TECHNICAL REPORT

Environmental Remediation Technologies: Surface Water Modeling of Tims Branch

Date submitted:

June 30, 2016

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Submitted to:

U.S. Department of Energy
Office of Environmental Management
Under Cooperative Agreement # DE-EM0000598

Applied Research Center
Florida International University

EXECUTIVE SUMMARY

This report describes continued research related to development of a surface water model of the Tims Branch Watershed (TBW) at the Savannah River Site (SRS) to correlate the hydrology of SRS and TBW with the distribution of tin within the overland and river sub-domains. Tin was introduced into TBW during the application of an innovative remediation technology implemented by the U.S. Department of Energy's Office of Environmental Management, which involved the injection of stannous (tin) chloride into mercury contaminated groundwater. Understanding the fate of tin and its compounds is of primary importance due to their potential impact on the environment. Tin methylation in particular is of great environmental concern because of its toxicity to humans and animals. Although tin is primarily deposited as sediment, remobilization may occur during episodic extreme events, such as storms or heavy rainfall. In these cases, sediment can be resuspended in the water column and deposited further downstream. It is therefore important to study the fate and transport of tin during such events, in particular its potential for methylation. The main objective of this study, therefore, is to develop an overland hydrology model capable of simulating surface flow depth and velocity throughout the TBW. The modeling application uses historical precipitation data, groundwater levels, geological data, and river discharges that were retrieved from government databases and input to the model. Subsequent to the implementation and calibration phases, the model will be able to simulate flow discharges, flow duration, and water levels.

Efforts over the past year (2015-2016) have focused on revision of the preliminary model to incorporate a study area that encompasses the full extent of the TBW as opposed to just the portion of the watershed lying within the SRS boundary which was initially used. The report therefore builds upon the work carried out in 2014 and outlines the changes to the input configuration parameters that were required in order to incorporate the new model domain.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ARC	Applied Research Center
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DOE	Department of Energy
EFPC	East Fork Poplar Creek
EPA	Environmental Protection Agency
ET	Evapotranspiration
IDW	Inverse Distance Weighted
LAI	Leaf Area Index
NLCD	National Land Cover Database
RD	Root Depth
RET	Reference Evapotranspiration
SCDNR	South Carolina Department of Natural Resources
SRNL	Savannah River National Laboratory
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site
SZ	Saturated Zone
TB	Tims Branch
TBW	Tims Branch Watershed
TCE	Trichloroethene
USDA	United State Department of Agriculture
USGS	United States Geological Survey
WSRC	Westinghouse Savannah River Company

INTRODUCTION

During the Cold War in the 1950s, the U.S. Department of Energy (DOE) built various facilities around the United States to produce nuclear materials including lithium isotopes. Today, the United States still undergoes the post-cold war nuclear cleanup activities. Facilities such as the Savannah River Site (SRS) in South Carolina, are part of the DOE long term cleanup strategy in the U.S.

SRS is in the sand-hills region of South Carolina and covers approximately 800 km^2. It encompasses parts of Aiken, Barnwell and Allendale counties and is bordered on the west by the Savannah River and the state of Georgia (Figure 1). SRS is close to several cities, including Augusta, Georgia and Columbia, South Carolina. It is located 24 km southeast of Augusta, Georgia, and 16 km south of Aiken, South Carolina. It is also within a few hours of Atlanta, Savannah, Charleston, Greenville and Charlotte. SRS includes facilities such as reactors, laboratories, waste disposal sites, cooling towers, incinerators, etc.

In the 1950's and 60's, SRS used millions of pounds of heavy metals, including mercury, and solvents such as trichloroethylene (TCE) to produce tritium, plutonium-239 and other radioisotopes to support national security, space exploration, and medicine. After several years of nuclear operations at the site, many of these pollutants have entered the environment, contaminating the soil, surface water and groundwater.

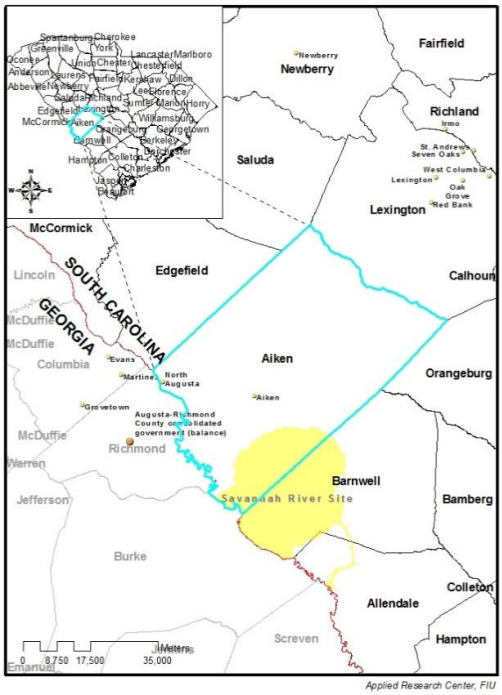

Figure 1. Location of Savannah River Site, SC.

SRS is home to the A/M Area. This area is located in the northwest portion of SRS and covers approximately 0.33 km^2. The A/M Area constitutes one of the largest groundwater contamination areas in the country, resulting from the production of fuel and target assemblies, research and development operations, and the disposal of waste and general debris. The principal contaminants in the A/M Area are solvents in the groundwater and vadose zone; however other contaminants such as uranium, nickel, and aluminum are also found in the subsurface, nearby streams, and infrastructure. Treatment of trace mercury in groundwater at the A/M Area started in 2007 by addition of stannous (tin) chloride prior to air stripping in a pump and treat operation. As a result, mercury was removed as vapor and tin dioxide was precipitated and released into the receiving stream in the treated water. Tin in its elemental or oxide form is not very toxic to biota, but the organic form is toxic. Organotin compounds are persistent and not readily biodegradable. They are known to be toxic to aquatic ecosystems (Amouroux et al., 2000). Therefore, understanding the fate and transport of tin and its compounds is of primary importance due to their potential impact on the environment (Donard and Weber, 1985; Maguire et al., 1986). Tin methylation is of environmental concern because of its toxicity to humans and animals. Although precipitated tin is primarily deposited as sediment, remobilization may occur during episodic

extreme events, such as storms or heavy rainfall. In these cases, sediment can be resuspended in the water column and deposited further downstream. It is therefore important to study the fate and transport of tin during such events, in particular its potential for methylation.

Numerical modeling has proven to be a cost effective tool in studying natural processes such as hydrology and fate and transport of contaminants. Numerical modeling can provide insight into how sediment may become resuspended, transported and redistributed in a waterbody during various extreme weather scenarios. It is possible to approximately determine the path of tin through the affected watershed using advanced watershed modeling software. MIKE SHE, developed by the Danish Hydraulic Institute (DHI), one of the hydrologic models being implemented in TBW, is an integrated surface water and groundwater software that can simulate the entire land phase of the hydrologic cycle, map the vulnerability of the aquifer, and delineate the floodplain of the watershed.

The objective of this task is to develop an integrated surface water and groundwater model to predict the fate and transport of tin in Tims Branch. This report describes the preliminary development of the hydrological model of Tim Branch using the MIKE SHE model and the extensive pre-processing that was carried out to prepare the data for input into the model.

STUDY AREA

The Tims Branch Watershed (TBW) is a second order watershed located within SRS. This watershed is within 12-digit hydrologic unit code (HUC) 030601060504 and is contained within the larger Upper Three Runs watershed which is a sub basin of Lower Savannah River Basin (hydrologic units 03060106, 03060107, 03060109, 03060110) along the border of Georgia and South Carolina (Figure 2).

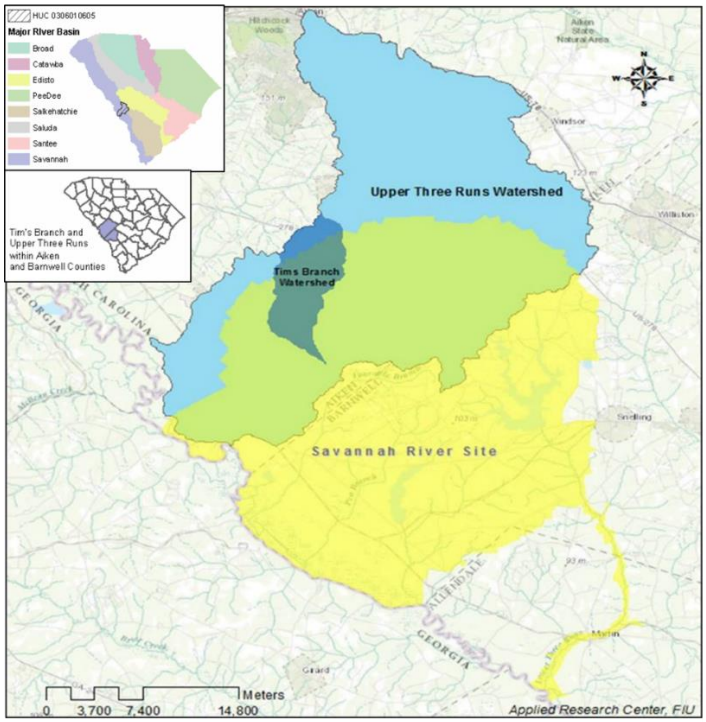

Figure 2. Tims Branch Watershed (TBW) located within Upper Three Run watershed, SC.

Tims Branch is a small braided, marshy, second-order stream that starts at the northern portion of SRS and passes through Beaver Ponds 1-5 and Steed Pond, and eventually discharges into Upper Three Runs (Figure 3). Its drainage area is nearly 16 km^2 (Batson et al., 1996). The average width of the stream varies between 2 to 3 m. Two major tributaries of Tims Branch are A014 and A011 outfalls which are approximately 230 m apart. They combine with the main stream of Tims Branch 1,400 m from the A014 outfall (Hayes, 1984). Flow in Tims Branch is strongly influenced by groundwater discharge (Mast and Turk, 1999). Because of the water table elevation and Tims Branch bed elevation, it is considered to be a losing stream (surface water discharges into the groundwater) near the A/M outfalls and a gaining stream (groundwater discharges into the stream) further south toward the confluence with Upper Three Runs (Looney et al., 2010; Varlik, 2013).

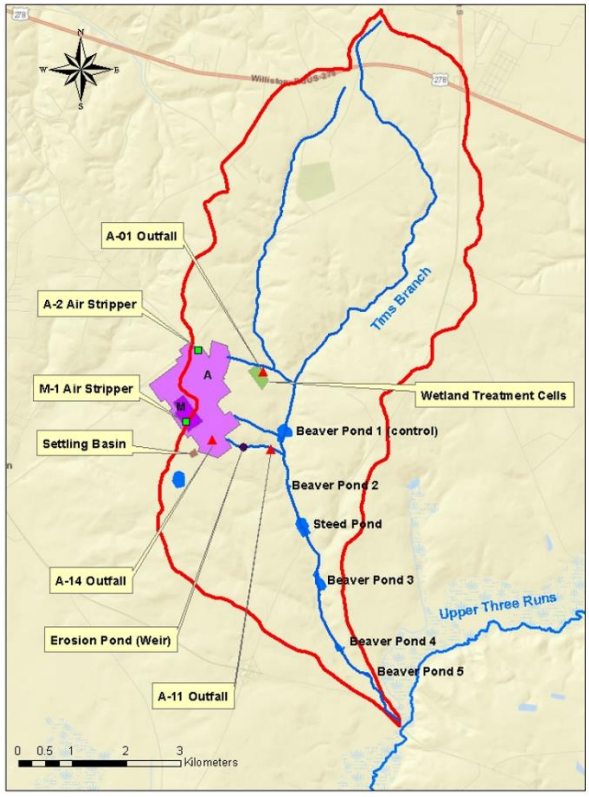

Figure 3. Tims Branch and Beaver Ponds 1 – 5, Steed Pond and wetland treatment locations in TBW. Tims Branch receives water from A/M area and discharges into Upper Three Runs.

BACKGROUND

Since the 1950s, Tims Branch has received contaminated wastewater from the A/M Area at outfalls A-1A, A-01, A-11, and A-014. The groundwater treatment process was started in 1985. The treatment process consisted of removal of chlorinated solvents using air strippers. Treated groundwater was discharged into Tims Branch. In November 2007, as part of mercury removal efforts, tin chloride ($SnCl_2$) was injected into the groundwater right before entering the air stripping system in order to convert mercury (II) to volatile mercury (0) form which could be removed through the air stripper. Dissolved mercury (II) reacts with tin chloride and produces tin dioxide (SnO_2) that precipitates as a sediment to the bottom of Tims Branch:

$$Hg^{2+} + SnCl_2 + 2H_2O \rightarrow Hg_{(g)} + SnO_{2\,(s)} + 4H^+ + 2Cl^-$$

The initial concentration of mercury in the groundwater was approximately 250 ng/L (Looney et al., 2010). After treatment with tin chloride, the mercury concentration has significantly reduced to approximately 10 ng/L (Looney et al., 2010). At the same time, the tin (IV) concentration, primarily as inorganic solid deposit, has increased substantially. Therefore, the sediment deposits in Tims Branch are high in tin (IV). Based on field observations and results of the present study, the best estimate of the theoretical average tin (IV) concentration in the sediment in Tims Branch from the A014 outfall downstream to the confluence of Tims Branch with Upper Three Runs Creek is approximately 28 μg/g. The depth of sediments in which tin has accumulated in significant amounts, due to the tin chloride treatment system, is between 1.5 and 3.5 inches. Although tin (IV) appears to be less toxic than mercury, it is essential to understand tin behavior and the impacts of the treatment system (both negative and positive) in Tims Branch. The literature suggest the possibility of the generation of organotin through a methylation process (Amouroux et al., 2000; Hallas and Cooney, 1981).

Very limited studies have accounted for the hydrology and sediment transport mechanisms of Tims Branch and SRS. These studies are primarily based on experimental work and field data collections rather than numerical modeling approaches. Modeling hydrological processes and sediment transport mechanisms requires a detailed understanding of soil and sediment characteristics, geologic formation, topography, climate, and hydraulic properties. Most of the previous hydrological modeling efforts were conducted in other areas of Savannah River and South Carolina. Conrads et al. (2006) developed a three-dimensional model of the Savannah River estuary to simulate changes in water levels and salinity conditions in the marsh by coupling a 3D hydrodynamic river-estuary model and the marsh-succession empirical model. The coupled model, however, may not be applicable to SRS and Tims Branch because they only simulate water levels in the marsh areas. In addition, empirical modeling may not produce valid results when applied to other locations.

In a recent study, Feaster et al. (2012) investigated the relationship between hydrological, geochemical, and ecological processes on mercury concentration in fish tissue. They applied two watershed hydrologic models to the Mc Tier Creek watershed in South Carolina: a topography-based hydrological model, TOPMODEL (Beven and Kirkby, 1979; Wolock, 1993), to simulate

surface flow hydrology, and a Grid-Based Mercury Model, GBMM (Dai T. et al., 2005), to simulate the fate and transport of mercury. Because TOPMODEL generates stream flow based on a variable-source-area concept, the model only reflects how rainfall moves through the watershed to become stream flow, so it is not feasible to apply it for an existing stream such as Tims Branch. In a similar study, Feaster et al. (2014) investigated the potential for scaling up the previous application of TOPMODEL for the Mc Tier Creek watershed (small scale) to the Edisto River Basin (large scale) in South Carolina.

As none of the previous hydrological modeling efforts were specifically applicable to SRS and Tims Branch, it is critical to develop a site specific flow and transport model to better understand the fate and transport of tin in surface water. FIU-ARC is developing integrated flow and transport models, this report presents the implementation of one of these models based on the MIKE software package created by the Danish Hydraulic Institute (DHI). The integrated flow and transport model (MIKE SHE/MIKE 11/ECOLAB) analyzes the effect of hydrological events on potential tin erosion, resuspension, and transport in the Tims Branch Watershed. The model includes the main components of the hydrological cycle and sediment transport; groundwater flow (saturated and unsaturated), overland flow, precipitation, and evapotranspiration. The main objective of these modeling applications is to provide the spatiotemporal distribution of tin in the sediment of Tims Branch and to forecast the fate and transport of tin and its possible methylation during extreme hydrological events.

METHODOLOGY

The hydrology of surface water is proven to be one of the key factors controlling erosion and deposition mechanisms in sediment transport processes in streams and rivers. Therefore, understanding the hydrology of Tims Branch is vital in determining the environmental conditions and the causes of enhanced sediment erosion and deposition in this stream. Developing a conceptual model and data acquisition are the primary steps toward building a physically-based numerical tool to simulate surface water hydrology. Performing numerical simulations will provide an improved understanding of how an extreme rainfall or flooding episode may affect

the transport of tin in Tims Branch. The following sections will provide information on data inquiry, model conceptualization, and numerical model development.

Conceptual Model Development

A conceptual model describes the general physical framework of the relationship between physical processes that are part of an environment. Figure 4 illustrates the general components involved in the MIKE SHE watershed hydrology model. MIKE SHE includes the precipitation, infiltration, evapotranspiration, surface flow, and subsurface flow in both unsaturated and saturated zones. In addition, a data-driven site specific conceptual model was developed for contaminant transport in Tims Branch (Figure 5). The conceptual model developed for SRS involves processes and features such as discharge points, groundwater/surface water interaction, geological formation, atmospheric characterization, infiltration, runoff, etc. This conceptual model includes location of outfalls, ponds, and other significant features within the study area. Water flows from A/M Area into Tims Branch through two outfalls: A-01 and A-014. A-01 discharges water from a wetland treatment facility north of the A/M Area, while A-014 discharges water from the southern groundwater wells into Tims Branch.

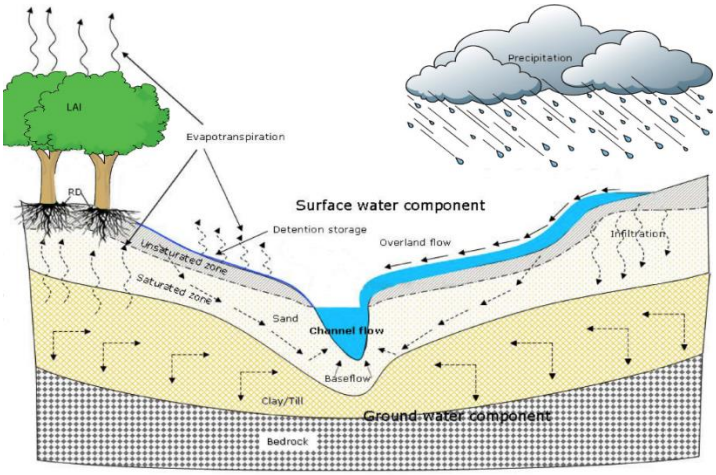

Figure 4. MIKE SHE components representing hydrological cycle. Each component is defined as a separate module which includes series of inputs parameters.

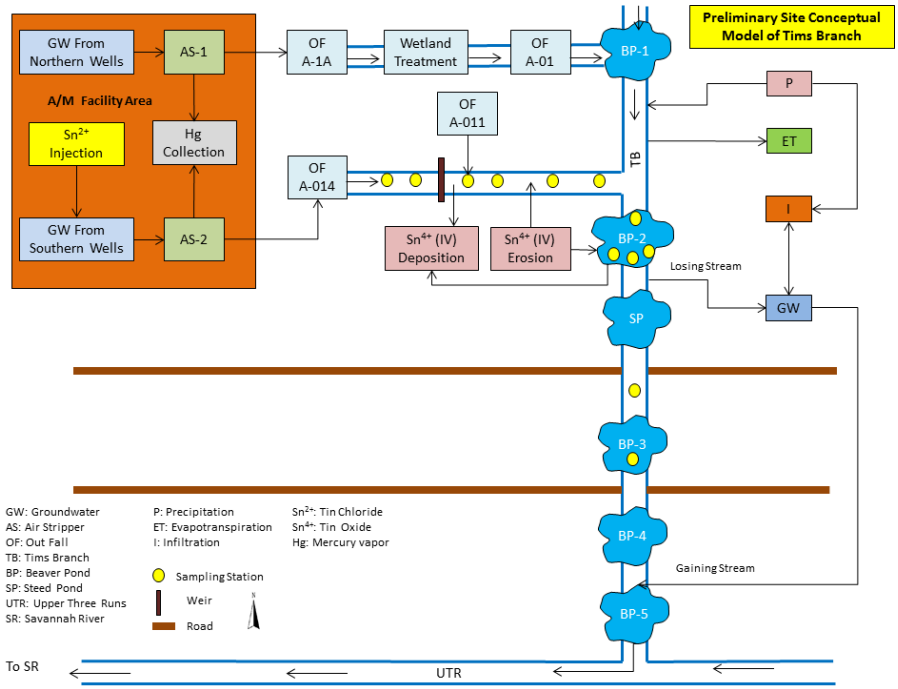

Figure 5. Tims Branch Watershed conceptual model.

A/M Area wastewater, including cooling water, steam condensate, groundwater treated by air strippers, stormwater runoff, steam and air-conditioning condensates, laboratory drain wastewater, well flushing water, and other industrial and sanitary wastewater, is discharged into Tims Branch through several outfalls and flows towards Upper Three Runs, eventually discharging into the Savannah River (Halverson, 2008).

There are seven potential areas in Tims Branch that tin (IV) can be deposited: the weir site, Beaver Ponds (2-5), and Steed Pond (Figure 3). The weir site and Beaver Pond 2 are the only two sites that show actual accumulation of tin (IV) due to the mercury treatment process in their sediment (Looney et al., 2010). Data collected indicates that tin accumulation in the sediment along Tims Branch is more non-uniform, with some sites showing elevated concentration while other sites report less tin accumulation. This non-uniform concentration distribution may be the result of an increase in bed erosion due to the discharge rate of approximately 450 gpm into Tims Branch after installation of the air stripper (Looney et al., 2010; Looney et al., 2012). Although tin is primarily deposited as sediment along Tims Branch, mainly at the weir site and Beaver Pond 2, remobilization may occur during episodic extreme events such as storms or heavy rainfall. Sediment can be resuspended, enter the water body, and be deposited further

downstream in Tims Branch. These suspended particles may be deposited along Tims Branch or carried by water flow further down the stream toward Upper Three Runs and eventually reach the Savannah River. If the environment along the path of particle transport is favorable, tin methylation may happen in the area where tin has been deposited.

Batson et al. (1996) investigated the remobilization of the uranium (U) rich sediment during rainfall events at SRS. Their findings show that a single storm event can effectively erode the sediment and transport it downstream towards Upper Three Runs. They reported a 15 to 28 fold increase in U transport out of the Tims Branch system during storm events due to sediment erosion. They showed that as little as 16 mm of rainfall was needed to cause a significant increase in stream turbidity and resuspension of sediment. This process may apply to tin sediment erosion when an extreme event occurs.

Looney (2001) has identified three main uncertainties related to mercury treatment using stannous chloride: tin methylation through aerobic and anaerobic processes, tin mediated mercury methylation, and deposition and accumulation of tin in sediments. While the fraction of tin that was observed to be methylated by natural processes in many environments was relatively low and the conditions that maximize methylation (e.g., high salinity) are not present in typical freshwater streams, the potential exists for tin methylation in freshwater streams and riparian systems receiving long term discharges from outfalls being treated using stannous chloride and air stripping.

Numerical Model Development

Developing the hydrology model for TBW consists of two parts: 2-D overland flow model (MIKE SHE) and 1-D stream flow model (MIKE 11). These two models will be coupled to simulate the full hydrological cycle in TBW. Phase 1 of this research includes development of the MIKE SHE model to simulate the spatiotemporal distribution of the overland flow. Phase 2 includes MIKE 11 stream and channel model development. This model simulates the flow discharge within the main streams of TBW. Two separate stand-alone MIKE 11 flow models are under development, one is to simulate flow along the A-014 outfall, and the other is to simulate

the flow in the entire Tims Branch stream. Each model is being developed independently and will be able to simulate flow within A-014 and Tims Branch.

The modeling system implemented in the initial phase of the project consists of MIKE SHE, an integrated 3-D saturated and unsaturated groundwater flow, and 2-D overland flow model. MIKE SHE is a deterministic, physically based and full distributed hydrological modeling system (Abbott and Refsgaard, 1996). It consists of the Water Movement and Water Quality modules. The hydrological processes are described mostly by physical laws (laws of conservation of mass, momentum and energy). The 1-D and 2-D diffusive wave Saint Venant equations describe channel and overland flow, respectively. The Kristensen and Jensen methods are used for evapotranspiration, the 1-D Richards‘s equation for unsaturated zone flow, and a 3-D Boussinesq equation for saturated zone flow. These partial differential equations are solved by finite difference methods, while other methods (interception, evapotranspiration and snowmelt) in the model are empirical equations obtained from independent experimental research. The basic steps for development of the hydrology model include:

- Modeling of the overland flow using MIKE SHE.
- Incorporating the evapotranspiration, unsaturated zone, and saturated zone modules into the MIKE SHE.

A 2-D integrated surface water and groundwater flow model (MIKE SHE) was developed for visualization of the overland flow distribution in TBW. Historical records derived from the preliminary data search were used as input for model development. Simulations included but were not limited to seasonal fluctuation of precipitation and extreme flood events. The developed model for TBW offers the ability to input relevant hydrologic parameters to create a watershed model which is capable of simulating flow in the subsurface (saturated and unsaturated zones) and surface sub-domains (overland and river) as well as contaminant transport and exchange between various sub-domains using an advection-dispersion module. Topography, river networks, flow velocities, precipitation, soils, aquifers, vegetation, and land use are some of the input parameters required for initial model configuration.

Data Preparation

MIKE SHE requires an extensive amount of hydrological data and parameters; however, the model has a built-in graphical user interface (GUI) that accepts many of these configuration files in geographic information system (GIS) shapefile format. The GIS data that is imported into MIKE SHE will be converted into MIKE SHE model specific DFS files through MIKE SHE internal processing. The data required for preliminary model set up are topography, land use, vegetation characterization, rainfall, etc. All data and parameters must go through a pre-processing procedure prior to use in the model. The following sections describe the data processing of the model development:

Model Domain

As this study is focused on flow and pollutant transport in Tims Branch, its watershed boundary, defined by the 12 digit hydrologic unit code (HUC) 030601060504, was specified as the model domain. This domain covers a drainage area of about 16 km^2 (Batson et al., 1996). The delineated model domain originally used for model development (Figure 6-a) was limited in extent to the SRS boundary. This domain was later modified to cover the entire TBW (Figure 6-b). As shown in Figure 6, MIKE SHE automatically assigns numbers 1 and 2 to grid cells inside the model domain and grid cells on the model boundary, respectively. This distinction between interior grid cells and boundary cells is to facilitate the definition of boundary conditions. For example, drainage flow can be routed to external boundaries but not to internal boundaries.

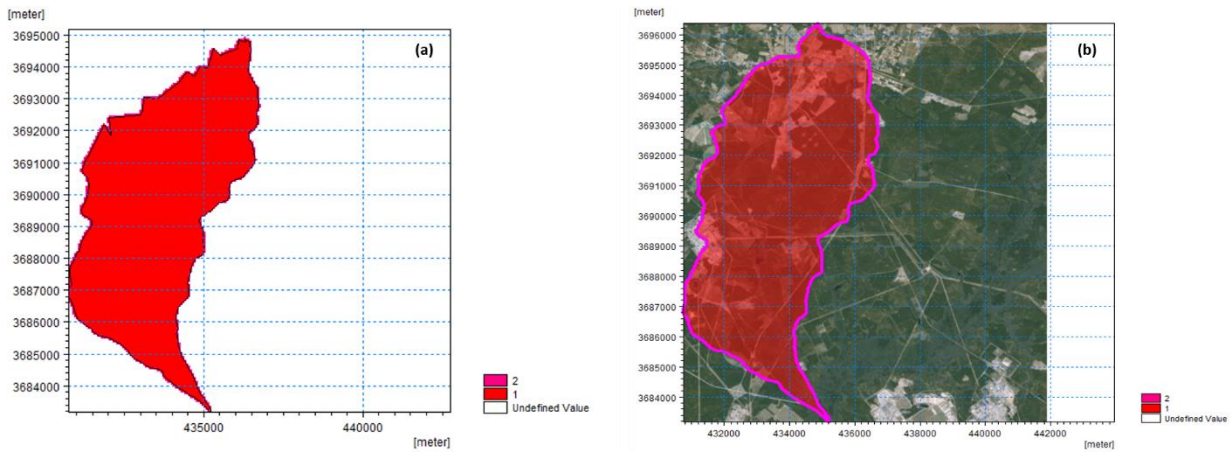

Figure 6. MIKE SHE model domain originally delineated to SRS boundary (a), and extended to the TBW boundary (b). Grid cells inside the model domain are assigned a value of 1 and grid cells on the model boundary are assign a value of 2 which dictates the flow drainage externally.

Geology and Topography

SRS is a typical coastal plain watershed that includes a network of rivers and streams that are tributaries to the Savannah River, which is the border between South Carolina and Georgia, and a portion of it borders the SRS (Halverson, 2008). The Savannah River is formed by the confluence of the Tugaloo and Seneca Rivers in northeast Georgia and flows southeast through the Piedmont and Coastal Plain to the Atlantic Ocean. Figure 7 is a general geologic map of South Carolina downloaded from the South Carolina Department of Natural Resources (SCDNR) website. As illustrated in this map, the geology of the SRS area is classified primarily as Tertiary (Pliocene, Paleocene, Eocene, and Miocene) and Triassic (Triassic Basins).

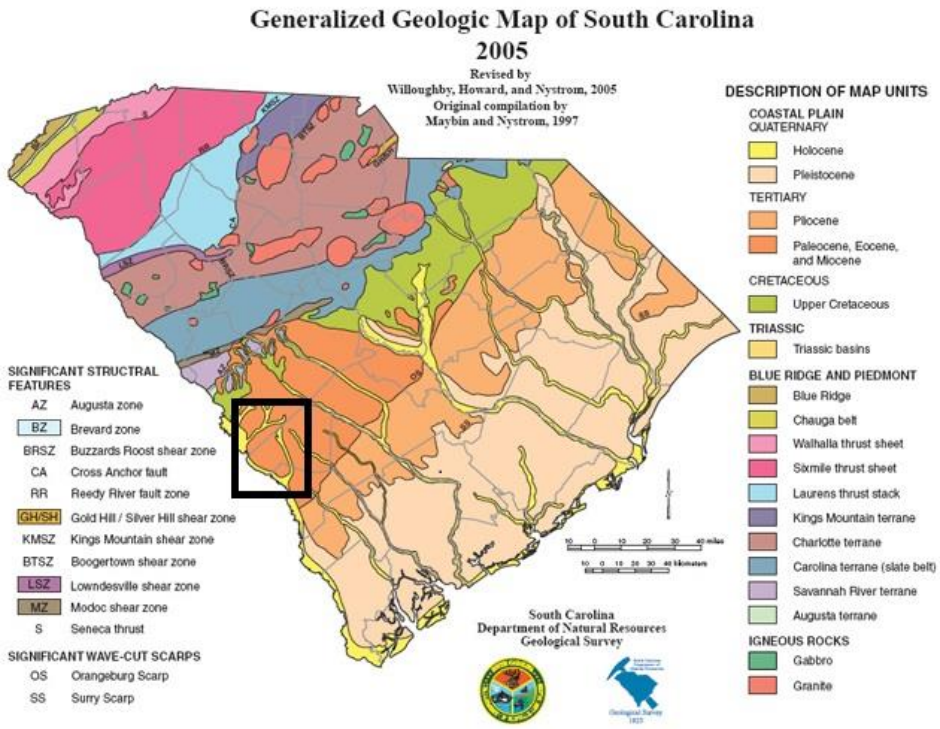

Figure 7. South Carolina geology map. The study area is indicated by a black rectangle. (http://www.dnr.sc.gov/geology/geology.htm).

The general topography of SRS includes upper and lower coastal plains. Lanier (1997) described the upper Coastal Plain as consisting of rounded hills with gradual slopes, areas of highly irregular terrain, and some elevations exceeding 200 m above sea level. The highest elevation at SRS is approximately 130 m above sea level, near Tims Branch and the northwest boundary of SRS. The land surface elevation at the boundary of the upper and lower Coastal Plains, located southeast of SRS, is usually less than 60 m above sea level. Upper Coastal Plain stream slopes range from 1.0 to 4 m/km (Lanier, 1997).

LiDAR elevation data was initially provided by SRNL, however, the dataset was limited to the SRS boundary and did not cover the entire TBW. New LiDAR data with 3 m spatial resolution that covered the entire TBW boundary was acquired from the U.S. Geological Survey (USGS). This data was processed and used to generate a Digital Elevation Model (DEM) of the TBW which was modified to a model-specific format for input into MIKE SHE. The data was resampled and interpolated to correspond to the element size used in the MIKE model. The resampling was performed using the Lago toolbox (a geoprocessing utility provided by Lago

Consulting & Services). Figure 8 shows the original (SRS boundary limit) and extended (TBW boundary limit) DEM of TBW.

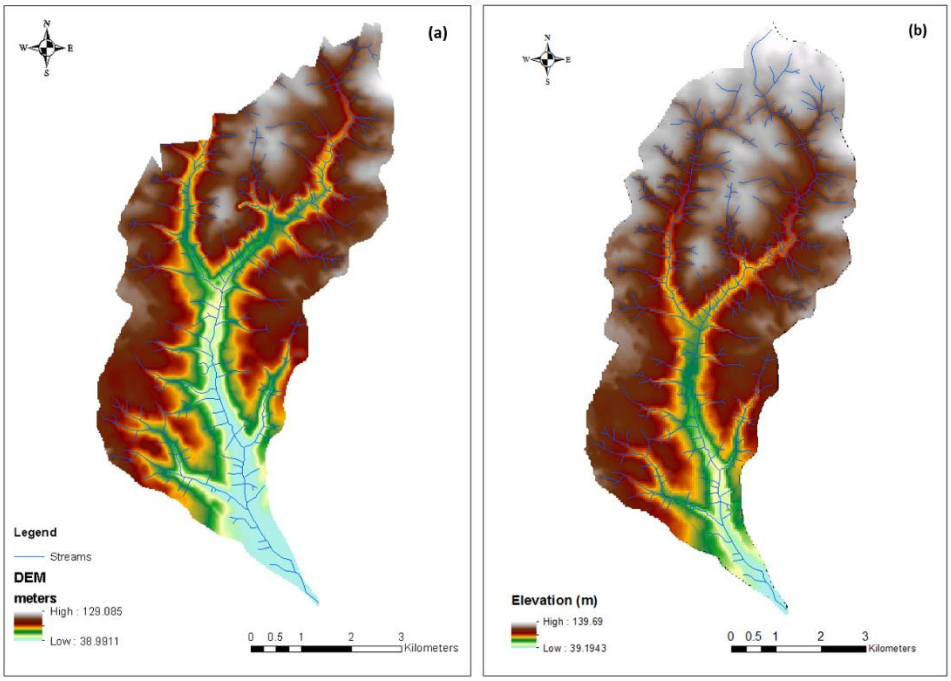

Figure 8. Topography within the TBW original model domain (a), and TBW model domain (b) that were derived from DEM.

In MIKE SHE, topography defines the upper boundary of the model. The topography is used as the top elevation in both the Unsaturated Zone (UZ) and Saturated Zone (SZ) modules. It also defines the drainage surface of overland flow (OL). The accuracy of the topography is therefore the most important parameter in the MIKE SHE model set up. The model input for topography was generated by converting the DEM to a GIS point shapefile which contained XY coordinate data with associated elevation values using ArcGIS software. This was then imported into MIKE SHE and converted to a .dfs2 file, which is the native MIKE SHE file format. The .dfs2 file was then used to replace the GIS point shapefile in the model.

Streams

Major tributaries from SRS to the Savannah River include Upper Three Runs, Beaver Dam Creek, Fourmile Branch, Steel Creek, and Lower Three Runs (Figure 9). Tims Branch discharges into Upper Three Runs Creek, a 40-kilometer waterway that meanders through hardwood and

cypress forests in SRS and finally empties into the Savannah River. The creek is a black-water stream because of its high concentration of naturally occurring tannic acid that gives the water its tea color. Forty-kilometers long, Lower Three Runs leaves the main body of SRS and runs through parts of Barnwell and Allendale Counties until it flows into the Savannah River. Government property on both sides of the stream acts as a buffer as it runs through privately-owned property. Fourmile Branch begins just upstream from Road F and flows into the Savannah River. It is about 242 km long and enters the Savannah River Swamp approximately 3.4 km upstream from its confluence with the Savannah River; downstream from this point, Fourmile Branch becomes braided and mixes with flow from the Savannah River.

Figure 9 (a) shows the original hydrology network data that was provided by SRNL which was limited to the SRS boundary. The complete stream network GIS shapefile in Figure 9 (b) was downloaded from the USGS online national Hydrography Dataset (NHD) and processed using geoprocessing tools in the ArcMap application for further use in hydrological model development.

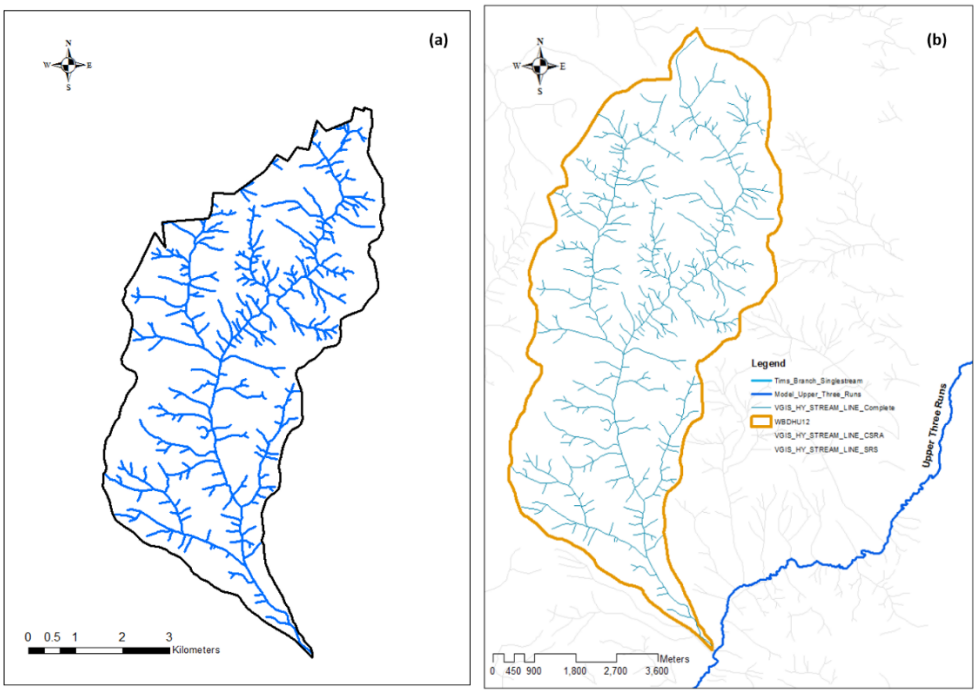

Figure 9. Stream and channel network in (a) TBW as original domain boundary, and (b) extended boundary.

Land Use/Land Cover

Land cover data depicts how much of a region is covered by natural vegetation, wetlands, agriculture, impervious surfaces, and other land and water types, while land use data indicates how the landscape is being used. Land cover and land use information are critical for deriving landscape pattern metrics, assessing ecosystem status and health, understanding spatial patterns of biodiversity, and modeling surface runoff. There are several land cover and land use types in the TBW. The A/M Area operates within the TBW and occupies about 14% of the total watershed area. Figure 10 maps the developed areas of the TBW, including roads and buildings, and illustrates the percent of impervious cover. Over 6 km of the total area of TBW has an imperviousness of 14% or less. This indicates that, overall, the watershed is mostly undeveloped or agricultural land. This conclusion is compatible with the land use data, which establishes that about 80% of the watershed is forested or agricultural land (Table 1).

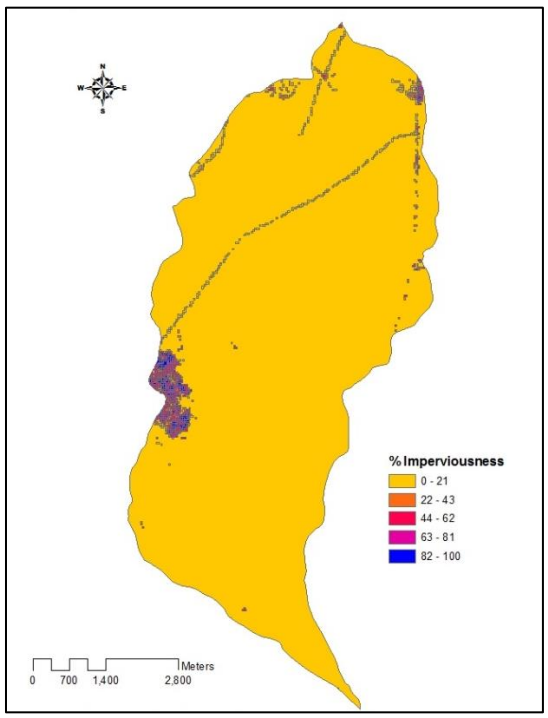

Figure 10. Impervious percentage.

Table 1. Land Use Classification and Percentage in TBW

Land Use	Area (m^2)	%
Agricultural	170,975	0.34
Barren Land	58,151	0.12
Forest	35,267,379	70.83
Rangeland	7,287,896	14.64
Urban/Built-up Land	6,816,222	13.69
Water	76,866	0.15
Wetland	115,658	0.23

Land cover data for the northwestern portion of Savannah River Site was provided in the form of a GIS feature class, which was clipped to the project's study domain, exported from ArcMap as a shapefile and then imported into the MIKE SHE model. Figure 11 maps the land cover distribution in TBW for the old and new model domains.

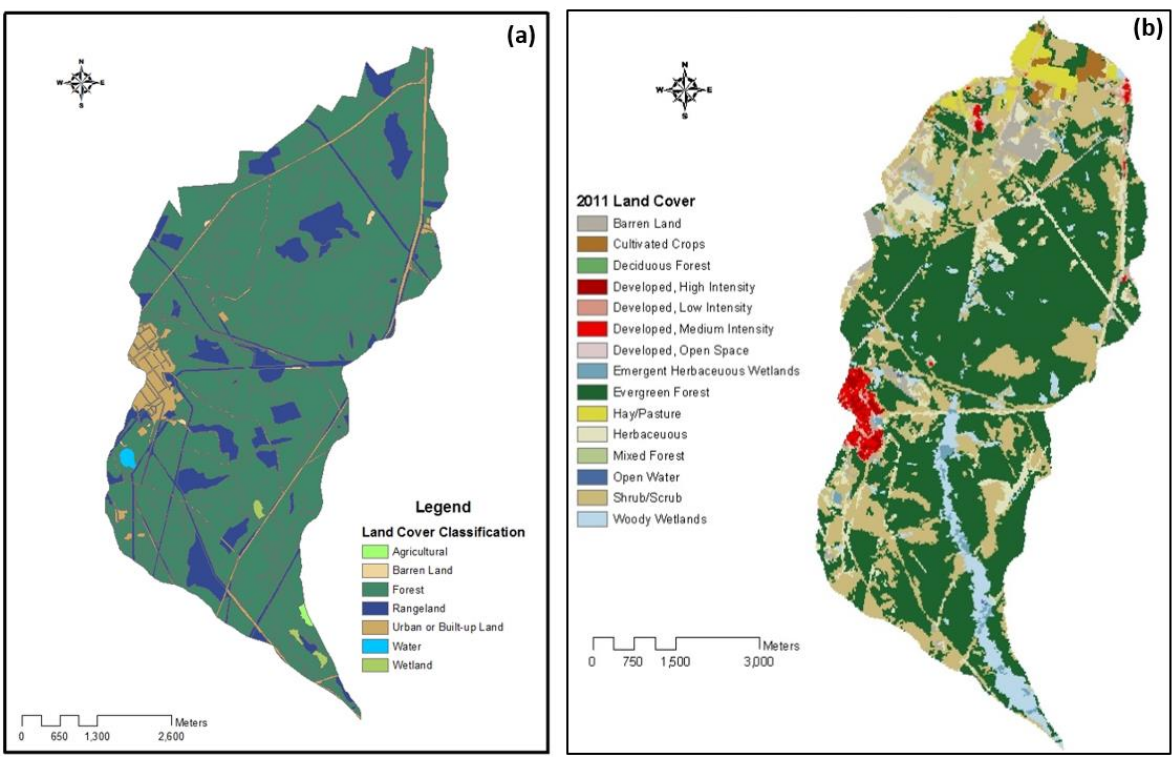

Figure 11. Map of land cover in original domain boundary (a), and extended boundary (b). Data derived from USDA-NLCD

Vegetation data

To calculate Actual Evapotranspiration, MIKE SHE requires vegetation properties, primarily, Leaf Area Index (LAI), and Root Depth (RD). MIKE SHE Vegetation Database defines the LAI and RD values for various vegetation types. Table 2 shows the vegetation data for TBW which was defined based on the land cover data depicted in Figure 11 (b).

Table 2. Vegetation Data for TBW

Vegetation ID	LAI	RD (mm)
Barren Land	1.31	4000
Cultivated Crops	3.62	1500
Deciduous Forest	5.5	2000
Developed Low Intensity	2.5	2000
Developed Medium Intensity	2.0	2000
Developed Open Space	3.0	2000
Emergent Herbaceous Wetland	6.34	2000
Evergreen Forest	5.5	1800
Hay/pasture	1.71	1500
Mixed Forest	5.5	2400
Open Water	0.0	0.0
Quarries	1.31	4000
transitional	1.31	4000
Urban/Recreational Grasses	2.0	2000
Woody Wetland	6.34	2000

The TBW vegetation parameters were used to spatially adjust the reference evapotranspiration in the model simulation as described in the Climate Data section of this report. In MIKE SHE, the ET process proceeds as follows: a portion of the rainfall is intercepted by the canopy and evaporates, the remainder reaches the soil and adds to runoff or percolates into the upper soil layer, part of the infiltrating water is either transpired by plant roots or evaporated, and the remaining water recharges the groundwater. The various sections where plants intercept the path of water are spatially distributed by the LAI and RD parameters of the vegetation maps.

Manning's Roughness Coefficient

Computation of flow in an open channel requires evaluation of the channel's resistance to flow, which is typically represented by a roughness parameter, such as Manning's *n*. (Phillips et al,

2007). MIKE SHE uses inverse of traditional Manning's value as Manning's M. Table 3 shows the values of Manning's M (1/*n*) that were assigned to each land use classification in the land cover shapefile previously described.

Table 3. Manning's Values Assigned to Each Land Use Coverage in TBW

Land Use	Manning's M (1/n)
Agricultural	41
Barren Land	81
Forest	21
Rangeland	25
Urban/Built-up Land	90
Water	11
Wetland	23

Manning's *n* values were obtained from standard civil engineering Manning's tables available online, as well as *n* values derived from the technical report by Tachiev et al, 2014, "Remediation and Treatment Technology Development and Support for DOE Oak Ridge Office: EFPC Model Update, Calibration and Uncertainty Analysis". The land cover shapefile attribute table was then modified to include a new field of Manning's M (i.e., 1/*n*) numbers. This added field was then used as the basis for generating a new polygon shapefile to represent the Manning's Roughness Coefficients within the SRS/Tims Branch study area. As the MIKE SHE model only accepts point/line shapefiles for spatially distributed Manning's M, ArcGIS tools were used to convert the polygon shapefile to a point shapefile which was then input into the model. The model then interpolated the values to generate a gridded surface which was saved as a MIKE (.dfs2) grid file. This grid file was then used to replace the shapefile in the model configuration (Figure 12).

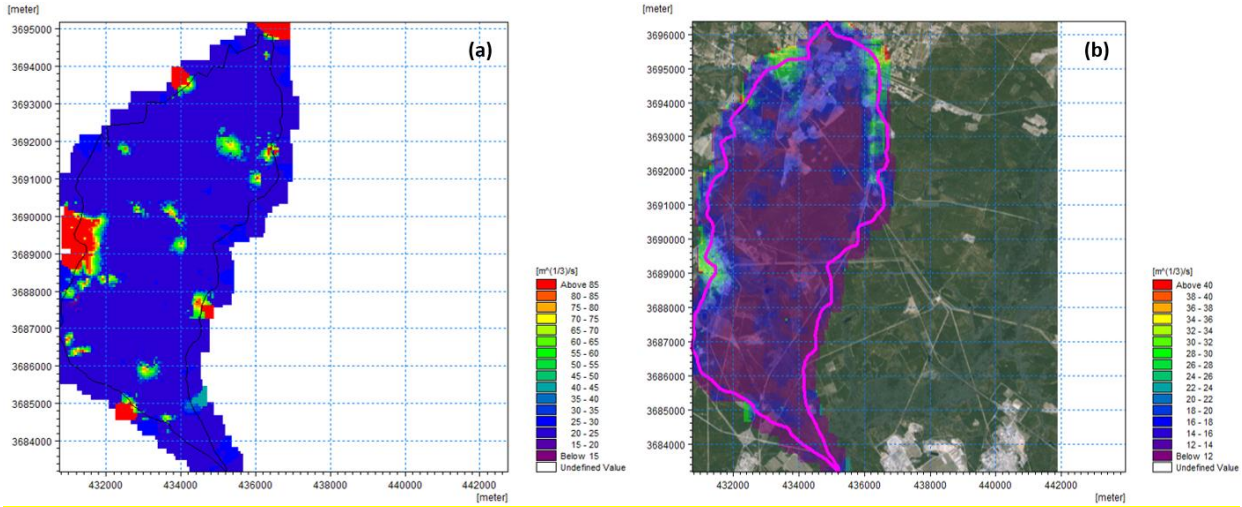

Figure 12. Manning's M (1/*n*) grid file as viewed in MIKE SHE original (a), and extended (b) domains.

Paved Runoff Coefficient

Paved runoff coefficient values were derived from the [1]Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment State Water Resources Control Board 5.1.3 FS-(RC) 2011, which specifies the runoff coefficient (C) as a dimensionless coefficient relating the amount of runoff to the amount of precipitation, with larger values for areas with low infiltration and high runoff (pavement, steep gradient), and lower values for permeable, well vegetated areas (forest, flat land). This data is required by the MIKE SHE model and can be a significant parameter indicating flooding areas during storm events as water moves fast overland on its way to a river channel or a valley floor. Paved runoff coefficient values were assigned to the land use classifications outlined in Table 1.

A value of 0.7 was given to the Urban/Built-up Land and a value of zero assigned to all other land use types. In the same manner as described above for development of the Manning's Coefficient GIS shapefile, the land cover shapefile attribute table was modified to include a new field of runoff coefficients. This added field was then used as the basis for generating a new

[1]Source: Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment State Water Resources Control Board 5.1.3 FS-(RC) 2011 is a factsheet prepared by the California Environmental Protection Agency State Water Resources Control Board that can be accessed online at the following URL: http://www.waterboards.ca.gov/water_issues/programs/swamp/docs/cwt/guidance/513.pdf.

polygon shapefile to represent the Paved Runoff Coefficients within the SRS/Tims Branch study area. As the MIKE SHE model only accepts point/line shapefiles for spatially distributed Paved Runoff Coefficients, ArcGIS tools were used to convert the polygon shapefile to a point shapefile which was then input into the model. The model then interpolated the values to generate a gridded surface which was saved as a MIKE (.dfs2) grid file. This grid file was then used to replace the shapefile in the model configuration.

Climate Data

MIKE SHE requires climate data as precipitation, snowmelt, and evapotranspiration (ET) rates. The climate data was acquired from the NOAA climatological dataset compiled for the state of South Carolina. Precipitation data is represented as water equivalent totals and includes liquid and melted frozen precipitation. The SRS climate is categorized as humid subtropical with mean temperature of 18 °C and a mean annual precipitation of 1225 mm (Kilgo, 2005). The SRS climate is heavily influenced by the Appalachian Mountains and Atlantic coast. As a result, SRS rarely experiences snow or icing conditions. Precipitation is mainly in the rainfall form with little to no snowfall. Approximately 50 years of daily rainfall records from SRS rain gauge station 700-A was provided by SRNS Geotechnical Engineering Department at SRS.

Precipitation

For use in MIKE SHE, the Precipitation can be specified as a rate (e.g., mm/hr) or as an amount (e.g., mm). If a rate is used, then the EUM Data Units must be Precipitation and the time series must be Mean Step Accumulated. If an amount is used, the EUM Data Units must be Rainfall and the time series must be Step Accumulated (see MIKE SHE Manual Volume 2, page 58). When an amount is used, MIKE SHE automatically converts this to a rate during the simulation.

Precipitation is one of the critical variables in the integrated hydrological model, which determines the surface water flow in the watershed and the dynamics of the groundwater table. For the TBW model, daily time series of precipitation was used as Step Accumulated Rainfall. Although, data was available for approximately 50 years (01/01/1964 – 09/30/2014); MIKE SHE will only use the data within the specified Simulation Period. In this case, the period of

10/01/1993 – 09/30/1996 was used. The selected time period shows the typical variability of rainfall events within a month and includes the timeseries of discharge recorded by the United States Geological Survey (USGS) station on Tims Branch. Although the current model uses rainfall time series data from a single rain gauge station (700-A), station-based time series rainfall data from several other nearby weather stations were downloaded in order to derive a spatially distributed rainfall grid file.

Reference Evapotranspiration

The calculation of evapotranspiration (ET) uses meteorological and vegetative data to predict the total evapotranspiration and net rainfall due to:

- Interception of rainfall by the canopy,
- Drainage from the canopy to the soil surface,
- Evaporation from the canopy surface,
- Evaporation from the soil surface, and
- Uptake of water by plant roots and its transpiration, based on soil moisture in the unsaturated root zone.

MIKE SHE estimates ET based on two methods: 1) the Kristensen and Jensen (1975) method which uses the Richards equation or the gravity flow method in the unsaturated zone, or 2) the Two-Layer UZ/ET model. The latter divides the unsaturated zone into a root zone where ET occurs and below the root zone, where ET does not occur (Yan and Smith, 1994). The Two-Layer UZ/ET model is suitable for areas where the water table is shallow such as South Carolina and the SRS area (Dai et al., 2010). MIKE SHE also requires the value of a reference ET (the rate of ET from a reference surface with an unlimited amount of water) that can be calculated in accordance with Food and Agriculture Organization (FAO) guidelines. Aadland et al. (1995) reported the value of 2.22 mm/day as the reference ET at SRS which was used in this study.

The 2-Layer Water Balance Method is based on a formulation presented in Yan and Smith (1994), the main purpose of which is to calculate actual evapotranspiration and the amount of water that recharges the saturated zone. The module is particularly useful for areas with a shallow groundwater table, such as swamps or wetlands areas, where the actual

evapotranspiration rate is close to the reference rate. The 2-Layer Water Balance Method includes the processes of interception, ponding, and evapotranspiration, while considering the entire unsaturated zone to consist of two `layers' representing average conditions in the unsaturated zone. The vegetation is described in terms of leaf area index (LAI) and root depth.

At this point in the model setup, only a reference ET is needed for the Climate module. The reference evapotranspiration is the rate of ET from a reference surface with an unlimited amount of water. This value is independent of everything but climate and can be calculated from weather data. Aadland et al. (1995) has reported an annual evapotranspiration of about 32 inches for South Carolina; therefore, a constant reference ET value of 2.22 mm/day was used. The reference ET will then be adjusted according to the vegetation data (leaf area index and root depth) described in the following section.

In addition, station-based time series data of reference ET (RET) were acquired from the only available station within Aiken County. RET data was downloaded from January 2008 to December 2015. This data was processed and interpolated/extrapolated to be used in the MIKE SHE station-based ET model.

Table 4. Parameter Values Used in the MIKE SHE – ET Module

Parameter	Value	Unit
Detention Storage	2.5	mm
Surface-Subsurface Leakage Coefficient	0.0001	1/sec
Reference Evapotranspiration	2.22	mm/day
Leaf Area Index	1.3 – 6.3	m^2/ m^2
Root Depth	0.0 – 4000	mm

Unsaturated Flow

The texture types of the various soils within the TBW study area were identified by investigating SRS soil map units on the basis of geologic formation, geomorphology, and soil parent material. Each soil texture has certain hydrological properties. The soil map was classified into 6 distinct categories which included 4 dominant soil types as loam, loamy sand, sand, sandy loam, and two additional categories as urban, and water within the study area (Figure 13).

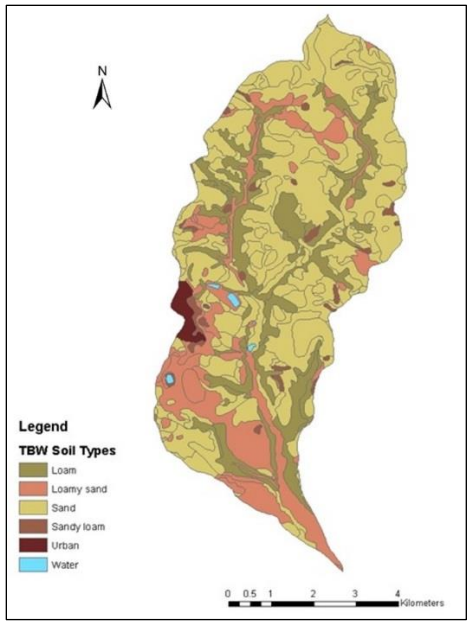

Figure 13. Soil type classification within Tims Branch Watershed.

The soil literature contains numerous assessments of soil water characteristics and hydraulic conductivity values, which are often not easy to determine experimentally. The van Genuchten (1980) water retention parameter is a simplified widely used approach for the prediction of soil water content as a function of pressure head. This model is represented by the following algorithm:

$$\theta = \theta r + \frac{(\theta s - \theta r)}{[1 + (\alpha h)^N]^M} \tag{1}$$

where: θ = water content; θ_r = residual water content; θ_s = total saturated water content; α = empirical constant, cm^{-1}; N = empirical constant; M = empirical constant; and h = capillary head, cm. The correlation between N and M is as follows:

$$M = 1 - \frac{1}{N} \tag{2}$$

Hydraulic conductivity is expressed by:

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{2}} \left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_s}\right)^{\frac{1}{M}}\right]^{M}\right\}^{2} \tag{3}$$

where $K(\theta)$ is the hydraulic conductivity for a given water content (cm h^{-1}) and K_s is the saturated hydraulic conductivity (cm h^{-1}). Parameters for equation (1) were obtained from the Carsel and Parrish database (1988).

As previously mentioned, the UZ module was developed using two methods: the Two Layer Unsaturated Zone (Figure 14 through Figure 17), and the Richards Equation (Figure 18 & Figure 19). The Richards equation is set to be used for the preliminary simulation setup.

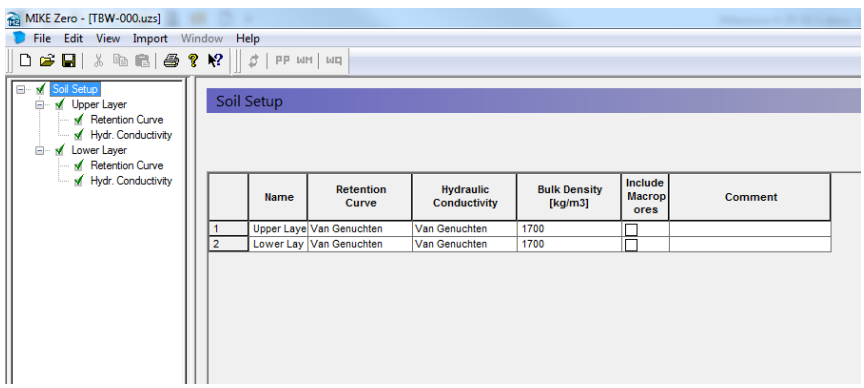

Figure 14. Two Layers UZ setup in MIKE SHE. For each layer, retention curve and hydraulic conductivity have been defined.

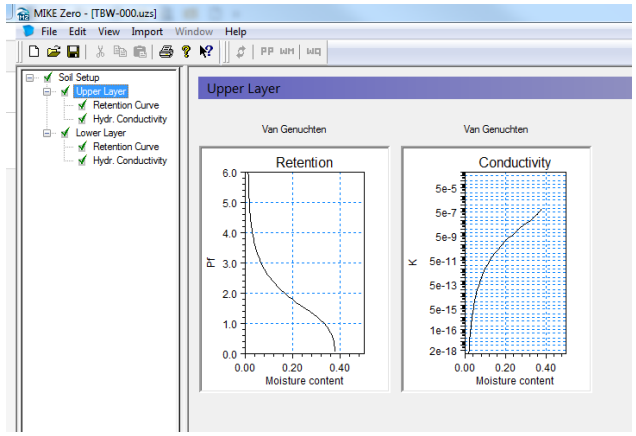

Figure 15. Two-Layers UZ retention curve and hydraulic conductivity. These parameters have been set up for each layer separately.

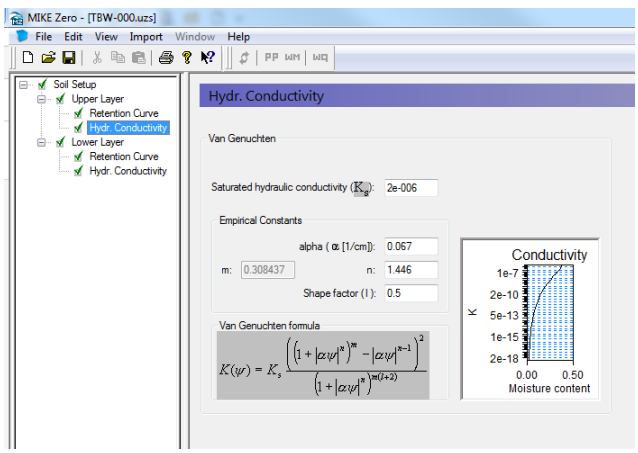

Figure 16. MIKE SHE default parameters for UZ module using two-layers set up.

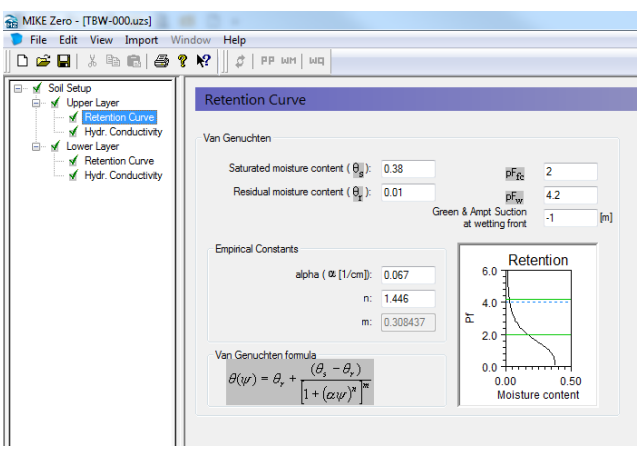

Figure 17. MIKE SHE default is being used for preliminary simulation in UZ set up.

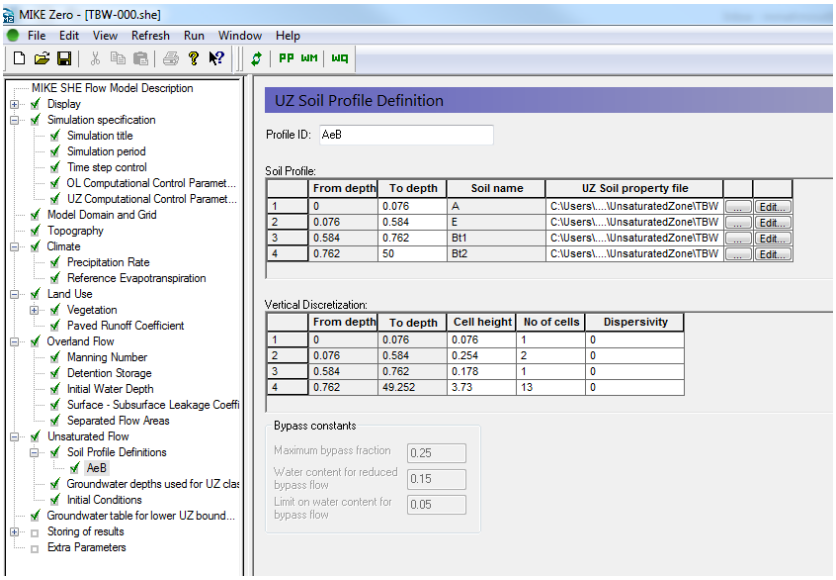

Figure 18. UZ set up module using Richards Equation. A uniform soil type of AeB (Ailey sand, 2 to 6 percent slopes, wet substratum) has been set up. This soil consists of four horizons.

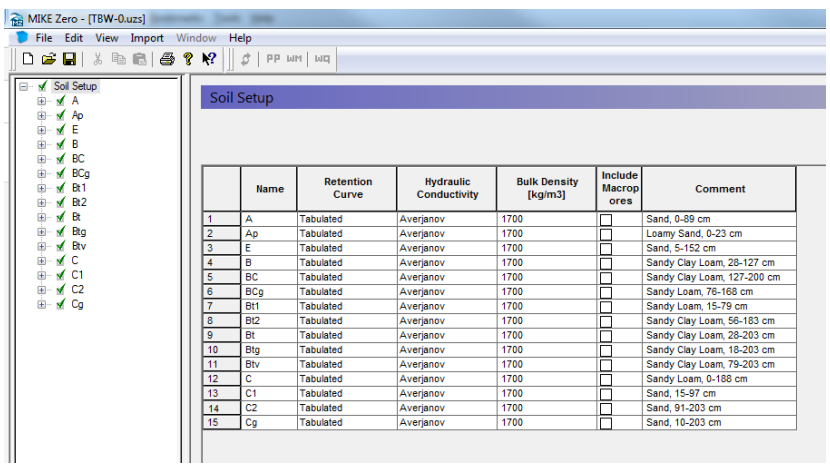

Figure 19. UZ file set up for soil horizons. Data was acquired from Web Soil Survey for South Carolina.

The spatial soil profile definition has been developed using both uniform and distributed methods. Currently, uniform spatial distribution has been set up. Soil profile data was acquired from the US Department of Agriculture (USDA) Web Soil Survey website. Each soil profile is comprised of several layers (horizons). The thickness of each layer varies from one soil type to another ranging from 0 – 80 in. Soil profiles consist of layers such as sand, sandy loam, loamy sand, and sandy clay loam. The complete report of various soil profiles is attached as an MS Excel file (Horizons.xlsx). Vertical discretization has been defined according to soil layer thickness, and considering finer discretization closer to the ground surface and coarser

discretization for deeper layers. In this model set up, the uniform soil profile is classified into 4 different uniform soil horizons. MIKE SHE unsaturated flow files (.uzs) for each soil horizon have been created. A total of 4 horizons were prepared. Default parameters have been used as a preliminary setup for soil characterization. Vertical discretization is set to represent 8 cell layers with various heights. Table 5 shows details of the cell discretization.

Table 5. UZ Vertical Discretization

From depth (m)	To depth (m)	Cell height (m)	Number of cells
0	0.076	0.076	1
0.076	0.584	0.254	2
0.584	0.762	0.178	1
0.762	1.762	0.2	5
1.762	2	0.238	1
2	4	1	2
4	20	2	8
20	50	3	10

At SRS, the depth of the unsaturated zone (also known as the vadose zone) varies from 7 ft to 179 ft (Aadland et al., 1995; Hiergesell, 2004). In this model set up, 179 ft (~50 m) is assumed as the thickness of the unsaturated zone. Station-based time series data of the groundwater table was acquired from 4 stations. Only one station was found inside the SRS boundary. The other stations are within the neighboring counties (Aiken and Barnwell). Groundwater head time series data has been processed and converted to the format accepted by the MIKE SHE model. Uniform groundwater table depth is also being tested as an additional option for UZ module set up.

Overland Flow

The overland flow can be calculated using either a semi-distributed method or a finite difference method using the diffusive wave approximation. The finite difference method should be used when calculating detailed overland flow, while the semi-distributed, simplified method should be used for regional applications where detailed overland flow is not required.

The outer boundary condition for the overland flow solver is a specified head, based on the initial water depth in the outer nodes of the model domain. Thus, if the water depth inside the

model domain is greater than the initial depth on the boundary, water will flow out of the model. If the water depth is less than the initial depth on the boundary, the boundary will act as a source of water. The domain of the model is a delineated watershed, which should indicate that all of the water that falls within the domain flows to the rivers and out toward Tims Branch. For this reason, all of the overland flow within the domain is treated as a source of water and the Initial Water Depth is set to zero to ensure flow in this direction and not out of the domain. Detention Storage is used to limit the amount of water that can flow over the ground surface. For the model, detention storage is set to zero.

When the net rainfall rate exceeds the infiltration capacity of the soil, water is ponded on the ground surface. This water is available as surface runoff, to be routed downhill towards the river system. The exact route and quantity is determined by the topography and flow resistance, as well as the losses due to evapotranspiration and infiltration along the flow path. The water flow on the ground surface is calculated by MIKE SHE's Overland Flow module, using the diffusive wave approximation of the Saint Venant equations, or using a semi-distributed approach based on the Manning's equation. USGS has described a procedure for estimating the roughness factor (Manning's number) for densely vegetated flood plains (Arcement Jr and Schneider). The n value is determined from the values of the factors that affect the roughness of channels and flood plains. In densely vegetated flood plains, the major roughness is caused by trees, vines, and brush. The n value for this type of flood plain can be determined by measuring the vegetation density of the flood plain.

MIKE SHE assumes Manning's number equal to 1/n, inverse of actual n values, for a planar surface of infinite width with uniform rainfall. Precipitation falls on the plane, accumulates on the surface in response to the surface roughness, and flows down the slope in the positive x-direction. In the equation below, *y* is the local depth of water on the surface at any point along the surface and α is the slope.

$$q = M \cdot y^{5/3} \sqrt{\alpha} \tag{4}$$

Manning's n units = $s/m^{1/3}$. In MIKE SHE, Manning M units = $m^{1/3}/s$.

Detention Storage is used to limit the amount of water that can flow over the ground surface. For the model, detention storage is set to 2.5 mm. The domain of the model is a delineated watershed, which should indicate that all of the water that falls within the domain flows to the rivers and out toward Tims Branch. For this reason, all of the overland flow within the domain is treated as a source of water and the Initial Water Depth is set to zero to ensure flow in this direction and not out of the domain. The domain boundary is used as the Separated Flow Area. This will keep the water within the watershed and direct it toward the streams.

MIKE SHE Simulation

In this study, a hydrology model is being developed to simulate the overland flow for the TBW through full hydrological cycle. At the current phase of model development, Overland flow (OL), ET, and UZ flow modules have been developed using inputs parameters such as topography, soil, vegetation, precipitation and potential evapotranspiration. The stream flow (developing using MIKE 11) model and the MIKE SHE Saturated Zone (SZ) modules will be completed in subsequent phases of model development; therefore, no drainage network data or geologic formation was added to the simulation. In this modeling effort, the study area was divided into 66 m by 66 m cells. To simulate overland flow (OL), the input data of initial water depth on the surface, surface detention storage, and Manning's number (M) were included in the model. The initial surface water depth is assumed to be zero. MIKE SHE uses the surface detention storage parameter to limit the amount of water that can flow over the ground in the watershed. The surface depth of water must exceed the surface detention storage in order to flow overland, otherwise it becomes ponded water.

In MIKE SHE, the Manning M (also known as Strickler coefficient) is the inverse of the traditional Manning's value (n) which varies between 0.01 and 0.1, corresponding to M value between 10 and 100. The overland flow is significantly influenced by the Manning M value. The higher the value, the faster overland flow occurs. The value of Manning M used in the TBW model is shown in Table 1. In this study, the preliminary simulation was performed for a period of 2 months rainfall from 07/30/2014 to 09/30/2014. Future simulation will be performed for the period from 10/01/1993 to 09/30/1996 for which streamflow/discharge data was collected at the

USGS gauge station downstream of Tims Branch. Calibration and validation of the hydrological model will be performed in the future modeling framework using the USGS observed streamflow data. Calibration of the model will be performed during the period of 10/01/1993 to 10/01/1995 and model validation will be performed during 10/01/1995 to 09/30/1996. The model will be also tested for various scenarios including extreme rainfall and episodic storm events.

MIKE 11 Model Setup

In order to maximize the surface modeling capacity and enhance the existing modeling efforts, the preliminary development of a MIKE 11 stream model has been initiated prior to the planned timeframe outlined in the project technical plan. Two separate MIKE 11 stream models are under development, one for the A-014 outfall tributary and the other for the main stream of Tims Branch. MIKE 11 is a fully dynamic, 1-D modeling tool for simulation of flow, water quality, and sediment transport in estuaries, rivers, irrigation systems, channels, etc. The MIKE 11 hydrodynamic module (HD) uses an implicit, finite difference scheme for the computation of unsteady flows in rivers, channels, and estuaries. The HD module can simulate both sub-critical and supercritical flow conditions through a numerical scheme which adapts to time and space according to the local flow conditions, hydraulic structures, operation schedules, and tidal influence. MIKE 11 can be used independently as a stand-alone tool to simulate the flow conditions in a stream, or it can be coupled with the MIKE SHE model to simulate overland flow in the watershed.

Developing a model with MIKE 11 includes creating various model-specific files which involve different types of input data such as channel network (.NWK11), river cross-section (.XNS11), boundary condition (.BND11), and rainfall-runoff (.RR11). Hydraulic structures such as weirs, and culverts can also be introduced in the network and simulation.

In this study, MIKE 11 is used to simulate flow depth and velocity in both Tims Branch and the A-014 outfall tributary. Preliminary model setup was initiated by creating the channel network and cross-sections. The two stand-alone MIKE 11 models are under development and will be completed during the second phase of this project. The final model will be coupled with the

MIKE SHE watershed model to simulate the flow conditions in the entire Tims Branch watershed.

RESULTS AND DISCUSSION

Preliminary simulation of overland flow has been implemented to illustrate the model performance for a two-month period of August through September 2014. Rainfall data from August 01, 2014 to September 30, 2014 was used to perform this simulation. Figure 20 through Figure 23 show the results of the flow depth simulation in four different time steps. Each figure shows a snapshot of a specific time during the model simulation. Simulations were initially performed for the original TBW domain which was limited to SRS boundary. Several modifications were made to the input files in order to expand the simulation domain to cover the entire TBW.

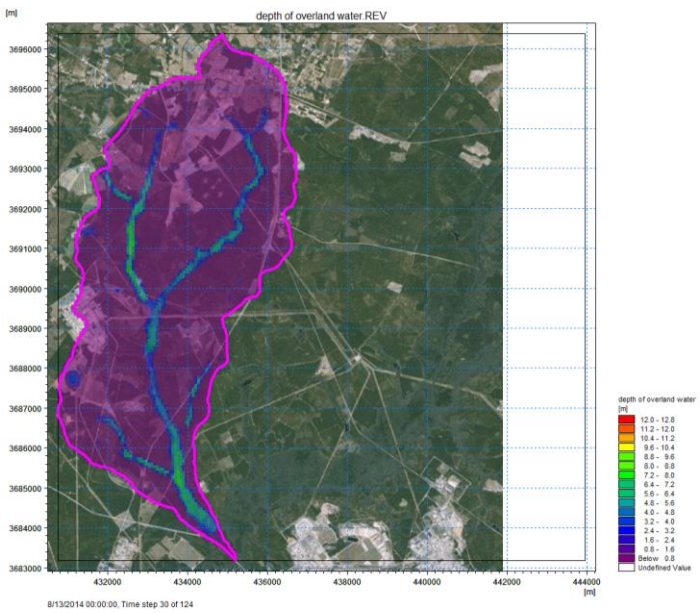

Figure 20. Depth of overland flow – day 13 of simulation (Aug. 13, 2014).

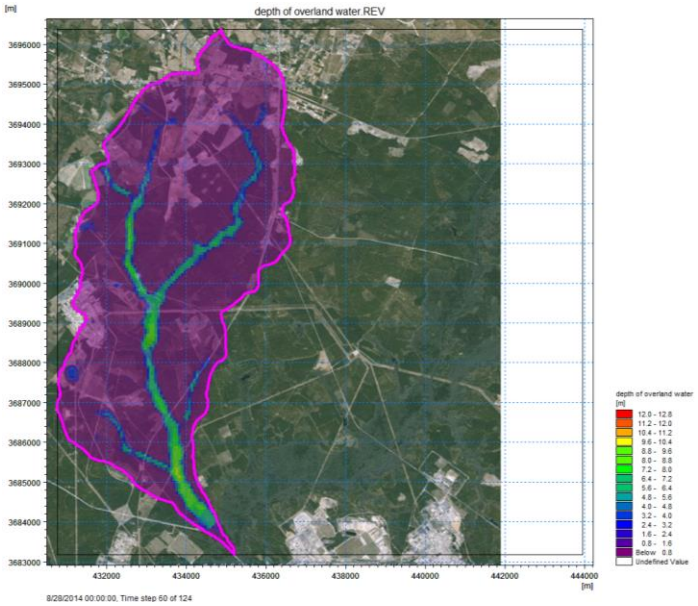

Figure 21. Depth of overland flow – day 28 of simulation (Aug. 28, 2014).

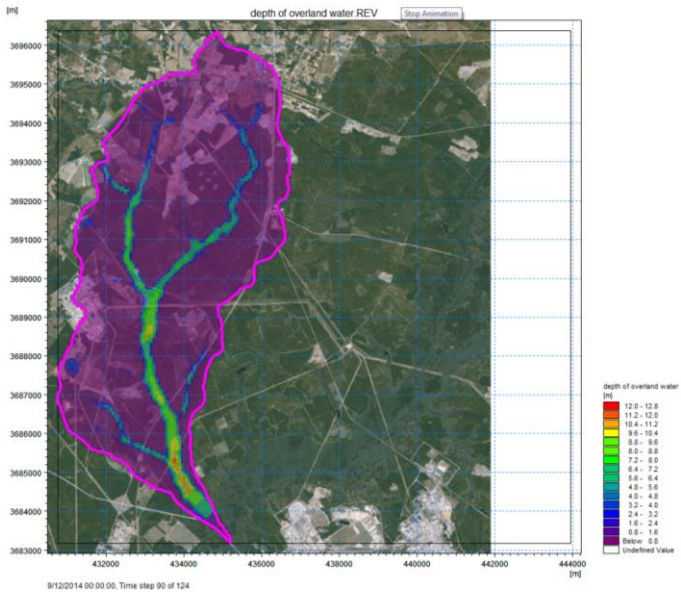

Figure 22. Depth of overland flow – day 43 of simulation (Sept. 12, 2014).

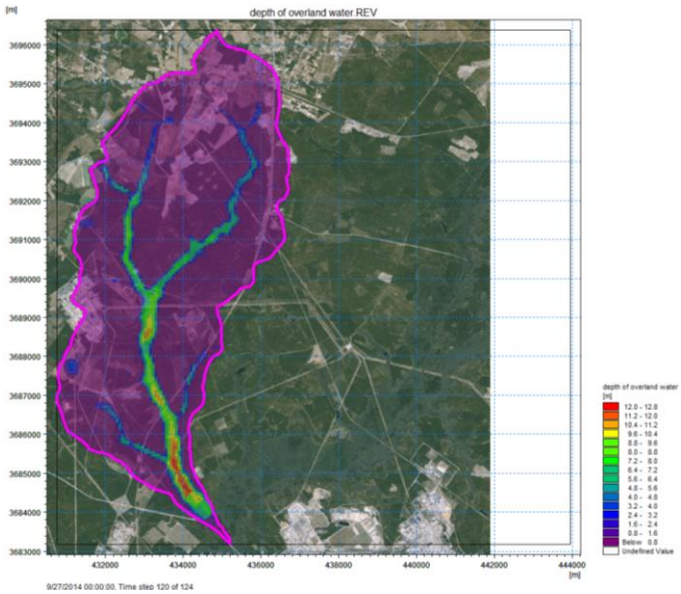

Figure 23. Depth of overland flow – day 57 of simulation (Sept. 27, 2014).

Figure 20 through Figure 23 show continuous increase in depth of water in Tims Branch as the time progresses. They also illustrate the variation in the depth of overland flow in the TBW due to rainfall intensity and distribution.

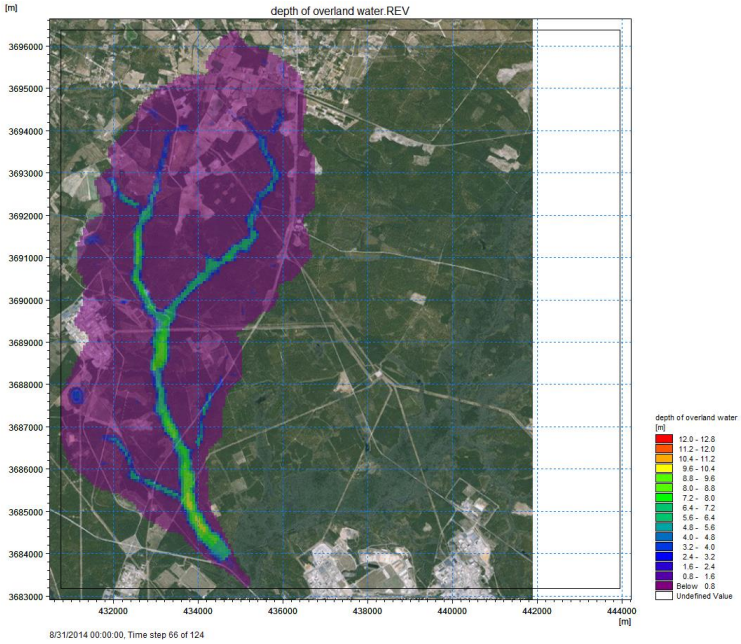

Figure 24: Depth of overland flow during the high intensity rainfall on Aug. 31, 2014. Maximum of 70 mm of rain was recorded during that day.

Figure 24 shows an increase in depth of water for a single relatively heavy rainfall event which occurred on August 31, 2014. Although the simulation results are preliminary with no calibration involved, visual comparison between and Figure 21 (3 days prior to the rainfall event) and Figure 24 indicates the rapid increase in depth of water downstream in Tims Branch due to heavy rainfall.

The main purpose of this study is to develop overland hydrology models capable of simulating surface flow depth and velocity throughout the TBW as well as to determine how extreme rainfall or storm events can remobilize and redistribute sediment and tin within the overland and river sub-domains, increasing the potential for tin methylation.

The model developed at this stage of the study is based on the MIKE SHE model that will be used as a tool to understand the dynamics of the different hydrological components of the Tims Branch Watershed and to perform a comparative assessment of these processes using alternative models. Preliminary model development has included the simulation of overland flow, which is one of the main components of the MIKE SHE modeling system in hydrological analysis due to the fact that a significant amount of water flows as overland flow/surface runoff that joins streams and waterbodies. Knowledge of the temporal and spatial distribution of overland flow helps to understand flow as a function of climate and catchment characteristics in the land phase of the hydrological cycle.

Model simulations performed so far are preliminary as not all of the hydrological components have been incorporated. However, model results already provide a general understanding of the watershed response as a function of precipitation and other catchment characteristics. The developed surface water model will undergo a considerable calibration and validation process using measured streamflow/discharge data within the target watershed. The calibration of the model will refine the parameter values which will help to fully develop the integrated model for better representation of the watershed. Different statistical evaluation methods will be employed to ensure the accuracy of the calibration results. This calibration and validation exercise will help to improve the predictive capability and reliability of the model.

FUTURE WORK

Development of the surface model of the TBW has been planned in three phases. The past year (2015 – 2016) was primarily focused on the completion of Phase 1 as shown in Figure 25, which involved extensive literature review, data acquisition, data processing, and preliminary MIKE SHE model development. Phase 2 will be fully initiated in the next year, although part of the MIKE 11 model development has been started ahead of schedule due in part to the training of FIU-ARC graduate students and DOE Fellows on how to use and implement the MIKE SHE and MIKE 11models in preparation for the next phase of model development.

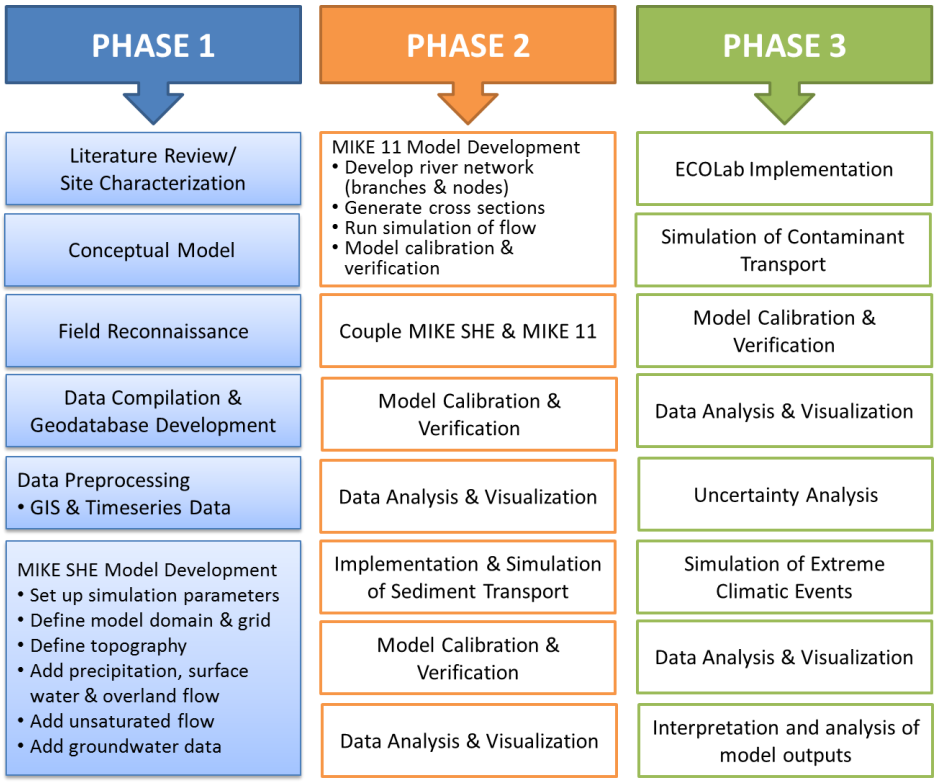

Figure 25. Project Technical Plan.

The future modeling tasks to be performed include:

1. Refinement of the input data for coupling of the surface water/groundwater model to include sub-surface parameters and develop the SZ module.

2. Running the UZ/SZ/ET modules simultaneously within MIKE SHE domain for prediction of the water balance of the TBW.
3. Calibration of the model will be carried out to evaluate and refine parameter values by comparing simulated and observed values in an attempt to develop a model that represents the watershed. Different statistical evaluation methods will be employed to ensure the accuracy of the calibration results. This calibration and validation exercise helps to improve the predictive capability and reliability of the model. The main steps used for model calibration include: identification of calibration parameters, sensitivity analysis and numerical optimization.
4. Development of two separate 1-D river models using MIKE 11, one for the entire Tims Branch stream and the second for the A-014 outfall tributary.
5. Calibration and validation of the MIKE 11 river models in accordance with the MIKE SHE simulation of the TBW.
6. Coupling the MIKE SHE watershed model and the MIKE 11 river model.
7. Implementing complementary hydrologic and fate and transport models to complete a model comparison application.
8. Integration of the developed hydrology models with a fate and transport model to simulate contaminant transport in the TBW and stream.

REFERENCES

http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

http://oceanservice.noaa.gov/facts/lclu.html

Aadland, R. K., Gellici, J. A., Thayer, P. A., and Carolina, S., 1995, Hydrogeologic framework of west-central South Carolina, State of South Carolina, Department of Natural Resources.

Abbott, M., and Refsgaard, J., 1996, Distributed hydrologic modeling, Kluwer Academics, Norwell.

Amouroux, D., Tessier, E., and Donard, O. F., 2000, Volatilization of organotin compounds from estuarine and coastal environments: Environmental science & technology, v. 34, no. 6, p. 988-995.

Arcement Jr, G., and Schneider, V., Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains United States Geological Survey Water-supply Paper 2339.

Batson, V. L., Bertsch, P., and Herbert, B., 1996, Transport of anthropogenic uranium from sediments to surface waters during episodic storm events: Journal of Environmental Quality, v. 25, no. 5, p. 1129-1137.

Beven, K., and Kirkby, M., 1979, A physically based, variable contributing area model of basin hydrology: Hydrological Sciences Journal, v. 24, no. 1, p. 43-69.

Conrads, P. A., Roehl, E. A., Daamen, R. C., and Kitchens, W. M., 2006, Simulation of water levels and salinity in the rivers and tidal marshes in the vicinity of the Savannah National Wildlife Refuge, Coastal South Carolina and Georgia: U. S. Geological Survey.

Dai T., A. R., Alvi, K., Wool, T., Manguerra, H., Choski, M., Yang, H., and Kraemer, S., 2005, Characterizing spatial and temporal dynamics: Development of a grid-based watershed mercury loading model. American Society of Civil Engineers Conference Proceedings. Managing Watersheds for Human and Natural Impacts: Engineering: Ecological, and Economic Challenges, Williamsburg, Virginia, USA.

Dai, Z., Li, C., Trettin, C., Sun, G., Amatya, D., and Li, H., 2010, Bi-criteria evaluation of the MIKE SHE model for a forested watershed on the South Carolina coastal plain: Hydrology and Earth System Sciences, v. 14, no. 6, p. 1033-1046.

Donard, O., and Weber, J., 1985, Behavior of methyltin compounds under simulated estuarine conditions: Environmental science & technology, v. 19, no. 11, p. 1104.

Feaster, T. D., Benedict, S. T., Clark, J. M., Bradley, P. M., and Conrads, P. A., 2014, Scaling up watershed model parameters: flow and load simulations of the Edisto River Basin, South Carolina, 2007-09: United States Geological Survey.

Feaster, T. D., Golden, H. E., Conrads, P. A., and Bradley, P. M., 2012, Simulation of Streamflow in the McTier Creek Watershed, South Carolina, Using TOPMODEL and GBMM.

Hallas, L., and Cooney, J., 1981, Tin and tin-resistant microorganisms in Chesapeake Bay: Applied and environmental microbiology, v. 41, no. 2, p. 466-471.

Halverson, N., 2008, Final Report on the Aquatic Mercury Assessment Study: SRS.

Hayes, D., 1984, Uranium studies in the Tims Branch and Steed Pond system: Westinghouse Savannah River Co., Aiken, SC (United States).

Hiergesell, R., 2004, An Updated Regional Water Table of the Savannah River Site and Related Coverages: Savannah River Site (US).

Kilgo, J., 2005, Ecology and management of a forested landscape: fifty years on the Savannah River Site, Island Press.

Kristensen, K., and Jensen, S., 1975, A model for estimating actual evapotranspiration from potential evapotranspiration: Nordic Hydrology, v. 6, no. 3, p. 170-188.

Lanier, T., 1997, Determination of the 100-year flood plain on Fourmile Branch at the Savannah River Site, South Carolina, 1996, US Department of the Interior, US Geological Survey.

Looney, B., 2001, Ultralow Concentration Mercury Treatment Using Chemical Reduction and Air Stripping: Savannah River Site (US).

Looney, B., Jackson, D., Peterson, M., Mathews, T., Southworth, G., Paller, M., Bryan, L., Eddy-Dilek, C., and Halverson, N., 2010, Assessing Potential Impacts of Stannous Chloride Based Mercury Treatment on a Receiving Stream Using Real-World Data from Tims Branch, Savannah River Site: SRS.

Looney, B., Larry, B., Mathews, T. J., Peterson, M. J., Roy, W. K., Jett, R. T., and Smith, J. G., 2012, Interim Results from a Study of the Impacts of Tin (II) Based Mercury Treatment in a Small Stream Ecosystem: Tims Branch, Savannah River Site: Oak Ridge National Laboratory (ORNL).

Maguire, R., Tkacz, R., Chau, Y., Bengert, G., and Wong, P., 1986, Occurrence of organotin compounds in water and sediment in Canada: Chemosphere, v. 15, no. 3, p. 253-274.

Mast, M. A., and Turk, J. T., 1999, Environmental characteristics and water quality of hydrologic benchmark network stations in the midwestern United States, 1963-95, US Geological Survey.

van Genuchten, M. T., 1980, A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils: Soil Science Society of America Journal, v. 44, no. 5, p. 892-898.

Varlik, B., 2013, Total Maximum Daily Load Document Tims Branch SV-324 and Upper Three Runs SV-325 Hydrologic Unit Codes 030601060501, 030601060502, 030601060503, 030601060504, 030601060505, 30601060506.

Wolock, D., 1993, Simulating the variable-source-area concept of streamflow generation with the watershed model TOPMODEL: US Geological Survey, Water Resources Division; US Geological Survey, Books and Open-File Reports [distributor].

Yan, J., and Smith, K. R., 1994, Simulation of Integrated Surface Water and Ground Water Systems-Model Formulation: Journal of the American Water Resources Association, v. 30, p. 879-890.