EVALUATING THE EFFECTS OF PAVER SYSTEMS ON URBAN DEVELOPMENT USING A DISTRIBUTED HYDROLOGICAL MODEL

A Senior Scholars Thesis

by

ALYSSA CATHERINE POLITTE

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2011

Major: Civil Engineering

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Approved by:

Research Advisor: Emily Zechman
Director for Undergraduate Research: Sumana Datta

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ABSTRACT

Evaluating the Effects of Paver Systems on Urban Development Using a Distributed Hydrological Model. (April 2011)

Alyssa Catherine Politte
Department of Civil Engineering
Texas A&M University

Research Advisor: Dr. Emily Zechman
Department of Civil Engineering

Cities are becoming increasingly more urbanized through the conversion of forest, pasture and croplands. By replacing the natural environment with impervious areas such as parking lots, roads, houses and other concrete structures, humans are causing an increase in storm water runoff problems with potentially deleterious environmental effects. Traditionally storm water runoff has been handled and controlled using Best Management Practices (BMPs) to control flood runoff events. An alternative approach is to use Low Impact Development (LID) options. LIDs have been proposed in an attempt to mimic the natural flow regime by controlling storm water at the source. LID practices such as rainwater harvesting, green roofs, and permeable pavement can be used to replace existing infrastructure with the goal of reducing runoff volumes and peak flows. A more specific type of permeable pavement which will be the focus of this paper, called Paver Systems uses permeable pavement and aggregate to deliver filtered water to aquifers and prevent initial runoff. A modeling approach to incorporate a type of permeable pavement, called paver systems, into an existing hydrological model will yield an estimation of the effects of paver systems on stream flow. The modeling approach has been applied to a watershed located in Houston, Texas in Brays Bayou called Harris Gully to predict the impact of paver systems on storm water runoff.

DEDICATION

I want to dedicate this research work and thesis to my parents, Eric and Sue Politte, for all of their guidance and love through the good and bad times. They put the world at my feet and gave me the drive to help change the world.

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This research work was possible through the assistance of the faculty and graduate students in the Department of Civil Engineering at Texas A&M University College Station. I would like to express my gratitude and appreciation to Dr. Zechman, Dr. Olivera, Tommi Jo Scott, Marcio Giacomoni and Chandana Damodaram. I would also like to acknowledge the EPA for providing essential knowledge needed to complete this research.

NOMENCLATURE

BMP	Best Management Practices
CGP	Concrete Grid Pavers
CN	Curve Number
d	Depth
GIS	Geographic Information System
HEC-HMS	Hydrologic Modeling System
HFR	Hydrologic Footprint Residence
Ia	Initial Abstractions
LID	Low Impact Development
n	Porosity
P	Precipitation
PP	Porous Pavement
R	Runoff
S	Maximum Potential Retention
t	Time

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CHAPTER I

INTRODUCTION

In the modern world of concrete structures and dense populations, the issue of urbanization has become an adversary to hydrological systems and causes flooding and erosion of creeks, bayous and rivers. Urbanization is a process in the evolution of the earth’s surface, but essentially replaces natural land cover with roads, houses, parking lots and other concrete structures. Impervious areas do not allow storm water to infiltrate through the soil, which causes an increase in runoff. This increased volume of storm water runoff fundamentally alters the characteristics of the natural flow regime and in stream ecosystem health (Poff et al. 1997).

Engineers typically use Best Management Practices (BMPs) to control increased volumes of stormwater. BMPs, such as detention ponds, have been able to control some stormwater runoff, but it has been found that the natural hydrology of the watershed is still negatively affected and can degrade ecosystem health (USEPA 2000). Alternatively, Low Impact Development (LID) is a newer type of stormwater management that has the design goal of maintaining or mimicking the pre-development hydrological regime. LIDs work by using site design techniques that detain, store, infiltrate and evaporate stormwater runoff (Coffman, 2000). There are many types of LID systems including

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rainwater harvesting, green roofs, and permeable pavements. This research explores a type of permeable pavements called paver systems. Paver systems are composed of concrete blocks or plastic web structures with voids filled with sand, gravel or soil. The void spaces allow stormwater to infiltrate through the pavement to the soil, which decreases runoff from the surface (Pratt et. al., 1995; Bratteo and Booth, 2003).

Literature review

Collins et.al (2008) completed a study that compared differences in the runoff reduction of four different types of paver systems in physical experimental trials. These paver systems include porous concrete (PC), two types of permeable interlocking concrete pavers (PICP) with pea gravel fill, and concrete grid pavers (CGP) with sand fill. The two types of PICP is ConPave^{TM} OctaBrick concrete pavers (12.9% void space) and SF-Kooperation^{TM} Rima concrete Stone (8.5% void space). These different types of pavers were installed in a parking lot in Kinston, North Carolina and observed for a two year time period, 24 hours a day. Due to poor drainage of the site, underdrains were installed to allow water entering the pavers to flow out of the system. The surface runoff was channeled to a gutter, leading to a monitoring vault, where the volume was measured and used to calculate the total reduction of stormwater runoff for each type of pavement. The rainfall data was recorded using ISCO 4230 flow meters. Other paver systems have been created and tested, and modeling results will be utilized in this research to provide an additional example of the difference between paver systems, predevelopment conditions and urbanized post development conditions.

Bratteo and Booth (2003) also completed similar research comparing four different permeable pavement systems and was based on an earlier study that explored watershed hydrology and urbanization (Booth et al., 2002). In these experiments eight stalls were constructed with four types of paver systems, Grasspave^2, Gravelpave^2, Turfstone and UNI Eco-Stone. The runoff from the parking lot was recorded over a six-year period to evaluate how the paver systems compared to the asphalt in respect to the amount of runoff from the surface.

Williams and Wise (2006) also completed a simulation study to model LID and evaluate the runoff impacts of this technology. The study used two different design storms in the simulation and a continuous rainfall record. Recorded observations of rainfall and runoff are used in the following sections to calculate values for parameters in a hydrologic model.

The literature demonstrates that some work has been done to collect hydrologic information about paver systems, and this data has been used to develop and test a hydrologic model, based on the SCS Curve Number method to calculate the runoff from the different types of systems (USDA, 1986). In the existing studies, results were evaluated using the peak flow of a storm hydrograph. This research will explore the use of a recently developed sustainability metric, the Hydrologic Footprint Residence.

Researchers have identified a lack of studies revealing the valuable use of LID on a watershed scale (Dietz and Clausen 2008). Damodaram et. al. (2010) created a computer modeling simulation of combined BMPs and LID for sustainable stormwater management. In this study, researchers touched on several different types of the LID practices, using the SCS Curve Number method to model the watershed runoff. The curve numbers for three types of permeable pavement were calculated using field data developed by Collins et.al (2008) and will be used in the detailed modeling of permeable pavement. Researchers modeled the LID practices by assuming replacement of 100% of the watershed area, which led to an inflated peak flow reduction and somewhat misleading results. In order to get more accurate results this research will aim to model particular land uses and only replace parking lots and driveways with permeable pavement.

The goal of the research is to provide computer modeling to represent paver technology and increase the understanding of and capabilities for planning paver systems. The simulation model that is described here is implemented to test different paver systems and watershed conditions. The research demonstrates three different types of paver systems and compares the simulation results. In this final stage of research, the runoff results are measured based on the Hydrological Footprint Residence (HFR), which is compared to the more conventionally used metric, peak flow. HFR is designed to capture temporal and spatial changes to flow regime by calculating the areas under water for a particular duration of time (Giacomoni and Zechman, 2010).

CHAPTER II

METHODS

Hydrologic footprint residence

To calculate an HFR value for a specific reach of a water body, consider a flood that passes through a river reach downstream of a hypothetical watershed. At each time step, the amount of flow in the channel inundates a corresponding area of land, depending on the elevation of the water surface and the shape of the channel and floodplain. The time series of the inundated land is plotted in a similar fashion as a hydrograph, and labeled as the inundated land curve. The flooding event due to the specific rainfall event can be evaluated as the definite integral of the inundated land curve, or area under the inundated land curve, which is termed the HFR. This represents the amount of land that was inundated and the length of time during which each individual unit of land was inundated. The HFR is calculated in units of area*time, such as acre-hours (Giacomoni and Zechman, 2010).

Illustrative case study

An illustrative watershed is used to demonstrate the use of the HFR and the peak flow for evaluating runoff for a set of design storms. Brays Bayou watershed of Houston, TX, has been selected for the case study. Brays Bayou is located in southwest Harris County and Ft. Bend County and drains parts of Missouri City, Stafford, Bellaire, West University, Southside Place and the Meadows, which are all cities near Houston, TX, and the Bayou ultimately flows eastward to the Houston Ship Channel (Fig. 1). This watershed includes three primary streams: Brays Bayou, Keegans Bayou and Willow Waterhole Bayou (HCFCD, 2010). Issues in Brays Bayou include large amounts of storm water during typical rainfall events and erosion along the banks has been caused by the urbanization of the area.

Brays Bayou Watershed covers 127 square miles of land with an imperviousness percentage of approximately 49.29% for the overall watershed. The watershed's land uses are distributed as follows: 41.7% high density urban areas, 21.3% residential areas and 37% open space/ pasture areas (GBIC, 1992). A hydrological model of Brays Bayou was developed to study the storm water's inflows and outflows during rainfall events (HCFCD, 2010).

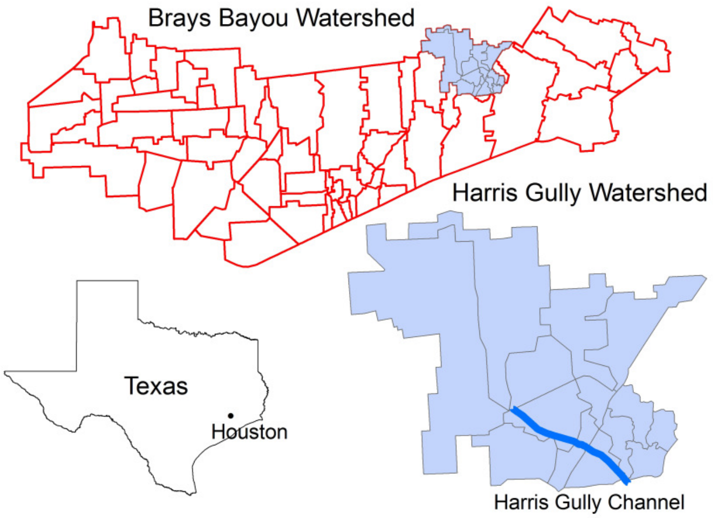


Figure1. Brays Bayou and Harris Gully Watersheds located in Houston, TX.

This research will focus on a particular watershed within Brays Bayou, the Harris Gully watershed, which encompasses 17 sub-catchments. These 17 different sub-catchments can be seen in Fig. 2 along with the 9 different reaches of the Harris Gully Watershed.

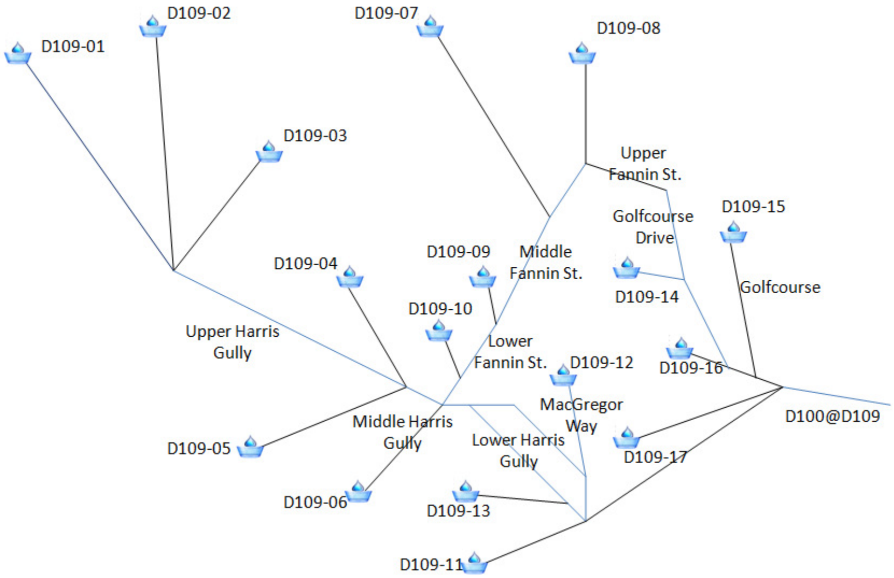


FIGURE 2: Harris Gully sub-catchments and reaches from the modeling simulation.

To explore different paver options, it is necessary to identify the area of impervious area in each of the 17 catchments in the Harris Gully watershed that is covered by asphalt or pavement and can be replaced with porous pavement. Building, land use and watershed data of the Harris Gully Watershed are provided by the Harris-Galveston Area Council data collection, and by using Arc GIS (Geographic Information Systems), individual building data could be found for each sub-catchment. The data provided categorizes 27 different building types in the Harris Gully watershed. The amount of paved area that corresponds to each building type is calculated using the following approach. The percent of landscaped area for individual land use was estimated as 100% minus an average percentage of impervious area; according to Arnold and Gibbons (1996) 54% of a total lot is assumed as landscaped area for single family dwellings, and 53%, for multi-family dwellings (Table 1).

TABLE 1: Percent landscaped for different land uses (Arnold and Gibbons, 1996).

Building Type Category	Parking Requirements	% Landscaped
Apartment	2 spaces per unit w/ 1 spot per 5 units	53%
Auto Dealer	1 space per 2400 sq ft	15%
Auto Garage	3 spaces per 100 sq ft	15%
Carwash	1 space per 300 sq ft	15%
College	1 space per 80 sq ft	25%
Day Care	1 space per 500 sq ft	15%
Fast Food	1 space per 75 sq ft	15%
Gas Station	3 spaces plus 1 spaces per 100 sq ft	15%
General Office	1 space per 300 sq ft	15%
Hospital	1 space per 75 sq ft	25%
Hotel/ Motel	1 space per 225 sq ft	25%
Industrial	1 space per 350 sq ft	25%
Lot of Land	predevelopment	100%
Medical Office	1 space per 250 sq ft	15.%
Mini Warehouse	1 space per 4000 sq ft	5%
Multi Family Residential	driveway	53%
Parking Miscellaneous	Parking Miscellaneous	0%
Police	1 space per 20 sq ft	15%
Post Office	1 space per 40 sq ft	15%
Recreational	1 space per 80 sq ft	25%
Religious	1 space per 80 sq ft	15%
Restaurant	1 space per 60 sq ft	15%
Retail	1 space per 300 sq ft	5%
School	30 spaces per 225 sq ft	25%
Single Family Residential	driveway	54%
Studio	1 space per 350 sq ft	15%
Warehouse	1 space per 1000 sq ft	5%

To estimate the parking lot sizes for non-residential building types, the Santa Monica Building Codes and Parking Lot Requirements were used to determine the number of parking spaces required for a certain square footage for commercial lots (9.04.10.08.040 Number of Parking Spaces Required, 2006). For single family residential lots, 6% of the total lot is driveway and therefore replaceable impervious area. For a multifamily residential lot, the replaceable impervious cover is 17% of the total lot area (Arnolds and Gibbons 1996).

By looking at the GIS data for each of the 17 sub-catchments at a time, the area of each building type and the number of buildings in each building type category was determined. An equation sequence was created for each building type based off of the landscaping percentages and parking lot requirements. For commercial, industrial and recreational building types the total square footage (*Y*) is multiplied by one minus the percent landscaped of the land use (*l*). This value is set equal to the sum of the area of the building and the parking lot. The area of the parking lot is found by multiplying the area of the building (*x*), the proportion of the number of parking spaces required per a certain square footage of the building (*p*) which can be found in Table 2, the assumed area of each parking space (128 sq) and the assumed required aisle space factor (1.135). To find the total amount of replaceable impervious area of a commercial property, the area of the building and landscaped areas will be subtracted from the total area of the lot (Equation 1).

$$x = \frac{Y(1-l)}{128 \times 1.135 \times p + 1} \quad (1)$$

According to the Santa Monica Parking requirements, apartments must meet additional standards, requiring a different equation for finding the area of replaceable concrete. Per specifications, an apartment must have two spaces per unit and one visitor parking space for every five units on the property. Initially the area of impervious area (building and parking lots) was found by multiplying the total square footage (*Y*) by one minus the percent landscaped of the land use (l). An expression describing the area of the resident's parking lot as a function of the building area is calculated using the following assumptions: two parking spaces are required for each apartment unit; the average area of an apartment unit is 2000 square feet; the area of a parking spot is 128 square feet; and the required aisle space factor is1.135. The aisle space factor increases the parking lot size by a factor of 1.135 to allow space for aisles in the parking lot. IN addition, one visitor parking spot is allocated for every 10,000 square feet of apartment. The area of impervious land cover in a sub catchment is known from the total area of the building (*x*) is the area of impervious land cover minus the replaceable impervious land cover area, The total amount of replaceable impervious area for apartments is calculated as:

$$x = \frac{Y(1-l)}{\frac{2 \times 128 \times 1.135}{1{,}000} + \frac{128 \times 1.135}{10{,}000} - 1} \quad (2)$$

The total area of impervious land cover (parking lots and driveways), landscaped area and building area per each building type is calculated for each sub-catchment (Table 2). The respective percentages of the various areas in each sub-catchment are calculated in Table 3.

TABLE 2: The individual reaches area characteristics including the area of replaceable concrete, landscaping and buildings for each sub-catchment in acres.

Subwatershed	Area of Sub-Watersheds	Area of Replaceable Conc.	Area of Landscaping	Area of Buildings
1	2160.5	474.1	1298.1	388.3
2	1228.3	288.8	771.5	168.0
3	391.9	82.9	262.9	46.0
4	392.4	213.2	98.1	81.0
5	413.3	100.7	258.9	53.8
6	105.3	22.6	64.7	18.0
7	545.6	133.0	357.3	55.3
8	596.5	133.4	378.4	84.7
9	124.4	64.6	55.6	4.2
10	28.8	15.3	7.1	6.4
11	94.7	45.9	23.7	25.1
12	97.6	47.3	24.4	26.0
13	232.0	100.0	77.5	54.6
14	193.2	75.7	58.8	58.8
15	291.4	71.2	173.1	47.1
16	109.9	47.4	36.5	26.1
17	157.3	131.1	25.5	0.6
TOTAL	7163.2	2047.3	3972.1	1143.9

TABLE 3: The individual reaches percentage characteristics including percent of replaceable concrete, landscaping and buildings for each sub-catchment.

Subwatershed	Replaceable conc.	Landscaping	Percent Buildings
1	21.9	60%	18%
2	23.5	63%	14%
3	21.2	67%	12%
4	54.3	25%	21%
5	24.4	63%	13%
6	21.5	61%	17%
7	24.3	65%	10%
8	22.4	63%	14%
9	51.9	45%	3%
10	53.2	25%	22%
11	48.5	25%	27%
12	48.4	25%	27%
13	43.1	33%	24%
14	43.0	33%	33%
15	24.4	59%	16%
16	43.1	33%	24%
17	119.3	7923%	1%

Calculating curve numbers

A set of field experiments were conducted to collect data concerning runoff from different permeable pavement systems. Field experiments were conducted on a porous concrete parking lot with an effective storage of 40 mm (1.57 in.) in Wilmington, NC and monitored for a set of 19 storms (Bean et al. 2007). The study also reported results for concrete grid pavers filled with coarse grade sand and a base of gravel providing 70 mm of effective storage. The field experiments for this material were completed in Kinston, NC for a set of 47 rainfall events (Bean et al. 2007). Finally, the study included porous concrete with an underdrain replacing the impervious concrete areas. The curve number calculations for porous concrete with an underdrain were based off a field study completed in Edinburgh, Scotland for a set of 15 rainfall events (Schulter and Jefferies 2002). The curve numbers used to describe the different scenarios were calculated by Damodaram et al. 2009 and 2010 using the field experiments hydrograph data and can be seen below in Table 4.

TABLE 4: Curve numbers of land use classifications with the use of different replaceable pavements (Chandna).

Land Use Classification	**Post Development** Curve Number	**Porous Pavement** Curve number	**Concrete Grid Pavers** Curve number	**PP & Underdrain** Curve number
Replaceable concrete	98	85.4	77.5	95.4
Landscaping	75	75	75	75
Buildings	98	98	98	98

Modeled scenarios

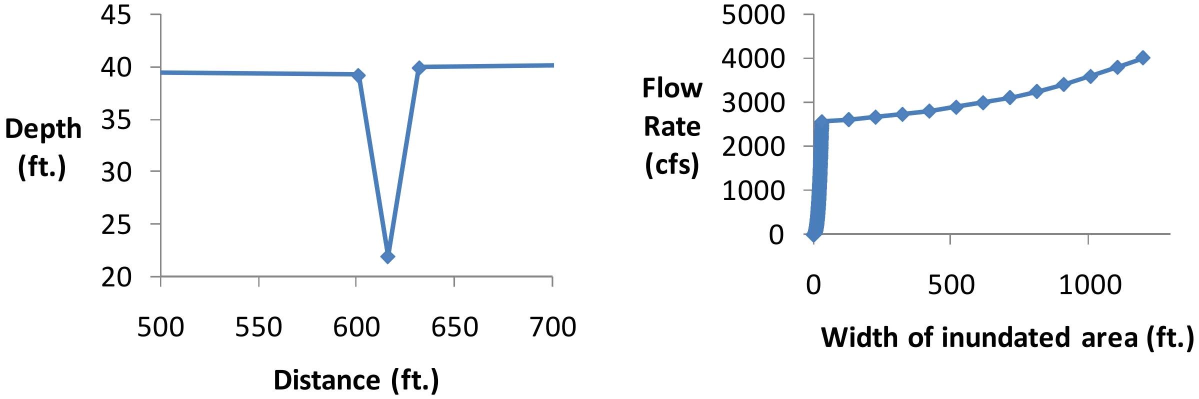
The area totals as shown in Table 2 for each sub-catchment are used to determine the overall curve number in the four different modeled scenarios. For each scenario, a weighted curve number is calculated for each sub catchment to represent the maximum potential retention and initial abstractions for the aggregated impacts of landscaped areas, impervious areas, and permeable pavements. Curve numbers represent the landscaped areas and irreplaceable impervious areas (buildings), which remain constant among four scenarios, while the curve numbers for the replaceable impervious areas are varied for four scenarios.

The post development conditions will be the first scenario modeled to provide a reference point as to what the current stormwater footprint and peak flow of the watershed are. A curve number of 98 is used to describe the current impervious concrete used in parking lots. The second scenario provides the stormwater footprint and peak flow of the watershed if the concrete parking lots were replaced with Porous Pavement. The third modeling scenario provides the results for concrete grid pavers filled with coarse grade sand and a base of gravel providing 70 mm of effective storage. The fourth scenario being modeled is simulating porous concrete with an underdrain replacing the impervious concrete areas. The calculations for each of the scenarios across all sub catchments in the watershed are shown in Table 5.

TABLE 5: Weighted curve numbers of each sub-catchment dependent on the characteristics of the four different types of replaceable concrete.

	Pavement		**Porous Concrete**		**Concrete Grid Pavers**		**PP and Underdrain**	
Sub-catchments	**CN**	**Ia**	**CN**	**Ia**	**CN**	**Ia**	**CN**	**Ia**
1	84.2	0.38	81.4	0.46	79.7	0.51	83.6	0.39
2	83.6	0.39	80.6	0.48	78.7	0.54	82.9	0.41
3	82.6	0.42	79.9	0.50	78.2	0.56	82.0	0.44
4	92.2	0.17	85.4	0.34	81.1	0.47	90.8	0.20
5	83.6	0.39	80.5	0.48	78.6	0.54	83.0	0.41
6	83.9	0.38	81.2	0.46	79.5	0.52	83.3	0.40
7	82.9	0.41	79.9	0.50	77.9	0.57	82.3	0.43
8	83.4	0.40	80.6	0.48	78.8	0.54	82.8	0.41
9	87.7	0.28	81.2	0.46	77.1	0.59	86.4	0.32
10	92.3	0.17	85.6	0.34	81.4	0.46	90.9	0.20
11	92.3	0.17	86.1	0.32	82.3	0.43	91.0	0.20
12	92.3	0.17	86.1	0.32	82.3	0.43	91.0	0.20
13	90.3	0.21	84.9	0.36	81.5	0.45	89.2	0.24
14	90.3	0.21	84.9	0.36	81.5	0.45	89.2	0.24
15	84.3	0.37	81.3	0.46	79.3	0.52	83.7	0.39
16	90.4	0.21	84.9	0.35	81.5	0.45	89.2	0.24
17	84.1	0.38	80.9	0.47	78.9	0.54	83.4	0.40

This data is used to model the four different scenarios, using a modeling study which simulates stormwater runoff using HEC-HMS (US Army Corps of Engineers, 2008). The simulation models a 24-hour 2-year storm event (4.4 inches). HEC-HMS converts rainfall into overland storm water runoff. Harris Gully is simulated as one reach downstream of the watershed outlet, and the reach receives the hydrograph from the HEC-HMS model. The HFR is calculated in this one reach alone based on the stream bank and floodplain area that is inundated by the storm hydrograph from Harris Gully watershed. Harris Gully has a reach length of 2,954.8 feet with a cross-sectional view shown in Fig. 3(a). In Fig. 3(b) a graphical view of discharge vs. width can be seen.



(a) **(b)**

FIGURE 3. Harris Gully geometry: (a) Cross-sectional area of Harris Gully Channel. (b) Width of inundated area in Harris Gully Channel for increasing flow rates.

The hydrograph data is presented as inflow and outflow values recorded every five minutes over the course of 24 hours as the stormwater runoff passes through the watershed system. From this data, the peak flow of the hydrograph and the HFR are calculated.

CHAPTER III

RESULTS

Peak flow was simulated by using HEC-HMS modeling to generate the hydrograph that is routed through the Harris Gully reach. To simulate the HFR for a rainfall event, the hydrograph and time series of depth of flow were simulated using the HEC-HMS modeling framework, which is based on the SCS Curve Number Method. The time series of inundated area was calculated using the geometry of the reach and the depth at each time step, and the HFR was calculated as the area under the inundated land curve. HFR and Peak Flow were both simulated for a 24-hour 2-year storm event (4.4 inches).

Simulation results, including the peak flows and HFR values for the five scenarios are shown in Table 6.

TABLE 6: Peak flow and HFR results for scenarios.

Scenario	**HFR (acre*hr)**	**Peak Flow (cfs)**
Pavement	250	1265
Porous Concrete	232	1101
Concrete Grid Pavers	222	1004
PP & Underdrain	246	1231

Hydrographs for the five different scenarios can be seen in Fig. 4. This hydrograph models the discharge flow rate at the outlet point of the watershed over 100 hours. The maximum value on the graphs represents the peak flow for the scenario. When comparing the different scenarios to one another based on these hydrographs, all four scenarios have very similar hydrographs. This is due to the fact that the area that is replaced by the permeable pavement systems is a fraction of the total area and results in a peak flow reduction of only a small percentage. Porous concrete and concrete grid pavers reduce the flow by around 100 cubic feet per second. Permeable pavement with an underdrain reduced the peak flow to a smaller extent, and may be a less efficient LID system to place in this watershed.

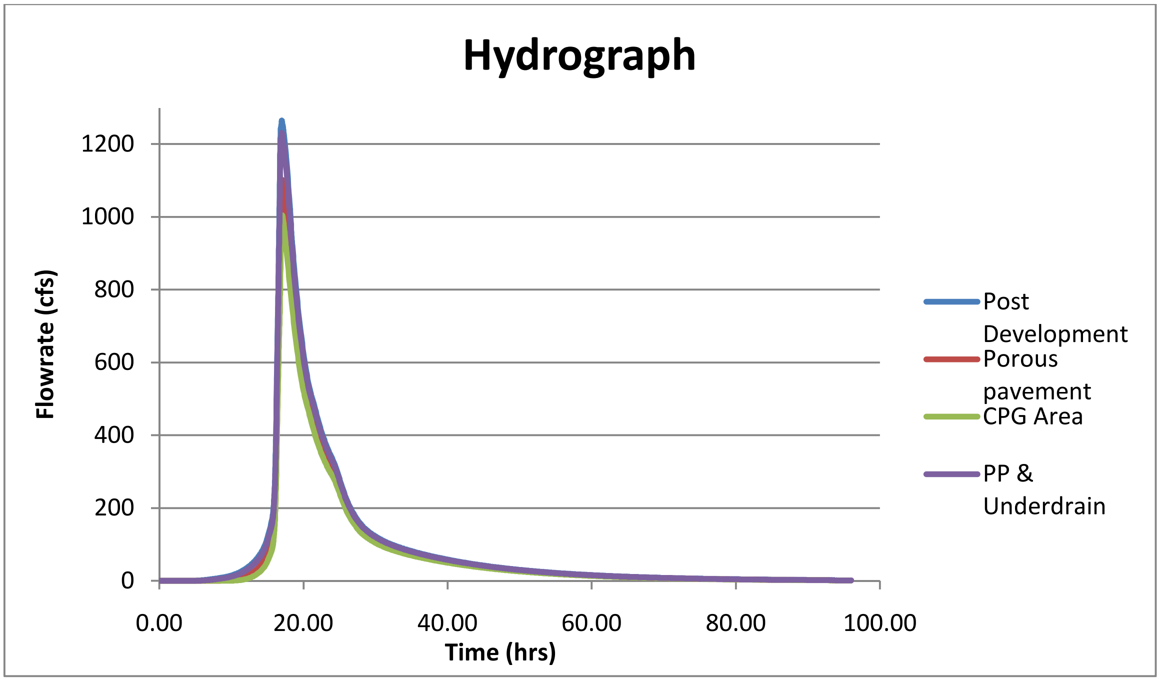


FIGURE 4: Hydrographs for the four simulated scenarios.

The overall Inundated land curves for the four different scenarios and all nine reaches are shown in Fig. 5. The post development scenario generates a HFR that is only slightly higher than the HFR generated by porous pavement with an underdrain (Table 6). The Porous Pavement and Concrete Grid Pavers (CPG) inundated land curves are significantly lower than the post development inundated land curve. These two permeable pavement scenarios lower the HFR to a level similar to Pre-Development

Conditions, demonstrating that the permeable pavement and CPG scenarios may help to restore a pre-development flow regime.

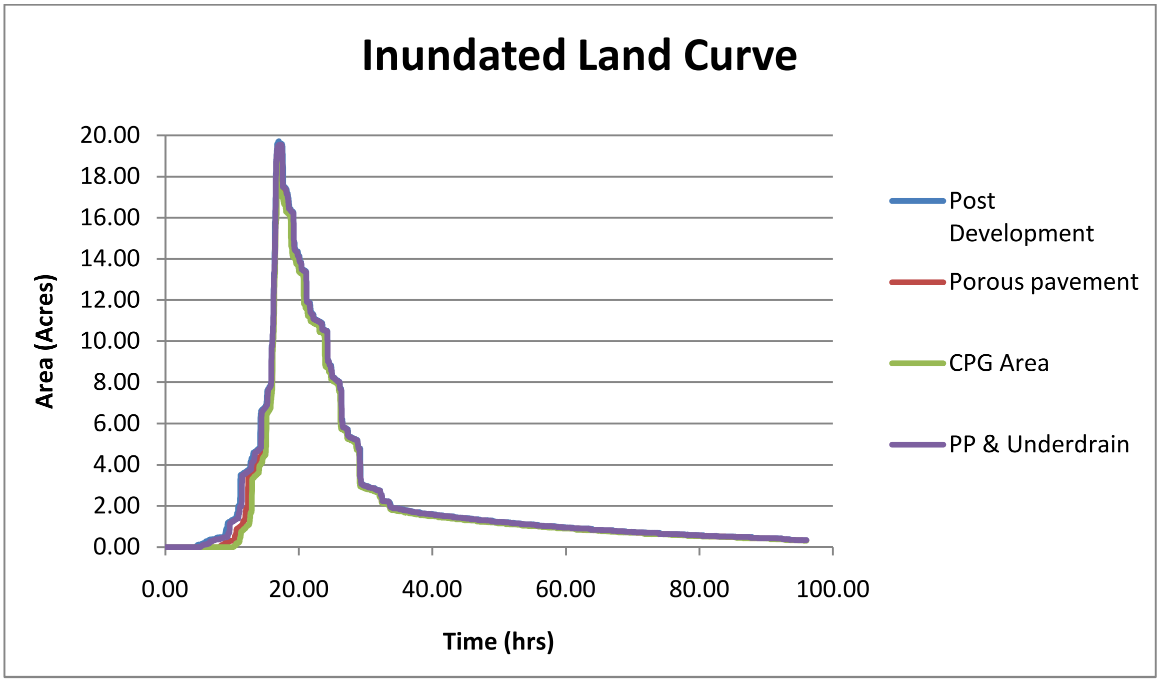


FIGURE 5: Inundated Land Curve for the four simulated scenarios.

Hydrographs are created for each of the nine reaches in Harris Gully (Figs. 6-14). These graphs provide data on the amount flow coming into the reach. The peak flow in each reach is listed in Table 7. This table shows the peak flow for each reach when the percent replaceable concrete was replaced by the four different scenarios.

TABLE 7: Peak flow results for each sub-catchment for each replaceable concrete in each sub-catchment in cubic feet per second (cfs).

Reach	**Post Development**	**Porous Pavement**	**CGP**	**PP & Underdrain**
Golfcourse	55.80	46.50	40.80	53.9
Golfcourse Drive	0.00	0.00	0.00	0
Upper Fannin St	164.90	148.40	138.40	161.4
Middle Fannin St.	280.40	250.00	233.50	273.8
Lower Fannin St.	299.70	270.50	258.60	293.4
Upper Harris Gully	266.00	236.20	218.30	259.7
Middle Harris Gully	510.30	442.10	400.30	496.3
MacGregor Way	0.00	0.00	0.00	0
Lower Harris Gully	904.00	803.60	726.30	889.8

The hydrographs for the two different Golfcourse reaches can be seen in Figures 6-7.

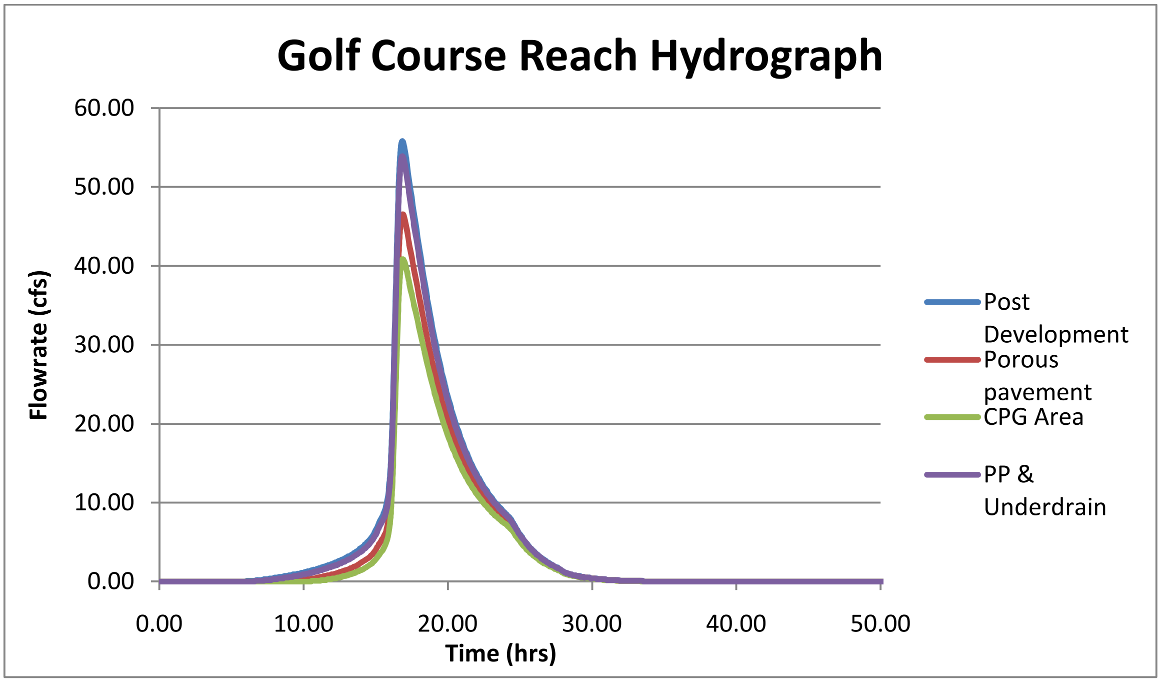


FIGURE 6: Golf Course Reach Hydrograph for the four simulated scenarios.

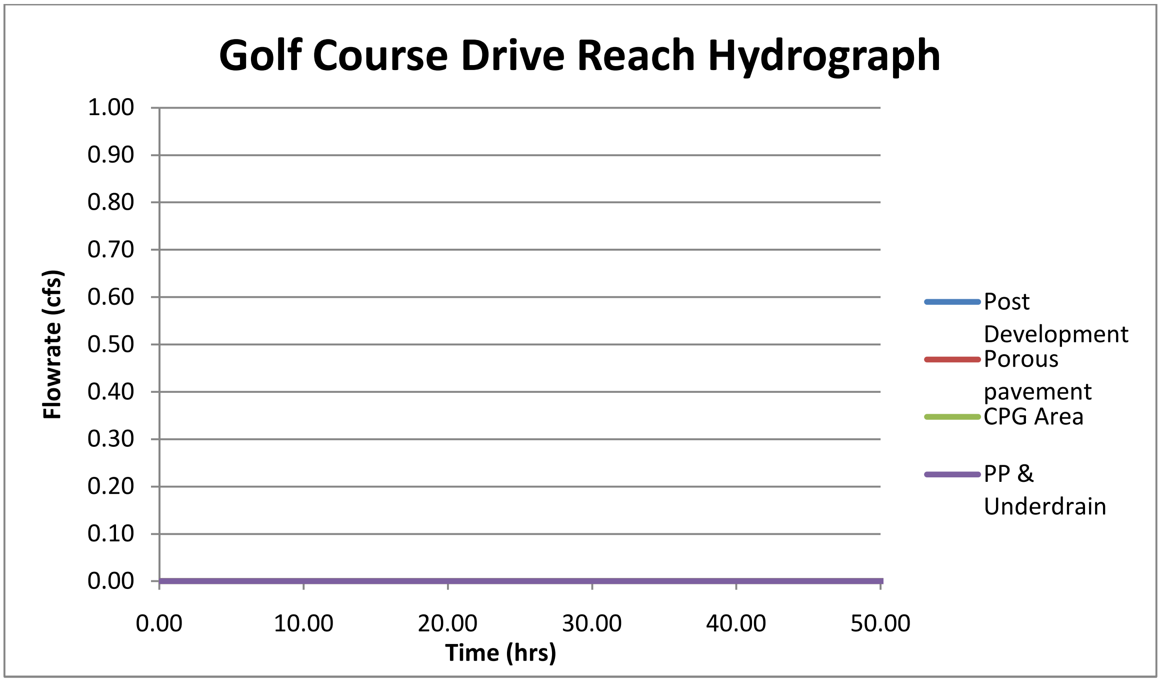


FIGURE 7: Hydrograph for the Golf Course Drive Reach for the four simulated scenarios.

The hydrographs for three different Fannin Street reaches can be seen in Figures 8-10.

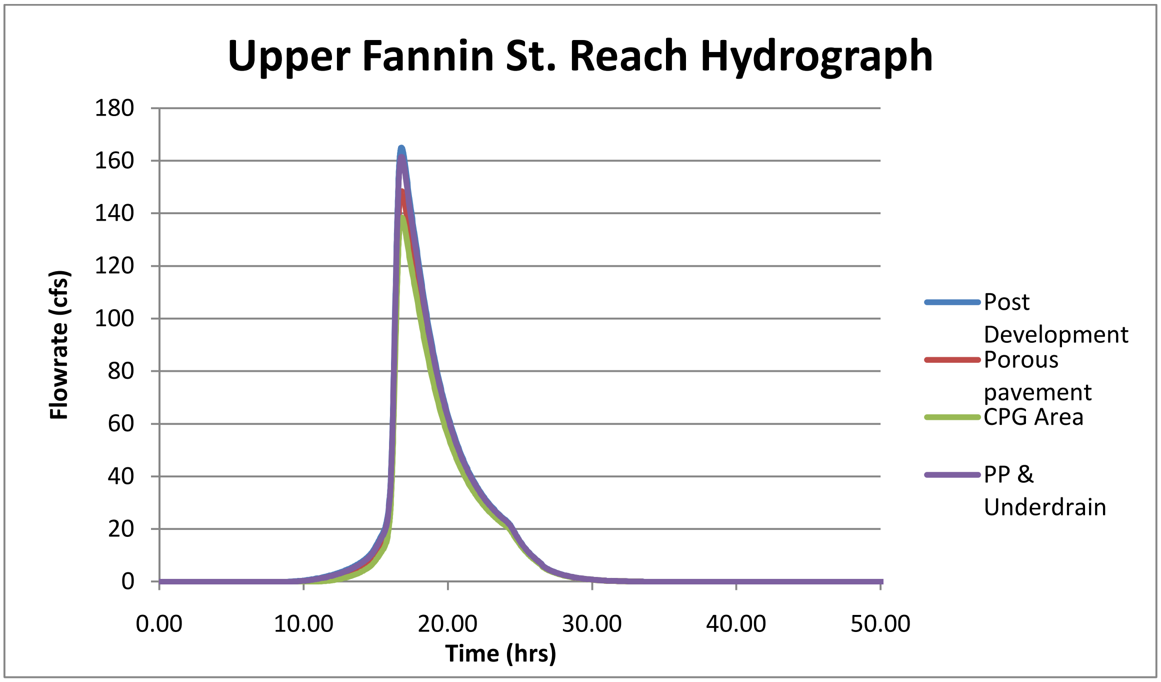


FIGURE 8: Hydrograph for the Upper Fannin Street Reach for the four simulated scenarios.

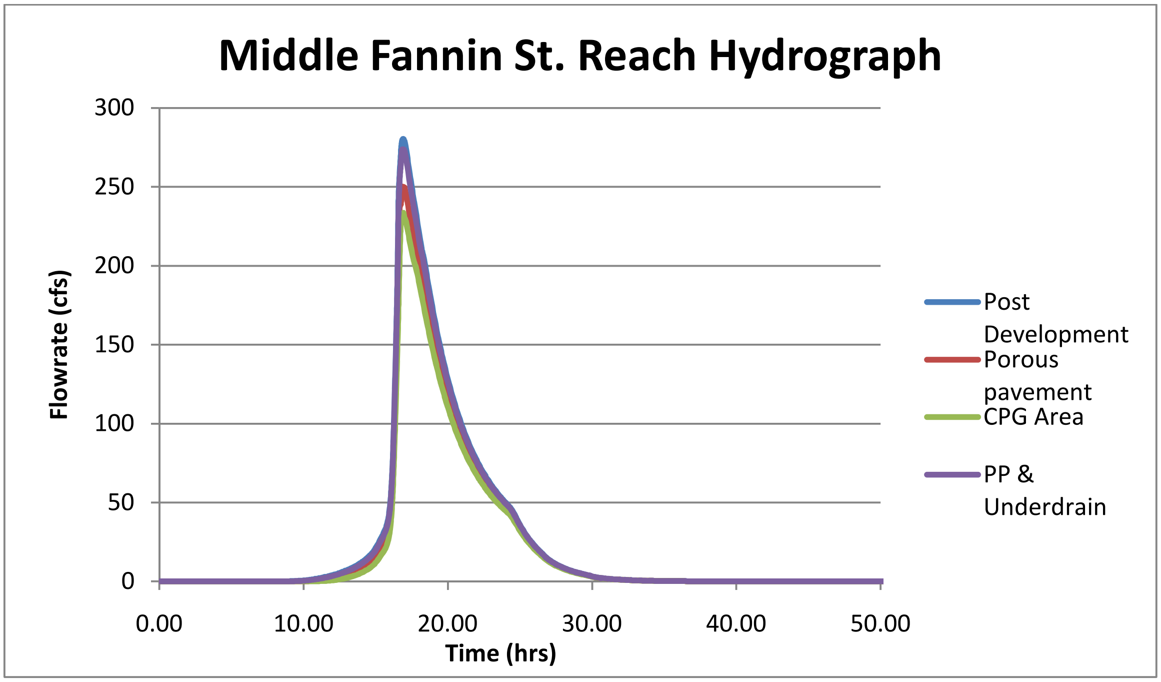


FIGURE 9: Middle Fannin St. Reach Hydrograph for the four simulated scenarios.

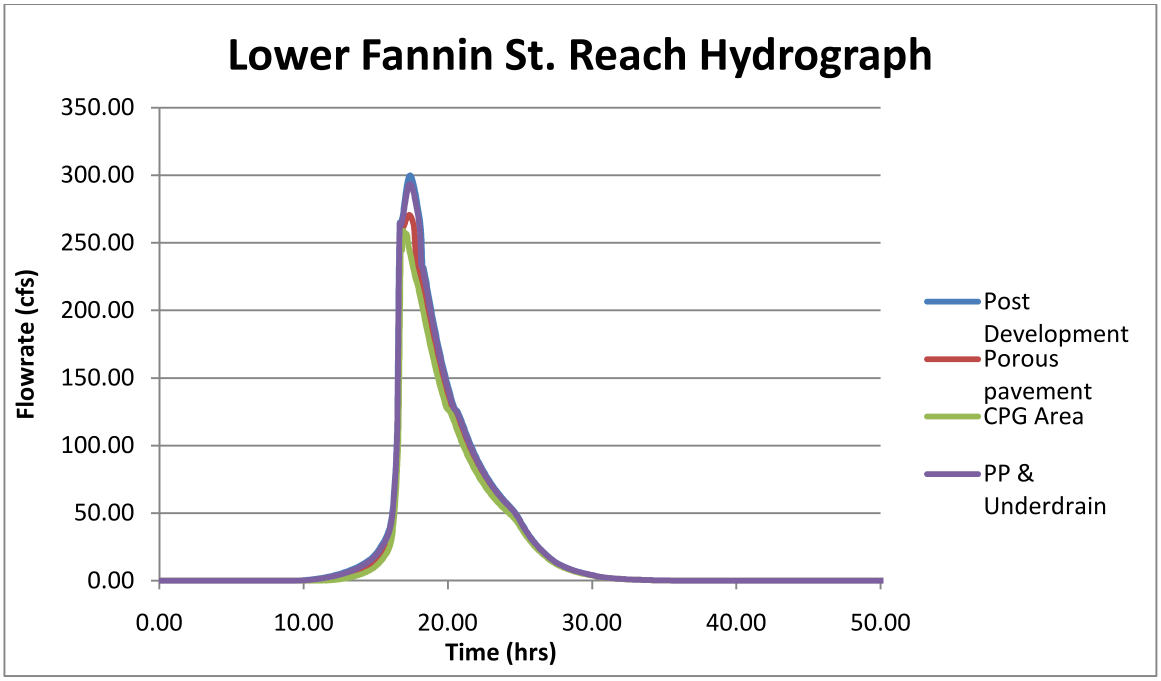


FIGURE 10: Lower Fannin Street Reach Hydrograph for the four simulated scenarios.

The hydrographs for three different Harris Gully reaches can be seen in Figures 11-13.

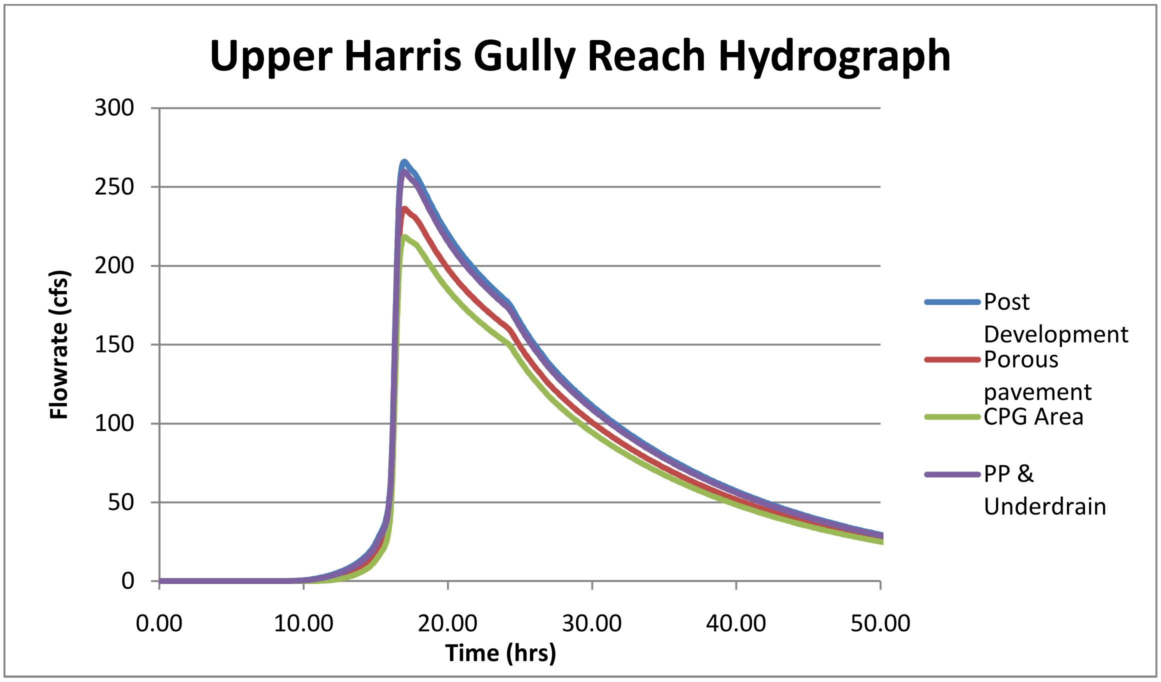


FIGURE 11: Upper Harris Gully Reach Hydrograph for the four simulated scenarios.

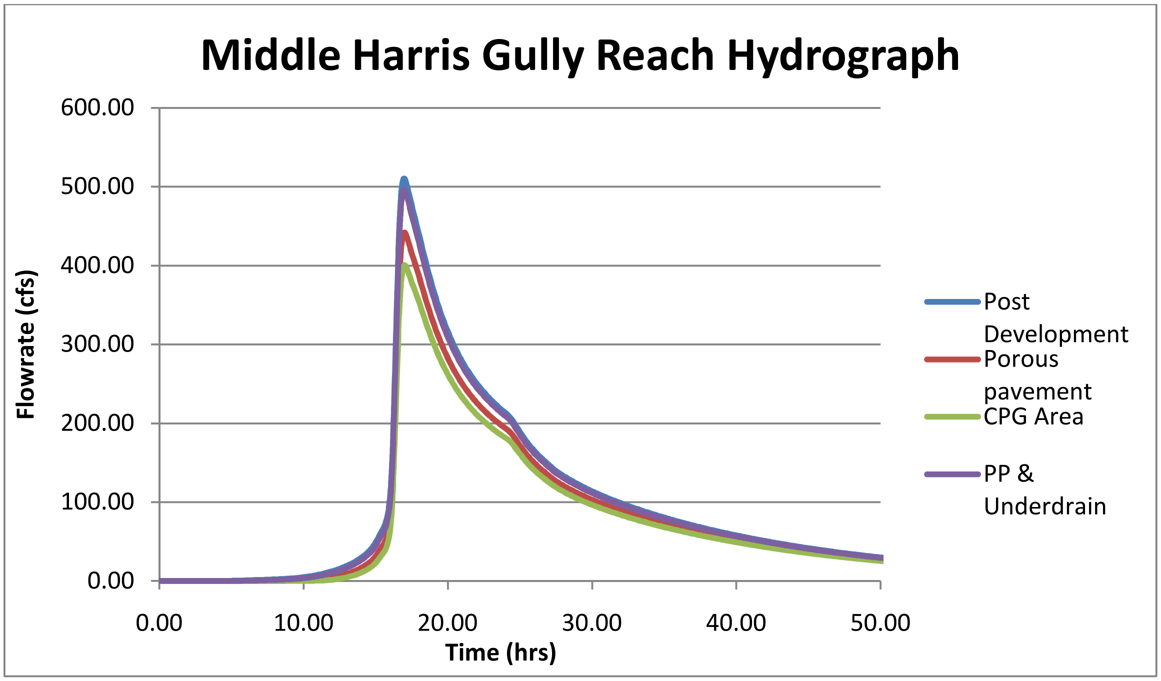


FIGURE 12: Middle Harris Gully Reach Hydrograph for the four simulated scenarios.

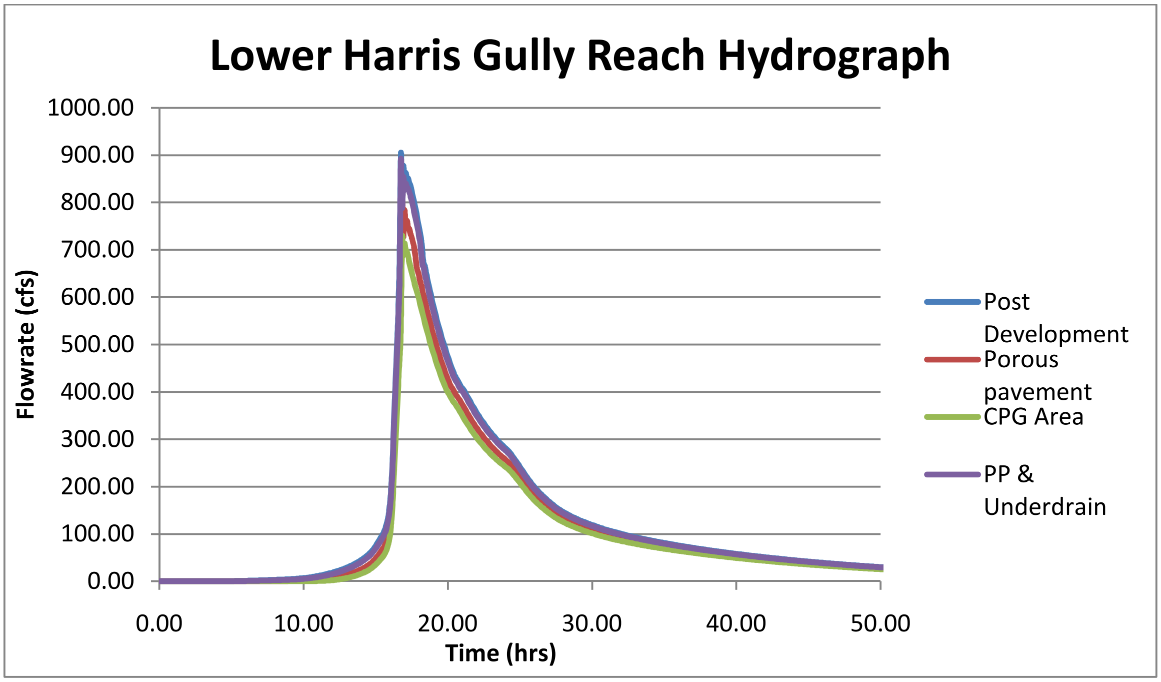


FIGURE 13: Lower Harris Gully Reach Hydrograph for the four simulated scenarios.

The hdyrograph for MacGregor Way reach can be seen in Figure 23. This hydrograph is in existent because of the small rainstorm and the topography of the land.

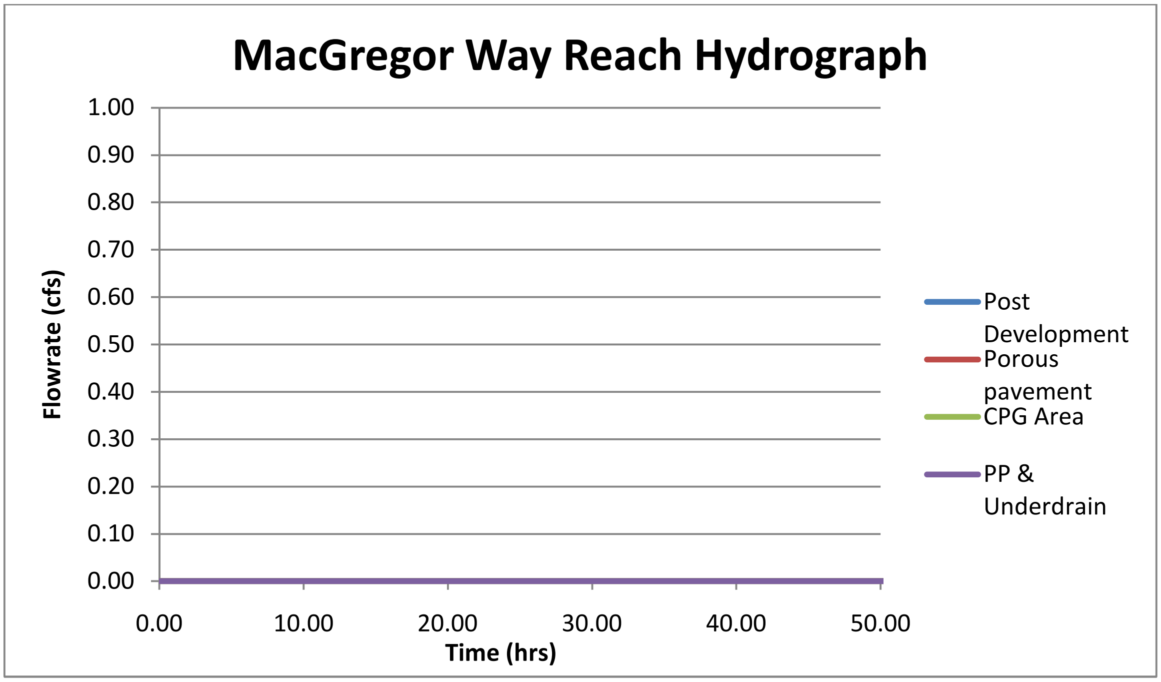


FIGURE 14: MacGregor Way Reach Hydrograph for the four simulated scenarios.

Inundated land curves are also created for each of the nine sub-catchments (Figs. 15-23). These inundated land curves provide data on the amount of land inundated over a 100 hour period into the reach. The stormwater footprint, also known as the HFR, in each reach is listed in Table 8 these HFR's are calculated as the area under the inundated land curve for each replaceable concrete scenario.

TABLE 8: HFR calculations for each sub-catchment replaceable concrete for each sub-watershed in acre-hours.

Reach	Post Development	Porous Pavement	CGP	PP & Underdrain
Golfcourse	14.37	12.44	11.40	13.91
Golfcourse Drive	0.00	0.00	0.00	0.00
Upper Fannin St	16.24	15.16	14.50	16.01
Middle Fannin St.	64.90	60.51	58.08	63.94
Lower Fannin St.	0.00	0.00	0.00	0.00
Upper Harris Gully	6.03	5.63	5.38	5.94
Middle Harris Gully	17.97	16.80	16.15	17.71
MacGregor Way	100.14	92.82	88.64	98.63
Lower Harris Gully	30.35	28.89	28.01	30.05

The inundated land curves for two different Golfcourse reaches can be seen in Figures 15-16.

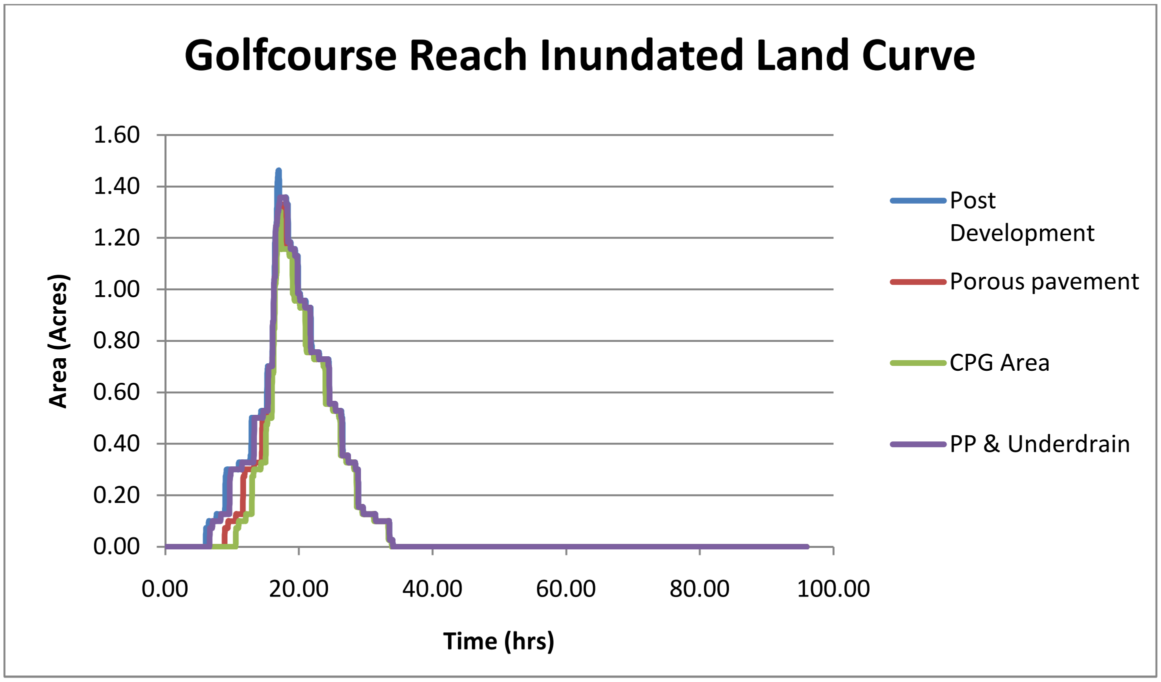


FIGURE 15: Golf Course Reach Inundated Land Curve for the four simulated scenarios.

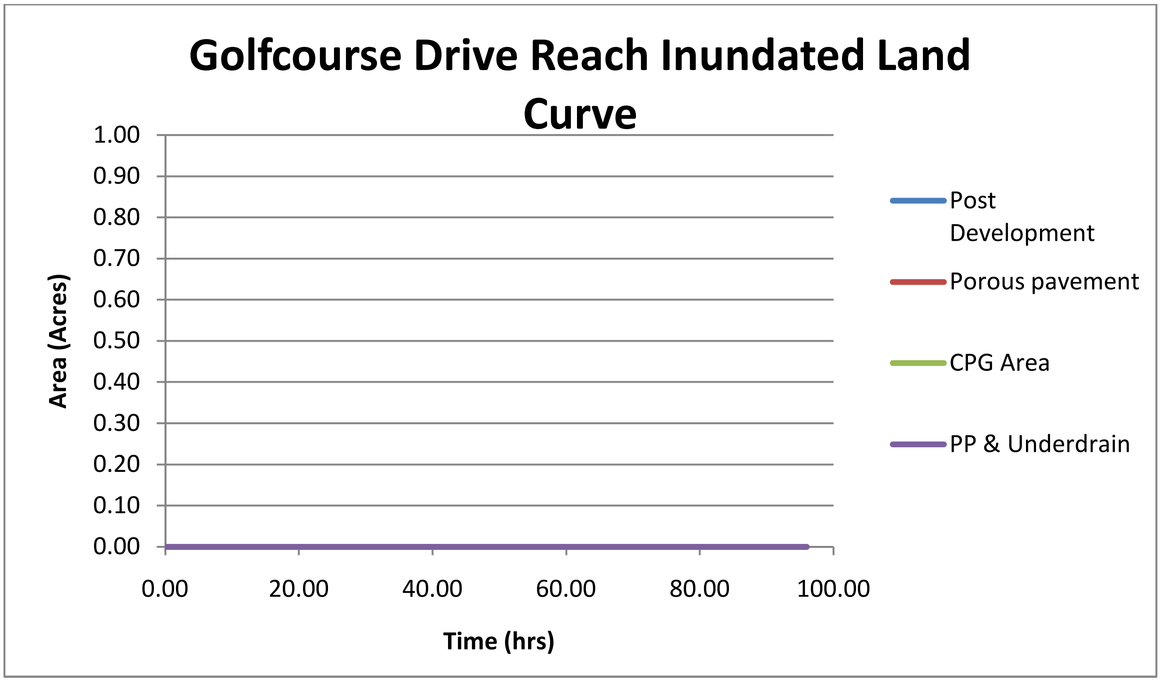


FIGURE 16: Golf Course Drive Reach Inundated Land Curve for the four simulated scenarios.

The inundated land curves for three different Fannin Street reaches can be seen in Figures 17-19.

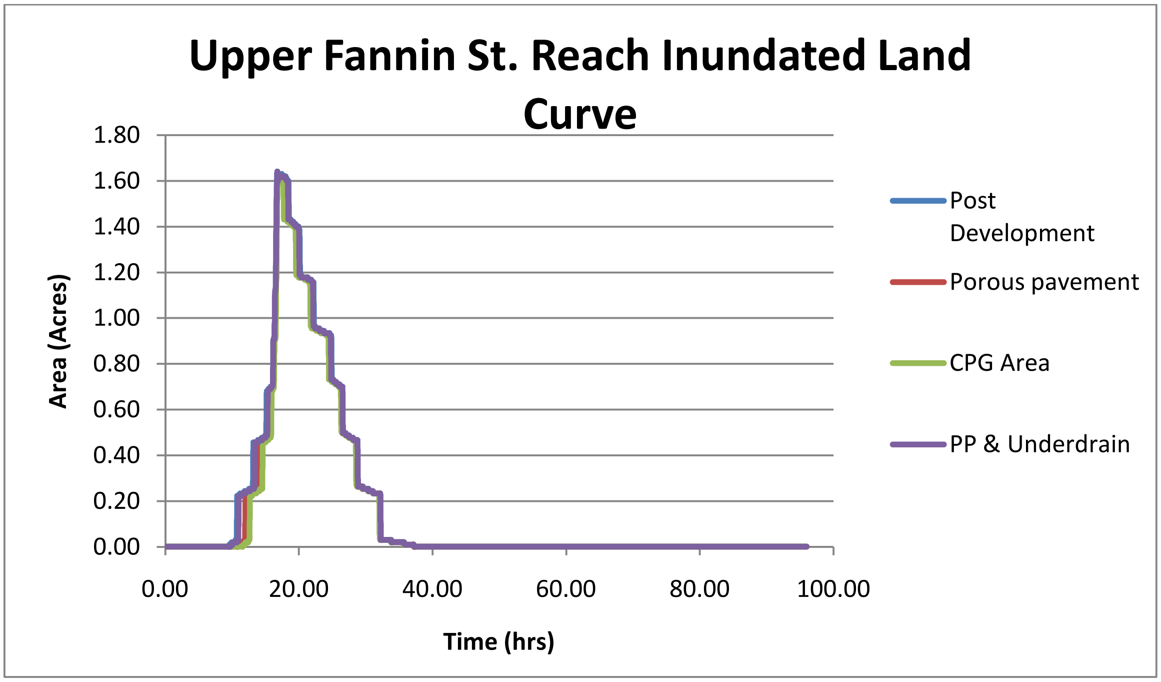


FIGURE 17: Upper Fannin Street Reach Inundated Land Curve for the four simulated scenarios.

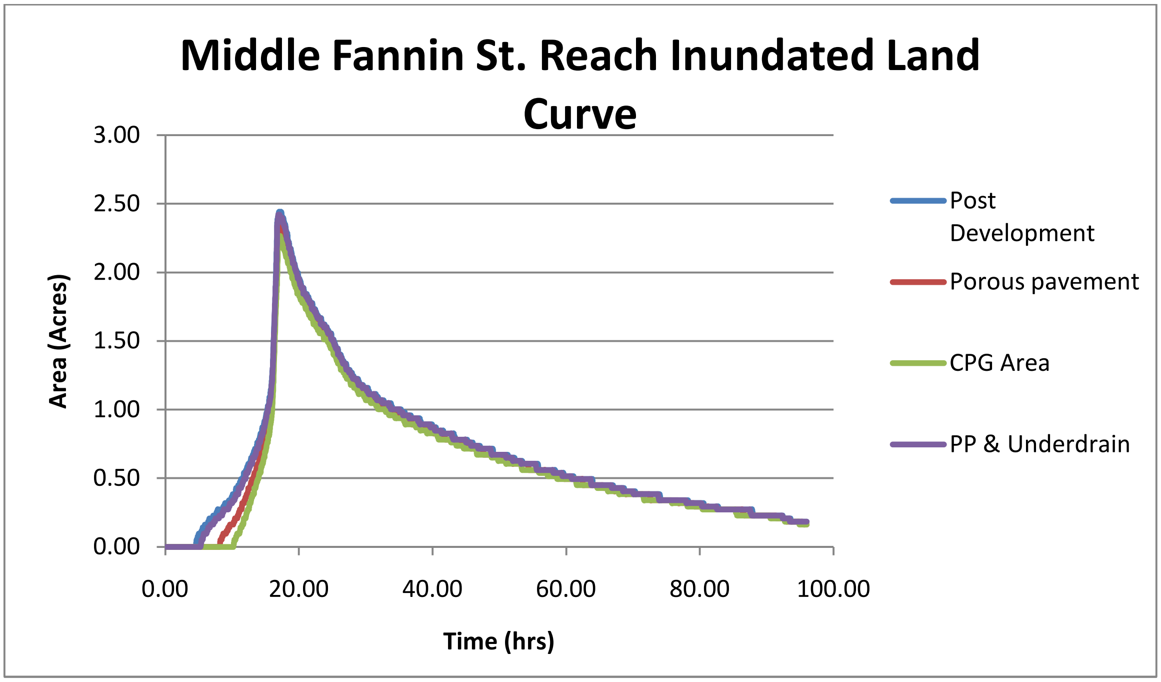


FIGURE 18: Middle Fannin Street Reach Inundated Land Curve for the four simulated scenarios.

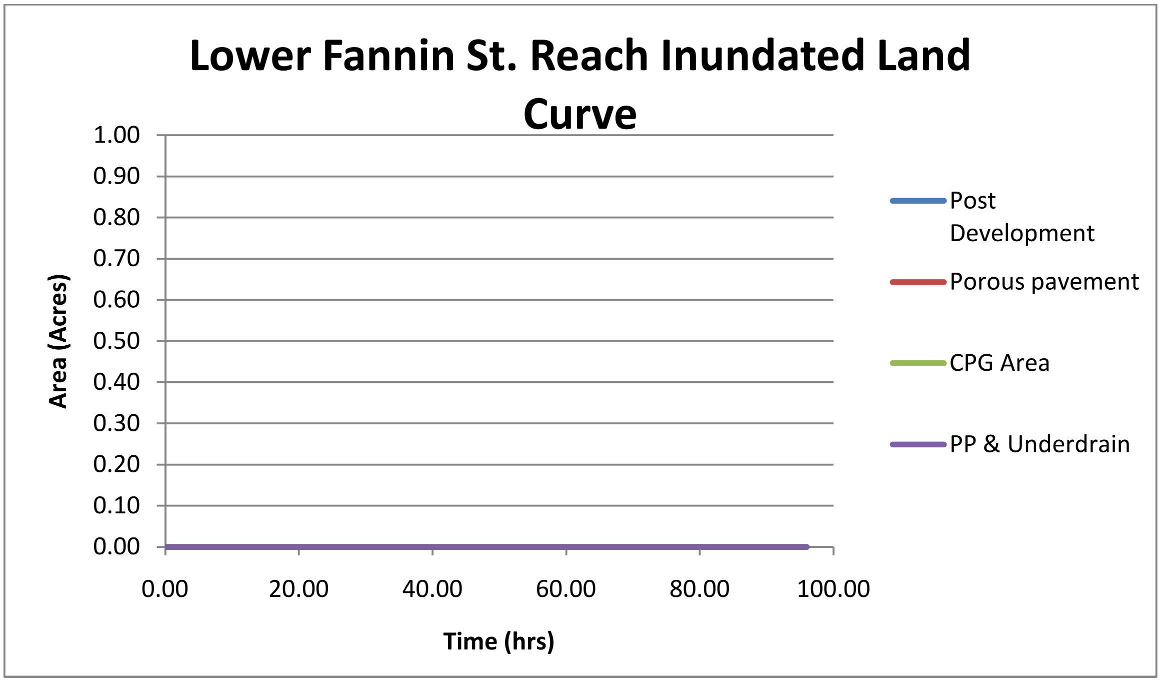


FIGURE 19: Lower Fannin Street Reach Inundated Land Curve for the four simulated scenarios.

The inundated land curves for three different Harris Gully reaches can be seen in Figures 20-22.

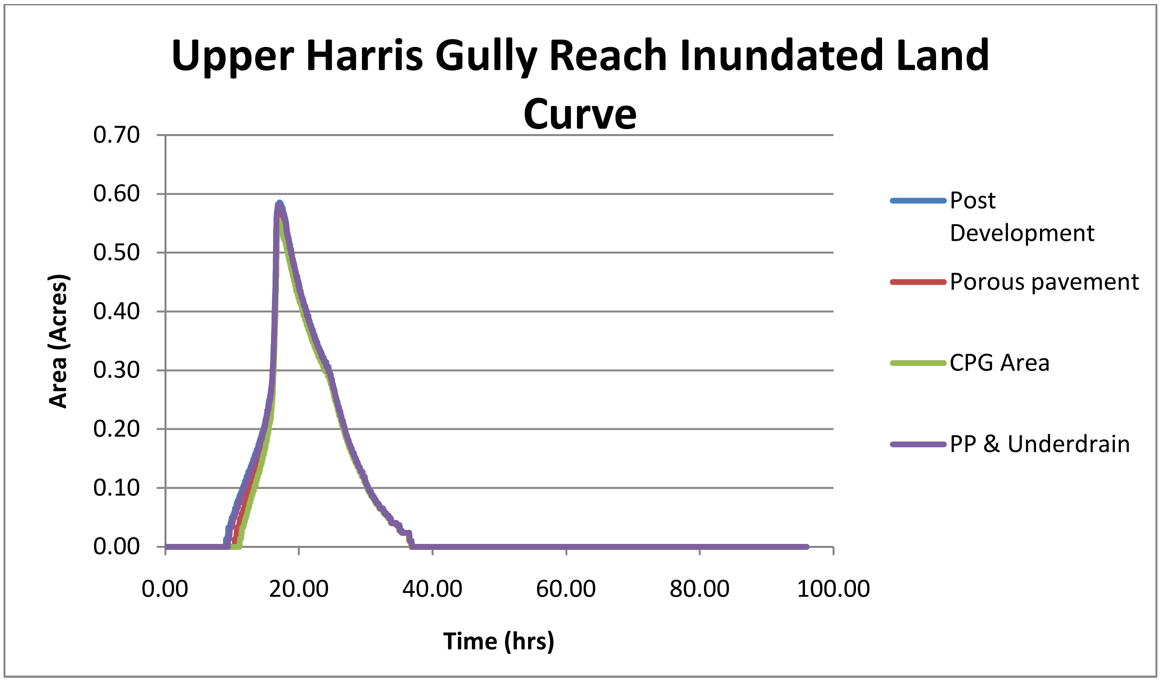


FIGURE 20: Upper Harris Gully Reach Inundated Land Curve for the four simulated scenarios.

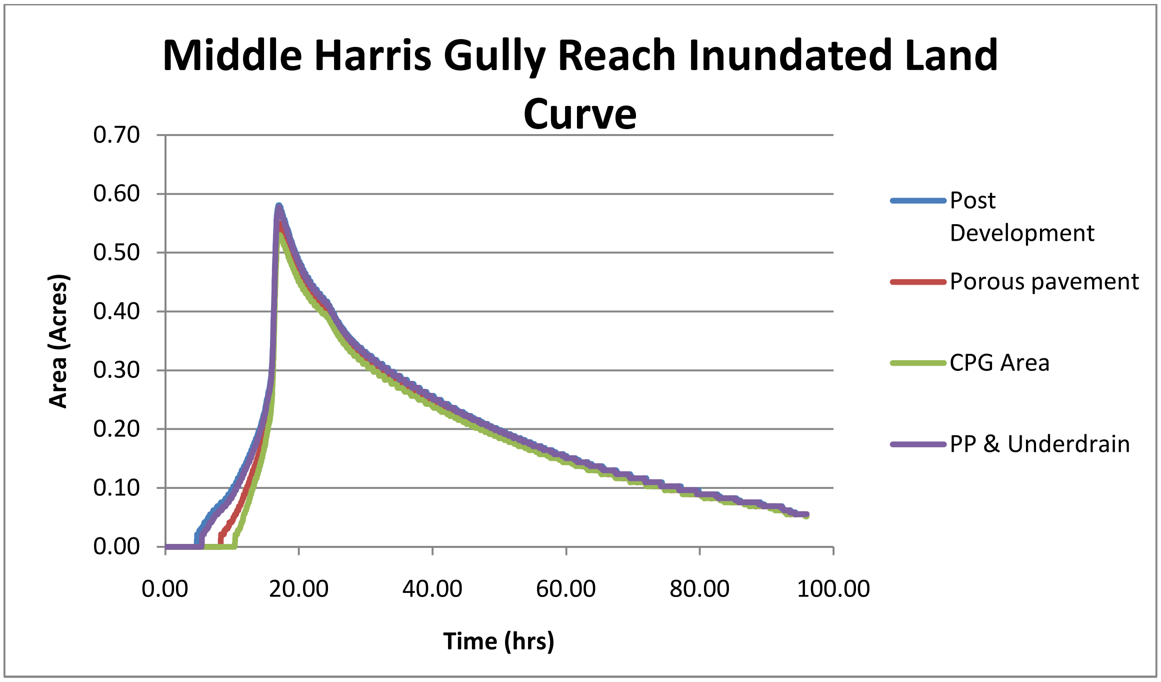


FIGURE 21: Middle Harris Gully Reach Inundated Land Curve for the four simulated scenarios.

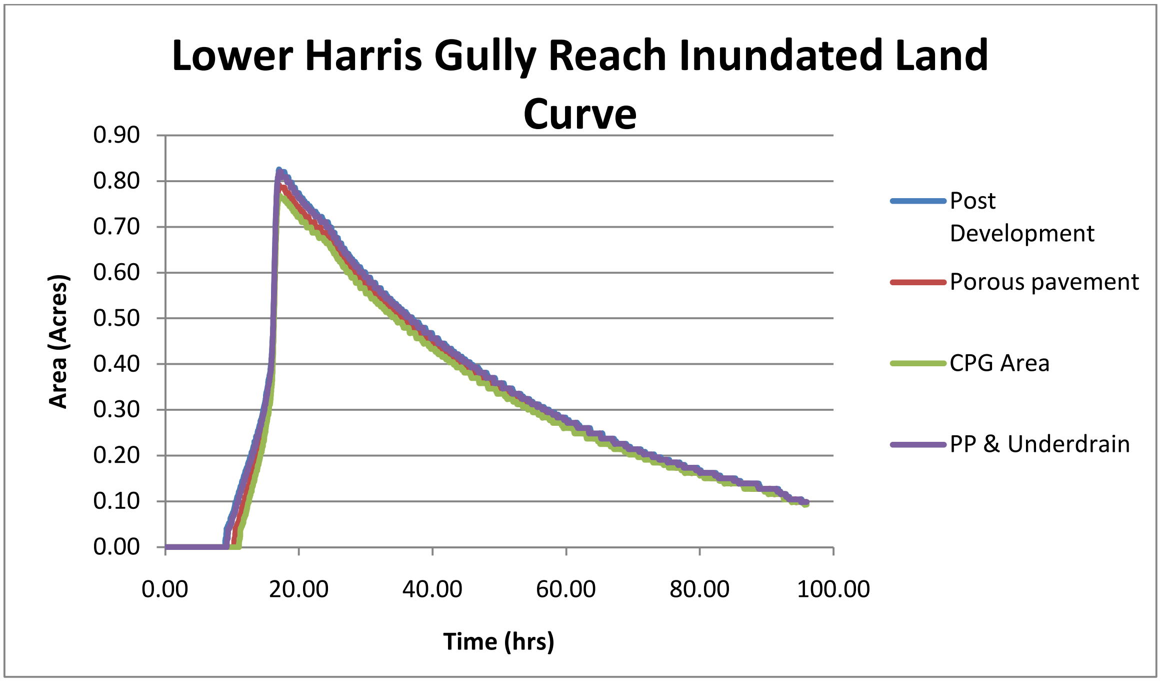


FIGURE 22: Lower Harris Gully Reach Inundated Land Curve for the four simulated scenarios.

The inundated land curve for MacGregor Way reach can be seen in Figure 23.

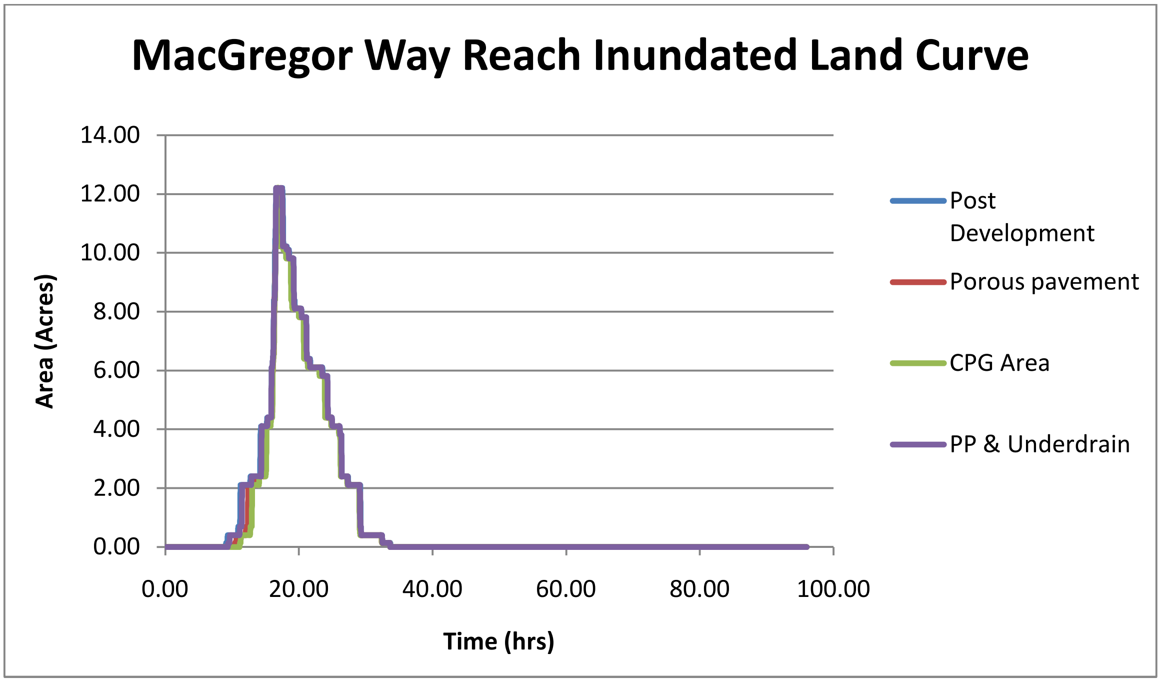


FIGURE 23: MacGregor Way Reach Inundated Land Curve for the four simulated scenarios.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Urbanization is an important issue for municipalities to address, and without efficient planning for stormwater management, cities will experience flooding and the degradation of the natural flow regime. The use of LID technologies can help to reduce the consequences of excessive stormwater runoff and serve as a part of a city's stormwater management. The analysis conducted here indicates that when replacing only a portion of a watershed with LID, a limited effect may be seen in reducing the peak flow and stormwater footprint. Permeable pavement systems were most effective in lowering peak flow and stormwater footprint, and could be used in combination with BMPs to lowering the stormwater footprint close to the pre-development conditions for small storms.

This research established a new hydrologic and hydraulic simulation approach that was used to test the advantages to using permeable pavement systems over concrete for parking lots and driveways. This new approach took into account the amount of area that could be replaced in the watershed. Previous research assumed that 100% of impervious area would be replaced with permeable pavement systems..The new modeling approach developed here can provide more accurate data and predictions about the effects permeable pavements may have for reducing stormwater runoff.

This research also provided data for comparing three different permeable pavement systems based on the peak flow and stormwater footprint to the hydrologic performance of pavement. Analysis of the hydrographs for the Harris Gully watershed reveal that the four simulation scenarios produce similar times to peak and peak flow values, which vary by only 261 cubic feet per second. The results demonstrate that Concrete Grid Pavers (CGP) reduce the peak flow of the current urbanized watershed by 261 cfs and reduce the watershed's stormwater foot print (HFR) by 28 acre-hours, making this permeable pavement system the most effective. Porous pavement reduces the peak flow by 164 cfs and the stormwater footprint by 18 acre- hours. The porous pavement results show this is an effective alternative for this area. On the other hand, Porous Pavement with an Underdrain did not prove to be an effect Permeable Pavement system because it was only able to reduce the peak flow by 34 cubic feet per second and the HFR by 4 acre-hours. This particular permeable pavement would not be recommended for reducing the stormwater runoff for this area. The use of this system would be more effective in an area with clayey soils where the existing ground is more impermeable (Collins et al. 2008).

By using HFR as a basis for comparisons beyond the peak flow, this analysis provides a comparison for evaluating the impact of different development patterns on the downstream reach. For the scenarios modeled here, there is a linear relationship between HFR and peak flow; as peak flow increases, HFR increases as well. This indicates that the HFR can be used for this scenario in place of peak flow. For other watersheds, some scenarios show an increase in HFR even when peak flow is decreased. This is due to change in the shape of the hydrograph that accompanies traditional stormwater controls, such as detention ponds. Future research will explore detention pond based scenarios to explore any changes in the hydrograph shape and the accompanying changes to the HFR values. In addition, on-going research is investigating the use of HFR as a tool for communicating the impacts of development on the sustainability of water resources to home owners and land developers.

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CONTACT INFORMATION

Name: Alyssa Catherine Politte

Professional Address: c/o Dr. Emily Zechman
Department of Civil Engineering
MS 4227
Texas A&M University
College Station, TX 77843

Email Address: apolitte08@gmail.com

Education: B.S., Civil Engineering, Texas A&M University, December 2011
Magna Cum Laude
Undergraduate Research Scholar
Chi Epsilon