IDENTIFYING CONTROLS ON AND POTENTIAL SOLUTIONS TO STORM WATER FLOODING IN URBAN AREA- A CASE STUDY OF THE UA CAMPUS

by

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ABSTRACT

Flash flooding in the University of Alabama (UA) campus has become more frequent than before due to the rapid development throughout the campus and the City of Tuscaloosa. To function as a robust and flood free area, the UA campus requires updated and data-informed flood mitigation measures. Identifying flood-prone areas on the campus as well as the reason behind flooding in these areas is, therefore, an important first step before developing suitable environment-friendly solution. This research focuses on investigating key drivers and mechanisms controlling flooding in urban environments. The MIKE URBAN model - a 2D hydrodynamic framework is used to simulate the 6th July, 2018 flood event on the UA campus. The results show that ~7.7% area of the campus was flooded with maximum water depth of 0.78 m and volume 16,100 m^3. Six out of seven major flood locations found in the campus shows the dominance of impervious surface ranging between 60-90%. Detail land cover classification in those flooded locations shows the presence of buildings (29%) and roads (23%) to be higher than other land covers. Following identification of flood-prone regions on campus, the flood-contributing factors are investigated through a field measurement campaign of infiltration rate, soil moisture, soil type, drainage system etc. The results of this analysis reveal that soil texture is quite homogeneous across campus (sandy loam) but with high degree of the spatial and temporal variation in infiltration rate and soil moisture. Comparison between different storm event return periods (1, 2, 10 and 100 years) and between the spatial resolution of the simulations (15, 10 and 5m) show the same flooding hot spots are persistent but with considerable variation in water depth and flood extent. To investigate the effect of stormwater infrastructure on flooding conditions, a simulation

without the drainage infrastructure was conducted. The results show that stormwater infrastructure decrease flooding extent and volume by factors of 2.5 and 15 respectively. To identify the contribution of green space to flood mitigation, a comparison of two land cover simulations were compared to the realistic land cover simulation (entirely pervious, entirely impervious). The results show that actual and entirely impervious land cover increase flooding volume by factors of 2.6 and 3.6 respectively. Lastly, a combination of different green infrastructures BMPs has been proposed as potential flood mitigation measures.

DEDICATION

I dedicate this thesis to every person who mentored me and helped me unfold the attainments of life including this manuscript. Most explicitly, my supportive family and friends without whom I wouldn’t be where I am today.

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1. INTRODUCTION

1.1 Background of the Study

Storm water could be considered as a problem or benefit, depending on the effects it produces. When considering it as a reason for urban flooding, a major concern is whether the drainage systems that convey the storm water are adequate to avoid unnecessary runoff in the urban premises. It is one type of solution for which the respective authority is responsible to provide necessary drainage infrastructure for minimizing flooding. In addition to the storm water infrastructure, drainage channels, as well as other factors such as different land use, rapid urban growth and loss of green space, might be involved in generating or mitigating storm water flooding in the urban area. Flooding is more frequent in the urban environment because of the presence of impervious surface without proper drainage network to convey the runoff. This generated runoff that travels over the surface pooling in the low-lying areas within the catchment until it drains out, infiltrated or evaporates naturally. However, infiltration rates in the urban environment tend to be much lower than that of a natural environment due to prevalence of impervious land cover.

The drivers and mechanisms controlling urban flooding can differ from those controlling fluvial, or a storm surge flooding. Urban flooding is caused by extreme runoff in a developed area where the water does not have anywhere to go (Weber, 2019). Identifying the causes behind urban flooding is not easy due to the demographic distribution, hydro-climatic condition, complex geometric shape of features and rapid land use and land cover changes (Di Baldassarre et al., 2010). To prevent storm water flooding, it is important to know all the contributing factors which are responsible for the flooding or inundation in a particular area.

After that, a plan and procedure to avoid the flooding can be implemented in that area of interest.

Urban flooding has become a more frequent natural disaster around the world due to continuous urbanization process (Huong and Pathirana, 2013). Many cities around the world do not have proper flood management and mitigation plan for the foreseeable future that can protect the city dwellers, properties, and infrastructures from such catastrophe (Grimm et al., 2008). The risk of flooding and its costs for people and property is often underestimated since major factors, such as climate change, is often ignored (Grimm et al., 2008). Nevertheless, even major changes in structural plans of a city cannot guarantee that urban drainage systems would survive all future rain events. Flood modeling techniques is fast becoming a standard tool for improving flood resilience in urban areas (Kulkarni et al., 2014). In urban flood modeling, model is prepared with all the necessary parameters in such a way that it will represent the catastrophic scenario as realistically as possible (Teng et al., 2017). Based on that a city could be better prepared for such events and could focus on finding the weaknesses in the city/disaster plan as well as where to strengthen the defense mechanism (Pelling, 2012).

1.2 Problems Caused by Urban Flooding

The effects of urban flooding on affected individuals and communities are enormous especially when also considering economic loss such as loss of hourly wages for those unable to reach their workplaces; hours lost in traffic rerouting and traffic challenges; disruptions in local, regional, and national supply chains; or school closings with resultant impact on parents or sudden power outages; and disruptions of communication system (Weber, 2019). For instance, in June 2018, eight inches of rain of four hours duration flooded over 2,000 homes in Ankeny, Iowa (Galloway et al., 2018). In East Michigan, nearly 7000 people were without power due to five inches of heavy rain in 2016 (Jordan, 2016). Urban flooding also

causes property damage, fatalities and injuries. For instance, in Englewood, Colorado, in July 2018 a tenant was trapped in her basement by waters from a major downpour and drowned (Galloway et al., 2018). In July 1994, a tropical storm named Alberto caused 10 Alabama counties to be declared as disaster-prone areas with damages of $112 million (NWS, 2019). The flood in 1993 on the upper Mississippi River and Midwest killed 47 people with the total economic loss at between 15 and 20 billion dollars (Nelson, 2015). In 1976 the orographic-induced thunderstorm with extreme elevation relief and a narrow canyon influenced the strength of the current as it moved down slope killed 156 and injured at least 250 in Colorado (Henz et al., 1976). Heavy rain occurred in Cambria County, Pennsylvania killed 74 people in 1977 (Bosart and Sanders, 1981). Over 80 people died and 100,000 homes were impacted due to ~52 inches of rain with large economic loss in Hurricane Harvey in Texas in 2017, primarily at the Houston Metropolitan area (NOAA, 2017 and Van Oldenborgh et al., 2017).

According to the flash flood reports (from 1969-1981) of National Weather Service (NWS) 93% percent of flood-related fatalities were due to drowning and 42% of these drownings were car related (French et al., 1983). Mooney (1983) found that 60% of the flood related deaths in the United States occurred in either urban or suburban areas and half of them occurred in vehicles, with nearly 75% of the fatalities taking place in the evening or overnight hours.

Flood waters are likely to be contaminated especially for prolonged rainfall event and may pose potential health risks to citizens exposed to pathogens in these waters (Ten Veldhuis et al., 2010). Elevated levels of faecal indicator bacteria and microbial pathogens were found in flood waters and in sediments left in the urban environment after the flood (Ten Veldhuis et al., 2010). Among the 548 reported outbreaks in the USA from 1948-1994, they found a statistically significant association between precipitation and waterborne diseases where overflows from combined sewer systems are mentioned as one of the

potential sources of contamination (Curriero et al., 2001). A research conducted by Donovan et al., (2008) showed that the combined sewer overflows (CSOs) increases the probability of contracting gastrointestinal illness from incidental ingestion of water near CSOs for visitors associated with the presence of faecal pathogens indicated by the presence of faecal *Streptococcus* and *Enterococcus*.

1.3 Different Flood Control Mechanism

Control or mitigation of flooding can be achieved through various physical or structural measures such as dykes, detention ponds, drainage channels, diversion channels, and reservoirs, as well as non-structural measures such as flood warning and mass evacuation (Qi and Altinakar, 2011). Different flood control procedures need to be examined in order to effectively mitigate floods in a particular area since the mitigation of floods varies from place to place due to variations in demographic and physical characteristics. This will also provide a better understanding of the relative effectiveness among the alternative solutions (Jonkman et al., 2008). Furthermore, among different flood control alternatives, such as engineering or technical and software-based solutions, decisions are made based on different criteria or parameters (topography, land cover, complex geometric shape of features, drainage facilities) that can address most of the issues related to flooding in that area (Bouwer et al., 2009).

One of the commonly used flood control mechanisms is channelization which includes straightening, deepening or widening the channel, clearing vegetation from the banks, and lining the channel with concrete (Nelson, 2015). This approach has been used in many locations worldwide (Nelson, 2015). An example of a large-scale implementation of the reconnection of the main channel in the Danube river- the second longest river in Europe to control flooding (Campana et al., 2014 and Tockner et al., 1998). Another example is the reconnection of cutoff channels and dredging of isolated pools within the channels of the Rhone River to avoid flooding (Campana et al., 2014 and Castella et al., 2012)

Flood modeling technique is another tool which is broadly used to create or project flood scenario for different locations that are susceptible to flooding. Using this flood simulation results, a city or locality could be well prepared on the response and recovery plan ahead of the event. In urban environment, it is assumed that most of the flow (flood water) passes through the streets and junctions and the flows in the streets are considered mostly one dimensional in flood modeling tool (Mignot, 2006). But near the junctions and bifurcations the flows are basically three dimensional (Weber et al., 2001 and Neary et al., 1999) which was later proved correct in a research project conducted by Huang et al., (2002). Nevertheless, 2D flood model can also be used to simulate flood extent in the urban areas which can predict the inundation accurately depending on the correct calibration of the model with associate parameters involved (Khan et al., 2000). In one dimensional flood model, it is assumed that majority of the water will flow toward one direction- from upstream to downstream. In 2D model, it gives more robust result by calculating the flow that moves in more than one direction. However, using 2D model needs great computational power and long-time to simulate results (Arrowsmith, 2019). Research related to urban flood modeling based on two-dimensional simulation got popularity due to its easy and comprehensible visual representation (Ishigaki et al., 2004).

An emerging flood control system or practice in urban area is Low Impact Development (LID) which aims at preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and drainage that treat stormwater as a resource rather than a waste product (EPA, 2019). LID is the process which results in infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat. There are different types of LID such as bio retention cell, porous pavement, infiltration trench, rain barrel, vegetative swale, rain garden and green roof.

Choosing an LID effectively for a flooded location depends on the topographic and demographic features, surrounding land use etc. (Liu et al., 2014).

1.4 Previous Urban Flood-Modeling Studies

Various types of flood modeling software both free and commercial are being used to detect flood extent, prepare flood mitigation plan and policy, sustainable water management etc. (Arrowsmith, 2019). Lee et al. 2012 describes the decision support system called SUSTAIN to determine alternative solutions for storm water management and flow abatement techniques in urban areas. The main features of this model are to identify topographic characteristics of the study area, improving both water quality and quantity and also the associated cost involved for execution within the project. The major focus of this research was to reduce flow volume and pollutant load by developing cost-effectiveness curves.

Torres et al. 2016 discussed the importance of sustainable drainage systems to manage the urban runoff and landscape improvement. Emphasis was also given to a decision support tools developed by them. They used the E^2STORMED tool to analyze the impact of storm-water management in urban areas. This model also identifies the gaps between Sustainable Drainage System (SuDS) manuals and guidelines and regional decision-makers by calculating the benefit of the SuDS. That study also showed the comparison between different storm water scenarios and the effectiveness of the model.

Mignot et al. 2006 used a 2D shallow water equation for flood modeling in a densely populated city in France. In that research, importance was given on the effectiveness of various parameters (impervious surface, rainfall boundary, drainage data, topography) that is used in the model. The sensitivity analysis shows same level of accuracy in global scale. After that, they tried to include local parameters and the accuracy changed which gave more realistic results.

Basnet, 2017 used the MIKE URBAN model in an analysis of the city of Kulmbach in Germany, which experiences frequent urban flooding. That research addressed the critical parameters and factors influencing the MIKE URBAN model and explained the stepwise procedures followed to prepare the model. Using both the hydrologic and hydraulic modeling tools, a flood map was prepared which will be used for further analysis of Kulmbach.

The MIKE URBAN model was also used in Los Angeles to perform wet-weather calibration for the city's primary sewerage system (Carr, 2007). The study helped the city authority to prepare and validate the primary sewerage basin master plan, prioritize the wastewater capital improvement plan, and improve the flow-monitoring program using the MIKE URBAN results. In that study, both the Rainfall Dependent Inflow and Infiltration (RDII) runoff model and hydraulic-network (drainage pipes) model simulation were used. It predicted the inflow within the primary sewerage system, which will be incorporated into the design of the master plan of the sewage network.

From the previous research it could be agreed upon that various topographic features as well as drainage infrastructure are one of the most important parameters while modeling flood for urban environment. These features help draw the actual scenario for the model.

1.5 Flood Modeling for the University of Alabama Campus

This research investigates urban flooding on the University of Alabama (UA) campus, which experiences frequent flooding in several hot-spots. Like most urban environment, the UA campus has mixed land uses, i.e. a combination of green areas and man-made infrastructure, runoff generated from the study area can vary spatially and temporally depending on the local drainage capacity, vegetation type and density, and topographic features. Therefore, realistic calculation of runoff dynamics is highly dependent on accurate classification of the land cover, soil type, as well as other key soil properties. At the same time, runoff generation and accumulation depend on how the surface is connected with the

storm water drainage system. For instance, in an urban environment, the impervious surfaces (buildings, roofs, roads, and parking lots) are often connected to an underground stormwater drainage system. For roads, parking lots, and similar types of surfaces, stormwater is collected through street curbs and gutters and eventually drain to drainage network (DHI, 2015). However, there are some impervious surfaces that are less likely to be connected to the drainage network, such as sports grounds, playing grounds, and paved paths, and when an extreme event occurs, they can get flooded within a short time span (Figure 1).

Figure 1: Flood event on campus on 20th February, 2019. Left: water accumulated along the street gutters; Top right: water draining through manhole or inlet; bottom right: Soccer stadium flooded due to absence of connected drainage

Runoff generated from impervious surfaces is simple to calculate in a model, but when pervious surfaces are included in the model, the runoff calculation becomes more complex since more variables such as infiltration rate (low, medium, high), soil moisture, soil types, soil compactness, and topographic slopes need to be considered for more reliable results (DHI, 2015). Depending on the rainfall intensity, pervious surfaces can also contribute to runoff after they becomes saturated. Because of ongoing urban development and the active use of spatial distribution of urban pervious land covers tend to be quite complex (DHI, 2015). In this research, MIKE URBAN flood-modeling software is used, which allows the

users to produce different flood-modeling events, incorporating both pervious and impervious surfaces and the stormwater drainage network.

The UA administration is preparing a flood-mitigation and risk-management plan for the campus to avoid unexpected incidents in the future. This type of management plan seeks to reduce the social, economic, and environmental consequences by addressing a number of systematic activities (Horita et al., 2015). Before preparing the mitigation plan, it is necessary to identify the flood extent as well as flood locations around campus. The factors responsible for flooding in those parts of the campus could then be further investigated. Depending on the variation in the land use, existing drainage connectivity, antecedent soil moisture and soil properties, different factors could be responsible for flood incidents in different locations (Funk, 2006).

Figure 2 shows the flood event that occurred on 6th July 2018 with a total rainfall of 101 mm (~ 4 inch). This 4-hour rainfall event caused flooding at several locations on campus especially, at the intersection of Paul Bryant Dr. and Colonial Dr. near Bryant Denny stadium, behind Tutwiler Hall, some parts of University Blvd. and the area adjacent to the Publix supermarket (Figure 3).

Figure 2: Flood event on campus on 6th July, 2018. Top left and bottom: near Bryant Denny stadium and Tutwiler Hall; right: near Publix. (Top left and right-side image are from secondary source)

Another recent flood event occurred on 20th February, 2019, with a total rainfall of 31 mm (1.2 inch). Different locations of the campus were visited from 12 to 2 pm to observe the event (Figure 4). It was found that, even in this relatively small rainfall event, pervious (green space) surfaces of the campus become easily saturated and contribute to the runoff. This seems to have led to the drainage inlets near the curb of the street to become flooded very quickly (middle row of Figure 4).

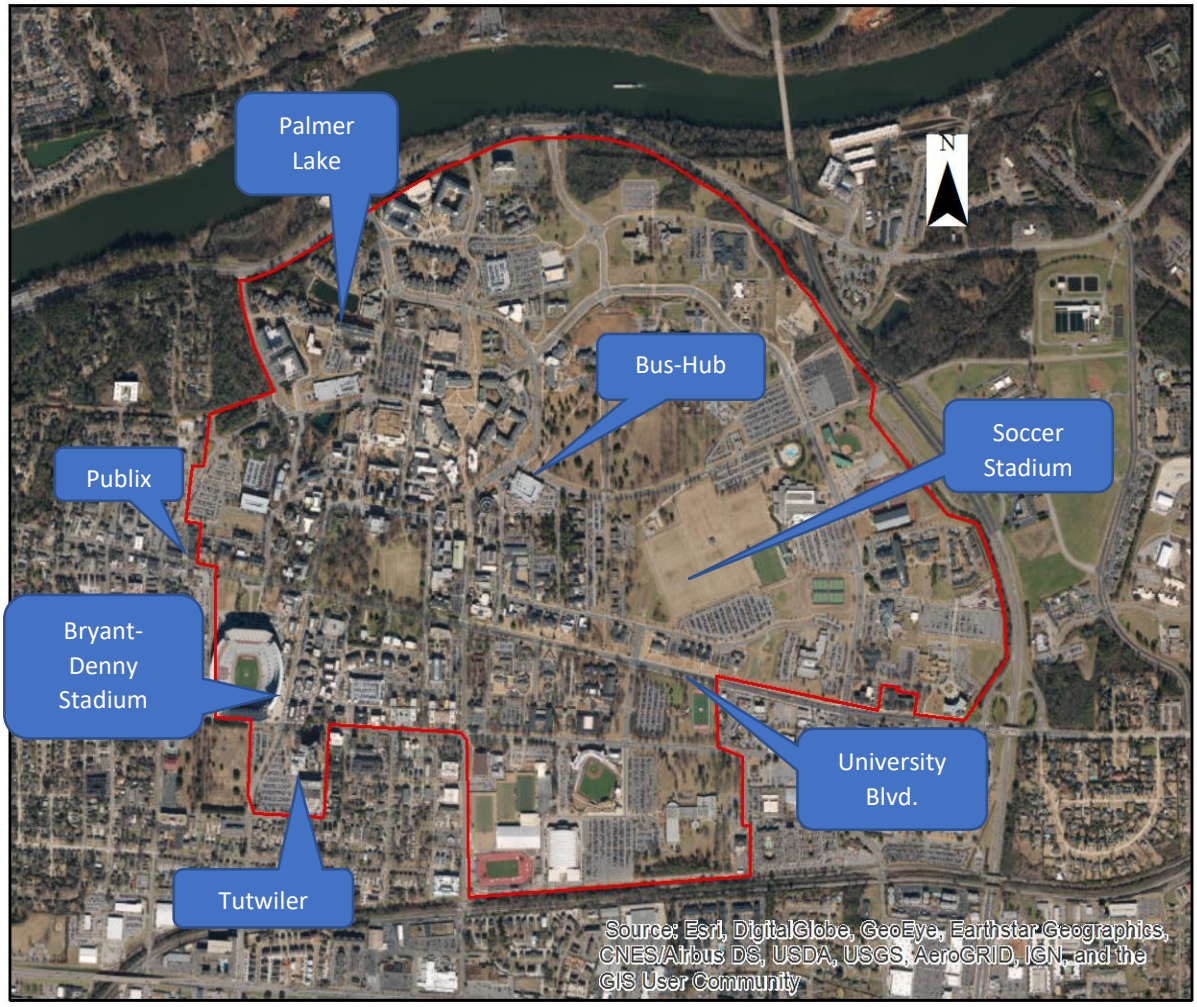

Figure 3: Flood locations on UA campus, red line showing UA boundary

Figure 4: Flood event on campus on 20th February, 2019. Top left: near soccer stadium adjacent to 4th Street; Top right: in front of Pi Kappa Alpha adjacent to 4th Street; middle left: southern side of Bus Hub; middle right: Quad adjacent to Colonial Dr.; bottom left: in front of Gorgas Library; bottom right: in front of Capstone Dr.

1.6 Research Questions

In this study, I will investigate on the issues that are responsible for urban flooding such as land cover, presence of impervious surface, drainage infrastructure, soil properties etc. Later, the importance and effectiveness of implementing different LID in reducing urban flooding will be discussed. Based on that, the research questions formulated for this study are:

1. What are the factors contributing to storm water flooding on urban area?
2. What is the contribution of strom water infrastructure and impervious land cover on flooding?
3. How can we reduce frequent flooding on urban area?

1.7 Objectives

1. Use the MIKE URBAN model to identify flooding hot-spots on campus.

   In order to identify the factors that control flooding on campus, prominent flooding locations first needs to be identified. MIKE URBAN, a hydrologic and hydraulic flood modeling software, was used to simulate extreme rainfall events and generate flood water depth maps. That will enable investigation on those flooded locations by looking into the infiltration rate on pervious surface, comparing built and non-built area in each flooded location, importance of drainage infrastructure in urban environment etc.

2. Analyze the built and non-built area ratio for flood-prone areas of the campus.

   Comparing built and non-built area in the flooded locations will allow an analysis into the contribution of built area to flooding in those locations. Since built areas are mostly impervious, runoff generated from those surfaces is higher than the pervious surface.

3. Analyze infiltration rates for flood-prone and non-flood-prone portions of the campus.

A detailed field measurement was conducted to identify the infiltration rate and soil moisture at different locations of the campus. Infiltration rate at various locations would be different based on the human activity around it such as walking, construction work. More compact soil tends to have lower infiltration rate than the soil which is not disturbed.

4. Analyze soil types in different parts of the campus.

Soil texture, soil moisture, presence of organic matter etc. are important parameters for flood analysis. Different soil have different infiltration capacity depending on the amount of sand, silt and clay particles in it and it is important to know whether soil texture in the flooded locations show lower infiltration rate.

5. Quantify the contribution of the UA storm drain system to reducing flooding.

The role of drainage infrastructures to prevent flooding is analyzed by comparing two simulations, one with and the other without stormwater infrastructure. The difference between the two simulation results is used to quantify the contribution of stormwater infrastructure to reduce flooding extent and depth.

6. Quantify the contribution of impervious land cover to flooding on the UA campus.

The relative contribution of impervious land cover to flooding conditions is analyzed by comparing simulations with different land cover. Here the ‘real’ land cover is compared to fully pervious land cover. The difference between the two simulation results is used to quantify the contribution of the UA impervious land cover to flooding extent and depth.

7. Identify best management practices (BMP’s) that are effective in reducing flooding on campus.

Best Management Practice (BMP’s) are widely used in urban environment to prevent flooding. Installing different types of BMP’s such as porous pavement,

infiltration trench, bio-swales, rain garden etc. can help reduce runoff from urban areas.

1.8 Study Area

The University of Alabama campus was founded on 12th April, 1831, with 52 students. At that time, the campus consisted of seven buildings: two faculty houses, two dormitories, the laboratory, the hotel (now Gorgas House), and the Rotunda (UA, 2019). Over time the campus flourished and thrived having an enrollment record of ~ 40,000 in 2017 (UA, 2019). To keep pace with the increasing number of students, the university went through several infrastructural developments, especially after 2007, all around the campus by erecting new buildings for various departments, increasing lab facilities, administrative buildings, and recreation facilities. As a result, many areas of the campus that were once open green space now have become impervious or developed areas. The ongoing development and the expansion of the campus keep stressing the stormwater infrastructure, which eventually leads to capacity failures during large storm events. The storm drainage networks systems on campus are quite old, and detailed information about some parts of these network systems are not available from the UA authorities (Tim Leopard, UA Associate Vice President for Construction Administration, personal communication). Tuscaloosa receives 53 inches of rain on average annually and the average temperature is 65˚F (U.S. climate data, 2019). During fall season rain increases specially from November - February and then decreases as summer approaches.

A major flooding hot-spot on the UA campus is the intersection between Bryant-Denny Stadium and Tutwiler Hall. This place experiences flooding frequently at different times of the year due to inadequate drainage systems (Campus Water Matters, 2017; Figure 2). Other locations of the campus - such as behind the Bus-Hub, Bryce Lawn, and near Ten Hoor Hall - also experience flooding during different rainfall events.

2. METHODOLOGY

2.1 Modeling- MIKE URBAN

The combined hydrologic and hydraulic model MIKE URBAN was used to simulate surface water dynamics during extreme precipitation events for the UA campus. Amidst other available free flood modelling software such as SWMM, the reasons for using MIKE in this study include: (1) comparatively better user interface and better display of results, (2) compatibility with other MIKE products like MIKE ZERO, MIKE FLOOD, MIKE 21, MIKE ANIMATION etc., (3) seamless dissemination of GIS data into the model framework, (4) its 1D-2D hydraulic coupling which is particularly advantageous for urban flood simulations (Basnet, 2017). The general description of the basis upon which the model simulates runoff, pipe-flow (network), and overland flow is given below. When developing a new simulation domain in MIKE, it is possible to choose either the MOUSE engine or the SWMM5 engine for the modeling process. Though SWMM is a free open source software and provide a decent display of results, SWMM has no linkage with ArcGIS like MIKE as a result user has to build the linkage with ArcGIS. Unlike MIKE, SWMM only allows 1D modeling to produce urban rainfall runoff modeling (Basnet, 2017). The MIKE model allows for the set-up of a 1D-2D urban model to perform MOUSE simulations (DHI user guide, 2017). Here, the MOUSE engine is chosen in the MIKE model to perform all the simulations.

MOUSE is a powerful and wide-ranging engine for modelling complex hydrology and advanced hydraulics in both open and closed conduits, water quality and sediment transport for urban drainage systems, storm water sewers and sanitary sewers (DHI user guide, 2017). In particular, urban flood models require:

MIKE URBAN- to model the 1D-sewer network including the manholes and pipes in general,

MIKE ZERO- to generate a time series for rainfall data (in .dfs0 format) and to convert the DEM raster data to the model's native (DEM.dfs2) file format,

MIKE 21 -to model surface runoff/overland flow and

MIKE FLOOD- to couple the 1D and 2D models. Figure 5 shows an outline of methods for urban flood modeling using MIKE.

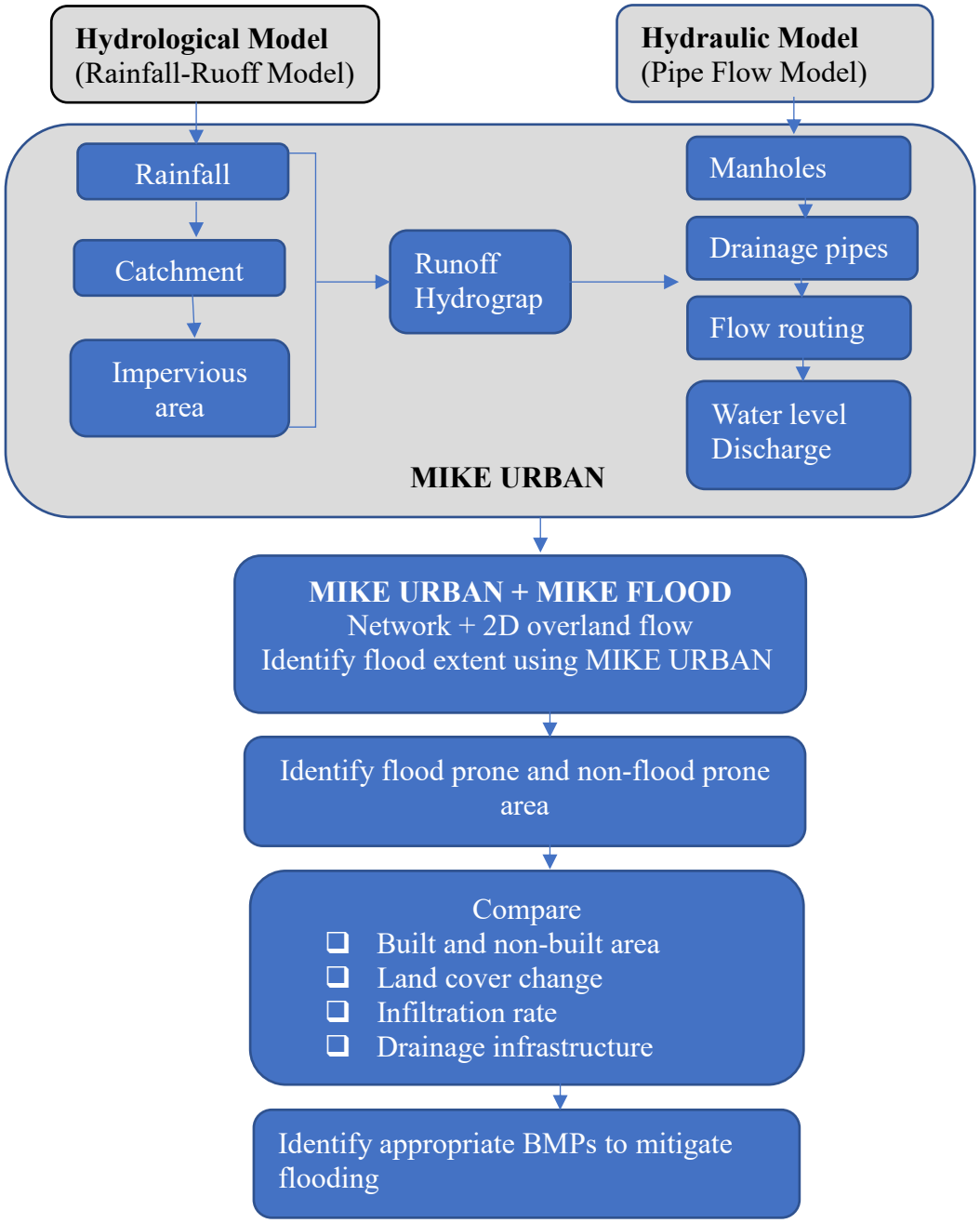

Figure 5: Stepwise methods for the flood modeling

2.2 Rainfall-Runoff Modeling

The MOUSE engine provides tools to model surface runoff, infiltration and evapotranspiration in urban catchments. The outputs from the rainfall-runoff model are used as an input to the stormwater infrastructure network. Precipitation data (time series) is applied over the urban catchments and transformed into surface runoff using the hydrological model.

MIKE URBAN offers various runoff-estimation methods, including: Time-Area method (MOUSE model A), Kinematic wave (MOUSE model B), Linear reservoir (MOUSE model C), Unit Hydrograph Method – UHM and Additional flow and Rainfall Dependent Inflow and Infiltration – RDII. MOUSE Model A does not provide any specific method for the computation of infiltration but an appropriate hydrological reduction based on the rainfall intensity can be specified by the user. MOUSE Model B uses Horton's infiltration equation for runoff simulation. It is the most popular runoff model for pervious area because it is conceptually simple (DHI user manual, 2015). The Horton's formula is given below:

$$I_H(t) = I_{Imin} + (I_{Imax} - I_{Imin}) * e^{-ka.t} \quad (1)$$

where

$I_H(t)$ is infiltration volume per unit of time (LT^{-1}),

I_{Imin} is initial (maximum) infiltration capacity (LT^{-1}),

I_{Imax} is final (minimum) infiltration capacity (LT^{-1}),

k_a is an empirical constant (time factor) (T^{-1}) and

t is time since the start of rainfall (T)

The MOUSE model B (Kinematic Wave model) was used due to its minimum data requirement for the computation of surface runoff. This model is one of the most popular one because it includes the infiltration rate in the model to compute runoff on pervious surface and it is conceptually simple (DHI, 2015). After the surface runoff was computed, it was then used as an input for pipe-flow simulations.

2.3 Hydraulic Network Modeling

Hydrodynamic simulations in urban storm water drainages can be performed under various boundary conditions (e.g., rainfall-runoff and external inflows to the network). For this research, only rainfall timeseries were used as the boundary condition to the MIKE model. Runoff, simulated in each sub-catchment, is drained into the storm water network

through catchment connections to the nearest manholes (nodes). One or multiple storm catchments can be connected to each node.

2.4 1D to 2D Overland Flow Modeling

A 1D-2D coupling approach can be used to simulate a flood event in an urban area (Cadus and Poetsch, 2012). In 1D Drainage network model, runoff is simulated using the hydrologic model and inflows through the connected drainage channels. After that the 2D overland is simulated to show the overland flow throughout the catchment. This procedure allows for more accurate predictions of the flooded regions and the flood depth over the simulated domain. When underground storm water drainage pipes are linked with overland surface runoff, the generated floodwater covers the surface after the drainage capacity of the storm water system is reached.

2.5 Data

The data required and used in this study, for modeling the 1D storm water network and 2D surface hydraulics is:

a. Digital elevation model (DEM): 1-m LiDAR DEM (University of Alabama (UA))
b. Soil infiltration: SSURGO, STATSGO and field measurements
c. Land use/land cover: classification of high-resolution (3-m) satellite imagery (Planetscope).
d. Precipitation: NOAA, Tuscaloosa station (The Weather Underground, 2019)
e. Site configuration: conduit geometry and length, diameter of pipes, conveyances, manholes, nodes, junctions, network schematic (Figure 6).

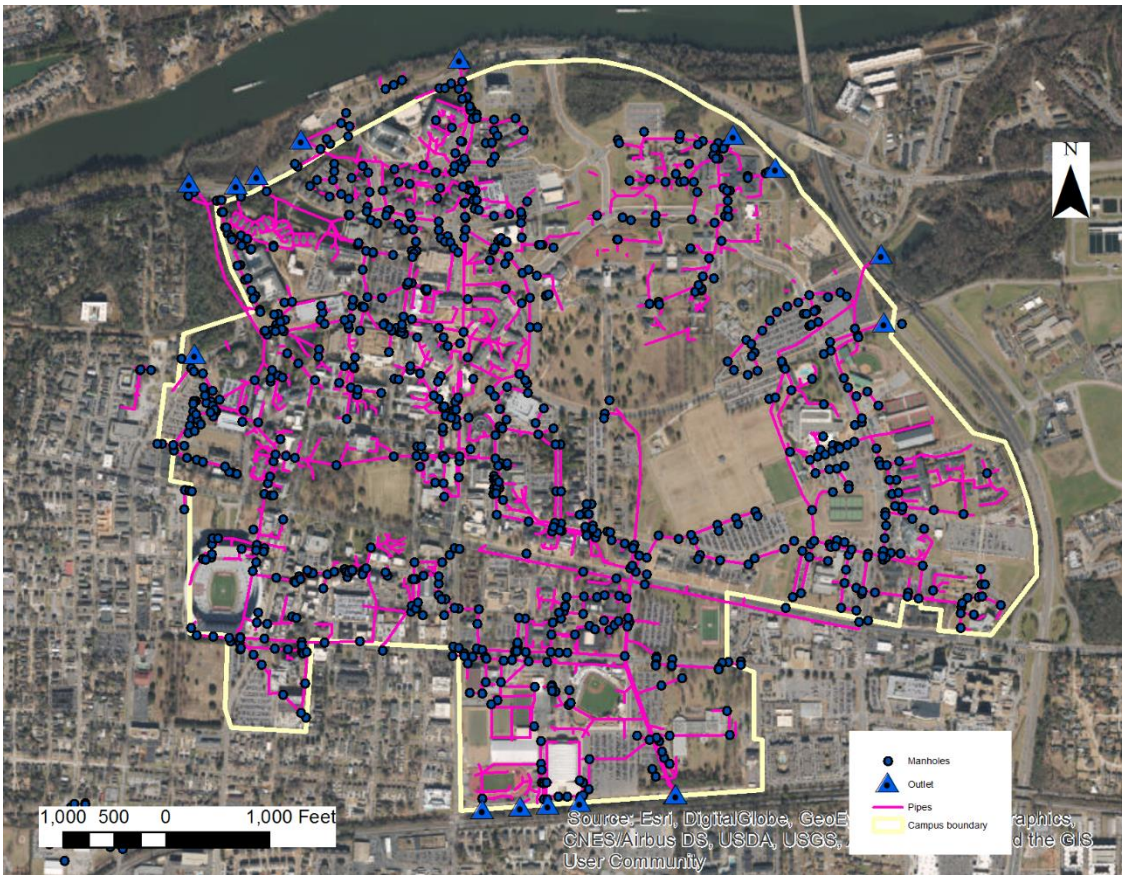

Figure 6: Schematic of existing drainage network system for UA

2.5.1 Storm Water Drainage Network

Available data for the study area - such as the area boundary, pipes/links, manholes/nodes and storm water network geometry were provided by the UA administration. The network system consists of 871 nodes (manholes), and 16 “virtual outlets” (i.e. pre-existing nodes in the study area were converted into outlets for analysis purposes) that connect the drainage system of the study area with the catchments’ outlet at the Black Warrior River (Figure 6) to drain out storm water. Outlets at the other three sides of the campus (east, west and south) are connected to the main drainage channel of the city of Tuscaloosa to drain out storm water from the campus (Figure 6). For analysis purposes, the number of junctions in the network model was increased to 1731 to maintain a sloping direction of water in the pipe system. The number of pipe segments in the system is 2613, with varying length and diameter. The total length of pipes in the study area is 65,606 m. The

drainage system of some parts of the UA campus is not continuous/connected to the main drainage pipeline. For instance, some parts of the Bryce lawn in the UA campus was not the property of the UA campus until 2017. As a result, UA do not yet have detailed information about the drainage network or other detailed utility information for this part of the campus. This may lead to errors in model simulations in that part of the campus. Furthermore, a number of cutoffs were found in the drainage network. As no detailed information is found to correct these, these were fixed in this study by manually linking the disconnected segments to the main drainage network. As this is based on 'guessing' the appropriate connectivity, it may lead to inaccurate representation of the UA storm water network in some locations with propagating effects downstream.

2.5.2 Land Cover and Terrain

Landcover data, including buildings, roads, paths, parking lots, grass, and trees, was obtained from satellite imagery from Planetscope of 3-m spatial resolution (Figure 7). For each of the landcover classes, a roughness value (Manning's n) was assigned based on Modelers' Guideline for MIKE URBAN (DHI, 2015). Roughness value is an input parameter to the model's overland simulation. A Digital Elevation Model (DEM) of the UA campus (LiDAR-based) at a spatial resolution is 0.91 m (3 ft) was used in this study (Figure 8). A DEM is used in MIKE to simulate 2D overland flow. The highest ground-level elevation found in the study area is 90.54 m and the lowest is 38.75 m. The DEM raster data was converted to .dfs2 (required file format for the model) using MIKE ZERO so that it can be used in the model. This specific data is required for model simulations in MIKE URBAN only.

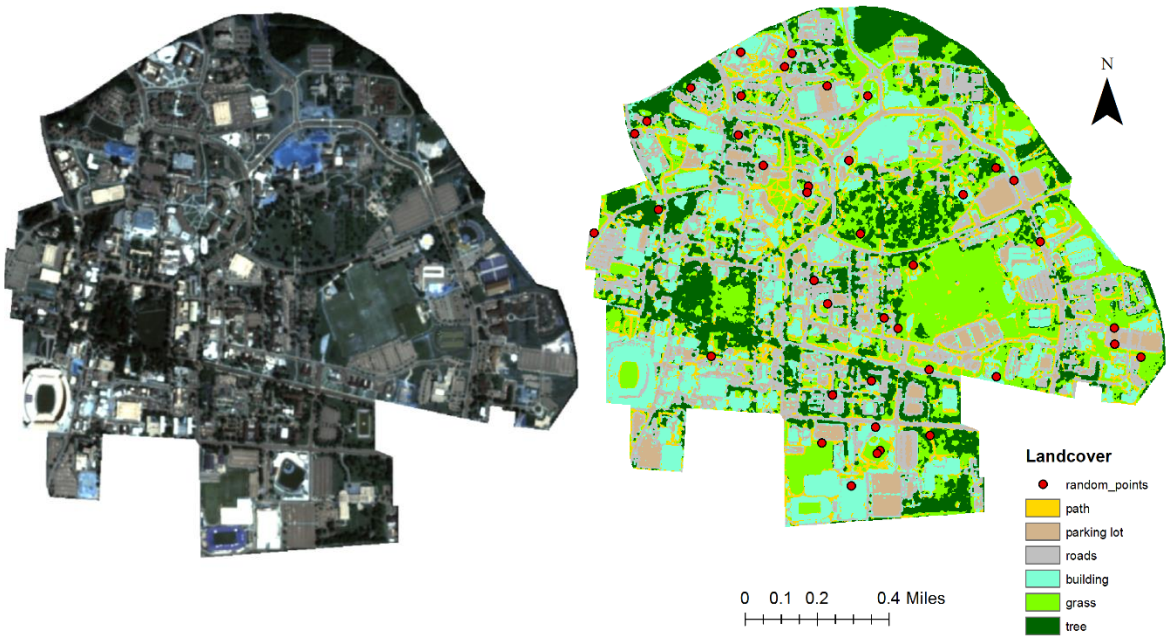

Figure 7: Landcover classification: raw image (left panel) and classified image (right panel)

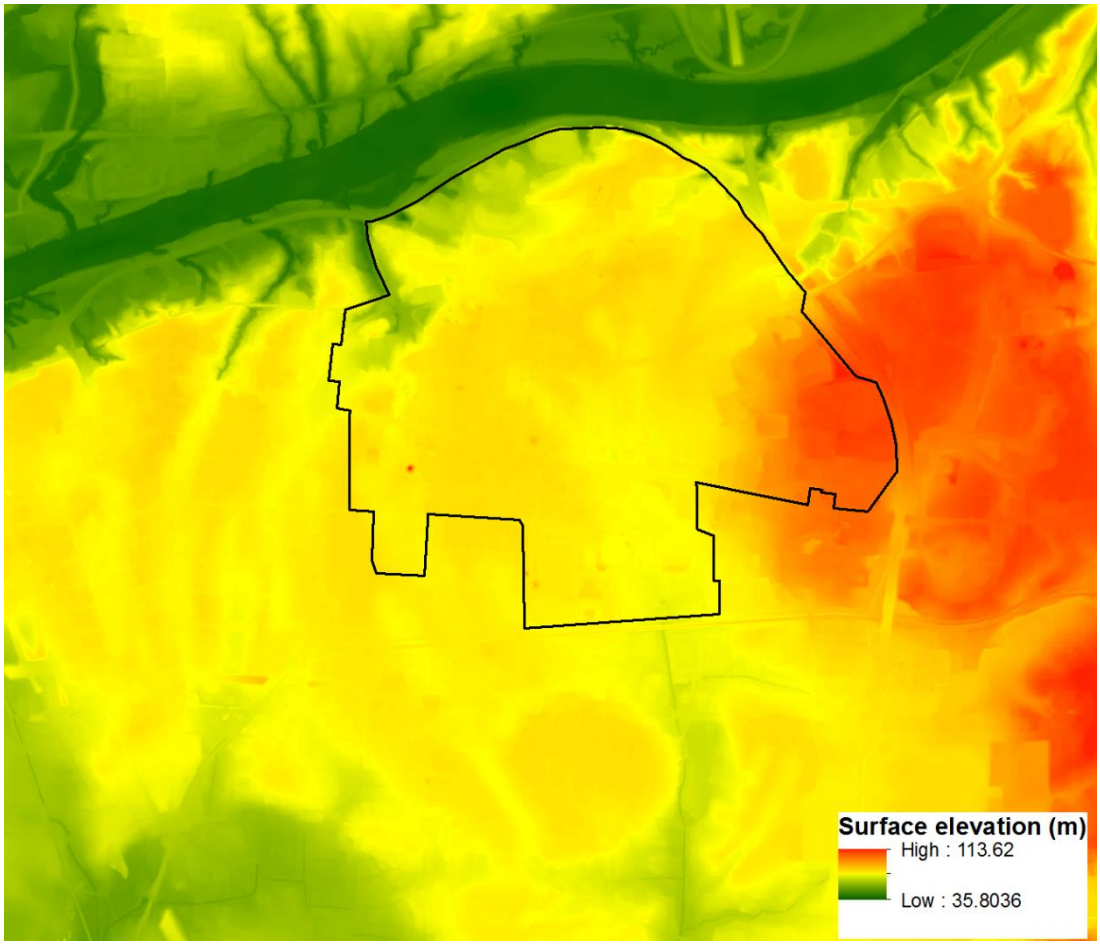

Figure 8: Digital elevation model (DEM) of the UA campus

2.5.3 Rainfall Data

Precipitation records were obtained from Tuscaloosa Municipal (Weather Underground: KTCL- Tuscaloosa Regional Airport), where data is recorded at 15 minutes intervals. From that record, rainfall from the flood event of 6th July, 2018, was collected and used in the model to simulate the flood. The flood event was caused by a 4-hour rainfall event (between 4:00 pm to 8:00 pm), which yielded a total of 101 mm (~4 inch) of rainfall. The return period for this rainfall event is 7 years.

2.6 Land-Cover Classification

To identify different land cover for the campus, a Planet Lab image of 3-m spatial resolution was used, which was taken on April 16th, 2017. Using ERDAS IMAGINE software, supervised classification was conducted to identify different land-cover types on campus such as buildings, roads, paths, parking lots, grass, and trees. In order to identify the accuracy of the classification, 40 points were randomly generated using an ArcGIS 'Random Point Generator' tool (Figure 7). The land cover type in each point was observed by visiting the points and by using Google Earth Pro. The classification accuracy was found to be 80%, with 32 points out of 40 found to be accurately classified.

The land cover map was used in the model's catchment-delineation procedure to represent its 'imperviousness' parameter. This % impervious value is user defined value set by the user depending on the types of landcover. The land cover map was also used to generate a surface roughness input for the model (Manning's n). Here, higher the value means higher surface roughness. The % impervious and surface roughness values were defined for each land cover class (Table 1) based on the user guide of MIKE URBAN.

Table 1: Imperviousness according to land cover types

Land cover type	Imperviousness (%)	Manning Roughness, n
Buildings	100	0.012
Parking lots	95	0.012
Roads	95	0.012
Paths	92	0.012
Tress	10	0.05
Grass	10	0.25

2.7. Field Data

2.7.1 Soil Data Collection and Measurement Procedure

A field-measurement campaign was conducted to determine the soil properties of the study area and their seasonal variations. Particle-size analysis and organic-matter content analyses were conducted to determine the characteristics of the soil that can affect its infiltration rates. Infiltration rates and soil moisture conditions were measured at under different antecedent-moisture conditions (dry, wet, before and after rain etc.) to better represent the relevant parameters in the model and to analyze spatial and temporal trends in infiltration and its link to soil characteristics. The field and laboratory tests conducted were:

a. Soil moisture test (both field and lab test)
b. Organic matter test
c. Infiltration rate
d. Particle size analysis

2.7.2 Soil Moisture Analysis

The SM150 hand-held soil moisture sensor was used to measure in situ soil moisture. A total of 60 measurements were conducted (Figure 9, 10). The sensor measures the soil's

electric conductivity (in millivolt, mV). Soil-specific calibration is required in order to accurately convert electric conductivity to soil moisture (SM; %). To do that the "Laboratory calibration for non-clay soil" (pg. 40 of SM 150 User Manual) was followed. From that calibration, values of a_0 and a_1 were determined, and using that in the equation given below, SM for the sample was calculated:

$$\sqrt{\varepsilon} = a_0 + a_1 * \theta \qquad (2)$$

where

$\sqrt{\varepsilon}$ is soil refractive index,

θ is soil moisture content and

a_0 and a_1 are co-efficient of dielectric properties of soil

In addition, the gravimetric method to measure soil moisture was also conducted to verify the results of the SM150 sensor. Soil samples at 10-15 cm (4-6 inches) deep and ~50 g were collected from each site (Figure 9, 10) and oven dried in the lab at 100°C for 12-hours. The weight of the samples before and after oven-drying were measured. SM (%) was calculated as follows:

$$SM = \frac{W_w - W_d}{W_d} * 100 \qquad (3)$$

where

W_w is weight of soil and water (g) and

W_d is weight of dry soil (g)

Two repeat analyses were conducted for each site.

2.7.3 Organic Matter Analysis

Following the SM analysis, each soil sample was used for the organic matter (OM; %) analysis. The weight of each sample was measured and put in small crucibles to combust at

500 ˚C for 5 hours. The difference in weight before and after combustion gives the quantity of organic matter in the soil samples (Figure 9, 10) using the formula:

$$OM = \frac{W_0 - W_d}{W_o} * 100 \qquad (4)$$

where

W_o is pre-ignition weight (g) and

W_d is post-ignition weight (g)

2.7.4 Infiltration Rate

The Turf-Tech infiltrometer (Figure 11) was used to measure the infiltration rate at four selected locations on campus (Figure 9): Shelby Hall parking lot, Bryce Lawn, the Quad and Tutwiler (near Bryant-Denny Stadium). For each location, infiltration on grass were measured. Measurements were taken at different soil conditions: dry periods, wet periods (after rain), and after football game days. Infiltration measurement using the Turf-Tech infiltrometer is conducted by inserting it at ~3 inches deep into the soil. Field data (infiltration, soil moisture) were collected from September to December in order to represent seasonal changes. Note that October is the driest month in Alabama.

2.7.5 Particle Size Analysis

Particle-size analysis was conducted using samples collected in four locations (Shelby Hall, Quad, Bryce Lawn and Tutwiler parking lot) on the campus (Figure 9, 12). Two samples were analyzed from each location. One of the objectives was to select sample locations that will incorporate both the flood-prone and non-flood prone areas. That way, it is possible to distinguish between the general characteristics of those locations. From the West campus storm drainage study report (2005) it has been found that areas near Tutwiler, Paul Bryant Drive and Colonial Drive are regularly flooded because these are lower-laying areas. In Bryce Lawn groundwater level is higher than the surrounding area, which can also lead to

flooding. These characteristics of the locations make them suitable to choose as a flood-prone area sample. The Quad and Shelby Hall were chosen as non-flood prone areas. The Quad is near the center of the campus and has a large grassed area. Shelby Hall is at higher elevation compared to the other locations, which makes it a non-flood prone area as well.

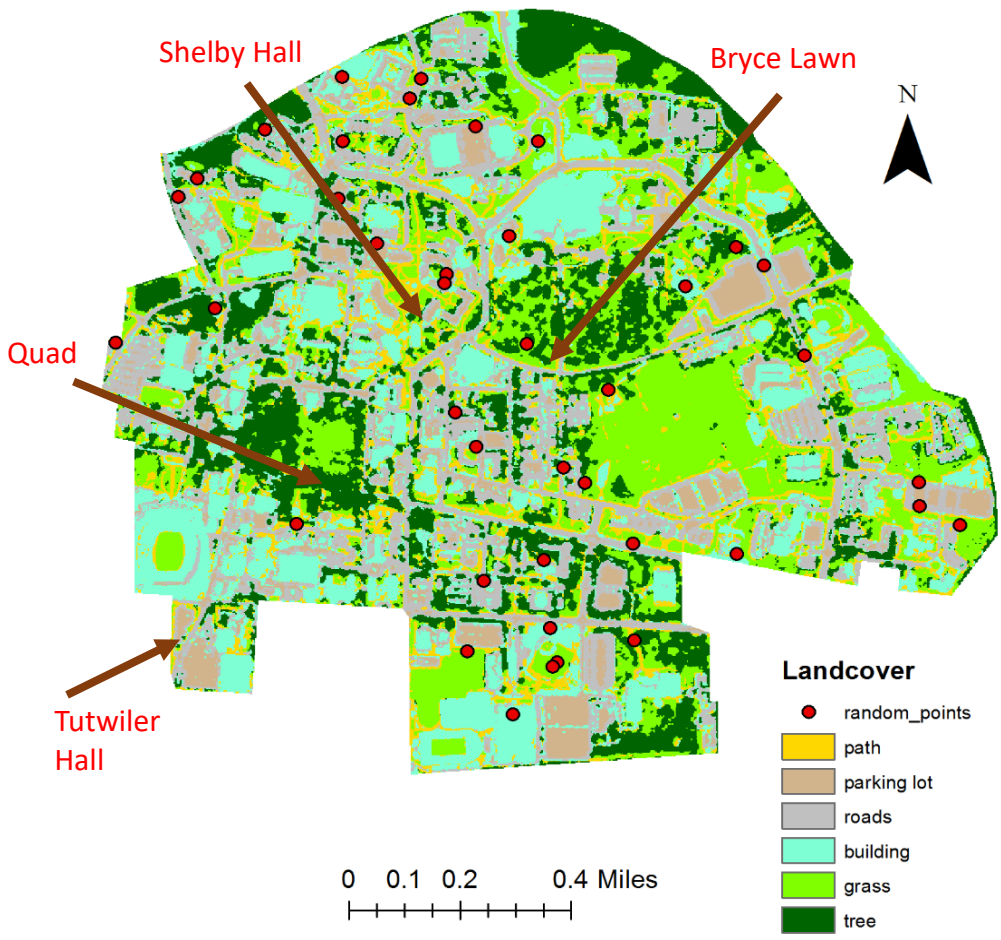

Figure 9: Soil samples collected from various parts of the campus for particle size analysis, soil moisture and organic matter test.

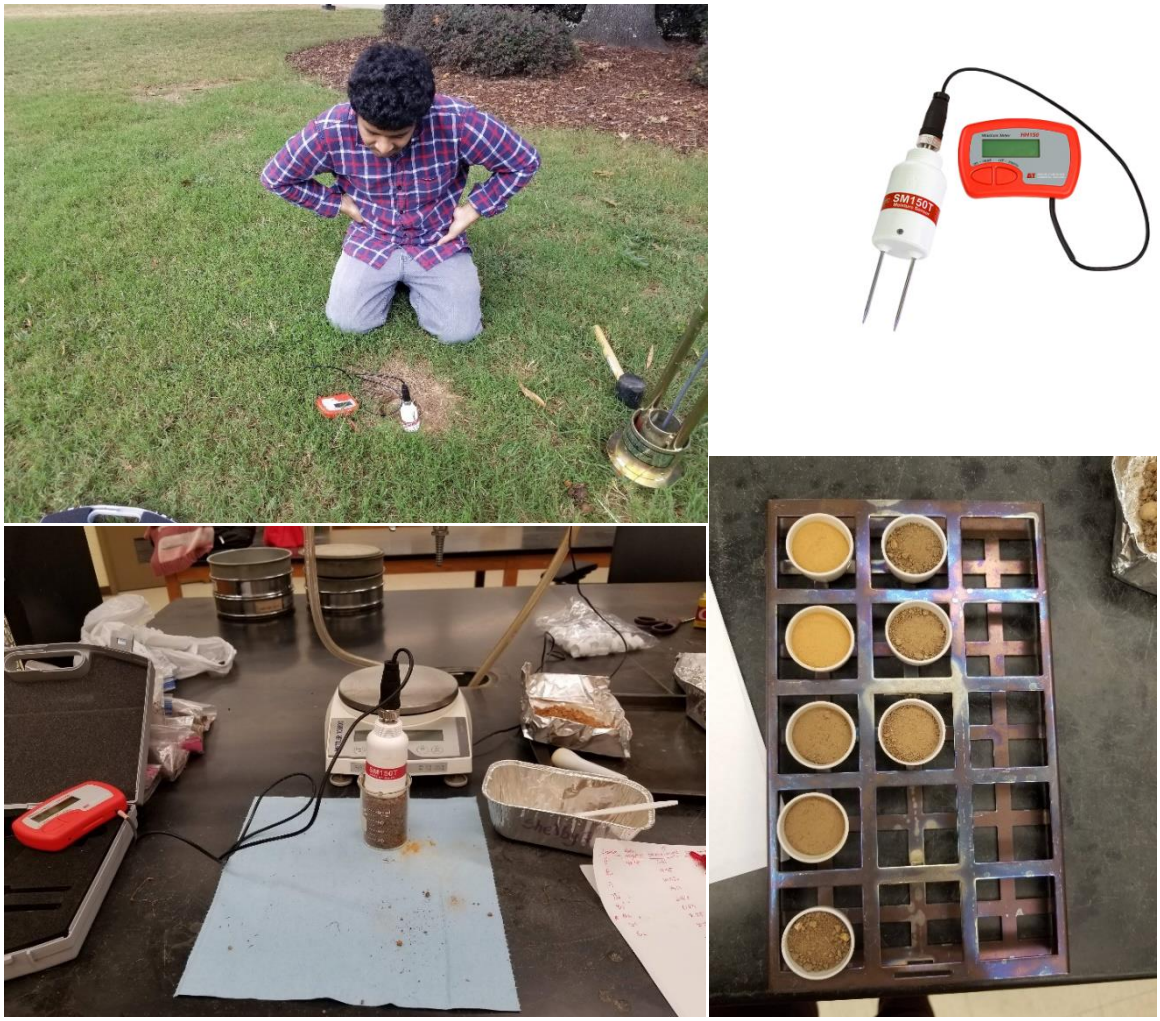

Figure 10: Soil moisture tests in the UA campus (top left: in Quad; top right: SM 150; bottom left: soil moisture test in the lab; bottom right: organic matter test of four different locations)

Figure 11: Infiltration and soil moisture tests in the UA campus (top two from Quad, bottom left : Shelby hall, bottom right: Bryce lawn)

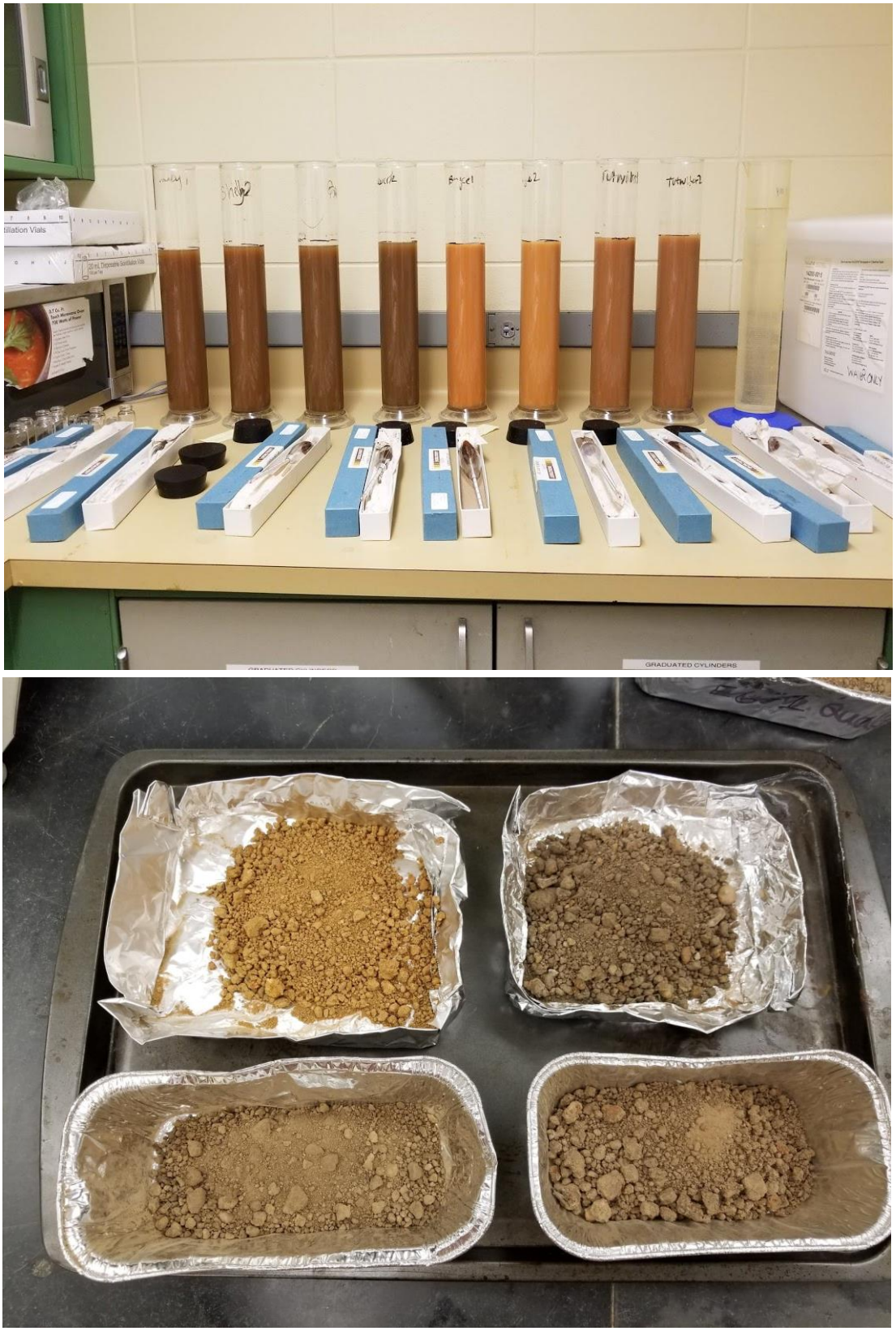

Figure 12: Particle size analysis (top image); soil samples of four different locations (Bryce lawn, Tutwiler, Quad and Shelby Hall) (bottom image)

3. RESULT

3.1 Soil Characteristics and Distribution

3.1.1 Particle Size Analysis

The results of the particle-size analysis show that soil texture in the campus is sandy loam. Soil texture was found to be relatively homogenous across campus, with a range of 24% (76-52) in the sand fraction and 24% (38-14) for clay. The infiltration rate for this soil type is high due to the relatively large proportion of sand particles, resulting in high porosity and permeability. According to Horton's initial infiltration capacity values for dry sand and loam with thick vegetation, the infiltration rate is expected to be 254 mm/hr and 152 mm/hr, respectively (DHI, 2015). These values correspond with the infiltration data collected from the field (Figure 13).

Table 2: Particle size analysis

Sample	Sand (%)	Silt (%)	Clay (%)	Texture
Shelby 1	64	4	32	Sandy loam
Shelby 2	60	2	38	Sandy loam
Quad 1	68	2	30	Sandy loam
Quad 2	60	2	38	Sandy loam
Bryce Lawn 1	60	16	24	Sandy loam
Bryce Lawn 2	52	18	30	Sandy loam
Tutwiler 1	76	10	14	Sandy loam
Tutwiler 2	68	10	22	Sandy loam

3.1.2 Organic Matter Content

Organic matter analyses were conducted twice (17th October, 2018 and 31st October, 2018) using two samples for each site (Table 3). Organic matter was also found to be homogeneous. Differences between the two analyses are likely due to the temporal and spatial variation. The soil was collected from those locations but not from the exact spots. These values (% OM) are within the typical range for upland soils (LJWORLD, 2019).

Table 3: Organic matter

Sample locations	Test conducted on 17th October, 2018 Organic matter (%)	Test conducted on 31st October, 2018 Organic matter (%)
Quad	2.6	3.6
Tutwiler	2.3	4.4
Shelby Hall	2.6	3.8
Bryce Lawn	2.7	3.8

3.1.3 Soil Moisture

Gravimetric soil-moisture measurements were conducted on 16th October 2018, and 30th October 2018, for four different locations on campus. These soil moisture measurements were conducted to check the accuracy of the soil moisture sensor (SM 150) used for the research. Table 3 shows the soil-moisture results from both the Gravimetric method and the SM 150 sensor. The soil moisture from the sensor was found to be within the range of ± 3% of that of the results from the Gravimetric method. The soil moisture from the 2nd test was higher than the first test because the samples collected for the 2nd test were wet due to rain in that week. Among the four locations, the soil moisture in Bryce Lawn was found highest and lowest in Quad in both tests (Table 4). It is an interesting observation that, both Quad and Bryce Lawn are green open spaces but the differences in soil moisture between the two dates are the highest (15.3-9= 6.3% and 42-11= 31% respectively) compared to the two other

locations. One of the reasons could be that the soil in Quad is more compact than Bryce Lawn because of the daily activities and traffic movement involved with it such as walking, playing, recreation activities, game day activities etc. And none of these activities happen in Bryce Lawn. Wet soil increases the chance of soil compactness when because soil moisture works as lubricants between soil particles under pressure from traffic movement and daily activities (Al-Kaisi and Licht, 2005).

Table 4: Soil moisture from Gravimetric method and the SM 150 sensor

	% water content- 16th October, 2018		% water content - 30th October, 2018	
Sample	Gravimetric method	SM 150 sensor	Gravimetric method	SM 150 sensor
Shelby Hall	14.4	16.0	17.9	19.2
Quad	9.0	8.9	11.0	11.0
Bryce Lawn	15.3	13.0	42.0	44.7
Tutwiler	12.5	12.9	19.9	20.8

3.1.4 Infiltration Rate and Soil Moisture

Infiltration and soil-moisture data was collected from different locations (Figure 9) of the campus between September to December of 2018. Total infiltration data collected from 4 locations were 48 (12 data for each location). As the variability in soil moisture is higher even in a small soil sample, 10 soil moisture data were collected from each location every time and then the average was used. In total, 480 (120 in each location) soil moisture reading was collected over the time-period. From these observations, it was found that there is an inverse relationship between these two variables. An increase in soil moisture results in a decrease in the infiltration rate and vice versa (Figure 13). This relationship was strongest in Shelby and Quad (R^2 = 0.6 and 0.96 respectively) but much weaker in Bryce Lawn and Tutwiler (R^2 = 0.12 and 0.32 respectively). These results show the non-stationarity and

spatially variable co-dependence in soil moisture and infiltration rates, even for soils with similar texture and OM.

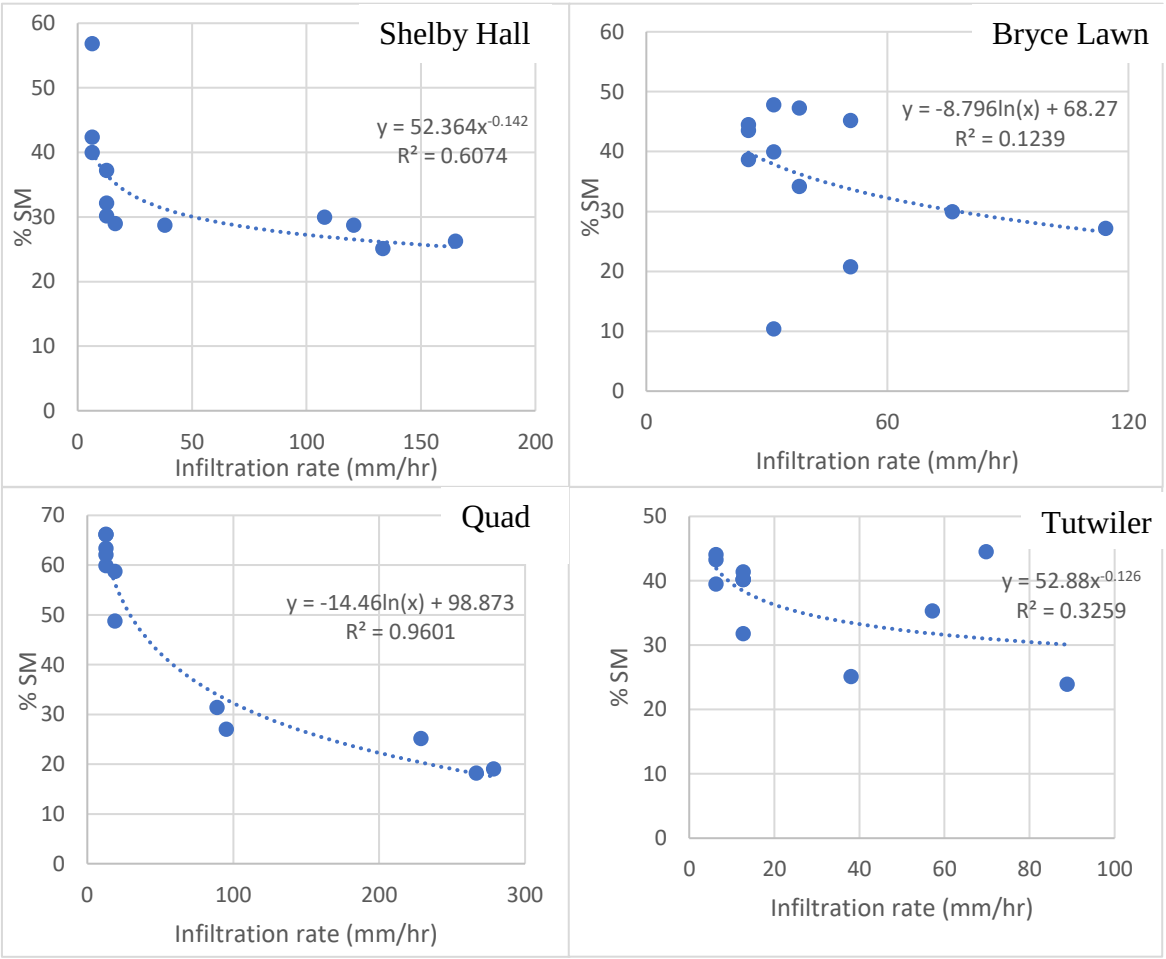

Figure 13: Scatterplot of observed soil moisture and infiltration

The temporal variation in infiltration rate and soil moisture was observed in Figure 14. It shows that before November the infiltration rate was higher in all locations, but it decreased in November-December. The antecedent rain was lower before November and so the soil moisture, but the rain increased after October which resulted in higher soil moisture and lower infiltration rate in the study areas.

Looking into various soil properties- the soil texture and organic matter found to be homogeneous all around the campus but the existence in variation in soil moisture and infiltration rate were found both spatially and temporally.

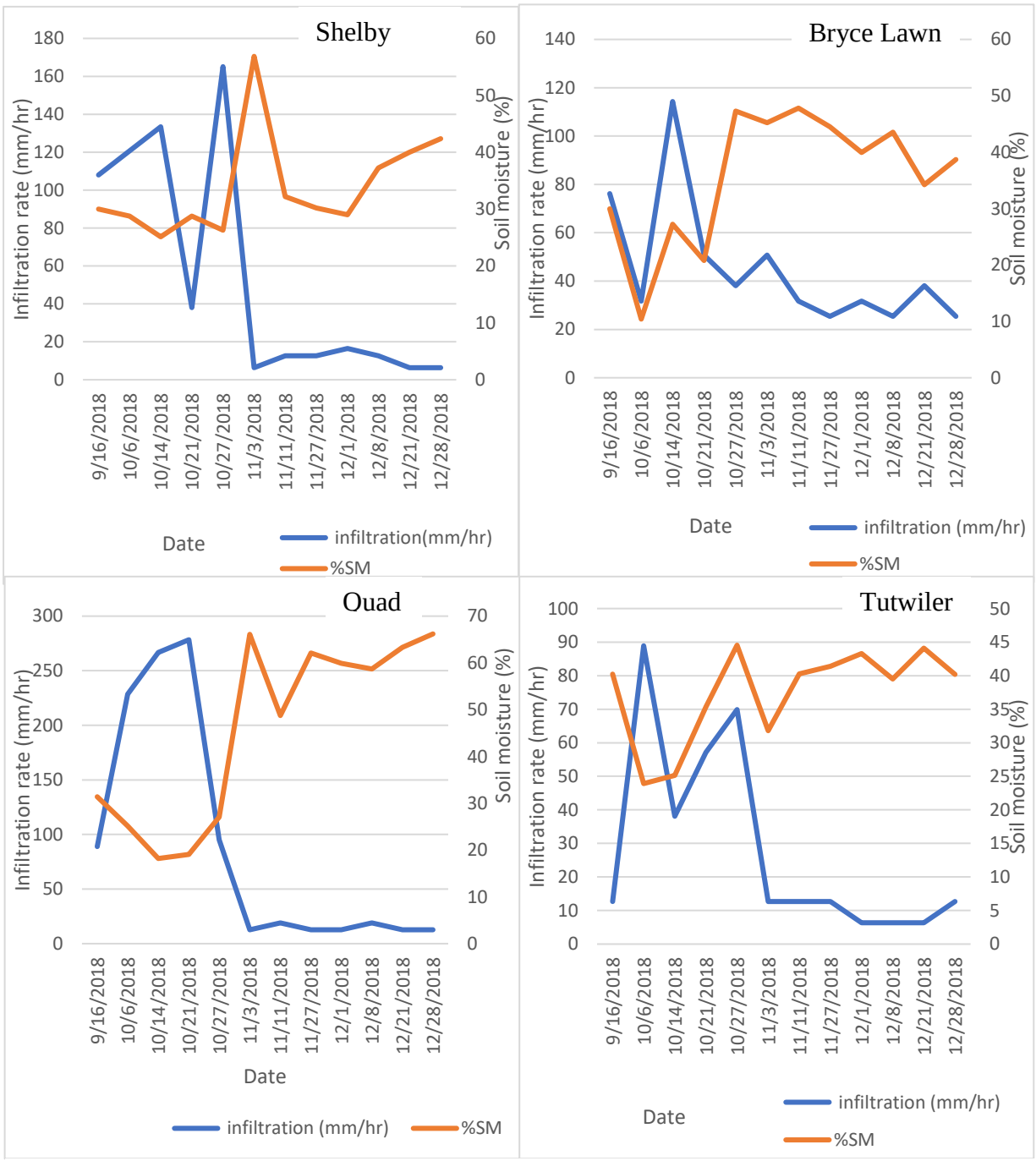

Figure 14: Observed soil moisture and infiltration rate

3.2 The Effect of Spatial Resolution on Flood Simulation Results

Simulated flood map with different spatial resolution (15 m, 10 m and 5 m) shows distinctly different flood extents and water depths (Table 5). Coarser resolution resulted in greater total flood extent but smaller water depth. As expected, the finer resolution simulation (5m) captured more detailed flooding extent including more extensive flooding in some

locations (Figure 15). Here, except for the simulated grid cell size (15-m, 10-m, and 5-m) all the parameters in the model were same for all three simulations. Simulation time increases with finer resolution, being 1.5 hours, 4 hours and 8 hours for simulating 15-m, 10-m and 5-m flood maps respectively. Here all further analysis was conducted using 10-m resolution as a compromise between spatial details and simulation run-time.

Table 5: Variation of flooded area with changes in spatial resolution

Spatial resolution	Flood area (m^2)	Average depth (m)	Maximum depth (m)
15 m	310,950	0.31	0.62
10 m	301,000	0.39	0.78
5 m	213,375	0.55	1.09

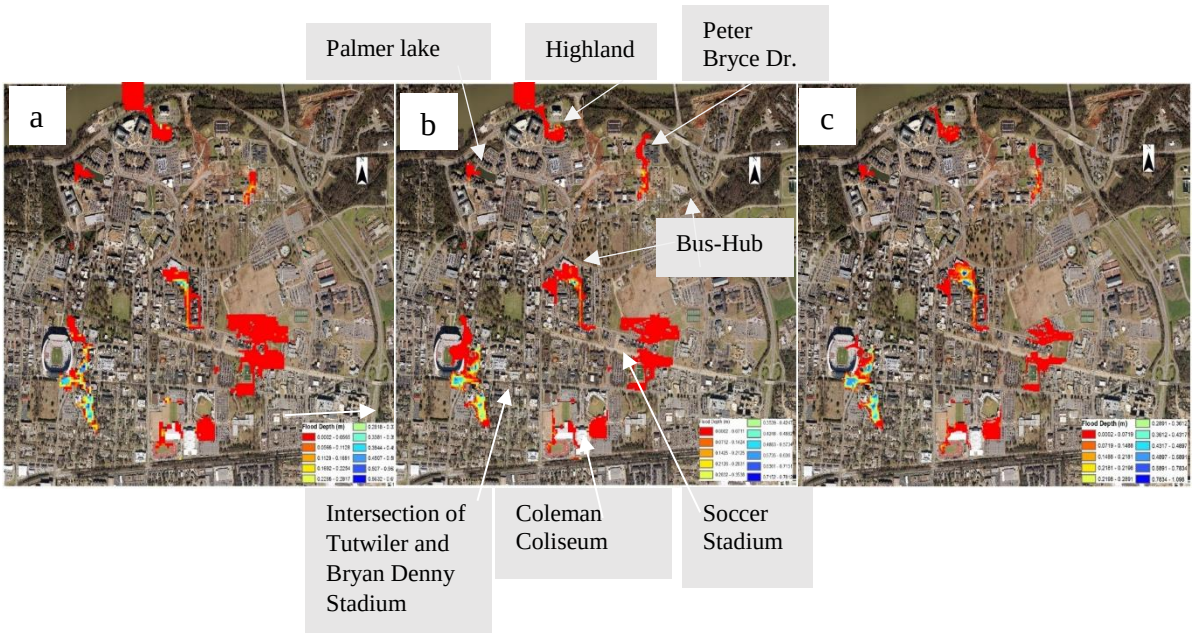

Figure 15: Flood event of 6th July 2018 with cell size of- a: 15 m, b: 10 m and c: 5 m

3.3 Flood Map with Different Return Periods

Flooding at different return periods (1, 2, 10 and 100 years) were simulated (Figure 16) to analyze the variation in flooding on the UA campus. Here, rainfall data for different return periods was collected from "Oliver Dam" station (NOAA) which is ~6 km away from the campus. Table 6 shows that, as expected with larger return period both flooded area and

average water depth increases. Flooding ‘hot-spots’ on campus were the same for all simulations but with increasing extent and water depth. The purpose of these flood maps with different return periods was to observe the changes in flood locations as well as flood extents from small rain to large rain events. For 1-year return period, only four locations were detected to be flooded which were the intersection between Tutwiler and Bryan Denny stadium, Bus-Hub, Peter Bryce Dr. near Bryce Lawn and Palmer Lake (Figure 16). The flooded area found from this map was the smallest among the different return period flood maps. The 2-years return period flood map was almost similar to the 1-year flood map except the addition of flood location near Soccer stadium (Figure 16). The 10-years return period flood map (Figure 16) looked similar to the 6th July 2018 flood event (Figure 15 b) where 7 flood locations were found in both maps. The 100-years flood map showed the largest flooded area with 8 flooded locations in the campus. An additional new flood location was found in 100-years flood map which was the location near Cyber Hall (Figure 16). The flood water depth increased in all flood locations in the 100-years flood map.

Table 6: Flood scenario for different return periods

Return period (year)	Flooded area (m^2)	Average water depth (m)	Maximum depth (m)
1	54,500	0.35	0.71
2	85,900	0.35	0.71
10	231,600	0.38	0.76
100	312,768	0.75	1.49

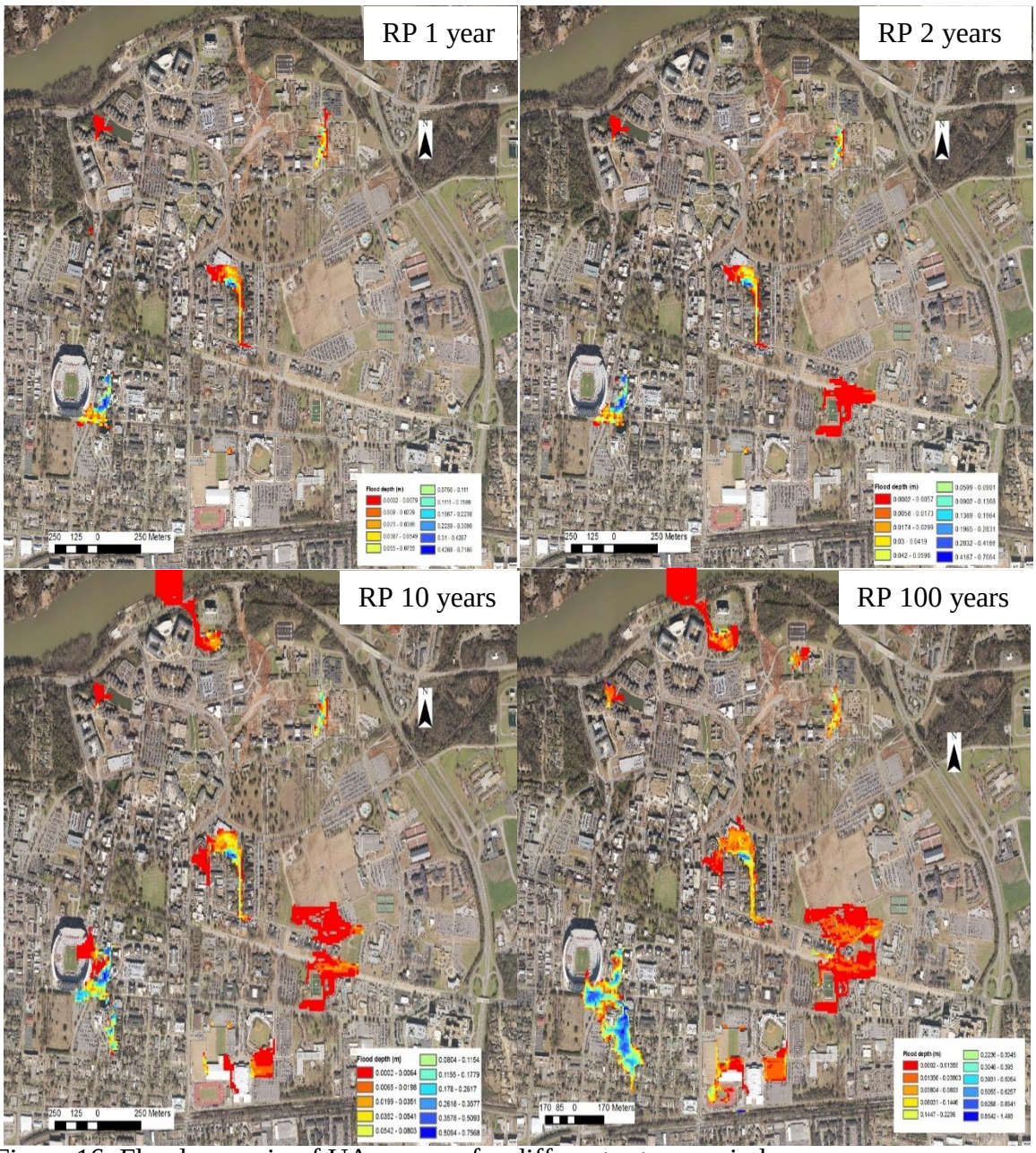

Figure 16: Flood scenario of UA campus for different return periods

3.4 Impact of Built Area on Flooding

The simulated flooded area from the 6th July, 2018, flood event was 301,000 m^2 (the total area of the UA campus is 3,899,223 m^2). The ratio between flooded and non-flooded area is therefore 7.7%. The major inundated areas were near Tutwiler Hall with a flood depth of 0.78 m, behind the Biology building, and the parking deck (also known as the Bus-Hub) where the flood depth was also 0.78 m (Figure 15 b). These locations are adjacent to student/fraternity housing. Toward the northeast side of the campus, the maximum inundation

depth found near the parking lot just behind Cyber Hall and adjacent to Peter Bryce Boulevard was 0.35 m. Other than these locations, the flood water depth in different parts of campus was around 0.15 m.

To find out the reason for these flooding hot-spots, it is important to know the types of land cover present in the flooded locations, because the presence of impervious surfaces is hypothesized to be one of the major drivers for flooding in urban areas. Table 7 shows the classification of land cover in the campus. From this classification around 60% land cover in the campus is impervious and 40% pervious. From the flood map (Figure 15 b) 7 major flooded locations were identified and their flooded areas were classified based on the six types of land cover. To do that, land cover layer was extracted for the flood extent and afterward land cover was classified within each flooded area. The purpose of this classification was to identify the presence of impervious and pervious surface in the flooded area. Table 8 shows the flooded area for each of these land cover.

Table 7: Types of land cover in the study area

Land-cover type	Area (m^2)	Area (%)
Path	398,304	10.2
Parking lot	239,769	6.10
Roads	856,404	22.0
Building	893,664	22.9
Grass	787,014	20.2
Tree	724,068	18.6
Total Area	3,899,223	

Table 8: Floods over different land covers

Land-cover	Tutwiler (m^2)	Bus hub (m^2)	Soccer stadium (m^2)	Peter Bryce Dr. (m^2)	Highland (m^2)	Coleman Coliseum (m^2)	Palmer Lake (m^2)
Path	7,017	2,815	8,946	2,204	805	2,924	259
Parking lot	4,955	1,391	11,051	1,223	803	8,632	0
Roads	12,353	14,906	13,985	7,376	6,760	1,904	473
Buildings	31,994	12,155	8,180	2,453	2,381	13,645	855
Grass	4,192	900	19,894	2,697	1,711	2,832	579
Tree	4,596	6,496	9,093	2,946	3,814	244	3,862
Total Area	65,106	38,663	71,150	18,898	16,273	30,180	6,028

The ratio between pervious and impervious area within the flooded locations is shown in Figure 17. Except for Palmer Lake, all the other 6 locations show the dominance of impervious surfaces in the flooded areas. From the map (Figure 15 b) and also from Figures 17 and 18 it can be seen that, in Palmer Lake, over 60% of the area is covered by trees and about 10% is grass, while the amount of impervious area (path 4%, roads 8%, and buildings 14%) is very low compared to other flooded locations. The reason for flooding at this location could be overflow of the lake due to excessive rainfall. Figure 18 shows the detailed land-cover percentages for each of these flooded locations. This figure shows that the presence of buildings is much higher at Tutwiler and Coleman Coliseum, the presence of both roads and buildings is much higher at the Bus-Hub, and the presence of roads is also higher at Peter Bryce Dr. and Highland. Although 40% of the land cover of the Soccer stadium is green (grass and trees), it gets flooded during rain because of insufficient connected drainage system (Figure 6). Despite having nearly 30% grass at the stadium, compacting of the grass resulting in very little infiltration capacity could be another reason behind flooding. However, the presence of green space is the lowest (~10%) at Tutwiler and Coleman Coliseum.

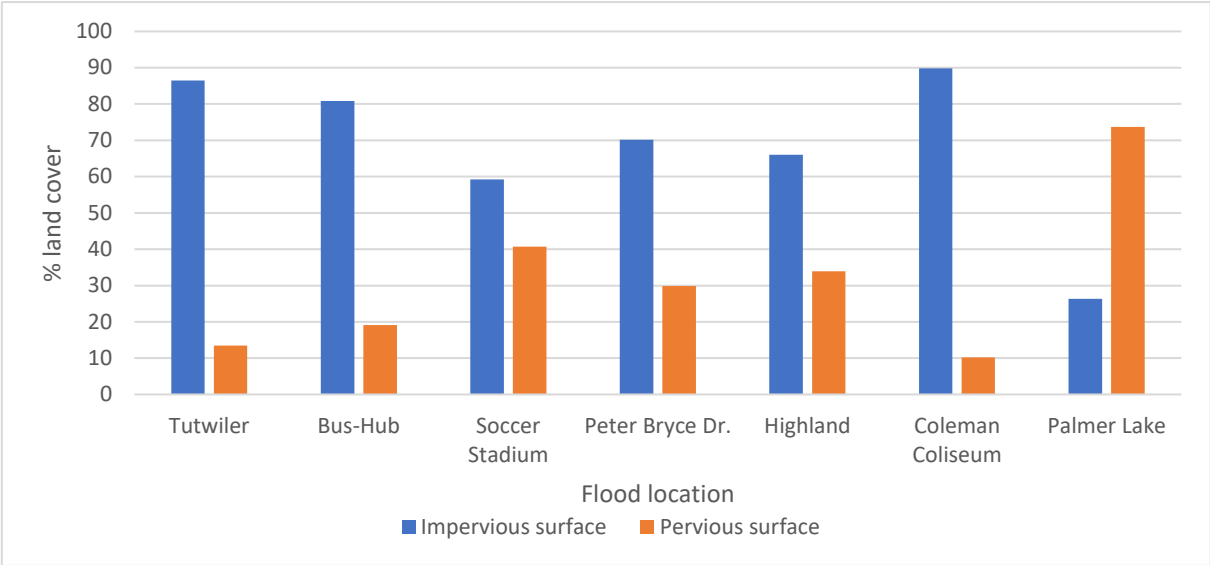

Figure 17: Percentage pervious and impervious area in the flooded locations

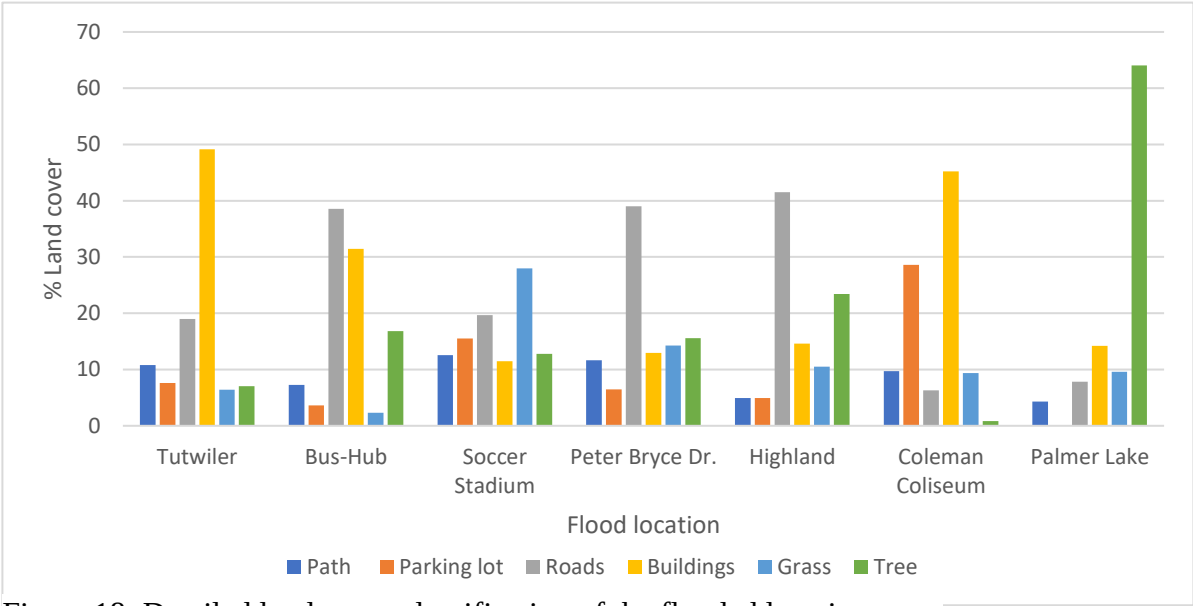

Figure 18: Detailed land cover classification of the flooded locations

3.5 Infiltration Rate for the Flooded and Non-Flooded Areas of Campus

From the observed infiltration data, it was found that the average infiltration rate on the Quad is much higher (~90 mm/hr) than the other three locations over the study period (September to December) (Figure 19). The highest infiltration rate was found on the Quad (278 mm/hr) on 21st October, 2018, which was much higher compared to the other three locations on campus. The lowest infiltration rate recorded on campus was in the Tutwiler and

Shelby areas on 21st December, 2018. Comparing the lowest infiltration rate among the four locations in the study area, the infiltration rate in Bryce Lawn (25.4 mm/hr) is quite higher than the other three locations. It's been found that, among the lowest infiltration, Bryce Lawn was 4 times higher than Shelby and Tutwiler and 2 times higher than Quad. This could be a reason why Bryce Lawn was used as a natural detention pond in the campus to store water temporarily during rain. The soil in the Tutwiler area is very compacted because of activities such as walking and construction, which leads the soil to be disturbed and to act more like impervious surfaces. Although the soil texture for Tutwiler was found to be sandy loam, the type with the highest infiltration rate among the soil textures, it demonstrated low infiltration rates, which means that the consistent human activity can cause changes in the behavior of soil particles.

Other major flooded locations on campus such as the Soccer stadium, the athletic facility, and the practice stadium near Coleman Coliseum also get flooded because there is no connected collection system (manholes, pipes etc.) (Figure 6) to drain the water from the surface. Though pervious surface exists in those locations, regular human activities- walking, playing, practicing for tournaments, exercising etc. made the soil compacted and impermeable. Another major flooded location was near the Bus-Hub, where the soil is highly disturbed because of the daily traffic movement around the bus stop, playground for student housing.

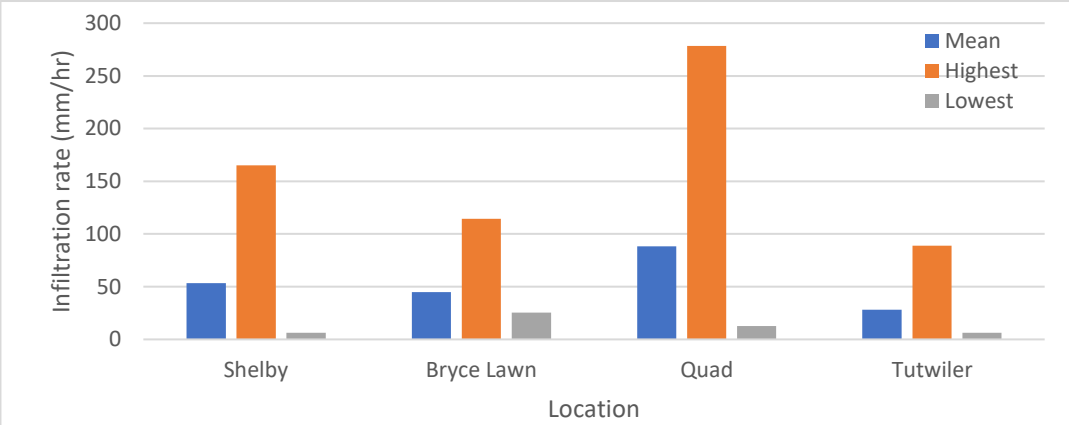

Figure 19: Variation in observed infiltration rate in four different locations of the campus

Figure 20: Runoff over pervious surface; top two: water flowing toward depression located behind Bus-Hub; bottom left: flow accumulated on flat surface; bottom right: runoff over impervious surface at Bus-Hub

3.6 Flood Scenarios

3.6.1 The Contribution of Storm Water Infrastructure to Flood Reduction

A simulation was set up without the UA stormwater infrastructure in order to isolate and quantify its impact on flooding.

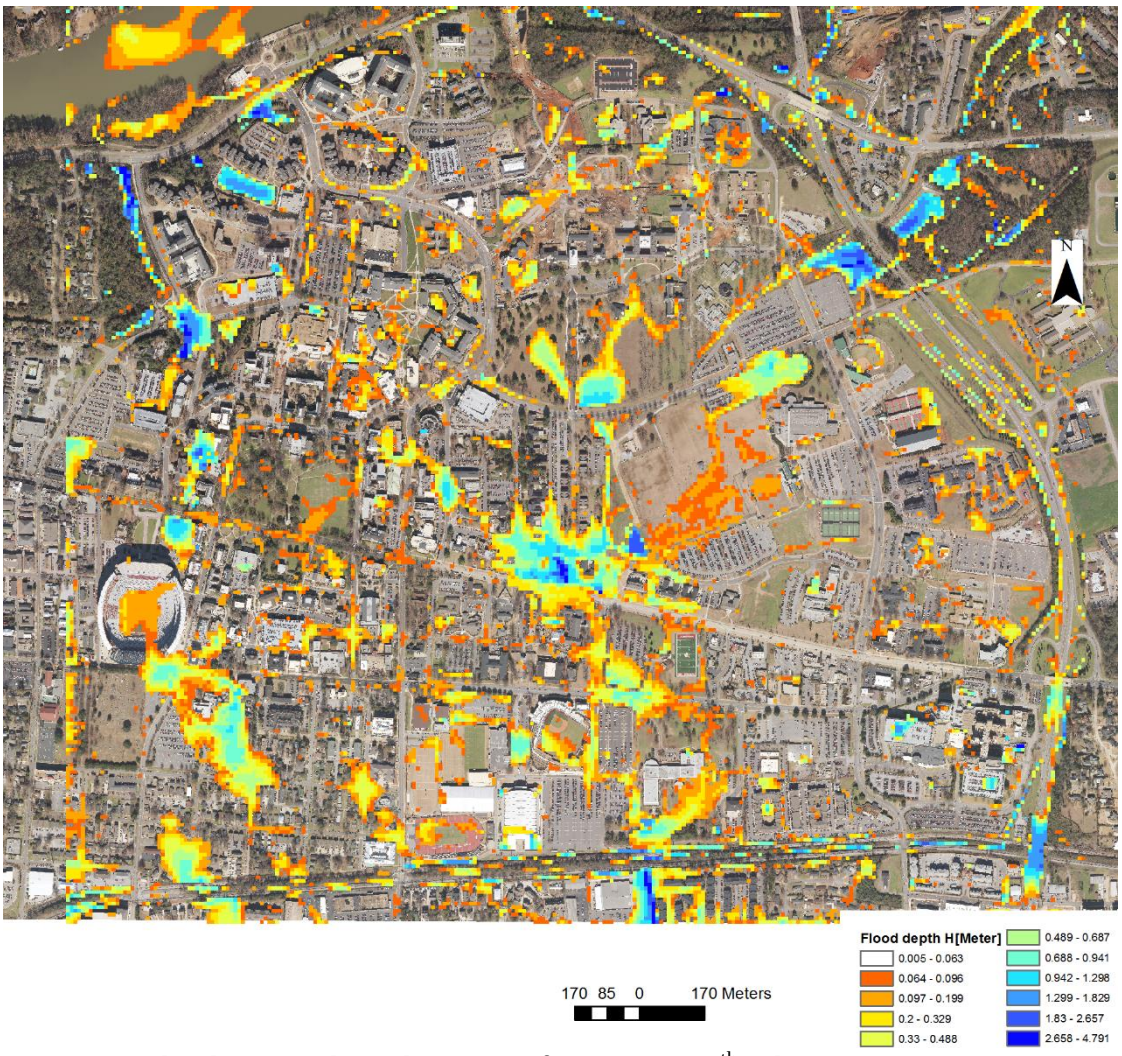

Figure 21: Flood map without drainage infrastructure -6th July 2018

Figure 21 shows that without stormwater infrastructure, for 6th July, 2018 flood event (return period of 7 years and a duration of 4-hour rainfall event) considerably wider flooding extent is predicted. Most noteworthy are flooding near Bryan Denny stadium, at the intersection of University Blvd. and 4th street which was located behind Bus-Hub, near Bryce Lawn, Law school, Good Bid Hall, along the streets etc. The highest flood water depth within the campus area was 4.79 m near the boundary of the campus close to the McFarland Boulevard East which is a low-lying forest area. The highest water depth was also found near Mars Spring road which was a natural open drainage to collect rain water and drain it to the Black Warrior river. Furthermore, near 4th street water depth was also high because that was also a low-lying area (Figure 24). The map also shows that there were some locations where

water pools, such as near Tutwiler, near Coleman Coliseum adjacent to the rail crossing, Bryce Lawn etc. The reason behind the pooling of water in those locations is investigated further below.

MIKE URBAN uses an input DEM to simulate the 2D overland flow. If there is a low-lying land or depression in an area, water will flow in that direction. To evaluate the model performance, a watershed analysis was conducted in ArcGIS to see if the natural flow of water across the surface of the campus matches the overland flow of the model. Figure 22 shows that there are 3 basins in the campus area and much of the water naturally drains out toward the north (Black Warrior River) and south (near the rail crossing). Water is also draining out from the campus using the East and West side outlet or natural flow path. Overlaying the flood map over the watershed map (Figure 23) shows that the model results and the natural topographic flow of water from the ArcGIS watershed analysis use the same flow directions. Figure 21 shows that, at the center of the campus near University Boulevard, inundation occurs because that area is topographically low-lying (Figure 23 a) and is located toward the downstream end of that basin (Figure 22 b), where there is more water coming from upstream and joining that location (near University Boulevard). At the boundary of the campus, floods occurred because those locations are topographically downstream areas, where all the water from the campus is collected from upstream and drains out using those outlet points. At Tutwiler, frequent floods happen because Tutwiler and Bryant-Denny Stadium both are located in a low-lying area compared to their surrounding land, and floods happen regularly between Tutwiler and Bryant-Denny stadium because that is a downstream area where water is collected from the Tutwiler area (Figure 22, 23). Focal statistics analysis was conducted using DEM to better understand the relative elevation of each grid than its surrounding. The idea is that, if a grid is in lower elevation than its surrounding then water will flow toward those lower cells. In doing so, the relative elevation of neighboring cells

could be easily visualized and a primary driver of the water flow could be understood easily. To calculate focal statistics, at first, for each cell the variation in elevation among its neighboring cells' have been identified by calculating the average elevation of the neighboring cells. Here, 200 cells buffer was used for focal statistics. Then subtracting the average elevation from the cell's own elevation gives the relative elevation of each cell. From that value, the negative relative elevation represents low-lying area or depression and positive value represents higher elevation than its surrounding. Figure 24-b shows that water is flowing through those low-lying grids. This analysis shows that when there is absence of drainage system, there is no control over the surface water and so, it will drain following the topography. The rain water will fill up the natural depression or low-lying grids on the surface first and accumulate the flow by running over more lower grids next to it to drain out from the catchment.

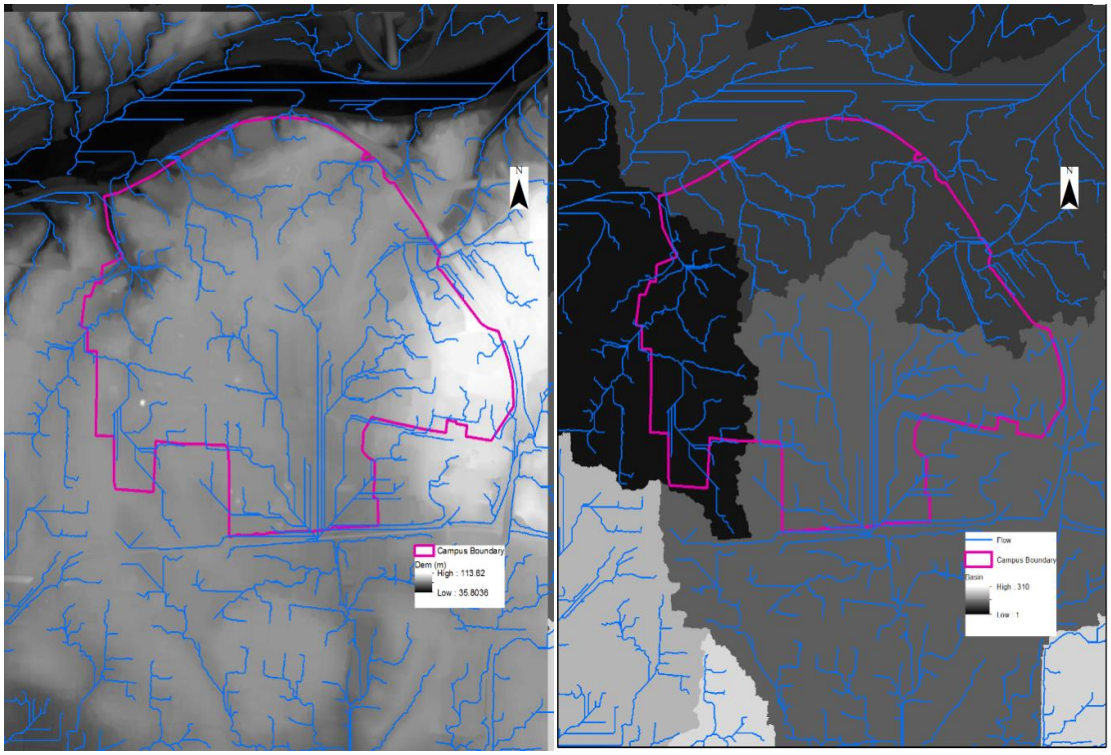

Figure 22: Watershed map of UA campus: left: campus DEM; right: campus basins

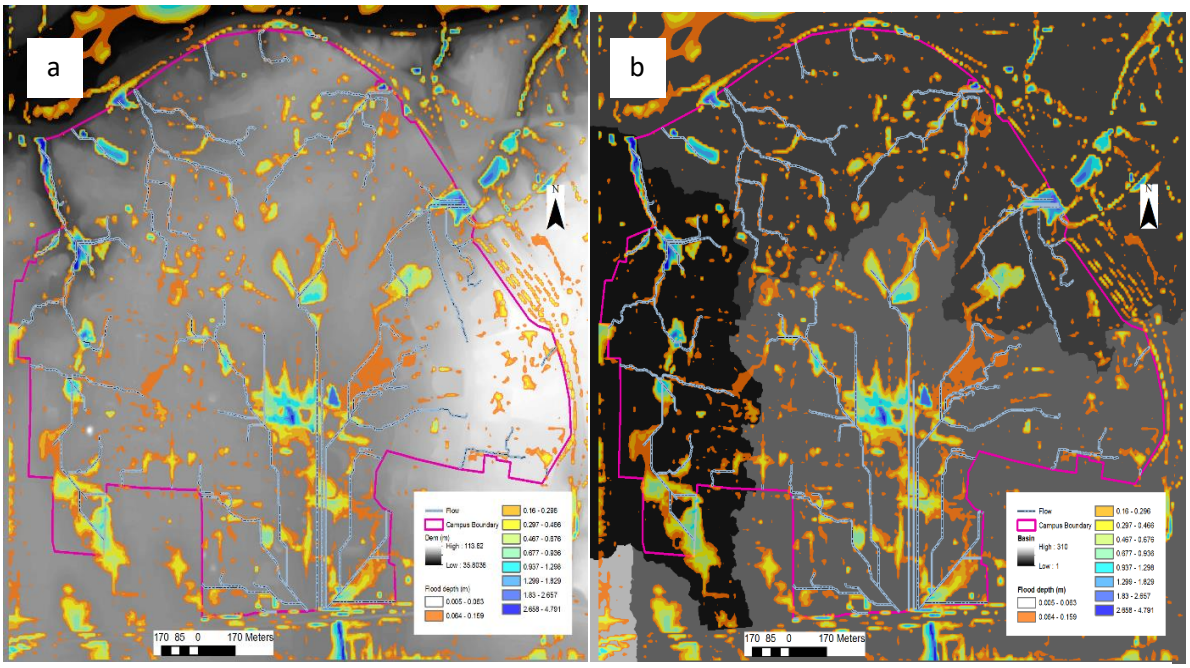

Figure 23: Flood map (without drainage infrastructure) overlaid on watershed map of UA campus; a: campus DEM; b: campus basin

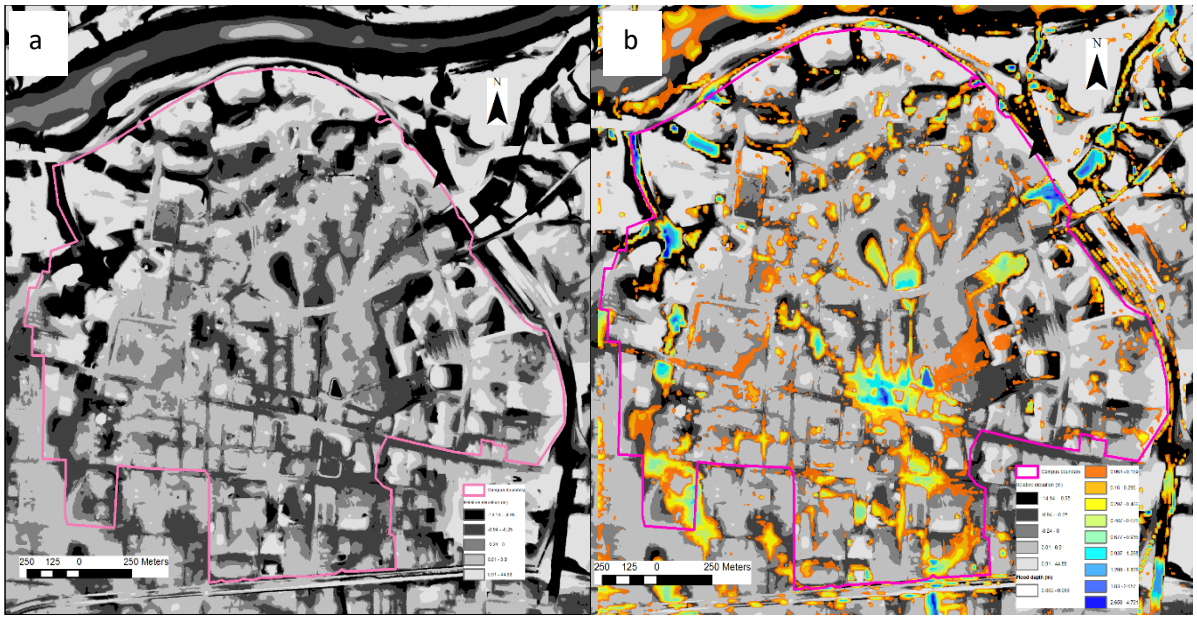

Figure 24: Focal statistics of elevation with radius of 200 cells; a: relative elevation; b: flood depth overlaid on relative elevation layer

Table 9: Flood volume for two different events

Flood scenario	No. of flooded cells	Average flood depth (m)	Maximum flood depth (m)	Total flood depth (m)	Flooded area- each cell size (m^2)	Water volume (m^3)	Difference in volume (m^3)
With stormwater infrastructure	3,010	0.39	0.78	161	100	16,100	232,500
Without stormwater infrastructure	7,498	2.4	4.79	2,486	100	248,600	

A comparison between two flood scenarios shows that flood depth (maximum) for without stormwater infrastructure was ~6 times higher than the maximum depth of the simulation with stormwater infrastructure (Table 9). The flooded area found from without stormwater infrastructure was ~2.5 times greater and the volume of water was ~16 times greater. From the table, the difference in volume between the two scenarios was 232,500 m^3. From these comparisons the effects of drainage system on flooding could be easily perceived. Rain water is collected from the surface through manholes, inlets and draining out through the pipe systems outside the catchment through outlets, thus keeping the surface from flooding. The presence of stormwater infrastructure is important because it drains out storm water every second to prevent water clogging in urban environment. The difference in volume between two scenarios was found to be 232,500 m^3 which means that storm drainage was draining out 232,500 m^3 of water in the 4-hour duration of the simulated the storm event. So, every hour the drainage system was draining out 58,125 m^3 of water from the catchment. And from that it can also be said that its capacity to discharge water from the surface was 16 m^3/s. This clearly demonstrate the importance of incorporating stormwater infrastructure in urban flood simulations and analyses.

The flooded area found from without drainage simulation was 708,669 m^2 (Table 10) which constitutes 18% of the total area of the campus. The flooded area found from without drainage simulation was ~2.5 times the area of actual flood event (Table 11). 47% and 53% land cover found in this flooded area were pervious and impervious respectively (Table 11). Without the drainage system both pervious and impervious area were almost equally contributing to the flooding on campus. In this simulation, the highest flooded area was found for grass (24.4%) and tree (22.5%) and lowest for parking lot (4%). Among the impervious surface- the highest flooded area was found for buildings (19.3%) and roads (20.3%) (Table 10). The presence of buildings (29%) and roads (23%) were also higher in the actual simulation (with drainage) and found lowest for path (10%) and parking lot (11%) (Figure 18). With drainage simulation- the pervious area found in the flooded area was 26% which increased to 47% for without drainage simulation (Table 11). Again, the impervious area was found higher (74%) for actual simulation than the without drainage simulation (53%).

Table 10: Flooded area over different land cover for without drainage simulation

Land cover	Total campus area (m^2)	Flooded area (m^2)	% flooded area
Path	398,304	68,490	9.7
Parking lot	239,769	28,098	4.0
Roads	856,404	143,640	20.3
Building	893,664	136,530	19.3
Grass	787,014	172,764	24.4
Tree	724,068	159,147	22.5
Total	3,899,223	708,669	

This is an interesting observation that without drainage infrastructure, the contribution toward flooding was almost similar for both pervious (47%) and impervious (53%) surface. It means that, when there is no drainage system installed in the study area, there is no control over the movement of surface water- water is mostly flowing toward the

downslope or low-lying areas and get accumulated (Figure 24). Pervious surface was also contributing to water clogging like impervious surface after being saturated. Since water doesn't move so quickly over the pervious surface due to higher roughness, water gets deposited on the pervious surface, this could be another reason why flooded area on pervious surface was close to impervious surface in the without drainage simulation. But the result was different when drainage system was included in the simulation. The contribution of pervious surface for flooding became smaller (26%) and higher for impervious surface (74%). The reason behind this could be that, the drainage network such as manholes, inlets are collecting rain water from different parts of the study area continuously and so there is a control over the surface water to drain it through the pipes. The drainage system (manholes, inlets) break the natural flow direction of rain water by collecting water from the source points near it and avoid runoff by draining it into the pipes. So, manholes near the green space in the campus were draining rain water from those locations and keeping the surface from inundation. That's why the percent pervious surface is lower in this simulation. But for impervious surface the runoff is essentially higher than pervious surface due to lower roughness. The impervious surface produces runoff more quickly due to lower roughness than pervious surface and when drainage system (manholes, pipes) fails to drain the accumulated runoff immediately from that source, it becomes flooded. And that's why the percentage impervious area is quite higher in the simulation.

Table 11: Flooded area for with and without drainage simulations

Land cover	With drainage		Without drainage	
	Area (m^2)	Area (%)	Area (m^2)	Area (%)
Impervious	222,740	74	376,758	53
Pervious	78,260	26	331,911	47
Total area	301,100		708,669	

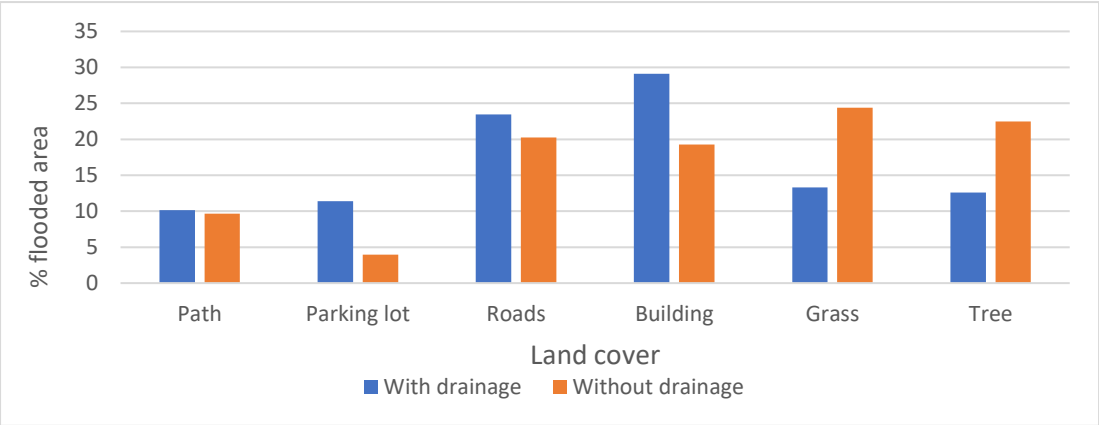

Figure 25: Comparison of flooded area for with and without drainage simulation

This analysis demonstrates the importance of storm infrastructure in urban areas and its contribution toward reducing runoff from urban premises. It also explains the flood controlling mechanism for pervious and impervious areas found in “with” and “without” storm infrastructure simulations.

3.6.2 The Effect of Impervious Land Cover on Flooding

In order to understand the potential impact of impervious land cover, an extreme scenario was simulated in which the entire campus's land cover was set as impervious. The objective of this map is to know the flood scenario that would be produced if there were no green space on campus. In this simulation, the drainage infrastructure was included in the model and the catchment impervious surface area is given as 100%.

The mean and maximum water depth found from the impervious flood map were 0.781 m and 1.54 m respectively (Figure 26 a). This is compared to the original simulation with mean and maximum water depth of 0.391 and 0.781 m, a difference of 0.39 and 0.76 m respectively. The simulated inundation area for the impervious simulation was 355,700 m^2, compared to 301,000 m^2 in the original simulation, a difference of 57,019 m^2 (which was a 19% increase from the actual event’s flood area).

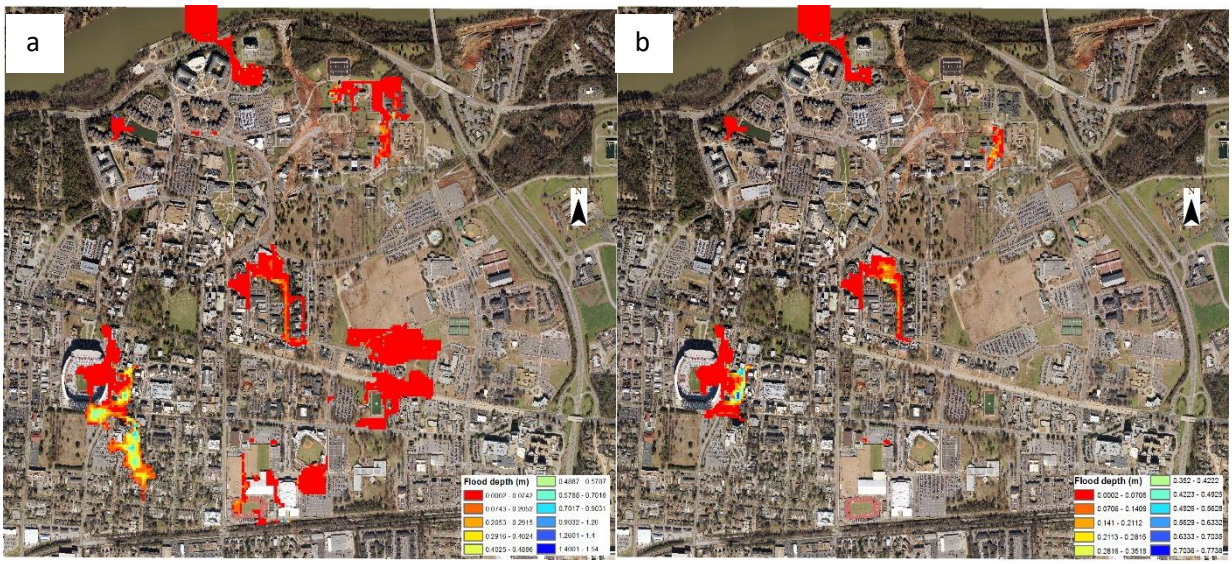

Figure 26: Flood map of UA campus; a: all landcover as impervious; b: all landcover as pervious

Additionally, a simulation considering all the land cover as pervious was conducted in order to understand the extent of flooding if there were no impervious surfaces (buildings, roads, parking lots, and paths) on campus. In this simulation, the drainage infrastructure was also included in the model and the catchment impervious surface area is given as 0%. The mean and maximum flood depths found from the pervious flood map were 0.387 m and 0.77 m respectively (Figure 26 b). This is compared to the original simulation with mean maximum water depth of 0.391 and 0.781 m, a difference of 0.004 and 0.01 m respectively. The simulated inundation area for the impervious simulation was 140,100 m^2, compared to 301,000 m^2 in the original simulation, a difference of 160,900 m^2 (which was a 53% decrease from the actual event's flood area).

Figure 27 shows the flood maps for three different sets of land cover (all pervious land cover, actual land cover and all impervious land cover) for 6 July, 2018 flood event. From these 3 different flood scenarios, the common flooded area which were present in all these 3 maps was identified and extracted and was shown in Figure 27 (bottom row). However, there were variations in the flood depth within these common flooded locations for 3 different land covers. Amidst 3 different maps, the maximum flood depth (1.54 m) was

found for “impervious land cover” simulation. Thus, it supports the fact that more impervious surface means more runoff in an area. Again, among “pervious land cover” and “actual land cover” maps the highest elevation (~0.78 m) found was almost similar.

Irrespective of the variation in land cover, these common locations always get flooded because of the topography. Naturally, those flooded locations are in low-lying areas relative to their surrounding areas and their positions in the downstream portion of the basins, where flow accumulated from the surrounding area makes those area easily flooded (Figures 22, 23, and 24).

Table 12 summarizes of the flooded areas and depths for each of these sets of land cover on campus. Keeping all the parameters constant in the model except the land cover, the flooded area for “impervious surface simulation” is 2.54 times the flooded area of “pervious surface simulation”. The flooded area for “actual land cover surface simulation” is 2.13 times the flooded area of “pervious surface”. The average and the maximum flood depth for “all impervious surface” was 2 times the average and maximum flood depth for both “actual” and “all pervious” maps. The simulated water volume for the impervious simulation was 21,900 m^3, compared to 16,100 m^3 in the original simulation, a difference of 5,800 m^3 (which was a 36% increase from the actual event’s flood volume). Again, the simulated water volume for the pervious simulation was 6,100 m^3, compared to 16,100 m^3 in the original simulation, a difference of 10,000 m^3 (which was a 62% decrease from the actual event’s flood volume).

For all 3 maps, the highest flood depth was found around Magnolia Drive adjacent to Bryant-Denny Stadium and Tutwiler Hall and behind the Bus-Hub. In both locations, a cluster of student housing is found. Drainage systems in those locations should be designed in such a way that it would be capable of draining out a large amount of water in a short time.

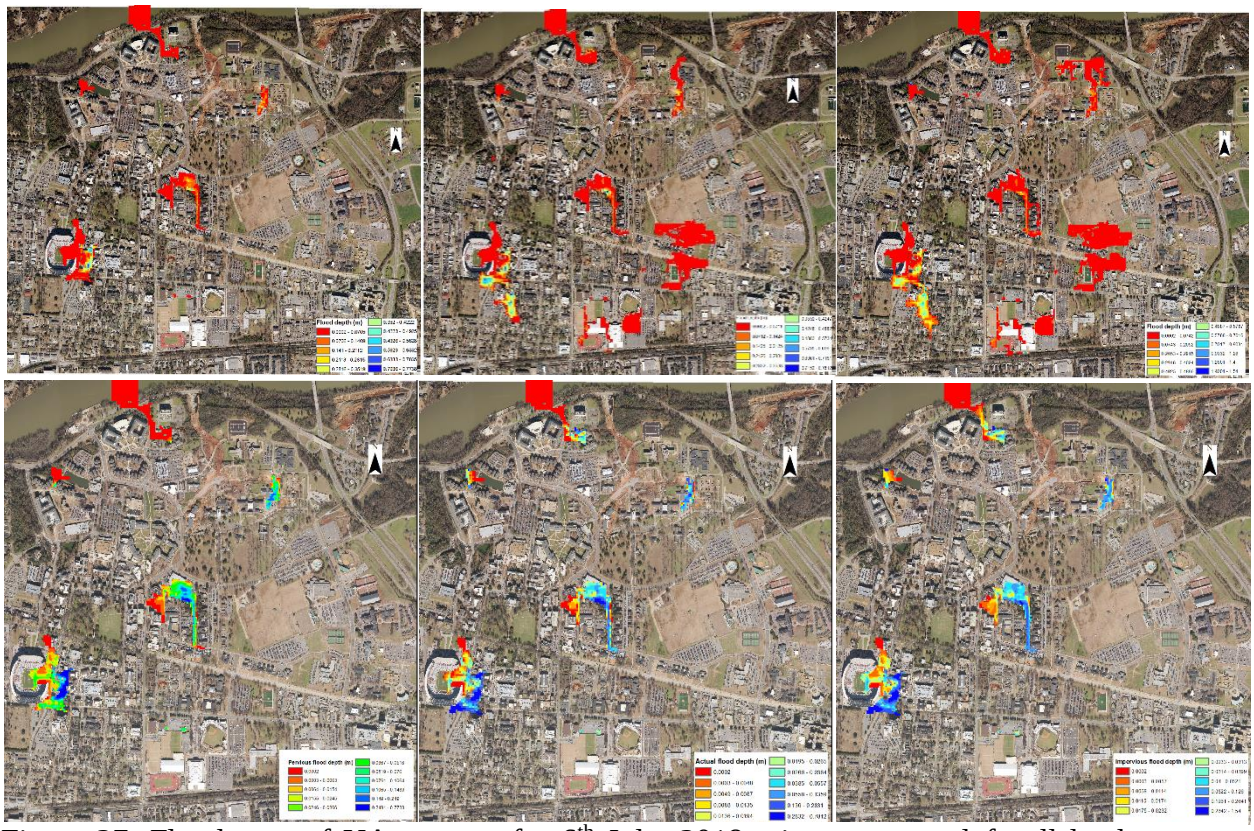

Figure 27: Flood map of UA campus for 6th July, 2018 rain event; top left: all land cover as pervious, top middle: actual land cover, top right: all land cover as impervious; bottom left: common flooded area found in all 3 top maps -for pervious land cover, bottom middle: common flooded area for actual land cover, bottom right: common flooded area for impervious land cover

Table 12: Flooded area and volume for different land cover

Flood scenario	No. of flooded cells	Average flood depth (m)	Maximum flood depth (m)	Total flood depth (m)	Flooded area (m^2)	Volume (m^3)	Difference in volume (m^3)
All pervious	1,401	0.38	0.77	61	140,100	6,100	Actual-pervious = 10,000
Actual land cover	3,010	0.39	0.78	161	301,000	16,100	
All impervious	3,557	0.78	1.56	219	355,700	21,900	Impervious -actual= 5,800

This analysis demonstrates the importance of incorporating detailed land cover conditions in flood modeling and analyses. It also demonstrates the sensitivity of urban areas to the characteristics, distribution and changes in land cover and the great potential for runoff-reducing (green) infrastructure. The latter will be discussed later.

4. DISCUSSION

The detail soil characteristics analysis revealed the homogeneous texture (sandy loam) and organic matter of soil all around the campus but with high degree of spatial and temporal variation in soil moisture and infiltration rate. Among the four locations, infiltration rate in Quad was found to be the highest (278 mm/hr) and lowest in both Tutwiler (6.35 mm/hr) and Shelby (6.35 mm/hr) area. The average infiltration rate in Tutwiler was also the lowest (28 mm/hr) among the four locations over the study period. The soil moisture from the field observation was found to be lower with corresponding higher infiltration rate before November but the soil moisture increased after November due to the increase in antecedent rain during November-December which resulted in lower infiltration rate in the study area. The soil properties found from the analyses showed complex behavior of soil both temporally and spatially. More detail investigation on soil properties are needed to comment on the contribution of soil over flooding.

The detail land cover analysis over different flooded areas was conducted to show the contribution of different land cover on flooding. The reason behind flooding in Tutwiler area could be imperviousness, soil compactness leading to lower infiltration rate and topography. More than 80% area in Tutwiler is impervious (50% building, 10% parking lot, 20% roads, 8% paths) and less than 15% area is green (Figure 17 and 18). Within this greenery the infiltration rate is very low (Figure 18) compared to other locations in the campus. The soil near Tutwiler area was very compact because of the traffic movement, construction activity around it which made the soil disturbed. Finally, another major reason behind flooding in Tutwiler was topography. This location was topographically situated in a low-lying area and

below upstream where water from surrounding pool into the intersection of Bryan-Denny stadium and Tutwiler (Figure 22, 23 and 24).

The flooding near Bus-Hub could be also because of imperviousness since about 80% area was impervious (40% roads, 30% buildings) and less than 20% is greenery (Figure 17 and 18). The infiltration rate near Bus-Hub wasn't recorded but infiltration rate from its surrounding such as Bryce Lawn, Quad and Shelby was collected and from that observation it could be assumed that the infiltration rate near Bus-Hub could be similar to those locations. However, traffic movement near Bus-Hub was the highest since it was the junction point for the university bus network as well as the drop in and drop off point for not only the traffic within the campus and but also outside residence students and university employees. As a result, the soil near Bus-Hub could be compacted and disturbed like Tutwiler and caused flooding due to less infiltration capacity. Furthermore, like Tutwiler this location was situated also in depression than its surrounding (Figure 22, 23 and 24). Flood near Highlands close to Presidential Hall happened because of the high imperviousness (~66%) as well as it is topographically in downstream position where water was accumulated from upstream and draining out to Black Warrior river.

The major difference in flooded area and volume was found between the with and without storm water infrastructure scenarios. The flooded volume was also higher for all-impervious scenario when compared to actual and pervious simulations (Table 11 and 12). The presence of storm drains and their size as well as land cover characteristics both are important for controlling flooding on campus, so future efforts to reduce flooding should concentrate on expanding/enlarging storm water drains and reducing effective impervious surfaces. The presence of green space helps reduce the flow through higher roughness that reduce the speed of water for movement. The volume difference between actual and all pervious simulation was 10,000 m^3 which was 2.6 times higher than the "all-pervious land

cover simulation" and it demonstrations the contribution of impervious land cover in "the actual land cover simulation" for producing this extra load on surface. The volume difference between "all-pervious" and "all-impervious" was even more (~3.6 times higher than actual event) which represent the dominance of impervious land cover. However, the presence of green space is limited in its capacity to reduce runoff and flooding as once the soil gets saturated its infiltration capacity will reduce and it will act as impervious surface. The flooded area from the all-pervious simulation was the lowest among all the other simulations. This is because the roughness of the pervious surface reduces the water velocity over the surface which prevents the quick accumulation of water in an area and gives more time for water to be infiltrated. Both total water depth and flooded area are more than a factor of 2 greater in the all-pervious scenario compared to the realistic scenario. The rain water moves quickly over the smooth impervious surface and gets accumulated resulted in a high water depth and flooded area. The results from the comparison maps and recurrence interval maps (Figure 16) showed some common flooded areas which gets flooded every time, those locations were topographically low-lying area or their position toward downstream (Figure 22, 23 and 24) made them easily flooded during rain events.

From the map (Figure 15-b and 21) with and without drainage system scenario signifies the importance of storm water network in urban environment to avoid flooding. Without the storm water infrastructure the flood water depth was highest (4.79 m) among all the flood scenario in the research. The water volume was more than a factor of 15 greater in the realistic scenario compared to the without drainage system scenario. The difference in volume between two scenarios was found to be 232,500 m^3 which means that storm drainage was draining out 232,500 m^3 of water in the time (4-hours) of the storm event. So, every hour the drainage system was draining out 58,125 m^3 of water from the catchment. And from that it could also be said that its capacity to discharge water from the surface was 16 m^3/s. The

storm water inlets around the campus is collecting water from different locations and draining it through the pipes continuously to keep the area from waterlogging. The presence of drainage is superior to the pervious surface in reducing flooding because the later one will reach the steady state for infiltrating water after some time where the storm network will drain out water continuously. But the drainage network has a capacity limit beyond which it may also become ineffective. For the UA campus, it was known that the capacity of the storm water infrastructure was insufficient in many locations due to small pipe diameter, slope, bottom level elevation etc. In urban flood risk management planning, widening storm drain infrastructure is also considered as one of the important structural measures (Tingsanchali, 2012) but these measures are expensive. In some locations flooding can be attributed to absence of storm water inlets, such as flooded areas are close to parking lots (Tutwiler, Coleman Coliseum, parking lot near Law school, parking lot near Soccer stadium) (Figure 28).

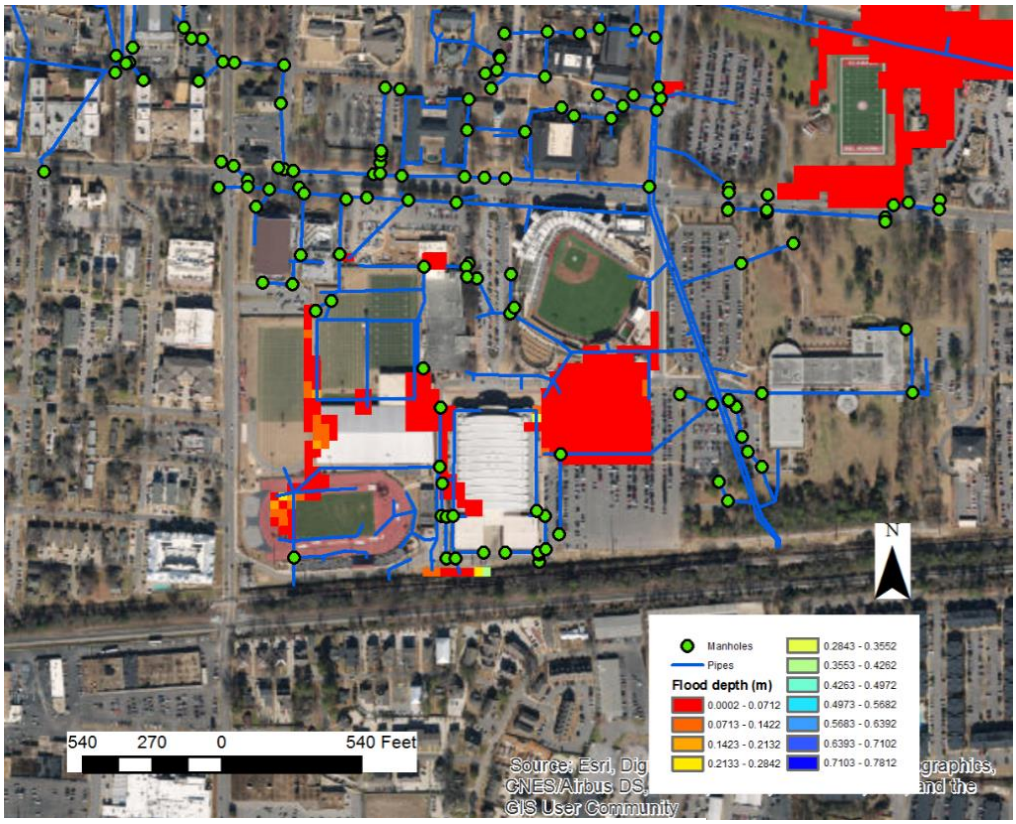

Figure 28: Flood at Coleman Coliseum

4.1 Introducing BMP's to Control Flooding

Since the flood locations found in the campus are naturally low-lying areas and the presence of impervious surfaces around those locations increase runoff generation, different types of BMP's could be introduced to reduce the runoff. While improvement to stormwater infrastructure is costly, BMPs can be a cheaper solution to reduce the runoff from those locations. There are different types of BMPs that are commonly used in the urban environments to reduce runoff. The integrated Green Infrastructure (GI) facility successfully reduced the runoff or peak flow in the impervious areas in an urban community in Beijing. However, it also showed that the reduction of runoff is not significant when single GI is used but a combination of 5 types of GI were needed (Liu et al., 2014). To avoid flooding the UA has already installed some BMP's such as detention pond near the Soccer stadium and University Boulevard, an open drainage or channel that connects Bryce Lawn to 4th street, established rain barrels near Shelby Hall and bio-swales and infiltration trench close to Jack Warner Parkway.

Porous pavement can be introduced near the Tutwiler area (Figure 29). Porous pavement built with pervious concrete allow water to percolate almost immediately and a retention basin under it can store water for an extended period of time, which will let the soil infiltrate the water and help recharge groundwater (EPA, 2019). Later, this water can be used for campus activities such as watering the plants and cleaning. Other types of BMPs such as infiltration trenches, bioswales, porous pavement, and rain barrels can be introduced to reduce runoff at this location. For other parts of the campus - such as the soccer stadium Coleman Coliseum, and the practice stadium - rain barrels and porous pavement can be used to collect rainwater (Figure 30). Other parts of the campus where flooding happen mostly in parking lots and play grounds, where direct connections (inlets, manholes, pipes) with the drainage system can take the water away from the surface and help reduce runoff (Figure 28).

Figure 29: Porous pavement; top left: porous concrete that infiltrate water immediately; top right: design structure of porous pavement; bottom left: porous path; bottom right: porous parking lot

To avoid flooding, the university is using the Bryce Lawn area as a natural detention pond to hold water for a time being and get infiltrated into the soil. There is also an open drainage or culvert starting from Campus Drive East to 4th street to drain water from the Bryce Lawn area. This culvert is also used to collect storm water from the Soccer stadium and finally draining water to a pipe (Figure 1, 2 and 31). But this place also gets flooded because this connecting pipe fails to drain large amount of water during heavy rain. Also, there is a triangular retention pond between Soccer stadium and this culvert to hold runoff from the stadium and nearby parking lots. A proper plan incorporating more improved drainage system and BMP's can solve the water logging situation in the University of Alabama campus.

Figure 30: Low impact development, BMP's; top left and right: rain barrel to store rain water; bottom left: bioswales near highway; bottom right: infiltration trench near roads and buildings

Detention pond in between University Blvd. and 4th street and near Soccer stadium

Open drainage connected from Bryce Lawn to 4th street

Figure 31: Some BMP's in the campus

5. CONCLUSION

This study showed that 7.7% of the area of the UA campus experienced flooding during the 6th July, 2018 rainfall event. Though homogeneity found in the soil texture (sandy loam) but the spatial and temporal variability in soil moisture and infiltration rate prevailed at different locations of the campus. These variabilities showed the complex characteristics of soil which leaded to the need for more detail information and analysis regarding soil. Keeping everything else (parameters) constant in the model, changes in land cover shows that flood volume for "actual land cover surface" is almost 2.6 times greater than the flood volume of "all-pervious surface" but with about similar average flood depth (~0.78 m). The flood volume for "all impervious surface" was almost 3.5 times greater than the volume of "all-pervious surface". From the with and without storm water infrastructure analysis, the flood volume for "without drainage system" was almost 15 times greater than the volume of "with drainage system (actual event)" simulation as well as the water depth found from "without drainage system" simulation was the highest (4.79 m) among all the simulations in the research. The discharge capacity of storm water infrastructure from the surface was found to be 16 m^3/s. These results show the importance of storm water infrastructure as well as the pervious land cover in the urban area to reduce flooding.

Implementing different types of Low Impact Development BMP's in urban environment help reducing the runoff. It is also important to choose the correct Best Management Practices (BMP's) to achieve appropriate results from it. Among different BMP's using pervious pavement in the parking lots, roads will be efficient for UA campus since most of the flood locations are consisting of parking lots and roads. Also, bioswales and

infiltration trench could be helpful near buildings and paths etc. For naturally low-lying area, retention pond or rain barrel could be efficient way to manage runoff since flow accumulation will be higher in those area. Besides, implementing new and large drainage pipes in the system is a necessity with the increasing population in the university. Investigation on the capacity of the pipes network should be conducted to find out the problematic pipes, old pipes, also to find out the locations where the loads are higher than the drainage capacity of the pipe system. If the storm water could be caught immediately or within a small distance through the manholes from the impervious area before it gets accumulated and drains out through the pipes capable of draining large amount of water immediately from the surface, flooding could be avoided and managed with proper strategy.

This study is only focused on identifying the flood locations and flood extents on the campus and the factors behind flooding in those locations. More detailed research such as the consequences of flooding and how this problem can be solved could be an interesting topic for future research, where findings and flood maps prepared in this study could be used as an essential input resource. The University Authority may look into those common flooded areas found in this research and investigate the performance of drainage system and how to improve it by increasing the diameter of the pipes and manholes, increasing the slopes of the pipes so water will drain more quickly. Furthermore, to prepare a flood-mitigation plan and policy for the UA campus, this research will be a valuable source to provide input for the decision-making process.

REFERENCES

Al-Kaisi, M. and Licht, M., 2005. Soil moisture conditions -- consideration for soil compaction. Iowa State University, IC- 494 (9), pp. 78-79.

Arrowsmith, J., 2019. What is a two-dimensional hydraulic model? Straughan Environmental, p 1-3.

Basnet, M., 2017. MIKE URBAN as a tool to model the 1D drainage system; Case study: Kulmbach (Germany). Civil, Geo and Environmental Engineering, the Technical University of Munich, pp-1-50.

Bosart, L. F., and F. Sanders, 1981. The Johnstown flood of July 1977: A long-lived convective system. *J. Atmos. Sci.*, **38,** 1616–1642.

Bouwer, L.M., Bubeck, P.,Wagtendonk, A.J., Aerts, J.C.J.H., 2009. Inundation scenarios for flood damage evaluation in Polder areas. Natural Hazards and Earth System Sciences 9, 1995-2007.

Cadus, S., and Poetsch, M., 2012. Dynamic modeling of urban rainfall runoff and drainage coupling DHI MIKE URBAN and MIKE FLOOD. University of Salzburg, pp 1-52.

Campana, D., Marchese, E., Theule, J.I. and Comiti, F., 2014. Channel degradation and restoration of an Alpine river and related morphological changes. *Geomorphology*, *221*, pp.230-241

Campus Water Matters, 2017. Design of a Retention/Infiltration Basin and Bioswales: Alleviating Flooding and Water Quality and Use Issues near Bryant-Denny Stadium, The University of Alabama

Carr, R., Fontenot, E., Schroeck, J., 2007. City of Los Angeles primary sewer system wet weather flow calibration- MIKE URBAN, DHI Water and Environment Inc.

Castella, E., Beguin, O., Besacier, A.L., Dolédec, S., Forcellini, M., Lamouroux, N., Mayor, H., McCrae, D., Mérigoux, S., Paillex, A. and Sagnes, P., 2012. What have we learnt? A multi-year monitoring of invertebrates and fish in the Rhône River under restoration. In *International Conference IS. Rivers Recherches et actions au service des fleuves et grandes rivières* (pp. 3-p).

CNN News, 2017. Flint water crisis fast facts, http://www.cnn.com/2016/03/04/us/flint-water-crisis-fast-facts/index.html, accessed on 12/05/2017

Curriero, F.C., Patz, J.A., Rose, J.B. and Lele, S., 2001. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *American journal of public health*, *91*(8), pp.1194-1199.

Danish Hydraulic Institute (DHI). Business Management System, 2015. Storm Water Runoff from Green Urban Areas - Modelers Guideline. CRC for Water Sensitive Cities.

Danish Hydraulic Institute (DHI), 2017. Collection System. Modelling of storm water drainage networks and sewer collection systems. MIKE URBAN® user's guide, 2017.

Danish Hydraulic Institute (DHI), 2016. MIKE URBAN®. Delineation of catchment and calculation of model parameters. Step-by-step training guide, 2016.

Danish Hydraulic Institute (DHI), 2016. MIKE URBAN®. Model manager, 2016. Danish Hydraulic Institute (DHI). MOUSE. Pipe flow reference manual, 2016.

Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L. and Blöschl, G., 2010. Flood fatalities in Africa: from diagnosis to mitigation. Geophysical Research Letters, 37(22).

Donovan, E., Unice, K., Roberts, J.D., Harris, M. and Finley, B., 2008. Risk of gastrointestinal disease associated with exposure to pathogens in the water of the Lower Passaic River. *Appl. Environ. Microbiol.*, *74*(4), pp.994-1003.

EPA, 2018. https://www.epa.gov/water-research/storm-water-management-model-swmm

EPA, 2019. Polluted Runoff: Nonpoint Source (NPS) Pollution- Low Impact Development, https://www.epa.gov/nps/urban-runoff-low-impact-development

French, J., Ing, R., Allmen, S. V., and Wood, R., 1983. Mortality from flash floods: a review of national weather service reports, 1969-81. National Centre for Biotechnology Information, 98 (6), 584-588.

Funk, T., 2006. Heavy convective rainfall forecasting: A look at elevated convection, propagation, and precipitation efficiency. *Proc. 10th Severe Storm and Doppler Radar Conf.*,Des Moines, IA, National Weather Association.

Galloway, E. G., Reilly, A., Ryoo, S., Riley, A., Haslam, M., Brody, S., Highfield, W., Gunn, J., Rainey, J., and Parker, S., 2018. THE GROWING THREAT OF URBAN FLOODING: A NATIONAL CHALLENGE 2018, University of Maryland and Texas A&M University.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X. and Briggs, J.M., 2008. Global change and the ecology of cities. science, 319(5864), pp.756-760.

Gsshawiki, 2018. Gridded Surface Subsurface Hydrologic Analysis, https://www.gsshawiki.co m/Overview:Description, accessed on 30th June, 2018

Haq M., Akhtar M., Muhammad S., Siddiqi, P. and Rahmatullah J., 2012. Techniques of Remote Sensing and GIS for flood monitoringand damage assessment: A case study of Sindh province, Pakistan, The Egyptian Journal of Remote Sensing and Space Sciences, 15, 135–141

Henz, J. F., V. R. Scheetz, and D. O. Doehring, 1976. The Big Thompson flood of 1976 in Colorado. *Weatherwise*, 29, 278–285.

Horita, F.E., de Albuquerque, J.P., Degrossi, L.C., Mendiondo, E.M. and Ueyama, J., 2015. Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. *Computers & Geosciences*, *80*, pp.84-94.

Huang, J.C., Weber, L.J., Lai, Y.G., 2002. Three-dimensional numerical study of flows in open-channel junctions. Journal of Hydraulic Engineering-ASCE 128 (3).

Huong, H.T.L.; Pathirana, A., 2013. Urbanization and climate change impacts on future urban flooding in Can Tho City, Vietnam. Hydrol. Earth Syst. Sci. 17, 379–394

Introduction to EPA's storm water management model, 2018. https://www.youtube.com/ watch? v=76BF9fznh1w&feature=youtu.be&ab_channel=BilltomKrickman, accessed on 4/2/2018

Ishigaki, T., Nakagawa, H., Baba, Y., 2004. Hydraulic model test and calculation of flood in urban area with underground space. In: 4th International Symposium On Environmental Hydraulics. In: Lee, Lam (Eds.), Sustainable Water Management in the AsiaPacific Region, vol. 2. A.A. Balkema Publishers, Lisse, The Netherlands.

Agnew, J., 2011. Waterpower: Politics and the Geography of Water Provision, Annals of the Association of American Geographers, 101:3, 463-476

Jonkman, S.N., Bo_ckarjovab, M., Kokc, M., Bernardinid, P., 2008. Integrated hydrodynamic and economic Modelling of flood damage in the Netherlands. Ecological Economics 66 (1), 77-90.

Jordan, H., 2016. Heavy rain causes minor flooding, some power outages on east side of state, Live Michigan

Khan, A.A., Cadavid, R., Wang, S.S.Y., 2000. Simulation of channel confluence and bifurcation using the CCHE2D model. Water and Maritime Engineering 142.

Kulkarni, A.T., Mohanty, J., Eldho, T.I., Rao, E.P. and Mohan, B.K., 2014. A web GIS based integrated flood assessment modeling tool for coastal urban watersheds. Computers & Geosciences, 64, pp.7-14.

Lee G. Joong, Selvakumar Ariamalar, Alvi Khalid, Riverson John, Zhen X. Jenny, Shoemaker Leslie, Lai Fu-hsiung, 2012. A watershed scale design optimization model for storm water best management practices, *Environmental modelling and software*, 37, 6-18

Liu, W., Chen, W. and Peng, C., 2014. Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. Ecological Modelling, 291, pp.6-14.

LJWORLD, 2019. Organic matter content contributes to best topsoil. https:// www2.ljworld. com/news /2007/may/10/organic_matter_content_contributes_best_topsoil/

Mignot, E., Paquier, A. and Haider, S., 2006. Modeling floods in a dense urban area using 2D shallow water equations. Journal of hydrology, 327(1-2), pp.186-199.

Mooney, L. E., 1983. Applications and implications of fatality statistics to the flash flood problem. Preprints, *Fifth Conf. on Hydrometeorology*, Tulsa, OK, Amer. Meteor. Soc., 127–129.

National Weather Service, 2019. Floods in Alabama. https://www.weather.gov/safety/flood-states-al#

NBC News, 2017. Clean water is a human right, not a private commodity, https://www.nbcnews.com/think accessed on 12/05/2017

Neary, V.S., Sotiropoulos, F., Odgaard, A.J., 1999. Three-dimensional numerical model of lateral-intake inflows. Journal of Hydraulic Engineering 125 (2), 126–140.

Nelson, S. A. 2015. Flooding Hazards, Prediction & Human Intervention. Natural Disaster course, Tulane University.

NLCD, 2018. https://catalog.data.gov/dataset/national-land-cover-database-nlcd-land-cover-collection

NOAA, 2018. https://www.ncdc.noaa.gov/cdo-web/datatools

NRCS, 2018. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs 142p2 of Natural Disasters, ICLR Research Paper Series e No. 24.

Pelling, M., 2012. The vulnerability of cities: natural disasters and social resilience. Routledge.

Planet Imagery and Archive, 2019. https://www.planet.com/products/planet-imagery/

Qi Honghai and Altinakar M. S., 2011. A GIS-based decision support system for integrated flood management under uncertainty with two dimensional numerical simulations, Environmental Modelling & Software, 817-821

Rickly, 2018. Measuring the world's water- Turf- Tec Infiltrometer, http://rickly.com/turf-tec-infiltrometer/

Schoel and McGiffert, 2017. SWMM ANALYSIS OF WEST BASIN, 1-30

Simonovic, S.P., 2002. A Spatial Fuzzy Compromise Programming for Management

Soil survey field and laboratory methods manual, 2014. USDA, Soil survey investigation report no. 51, version 2; ASTM no. 1. 152H-type with Bouyoucos scale in g L-1 (developed by Stillwater, OK soil survey office and modified by NSSC and Ricky Lambert, Nacogdoches, TX)

Stormwater and Groundwater Recharge Integrated Management Research Opportunity, 2016. version 2

Ten Veldhuis, J.A.E., Clemens, F.H.L.R., Sterk, G. and Berends, B.R., 2010. Microbial risks associated with exposure to pathogens in contaminated urban flood water. Water research, 44(9), pp.2910-2918.

Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F., Dutta, D. and Kim, S., 2017. Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. Environmental Modelling & Software, 90, pp.201-216.

The University of Alabama, 2017. SWMM analysis of West Basin, UA

The Weather Underground, Tuscaloosa Municipal, 2019. http://api.wunderground.com /history/airport /KTCL/2018/7/6/Daily History.html? theprefset=SHOWMETAR &theprefvalue=1, accessed on February 22, 2019.

Tingsanchali, T., 2012. Urban flood disaster management. Procedia engineering, 32, pp.25-37.

Tockner, K., Schiemer, F. and Ward, J.V., 1998. Conservation by restoration: the management concept for a river-floodplain system on the Danube River in Austria. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *8*(1), pp.71-86.

Torres M. Adrian, Bueno E. Ignacio, Domenech A. Ignacio, Momparler P. Sara, 2016. Decision support tool for energy efficient, sustainable and integrated urban storm water management, *Environmental modelling and software*, 84, 518 -528

U.S. climate data, 2019. https://www.usclimatedata.com/climate/tuscaloosa/alabama/united-states/usal0542

Van Oldenborgh, G.J., Van Der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G. and Cullen, H., 2017. Attribution of extreme rainfall from Hurricane Harvey, August 2017. Environmental Research Letters, 12(12), p.124009.

Weber, Anna., 2019. What is urban flooding?, Natural Resources Defense Council (NRDC), https://www.nrdc.org/experts/anna-weber/what-urban-flooding

Weber, L.J., Schumate, E.D., Mawer, N., 2001. Experiments on flow at a 90 open-channel junction. Journal of Hydraulic Engineering 127 (5).

West Campus Storm Drainage Study Report, The University of Alabama. 2005. UA Project No. UTL-05-004