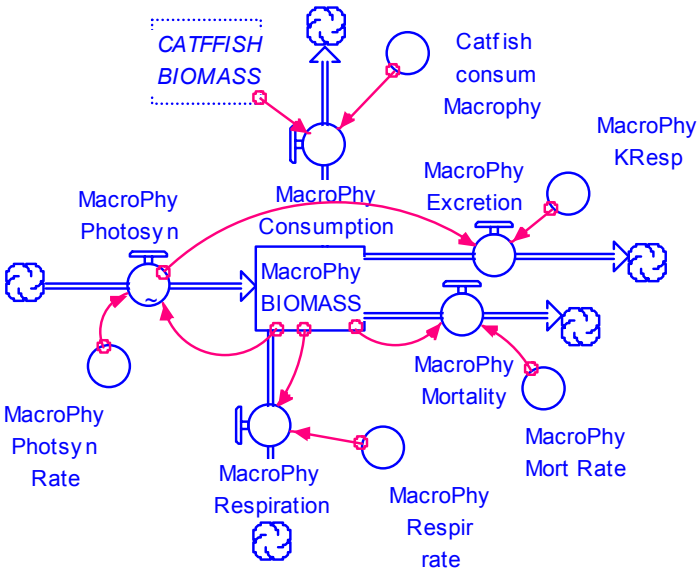

Figure 8. Graphical depiction of macrophyte variable within the carbon model. Dotted boxes represent connections to other state variables.

6.7 MAYFLY INVERTEBRATE

Aquatic invertebrates comprised the next layer of complexity within the simulated food web (**Figure 3**) of the carbon model. All of the invertebrates were modeled in a similar manner, but with different input parameters and rates of transfer. Of the three macroinvertebrates simulated, the diet of mayflies was the one composed with the highest percentage of primary producers. The general model for change in invertebrate biomass was:

$$dBiomass_{biota}/dt = Loading + Consumption - Defecation - Excretion - Respiration - Mortality - Predation$$

where $dBiomass_{biota}/dt$ is the species-specific change in biomass (kg C) per year. Consumption is the sum of ingestion as governed by the dynamics of the simulated food web, and species-specific consumption rates (**Table 16**). *Defecation* of unassimilated food was modeled, and loss of assimilated food was modeled as *Excretion* by using proportionality constants for the radio of excretion to respiration (Park and Clough, 2004). *Respiratory* loss was modeled, as well a species-specific, non-predatory *Mortality*. *Predation* was simulated as the biota of interest consumed by predators, with rates governed by characteristics of the predator and the food web dynamics. Values for the various rate constants were derived from data within AQUATOX (Park and Clough, 2004). **Tables 16 and 17** summarize the rate constants by species.

Table 17. Excretion to respiration proportionality constant (KExcr; when multiplied by respiration it yields an estimate of excretion of assimilated food; kg C / m^3 – y); and Egestion Coefficient (fraction of ingested food that is unassimilated and defecated); from AQUATOX model (Park and Clough, 2004).

Organism	KExcr	Egestion Coefficient
Bass	0.05	0.16
Bluegill	0.05	0.16
Catfish	0.05	0.20
Caddisfly	0.17	0.16
Mayfly	0.17	0.30
Stonefly	0.17	0.15

The specific model equations for the mayfly simulation, as well as a graphical depiction of the sub-model (**Figure 9**) follow.

Mayfly Model Equations:

MAYFLY_BIOMASS(t) = MAYFLY_BIOMASS(t - dt) + (Mayfly_CONSUMPTION - Mayfly_DEFECATION - Mayfly_RESPIRATION - Mayfly_PREDATION - Mayfly_MORTALITY - Mayfly_EXCRETION) * dt

MAYFLY INFLOWS:

Mayfly_CONSUMPTION = GRAPH (Mayfly_EATS__Periphyton+Mayfly_EATS_POC) * MAYFLY_BIOMASS) : (0.00, 0.0615), (0.1, 0.0885), (0.2, 0.102), (0.3, 0.122), (0.4, 0.14), (0.5, 0.168), (0.6, 0.195), (0.7, 0.211), (0.8, 0.236), (0.9, 0.255), (1, 0.272)

Mayfly_EATS_POC = 0.23*0.4*365*POC_FM_Creek

Mayfly_EATS__Periphyton = 0.23*365*Periphyton_BIOMASS*0.6

MAYFLY OUTFLOWS:

Mayfly_DEFECATION = Mayfly_CONSUMPTION * Mayfly_defec_rate

Mayfly_RESPIRATION = Mayfly_Resp_Rate * MAYFLY_BIOMASS

Mayfly_PREDATION = (Bluegill_EATS_mayfly_3 + Cdfly_EATS_Mayfly) * MAYFLY_BIOMASS

Mayfly_MORTALITY = MAYFLY_BIOMASS * Mayfly_Mort_rate

Mayfly_EXCRETION = Mayfly_RESPIRATION * Mayfly_excret_rate

Bluegill_EATS_mayfly_3 = 0.068*365*0.1*BLUEGILL_BIOMASS

Cdfly_EATS_Mayfly = 0.25*365*0.1*CADDISFLY_BIOMASS

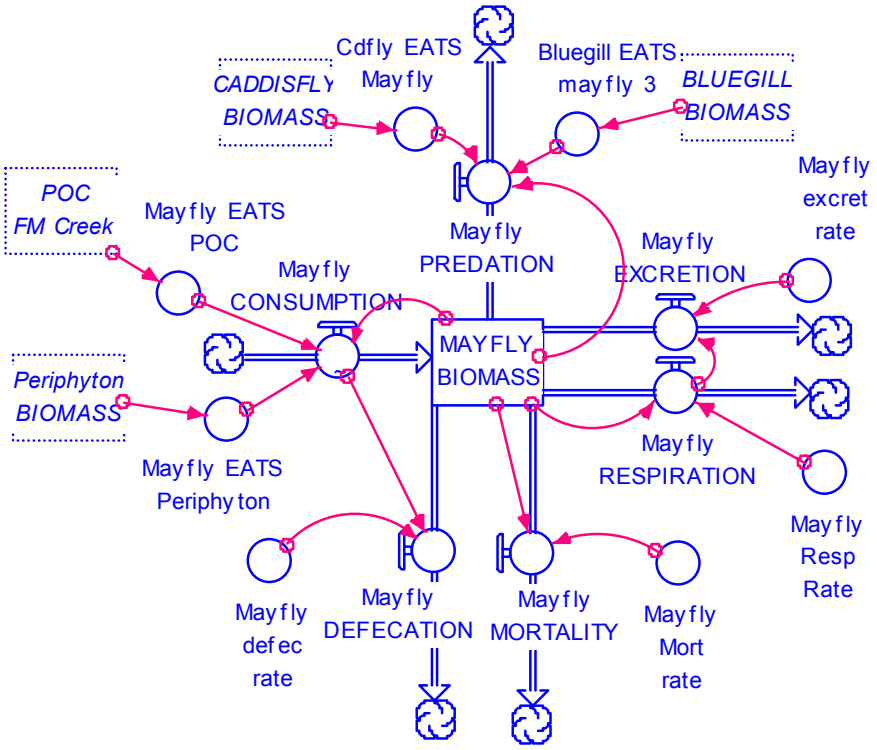

Figure 9. Graphical depiction of mayfly (aquatic invertebrate) state variable within the carbon model. Dotted boxes represent connections to other state variables.

6.8 CADDISFLY INVERTEBRATE

The aquatic invertebrate, Caddisfly, represented an omnivorous diet that included primary producers as well as the consumption of other invertebrates (**Figure 3**). The general approach of simulating the caddisfly population was similar to that described for Mayflies (Section 6.7). The specific model equations for the caddisfly simulation, as well as a graphical depiction (**Figure 10**) of the submodel follow.

Caddisfly Model Equations:

CADDISFLY_BIOMASS(t) = CADDISFLY_BIOMASS(t - dt) + (Cdfly_CONSUMPTION - Caddisfly_DEFECATION - Cdfly_RESPIRATION - Cdfly__PREDATION - Cdfly_MORTALITY - Cdfly_EXCRETION) * dt

CADDISFLY INFLOWS:

Cdfly_CONSUMPTION = GRAPH (CADDISFLY_BIOMASS * (Cdfly_EATS__Mafly + Cdfly_EATS__Periphyton + Cdfly_EATS__POC)): (0.00, 0.044), (0.5, 0.064), (1.00, 0.082), (1.50, 0.094), (2.00, 0.111), (2.50, 0.133), (3.00, 0.15), (3.50, 0.163), (4.00, 0.167), (4.50, 0.179), (5.00, 0.189)

Cdfly_EATS__Mafly = 0.25*365*0.1*MAYFLY_BIOMASS

Cdfly_EATS__Periphyton = 0.25*365*0.3*Periphyton_BIOMASS

Cdfly_EATS__POC = 0.25*0.6*365*POC_FM_Creek

CADDISFLY OUTFLOWS:

Caddisfly_DEFECATION = Cdfly_CONSUMPTION * Cdfly_defec_rate
Cdfly_RESPIRATION = Cdfly_Resp_Rate * CADDISFLY_BIOMASS
Cdfly__PREDATION = (Bluegill_EATS_Cdfly + Catfish_EATS_Cdfly) * CADDISFLY_BIOMASS
Cdfly_MORTALITY = CADDISFLY_BIOMASS * Cdfly_Mort_rate
Cdfly_EXCRETION = Cdfly_RESPIRATION * Cdfly_excret_rate
Bluegill_EATS_Cdfly = 0.068*365*0.1*BLUEGILL_BIOMASS
Catfish_EATS_Cdfly = 0.0262*365*0.1*CATFFISH_BIOMASS
Cd_defec_rate = 0.158

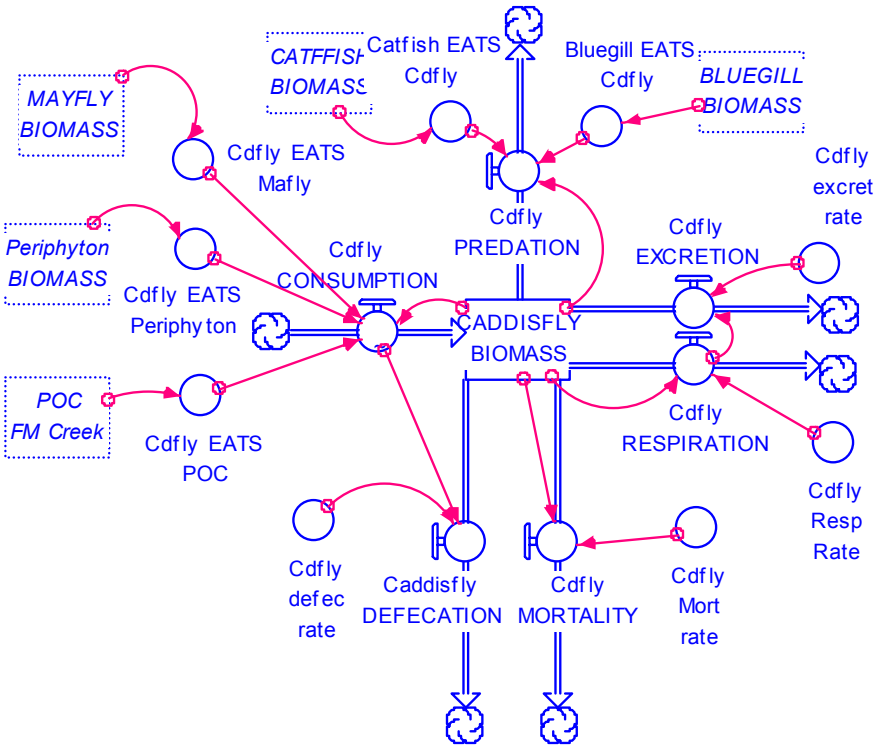

Figure 10. Graphical depiction of caddisfly (aquatic invertebrate) state variable within the carbon model. Dotted boxes represent connections to other state variables.

6.9 STONEFLY INVERTEBRATE

The Stonefly subroutine, depicted the most predatory of the three macroinvertebrates modeled (**Figure 3**). The general approach of simulating the stonefly population was similar to that described for Mayflies (Section 5.7). The specific model equations for the stonefly simulation, as well as a graphical depiction of the sub- follow model (**Figure 11**).

Stonefly Model Equations

STONEFLY_BIOMASS(t) = STONEFLY_BIOMASS(t - dt) + (Stnfly_CONSUMPTION - Stnfly_DEFECATION - Stnfly_RESPIRATION - Stnfly_PREDATION - Stnfly_MORTALITY - Stnfly_EXCRETION) * dt

STONEFLY INFLOWS:

Stnfly_CONSUMPTION = GRAPH (STONEFLY_BIOMASS * (Stnfly_EATS__Cdfly + Stnfly_EATS__POC)) : (0.00, 0.023), (0.05, 0.043), (0.1, 0.057), (0.15, 0.076), (0.2, 0.091), (0.25, 0.097), (0.3, 0.113), (0.35, 0.126), (0.4, 0.137), (0.45, 0.147), (0.5, 0.162)

Stnfly_EATS__Cdfly = 0.09*365*0.2*CADDISFLY_BIOMASS

Stnfly_EATS__POC = 0.09*365*0.8*POC_FM_Creek

STONEFLY OUTFLOWS:

Stnfly_DEFECATION = Stnfly_CONSUMPTION * Stnfly_defec_rate

Stnfly_RESPIRATION = Stnfly_Resp_Rate * STONEFLY_BIOMASS

Stnfly_PREDATION = Bass_EATS_Stnfly * STONEFLY_BIOMASS

Stnfly_MORTALITY = STONEFLY_BIOMASS * Stnfly_Mort_rate

Stnfly_EXCRETION = Stnfly_RESPIRATION * Stnfly_excret_rate \

Bass_EATS_Stnfly = 0.0437*365*0.4*BASS_BIOMASS

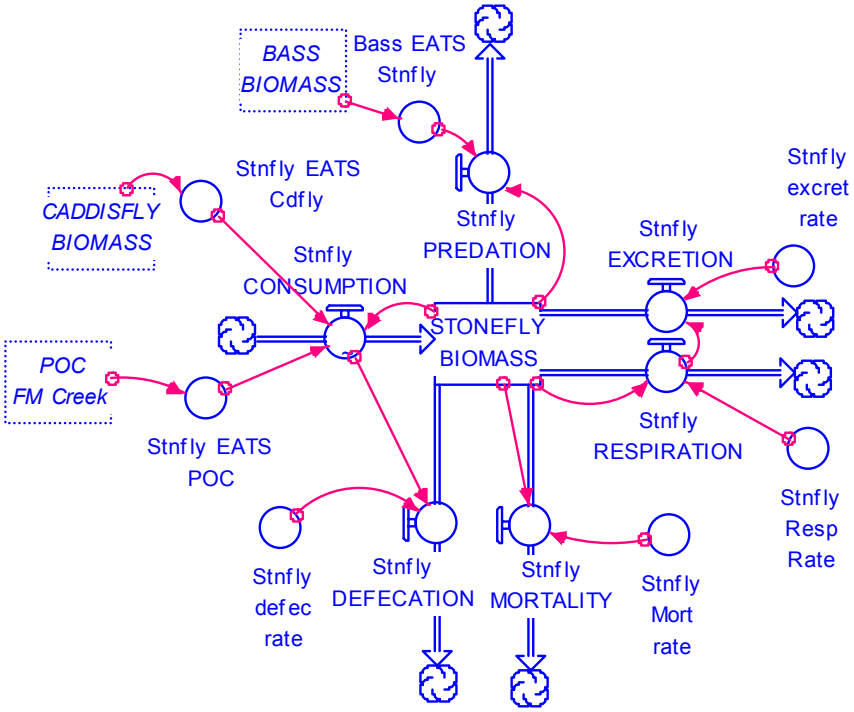

Figure 11. Graphical depiction of stonefly (aquatic invertebrate) state variable within the carbon model. Dotted boxes represent connections to other state variables.

6.10 BLUEGILL

Fish were simulated within the carbon model in an analogous manner to the aquatic invertebrates (*Biomass, Consumption, Defecation, Excretion, Respiration, Mortality and Predation*), but with different input parameters and rate constants. Of the three fish species simulated, the diet of

bluegill was composed of the greatest fraction of plant material, although 20% of the bluegills' diet was simulated by consumption of aquatic invertebrates (**Figure 3**). The specific model equations for the bluegill submodel, as well as a graphical depiction of it follow (**Figure 12**).

Bluegill Model Equations:

BLUEGILL_BIOMASS(t) = BLUEGILL_BIOMASS(t - dt) + (Bluegill_CONSUMPTION - Bluegill_DEFECATION - Bluegill_RESPIRATION - Bluegill_PREDATION - Bluegill_MORTALITY - Bluegill_EXCRETION) * dt

BLUEGILL INFLOWS:

Bluegill_CONSUMPTION = GRAPH (BLUEGILL_BIOMASS * (Bluegill_EATS__Periphyton + Bluegill_EATS__Caddisfly + Bluegill_EATS__POC + Bluegill_EATS_Mayfly)) :(0.00, 0.00165), (0.1, 0.00245), (0.2, 0.00335), (0.3, 0.004), (0.4, 0.00455), (0.5, 0.00495), (0.6, 0.0054), (0.7, 0.00615), (0.8, 0.00665), (0.9, 0.007), (1, 0.00795)

Bluegill_EATS_Mayfly = 0.068*365*0.1*MAYFLY_BIOMASS

Bluegill_EATS__Caddisfly = 0.068*365*0.1*CADDISFLY_BIOMASS

Bluegill_EATS__Periphyton = 0.068*365*.32*Periphyton_BIOMASS

Bluegill_EATS__POC = 0.068*365*.48*POC_FM_Creek

BLUEGILL OUTFLOWS:

Bluegill_DEFECATION = Bluegill_CONSUMPTION * Bluegill_defec_rate

Bluegill_RESPIRATION = Bluegill_Resp_Rate * BLUEGILL_BIOMASS

Bluegill_MORTALITY = BLUEGILL_BIOMASS * Bluegill_Mort_rate

Bluegill_EXCRETION = Bluegill_RESPIRATION * Bluegill_excret_rate

Bluegill_PREDATION = (Bass_EATS_Bluegill + Catfish_EATS__Bluegill_2) * BLUEGILL_BIOMASS

Catfish_EATS__Bluegill = 0.0262*365*0.2*CATFFISH_BIOMASS

Bass_EATS_Bluegill = 0.044*365*0.5*BASS_BIOMASS

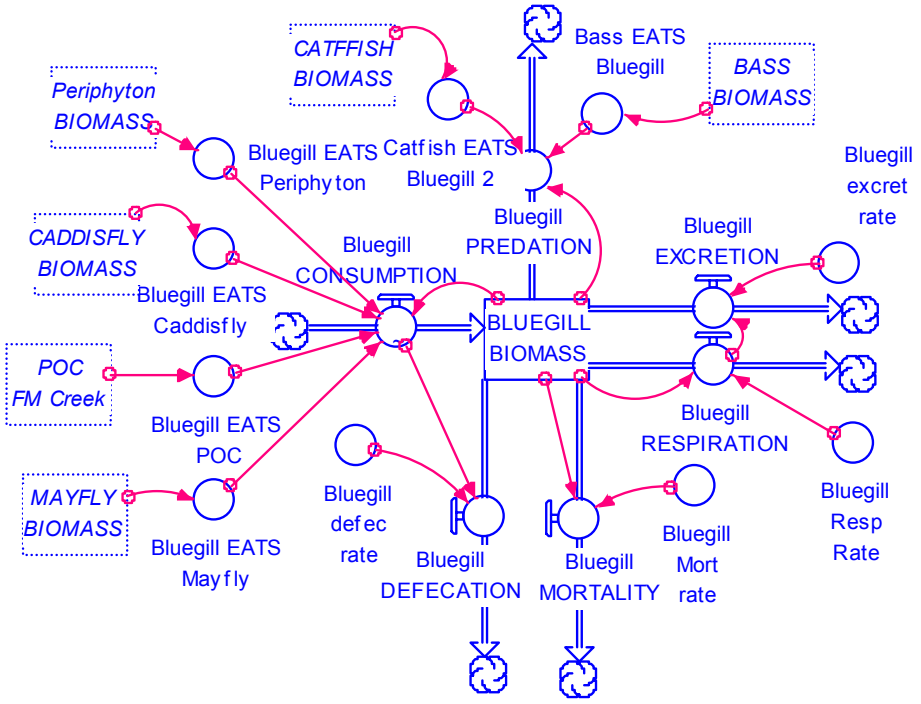

Figure 12. Graphical depiction of the bluegill state variable within the carbon model. Dotted boxes represent connections to other state variables.

6.11 CATFISH

Catfish were modeled to be a bit higher up the trophic chain. Twenty percent of their diet included the consumption of aquatic invertebrates and another 20% included the consumption of bluegill fish (**Figure 3**). The model equations and graphical depiction of the catfish submodel follow (**Figure 13**).

Catfish Model Equations:

CATFFISH_BIOMASS(t) = CATFFISH_BIOMASS(t - dt) + (Catfish_CONSUMPTION - Catfish_RESPIRATION - Catfish_PREDATION - Catfish_MORTALITY - Catfish_EXCRETION - Catfish_DEFECATION) * dt

CATFISH INFLOWS:

Catfish_CONSUMPTION = GRAPH (CATFFISH_BIOMASS * (Catfish_EATS__MacroPhy + Catfish_EATS__Caddisfly + Catfish_EATS__POC + Catfish_EATS_Bluegill)) : (0.00, 7e-005), (0.05, 0.00021), (0.1, 0.000335), (0.15, 0.000465), (0.2, 0.000545), (0.25, 0.000625), (0.3, 0.00071), (0.35, 0.000745), (0.4, 0.00078), (0.45, 0.000825), (0.5, 0.00091)

Catfish_EATS_Bluegill = 0.0262*365*.2*BLUEGILL_BIOMASS

Catfish_EATS__Caddisfly = 0.0262*365*0.2*CADDISFLY_BIOMASS

Catfish_EATS__MacroPhy = 0.0262*365*MacroPhy_BIOMASS*0.2

Catfish_EATS__POC = 0.0262*365*0.4*POC_FM_Creek

CATFISH OUTFLOWS:

Catfish_RESPIRATION = Catfish_Resp_Rate * CATFFISH_BIOMASS
Catfish_PREDATION = Bass_EATS_Catfish * CATFFISH_BIOMASS
Catfish_MORTALITY = CATFFISH_BIOMASS * Catfish_Mort_rate
Catfish_EXCRETION = Catfish_RESPIRATION * Catfish_excret_rate
Catfish_DEFECATION = Catfish_CONSUMPTION * Catfish_defec_rate
Bass_EATS_Catfish = GRAPH(0.044*365*0.1*BASS_BIOMASS)
(0.00, 0.074), (0.1, 0.073), (0.2, 0.0705), (0.3, 0.0675), (0.4, 0.067), (0.5, 0.065), (0.6, 0.0625), (0.7, 0.0595), (0.8, 0.0515), (0.9, 0.039), (1, 0.0295)

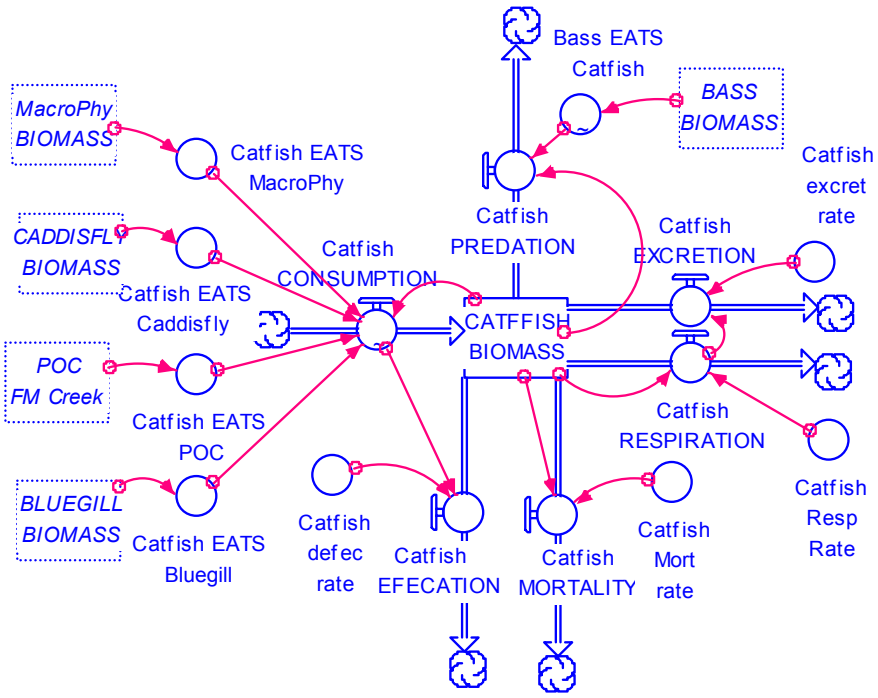

Figure 13. Graphical depiction of the catfish state variable within the carbon model. Dotted boxes represent connections to other state variables.

6.12 BASS

Large mouth bass represented the top predator in the system as modeled. Their diet was composed entirely of other animals (40% stoneflys, 10% catfish and 50% bluegills; **Figure 3**). Bass are the key species in this modeling scenario from a human risk perspective in that bass are the species most actively sought by fishermen. It is ^{14}C contamination of bass that we ultimately want to predict. The equations and graphical depiction of the submodel follow (**Figure 14**).

Bass Model Equations

BASS_BIOMASS(t) = BASS_BIOMASS(t - dt) + (bass_CONSUMPTION - bass_DEFECATION - bass_RESPIRATION - bass_MORTALITY - bass_EXCRETION) * dt

BASS INFLOWS:

bass_CONSUMPTION = GRAPH ((bass_EATS__bluegill + bass_EATS__catfish + bass_EATS__Stonefly) * BASS_BIOMASS) : (0.00, 0.000175), (0.1, 0.000285), (0.2, 0.000345), (0.3, 0.00037), (0.4, 0.000385), (0.5, 0.00043), (0.6, 0.00046), (0.7, 0.000495), (0.8, 0.000535), (0.9, 0.000585), (1, 0.00069)

bass_EATS__bluegill = 0.044*365*.5*BLUEGILL_BIOMASS

bass_EATS__catfish = 0.044*365*.1*CATFFISH_BIOMASS

bass_EATS__Stonefly = 0.044*365*0.4*STONEFLY_BIOMASS

BASS OUTFLOWS:

bass_DEFECATION = bass_CONSUMPTION * bass_defec_rate

bass_RESPIRATION = bass_Resp_Rate * BASS_BIOMASS

bass_MORTALITY = BASS_BIOMASS * bass_Mort_rate

bass_EXCRETION = bass_RESPIRATION * bass_excret_rate

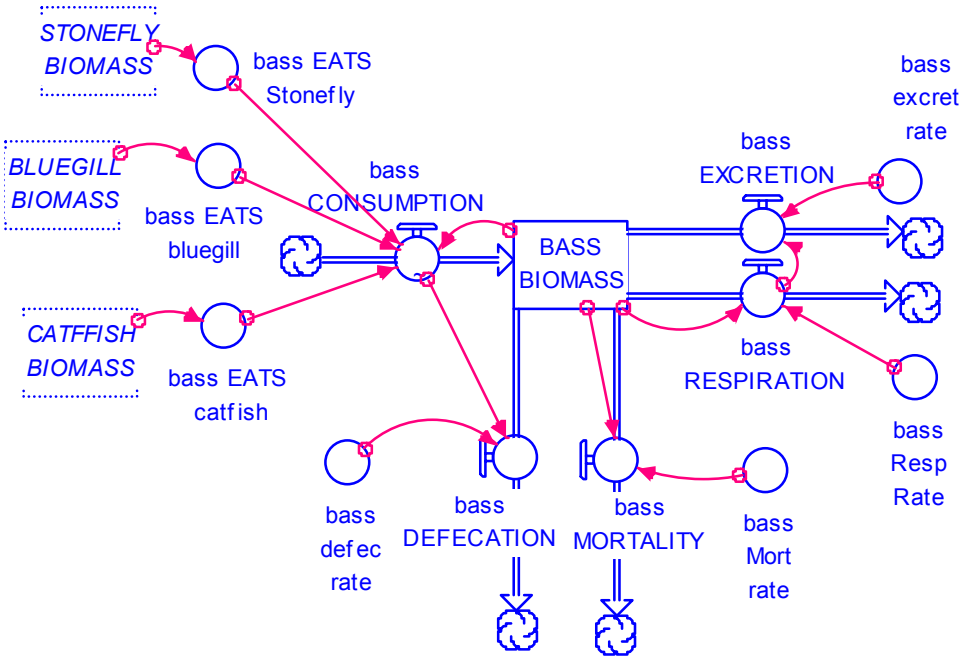

Figure 14. Graphical depiction of the bass state variable within the carbon model. Dotted boxes represent connections to other state variables.

A depiction of the entire model, including POC, DOC, DIC, primary producers, aquatic invertebrates, and fish is presented in **Figure 15**.

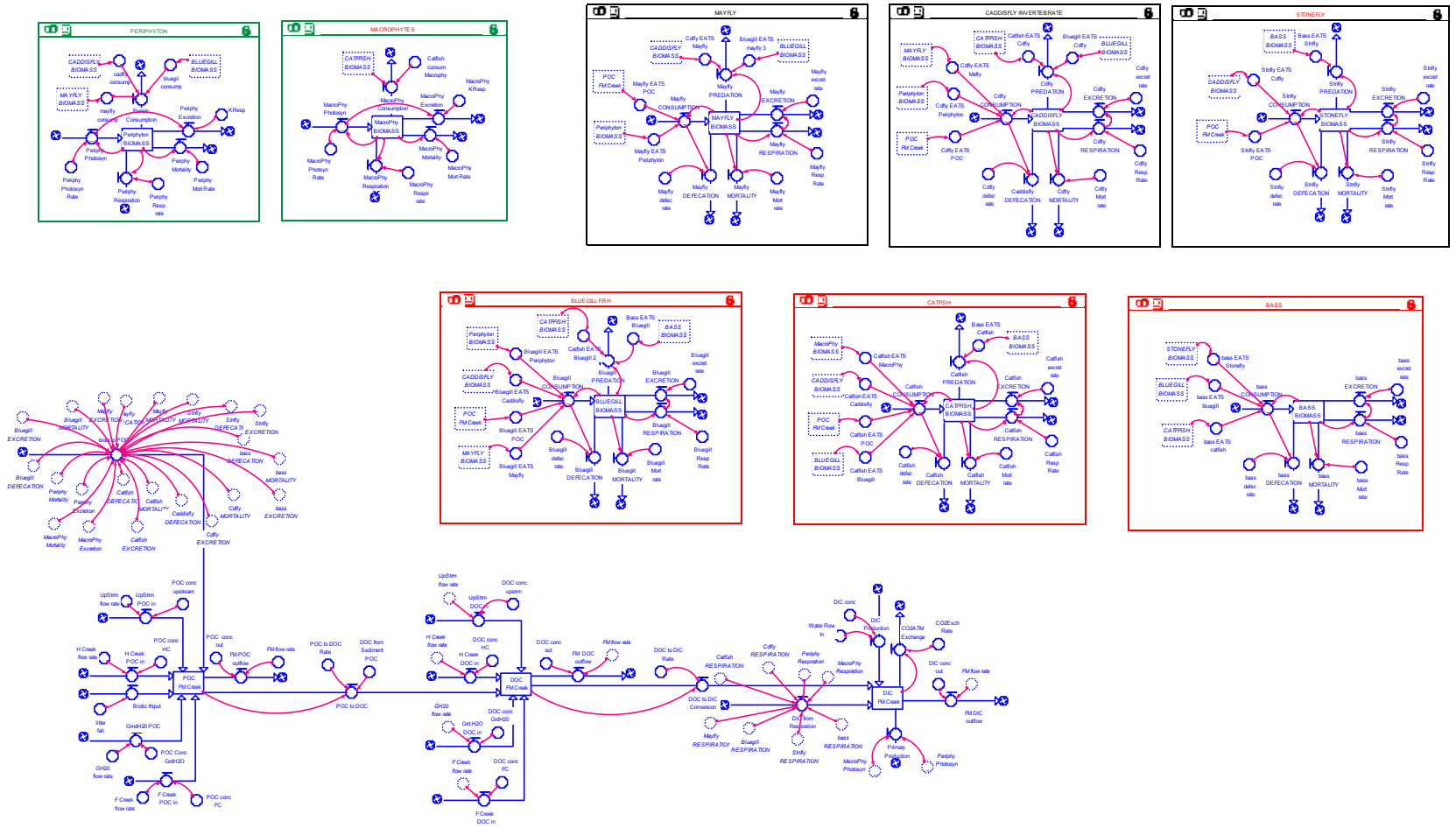

Figure 15. A graphical depiction of the entire model, showing the various components. The unboxed section in the lower portion of the figure is the part of the model that simulates POC, DOC and DIC dynamics. The primary producers (periphyton and macrophytes) are simulated in the two boxes, top row, left hand side. Three aquatic invertebrates are simulated by model flows as depicted in the three boxes on the top row, right side. Three fish species are represented by the boxed diagrams in the second row of the figure. All compartments are coupled and each component is described in detail within the text.

7.0 STABLE CARBON MODEL RESULTS

The model (**Figure 15**) simulated stable carbon concentrations in 4MB (kg C / 1.5 km stream reach) to be within a factor of three of the concentrations estimated from field measurements (**Table 18**). The largest variance was in the prediction of periphyton biomass, resulting in a predicted to observed ratio of 0.32. The upper trophic levels were predicted more similarly to the actual field measurements of carbon within the creek systems (**Table 18**). Likewise, the model was reasonably stable when predictions were simulated over long periods of time (300 years). Model predictions of periphyton biomass were the least stable and erratically fluctuated by one order of magnitude over time (**Figure 16).** Simulations of the other primary producer (macrophytes) quickly reached stable equilibrium (**Figure 17**). The variation in periphyton did not overly influence the organisms consuming periphyton. Biomass simulations of Mayflies, the aquatic invertebrate whose diet was simulated to be composed of a relative high proportion of periphyton (**Figure 18**), reached and maintained equilibrium conditions. Simulations of the other two aquatic invertebrates (Caddisfly and Stonefly) were also stable and reached equilibrium quickly. The diets of the later two invertebrates were more varied and less dependent on periphyton (**Figure 3**). **Figure 19** shows that predictions of stable carbon in the simulated fish species, including the top predator and primary organism of interest in this project (Bass) quickly reached equilibrium condition. The stable carbon model results were sufficiently precise that we proceeded to the next step and simulated ^{14}C contamination within the system.

Table 18. Stable carbon model performance. A comparison of calculated annual inventory of carbon (kg C / 1.5 km reach of stream) in primary ecosystem components (based on field data; Table 15) to that of model simulations.

Parameter	Calculated	Modeled	Predicted / Observed
DIC	287,028	272,174	0.95
DOC	49,837	43,260	0.87
POC	16,488	12,360	0.75
Periphyton Biomass	51.0	16.4	0.32
Macrophyte Biomass	0.02	0.02	1.00
Invertebrate Biomass	54.3	47.1	0.87
Fish Biomass	2.1	1.5	0.71

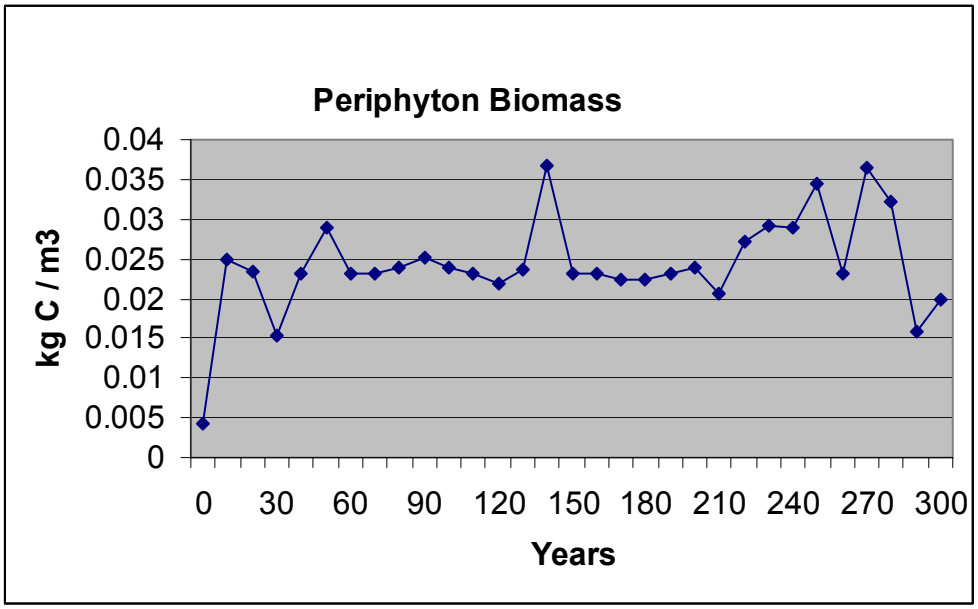

Figure 16. Model predictions of stable carbon (kg C) as represented by periphyton biomass simulated for the 1.5 km reach of Four Mile Branch. Data show the instability of the model simulations under steady state conditions.

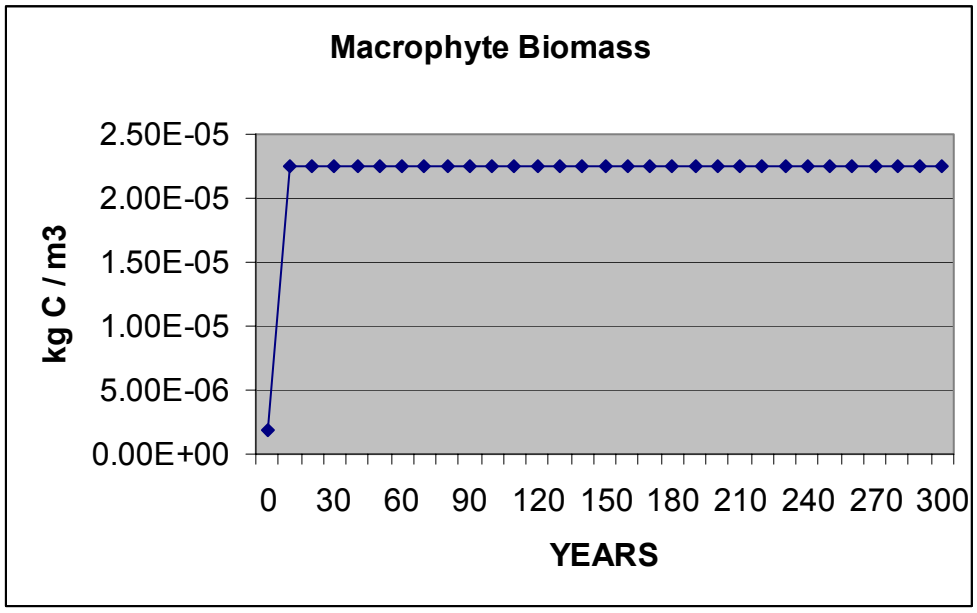

Figure 17. Model predictions of stable carbon (kg C) of the macrophyte population simulated for the 1.5 km reach of Four Mile Branch. Data show the stability of the model simulations under steady state conditions.

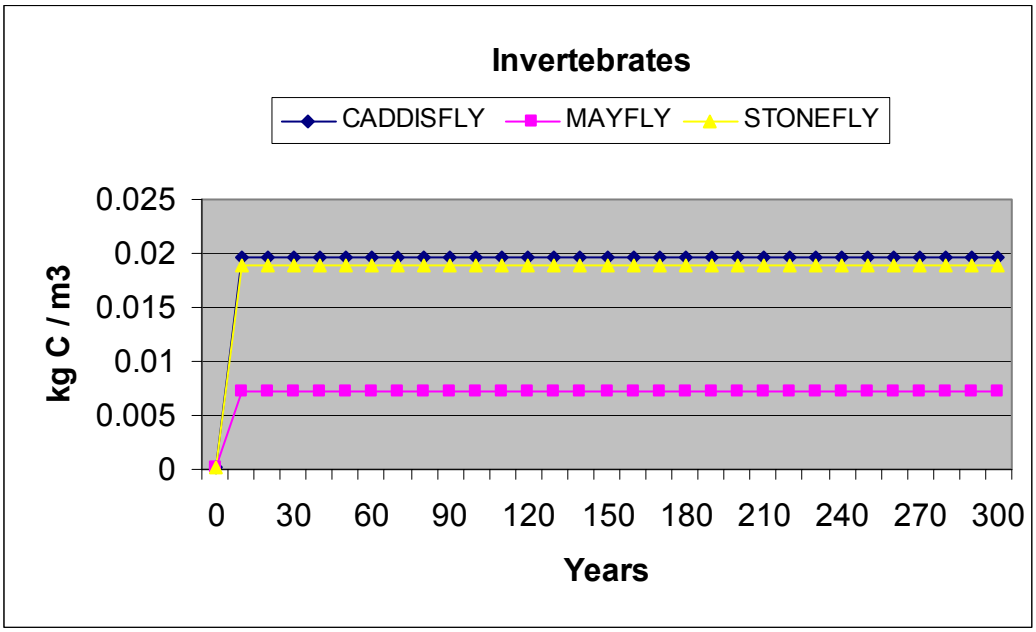

Figure 18. Model predictions of stable carbon (kg C) in aquatic invertebrates simulated for the 1.5 km reach of Four Mile Branch. Data show the instability of the model simulations for Mayfly invertebrates as opposed to the stability of the predictions.

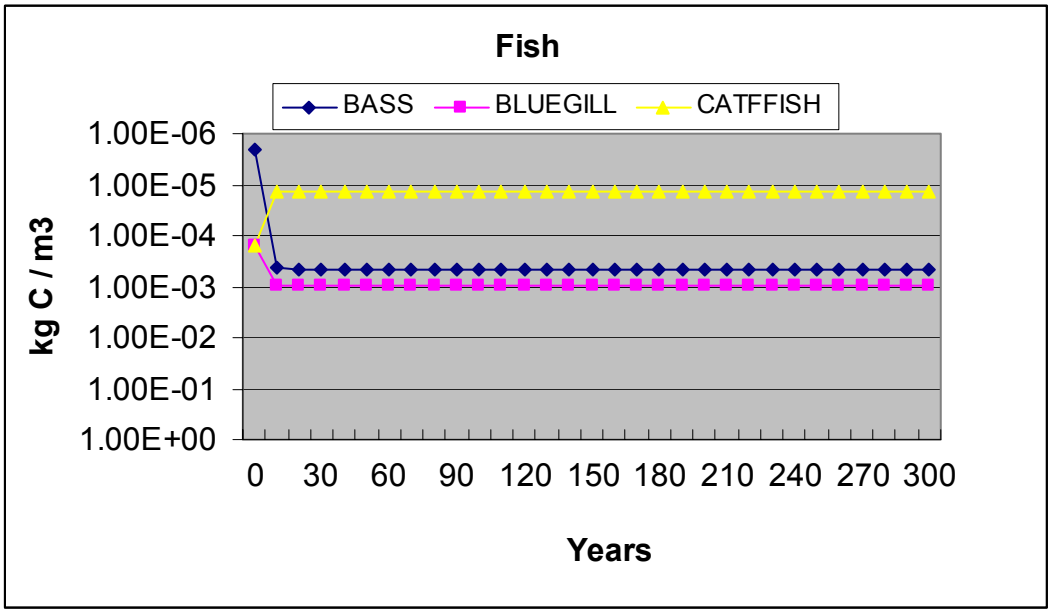

Figure 19. Model predictions of stable carbon (kg C) within fish populations simulated for the 1.5 km reach of Four Mile Branch. Data show the stability of the model simulations under steady state conditions.

8.0 ^{14}C MODEL

An overall objective of this project was to estimate the influence of stable carbon on the dynamics of ^{14}C groundwater contamination; more specifically, to determine if the bioconcentration factor (BCF = Bq kg^{-1} fresh weight fish / Bq L^{-1} water) of 4500 would be altered by accounting for stable carbon within the aquatic system. A dynamic systems model of stable carbon was used to simulate the stable carbon content of environmental components within the stream reach of interest (Section 6.0). In Section 7.0, the same systems model was used to simulate ^{14}C dynamics. The same parameters and assumptions used in the stable carbon model are used to model ^{14}C activity dynamics. A ratio of the simulated ^{14}C concentrations in bass to that of the ^{14}C concentrations in water (having accounted for stable carbon) will permit comparison of the modeled BCF to the 4500 L kg^{-1} value currently in use by risk models on the SRS. ^{14}C was assumed to enter 4MB through contaminated groundwater inflow as inorganic carbon ($^{14}CO_2^0$, $H^{14}CO_3^-$, or $^{14}CO_3^{2-}$). The contaminant was assumed to be bioavailable and to chemically and physically distribute within the ecosystem like stable carbon. A scenario of ^{14}C activity concentration in the groundwater of 1 kBk L^{-1} (27,000 pCi L^{-1}) was assumed. This is a hypothetical concentration that is 100 times greater than any concentration measured in groundwater at the study site (Carlton et al. 1993). For reference, the Drinking Water Limit is 74 Bq L^{-1}. Although ^{14}C is known to be entering 4MB from a groundwater source (Carlton et al. 1993), no stream or groundwater concentrations were measured for this report. Nonetheless, an assumed contaminant concentration was used to test whether stable carbon influences the derived ratio of fish to water ^{14}C activity concentrations.

Annual groundwater influx to 4MB was 2.2 x 10^9 L (Eq. 2). At an assumed concentration of 1 kBq L^{-1}, annual ^{14}C input into 4MB was 2.2 x 10^{12} Bq (59.5 Ci). When diluted by the other water sources coming into 4MB (1.14 x 10^{10} L; **Table 3**) the concentration of ^{14}C in the stream water was modeled at 19,300 Bq m^{-3}. This ^{14}C, however, was assumed to be partitioned to dissolved inorganic carbon within the stream water. The latter has been determined (section 4.6) to be at a concentration of 24.8 g DIC m^{-3} water. Thus, the activity concentration of the ^{14}C contaminant when partitioned to its primary and most logical component within the stream was modeled to be:

$$\frac{19{,}300\,\frac{Bq}{m^3}}{24.8\,\frac{g\,C}{m^3}} = 778\,\frac{Bq\ ^{14}C}{g\,C\ as\ DIC} \qquad (Eq.20)$$

The number in equation 20 is critical to subsequent modeling of ^{14}C within 4MB. It, in essence, accounts for the initial partitioning of ^{14}C, as well as for the large portion of DIC within 4MB.

The concentration of ^{14}C in primary producers was modeled as being equal to that derived in the DIC component of the water. This assumption simplified the ^{14}C component of the modeling exercise and allowed modeling to focus on the food-web dynamics and concentrations in bass. The assumption that ^{14}C concentrations in plants are in isotopic equilibrium with the water is commonly made (Kumblad et al. 2003; Cliffroy, et al. 2005; Sheppard et al. 2006); and is

particularly valid for periphyton, algae or phytoplankton because their tissues are in complete contact with the water and they exhibit a rapid turnover of tissues. Having established the activity concentration of ^{14}C in primary producers, the transfer of ^{14}C further up the food chain was modeled similarly to that of stable carbon.

Thus, the ^{14}C model started with an activity concentration of 778 Bq g^{-1} C in plant tissues and used the food web dynamics portion of the stable carbon model presented in section 5.0 to determine the ^{14}C activity concentration in bass. The simulation resulted in an estimate of 5.3 x 10^{-4} Bq g^{-1} C bass tissue per m^{-3} water. Converting this value into a ^{14}C activity per kg fresh weight bass tissue was done as follows:

$$\frac{5.3e-4\,Bq}{g\,C\,fish-m^3}\ x\ \frac{0.492\,g\,C}{g\,dry\,wt.}\ x\ \frac{0.2\,g\,dry\,wt.}{g\,fresh\,wt.}\ x\ \frac{1000\,g}{kg}\ x\ 1030\,m^3 = 53.5\frac{Bq}{kg\,fresh\,wt.bass} \qquad (Eq.21)$$

The value in equation 21 was then used to develop a concentration ratio. Concentration ratios for ^{14}C are based on the activity in the water, not the activity in the DIC component. The ^{14}C activity concentration in water (Eq. 20) is 19.3 Bq L^{-1}. Thus the following bioconcentration factor was obtained:

$$\frac{53.5\dfrac{Bq}{kg\,f.w.bass}}{19.3\dfrac{Bq}{L}} = 2.8\,\frac{L}{kg} \qquad (Eq.22)$$

Thus, accounting for the stable carbon within 4MB reduced the bioconcentration factor of ^{14}C in the top predatory fish from 4500 L kg^{-1} (NCRP, 1985) to 3 L kg^{-1}. This drastic reduction was due to the abundant DIC within the 4MB system. The reduction in BCF is directly transferable to a similar reduction in risk calculations to humans that might consume ^{14}C-contaminated bass.

To account for the numerous ecosystem variables that can influence fish uptake of ^{14}C, including the very important process of ^{14}C isotopic dilution by $^{stable}C$, it is recommended that a ^{14}C BCF of 3 L kg^{-1} be used instead of the literature value of 4500 L kg^{-1}. The BCF of 3 L kg^{-1} should be replaced with a measured value once such a value is available.

9.0 MODEL VALIDATON

"All models are wrong; some, however, are useful": Dr. Ward Whicker, Colorado State University.

Considerable effort and expense were expended to ascertain the validity of the carbon calculations made in this report. An extensive field sampling program of 4MB was conducted in the fall of 2008. Fish samples were collected of several fish species and processed for ^{14}C analyses. Invertebrates and water samples were also collected. Fish samples were given to the radiochemistry laboratory at the SRNL. All fish samples results were returned as being below the detection limits (<0.052 Bq g^{-1} or 1.4 pCi g^{-1} fish; **Table 19**). Following the fish analyses and due to the smaller mass of samples, no attempt was made to analyze the invertebrate or water samples for ^{14}C. In addition to the fish samples collected during the fall of 2008, Dr. Dean Fletcher (Savannah River Ecology Laboratory) had many archived fish samples that he had collected from 4MB during the mid-1990s. The 2008 sampling program was conducted in the same general stream locations as Dr. Fletcher's some 15 years earlier. Combined, these two data sets would have provided extremely valuable insight into the precision of the ^{14}C model. Equally important, the two data sets would have been useful in discerning how ^{14}C concentrations in fish might be changing over time. Future work recommendations include trying to detect ^{14}C in the fish samples and 4MB water, using a more sensitive method, low-level liquid scintillation counting.

Lacking the attempted field validation of the model, a rigorous independent assessment of the model, calculations and interpretations of results is required. Until such an assessment is made, the reduced CR should be viewed as a preliminary finding. Despite the need for model validation, the findings of this study have provided a model framework from which hypotheses can be formulated about mechanisms and processes controlling ^{14}C dynamics in streams of the SRS. As such it is a useful tool.

Table 19. Carbon-14 analytical results from fish sampled in Four Mile Branch. All samples were reported as being below the lower limit of detection. Samples were assayed for ^{14}C by the Savannah River National Laboratory's radiochemistry lab. Field collection and sample preparation was performed by the University of Georgia's Savannah River Ecology Laboratory. Data reported as dpm g^{-1}. All samples preceded by a "4" are recent and collected in the fall of 2008.

User SampleID	Result	Result (dpm g^{-1})	1 SIGMA % Unertainty
F_BDR+200/ #28 MUSCLE	<	4.37E+00	mda
F_RD3+100/ #1 MUSCLE	<	4.15E+00	mda
F_RD3+600/ #23 MUSCLE	<	6.10E+00	mda
F_BRD+100/ #9 MUSCLE	<	6.26E+00	mda
F_BKD+100/ #20A MUSCLE	<	3.99E+00	mda
F_BKD+200/ #24 MUSCLE	<	8.57E+00	mda
F_RD3+100/ #4 MUSCLE	<	7.60E+00	mda
F_RD3+600/ #20 MUSCLE	<	4.86E+00	mda
F_RD3+300/ #14 MUSCLE	<	1.09E+01	mda
F_BKD+200/ #27 MUSCLE	<	8.08E+00	mda
F_BDR+200/ #28 BONE	<	4.48E+00	mda
F_RD3+600/ #23 BONE	<	5.08E+00	mda
F_BRD+100/ #9 BONE	<	5.33E+00	mda
F_BKD+100/ #20A BONE	<	6.84E+00	mda
F_BKD+200/ #24 BONE	<	4.79E+00	mda
F_RD3+100/ #4 BONE	<	5.57E+00	mda
F_RD3+600/ #20 BONE	<	7.57E+00	mda
F_RD3+300/ #14 BONE	<	1.34E+01	mda
F_BDK+200/ #27 BONE	<	7.74E+00	mda
4RB_A	<	7.63E+00	mda
4RB_B	<	5.95E+00	mda
4RB_C	<	1.11E+01	mda
4RB_D	<	1.76E+01	mda
4RFP_C	<	5.73E+00	mda
4BH_A	<	4.05E+00	mda
4LMB_A	<	3.17E+00	mda
4LMB_A1	<	3.13E+00	mda
4LMB_A2	<	3.07E+00	mda
4LMB_A	<	4.02E+00	mda
4LMB_A1	<	5.05E+00	mda
4LMB_A2	<	4.01E+00	mda
4CP_A	<	5.86E+00	mda
4RFP_B	<	4.52E+00	mda

10.0 FISH SPECIES MOST PROBABLY CAUGHT BY ANGLERS

In addition to modeling ^{14}C, this project included identifying the fish species most probably caught by anglers using 4MB. We selected species based on their distribution and abundance in 4MB and their potential to be caught by anglers. These species vary greatly in size, value to fishermen, biology, and migratory behavior. Six species within two families are of primary concern. Two genera including four species fall within the family Centrarchidae, the sunfishes and basses. These are generally diurnal visual predators. Three species of the genus *Lepomis,* commonly referred to as bream, are common in 4MB and large enough to be potentially a risk to fishermen. The *Lepomis* are typically invertivores, but fish can sometimes make up a significant part of the diet of a few species. The spotted sunfish is abundant in Foumile Branch, but is a relatively small species in which only the largest individuals are likely to be kept by a fishermen. Both redbreast sunfish and warmouth are larger, thus more prized by anglers. The redbreast is both common and abundant in 4MB. The warmouth is common, but rarely present in large numbers. The most prized game fish will be the largemouth bass (*Micropterus salmoides*). It is a highly piscivorous upper level predator in stream communities. It can be common in the lower reaches of 4MB, but will be more rare in the headwaters. Several other species such as bluegill (*Lepomis macrochirus*), redear (*Lepomis microlophus*) and pumpkinseed (*Lepomis gibbous*) can be found in 4MB, but not in large enough numbers to be of serious concern. Dollar Sunfish (*Lepomis marginatus*) are both common and abundant, but are too small to be a direct risk to humans.

The family Ictaluridae consists of the catfishes, bullheads and madtoms. In contrast to the centrarchids, ictalurids are nocturnal in habit, vision is generally poor, and feeding relies more on smell and taste. They also frequently have a greater affinity to the stream or lake bottom than centrarchids. Ictalurids are easily recognized by their lack of scales and presence of eight barbells on their heads. Protection is provided by sharp, stout spines at the front of their dorsal and pectoral fins. Toxins released from glands at the base of the fin can cause painful puncture wounds. Primarily two ictalurids, were considered to be of concern in 4MB. Both the yellow and flat bullheads are common in 4MB and would be commonly sought by anglers. Both species are reported as omnivous, but feed primarily on animal material. The biology of these species is not as well known as the centrarchids. Channel catfish may also be found in 4MB, but their distribution will be largely restricted to the lowest reaches. Snail bullheads are found in 4MB especially around rock rip rap in swift water, but again their distribution will be limited. Madtoms are common, but all species are too small to be of concern.

10.1 REDBREAST SUNFISH; *LEPOMIS AURITUS*

Description— The redbreast sunfish has a laterally compressed and deep, but rather elongate body. Their terminal mouth is moderate in size. Males and females are distinctly sexually dimorphic in color and morphology. Redbreast sunfish will grow over 200 mm SL in the area, but are more commonly less than 160 mm SL in SRS tributary streams. Most nest guarding male redbreast sunfish sampled in 4MB were three to five years old, but ranged from two to seven years.

Habitat— The redbreast sunfish is one of the more abundant and widespread *Lepomis* species on the SRS because it is common in both lotic and lentic systems. It inhabits many larger ponds and reservoirs on site. Though most abundant in intermediate size streams, redbreast sunfish occur in nearly all SRS streams including 4MB where it ranges from the headwaters above Road 4 to down to the stream's confluence with the Savannah River. Their habitat in streams is generally slower, deeper pools often associated with woody debris, stumps or undercut banks (Aho 1986b; Meffe and Sheldon 1988). Beaver ponds can provide important spawning and nursery habitat (Snodgrass and Meffe 1999). This is likely the case in the headwaters of 4MB.

Biology— In SRS streams, spawning generally occurs from late May through the end of July. However, spawning season is temperature dependent so may vary both annually and spatially within a year. For example cold water effluent releases from L Lake delayed spawning to as late as July in Steel Creek (DEF pers. observ.). Spawning occurs from 20 to 31 C. Redbreast sunfish spawning behavior is typical of the genus *Lepomis*. Male redbreast sunfish sweep large saucer nests in the substrate with their tail (Lukas and Orth 1993; Breder and Rosen 1966). Females are courted to the nest and following spawning only the male guards the developing offspring until the fry swim up and leave the nest. Based on genetic studies conducted in 4MB, multiple females spawn in each nest, and low rates of cuckoldry occurred by intruding males (DeWoody et al. 1998). Redbreast sunfish in streams spawn in whatever slower water is available. This may be along the bank behind a stump or log or in beaver ponds, backwaters, or larger coves. Nests may be solitary, in loose aggregations, or large dense colonies of over 80 nests (Fletcher 1993). The number of ova in females was size dependent and ranged from 940 to almost 10,000 (Davis 1971; Bass and Hitt 1974). Dusky shiners (*Notropis cummingsae*), an abundant fish in some SRS streams including 4MB, spawn on redbreast sunfish nests (Fletcher 1993). Thus redbreast sunfish influences abundance of a common forage species in some habitats.

Redbreast sunfish are diurnal invertivores that feed on a variety of aquatic and terrestrial insects, microcrustaceans, and crustaceans (Wiltz 1993; Sheldon and Meffe 1993). Diets of juveniles in SRS streams fed primarily on microcrustaceans and aquatic insects, particularly chironomids, and microcrustaceans (Sheldon and Meffe 1993). Nest-guarding males may forage less while guarding a nest (Thorp et al. 1989), but males commonly cannibalize offspring from their nest (DeWoody et al. 2001).

Migratory patterns of redbreast sunfish were studied in two Tennessee streams (Gatz and Adams 1994). The redbreast sunfish was relatively sedentary with small home ranges although a few individuals within a population moved long distances. They were most sedentary in the winter, with greatest mobility in the spring before spawning season (Hudson and Hester 1975; Gatz and Adams 1994). Larger redbreast sunfish moved further distances. No general tendency for upstream versus downstream movement was observed, but site-specific directional patterns were noted for some seasons. Gatz and Adams (1994) ranked redbreast sunfish to be more sedentary than warmouth or largemouth bass. However, redbreast sunfish and warmouth were more similar.

10.2 SPOTTED SUNFISH; *LEPOMIS PUNCTATU*S

Description— The spotted sunfish has a deep and laterally compressed but moderately stocky body and a small terminal mouth. Sexes are dimorphic in morphology and color, but not as

brightly colored as the redbreast sunfish. Spotted sunfish are generally less than 120 mm SL in SRS tributaries, but a few reach between 120 and 160 mm SL.

Spotted sunfish are one of the more wide spread *Lepomis* species among SRS tributaries, but is more common in small or intermediate streams. It is often found among woody debris, stumps, or undercut banks. Beaver ponds may be important spawning and nursery grounds in swift flowing streams (Snodgrass and Meffe 1999).

Biology— In SRS tributary streams, spawning typically occurs from late May through the end of July at water temperatures around 24-27 C. Larger, sexually dimorphic males sweep small nests, generally 15-30 cm in diameter, in shallow water near or against the bank (Carr 1946; DEF Pers. obs.). Nests in tributary streams on the SRS are generally solitary (DeWoody et al. 2000a), but aggregations of 2-3 nests were reported in a Florida stream (Carr 1946). Nest guarding males court females into the nest. Genetic evidence confirmed the spawning of multiple females in a nest (DeWoody et al. 2000a). Males remain on the nest after spawning, defending it from predators and fanning the offspring keeping them free of silt. The small dark brownish olive, adhesive eggs are frequently attached to fine roots. Filial cannibalism by nest guarding males was genetically confirmed (DeWoody et al. 2001).

In 4MB, a second morphological type of reproductively mature male was identified. In addition to the larger nest guarding males, a smaller in size morph displays no secondary sexual characteristics, has greatly enlarged testes, and apparently sneaks onto nests guarded by larger males to acquire spawnings (DeWoody et al. 2000a). These reproductively parasitic morphs were very rare in 4MB and genetic analyses indicated that nest guarding males sired most of the offspring in their nest (DeWoody et al. 2000a).

Spotted sunfish are also invertivores. In SRS tributaries large spotted (over 75 mm SL) fed on terrestrial insects, with lesser amounts of aquatic insects, snails, and decapods. Smaller individuals ate more chironomids, with other aquatic and terrestrial insects and a few water mites and, crustaceans (Sheldon and Meffe 1993). Similarly in the Savannah River, they fed primarily on aquatic and terrestrial insects, microcrustaceans, and decapods but also ate snails, clams and occasionally fish (Wiltz 1993).

10.3 WARMOUTH; *LEPOMIS GULOSUS*

Description— The warmouth has a compressed, but stocky and relatively elongate body with a relatively large terminal mouth. Sexual dimorphism is not as pronounced in warmouth as in many *Lepomis***.** Warmouth are generally under 180 mm SL in SRS tributary streams.

Habitat— Warmouth are widely distributed in SRS streams and lentic waters. It is common in backwaters of the Savannah River and in larger tributaries. Warmouth are common in 4MB, but not extremely abundant. Warmouth generally inhabit still or sluggish waters. It is common in ponds, reservoirs, backwaters, or Carolina bays, but is also commonly collected in slower reaches of streams and rivers. It is often found in shallows along shorelines around aquatic vegetation or other submerged structure. On the SRS, warmouth are particularly abundant hidden among boulder riprap used to stabilize the shorelines along dams or the banks of streams and the Savannah River.

Biology —Warmouth has been reported to be a late spring/summer spawner throughout most of its range (Larimore 1957; Pflieger 1975; Robison and Buchanan 1988; Etnier and Starnes 1993).

Spawning began at water temperatures around 21 C in Illinois (Larimore 1957). In SRS tributaries spawning likely occurs from May through July.

Males sweep depression nests in shallow water usually near submerged structure such as stumps, wood debris, rock rip rap (Larimore 1957). In Fire Pond on the SRS, warmouth nests are frequently hidden among submergent vegetation (DEF, pers. obs.). Nests may also be in cavities such as those created by the buttressing roots of cypress trees (Fletcher and Burr 1992).Nests are generally solitary. Males court females to the nest and females may spawn in the nests of more than one male (Larimore 1957). Males continue to guard the nest until the offspring leave the nest. Warmouth sexually matured in one or two years in Illinois and lived up to eight years (Larimore 1957). Ovaries of mature females that ranged from 96 to 222 mm TL contained an estimated 798 to 34,257 in Lake Robinson of northern South Carolina. (Panek and Cofield 1978).

In a local study warmouth 65 - 215 mm TL fed on aquatic insects, microcrustaeans, decapods, gastropods, and, in only a few individuals, fish (Wiltz 1993). Fish may become a more important part of the diet in larger warmouth above 125 mm TL when 6-20 % of the diet may consist of fish (Mittelbach and Persson 1998). In a lake study, the warmouth's diet overlapped with the largemouth bass, but feeding habitat differed with the warmouth feeding in shallower water, closer to the bank (Larimore 1957). Warmouth are generally solitary outside of spawning season, but may aggregate in desirable cover (Larimore 1957). This may make them less susceptible to fishing than schooling *Lepomis* species.

In two Tennessee streams warmouth were relatively sedentary with small home ranges (Gatz and Adams 1994). They were however ranked intermediate between redbreast sunfish and largemouth bass in tendency to move. No general tendency for an upstream or downstream direction was noted. Warmouth were classified as a motile species in a North Carolina stream, with home ranges of more than 200 m (Whitehurst 1981).

10.4 LARGEMOUTH BASS; *MICROPTERUS SALMOIDES*

Description— Largemouth bass as typical for *Micropterus* have a laterally compressed, but a more elongate body than typical of other sunfish species commonly collected in 4MB. The body shape and coloration lend it to be suited to more open water habitats. Its larger size and large mouth allows it to be one of the top predators within fish communities. Also in contrast to most *Lepomis* species that often develop distinctive sexually dimorphic characters, *Micropterus* species are largely monomorphic. Largemouth bass can grow quite large, reaching 690 mm TL in the Savannah River, but most bass in 4MB above the Savannah River Swamp are smaller, generally less than 350 mm SL. In Steel Creek below L Lake during the drought conditions of 1999-2003, bass also rarely exceeded 350 mm SL.

Habitat— On the SRS, largemouth bass are most abundant in larger reservoirs, ponds or backwaters of the Savannah River. It can also be common in tributary streams, particularly the lower reaches near the Savannah River. Such is the case with 4MB where it is relatively common downstream, but progressively becomes rarer in the headwaters. However, it can be common further upstream in tributaries with large reservoirs in their headwaters such as Steel Creek. It frequents large pools around structure such as stumps or wood debris in tributary streams.

Biology— Largemouth bass spawned in March and April at 19-23 C in Steel Creek and L Lake (DEF, unpubl. data). Spawning is temperature dependent occurring at this same period in Par Pond at ambient temperatures, but earlier in heated areas of the reservoir (Bennett and Gibbons 1975). Largemouth bass spawning behavior was described in detail in Steel Creek and L Lake (De Woody et al. 2000b). Bass sweep weakly formed, irregularly shaped nests in shallow water, usually no more than 1 m deep. These contrast to the well-swept circular saucers of most *Lepomis*. Sometimes nests are swept at the base of submerged objects such as stumps, logs, boulders, or aquatic plants such as cattails. In the latter case, the fine roots are swept clean and the adhesive eggs attached to the roots. However the tops of these objects may also be swept clean and spawned upon. Nests were generally large, about 70 cm in diameter, but the tops of small diameter stumps were used. After spawning, both parents remain with the nest and protect the developing offspring from predators (Smith 1907; Hankinson 1908; DeWoody et al. 2000b). Parental care continues after the fry leave the nest. Genetic analyses confirmed that largemouth bass were largely monogamous (DeWoody et al. 2000b). Only a low level of cuckoldry by males or females occurred. Golden shiners (*Notemigonus crysoleucas*) or the taillight shiners (*Notropis maculatus*) are known to spawn on nests of largemouth bass (Chew 1974).

Due to lack of fishing pressure, largemouth bass were 3 to 4 times more abundant, and 10-30% larger in the post-thermal Par Pond than in other southeastern reservoirs (Belk and Hales 1993). Largemouth bass may live to at least 15 years (Bennett 1937; Carlander 1977) with the oldest largemouth bass on record having 23 annuli in its otolith (Green and Heidinger 1994). Males may mature at a smaller size and younger age than females (Pardue and Hester 1967). Females generally mature at 2 or 3 years of age (Carlander 1977).

Young bass feed primarily on invertebrates with prey size gradually increasing as the bass grow, becoming primarily piscivorous by 50-100 mm TL (Chew 1974; Keast 1985; Mittelbach and Persson 1998). Larger bass are highly piscivorous, but will also feed on feed on crayfish, insects, other crustaceans, or amphibians (Pflieger 1975; Wiltz 1993). A variety of fish species may be preyed upon. Largemouth bass in the Savannah River had eaten primarily cyprinids, but 6 other families of fishes were preyed upon (Wiltz 1993). In a Florida lake, stable isotope studies indicated a diet dominated by planktivorous fish (Gu et al. 1996).

The migratory behavior of largemouth bass was studied in Steel Creek and the Savannah River by Paller et al. (2005). Largemouth bass were relatively sedentary in the upper portion of Steel Creek with most movements under 300 m. Fish rarely moved from this upper reach to the Savannah River. Movement between the lower portion of Steel Creek located on the Savannah River floodplain and the Savannah River was common. Longer distances were moved in the Savannah River, but 70% of the movements were less than 200m and 85% less than 1km. Movements over 10 km were noted. It was concluded to be unlikely that largemouth bass dispersed substantial radiological contamination long distances in the Savannah River. Bass were most active during the spring spawning season.

10.5 YELLOW BULLHEAD; *AMEIURUS NATALIS*

Description— The yellow bullhead is a heavy bodied bullhead with a broad head and small eye. Yellow bullhead may reach a size of 465 mm TL (Marcy et al. 2005), but are generally less than 250 mm SL in SRS tributary streams.

Habitat— Yellow bullhead are typically found in slow or still waters of streams, rivers, ponds, swamps, backwaters, and impoundments (Marcy et al. 2005). It is common in small and intermediate sized SRS tributary streams (Paller 1994), where it is usually found in slow-flowing pools (Meffe and Sheldon 1988) often around structure.

Biology— Yellow bullhead has been reported to be a late spring/early summer spawner in much of its range (Marcy et al. 2005). Parents may excavate nest sites that range from shallow depressions a little larger in diameter than the fish's length to burrows (Adams and Hankinson 1932). Cavities may also be used. Their adhesive eggs are sometimes attached to roots left in the nest. Males guard the developing offspring in the nest and parental care extends to the free swimming juveniles after they leave the nest. A female's ovaries may contain 1650 to 7000 eggs, but clutches of 300-700 eggs are spawned at a time (Marcy et al. 2005). Yellow bullheads mature at ages of two or three and a length of 140 mm and may live 7 years (Marcy et al. 2005).

Yellow bullhead are largely nocturnal, hiding among cover by day, but moving into more open water at night. Such activity patterns have been noted in SRS streams. Adults are omnivorous feeding on a wide range of invertebrates, fishes and plant material (Jenkins and Burkhead 1993). In SRS tributaries, yellow bullhead over 100 mm SL prey on crayfish, aquatic and terrestrial insects and fish (Sheldon and Meffe 1993). The diets of individuals less than 100 mm was dominated more by aquatic and terrestrial insects. Yellow bullhead will opportunistically feed on offspring in sunfish nests

Yellow bullhead were considered a relatively motile species in a North Carolina stream (Whitehurst 1981). Seasonal variation was noted with yellow bullhead being most active in late spring and summer and being sedentary in other parts of the year. Fish moved upstream more frequently, but the longest recorded distances were downstream.

10.6 FLAT BULLHEAD; *AMEIURUS PLATYCEPHALUS*

Description— The flat bullhead is less heavy bodied than the yellow bullhead, has a flat, sloping head and relatively large eyes. Flat bullhead will grow to over 250 mm SL in SRS tributary streams, but is most commonly less than 200 mm SL.

Habitat— Habitat of the flat bullhead includes streams, lakes, reservoirs, and ponds, and slow flowing areas in large rivers. On the SRS, the flat bullhead is most common in tributary streams. Within streams, the flat bullhead occurs in faster water than the yellow bullhead (Meffe and Sheldon 1988) but slower flows than the snail bullhead (Marcy et al. 2005). It is often collected from among woody debris or undercut banks.

Biology— The biology of the flat bullhead is poorly known (Marcy et al. 2005). Like other bullheads, it is likely a late spring/early summer spawner on the SRS. In North Carolina spawning occurred in June and July at water temperatures of 21-24 degrees C (Jenkins and Burkhead 1993). Females matured at three years of age. Female's ovaries contained 207-1742 mature ova. Males lived to 5 years and females to 7 years (Marcy et al. 2005). Flat bullheads are an omnivorous species, but feed primarily on aquatic invertebrates and fish (Jenkins and Burkhead 1993). In SRS tributary streams flat bullhead ate primarily snails, crayfish, and aquatic insects (Sheldon and Meffe 1993).

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12.0 APPENDIX A: ABBREVIATIONS AND DEFINITIONS

Abbreviations and Definitions

Taken in large part from: The Institute of Ecology. 1974. *An Ecological Glossary for Engineers and Resource Managers*. TIE Publication #3, 50 pp.

- AFDW = Ash Free Dry Weigh
- Bq = Becquerel; unit of radiation activity equal to 1 disintegration per second; 3.7E10 Bq is equivalent to 1 Curie
- C = Carbon
- cm = centimeter
- DW = Dry Weigh
- FW = Fresh Weight
- g = gram
- kg = kilogram
- m = meter
- 4MB = Four Mile Branch
- Upstream reach; when referring to Fourmile Branch refers to stream reach above Road 4, before its confluence with H-Area Creek; The area of the upstream watershed is 12.6 km^2 (Williams and Pinder 1990)
- FMC_{reach} = Fourmile Branch stream reach of interest in this study; 2.2 km^2 watershed between station 34 and the confluence with F-Area Creek (Williams and Pinder 1990).

Abiotic nonliving, pertaining to physico-chemical factors only
Aerobic living, acting, or occurring in the presence of oxygen
Algae any of a group of chlorophyll-bearing aquatic plants with no true leaves, stems, or roots
Allochthonous material derived from outside a habitat or environment under consideration
Anaerobic capable of living or acting in the absence of oxygen
Anoxic pertaining to conditions of oxygen deficiency
Aphotic below the level of light penetration in water
Assimilation transformation of absorbed nutrients into living matter
Autochthonous material derived from within a habitat, such as through plant growth
Bioaccumulation the uptake of contaminants from all sources including direct sorption to the body, transport across gill membranes, and through ingestion of prey and sediments
Bioavailability the existence of a chemical in a form that it can be readily integrated into an organism by means of any form of intake or attachment
Biodegradation the process of breaking down into simple organic substances by decomposers (bacteria and fungi)
Biomagnification the step by step concentration of chemicals in successive levels of a food chain or food web
Biomass the total weight of matter incorporated into (living and/or dead) organisms
Biota the fauna and flora of a habitat or region
Chlorophyll the green, photosynthetic pigments of plants
Consumer an organism that consumes another
Decomposers bacteria and fungi that break down organic detritus
Depuration excretion of contaminant by an organism
Desorption the process by which chemicals are detached and released from solid surfaces; the opposite of adsorption
Detritus dead organic matter

Diurnal pertaining to daily occurrence
Dynamic equilibrium a state of relative balance between processes having opposite effects
Ecology the study of the interrelationships of organisms with and within their environment
Ecosystem a biotic community and its (living and nonliving) environment considered together
Emergent aquatic plants, usually rooted, which have portions above water for part of their life cycle
Environment the sum total of all the external conditions that act on an organism
Equilibrium a steady state in a dynamic system, with outflow balancing inflow
Euphotic pertaining to the upper layers of water in which sufficient light penetrates to permit growth of plants
Eutrophic aquatic systems with high nutrient input and high plant growth
Fauna the animals of a habitat or region
Flood plain that part of a river valley that is covered in periods of high (flood) water
Flora plants of a habitat or region
Food chain animals linked by linear predator-prey relationships with plants or detritus at the base
Food web similar to food chain, but implies cross connections
Forage fish fish eaten by other fish
Habitat the environment in which a population of plants or animals occurs
Humic pertaining to the partial decomposition of leaves and other plant material
Hydrodynamics the study of the movement of water
Inorganic pertaining to matter that is neither living nor immediately derived from living matter
Invertebrate animals lacking a backbone
Kinetic processes description of the dynamic rate and mode of change in the transformation or degradation of a substance in an ecosystem
Limiting factor an environmental factor that limits the growth of an organism; the factor that is closest to the physiological limits of tolerance of that organism
Macrophytes large (non-microscopic), usually rooted, aquatic plants
Mass balance an equation that accounts for the flux of mass going into a defined areaand the flux of mass leaving the defined area; the flux in must equal the flux out
Organic chemical compounds containing carbon;
Periphyton community of algae and associated organisms, usually small but densely set, closely attached to surfaces on or projecting above the bottom
Oxidation a reaction between molecules, ordinarily involves gain of oxygen
Producer an organism that can synthesize organic matter using inorganic materials and an external energy source (light or chemical)
Production the amount of organic material produced by biological activity
Productivity the rate of production of organic matter
Productivity, primary the rate of production by plants
Productivity, secondary the rate of production by consumers
Sediment any mineral and/or organic matter deposited by water or air
Trophic level all organisms that secure their food at a common step in the food chain
Volatilization the act of passing into a gaseous state at ordinary temperatures and pressures

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