FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

THE EFFECTS OF FREQUENT ATMOSPHERIC EVENTS AND HYDROLOGIC

INFRASTRUCTURE ON FLOW CHARACTERIZATION IN TIMS BRANCH AND

ITS MAJOR TRIBUTARY, SC

A thesis submitted in partial fulfillment of the

requirements for the degree of

MASTER OF SCIENCE

in

CIVIL ENGINEERING

by

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2018

To: Dean John L. Volakis
    College of Engineering and Computing

This thesis, written by Mohammed Albassam, and entitled The Effects of Frequent Atmospheric Events and Hydrologic Infrastructure on Flow Characterization in Tims Branch and its Major Tributary, SC, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

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Date of Defense: June 15, 2018

The thesis of Mohammed Albassam is approved.

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Florida International University, 2018

ACKNOWLEDGMENTS

I would like to acknowledge and sincerely thank all who contributed to the work presented in this thesis. Specifically, I would like to thank my committee members, starting with my major advisor Dr. Shonali Laha, who, without her support, this work would not have progressed to this stage. In addition, I would like to thank Dr. Leonel Lagos for the opportunity to be a DOE Fellow and participate in meaningful research upon which this thesis is based. Finally, I would like to thank Dr. Walter Tang for providing insightful perspective during this research.

At the Applied Research Center, I would like to thank my mentor Dr. Mehnoosh (Noosha) Mahmoudi whose mentoring went beyond the technical subject of this work and who always paved a clear path for me to take. I would also like to thank Ms. Angelique Lawrence and the rest of the modeling and simulation team.

Finally, I would like to thank my family, especially my lovely parents for all their support and sacrifice during my journey from childhood to a Master's degree student in engineering. Their love and care has been a constant source of inspiration for me. Without them I am nothing, so may God keep them safe and healthy, as I will always be in need of their inspiration in my life.

ABSTRACT OF THE THESIS

THE EFFECTS OF FREQUENT ATMOSPHERIC EVENTS AND HYDROLOGIC

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by

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Hydrological models are powerful tools used to predict water systems behavior such as flow and water level characteristics for rivers and streams. In this research, a fully dynamic 1-D model was developed using the MIKE 11 model for a specific stream called A-014, this stream is in the Savannah River Site (SRS), SC.

A field study was conducted in order to collect data needed as inputs for the model development. Data like water velocity and cross-section measurement played a major role in understanding the behavior of the A-014 and the validation of our model.

Results showed a correlation capable to predict the water flow of the A-014 stream and how it can be affected by atmospheric events and hydrologic infrastructure. Rain fall events had a big effect in the stream flow by increasing it along many cross-sections. In addition, hydrological infrastructures effected the stream flow by slowing

it down and by forming ponds around the culvert and weir which are located in the A-014 stream.

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Chapter I - Background

The U.S. Department of Energy (DOE) has one of the richest and most diverse histories in the Federal Government. It all began in 1977, shortly after the Manhattan Project was implemented. After the development of the atomic bomb during World War II, USDOE began energy-related programs that had previously been dispersed throughout various federal agencies (Carnes, Schweitzer, Peelle, Wolfe, & Munro, 1998).

The DOE's Office of Environmental Management (DOE-EM) program was established in 1989 to address the nation's Cold War legacy of environmental contamination, resulting from five decades of nuclear weapons production and government-sponsored nuclear energy research. While pursuing this mission, DOE-EM is committed to sound safety principles and will continue to maintain and demand the highest safety performance to protect workers and communities where DOE-EM cleanup activities occur. The DOE-EM has an overall straightforward goal, to complete remediation in a safe, secure, and compliant manner within prescribed costs and schedules. As the largest environmental cleanup program in the world, DOE-EM has been mandated to remediate up to 107 sites across the country. Fortunately, nearly 91 of the total 107 sites have completed their projects with successful outcomes (Burger, 2008).

The Savannah River Site covers almost 200,000 acres (310 square miles), which contain parts of Aiken, Barnwell, and Allendale counties in South Carolina. During construction, there were a total of five reactors built in order to generate nuclear fuel for the defense program. The primary motive of construction was to produce the basic materials

necessary in the fabrication of nuclear weapons, primarily tritium and plutonium-239. Five reactors were also built in an effort to produce these materials for our nation's defense programs. In support of these efforts, the Savannah River National Laboratory (SRNL) was created. SRNL has evolved to be designated as the only national laboratory for the DOE-EM and is the nation's only complete nuclear material management facility.

At the U.S. Department of Energy's Savannah River Site (SRS) in Aiken, SC, the contamination of soil and streams was compounded by insufficient knowledge and inadequate regulations during the early years of facility operation (Crowley & Ahearne, 2002). Previously in SRS, the United States government manifested the release of contaminants into the environment and is currently involved in numerous cleanup projects in order to remediate the damage and protect the health of the wildlife and the community. Extensive methods such as monitoring wells, which have been constructed to monitor, identify and quantify mechanisms to control processes enabling the transport of these contaminants.

Many supporting facilities were constructed in different locations within the site including the A/M area, which occurs within this project's study domain. The administrative buildings were located in the A area, and the fuel and target fabrication facilities of SRS were situated in the M area (Solutions, 2011).

In the late 1950s and early 1960s, high-strength process wastes such as metal plating wastewater and aluminum forming were discharged into the headwaters of the A-014 outfall tributary, which is located in the Tims Branch watershed. Between 1958 and 1979 a settling basin was constructed to receive the contaminated wastewater produced by the

nuclear fuel fabrication facilities. As a result, the discharge of process wastewater created major contamination of the Tims Branch watershed ecosystem and its groundwater system. Starting from 1985, another stream located in the A/M area called Tims Branch (connects to A-014) has been receiving treated ground water from an air striper (M-1) as showed in figure 1, the air stripping process was used to remove chlorinated solvents from the ground water. Later in 2007, an innovative treatment process to remove mercury (Hg) from the ground water was established (Mary Beth Reed, 2006). The injection of stannous chloride (SnCl2) will convert the mercury from Hg (II) to Hg (0) which is a strippable form (volatile). The result of this treatment method lowered the discharge of mercury from approximately 250 ppt to 10 ppt into the Tims Branch system including the A-014 stream, which is below the national pollution discharge elimination system (NPDES) permit limit of 51 ppt (monthly average). The gas emissions from the M1 air stripper including Hg (0) are captured and regulated by air permits and waivers from the environmental protection agency (EPA), and it has been monitored monthly (Mathews et al., 2015).
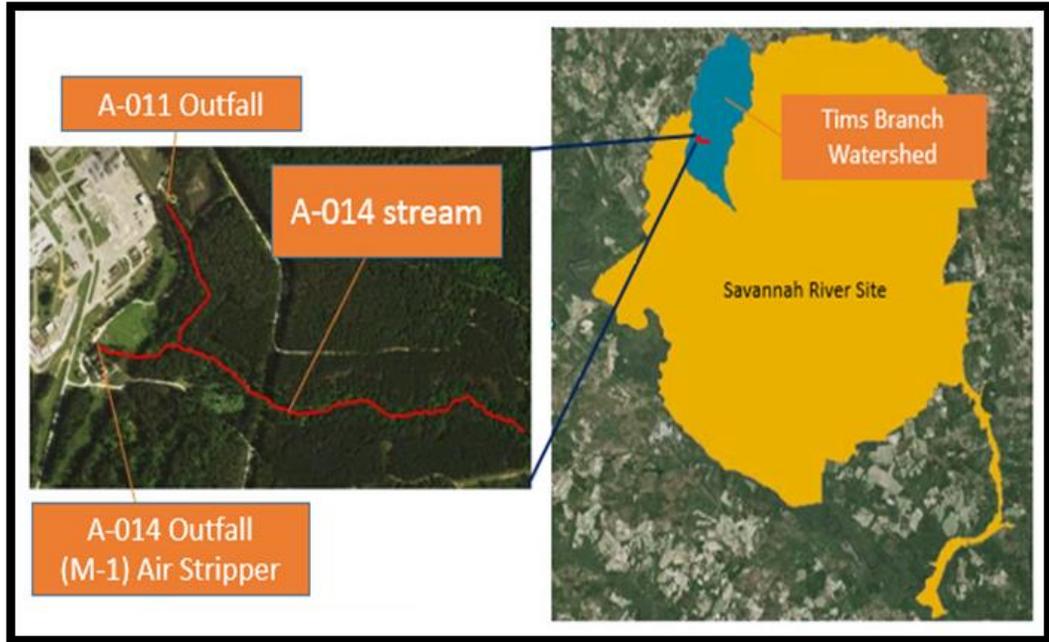
Figure 1: Savannah River Site (Tims Branch System in GIS)

The M-1 air stripper discharges the treated groundwater via the A-014 outfall into the receiving tributary referred to as the A-014 outfall tributary, which is the stream being modeled in this research. The A-014 outfall tributary originates in the SRS A/M area and flows into the Tims Branch stream. A flow model is being developed to predict the water movements in the A-014 outfall tributary during regular and extreme atmospheric events. This is very important since this is the first step in simulating the fate and transport of pollutants in the Tims Branch watershed. In addition, the A-014 outfall tributary contains a weir that was built in order to slow down the flow of water coming from the A-014 outfall. The model being developed will be able to capture the impacts on stream flow of such engineered hydrologic control structures. Finally, the developed A-014 model will serve as the basis for any further surface water hydrological model development efforts at SRS.

Chapter II - Literature Review

This literature review will cover the theory and practice of hydrological modeling both nationwide and worldwide. Firstly, an overview of the hydrologic cycle and surface water flow will be provided. This will be followed by theoretical background on surface water hydrological modeling and its application worldwide, in the United States, and specifically at the Savannah River Site (SRS) located in South Carolina. The review will conclude with surface water hydrology applications, specifically focusing on those where the MIKE 11 stream flow model was used.

2.1 The Hydrologic Cycle

The hydrologic cycle is the continuous process by which water is circulated throughout the Earth and its atmosphere. Water transitions into ice, fresh water, saline water and atmospheric water depending on a wide range of climatic variables. This partitioning occurs through the physical processes of evaporation, condensation, precipitation, infiltration, surface runoff, and subsurface flow as seen in figure 2 which was derived from the United States Geological Survey (USGS) below.
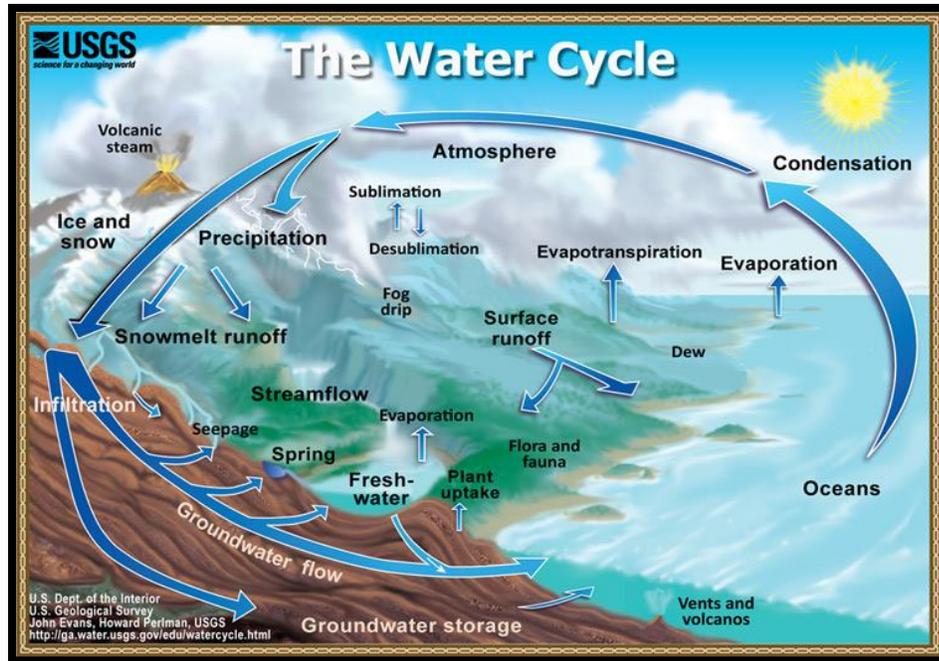
Figure 2: The Water Cycle ("The Water Cycle," 2017)

The hydrologic cycle is essential for the maintenance of most life and ecosystems on the planet. Besides providing people, animals and plants with water, the hydrologic cycle is important as it moves nutrients, contaminants and sediment in and out of aquatic ecosystems. Streams and rivers play a critical role in the hydrologic cycle. Surface water/groundwater interaction and stream flow are significant in the movement of water from underground aquifers over land to the oceans. For this reason it is important to study hydrological systems which determine the fate and transport of contaminants.

2.2 Surface Water Flow

River or stream flow is defined as the volume of water that moves through a given area of a water body within a specific period of time. The water flow is usually measured in cubic feet per second (cfs). One method of determining the flow rate in a stream is to first measure its cross-sectional area, then use a flow tracker or flow rate sensor to measure

the velocity of the water through this cross-section. The discharge/flow (Q) can then be calculated via the following algorithm (where A represents the cross-sectional area and v is the water velocity):

$$Q = v * A \quad (1)$$

Flow plays a major factor in any stream ecosystem; it is responsible for most of the physical and chemical characteristics of the stream. Many studies have shown that stream flow can modify the chemical and biological aspects of a stream. Aquatic plants and animals depend upon stream flow to bring vital food and nutrients from upstream, or remove wastes downstream (Johnson, Redding, & Holmquist, 2007).

2.3 Hydrology Modeling

Models are very powerful tools, which can be considered as simplified representations of real world systems. In hydrology studies, models are used to predict the behavior of hydrologic systems such as lakes, rivers and even oceans. They also help in understanding the various hydrological processes occurring in each environmental compartment, and the factors that can potentially affect them (Devia, Ganasri, & Dwarakish, 2015). There are hundreds of hydrological models used around the world, with each model having a different capability. For example, there are steady state and dynamic models, one-dimensional to three-dimensional models, and models used for either point source or non-point sources (Wang, Li, Jia, Qi, & Ding, 2013).

Beside the capability of hydrology models to predict systems behavior for specific water bodies, many models have been developed in order to concentrate in a specific watershed system which means surface and subsurface hydrology (Golmohammadi, Prasher,

Madani, & Rudra, 2014). Watershed models including Soil and Water Assessment Tool (SWAT) and the MIKE package (including MIKE 11, the model used in this research) have been proven as a powerful tool in investigating the complex mechanism of predicting soil erosion and the fate and transport of contaminants in watersheds (Singh, Knapp, Arnold, & Demissie, 2005).

2.4 Modeling around the World

Water models around the world have an important history and have gone through many developments since Streeter and Phelps built the first water quality model (S-P model) to control river pollution in Ohio State in the US (Rauch et al., 1998).

As previously mentioned, each hydrological model has a different capability, Cao and Zhang classified existing water models based on water body types, model-establishing methods, water quality coefficients, water quality components, model properties, spatial dimensions, and reaction kinetics, In addition, it is known that each surface water quality model has its own limitations (Wang, Li, Jia, Qi, Ding, 2013). Some popular models used to simulate hydrological systems are represented below.

2.4.1 SWAT Model

The Soil and Water Assessment Tool (SWAT) is a public domain watershed scale model developed by the U. S. Department of Agriculture (USDA) to quantify the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time. SWAT can be used to simulate the cycling of water and nutrients at the basin scale. SWAT was designed to simulate nutrient and pesticide loading as well as

water and sediment transfer from agricultural runoff, which may contain hazardous chemicals. It is very complex physical model that can break down large catchment basins into smaller sub-catchments that are divided by hydrologic responses units or HRUs, vegetation and soil characteristics, and land use. This model uses the following water balance equation in order to obtain the most accurate forecasting of water and sediment transfer (Devia, Ganasri, & Dwarakish, 2015):

$$SW_t = SW_o + \sum_{i=1}^{t}(Rv - Qs - W_{seepage} - ET - Q_{gw}) \qquad (2)$$

Where:

SW_t : Soil humidity

SW_o : Base humidity

Rv : Rainfall volume (mm)

Qs : Surface water runoff

$W_{seepage}$: Seepage of water from soil

ET: Evapotranspiration

Q_{gw} : Ground water runoff

t : Time (days)

2.4.2 HBV Model

The Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrology model was developed by Sten Bargstrom at the Swedish Metrological and Hydrological Institute (SMHI) to simulate and analyze river discharge and water pollution, and has been used in more than 30 countries. The latest version of this model is called HBV-96 and includes improvements for its use in addressing hydrological problems related to hydropower production and design (Lindström, Johansson, Persson, Gardelin, & Bergström, 1997).

The general water balance equation used in this model is:

$$P - E - Q = \frac{d}{dt} (SP + SM + UZ + LZ + lakes) \qquad (3)$$

Where:

P: precipitation

E: Evaporation

Q: Runoff

SP: Snow pack

SM: soil moisture

UZ/LZ: Upper/lower ground water zone

The HBV model is noted to be better suited for cold weather countries since it was originally designed to assist the Scandinavian countries of Sweden, Norway, and Iceland based on its capability in simulating snow accumulation and melt rates in urban areas. In different watersheds, the HBV model uses the methodology of dividing the catchment basins into small sub-basins, then the model uses a normal daily values of rainfall, air temperature and the estimates of potential evaporation as a time series for its simulations to generate scenarios such as flood forecasting (Seibert, 1997).

2.4.3 TOPMODEL

TOPMODEL was originally developed in the United Kingdom; however, it has been extensively used in the United States, Germany, and Scotland. It is a topography-based hydrological model with a feature that integrates hydrological modeling with geographic information systems (GIS), in other words this model uses a topographic index as its main input parameter for the model development (Nystrom & Burns, 2011).

TOPMODEL also includes a set of programs for rainfall and runoff data modeling in catchment basins using gridded elevation data. More importantly it is used for measuring the factors effecting runoff, soil transmissivity, and water depth (Beven, 1997). One of the important advantages of the TOPMODEL is that it requires a few input parameters, which can be measured directly in situ (Gil & Tobón, 2016).

The following table, shows some of the advantages and disadvantages of the SWAT, HBV, and TOPMODEL (Cunderlik, 2003).

Table 1: Advantages and disadvantages of the models

Model	Advantage	Disadvantage
HBV	Can model most of the hydrologic systems with fairly low input data needed, user-friendliness	It can use only daily time step
SWAT	Very comprehensive model structure, can be linked with other software	Wide range of data needed in order to run the model
TOPMODEL	Has a broad coverage in research papers and public domains. Require a few input data	Lack of technical support

2.5 Modeling in the United States

Modeling in the U.S. has a long history, with the U.S. Environmental Protection Agency (USEPA) and the U.S. Geological Survey (USGS) playing major roles in the development of many hydrological models that have been used for decades both nationwide and worldwide. Table 2 lists some of the most widely used models that have been developed and used around the country (Wang, Li, Jia, Qi, Ding, 2013):

Table 2: Common models around the world

Model Name	Developer	Year	Capability
MODFLOW	USGS	1984	Simulating ground water flow and quality and predicts groundwater/surface-water interaction
QUAL	USEPA	1970	Monitoring non-point source pollutant, and that includes 1-d steady-state scenario or transition scenarios
WASP	USEPA	1983	Water quality simulation for rivers, streams, lakes, and wetlands, that includes 1-d,2-d, and 3-d models
BASINS	USEPA	1996	Integrates point and non-point pollutants sources and provide water quality analysis for watersheds
SWMM	USGS	1969	Used for planning, analyzing, and design stormwater runoff and it is a hydrology-hydraulic water quality simulation model
PRMS	USGS	2016	Evaluates the responses of various characteristics of climate and land use on streamflow in watershed hydrology

2.6 Modeling Efforts in SRS

Hydrological models have been used over the years to conduct environmental research at the Savannah River Site (SRS) in South Carolina; however, after extensive literature review, it became apparent that most of the models used were groundwater models, which were developed to track and monitor contaminated groundwater plumes that are still active today. One of the groundwater models widely used at the site was MODFLOW, which as previously discussed, is a groundwater modeling system generated by the USGS (Laboratory, 2010). In addition, there were some efforts where surface water models were employed in an attempt to understand the groundwater/surface water interchange in the SRS hydrological system, which may result in migration of contaminant plumes from underground aquifers into overlying surface water bodies via a

transition zone. One of the models used at SRS was the DYNHYD5 model which was developed by the EPA. This 1-D open channel hydrodynamic model was used to calculate channel flow cross-section areas for a given stream under various flow conditions. The DYNHYD5 model was applied at SRS in the McQueen and Tims Branches in order to simulate the transport of contaminants that were discharged into these two streams (Chen, 2000).

2.7 MIKE 11 Applications

MIKE 11 is software that was developed by the Danish Hydraulic Institute (DHI) and is a fully dynamic one-dimensional modeling package used to model rivers, channels, lakes, and reservoirs. MIKE 11 uses the dynamic Saint Venant equation (Mass conservation and fluid momentum conservation) to determine water level and flow.

MIKE 11 has many applications around the world based on its powerful capabilities to estimate flow and water levels of water bodies. The following describes some of its applications worldwide.

2.7.1 Euphrates River, IRAQ

A study was conducted in 2007 in Iraq using the MIKE 11 model, in which the unsteady flow of the Euphrates River was simulated. Field data was required in order to develop the model, and one of the most important pieces of information was the cross section measurement. In order to process the data for simulation, the following files were created:

1- River Network File: to define the river networks, cross-section and control structures located in the study area.

2- Cross Section File: contains the location and the cross section geometry measurements along the river network as shown in figure 3.
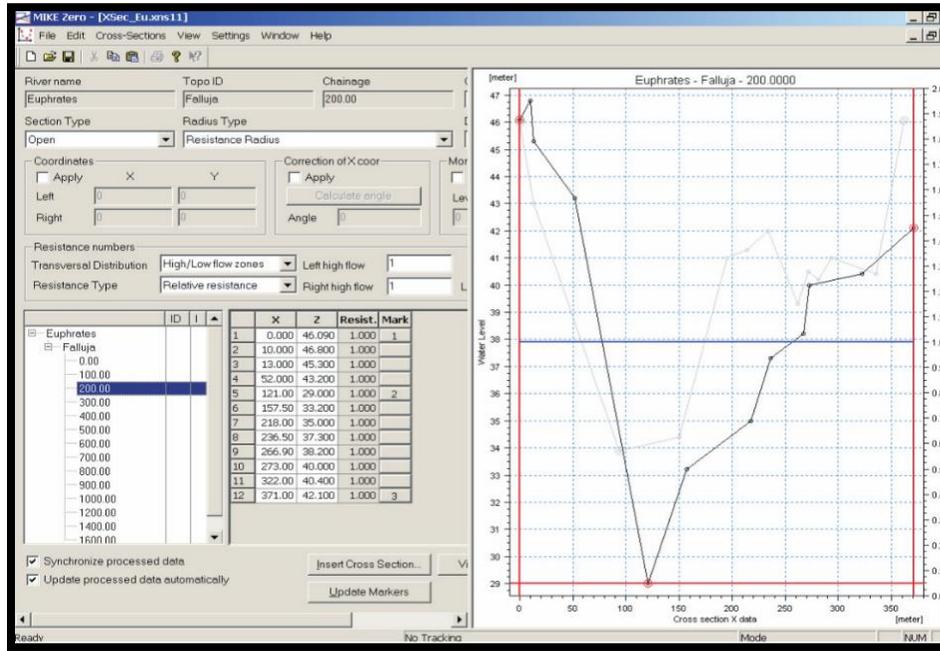
Figure 3: Cross section file for the river (Kamel, 2008)

3- Boundary File: consists of boundary conditions in a time-series form for the river network file.

4- The Hydrodynamic Parameter File: contains the bed and floodplain resistance data for the river.

The model approach taken resulted in an unsteady flow simulation along a stream channel reach. The method employed for validating the model was to compare a hydrograph (which the MIKE 11 model can generate) with the hydrographs of other models for the same study area (Kamel, 2008). It should be taken into consideration that the Euphrates River study was conducted in an area with high conflicts, so the data used in the model development might not be very accurate which is one of the limitations of this study.

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2.7.2 Rideau River, Canada

In this study, MIKE 11 was used to construct a detailed hydrodynamic model of the Lower Rideau river system located in Canada. This system is very complex and includes channels, drainage areas, and many control structures. In this study, the model was calibrated using measured stream flow data, which is similar to the method employed in this thesis research. The set-up of the Rideau River model was similar to the Euphrates River model set up, however the Rideau River model is much more accurate since it was developed and validated for almost 10 years. This model is now being used for various watershed management purposes, which include flood forecasting, dam safety assessment, quantification of wetland functions, and optimization of water control structures (Ahmed, 2010).

2.7.3 Grassland, South East England

In this study, both MIKE 11 and MIKE SHE were used to simulate an entire hydrological cycle in a grassland (a large scale Karts system located in South East England). MIKE SHE, another software component of the MIKE modeling package, is an integrated 3-D model that simulates surface and groundwater for an entire hydrological cycle, which includes infiltration, evapotranspiration, overland flow, groundwater flow, and channel flow. By coupling MIKE 11 and MIKE SHE, a fully dynamic representation of the linkage between the surface river flow and sub-surface flow of any hydrological system will be available. In Grasslands, this coupled model has been used to monitor the response of this hydrological system to atmospheric events, including 10 simulated years of rainfall data. The parameters used for the model calibration were within physical

ranges and some of them were fitting parameters. This study aimed at understanding and quantifying the physical processes occurring within the hydrological cycle, including extreme atmospheric events such as heavy rainfall and tornados (Doummar, Sauter, & Geyer, 2012).

2.8 Literature Review Summary

Literature review has shown MIKE 11 being used in various parts of the world to model different hydrological systems. These case studies were used to aid in the development of the flow model of the small stream described in this thesis, and provided comparative examples of the use of MIKE 11 at different scales and under varying hydrological conditions. Although spatial extent may vary, the same basic fundamental concepts will be applied in this study, with input parameters similar in nature to those used in the previous studies described above that were conducted in different parts of the world.

Chapter III - Research Objectives and Hypotheses

3.1 Research Objectives

The research objectives are:

a. Develop a fully dynamic 1-D model for the A-014 outfall tributary using MIKE 11 software.

b. Collect in-situ flow measurements and other data to support hydrological model devolvement for the Tims Branch watershed, SRS, SC.

This model development will ultimately be coupled with other models including MIKE SHE and ECO Lab to simulate the fate and transport of pollutants through the water bodies of the Tims Branch watershed.

3.2 Research Hypotheses

Atmospheric events, including extreme storms and heavy rainfall, play a major role in increasing the flow velocity of streams. Figure 4 below shows rainfall data for the years 2012 − 2016, the x-axis represent the year and the y-axis the rain intensity in mm/day. The data was extracted from the USGS online database for Aiken County, SC, and input into the MIKE SHE model.
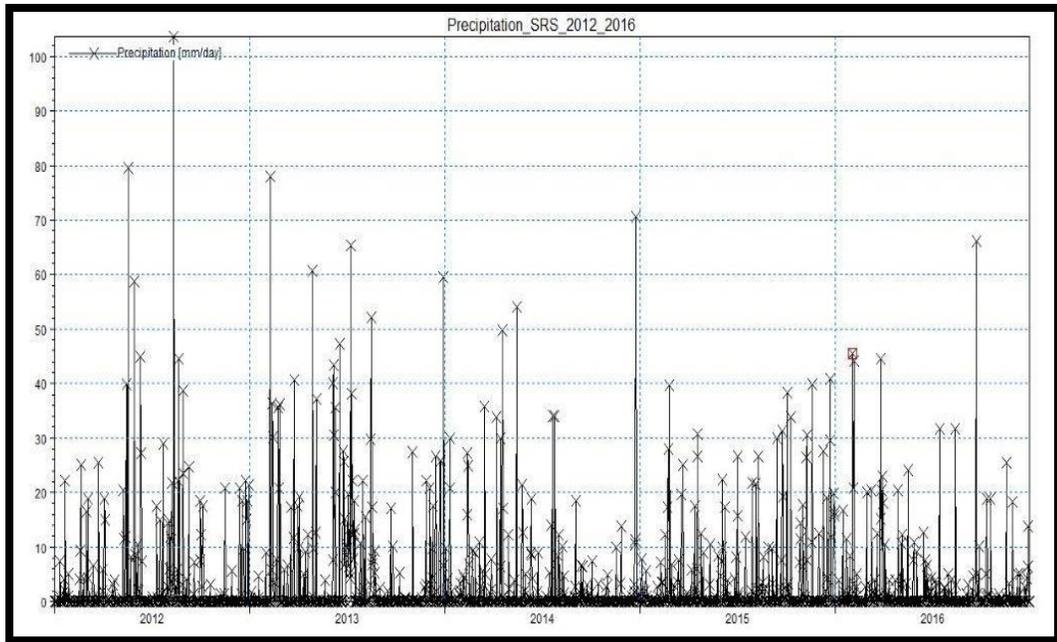
Figure 4: Rainfall data (2012-2016) for SRS as viewed in MIKE SHE

As we can see from the figure above, the rainfall for the years 2012 – 2016 (x-axis) ranges from 0 to more than 100 mm/day (y-axis) and the precipitation falls annually across the area. Based on the seasonal climate change in the area and the rainfall data, the water table and stream flow is constantly changing depending on the season (wet or dry). The aim of this research is therefore to develop a model that shows simulated data with peaks in discharge/flow rate at the same times when there are peaks in the observed rainfall input data.

Weirs and culverts are constructed to slow down the flow velocity of streams and have a major impact on the flow characteristics. A weir is a hydrologic infrastructure that is used as a barrier in streams and rivers. It is generally used to slow down and control the water flow of streams by changing the height of the water level. The A-014 outfall tributary contains a weir (figures 5 and 6) that was built in order to slow down the flow of water

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coming from the A-014 outfall. In addition, culverts are hydrologic infrastructures designed to slow down flow, pass water under roads, natural drainage, and stream crossings. Culverts can be designed in many shapes; however, round culverts that resemble an open pipe are the most common.
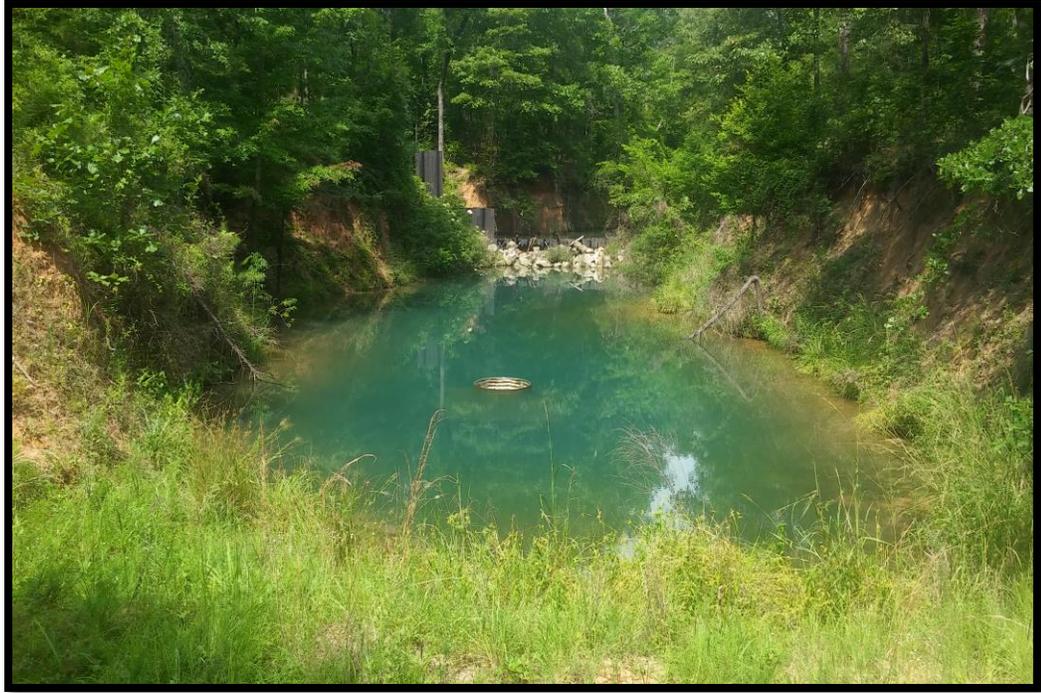
Figure 5: The pond formed around the A-014 culvert and weir (photo taken during 2016 field study)
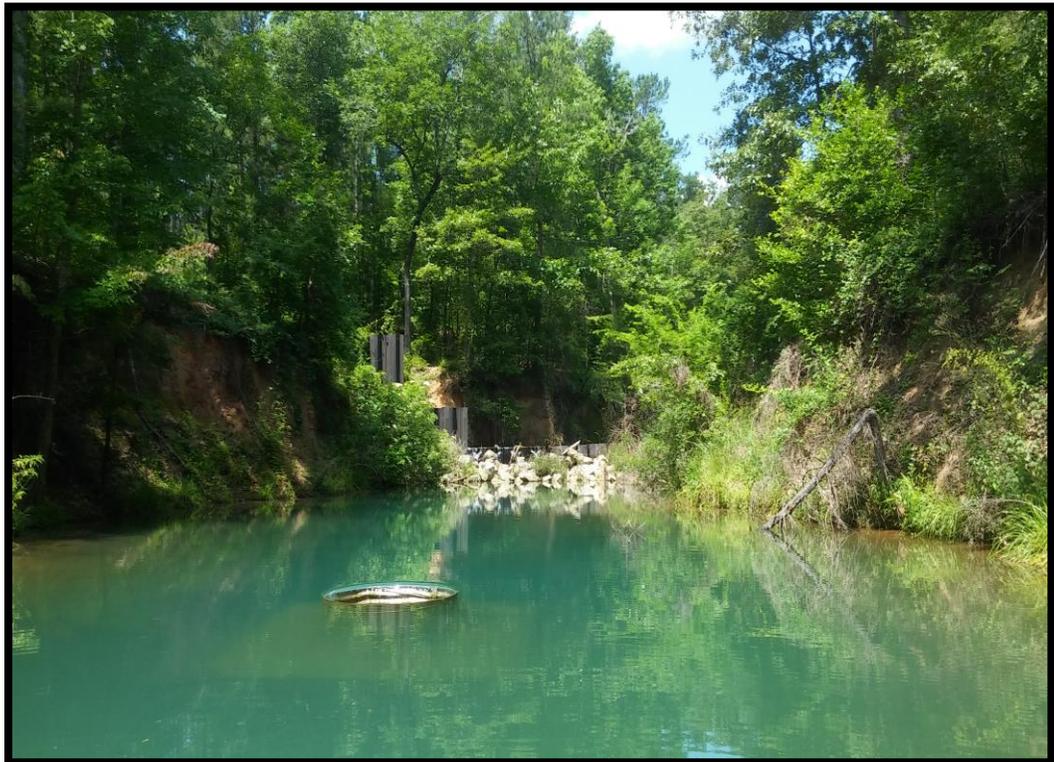
Figure 6: A-014 Culvert and weir (photo taken during 2016 field study)

Hypothesis #1: The developed model will be capable of simulating the impact of extreme atmospheric events, such as heavy rainfall or major storms, on the flow and water levels in the A-014 outfall tributary.

Hypothesis #2: The developed model will be able to simulate the flow velocity in the A-014 outfall tributary and capture the impact of engineered hydrologic control structures, such as weirs and culverts, on the stream's flow characteristics.

Chapter IV - Field Measurements and Data Collection

4.1 The Tims Branch Study Area

Tims Branch is a small stream-scale ecosystem located in the A and M areas (see Figure 7) of SRS that has received direct discharges of wastewater from on-site process and laboratory facilities contaminated with mercury, uranium, nickel, aluminum and other metals and radionuclides. The lower portion of Tims Branch has also received discharging groundwater containing trace organic solvent contaminants. A number of innovative treatment systems were deployed to limit the contaminant flux to Tims Branch, including a wetland treatment system (in the northern tributary in 2000) and a mercury removal system that uses a tin (II) reagent and air stripping (in the A-014 outfall tributary in 2007). The M-1 air stripper (figure 8) discharges the treated groundwater via the A-014 outfall into the receiving tributary referred to as the A-014 outfall tributary, which is the stream being modeled in this research.
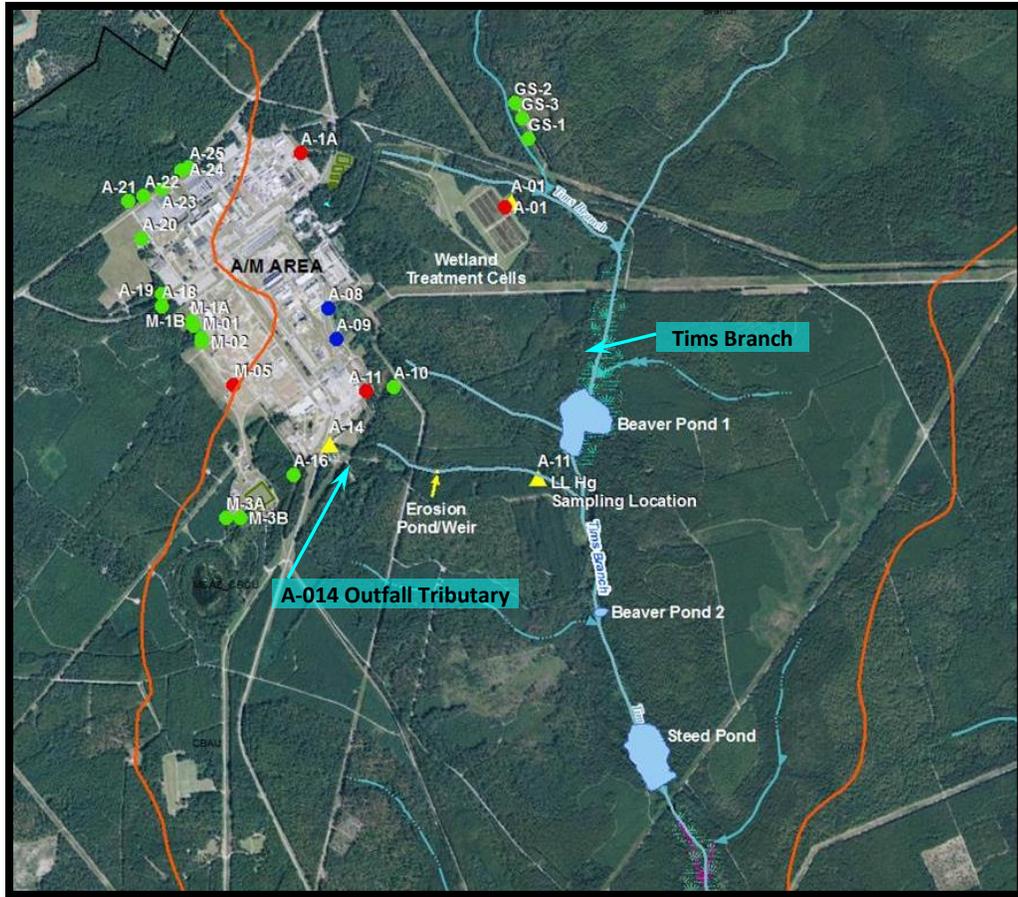
Figure 7: Location of SRS A/M Area, the A-014 outfall tributary and Tims Branch

Figure 8: M-1 air stripper (photo taken during 2016 field study)

The A-014 outfall tributary has the following characteristics:

- The length of the stream is approximately 1,500 m.

- The stream originates in the A/M area and drains into Tims Branch.

- A small stream that also originates in the A/M area and is referred to as the A-011 outfall tributary connects with the A-014 outfall tributary just outside of the A/M Area. The A-011 stream is approximately 350 m long and its outfall is about 216 m north of the A-014 outfall.

- The A-014 outfall tributary connects to the Tims Branch stream, which is connected to Upper Three Runs (a bigger stream), which eventually flows into the Savannah River that discharges into the Atlantic Ocean.

Table 3 shows the general land use percentage of the whole Savannah River Site and the A-014 Study Area. Land use/land cover is a significant parameter affecting runoff/overland flow.

Table 3: Land Use at SRS and the A-014 Study Area (LLC, 2009)

Land use	SRS Percentage %	A-014 Study Area Percentage %
Undeveloped	73 %	57 %
Wetlands/streams/lakes	22 %	10 %
Developed (e.g., buildings, roads)	5 %	33 %

4.2 In Situ Field Sampling and Data Collection

A rigorous calibration and validation exercise is necessary to increase confidence in a models' ability to estimate spatial distribution of flow depth and velocity, and contaminant concentration over time. The main challenges in hydrological modeling, however, are finding observed/measured time series data for the model calibration and validation process. As such, an analysis was conducted to identify data gaps and, where necessary, attempt to collect additional field data to support model validation. In the summer of 2016, field research was conducted at the Savannah River Site during which in-situ field measurements and data were collected. The in-situ field study was aimed of measuring cross-sections and stream flow velocity to support the Tims Branch watershed modeling effort. In particular, data was collected at several locations along the A-014 and A-011 outfall tributaries, the main streams receiving discharge from the A/M Area that flow into Tims Branch.

4.3 Flow Velocity Measurements

Flow velocity is the quantification of the bulk fluid movement, which can be measured in a variety of ways. A consistent record of observed flow data in the Tims Branch watershed will assist in calibration of the hydrological model being developed, and will improve the model's ability to estimate daily time series of stream flow and the potential for contaminant transport during extreme storm events.

4.3.1 Equipment Used

- Global Water Flow Probe (FP101 & 201)

The Global Water Flow Probe is a highly accurate water velocity instrument for measuring flows in open channels and partially filled pipes and consists of a protected water turbo prop positive displacement sensor coupled with an expandable probe handle ending in a digital readout display. The water flow meter incorporates true velocity averaging for the most accurate flow measurements and is therefore ideal for storm water runoff studies, sewer flow measurements, measuring flows in rivers and streams, and monitoring water velocity in ditches and canals.

Figure 9: FP101 Global Water flow meter ("FP101 & FP201 Global Water Flow Probe," 1990)

4.3.2 Methodology

1- A Global Water flow meter (FP101) (Figure 9) was used and calibrated with units set to SI units in meters per second (m/s).

2- The flow meter was held vertically upright with propeller (bottom part of flow meter) submerged in the water column oriented in the direction of flow, aiming the arrow indicator downstream, and moving it in a smooth vertical motion to measure the flow velocity.

Figure 10: Measuring water velocity in the A-014 stream at SRS during summer 2016

3- Three readings were recorded at each sampling location and an average value was computed.

4- After each measurement, the flow meter (computer display) was reset to zero.

5- Each sampling location was assigned an ID for tracking.

4.3.3 Results

The water velocity measurements were recorded in more than 18 locations along the Tims Branch watershed and several graphs were created based on the recorded data to understand the flow behavior. Table 4 below shows flow data recorded in the A-014 outfall tributary during site visits to SRS.

Table 4: Flow Data Recorded in the A-014 Outfall Tributary

Location ID	Location (m) (Dist., from ref. pt. A)	Flow Velocity (m/s)
A-014-1	0	0.12
A-014-2	141.90	0.04
A-014-3 (CULVERT-1)	238.6	0.27
A-014-4 (CULVERT-2)	266.03	N/A (no access)
A-014-5 (outfall)	328.19	0.05
A-014-6	450.19	N/A
A-014-7	913.5	0.05
A-014-8	932.87	0.04
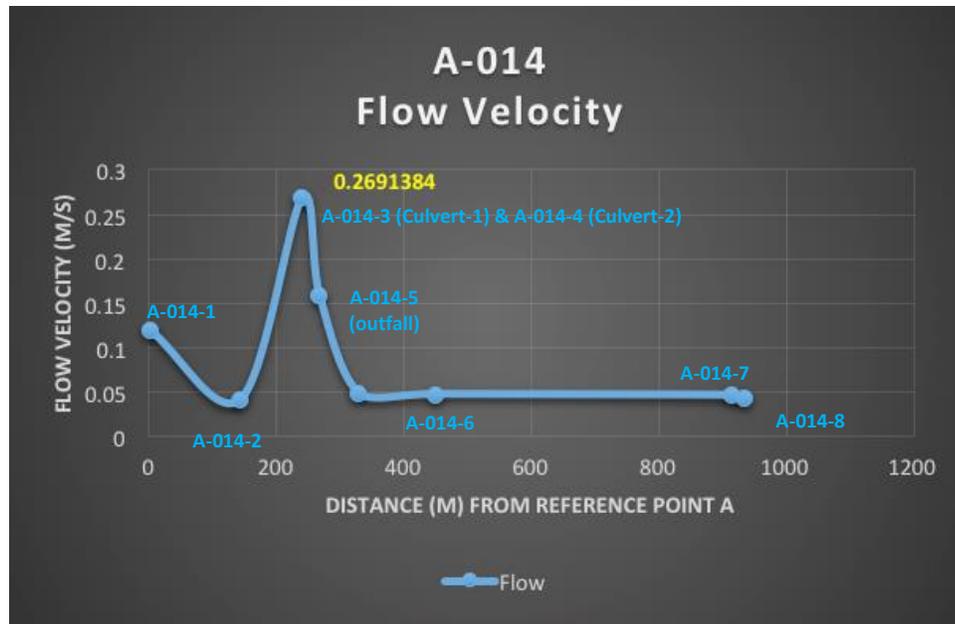
Figure 11: Measuring water velocity in the A-014 stream at SRS during summer 2016

Based on the data in Table 4 and associated plot in figure 11, the flow velocity in the A-014 outfall tributary generally ranged between 0.01 and 0.03 m/s, except for the area near the culvert where measurements of almost 0.3 m/s were recorded. This data was implemented for calibration and verification of the Tims Branch hydrology model and to determine the model's ability to simulate these hydrological conditions.

4.4 Cross-Section Measurements

Having an accurate representation of a stream's cross-sections is of great significance in modeling surface water systems since open-channel flow is governed by parameters such as cross-section area, wetted perimeter, and hydraulic radius. For a precise representation of the real system, accurate cross-sections are imperative.

4.4.1 Equipment Used

- LTI TruePulse 200X Laser Rangefinder which is a U.S made device used for measuring cross-sections (Figure 12)

- GPS tracker (eTrex HC series) (Figure 13)

- Measuring rod/tape

- Small flags (to mark the location)

Figure 12: Rangefinder used ("LTI TruPulse 200X User's Manual ", 2013)
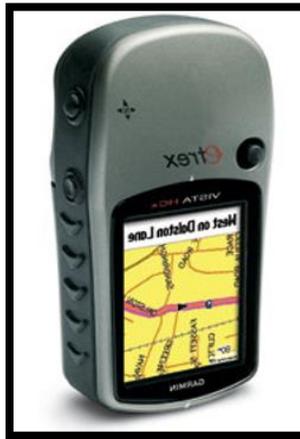
Figure 13: GPS unit used ("eTrex HC series," 2007)

4.3.2 Methodology

1- Small flags were placed along the stream width at each measurement location.

2- Exact location coordinates of sample points were recorded using the GPS unit.

3- The Rangefinder was placed upon a tripod on one side of the stream bank.

4- The 2-points shooting method was used which is useful when measuring distance, having one of the points as a reference point (Figure 14).

5- The first shot aims at one side of the stream while the second shot is aimed at the other side. The reading was then recorded.
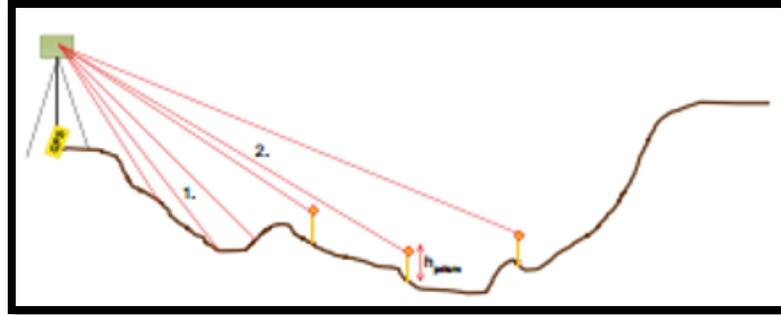
Figure 14: Schematics for using the rangefinder

6- To be more accurate a second reading was taken manually by measuring the stream width using a measuring tape.

7- After measuring the width of the stream, a rod was used to measure the stream geometry (depth).

Figure 15: Measuring the stream width manually

8- The measuring rod was placed at each flag location and the water depths and widths were recorded.

4.3.3 Results

The raw data collected for cross-sections in the field study were pre-processed prior to input into the model using Microsoft Excel. This was done by subtracting the measured water elevation at the different points along the width from the base elevation obtained

previously. The following tables and graphs show the cross-section measurements taken at the various monitoring locations.

A-014 Cross-sections:

- A-014-1

  DEM: 74.12 m

Table 5: A-014-1 cross-section data

X, Channel width(m)	Y, Terrain elevation (m)
0	74.19
0.58	74.11
1.15	74.11
1.73	74.09
2.3	74.19
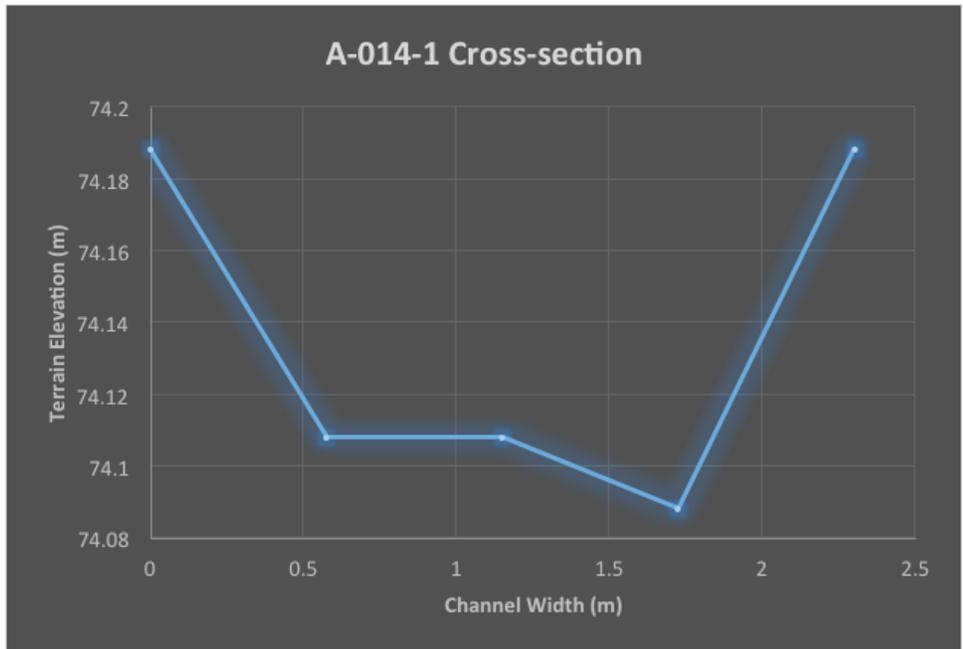
Figure 16: A-014-1 cross-section graph

- A-014-2

DEM: 74.937 m

Table 6: A-014-2 cross-section data

X, Channel width(m) (m)	Y, Terrain elevation (m)
0	74.94
0.41	74.79
0.82	74.68
1.22	74.82
1.63	74.94
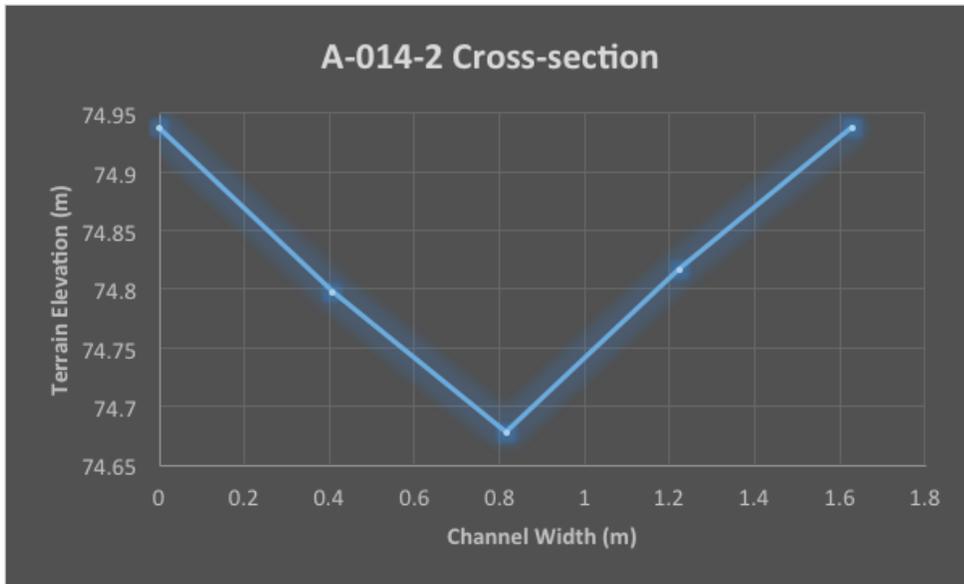
Figure 17: A-014-2 cross-section graph

- A-014-4

DEM: 83.258 m

Table 7: A-014-4 cross-section data

X, Channel width (m)	Y, Terrain elevation (m)
0	83.26
1.33	82.89
2.67	82.64
4	82.76
5.33	82.76
6.67	82.84
8	83.26
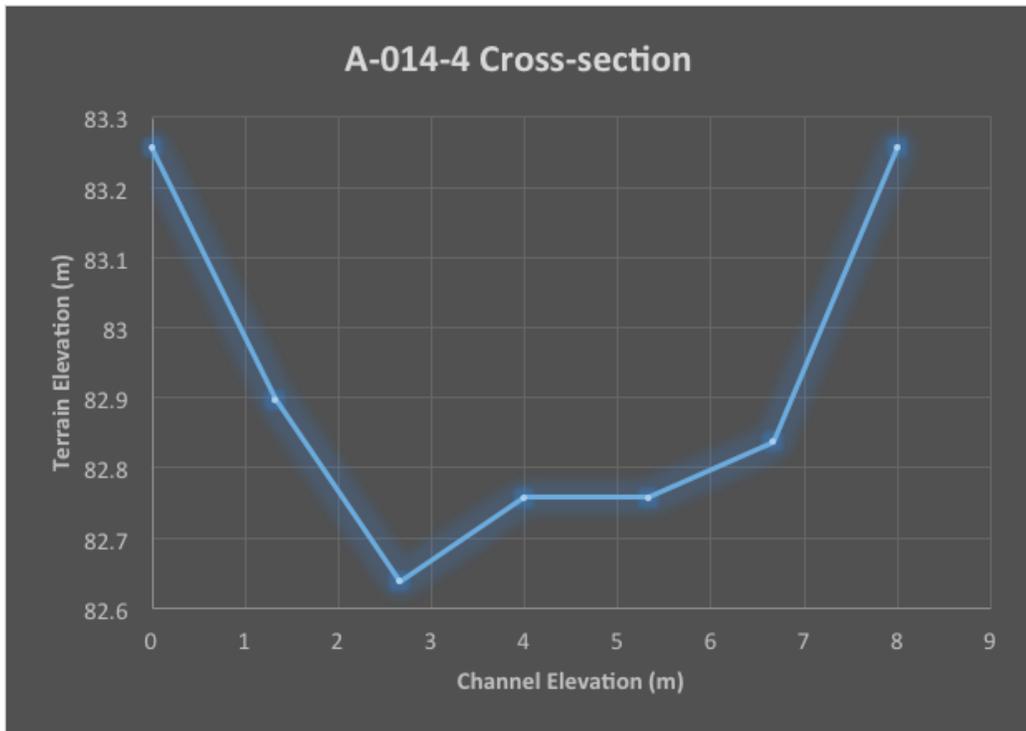
Figure 18: A-014-4 cross-section graph

- A-014-7

DEM: 105.514 m

Table 8: A-014-7 cross-section data

X, Channel width (m)	Y, Terrain elevation (m)
0	105.51
0.58	105.4
1.17	105.30
1.75	105.11
2.33	105.11
2.92	105.01
3.5	105.51
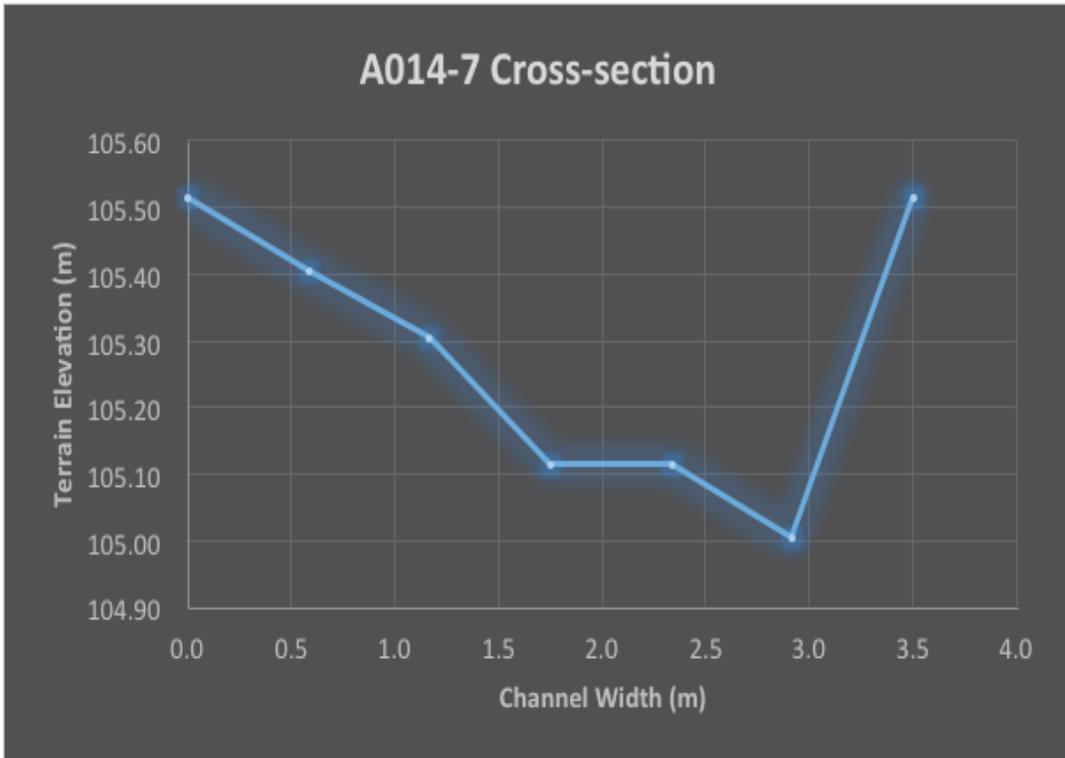
Figure 19: A-014-7 cross-section graph

Chapter V - Methodology and Model Development

5.1 Data pre-processing

As the hydrology model development is highly dependent on the use of geographic information system (GIS) data as input configuration parameters, ArcGIS software tools were extensively used by the modeling team for data pre-processing. This also included the Arc Hydro application which is used widely in water resources and stream delineation (Djokic, Ye, & Dartiguenave, 2011). The A-014 stream network was delineated from a digital elevation model (DEM) provided by the Savannah River Nuclear Solutions (SRNS) Geotechnical Engineering Department at SRS using ArcHydro. In addition, two other GIS files (shapefiles) were created using ArcMap; one being a point shapefile that contained the sampling locations (Figures 20 & 21) where cross-section measurements were taken and water level data was collected, and the second also a point shapefile, but this time representing the culvert and weir locations (Figure 22). These files are significant as they were needed as inputs into the MIKE 11 model in order to incorporate the *in situ* field data collected and account for the hydrologic infrastructure in the A-014 outfall tributary.
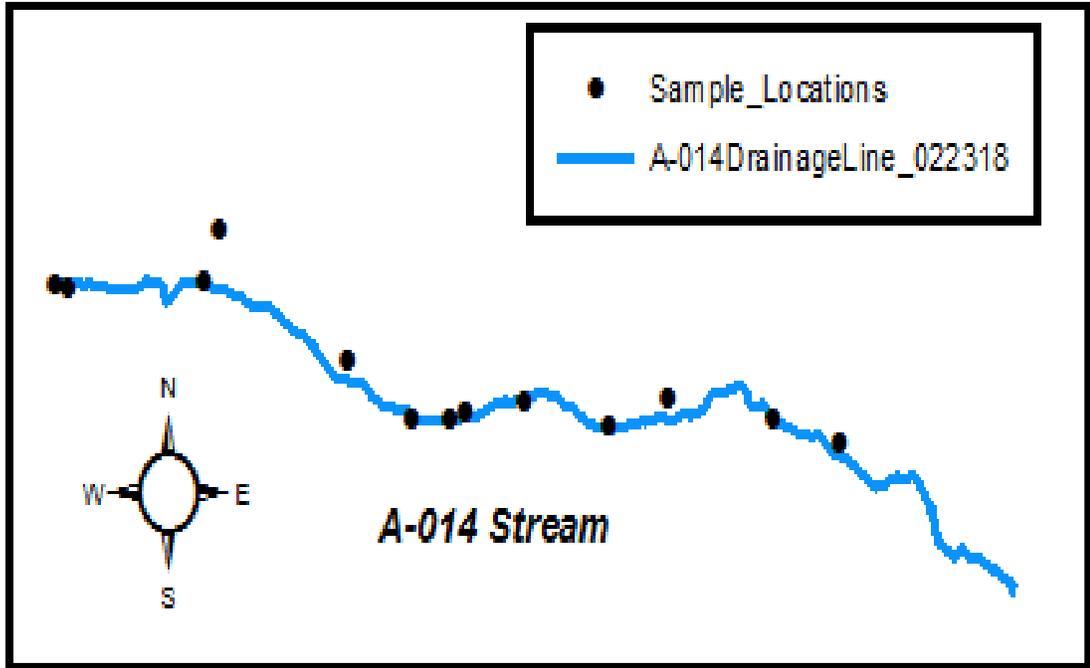
Figure 20: Sampling locations along the A-014 stream network as viewed in ArcMap
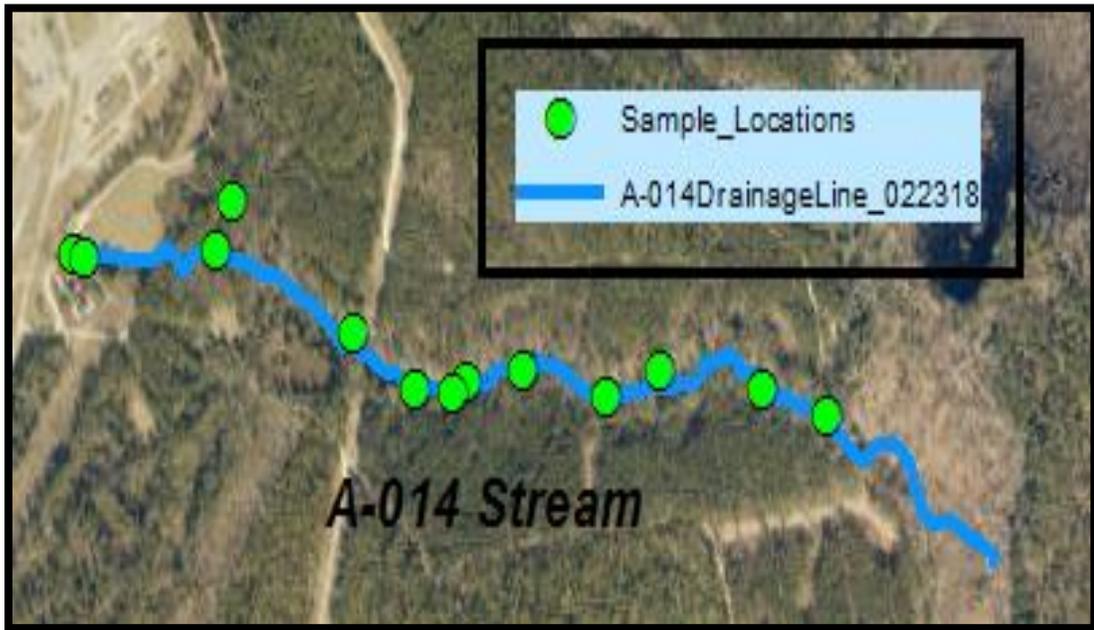
Figure 21: World imagery view of the A-014 stream with sampling locations viewed in ArcMap
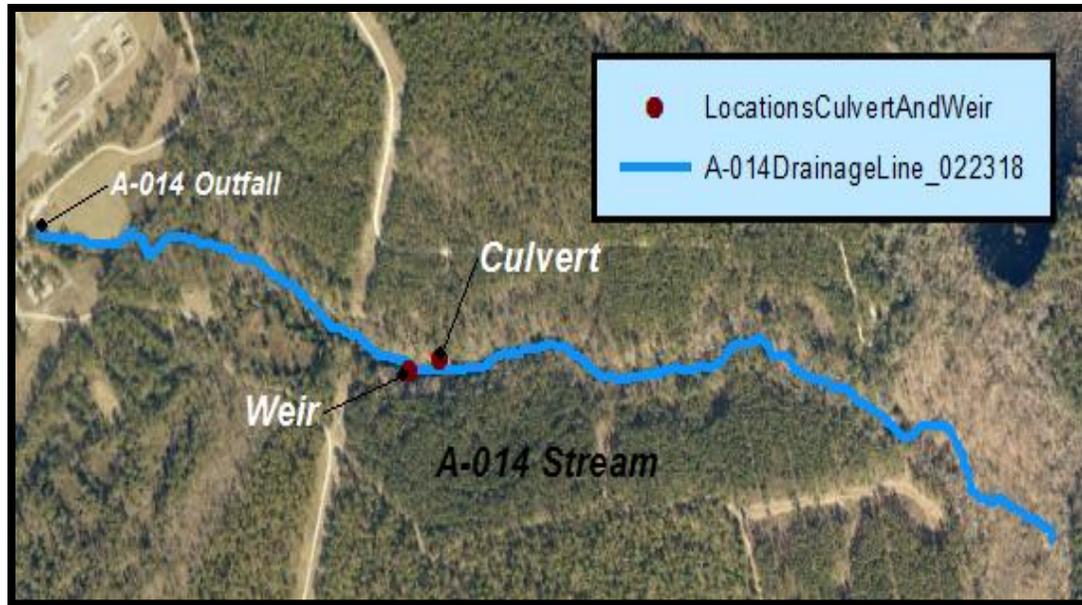
Figure 22: Culvert and weir locations along the A-014 stream network viewed through ArcMap

5.2 Model Development

In this research, MIKE 11 software was used to create a one-dimensional (1-D) stream model of the A-014 outfall tributary. MIKE 11 is a software product developed by the Danish Hydraulic Institute (DHI). It is a fully dynamic 1-D modeling package used to model rivers, channels, lakes, and reservoirs. MIKE 11 has been applied in many various parts of the world based on its powerful capabilities to estimate the flow and water levels of types of water bodies.

The MIKE 11 model uses the dynamic Saint Venant equation (mass conservation and fluid momentum conservation) to determine water level and flow as follows:

- Mass conservation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (4)$$

- Momentum conservation:

$$\frac{\partial Q}{\partial t} + \frac{\partial \left\{ \alpha \frac{Q^2}{A} \right\}}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \qquad (5)$$

Where:

- Q = Discharge, $(\frac{m^3}{s})$

- A = Flow area, (m^2)

- q = Lateral inflow, $(\frac{m^2}{s})$

- h = Stage above datum, (m)

- C = Chezy resistance coefficient, $(\frac{m^{0.5}}{s})$

- R = Hydraulic or resistance radius, (m)

- α = Momentum distribution coefficient

Model development using MIKE 11 requires several configuration files that contain all the parameters needed for the stream flow simulation which include:

- Simulation file   - River Network file

- Cross Section file   - Boundary file

- Hydrodynamic (HD) parameters file

5.3 Creating the Simulation File (.sim11)

The simulation file was the first file created in development of the A-014 stream model. It contains a simulation editor tool, which serves three important purposes:

1- It contains the simulations.

2- It is used to start the simulations.

3- It contains the link that stores other model files (Figure 24).

The simulation editor tool is comprised of several simulation models including:

- Hydrodynamic (HD)
- Advection-Dispersion (AD)
- Sediment Transport (ST)
- Data Assimilation (AD)
- Rainfall-Runoff (RR)
- River Ice modeling (Ice)
- Water quality (ECO Lab)

These models each serve a specific purpose and are only included in the simulations depending on what the user is trying to model. The fully hydrodynamic model (HD) (Figure 23) was used in the A-014 stream model development with the simulation mode set to an "unsteady" state, which means that the HD calculation was based on the hydrodynamic stream flow conditions.
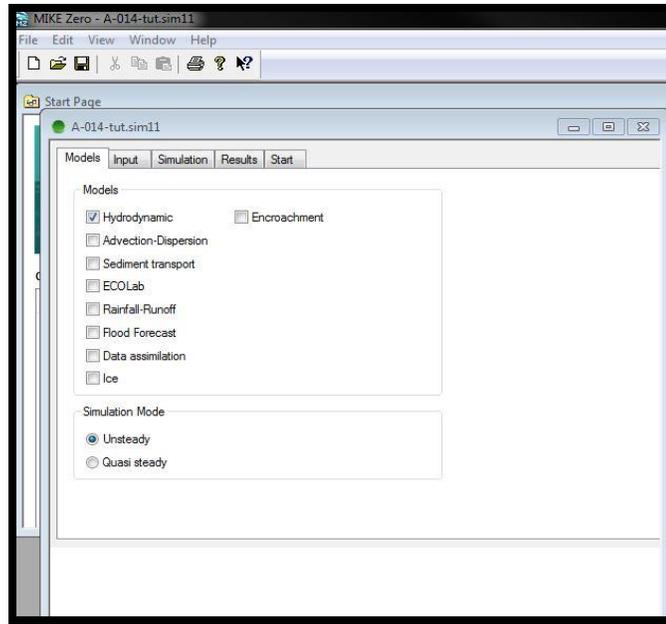
Figure 23: Selection of the model and simulation mode type in the MIKE 11 simulation file
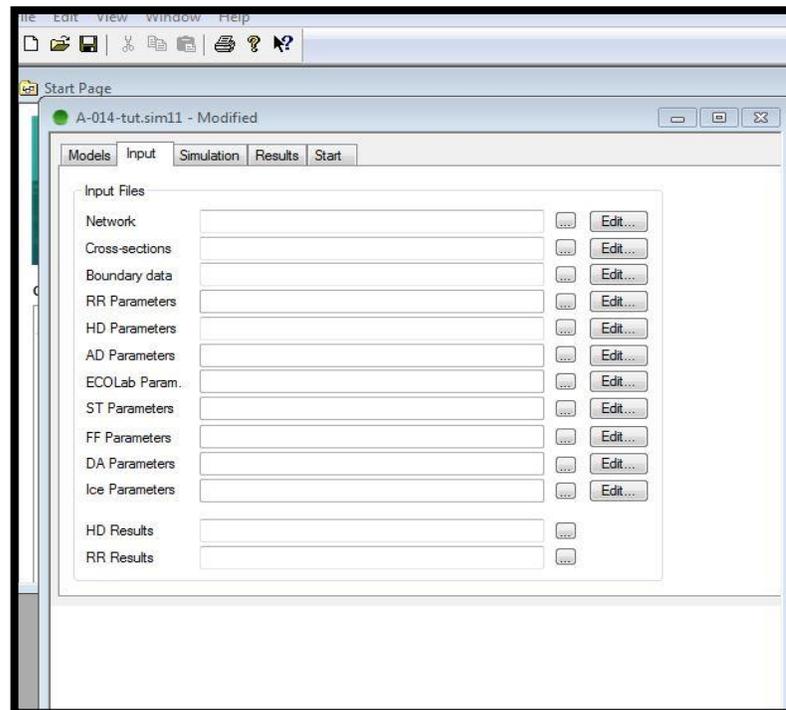
Figure 24: Input files window in the simulation file

5.4 Creating the River Network File (.nwk11)

After creating the simulation file, a river network file was created (.nwk11) which contains the network editor. This file provides an overview of the model setup as well as links for all other associated MIKE 11 files. The river network file allows the user to input and edit the following:

- Digitized river networks and branch connections
- Hydraulic infrastructures such as weirs and culverts

Model outputs from this file can be visualized in two ways: the geographical view and the tabular view. In order to create the file, the workspace area map projection and coordinates need to be specified. The North American Datum 1983 Universal Transverse Mercator (NAD83 UTM) Zone 17N was the projected coordinate system used in this model. The UTM conformal projection uses a 2-dimensional Cartesian coordinate system that gives a horizontal position representation on the surface of the Earth, i.e. it is used to identify locations on the Earth independently of vertical position. This coordinate system was used in the model as most of the GIS input data for the South Carolina region was provided in this format. The input coordinates, which define the model domain/workspace area can be viewed in figure 25 below.
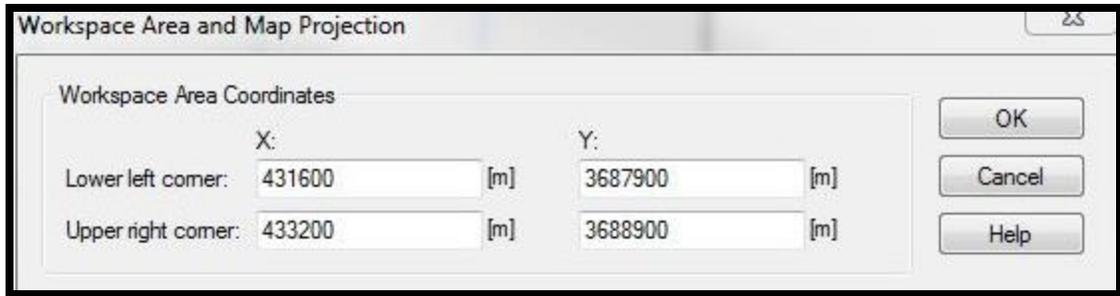
Figure 25: Input coordinates of the model domain/workspace area

After setting up the workspace area, the shapefiles that were created in the data pre-processing using GIS were imported into MIKE 11 as layers that included:

- A-014 model domain polygon

- A-014 stream polyline

- Sample location points

Note that when a stream polyline shapefile is imported into MIKE 11, it is loaded as a series of branches, which then need to be connected using the network editor tool in MIKE 11to create the stream network where the x-axis and y-axis represents the workspace coordinates (Figures 26 & 27).
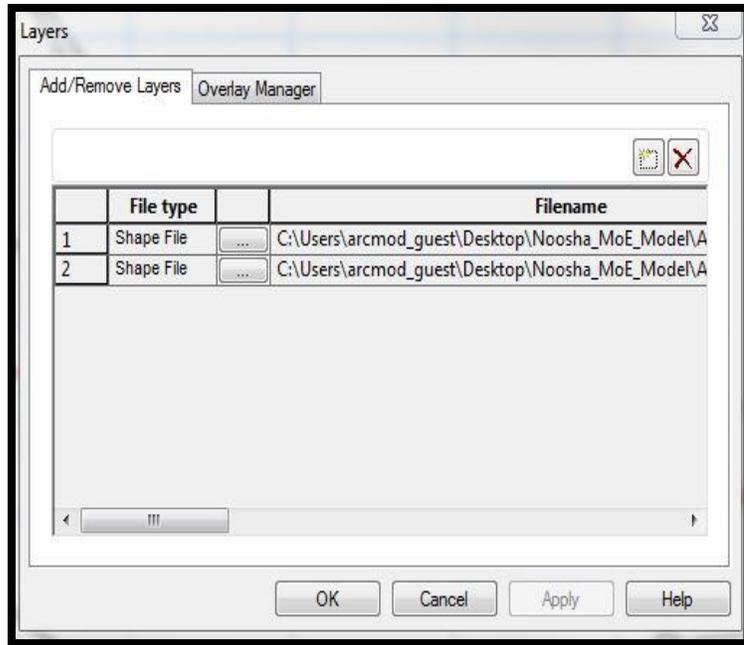
Figure 26: Adding pre-processed GIS shapefiles as layers in MIKE 11
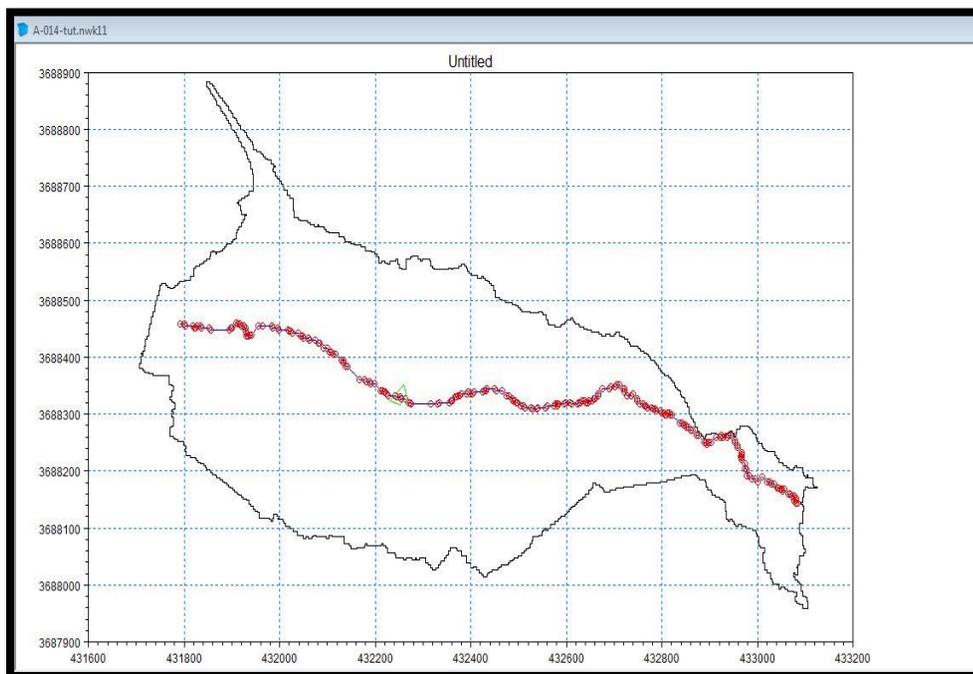
Figure 27: A-014 stream network and model domain in the geographical view of MIKE 11

5.5 Creating the Cross-Section File (.xns11)

The cross-section file is one of the most important stream flow model input files The Cross-Section editor in MIKE 11 manages, stores, and displays all model cross-section information. The Cross-Section editor provides two ways of generating stream cross-sections, manually inputting the raw survey data or automatic generation of the cross-sections using MIKE HYDRO tools. In this research both methods were employed. Firstly, the field cross-section measurements collected along the A-014 outfall tributary by FIU at SRS were input manually into the model. MIKE HYDRO tools were then used to automatically generate the remaining cross-sections along the parts of the A-014 stream that were not ground surveyed, based on a DEM file that was provided by the SRNS Geotechnical Engineering Department.

5.5.1 The Manual Cross-Section File (Field)

The raw cross-section measurements collected along the A-014 stream were pre-processed using Microsoft Excel, then imported t into the MIKE 11 river network file described in Section 5.4 above. The measured field values in the imported table were then inserted under the relevant cross-section locations that were manually generated based on the field coordinates as seen in figure 28. At each manually generated cross-section the topo ID "Field" was assigned and once all the data parameters were entered, the Cross-Section file was saved.
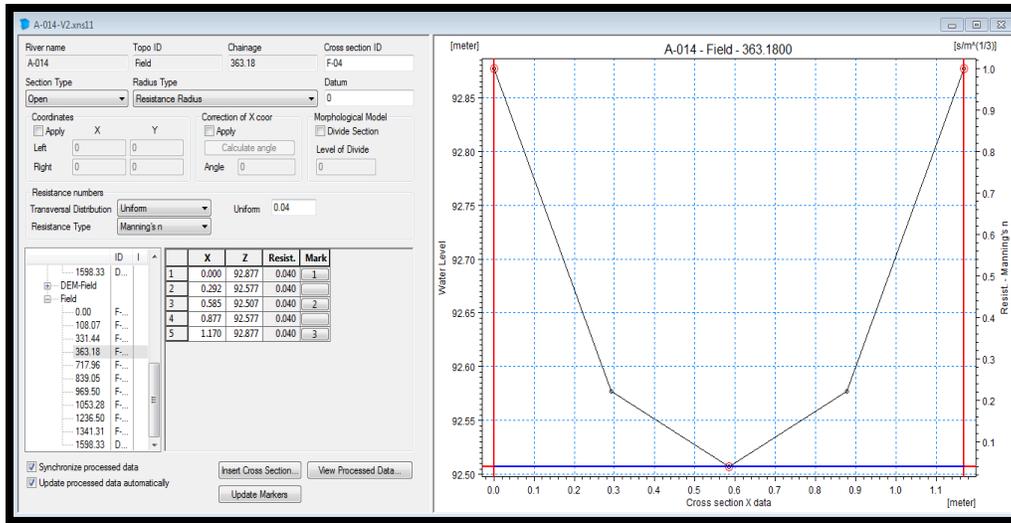
Figure 28: Manually processed cross-sections on MIKE 11 (Field)

5.5.2 Auto Cross-Section Generation from DEM using MIKE HYDRO

Auto generation of the A-014 stream network cross-sections was also possible using the MIKE HYDRO model, which is part of the MIKE (DHI) package. MIKE HYDRO can auto generate cross-sections using a Digital Elevation Model (DEM). In this case, a DEM file of the study area was provided by the SRNS Geotechnical Engineering Department and was input into MIKE HYDRO. Before generating the cross-sections in MIKE HYDRO, it was necessary to convert the DEM file from ASCII format to dfs2 format, which is readable in MIKE 11. This was done using the ArcGIS "Clipping" tool. Once the files were ready, a MIKE HYDRO (.mhydro) file was created and the converted DEM file and the simulation file created earlier were imported into MIKE HYDRO. The map view below in figure 29 shows the A-014 model domain and the stream network.

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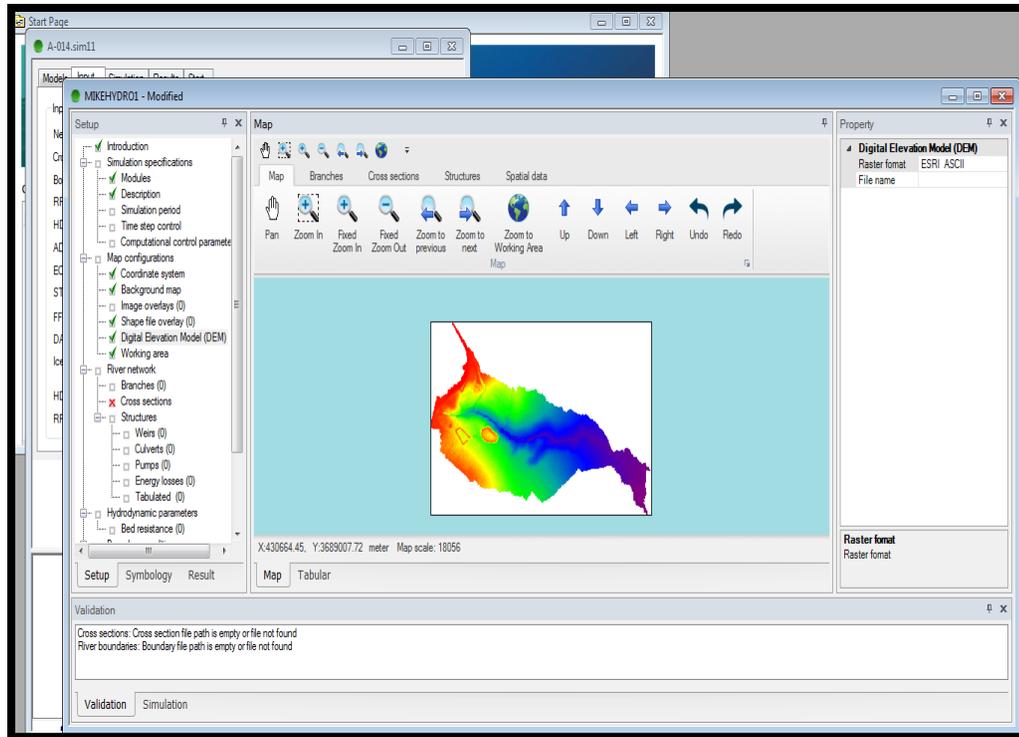
Figure 29: Map view of the A-014 model domain and the stream network in MIKE HYDRO

It was then possible to auto generate the cross-sections based on the imported DEM file. First the branch (A-014) had to be specified, then intervals were set to 100 m apart and 50m in width, which was an assumption based on the field data collected. Finally, the new cross-section file was saved and opened in MIKE 11. In the cross-section file a new topo ID "DEM" was assigned.
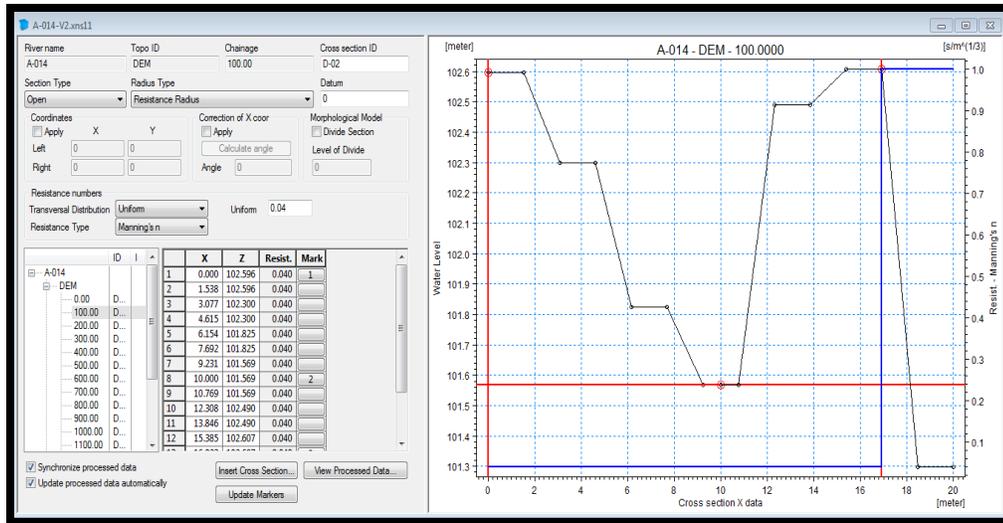
Figure 30: Auto generated cross-sections from a DEM using MIKE HYDRO

Once the cross-section files were prepared, it was then necessary to input certain parameter values such as section type, radius type and associated Manning's number.

The section type was set to "open" as this is ideal for river and stream cross-sections. The radius type was set to be resistance and uniform for transversal distribution. Finally, the Manning's number (n) with units of $\frac{s}{m^{\frac{1}{3}}}$, which is under the resistance type, was set based on literature review. The range of Manning's numbers recommended by the United States Department of Transportation - Federal Highway Administration for these types of stream characteristics was the following (James D. Schall & Morris, June 2008):

-   0.03-0.05 for channels with bottom of gravels, cobbles, and few boulders
-   0.04-0.07 for channels with bottom of cobbles with large boulders

In this model a value of 0.04 for the Manning's number was used. In addition, this number was verified by conducting calculations based on the actual data from the field study and by using the Manning's equation:

$$Q = V * A = \frac{1}{n} * A * R^{\frac{2}{3}} * S^{\frac{1}{2}} \qquad (6)$$

Where:

- Q is the flow rate $(\frac{m^3}{s})$

- V is the velocity $(\frac{m}{s})$

- n is the manning's number

- A is the cross-section area (m^2)

- R is the hydraulic radius (m)

- S is the slope $(\frac{m}{m})$

Since a field cross-section profile was measured, it was then possible to estimate the

Manning's number as follows:

$$n = \frac{A * R^{\frac{2}{3}} * S^{\frac{1}{2}}}{V * A} \qquad (7)$$

- The average velocity of A-014 stream was measured to be approximately

  $0.155(\frac{m}{s})$.

- The slope was calculated using ArcGIS tools between the first sampling

  location and the last one, $S = \frac{Eevation}{Disatnce} = \frac{105.5 - 74.2}{1270} = 0.024$

- The cross-sectional area was calculated at one of the sampling locations

  (Sample ID A-014-4) as shown in Figure 31.
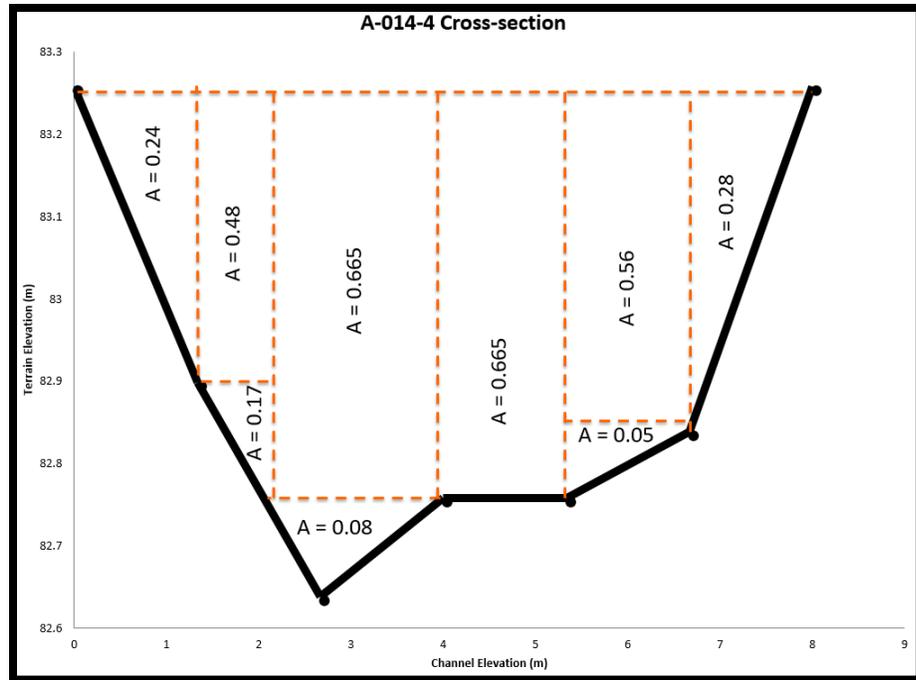
Figure 31: Dividing the cross-section area into small segments

- The total area (A) $= 3.19 \; m^2$

- The wetted parameter (P) $= 8.15$ m

- The hydraulic radius (R) $= \frac{A}{P} = \frac{3.19}{8.15} = 0.39 \; m$

- Solving for the Manning's number (n) using equation (7):

$$n = \frac{3.19 * 0.39^{\frac{2}{3}} * 0.024^{\frac{1}{2}}}{0.155 * 3.19} = 0.53$$

This Manning's number was out of the recommended range of 0.03-0.07, which is likely due to the fact that the actual cross-section measurements may not have been very accurate due to the method used and the fact the model was set to be unsteady flow. In addition, the rangefinder that was used was unable to record measurements through water. As a result, it was important to modify the cross-sections manually in the model, or use the DEM to generate more accurate cross-sections.

5.5.3 Inserting Hydrologic Infrastructure

The A-014 stream contains a culvert and a weir, which were constructed in order to slow down the stream velocity, so it was very important to include them in the model. In order to do so, the river-network file was used. Based on the actual location coordinates, these objects were inserted in the stream network in MIKE 11. It should be noted that many of the default parameter values, for example the head loss factor, were used in this model. The geometry of the weir was set to be at level 85 with a width of 6 m (Figure 32 &33).
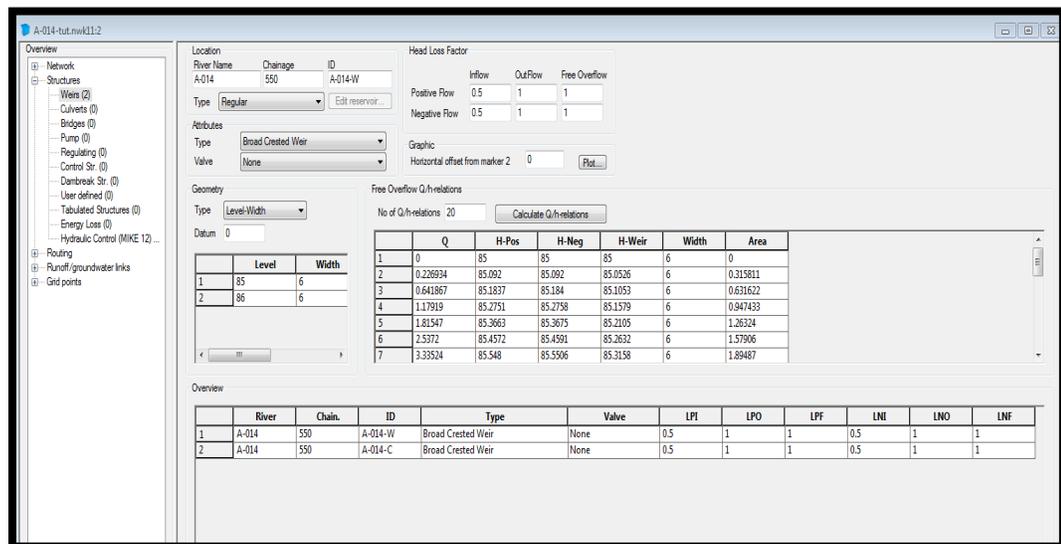
Figure 32: Input parameters for the hydrologic structures in MIKE 11

MIKE 11 has the ability to calculate the free overflow Q/h-relations, and display the data as a table that contains the following:

- Discharge (Q)

- Water level upstream

- Water level downstream

- Water level at the structure itself

- Area and width of the structure
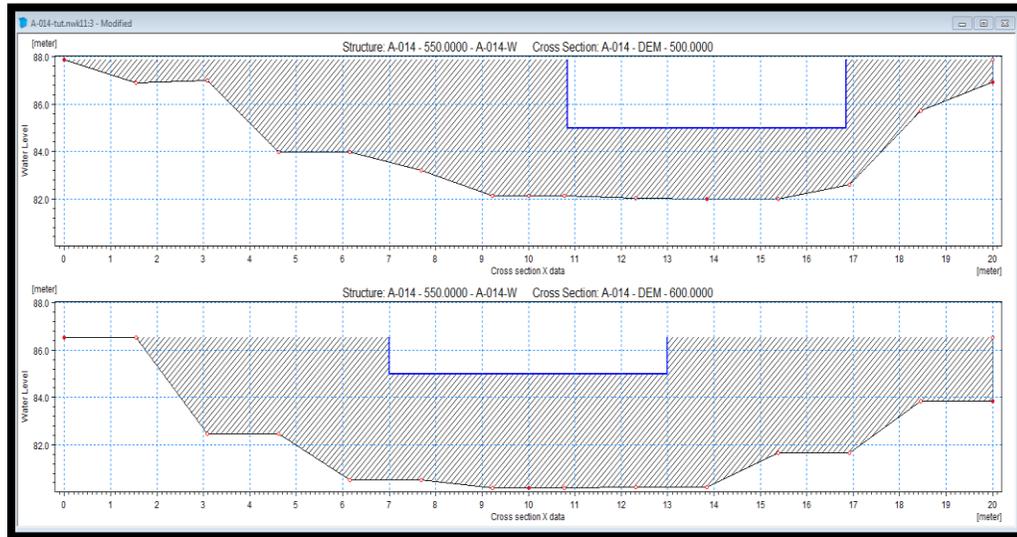
Figure 33: Plot generated by MIKE 11 that shows the weir

5.6 Creating the Boundary Conditions File (.bnd11)

The Boundary Editor is used to specify boundary conditions in a MIKE 11 model. It is used not only to specify common boundary conditions such as water levels and inflow hydrographs, but also for the specification of lateral flow along river reaches, solute concentrations of the inflow hydrographs, various meteorological data and certain boundary conditions used in connection with structures applied in a MIKE 11 model (Institute, 2017).

For this model, a Boundary Condition file was created (.bnd11), then within the river network file, two boundary conditions were inserted, one upstream at chainage 0, and the other at the last point downstream at chainage 1598.3 m as shown in Figure 34 (The x-axis and y-axis represents the workspace coordinates). The first boundary type at

chainage 0 was set to be "open" (inflow), and the volumetric flow values were calculated from the data collected during the field study using the flow velocity measured and the cross-sectional areas of the actual outfalls. The calculated discharge value was 0.03 m^3/s for the A-014 outfall and this value was used for this boundary condition.

The second boundary condition at chainage 1598.3 m was set to be open as well, and the boundary condition type was set to be "water level" with water elevation of 0.672 m as measured in the field study.
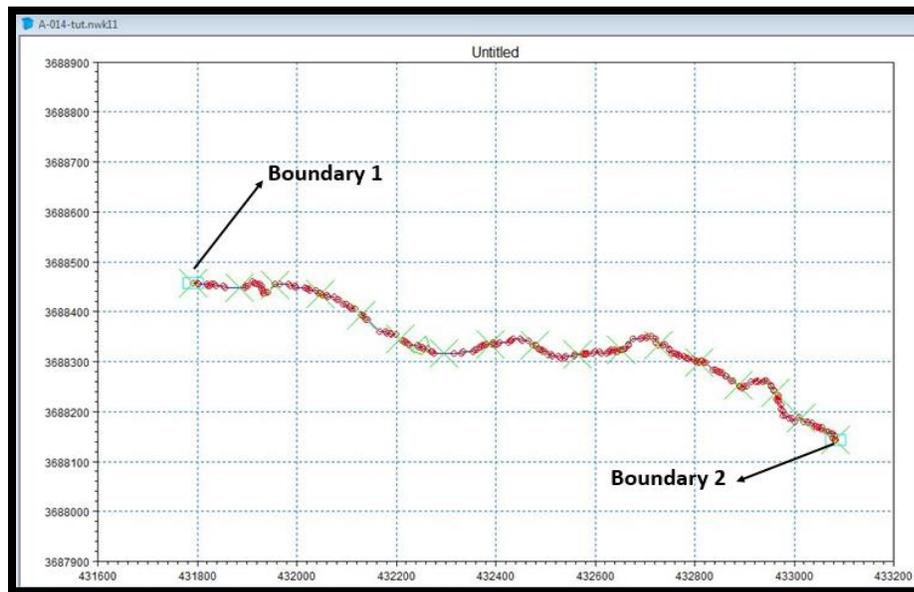
Figure 34: Inserting boundary conditions in the MIKE 11 River Network file

5.7 Creating a Hydrodynamic File (.hd11)

The hydrodynamic parameter editor is used for setting supplementary data used for the simulation as shown in figure 35. Most of the parameters in this editor have default values and in most cases these values are sufficient for obtaining satisfactory simulation results.

The hydrodynamic file was created (.hd11) and the initial conditions were set to be 0.01 m for water depth and 0 for discharge. Other parameters such as bed resistance, wind, and groundwater leakage were kept as default values. The Delta value for the Computation Scheme was changed to 0.75 in order to avoid problems with the Courant Number criteria.
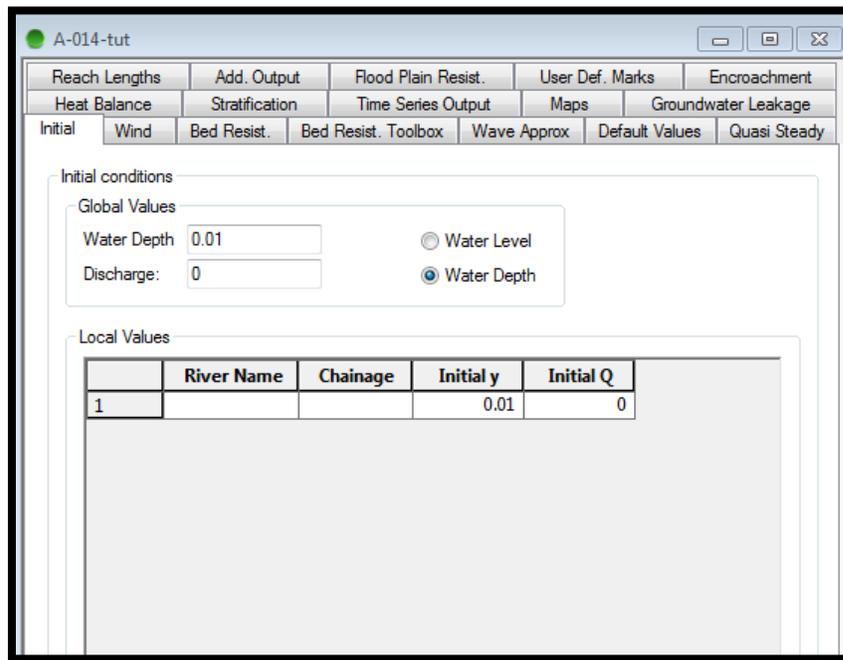
Figure 35: HD parameters in MIKE 11

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After creating these sets of files, the model was ready to run simulations. In the simulation editor a "fixed time step" for time step type was chosen and a value of 1 second was manually inputted. Finally, a start and end time was specified in the simulation editor and a results file was created.

Chapter VI - Results and Discussion

After setting up the stream model in MIKE 11 and creating a results file, the next step was to incorporate the rainfall time series data in order to simulate the effect of rainfall, particularly storm events or heavy rainfall, on the water levels and flow velocity in the A-014 outfall tributary. In addition, two copies of the stream model were created; one with the culvert and weir implemented, and the other without them. The purpose of this was to see if the model was able to capture any differences in flow characteristics with and without these hydrologic infrastructures. Simulations were run for the year 1993-1994 as consistent daily time series records of both rainfall and discharge data were available for that time period. This data was used for initial model calibration; however, the model will be improved over time as data from the remote monitoring stations deployed in February 2018 at SRS becomes available. The results were processed and visualized using MIKE VIEW, which is a visualization tool provided by DHI to show results for a wide selection of water models including MIKE 11.
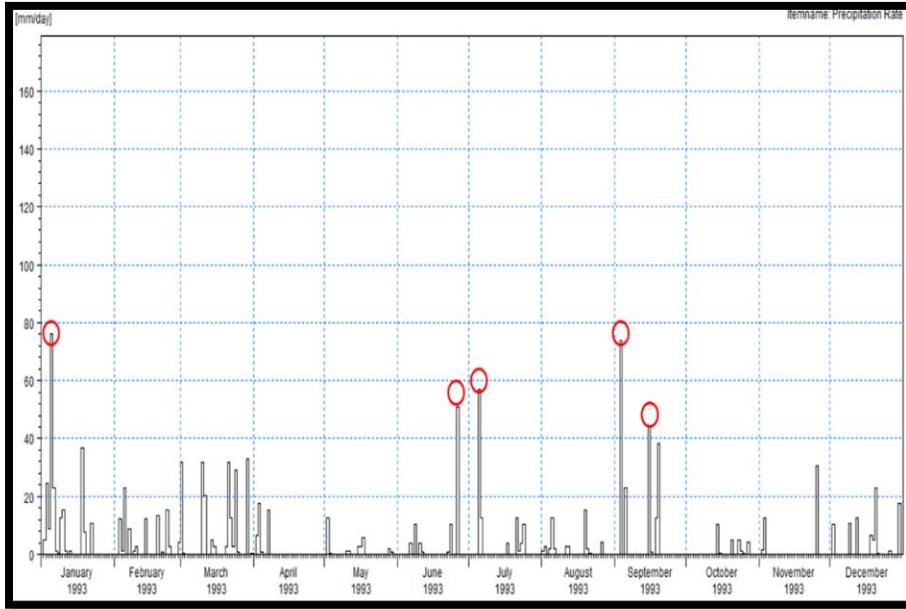
Figure 36: Rainfall data for year 1993 generated using MIKE SHE

In figure 36 above the x-axis represent the rain intensity and the y-axis represent the month, and the high peaks circled in red represent high rainfall events occurring at various times throughout the year 1993, particularly during the months of December, June, and July, with gauge readings in some cases reaching almost 80 mm/day, which were anticipated to have an impact on the flow characteristics of the stream being modeled.
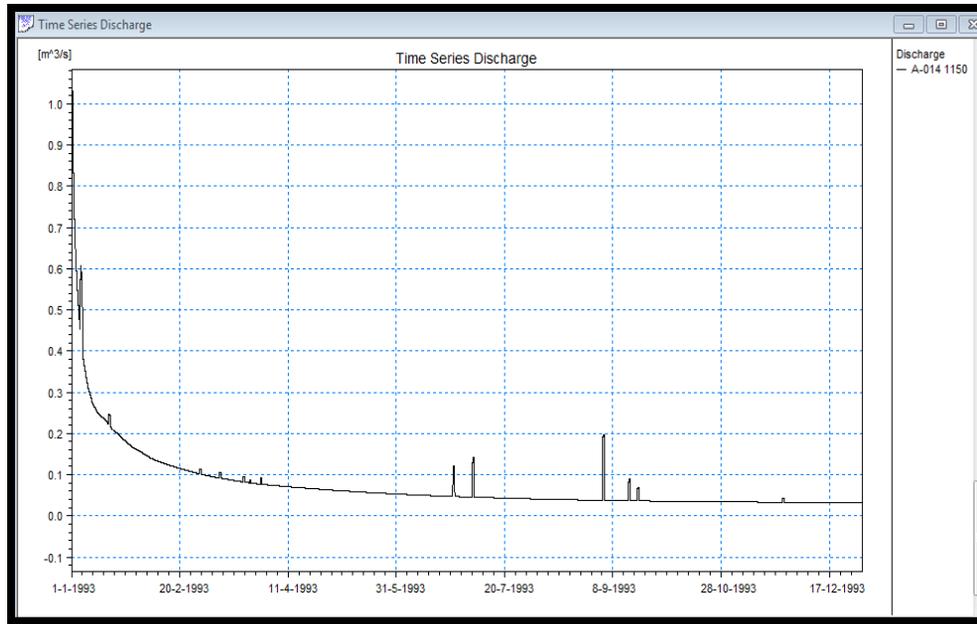
Figure 37: Discharge data for a cross-section (1150 m from outfall)

Figure 37 represents the discharge data for one of the cross-sections (at 1150 m) in the A-014 stream; the x-axis represent the flow rate Q in $(\frac{m^3}{s})$ and the y-axis represent the month. The high peaks observed in the discharge graph are correlated with the high peaks observed in the rainfall graph above (Figure 36) for the same year 1993. These results indicate that the model was able to simulate the observed high rainfall events during the year 1993 and produce a corresponding simulated discharge. In particular, a significant peak flow of 0.2 $(\frac{m^3}{s})$ was noted in late July, which corresponded to a high rainfall event at the same time. The discharge graph also showed the flow returning to a steady state value of 0.03$(\frac{m^3}{s})$ following the storm event, which was the value also measured in the field in the A-014 stream.

The following results seen in figure 38 and figure 39 show a screenshots from the model of a single cross-section profiles which depict how the water levels differ at a specific cross-section based on two simulation scenarios: Scenario #1 - with a culvert and weir; and Scenario #2 - without a culvert and weir, the x-axis represent the depth in meters and the y-axis represent the cross-section width in meters.

Scenario #1:
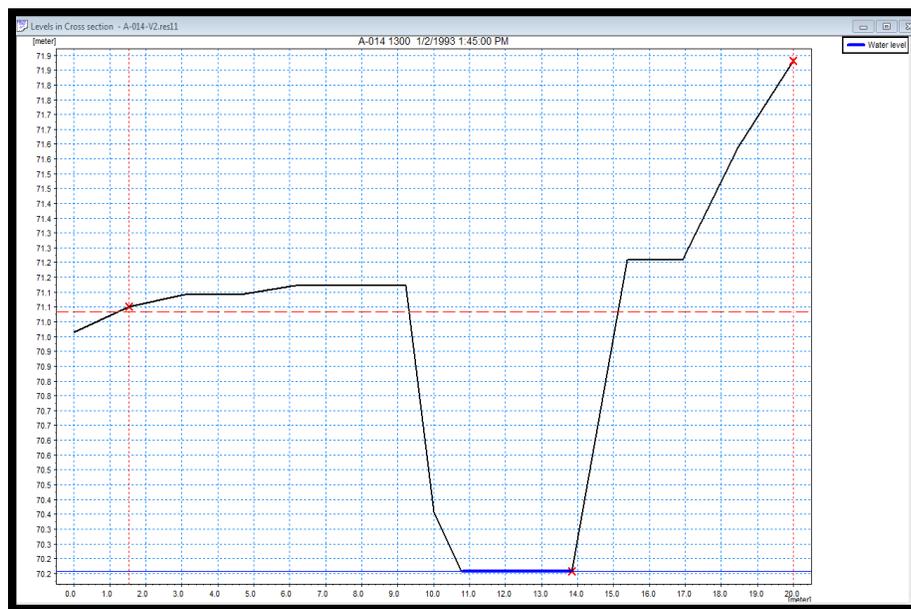
Figure 38: Water level at a cross-section with culvert and weir (1300 m from outfall)

In Scenario#1, it was observed that with culvert and weir implemented in the model, the water level at this particular cross-section (1300 m from the A-014 outfall) is low, almost 0.025m, which corresponded to a slow flow velocity at this same cross-section at this time of the year (January 1993).

Scenario # 2:

Figure 39: Water level at cross-section without the culvert and weir (1300 m from outfall)

In Scenario #2, the water level was observed to be much higher at the same cross-section as Scenario#1 and the same time of the year. The water level reached 0.2 m (almost 10 times higher than in Scenario#1), which means that the model was able to capture the impact of the hydrologic infrastructures in the A-014 stream which result in higher water levels.

The following results in figure 40 and figure 41 show the simulation results in profile view along the whole A-014 stream at several cross-section locations in the two scenarios formerly described above (i.e., with and without the hydrologic infrastructures) for the months of January and February 1993, the x-axis represent the elevation in meters and the y-axis represent the distance from outfall in meters.

Scenario #1:
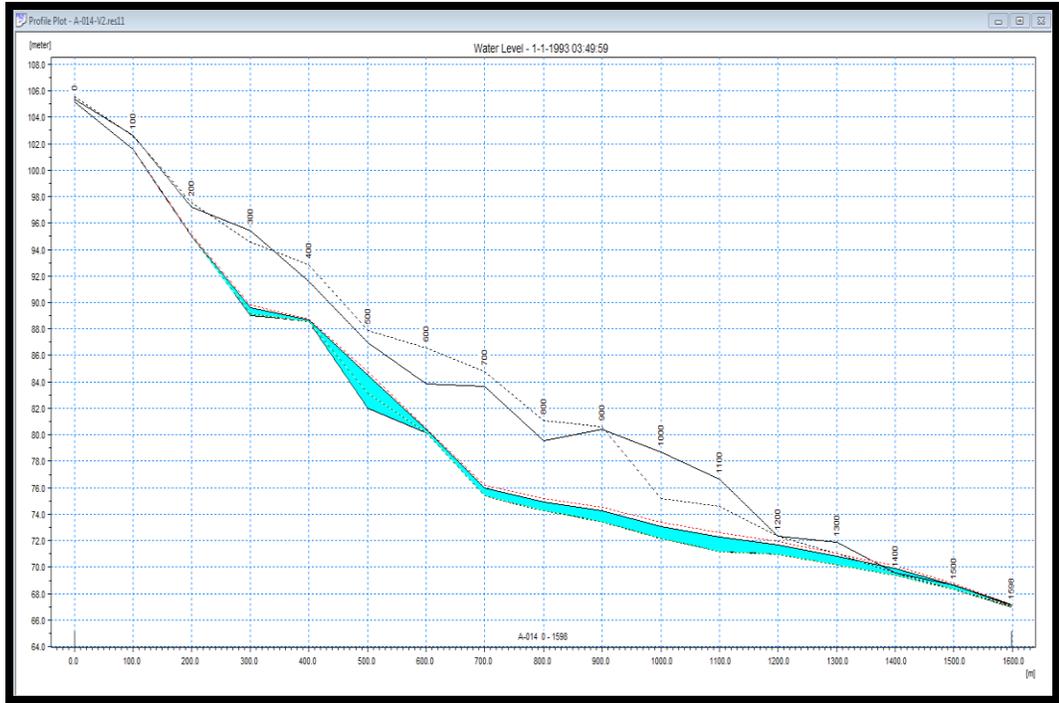
Figure 40: Water level along A-014 stream (January)
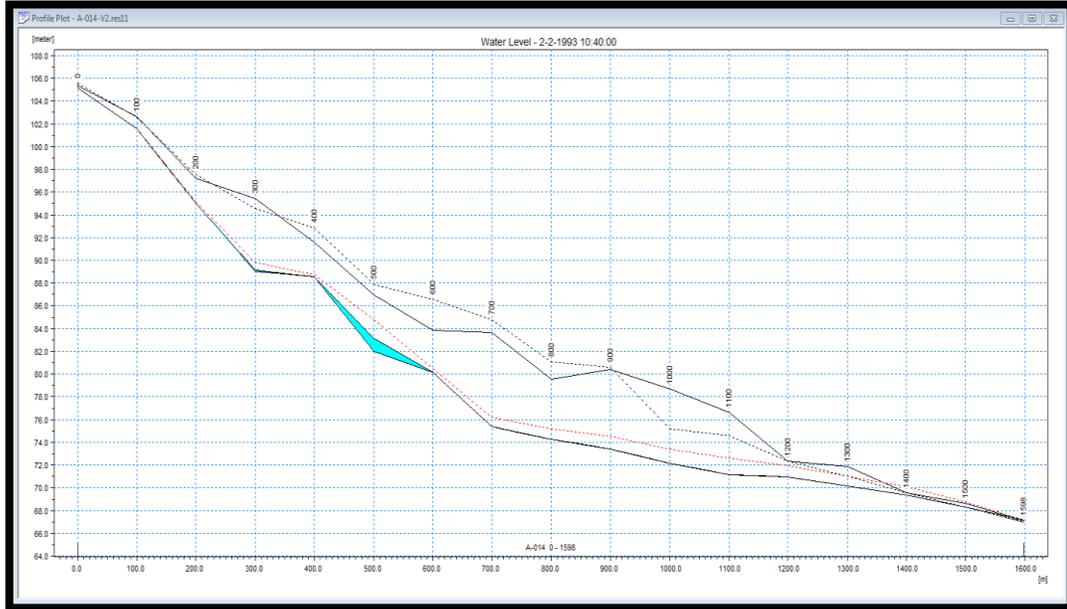
Figure 41: Water level along A-014 stream (February)

The graphs in Scenario#1 show that the water level along the stream reaches a steady state at approximately 10-20 cm of water depth, except for the areas where there is ponding between the weir and culvert.

Scenario #2:
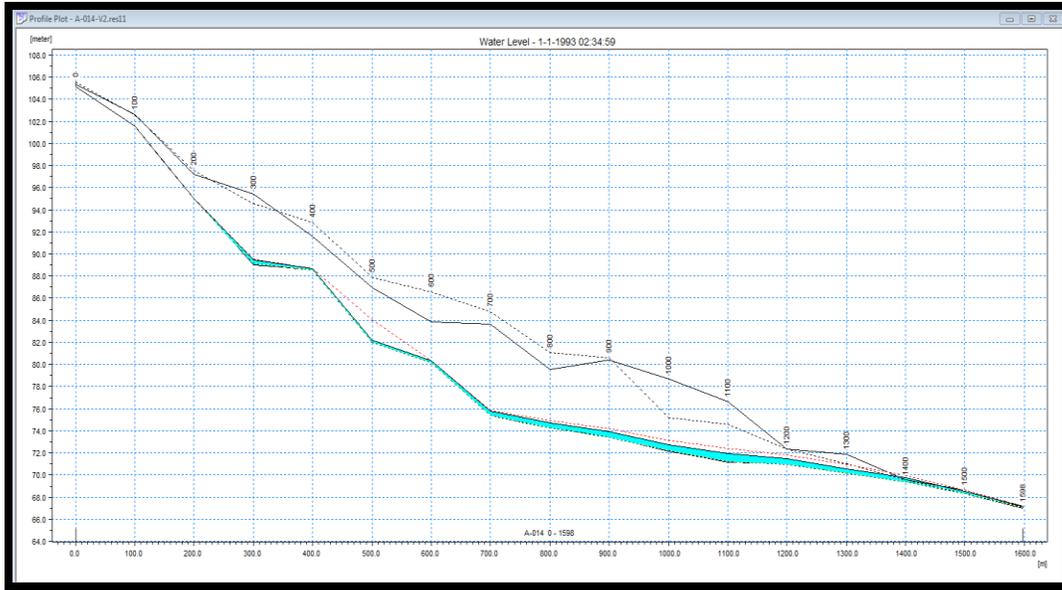
Figure 42: Water level along A-014 (January) without culvert and weir
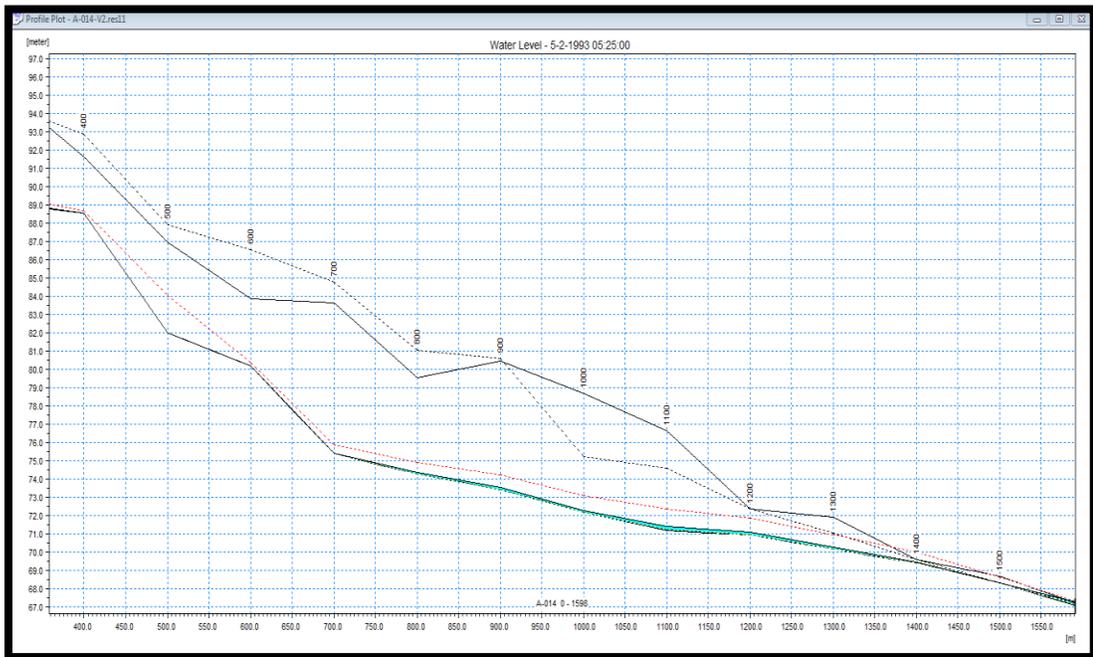
Figure 43: Water level along A-014 (February) without culvert and weir

The graphs in Scenario#2 show that the water level does not accumulate in certain locations as in Scenario #1. There appeared to be a more even distribution downstream and along most of the cross-sections in the A-014 stream.

This research was an attempt to develop a stream flow model that is able to simulate the hydrology of the A-014 outfall tributary of Tims Branch by showing a correlation between observed rainfall and simulated discharge in the model results. Simulation of the hydrology is a preliminary step in determining the movement and the long-term distribution of contaminants within the overland, subsurface, and river sub-domains. Simulation results indicate that the MIKE 11 model developed was able to capture the effect of significant high rainfall events by showing corresponding peaks in the discharge at the same time of these events. The model was able to predict the flow characteristics of the A-014 stream during heavy rainfall events, which took a place during the year 1994. For example, the model was able to capture the extreme rainfall events throughout the year, particularly in the months of June to August. The discharge data generated by the model showed large peaks during the storm events. Figure 37 shows the flow rate in the stream diminishing after each storm event to a steady state value of approximately 0.03 $\frac{m^3}{s}$ which correlates well with discharge values recorded during FIU's 2016 field study at SRS.

Review of some of the measured cross-sections and the associated water velocity data recorded in the 2016 field study, reveals a significant correlation between the discharge data calculated based on the flow data gained from the field study and the discharge data generated by the model. Table 9 shows flow rates at different cross-sections along the

length of the A-014 stream. The flow rates were calculated using equation (1) in which the cross-sectional area is multiplied by the water velocity measured at the same location:

Table 9: Flow rates at some measured cross-section during the field study

Sample ID	Cross-Section Area (A) m^2	Flow velocity (v) $\frac{m}{s}$	Flow rate calculated $Q = v * A$ $(\frac{m^3}{s})$
A-14-1	0.29	0.12	0.03
A-14-2	0.27	0.04	0.01
A-14-7	0.96	0.05	0.05

The calculated flow rates at some cross-sections vary between 0.01-0.05 $(\frac{m^3}{s})$. If these results are compared with the model results, it shows the model results do fall within the field results; A-014 stream is not solely dependent upon hydrological events that magnify the discharges at a given time. This tributary of Tims Branch is heavily influenced by discharges from regulated outfalls. Discharges from such regulated outfalls can thus be a contributing factor; in amplifying the differences between computed and observed averages. It should also be taken into consideration that the level of accuracy of the actual cross-section and water velocity field measurements is based on the tools used. For example, the rangefinder was not able to shoot points below the water level, and the flow meter was not able to detect velocities in areas with very low water movement and very shallow depths.

In addition, the results generated by the model indicate that the weir and culvert, which were constructed approximately 500 meters away from the A-014 outfall, affect the water level downstream. Model simulation results showed that the water levels were very low (0.025m) likely due to the culvert and weir holding the water upstream by forming a pond around these structures. Figures 40 and 41 show stream profiles where water accumulation was observed at approximately 500 m, which is the actual location of the weir and culvert (seen in Figures 5 and 6).

Overall, the model reveals general trends consistent with measured data. Observed and computed rainfall and discharge show an excellent match. The model results reveal the model's ability to best simulate flow or discharges during high flow. Dry conditions and low flow regimes establish a greater margin of error and numerical instability.

The model is intended to serve as a useful remediation tool since the study domain was characterized using relevant site specific historical records for precipitation, groundwater levels, and river discharges obtained from SRNS, federal and state databases, which were incorporated into the model in the form of boundary or calibration conditions. In situ field measurements were also incorporated as calibration parameters which improves the model's predictive capability.

Lastly, a comparative review of the A-014 stream model with other similar models was challenging due to several factors such as varying calibration and validation methods, and varying spatial extents. For example, in the case studies of the Euphrates River in Iraq and the Rideau River in Canada, both of these studies used a very similar approach in developing the model; however, the methods of model validation were different. The

Euphrates River in Iraq used hydrographs generated by MIKE 11 and compared them with similar hydrographs generated by a different model created for the same area. In the case of the A-014 stream flow model, there were no other surface water models formerly created for the same study area to provide a means of comparison of the model results. As a result, the only way to validate the A-014 stream flow model results was to compare them with actual field data, which was therefore the approach taken in this study. The Rideau River model is considered as one of the best and most accurate MIKE 11 models worldwide. The reason for this is because the calibration of the model was based on several years of measured stream flow data. This method is very similar to the method used in this study, however, the Rideau River calibration was based on 10 years of time series stream flow and rainfall data as opposed to only 1-2 years of stream flow data used in this study. Also, the Euphrates and Rideau Rivers, when compared to the small-scale A-014 stream, are considered to be two of the largest and longest rivers in the world, and therefore require a lot of time for calibration and validation.

Chapter VII - Conclusions and Future Work

Model simulation results have indicated that the flow characteristics of the A-014 outfall tributary are affected by natural phenomena such as storms or heavy rainfall, which occur year-round at the Savannah River Site (SRS). The developed model was able to simulate the varying water levels along the stream during heavy rainfall periods in the year 1993. A comparison between the graphs of the observed rainfall data and the simulated discharge during this period showed peaks in the discharge at the same points where there were peaks in the rainfall, which indicates a good correlation between the observed and simulated data. Simulation results showed the flow increasing 7 fold (from 0.03 to $0.2\frac{m^3}{s}$) during the occurrence of an extreme rainfall event in July 1993. This result supports the proposed hypothesis of atmospheric events causing increased flow velocity in streams.

In addition, the simulations in which the man-made structures were implemented, such as the culvert and weir, have shown that these engineering control structures do retard the flow in the stream. The man-made hydrologic infrastructure in the A-014 outfall tributary was designed to slow down the flow rate in the stream during periods of high discharge. The constructed weir alters the stream flow characteristics and results in a change in the water level height. The model results showed that the culvert and weir had a significant effect on the water velocity and the water level when observed at various cross-sections. Simulation results showed that the water level dropped to approximately 0.025 m when the culvert and weir were present in the stream, which ultimately resulted in a decreased flow velocity. A decreased flow rate in the A-014 outfall tributary using these kinds of

engineering control structures will aid in tracking the fate and transport of pollutants discharged from the M-1 air stripper through the A-014 outfall and into the stream.

In this thesis, a fully dynamic 1-D model of the A-014 outfall tributary was developed. This model is capable of predicting the flow in the A-014 stream over time and provides a better understanding of the stream flow characteristics during extreme atmospheric events. The hydrology model developed for this small stream can now be used as a platform to develop a larger stream flow model for the main Tims Branch stream, which, when coupled with other models in future, including the MIKE SHE overland flow model and the ECO Lab geochemical model, will be able to simulate the fate and transport of pollutants in the streams throughout the Tims Branch watershed.

The A-014 model will be of great assistance to any future hydrological model development efforts at the Savannah River Site (SRS), and serves as a basis for improvement of the conceptual and quantitative modeling of the real life hydrologic system that was impacted by the U. S. Department of Energy's nuclear operation more than 50 years ago.

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