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Analysis of Oak Ridge National Laboratory Outfall 211 Contributing Drainage Areas

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ABSTRACT

By the early 1950's, the U.S. Department of Energy (DOE) began the production of thermonuclear weapons in support of the Cold War. A key active ingredient in the design of the thermonuclear weapon was lithium-6 (Li-6) which is produced by separating lithium isotopes using an aqueous solution containing mercury (Hg). In 1953, Oak Ridge National Laboratory (ORNL) buildings 4501 and 4505 were built to conduct a pilot-scale evaluation of the lithium exchange processes. An estimated 56,200 lbs (25,500 kg) of Hg had been released during these operations.

ORNL is located within the White Oak Creek watershed (a portion of Bethel Valley watershed). White Oak Creek (WOC) is the main stream running adjacent to ORNL along its south-eastern border and is the main collector of mobile contaminants in the area. In order to understand the transport of contaminants, it is critical to understand the flow of water within the area of interest. Thus, a conceptual stormwater management model is being developed for the contributing drainage areas of Outfall 211. Outfall 211 discharges stormwater as well as water from the adjacent buildings such as cooling water and condensate from various air conditioning (AC) units and discharge from the Creep Laboratory (Building 4500S). The ORNL Outfall 211 drainage area represents a test bed for the larger and more complex Y-12 National Security Complex (NSC). The Outfall 211 area of interest is smaller in scale in comparison to the Y-12 NSC area of interest. Both facilities, ORNL and Y-12 NSC, were built using similar construction and drainage methods; thus many of the factors that impact water management are similar. Therefore, the model being developed is expected to provide a portion of the technical basis for developing a similar modeling approach for the Y-12 NSC, to improve forecasts of water flow and contaminant flux from facility infrastructure and surface water.

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1. INTRODUCTION

In the 1940's during World War II, the U.S. initiated its own research and development program—commonly referred to as the Manhattan Project—in a race to create the first atomic bomb. The 33,750 acre Oak Ridge Reservation (ORR) was the first site selected to support the Manhattan Project. This site consists of three major U.S. Department of Energy (DOE) facilities, the East Tennessee Technology Park (ETTP) formerly known as the Oak Ridge Gaseous Diffusion Plant or K-25 (2200-acres), the Y-12 National Security Complex (Y-12 NSC) (800-acres), and the Oak Ridge National Laboratory (ORNL) formerly known as X-10 (4470-acres). The reason for selecting ORR was because it provided the water supply (Clinch River), electricity (Tennessee Valley Authority), and workforce (citizens from the City of Knoxville) necessary for this operation. In addition to the workforce offered by the City of Knoxville, thousands of scientists, engineers, and support personnel relocated to the area in support of this mission (ORNL, 2008).

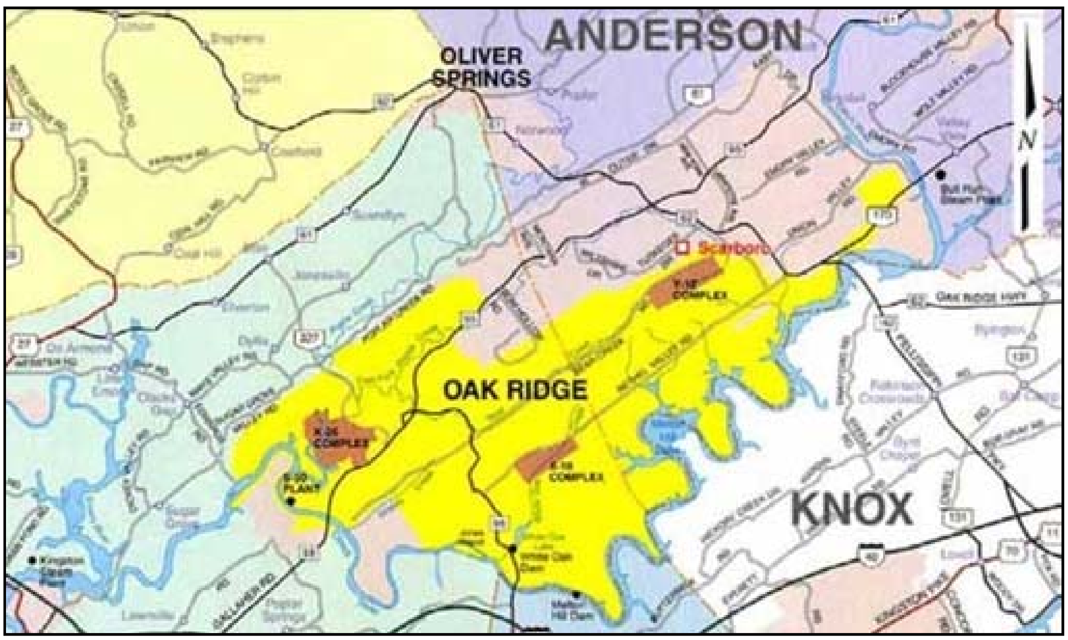

Figure 1. Oak Ridge Reservation

By the early 1950's, DOE began the production of thermonuclear weapons in support of the Cold War. A key active ingredient in the design of the thermonuclear weapon, or the hydrogen bomb, was lithium-6 (Li-6) which is produced by separating lithium isotopes using an aqueous solution containing mercury (Hg). The three separation processes that used large quantities of mercury to extract Li-6 were organic exchange (OREX), electrical exchange (ELEX), and column exchange (COLEX) (Brooks and Southworth, 2011). However, not all three of these exchange processes were employed at all three plants.

1.1 Oak Ridge National Laboratory

In 1953, buildings 4501 and 4505 located on ORNL's campus were built to conduct a pilot-scale evaluation of the lithium exchange processes for the development of thermonuclear weapons. Building 4501, the High-Level Radiochemical Laboratory, was a pilot plant for the OREX process. These pilot-scale tests were conducted in the basement of the 4501 building. The basement floor was flooded with 4" of water to subdue Hg fumes throughout the building. The seams of the basement floor were made of tar; thus, allowing Hg to seep into and contaminate surrounding soil and sediments. An additional 11,000 lbs of Hg was released during its transport to another building on-site for cleaning and recycling prior to its use. An estimated 56,200 lbs (25,500 kg) of Hg had been released during these operations (Taylor, 1989a).

Figure 2. ORNL Building 4501 and 4505 Location

In 1955, Building 4505, Experimental Engineering Laboratory, housed another process named METALLEX. Similarly to the OREX process, METALLEX uses a sodium amalgam (mercury containing solution) to transform uranium and thorium chlorides into their metallic forms. It was the most cost-effective way to produce thorium for reactor grade metal leaving mercury as a by-product. The process required approximately 296,000 lbs of Hg and it is estimated that 4,400 lbs were lost to the environment through spills (Taylor, 1989).

The DOE Office of Environmental Management (EM) has divided ORNL into two major cleanup areas, Bethel Valley and Melton Valley. Bethel Valley is undergoing surface and groundwater monitoring to track the effectiveness of the removal of contaminants thus far and to understand what is still required of the clean-up. Melton Valley has placed sixteen monitoring wells along the Clinch River in order to monitor water quality and remaining ORNL site-related contaminants. (DOE, 2011)

1.2 White Oak Creek

ORNL is located within the White Oak Creek watershed, which is within the Central Bethel Valley watershed (a portion of Bethel Valley watershed). White Oak Creek (WOC), a tributary of the Tennessee River, is the main stream running adjacent to ORNL along its south-eastern border and represents major route for water and contaminant transport (FFA, 2006). The WOC watershed is comprised of approximately 2,098 acres and collects runoff and treated wastewater discharge from ORNL where it is drained into White Oak Lake and into the Clinch River.

The fate and transport of Hg at ORNL have been investigated through numerous studies (EPA, 1997). The presence of residual Hg has been documented in soils and storm sewers as well as WOC sediments and bank soils. However, the quantity of residual Hg that remains within the soil beneath the basements and storm sewers at these facilities is still unknown. Mercury had been released to the environment causing soil and sediment, groundwater, and surface water contamination. As a result, the ecosystems surrounding the ORNL facilities — specifically White Oak Creek, White Oak Lake, and the Clinch River — have been contaminated.

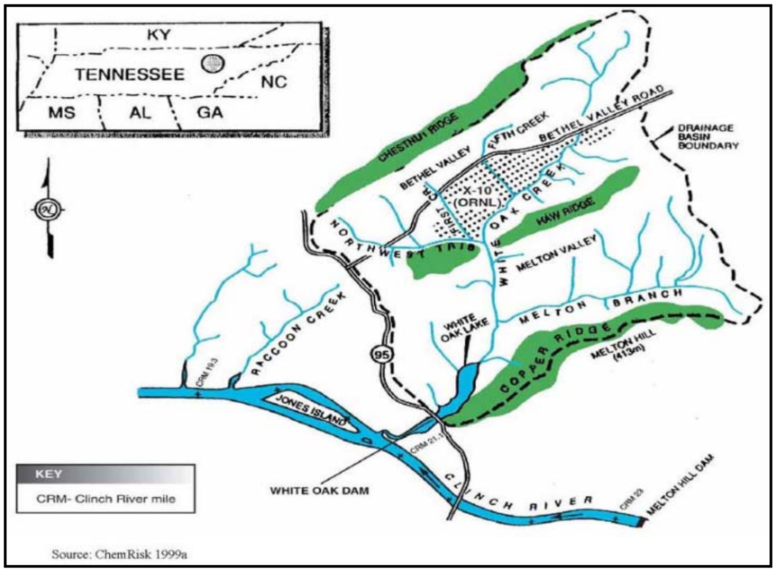

Figure 3. Oak Ridge Reservation

1.3 Area of Interest

The area of interest is approximately 5 acres and consists of a network of closed conduits discharging into a free surface creek. The water flow is represented by unsteady open channel flow because both the closed conduits and the creek are open to atmospheric pressure. The system will be modeled as one-dimensional gradually varied flow. The program chosen to develop the conceptual stormwater management model is XPSWMM which is the Microsoft Windows version of the Environmental Protection Agency (EPA) stormwater management modeling (SWMM) tool. The area of interest includes the following ORNL buildings:

1) 4500N Wings 1, 2, and part of Wing 3
2) 4500S Wings 1 , 2, and part of Wing 3
3) 4501
4) 4505
5) 4507
6) 4508

7) 4556 (note Building 4556 is considered a manmade structure)

Figure 4. Area of Interest

In order to understand the transport of contaminants, it is critical to understand the flow of water within the area of interest. Thus, a conceptual stormwater management model is being developed for the contributing drainage areas of Outfall 211 as well as sources from the adjacent buildings, such as cooling water and condensate from various AC units and discharge from the Creep Laboratory (Building 4500S). The water leaving the Creep Laboratory is treated with chlorine prior to its discharge via storm laterals into the main storm trunk line. A dechlorinator was therefore placed after Outfall 211 in order to reduce the chlorine concentration prior to its discharge into WOC. In 2007, Building 4501 was known as the primary location of Hg contamination (Taylor, 1989). Sump water from Building 4501's basement foundation dewatering sump, Sump I, was pumped into the Outfall 211's storm system. By December 2007, Sump I was rerouted to the on-site Process Waste Treatment Complex (PWTC) in order to receive pre-treatment prior to discharge. Similarly, Sump S (Building 4500N) was rerouted to the PWTC in 2011. Currently, there is only one sump, Sump P (Building 4556), connected that contributes water to Outfall 211.

In the 1950's, construction standards for storm and sanitary sewers did not exist as it does today. Similarly, water quality requirements for stormwater discharge were not as stringent at that time. They did, however, realize that the system must be flushed periodically in order to provide adequate conveyance which would explain the commingling of the two systems and the reason for the discharge of untreated waste water into WOC.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Environmental Management (DOE EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2012, a DOE Fellow (Ms. Heidi Henderson) spent 10 weeks doing a summer internship at DOE Oak Ridge National Laboratory for the Environmental Science Division under the supervision and guidance of Eric Pierce, Ph.D., Applied Remediation Science Lead. T he intern's project was initiated on June 4, 2012, and continued through August 10, 2012, with the objective of collecting pertinent data for the stormwater model of the contributing areas discharging via Outfall 211.

3. RESEARCH DESCRIPTIONS

The model being developed for ORNL will provide the basis for taking a similar approach for modeling the flow of water and contaminants at the Y-12 NSC. The ORNL facility is serving as a test bed for the Y-12 NSC because the ORNL area of interest is smaller in scale. Both facilities were built using similar construction and drainage methods, thus many of the factors that impact water management are similar. The model being will simulate rainfall over the site and provide estimated storm water levels for analysis. ORNL has very little flow rate data in the area; however, a few monitored flow rates were received and will be utilized to calibrate and validate the model.

3.1 XPSWMM Model

XPSWMM uses a spatially distributed link/ node network to analyze the hydraulic, hydrologic, and quality of a stormwater or wastewater system. The XPSWMM software package applies the Saint-Venant equations to solve for the one-dimensional unsteady open channel flow. The Saint-Venant equations are composed of the continuity, momentum, and energy equations. However, in order for the equations to hold true the following six fundamental assumptions must apply:

1) The flow is one dimensional, the velocity is uniform in a cross-section and the transverse free-surface profile is horizontal;
2) The streamline curvature is very small and the vertical fluid accelerations are negligible; resulting in the pressure distributions are hydrostatic;
3) The flow resistance and turbulent losses are the same as for a steady uniform equilibrium flow for the same depth and velocity, regardless of trends of the depth;
4) The bed slope is small enough to satisfy the following approximations:
    a. $\cos \Theta \approx 1$
    b. $\sin \Theta \approx \tan \Theta \approx \Theta$
5) The water density is constant; and
6) The Saint-Venant equations were developed for fixed boundary channels; that is, sediment motion is neglected (Chanson, 2004).

3.2 Modeling Parameters

XPSWMM is equipped with three modes the hydraulic, runoff, and sanitary modes. Both the hydraulic and the runoff modes are utilized in this model. The dialogs will request certain information depending on which mode is active.

Node data, conduit shapes, pumps, control structures and weirs may be modeled in the hydraulic mode. The node dialog requests the spill crest elevation where it can be the manhole elevation for a manhole, inlet elevation for an inlets, or top of pipe for a junction box. For the purpose of this project, a junction box is considered as a point where the storm pipe changes direction without a manhole or inlet or where the storm drain enters the main storm line. There is a dialog for the conduit information and selection of various shapes of pipe along with an aid to visualizing the conduit profiles.

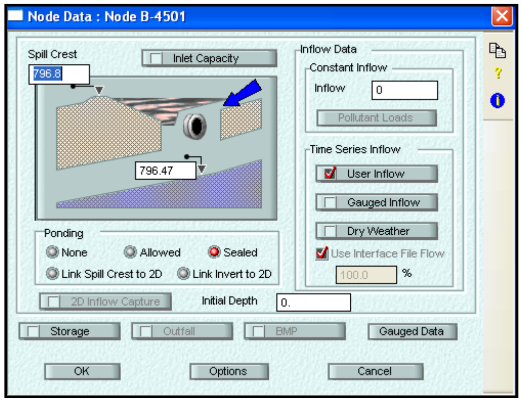

Figure 5. XPSWMM Node Data Dialog

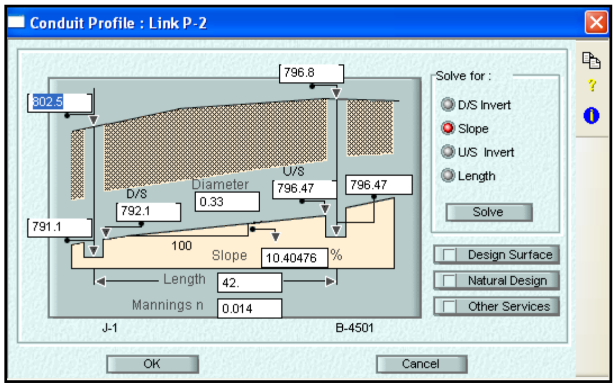

Figure 6. XPSWMM Conduit Profile

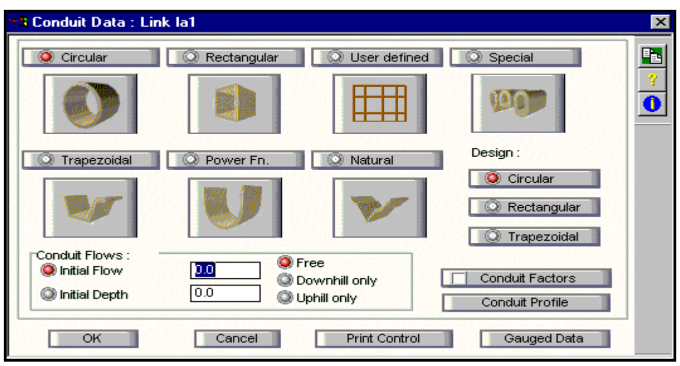

Figure 7. XPSWMM Conduit Shapes

In the runoff mode, drainage areas are delineated for the inlets via sub-catchments. One inlet can have up to five sub-catchment areas where each sub-catchment may have varying areas, impervious percentage, width, and slope. The various sub-catchments will make up the node catch basin incorporating the higher elevation contour surrounding the node. The sub-catchments are the areas that are directly connected to the inlet and will contribute runoff during the simulated rainfall events.

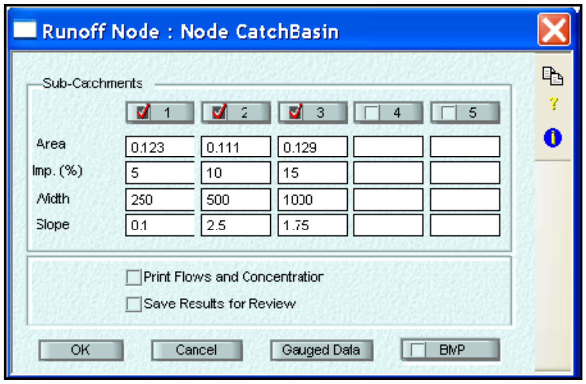

Figure 8. Sub-catchment Dialog

The network is made up of a series of links and nodes, a link being a conduit such as a storm drain, storm pipe, or culvert that conveys water from one node to another. Nodes are considered to intake stormwater or other discharges, in this case would be the A/C units condensate and cooling water or the chlorinated discharge water from the Creep Laboratory in Building 4500S, which would be either building drains, roof drains, manholes, inlets, or junction boxes. The required input data for the conveyance through the conduits are the Manning's roughness coefficient, slope, downstream invert, upstream invert, pipe length and spill crest elevations.

3.2.1 Topography

As an industrial area, ORNL is composed of mostly impervious area with sparse pervious areas and lies within the Tennessee State Plane North American Datum (NAD) 1983. The area bordering the area of interest ranges in elevation from 780 ft NAD to 855 ft NAD as shown on the digital terrain model (DTM). However, the area of interest is relatively flat ranging from 780 ft NAD to 810 ft NAD.

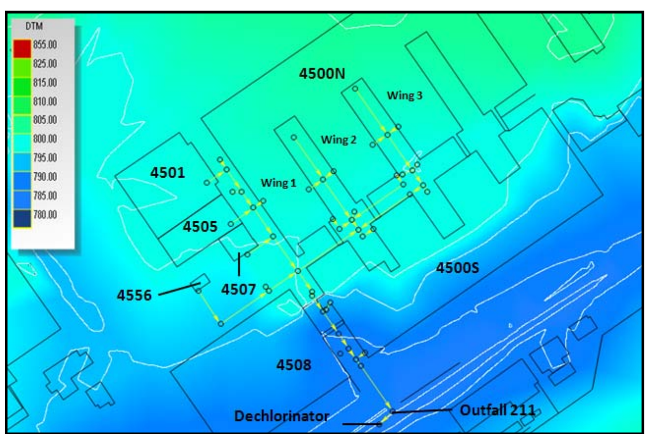

Figure 9. XPSWMM Digital Terrain Model

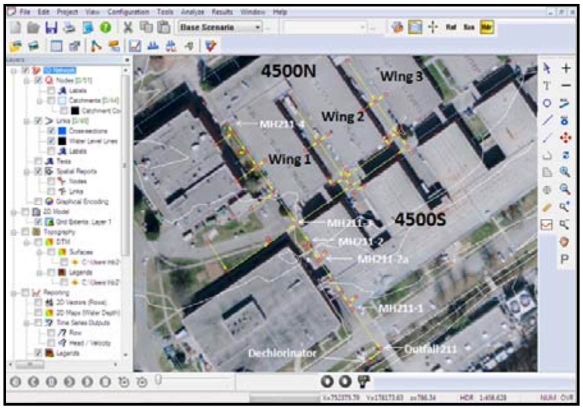

Figure 10. XSPWMM Model Main Storm Line

3.2.2 Open Channel Flow

The conveyance of water within the system is solved by the Manning's formula for open channel flow through the conduits:

$$v = \frac{1.49}{n} R^{\frac{2}{3}} \sqrt{S}$$

$$Q = v * A$$

$$R = \frac{A}{P}$$

Where Q represents water flow (cfs), v is the velocity (fps), A is the cross-sectional area of flow (sf), n is the Manning's coefficient (dimensionless), R is the hydraulic radius (ft), and S is the slope of the water surface or the linear hydraulic head loss (ft/ft). The hydraulic radius is equal to the cross-sectional area of flow divided by the wetted perimeter (ft) as shown in the third equation above. The wetted perimeter for partially filled circular conduits may be found by the following information and measurements:

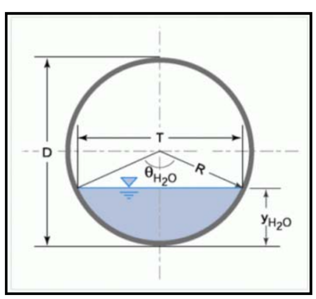

Figure 11. Partially Filled Circular Conduit

Angle from the centerline to the water level, $\Theta = cos^{-1}\left(1 - \frac{y}{r}\right)$
Depth of water in culvert, $y = r(1 - \cos\Theta)$
Cross-sectional area of flow, $A = r^2(\Theta - \cos\Theta \sin\Theta)$

Wetted Perimeter of water, $P = 2r(\Theta)$
Top width of water surface, $T = 2r(\sin\Theta)$

The Manning's roughness coefficient is based on the material of the pipe or the type of channel ranging from a minimum, normal, and maximum number. It is inversely proportional to the flow rate where the smaller the coefficient the larger the flow due to the friction caused by the channels roughness. The network contains the following types of pipes:

- Wrought iron
- Vitrified clay pipe (VP)
- Concrete pipe
- Reinforced concrete pipe (RCP)
- Polyvinyl chloride (PVC)

There is only one sump connecting to Outfall 211 today which is Sump P. Sump P is located within Building 4556 and is only active when a large rainfall event occurs. From Building 4556 a 4" VP connects to a 10" VP which conveys water into MH211-3. MH211-3 is located at the northwest corner of Building 4500S. The main storm line runs west of 4500N and 4500S and contains MH211-1, MH211-2, MH211-2a, MH211-3, MH211-4, and Outfall 211. It begins at MH211-4 and ends at Outfall 211. From MH211-4 to MH211-3, the main storm line is constructed of 15" RCP. South of MH211-3 the line is 30" RCP. Outfall 211 is a culvert located under a bridge. However, the water is not discharged into WOC at that location. There is a 65" long, 13.5" high metal plate acting as a weir directing water to discharge through an 8" PVC pipe. The 8" PVC pipe conveys the water into the dechlorinator. The 8" PVC is reduced to a 4" PVC where the water is disinfected via the dechlorinator.

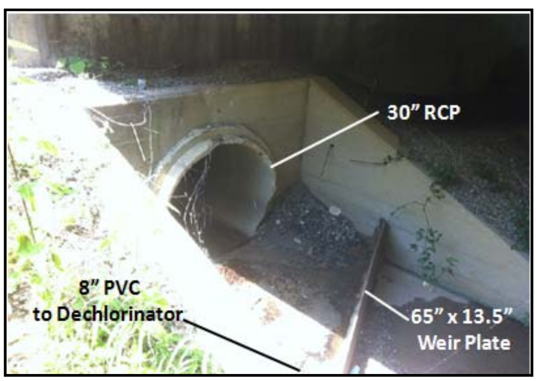

Figure 12. Outfall 211

Figure 13. WOC under Bridge

Figure 14. Dechlorinator in WOC

Additional pictures of Outfall 211 and the dechlorinator are located within Appendix A.

3.2.3 Infiltration

The Horton Infiltration has been chosen to calculate the pervious areas. The Horton equation is as follows:

$$F_p = F_c + (F_0 - F_c)e^{-kt}$$

Where:
Fp = infiltration rate into soil, in./hr (mm/hr)
Fc = minimum or asymptotic value of Fp, in./hr (mm/hr)
Fo = maximum or initial value of Fp, in./hr (mm/hr)
t = time from beginning of storm, sec
k = decay coefficient, 1/sec

The ORNL site is composed of buildings, pavement, and minor pervious areas. It is surrounded by ORR’s wooded lands. Soils in the area are a mixture of reddish-brown clays and silts resulting from in-situ weathering of shaley limestone bedrock. To begin the model, we will only consider dry weather conditions as opposed to wet weather conditions where the antecedent precipitation nine days prior to the start date is considered. Thus, due to the fact that the soils are clays and silts and dry weather is considered, the model utilizes XPSWMM default values for the Horton Infiltration equation as shown below.

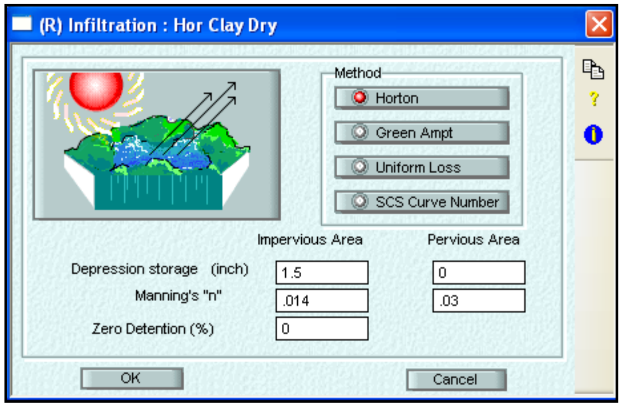

Figure 15. Horton Infiltration Dry Clay Parameter

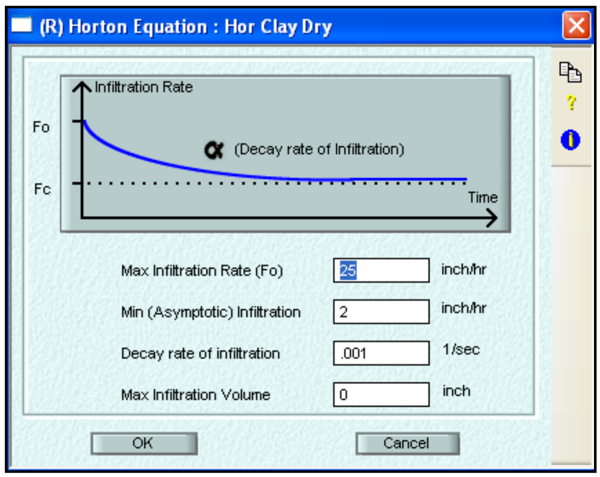

Figure 16. Horton Equation Dry Clay Parameter

3.2.4 Rainfall

U.S. Natural Resources Conservation Service (NRCS) formerly known as the U.S. Soil Conservation Services (SCS) method is used to compute rainfall distributions. The City of Knoxville (adjacent to the City of Oak Ridge) Land Development Manual suggests that the SCS unit hydrograph be utilized for the routing of the storm events. The unit hyetograph will be multiplied by the precipitation (P) for each storm event in order to produce the hyetograph that represents the design storm events for its corresponding rainfall event. The area of interest falls within Region II; thus, the SCS Type II storm event has been chosen to simulate the rainfall distributions for the following rainfall events:

- 25 year – 24 hour; P = 5.47 inch
- 100 year – 24 hour; P = 6.85 inch
- 500 year – 24 hour; P = 8.60 inch

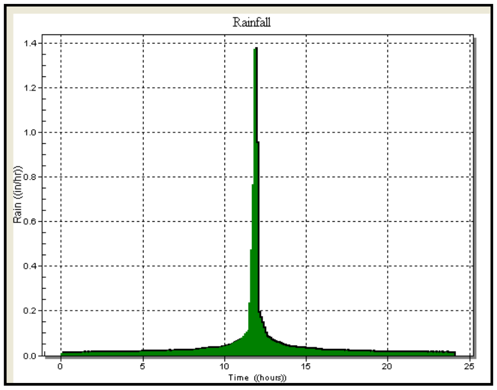

Figure 17. SCS Type II Unit Hyetograph

3.2.4 Routing Method

The Kinematic Wave Equation is utilized for overland flow routing where XPSWMM takes into account the area, slope and width of the sub-catchment areas.

3.2.5 Boundary Conditions

Tail water conditions (time series data) for Outfall 211 data mining is currently underway via the Oak Ridge Environmental Information System (OREIS) website in order to assess the actual WOC elevations during the routing of the storm events. A cross-section of WOC at Outfall 211 is shown below.

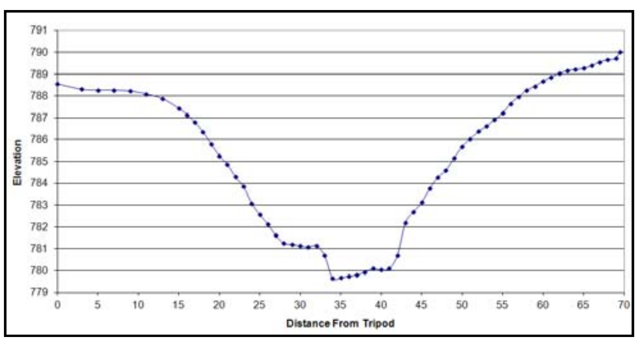

Figure 18. WOC cross-section at Outfall 211

4. RESULTS AND ANALYSIS

The construction of the ORNL 4500 area began in 1950 and some paving, grading, and drainage information was not found because they were on drawings that were no longer available. However, two sets of drawings were found and are noted as 1) original drawings from the 1950's and 2) ATLAS drawings, produced relatively recently, which are basically a sketch of what is believed to be underground with some invert and manhole elevations.

Based on the information found from the two sets of above-mentioned drawings the following assumptions and notes are made:

1. The original drawings indicate that the Outfall 211 drainage system begins from the east between 4500N and 4500S Wings 2 and 3. However, the ATLAS drawings show it interconnected with the drainage system to the east. I believe this may have been a mistake. This model will be in accordance with the original drawings where Outfall 211's drainage system stands alone and begins from the east at the manhole (B-4500S_E) located between 4500N and 4500S Wings 2 and 3.

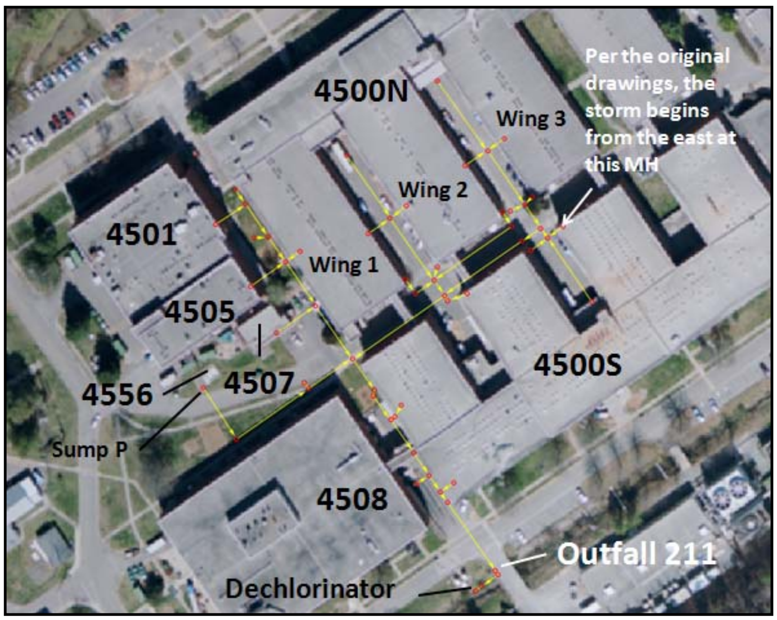

Figure 19. Location of MH B-4500S_E

2. The ATLAS drawings do not show the existing inlet (I-2) to the west of MH211-3.

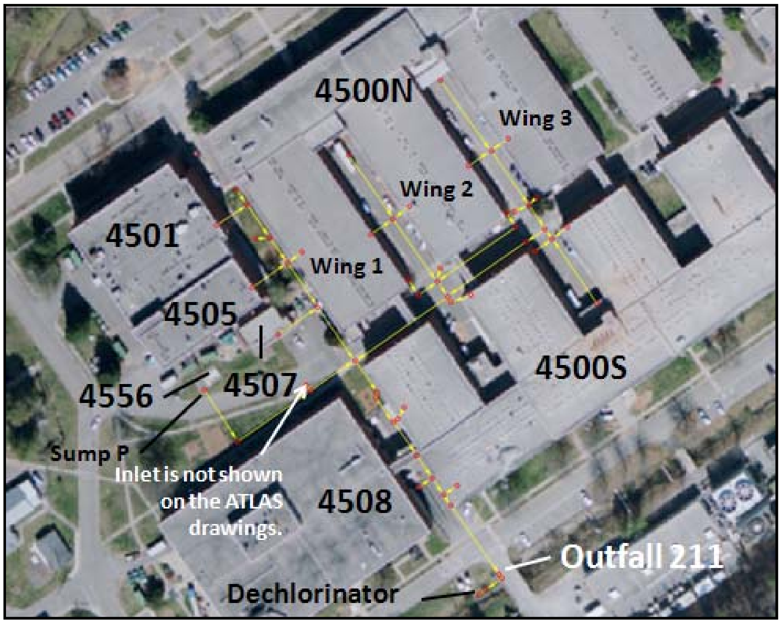

Figure 20. Location of Inlet I-2

3. The ATLAS drawings indicate that the inlet east of 4500N Wing 1 is shown to the west of the manhole located at the north-south centerline; however, it is located to the east of the north-south centerline (I-4).

Figure 21. Location of Inlet I-4

4. The ATLAS drawings do not show or have no symbol for the two inlets (I-8 and I-9) located east of 4500N Wing 2.

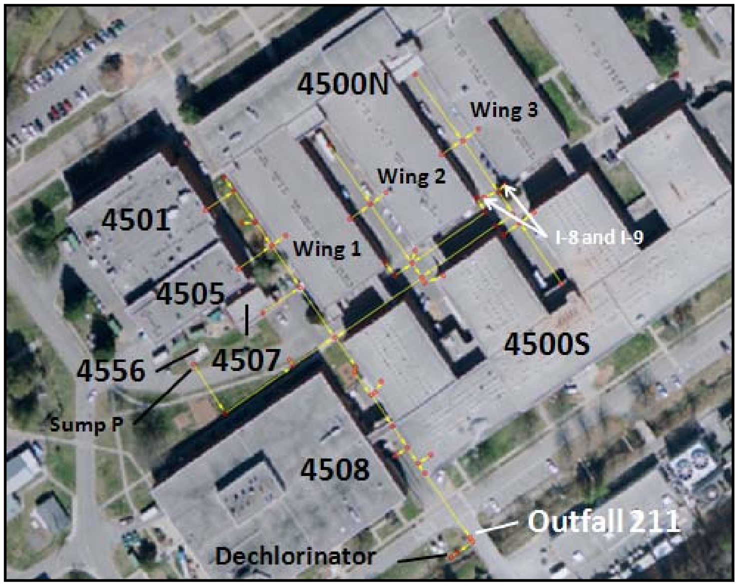

Figure 22. Location of I-8 and I-9

5. There are unknown inverts, manhole elevations, and inlet elevations throughout the system where reasonable assumptions will be made from analysis of surrounding or like data.
6. Assumptions will be made for the building area contributing to the roof drains. A single lateral for each building will be shown in places where there are multiple storm laterals/roof drains for simplistic purposes. There will be a user inflow placed at the nodes of the buildings of 2gpm/ lateral for condensate and/or cooling water discharging into the system as per the estimate provided by the ORNL Engineering Department.

4.1 Flood Risk Analysis

XPSWMM will provide estimated flows, velocities, and elevations throughout the system in order to understand where high and low flow rates will occur. The hydraulic grade line (HGL) which is a line indicating the pressure at any point throughout the system will allow for flood risk analysis within the area. If the HGL is shown above an inlet or manhole elevation then most likely there will be ponding at that location.

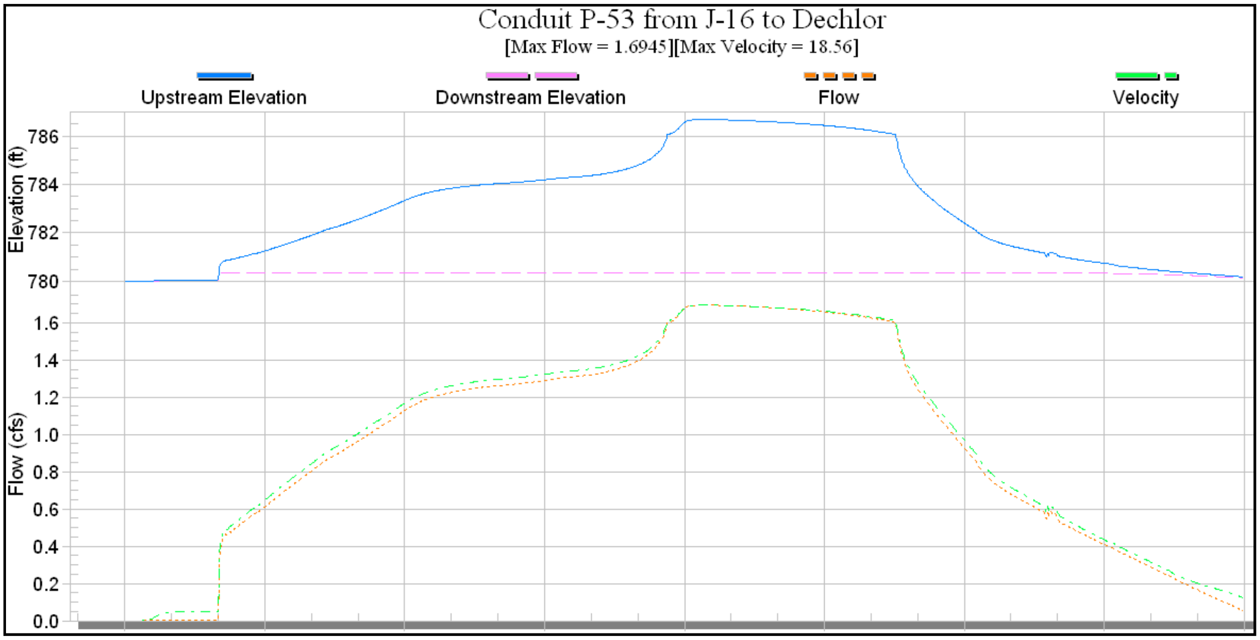

Figure 23. Hydraulic Grade Line

4.2 Probability Exceedance

In addition, XPSWMM will provide time series (flow rate at its corresponding time) for the nodes (inlets, manholes, and junctions) indicating peak flow rates at its corresponding time. The time series will be graphed to form a runoff hydrograph and will resemble the following graph for the following chosen storm events:

1. 25 year – 24 hour
2. 100 year – 24 hour
3. 500 year – 24 hour

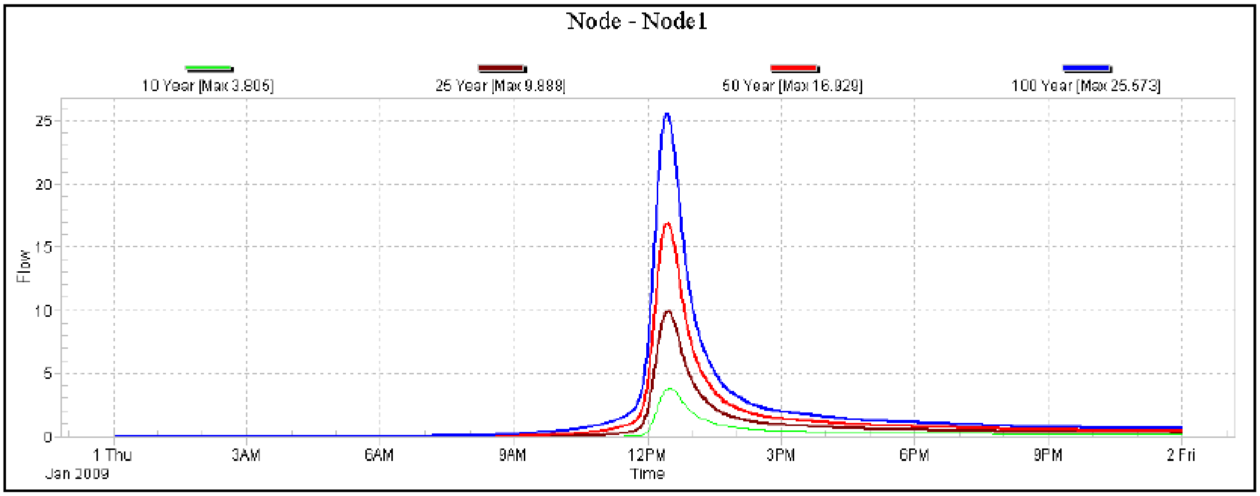

Figure 24. Runoff Hydrograph

.

The time series information will allow for a probability exceedance (PE) analysis of the nodes within the domain. PE is the amount of time (%) which the parameter will meet or exceed the calculated value which will be the amount of time (%) which the flow and/ or elevation will meet or exceed the estimated value calculated by XPSWMM.

5. CONCLUSION

The internship to ORNL was vital in obtaining the pertinent information – construction drawings, ArcGIS files, storm drain layouts – for the area of interest. For the purposes of this study, the amount of data retrieved from ORNL will be adequate to create, calibrate, and validate the model. The model will allow for a flood risk analysis by determining estimated water elevations, the HGL, within the domain for the chosen storm events. In addition, a probability exceedance analysis will be conducted at the various inlets within the domain to determine how often, percentage of time, the flow rates are expected to be exceeded. The model and its findings will be provided to ORNL for their use. Once this model has been approved by DOE EM it will be expanded to include the Y-12 stormwater management system for further analysis.

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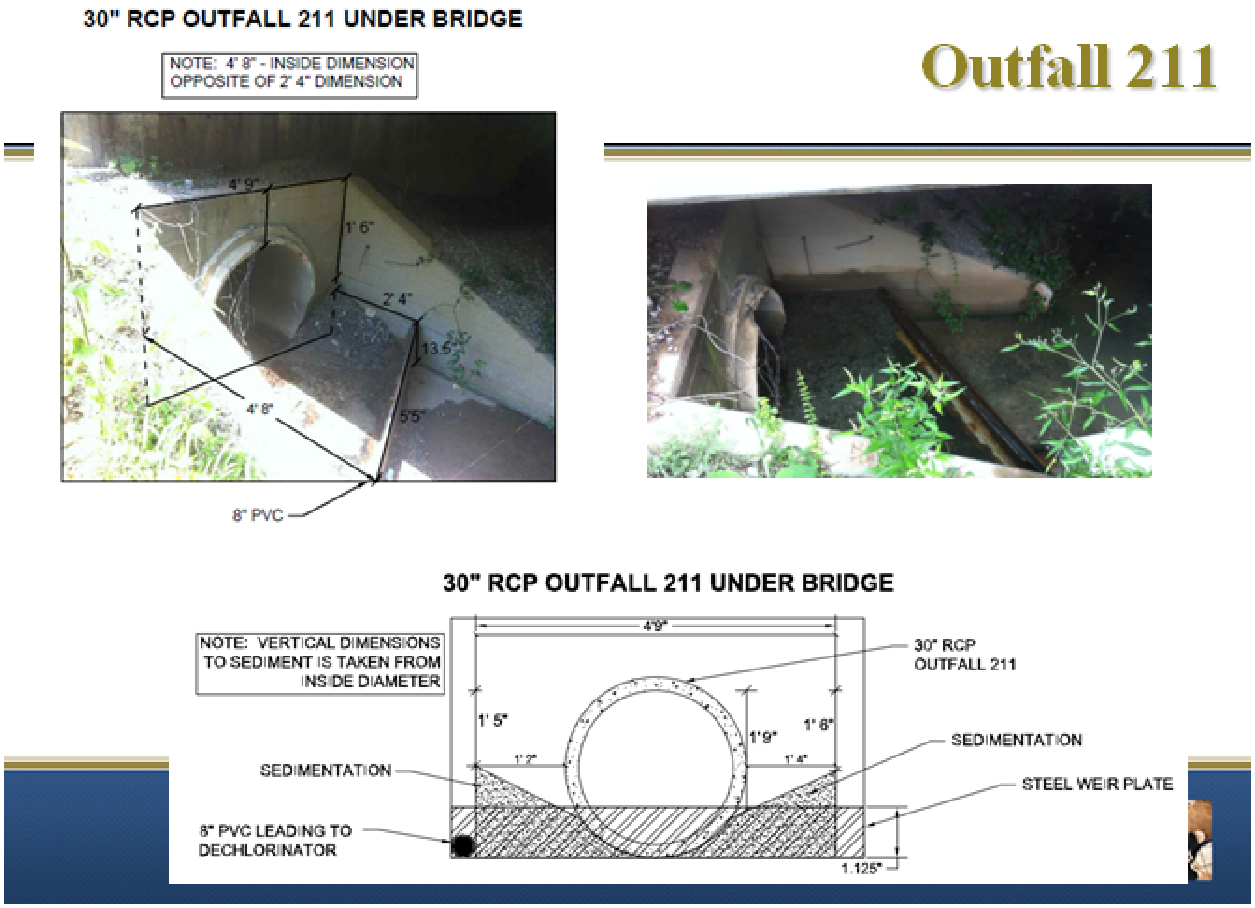
APPENDIX A.


30" RCP OUTFALL 211 UNDER BRIDGE
NOTE: 4' 8" - INSIDE DIMENSION OPPOSITE OF 2' 4" DIMENSION
Outfall 211
4' 9"
1' 6"
2' 4"
13.5"
4' 8"
5'5"
8" PVC
30" RCP OUTFALL 211 UNDER BRIDGE
NOTE: VERTICAL DIMENSIONS TO SEDIMENT IS TAKEN FROM INSIDE DIAMETER
4'9"
30" RCP OUTFALL 211
1' 5"
1'9"
1' 6"
1' 2"
1' 4"
SEDIMENTATION
SEDIMENTATION
STEEL WEIR PLATE
8" PVC LEADING TO DECHLORINATOR
1.125"

Dechlorinator