Mill Creek Watershed
Nashville, Tennessee

Photo of Mill Creek

Ecosystem Restoration and Flood Damage Reduction Feasibility Scoping Document

Hydrology and Hydraulics Appendix

US Army Corps of Engineers ®
Nashville District

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METRO WATER SERVICES

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1.0 INTRODUCTION

The Mill Creek Watershed Study takes a total view of hydrologic and hydraulic, processes occurring in the watershed. The study aims to improve the overall health of the stream and its corridor while also reducing flood damages. This report documents the evaluation of future development, watershed and floodplain management alternatives and ways to improve and maintain low flows.

2.0 RESEARCH AND DEVELOPMENT

The U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) located in Davis, California was an instrumental part in the development of GIS, hydrologic and hydraulic analysis for the study. An early goal of the study was to have a single software package to evaluation both flood risk and water quality instead of a variety of models that must be manually integrated. In 2003, HEC reviewed existing watershed modeling technology that included the following three studies:

1. Evapotranspiration Modeling Options for the Mill Creek Watershed Study – Nashville District (HEC, September 2003)
2. Surface Sediment Erosion: Comparison of selected models that might be incorporated in HEC-HMS (David Ford, October 2003)
3. Nutrient Yield: Comparison of selected models that might be incorporated in HEC-HMS (David Ford, October 2003)

The studies recommended enhancements to HEC-HMS (HMS) for water quality simulation including refinement of the gridded deficit-constant method and the addition of the gridded Priestly-Taylor evapotranspiration (ET) method. Surface sediment and nutrient modeling, however, was not added to HMS as part of this study because of cost factors. HEC acquired research and development funds from other sources to continue development of the sediment and nutrient component of HMS. A Beta version of Surface Sediment yield in HMS has been released. The Water Quality component of the hydrologic analysis did include the deficit-constant and ET enhancements to evaluate infiltration and baseflow characteristics of Mill Creek soils, impact of urbanization on direct runoff and baseflow, and use of infiltration Best Management Practices (BMPs) for ecosystem restoration and environmental sustainability projects in the Mill Creek Watershed.

In 2004, HEC developed the hydrologic model for Mill Creek Watershed. The hydrologic model was developed using the latest Geographic Information System (GIS) technology. The Nashville District had HEC standardize, and automate the process of developing spatially distributed (GIS-based) hydrologic parameters for an input to an HEC-HMS model. In 2005, HEC added tools to HEC-GeoHMS to automate the process. The tools have been used to assess the hydrologic impacts due to urbanization.

3.0 EXISTING CONDITIONS

The Existing Conditions hydrologic and hydraulic models were completed in 2004 and 2005. The existing conditions models were submitted for flood insurance purposes to the Nashville Metropolitan/Davidson County government in February 2006.

3.1 Basin Description

Mill Creek flows approximately 27 miles in a northerly direction from its headwaters in Williamson County, Tennessee to its confluence with the Cumberland River at Mile 194.4 in Nashville, Davidson County, Tennessee. The basin is teardrop shaped with a total drainage area of 108 square miles as shown below and in Map 1. It lies principally in Davidson County, although 35 percent of the upper watershed is in Williamson County and a small headwater portion extends into Rutherford County.

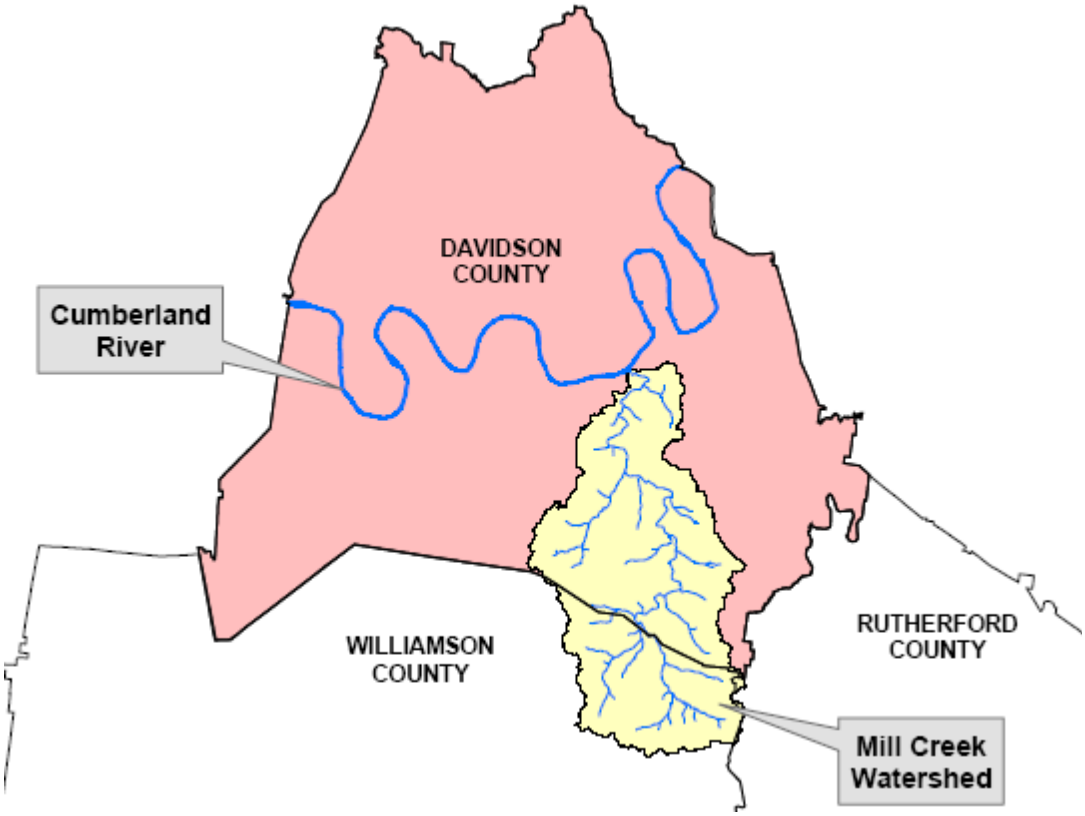


Illustration of Davidson County and Mill Creek Watershed

Topography in the Mill Creek Basin ranges from flat to moderately sloping along the main stem to rolling and hilly uplands which form the watershed divide. Elevations range from about 385 feet above mean sea level at the mouth to around 1200 feet in the upper extremities of the basin. The land use in the Mill Creek Basin varies greatly and is experiencing very rapid change.

Climate conditions in the watershed are relatively uniform. Normal mean monthly temperatures (Nashville Airport 1948 – 2005) vary from 89.8 degrees in July to 46.9 degrees in January and average 59.4 degrees annually. Normal annual precipitation is around 48.1 inches.

3.2 Historical Storms and Floods

Information is available for several significant floods on Mill and Sevenmile Creeks dating back to 1955. Although this is a relatively short time span, a wide variety of rainfall amounts and storm distributions and durations have occurred that provide excellent insight into the basin's flooding characteristics. A chronological discussion of storms and floods is given in the following paragraphs.

The flood of 20-21 March 1955 resulted from widespread rainfall during the night of the 20th and a heavy burst of 3 inches in a 6-hour period on March 21st. Total rainfall amounts averaged from 4.8 inches throughout most of the basin to 5.5 inches in the upper watershed. The Mill Creek gage at Blue Hole Road in Antioch reached a stage of 19.73 feet and families along both Mill and Sevenmile Creeks were evacuated.

During the night of 16-17 June 1960, a very intense thunderstorm produced a relatively narrow band of heavy rainfall centered near the Mill Creek headwaters in Nolensville. This flood was higher than the March 1955 flood just upstream of the gage. However, the maximum stage of 19.15 at the gage was one-half foot lower than the 1955 flood. The lower reaches of Mill Creek and Sevenmile Creek, where most urban development was located at the time, experienced only a moderate rise.

A wet winter and early spring in 1962 featured several storms that caused moderate flood rises on all streams in Middle Tennessee. The most severe in the Mill Creek watershed occurred in late February 1962 when a 60-hour period of precipitation, beginning on the 25th, produced an average of 6 inches of rainfall. Because the rainfall was widespread and long in duration, the flood crested along the entire lengths of Mill Creek and Sevenmile Creek on 27 February.

Approximately 3 inches of rainfall was recorded at the airport between 1:00 and 3:00 P.M. on August 25, 1976. This intense band of thunderstorms resulted in the flood of record on Whittemore Branch. No other flooding was reported in the Mill Creek basin for this event.

The 4 May 1979 flood is the flood of record on Mill Creek and produced the most severe flood damages ever experienced along the entire stream. Initial wetting occurred during the early morning of 3 May when an inch of rainfall fell over the entire basin. Starting at 8 p.m. that evening an intense thunderstorm centered in the upper half of the basin moved from west to east and deposited nearly 5.5 inches of rainfall in a 6-hour period. The lower half of the basin, including Sevenmile Creek, received 3.1 inches during this same 6-hour period. This resulted in a flood with about twice the magnitude of flow of any previously known flood on Mill Creek.

September in Nashville is usually a very dry month; however, the 11.44 inches of rainfall that fell during September 1979 made this the wettest September since records began in 1871. A part of this record rainfall resulted in severe flooding in the Mill Creek Basin for the second time in 1979. The heaviest rainfall for the month was a direct result of the tropical hurricane Frederick. During the 6-hour period from 1 p.m. to 7 p.m. on 13 September, rainfall amounts of 4.8 to 5.3 inches were recorded throughout the basin. Although the rainfall amounts for this storm closely resemble the May storm, the very dry antecedent moisture conditions resulted in peak discharges about one-third less than the May flood discharges.

During the months of April and May of 1984, residents were twice again alarmed by bothersome flooding on Mill and Sevenmile Creeks. These floods damaged mainly yards and basements.

Flood damages along Mill Creek and its tributaries have been documented for several flood events occurring in 1990s and 2000s. On June 4, 1998 flooding was reported

along both Sevenmile and Mill Creeks. Water threatened Harding Mall and other structures. Mill Creek near the Nolensville gage reached the year's highest marks on June 4th at 16.23 ft and a peak discharge greater than 10,000 cfs. On May 24, 2000 flooding occurred at Sevenmile Creek near the Harding Mall at 0120 CST. Minor flooding was reported on November 29, 2001 when Sevenmile Creek overflowed its banks spilling into many backyards. On May 5, 2003 spotters reported flooding at Edmonson Pike and Blackman Road along Sevenmile Creek. Six feet of water was over the roads and some homes were flooded. High water marks for this event were as high as the May 1979 flood at some locations along Sevenmile Creek.

The top 10 historic peak discharges for available Mill Creek gages are listed in Table 1.

Table 1: Historic Peak Discharges in the Mill Creek Watershed

Mill Creek At Nolensville			Mill Creek Near Nolensville			Mill Creek Trib at Glenrose Ave		
DA	12.0 square miles		DA	40.5 square miles		DA	1.17 square miles	
Years	1965 - 2003	37	Years	1992 - 2004	12	Years	1977 - 2004	30
Rank	Date	Peak Discharge (cfs)	Rank	Date	Peak Discharge (cfs)	Rank	Date	Peak Discharge (cfs)
1	5/7/1984	11400	1	10/5/1995	13000	1	5/6/1984	833
2	5/4/1979	11400	2	5/25/2000	12600	2	5/4/1979	830
3	6/26/1994	8630	3	5/14/1995	12600	3	6/26/1994	612
4	5/25/2000	8300	4	6/7/2003	12500	4	7/21/1996	550
5	9/22/2003	8160	5	5/5/2003	11100	5	5/3/1993	546
6	5/14/1995	7620	6	6/26/1994	10600	6	5/25/2000	535
7	10/5/1995	7370	7	3/3/1997	10500	7	3/17/2002	523
8	1/23/1999	7020	8	9/22/2003	10500	8	11/27/1994	501
9	12/1/1991	6820	9	6/4/1998	10000	9	7/3/1992	491
10	3/3/1997	6720	10	2/5/2004	10000	10	5/5/2003	460

Mill Creek Near Antioch			Mill Creek At Thompson Lane			Seven Mile Creek at Blackman Rd		
DA	64.0 square miles		DA	93.4 square miles		DA	12.2 square miles	
Years	1954 - 2004	50	Years	1965 - 2004	39	Years	1965 - 2003	38
Rank	Date	Peak Discharge (cfs)	Rank	Date	Peak Discharge (cfs)	Rank	Date	Peak Discharge (cfs)
1	5/4/1979	30100	1	5/4/1979	26200	1	6/4/1998	10500
2	9/13/1979	19000	2	9/13/1979	20000	2	5/5/2003	7320
3	3/4/1955	17000	3	2/14/1989	16000	3	9/13/1979	7320
4	6/17/1960	15600	4	5/5/2003	14200	4	2/14/1989	4780
5	2/27/1962	13800	5	3/12/1975	13600	5	4/25/1993	4040
6	5/5/2003	11500	6	6/4/1998	13500	6	3/29/1975	2960
7	5/25/2000	10800	7	5/7/1984	13400	7	10/5/1995	2930
8	6/4/1998	10800	8	5/25/2000	13300	8	5/25/2000	2500
9	5/7/1984	10700	9	10/5/1995	13000	9	5/19/1983	2070
10	11/27/1973	10500	10	2/5/2004	13000	10	5/6/1984	1880

Note: September 1979 Discharges at Antioch and Thompson Lane are estimated from Highwater Marks

Floods occur during all seasons of the year, but are most prevalent during winter and early spring when antecedent moisture conditions are highest. The floods are flashy, with rates of rise ranging from 2 to 4 feet per hour along the main stem and durations averaging 12 hours. The majority of storms move across the watershed in a northeasterly direction.

3.3 Previous Studies

Frequency profiles for Mill and Sevenmile Creeks were developed in conjunction with the Davidson and Williamson County Flood Insurance Studies (FIS) beginning in 1977. The

hydrologic and hydraulic analyses for these studies were performed by the U.S. Geological Survey (USGS). The work was completed just before the May 1979 flood of record. The statistical frequency analysis for FIS was revised in 1980 by the Corps to reflect this flood.

In 1980 work began on a Stage II report for the Mill Creek Basin. The backwater model developed for the FIS by USGS was converted to a "Water Surface Profiles, HEC-2" computer program format for use in this study. Verification runs were made using this model to determine its accuracy in reproducing the 1979 floods. Several updates were made to the HEC-2 model, but overall it was adequate to investigate and compare flood control alternatives.

Before the 1979 floods, a study was conducted by the USGS entitled, "Effects of Urbanization on Flood Characteristics in Nashville-Davidson County Tennessee." The severity of the 1979 floods and the findings in this report (a conclusion of no impact from urbanization) prompted a detailed study by the Corps of Engineers. The Corps study, completed in 1986, focused on the Mill and Sevenmile Creek floodplains within Davidson County. Detailed HEC-1 and HEC-2 models were developed. Large arrays of alternatives were analyzed including both structural and nonstructural solutions. A total of 43 plan combinations were evaluated from hydrologic, hydraulic, economic, and environmental viewpoints. The selected plan provided the greatest return on the investment of tax dollars (the most net benefits) and included the construction of two regional detention structures at Mile 16.81 on Mill Creek and Mile 3.70 on Sevenmile Creek and widening a section of Sevenmile Creek from Mile 0.70 to 1.51. The recommended plan was congressionally authorized for construction but never completed due to public opposition.

In 1990, the Corps of Engineers completed a Section 22 (Planning Assistance to States) study for the Mill Creek Basin within Williamson County to provide hydrologic information concerning the possible use of regional detention to reduce flooding in the Nolensville Community. The study evaluated two regional detention sites, but Williamson County did not proceed with the regional detention approach due to loss of valuable land in the proposed detention areas.

In 1996, the Corps of Engineers conducted a floodway storage analysis for the Cumberland River and Mill Creek in Davidson County to evaluate requiring storage compensation for fill in the floodway fringe. An unsteady flow (UNET) model was developed for Mill Creek within Davidson County. The analysis indicated that compensation storage was necessary along most of the Mill Creek main stem to attenuate flood hydrographs and minimize encroachment surcharge.

3.4 Flood Frequency Analysis

Flood frequency analysis was performed for the six stream gages listed in Table 1 using the Hydrologic Engineering Center's Flood Frequency Analysis (HEC-FFA, or FFA) program.

3.5 Hydrologic Modeling Analysis

The hydrologic models were developed using a gridded approach where the grids were generally equivalent to a 10-acre parcel as shown in Figure 1. This 10-acre grid size was well suited for urban areas allowing a more detailed analysis of potential infiltration,

landuse and runoff changes within the watershed. Figure 1 depicts a one square mile subbasin in the Mill Creek Watershed with 10-acre grids superimposed on it.

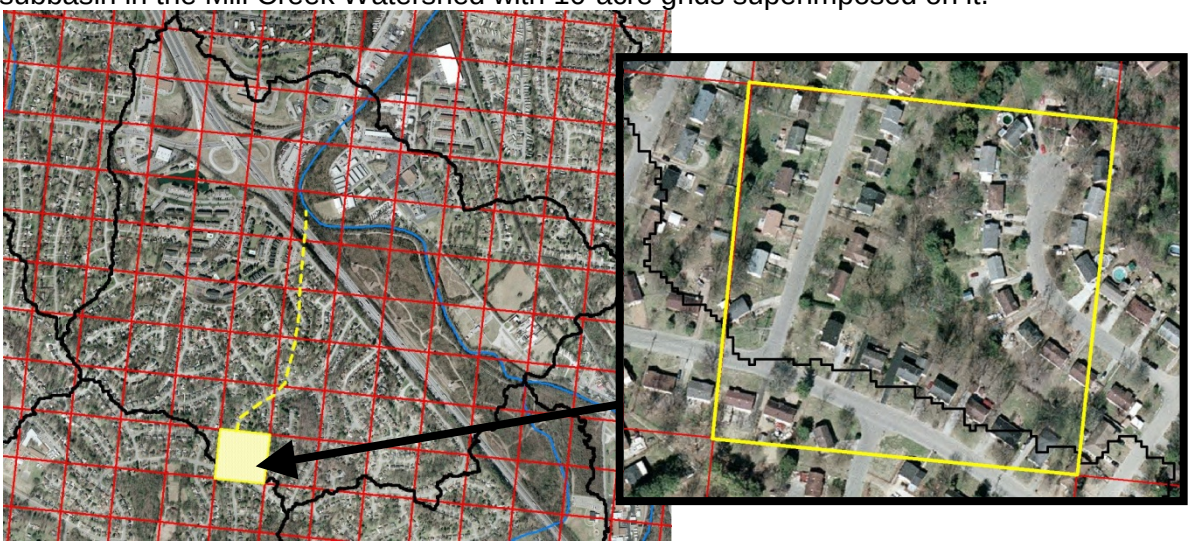


Figure 1: 10-acre grid cells superimposed on one square mile sub-basin

The runoff for each grid was routed independently to a sub-basin outlet. The model adjusted the timing for each grid hydrograph using a distance ratio multiplied by the time of concentration (Tc) of the sub-basin. For example, the grid shown in yellow is 1.3 miles to the sub-basin outlet. The maximum grid distance computed for the sub-basin is 2.4 miles. The travel time for the grid is 1.3 divided by 2.4, or 0.54Tc. A runoff hydrograph for each sub-basin was computed by adding the individual grid hydrographs. Both event and continuous simulation HEC-HMS (HMS) version 3.x models were developed. Continuous models account for the hydrologic cycle. Storm flow, evaporation, transpiration and baseflow are evaluated.

3.6 Hydraulic Modeling Analysis

About 50 miles of Mill Creek streams were evaluated for existing conditions including all tributaries with drainage areas greater than one square mile or addressed in existing flood insurance study. . The creek and tributaries were modeled using gradually varied steady flow simulation with peak flows computed by the HEC-HMS event model. The hydraulic models were calibrated to available high water marks for the May 1979, September 1979, and May 2003 floods. Frequency flood elevations, based on 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year frequency precipitation events and appropriate loss rate parameters, were calculated using HEC-RAS version 3.1.2. Floodways were computed for the 100-year event. The resulting elevations were transposed to flooded areas using HEC-GeoRAS version 3.1.1 and a detailed Triangulated Irregular Network (TIN). All data used for HEC-RAS modeling are referenced to the Tennessee State Plane Coordinate System and North American Vertical Datum (NAVD 88).

4.0 WATERSHED AND FLOODPLAIN MANAGEMENT EVALUATION

4.1 Watershed Development

The Mill Creek watershed was divided into 5 major zones (See Maps 2 and 3). Zones 1, 2, 3 and 4 lie within Davidson County and Zone 5 lies within Williamson County. Zones 1, 2 and 3 are very urbanized while zones 4 and 5 are less developed. The zones did provided a good separation of the watershed for GIS analysis. Davidson and Williamson

County data was combined into one GIS dataset (See Maps 2 and 3) similar to those used at the Metro/Davidson County Planning department. Two categories were added for right of ways (interstates, roads and easements) and open space within Williamson County. See the 2004 data presented in Tables 2 and 3.

Table 2: Land Use Categories in Mill Creek Watershed

LAND USE	**ZONE 1**	**ZONE 2**	**ZONE 3**	**ZONE 4**	**ZONE 5**
RIGHT OF WAY	16.2%	13.7%	11.5%	6.7%	3.2%
COMMERCIAL	4.9%	3.0%	2.8%	3.3%	0.4%
VACANT OR FARM	8.3%	9.7%	24.8%	36.1%	57.7%
COMMUNITY/INSTITUTIONAL/UTILITY	14.7%	5.4%	5.2%	1.4%	0.5%
OFFICE OR MEDICAL	8.3%	2.0%	1.7%	0.4%	0.0%
RESIDENTIAL - 1 UNIT	30.3%	52.4%	28.1%	43.6%	35.9%
RESIDENTIAL - 2 OR 3 UNITS	2.8%	2.4%	1.8%	0.9%	0.0%
INDUSTRIAL	9.9%	2.3%	14.1%	1.0%	0.1%
AUTO PARKING	0.6%	0.3%	0.1%	0.1%	0.0%
RESIDENTIAL - 4+ UNITS	3.5%	6.7%	8.6%	6.4%	0.0%
RESIDENTIAL - NON HOUSEHOLD	0.0%	0.0%	0.0%	0.0%	0.0%
PARK OR GOLF COURSE	0.3%	2.2%	1.2%	0.2%	0.0%
OPEN SPACE	0.0%	0.0%	0.0%	0.0%	2.3%

Table 3: Zoning Categories in Mill Creek Watershed

ZONING	**ZONE 1**	**ZONE 2**	**ZONE 3**	**ZONE 4**	**ZONE 5**
RIGHT OF WAY	16.2%	13.7%	11.5%	6.7%	3.2%
COMMERCIAL	6.7%	4.3%	3.1%	1.9%	0.4%
RESIDENTIAL - SINGLE FAMILY	39.8%	68.0%	45.8%	26.9%	33.8%
OFFICE	3.7%	1.9%	1.5%	0.2%	0.0%
AGRICULTURAL	10.8%	3.4%	22.8%	50.8%	59.8%
SHOPPING CENTER	0.1%	0.8%	0.5%	3.0%	0.0%
INDUSTRIAL	20.6%	2.2%	12.8%	2.8%	0.1%
RESIDENTIAL - MULTI FAMILY	2.2%	5.2%	1.9%	6.3%	0.0%
MIXED USE	0.0%	0.0%	0.1%	1.3%	0.0%
INSTITUTIONAL	0.0%	0.3%	0.0%	0.0%	0.4%
PARK OR GOLF COURSE	0.0%	0.0%	0.0%	0.0%	0.0%
OPEN SPACE	0.0%	0.0%	0.0%	0.0%	2.3%

Land cover was defined using hyperspectral imaging data collected in 2002 and 2003. Hyperspectral imaging collects electromagnetic radiation reflected from the earth's surface. Land cover was divided into four categories: impervious area (pavement, rock, and compacted stone), grass, trees, and disturbed (bare soil) areas. Land cover categories and percentages for the five major zones are listed in Table 4.

Table 4: Existing Land cover Classification

LAND COVER	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
IMPERVIOUS AREA	39%	30%	29%	13%	6%
GRASS	30%	29%	31%	40%	44%
TREES	30%	40%	39%	45%	48%
DISTURBED (BARE SOIL)	1%	1%	1%	2%	2%

4.2 Davidson County Build out Analysis

A build-out analysis for the Davidson County was performed using GIS data that summarized the residential and non-residential development potential. GIS data included typical Davidson County parcel data with six added fields:

Exist DU = Number of existing Dwelling Units on parcel
DU = the number of new dwelling units that could be added to parcel
Exist Comm = Amount of existing Commercial space (ft2)
Exist Empl = Number of existing Commercial employees
Retail = the number of new retail employees that could be generated
Non-Retail = the number of new non-retail employees that could be generated

Parcels available for development included green fields (vacant or farm) or underdeveloped parcels. Build out data was compared to existing GIS data to determine "build out potential" for each parcel. Five development categories were created:

1. No Change in Development – No change in dwelling units or employees
2. Residential Development – dwelling units increase
3. Non-Residential Development – number of employees increase
4. Residential and Non-Residential Development – dwelling unit and employees increase.
5. Right of Way

The percentage of each development category per watershed zone is listed in Table 5 and shown on Map 4.

Table 5: Davidson County Development Categories and Percent Build out

DEVELOPMENT CATEGORY	ZONE 1	ZONE 2	ZONE 3	ZONE 4
NO CHANGE	56%	53%	46%	24%
RESIDENTIAL	12%	25%	16%	35%
NON RESIDENTIAL	8%	2%	19%	4%
RESIDENTIAL AND NON-RESIDENTIAL	8%	6%	7%	30%
RIGHT OF WAY	16%	14%	12%	7%
PERCENT BUILDOUT	72%	67%	58%	31%

The "PERCENT BUILDOUT" values were computed by adding the "NO CHANGE" and "RIGHT OF WAY" rows and are representative of existing conditions. Although portions of residential and nonresidential parcels will eventually become right of way, it is impossible to determine at this time. Average percent imperviousness was computed in ArcMap for both developed and underdeveloped parcels and shown in Table 6 and 7.

Table 6: Percent Impervious for Developed and Underdeveloped Parcels by Land Use

Land Use	Average Percent Impervious (%)		
Category	All	Developed	Underdeveloped
Commercial	76	74	76
Community/Institutional/Utility	42	41	43
Industrial	77	82	72
Office or Medical	72	77	68
Residential - 1 Unit	22	27	18
Residential - 2 or 3 Units	29	30	22
Residential - 4+ Units	51	51	38
Residential - Non Household	34	34	34
Vacant or Farm	13	12	16
No Classification	11	12	10

Table 7: Percent Impervious for Developed and Underdeveloped Parcels by Zoning

Zoning	Average Percent Impervious (%)		
Category	All	Developed	Underdeveloped
Agricultural	8	11	7
Commercial	67	77	62
Industrial	68	80	62
Institutional	38	38	38
Mixed Use	12	11	13
Office	45	57	35
Residential - Single Family	21	28	18
Residential - Multi Family	46	48	20
Shopping Center	63	54	66
No Classification	14	15	7

In some instances, average conditions for underdeveloped parcels were more impervious than developed parcels per category. Build out imperviousness was computed for each zone by bringing its current imperviousness up to 100 percent buildout condition (See Table 8). Example calculation for Zone 3 is shown below:

$$\frac{\text{X\% Impervious}}{\text{100\% Build out}} = \frac{\text{29\% Impervious}}{\text{58\% Build out}}$$

Solving for X% Impervious,

$$X = 0.29/0.58 = 0.5 = 50\% \text{ Impervious}$$

Table 8: 100% Buildout Imperviousness

Watershed Zone	100% Buildout Imperviousness
ZONE 1	54%
ZONE 2	45%
ZONE 3	50%
ZONE 4	42%

4.3 Sensitivity to Changes in Imperviousness

Not all impervious surfaces are directly connected to the drainage system. The impact of runoff from impervious surfaces is reduced by runoff infiltrating directly into the soil or

flowing overland before entering the collection system. A gutter downspout draining to a lawn is an example of a disconnected impervious surface. The hydrologic model is a gridded model where each sub-basin is made up of multiple grids each having their own hydrologic properties two of which are impervious area and soil infiltration rate (constant loss rate). An option was created in HEC-HMS to allow the user to specify a multiplier to the parameter value in each grid. For example, one calculates the imperviousness of a contributing drainage area to be 25 of a total 50 acres. Grading and drainage plans and field inspection reveal that only 17 of the 25 acres are connected to the drainage system. One would apply a 0.68 multiplier (17/25) to the watershed or use GIS tools to evaluate each individual 10-acre grid.

A 25, 50, 75, and 100 percent impervious grid cell was analyzed to evaluate watershed sensitivity to imperviousness. Initial losses and infiltration rates used in the frequency rainfall-runoff simulation were used for this analysis. The analysis assumed that the timing of the 1-square mile sub-basin (Refer to Figure 1) did not change significantly with development. The results were compared to existing conditions discharges for gaged and ungaged locations in the watershed, and are presented in Table 9.

As annual exceedance probability increases (i.e., more frequent events), the watershed is more sensitive to imperviousness. The results show that as the drainage area increases, so does the impact of impervious surface. In other words, imperviousness has a cumulative impact as drainage area increases, or as you move downstream. The impact is lessened due to saturated soil conditions which occur during less frequent events. Note that Table 9 shows flow as a percentage. A ten percent flow increase on a small tributary like Turkey Creek equates to several hundred cubic feet per second (cfs) as compared to several thousand cfs on Mill Creek.

Calibration for the continuous simulation model for existing conditions showed that between 40 to 50 percent of the impervious surface in the watershed is directly connected to the drainage system. The watershed build out analysis (Table 8) resulted in an average imperviousness of approximately 50 percent for Davidson County. If 50 percent of this impervious surface is disconnected (based on the model calibration), a 25 percent impervious grid cell would best represent build out (future) conditions for Davison County. The same assumptions are made for Williamson County since detailed build out data is not readily available.

Table · ˙i ity to Imper i

		2 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	12%	24%	36%	48%
Mill Creek Nr Antioch Gage	64.2	12%	26%	40%	54%
Mill Creek at Nolensville Rd	40.5	11%	23%	35%	46%
Mill Creek at Sunset Rd	12.2	6%	13%	20%	27%
Sevenmile Creek at Mouth	17.6	4%	12%	21%	29%
Seven Mile at Blackman Rd	12.1	5%	13%	21%	30%
Collins Creek at Mouth	4.5	5%	12%	19%	26%
Indian Creek at Mouth	4.9	7%	14%	20%	28%
Sorghum Branch at Mouth	2.7	4%	12%	20%	28%
Whittemore Branch at Mouth	3.7	4%	12%	19%	26%

		5 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	5%	12%	18%	25%
Mill Creek Nr Antioch Gage	64.2	6%	13%	20%	27%
Mill Creek at Nolensville Rd	40.5	4%	8%	12%	17%
Mill Creek at Sunset Rd	12.2	2%	4%	5%	7%
Sevenmile Creek at Mouth	17.6	2%	5%	8%	11%
Seven Mile at Blackman Rd	12.1	2%	5%	7%	10%
Collins Creek at Mouth	4.5	1%	3%	5%	7%
Indian Creek at Mouth	4.9	2%	4%	6%	8%
Sorghum Branch at Mouth	2.7	2%	4%	7%	9%
Whittemore Branch at Mouth	3.7	2%	3%	4%	6%

		10 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	4%	8%	11%	15%
Mill Creek Nr Antioch Gage	64.2	4%	8%	13%	17%
Mill Creek at Nolensville Rd	40.5	3%	5%	8%	11%
Mill Creek at Sunset Rd	12.2	1%	3%	4%	5%
Sevenmile Creek at Mouth	17.6	1%	3%	4%	6%
Seven Mile at Blackman Rd	12.1	1%	3%	6%	8%
Collins Creek at Mouth	4.5	1%	2%	4%	5%
Indian Creek at Mouth	4.9	1%	3%	4%	6%
Sorghum Branch at Mouth	2.7	1%	3%	4%	6%
Whittemore Branch at Mouth	3.7	1%	2%	3%	4%

		25 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	2%	5%	9%	12%
Mill Creek Nr Antioch Gage	64.2	3%	6%	10%	13%
Mill Creek at Nolensville Rd	40.5	2%	4%	6%	8%
Mill Creek at Sunset Rd	12.2	1%	2%	3%	4%
Sevenmile Creek at Mouth	17.6	1%	2%	4%	5%
Seven Mile at Blackman Rd	12.1	1%	3%	4%	6%
Collins Creek at Mouth	4.5	1%	2%	3%	4%
Indian Creek at Mouth	4.9	1%	2%	3%	4%
Sorghum Branch at Mouth	2.7	1%	2%	3%	5%
Whittemore Branch at Mouth	3.7	1%	2%	3%	4%

		50 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	2%	5%	9%	13%
Mill Creek Nr Antioch Gage	64.2	3%	5%	8%	11%
Mill Creek at Nolensville Rd	40.5	2%	3%	5%	7%
Mill Creek at Sunset Rd	12.2	1%	2%	2%	3%
Sevenmile Creek at Mouth	17.6	1%	2%	4%	5%
Seven Mile at Blackman Rd	12.1	1%	2%	4%	5%
Collins Creek at Mouth	4.5	1%	2%	3%	3%
Indian Creek at Mouth	4.9	1%	2%	2%	3%
Sorghum Branch at Mouth	2.7	0%	2%	3%	4%
Whittemore Branch at Mouth	3.7	1%	1%	2%	3%

		100 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	1%	5%	8%	12%
Mill Creek Nr Antioch Gage	64.2	2%	5%	7%	10%
Mill Creek at Nolensville Rd	40.5	1%	3%	4%	6%
Mill Creek at Sunset Rd	12.2	0%	1%	2%	2%
Sevenmile Creek at Mouth	17.6	1%	2%	3%	4%
Seven Mile at Blackman Rd	12.1	1%	2%	3%	4%
Collins Creek at Mouth	4.5	1%	1%	2%	3%
Indian Creek at Mouth	4.9	1%	1%	2%	3%
Sorghum Branch at Mouth	2.7	0%	1%	2%	3%
Whittemore Branch at Mouth	3.7	1%	1%	2%	3%

		500 -Year			
		Mill Creek Watershed			
	Drainage	Peak Flow Increase above Existing Conditions			
Location	Area (Sq. Mi.)	25% Imp	50% Imp	75% Imp	100% Imp
Mill Creek at Thompson Lane	93.2	1%	4%	7%	9%
Mill Creek Nr Antioch Gage	64.2	2%	4%	6%	8%
Mill Creek at Nolensville Rd	40.5	1%	2%	3%	5%
Mill Creek at Sunset Rd	12.2	1%	1%	2%	2%
Sevenmile Creek at Mouth	17.6	0%	1%	2%	3%
Seven Mile at Blackman Rd	12.1	1%	1%	2%	3%
Collins Creek at Mouth	4.5	0%	1%	2%	2%
Indian Creek at Mouth	4.9	1%	1%	2%	3%
Sorghum Branch at Mouth	2.7	0%	1%	2%	2%
Whittemore Branch at Mouth	3.7	0%	1%	2%	2%

Note: Percent impervious is distributed uniformily across each subbasin. Constant loss rate parameter (infiltration rate) is in the range of 0.06 to 0.10 inches per hour for the frequency rainfall-runoff simulation. Initial loss (deficit) parameter is is the same as used for existing conditions.

4.4 Floodplain Management (Storage Analysis)

When flood flows exceed a channel's carrying capacity, water flows into overbank areas where it can be slowed greatly. This is commonly referred to as floodplain or valley storage. This storage can significantly attenuate the flood wave (hydrograph), especially on larger streams like Mill Creek. Most hydrologic models do not account for floodplain storage or its loss from development or placement of fill in a floodplain. The standard practice is to compute discharges, water surface profiles, and floodways based on existing conditions. A floodway is defined as the channel of a watercourse and the adjacent land areas that must be reserved to discharge the base flood (100 year) without cumulatively increasing the water-surface elevation by more than one foot. Past Corps of Engineers studies have addressed the significance of floodplain storage along Mill Creek. A 1996 study of storage analysis along Mill Creek concluded that compensating storage is required along Mill Creek above river mile 4.47.

For this analysis the floodplain storage was divided into 3 watershed zones called Nashville, Antioch and Nolensville (See maps 5, 6, or 7). The floodplain in the most downstream zone (Nashville) is urbanized with a combination of natural and man-made storage most of which is along Sevenmile and Mill Creeks. An example of man-made storage is backwater behind the CSX Railroad culvert over Sevenmile Creek. The middle zone (Antioch) has less floodplain development and abundant natural storage along Mill Creek's main stem. Some of the storage is in backwater areas at the confluences with tributary streams like Turkey and Collins Creeks. Most streams have some natural storage, but as the streams get smaller and steeper, storage becomes less significant in reducing flood elevations and attenuating flood waves. The upper zone (Nolensville) is less urbanized with natural storage along the headwater reaches of Mill and Owl Creeks, but as headwaters streams fan out, storage rapidly diminishes.

The Muskingum-Cunge and Modified Puls hydrologic routing methods were used in the hydrologic model to account for floodplain storage. These techniques have been shown to compare well against the full unsteady flow equations over a wide range of flow situations. They were calibrated to three continuous-recording gages having drainage areas of 40.5, 64.0, and 93.2 square miles and adequately reproduced observed hydrographs along Mill Creek. The main stem was divided into 23 reaches within Davidson County. Inflow hydrographs from the headwater reaches of Mill Creek and Owl Creek within Williamson County were also used. Each reach was defined using 8-point cross sections chosen to best represent the reach's geometry as shown in Figure 2. Reach length, slope and channel and overbank roughness (Manning's n) are specified at each section. The cross-section data was obtained from a combination of survey and LIDAR mapping.

The modified Puls routing method, also know as storage routing or level-pool routing, was used to route the upstream hydrographs along Sevenmile Creek, Sorghum Branch and Whittemore Branch. It used storage-outflow relationships computed from HEC-RAS models. Typical storage-outflow curves are shown in Figure 3. The Modified Puls method was used in lieu of Muskingum Cunge because the HEC-RAS model had an adequate number of cross-sections to define both the conveyance and storage characteristics of the tributaries. These tributaries also have several undersized structures that have significant backwater areas creating additional storage that would not be accounted for in a Muskingum-Cunge cross-section.

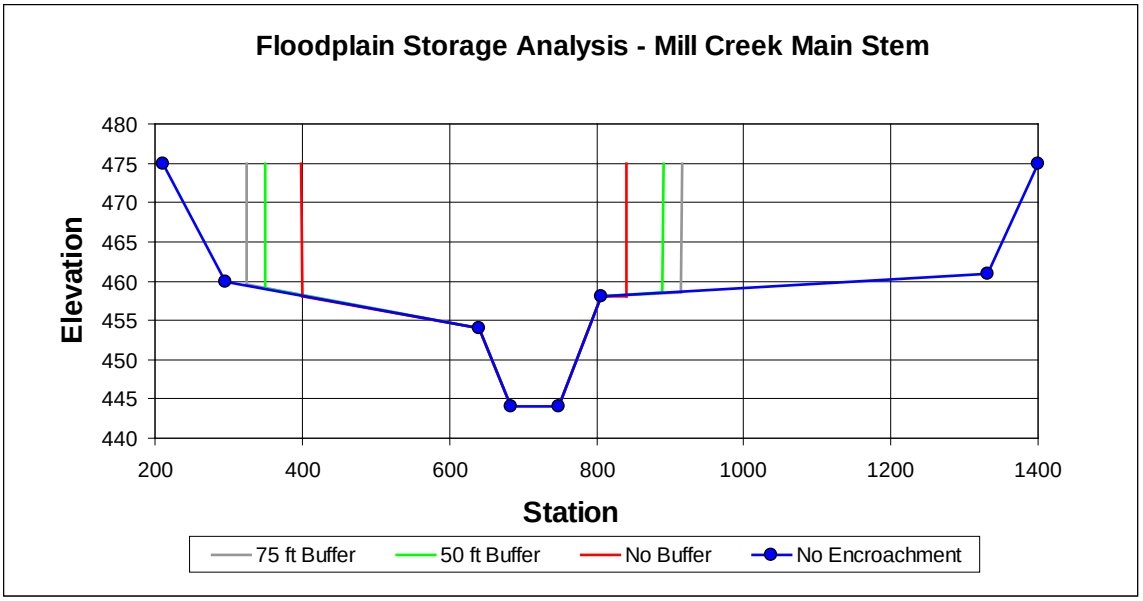


Figure 2: Floodplain Storage Graph – Mill Creek Main Stem

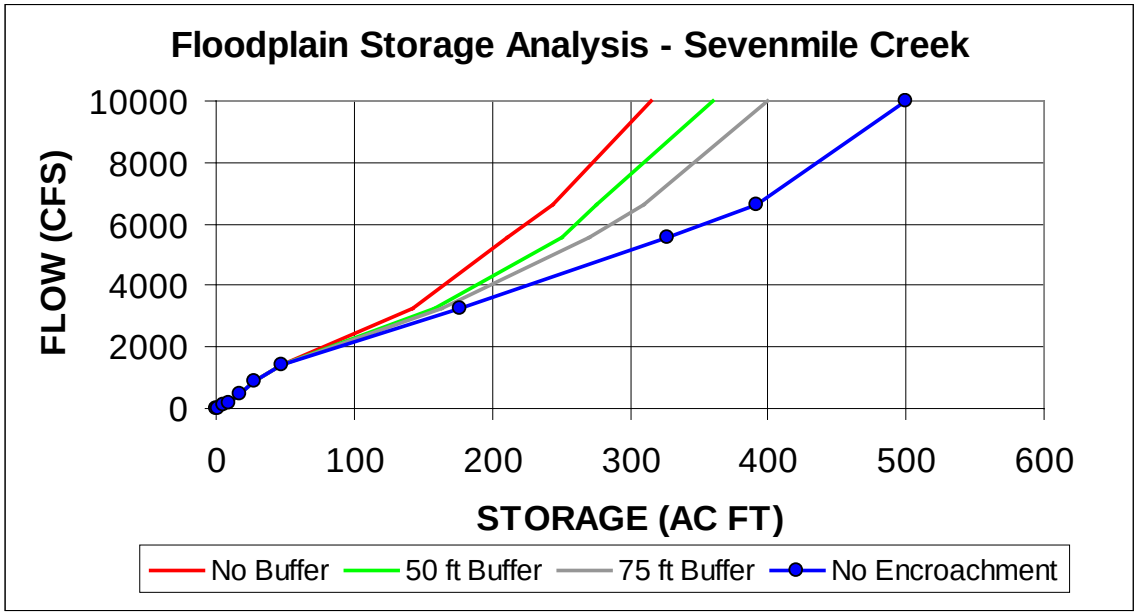


Figure 3: Floodplain Storage Graphs – Seven Mile Creek

Metro/Davidson County requires that all new development encumbered by natural floodplain or floodway, shall leave a minimum of fifty percent of the natural floodplain area, including all of the floodway area, or all of the floodway area plus 50 feet on each side of the waterway, whichever is greater, in its original, natural state. All floodplain alterations that result in filling or elimination of floodplain storage must provide compensating storage capacity by removing at least an equal amount of volume as occupied by the fill. Dredging or cut volumes below the 2-year flood elevation are not be included in the compensating storage capacity calculation. Metro's base flood and designated height are the 100-year event and one foot, respectively. Residential construction is required to have their lowest floor 4 feet above the base flood elevation.

Commercial, industrial, or non-residential construction is required to build their lowest floor one foot above the base flood elevation.

In Metro, new development and significant redevelopment are also required to preserve water quality buffers along intermittent and perennial streams, lakes and ponds with hydrologic connectivity, and wetlands that have been identified by the U.S. Army Corps of Engineers, Tennessee Department of Environment and Conservation (TDEC), or Metro Water Services (MWS) staff. Zone 1 for all buffers is considered a "no disturb zone" where vegetation cannot be disturbed, removed or replanted unless a buffer restoration plan has been approved by MWS. Zone 2 can consist of managed vegetation, meaning the buffer zone can be disturbed and planted with grass or other vegetation. However, no structures or impervious surface can be placed in Zone 2. For FEMA studied streams or streams with a drainage area greater than or equal to one square mile, the stream buffers are defined as Zone 1 = Floodway + 50 feet, and Zone 2 = 25 feet. An illustration of the 75 foot buffer for streams with floodways is shown in Figure 4.

The Williamson County portion of the Mill Creek Watershed includes mostly the Cities of Nolensville and Brentwood, Tennessee. Both the Cities of Nolensville and Brentwood have similar compensation storage regulations requiring at least an equal amount of compensation storage volume as occupied by fill. Nolensville has a 50-foot water quality buffer. Brentwood has no water quality buffers.

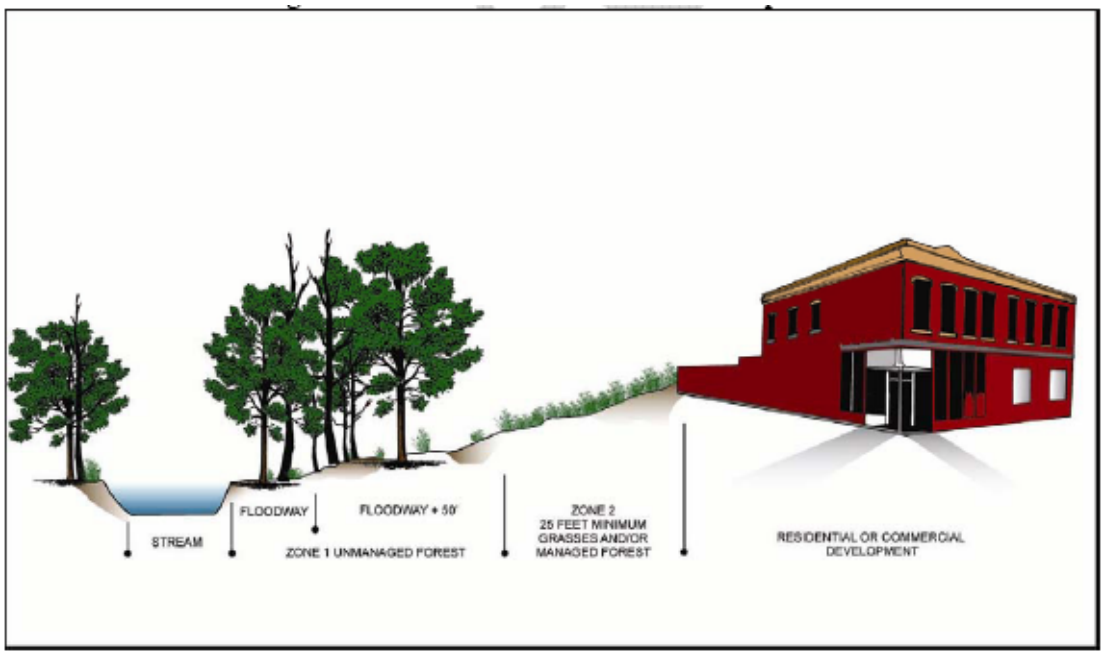


Figure 4: Buffer Example for Streams with Floodways

Compensation storage and stream buffers are not required by the Federal Emergency Management Agency (FEMA). FEMA accepts hydrologic and hydraulic studies that include the evaluation of floodplain storage. They recommend using standard hydrologic routing techniques like Muskingum-Cunge and Modified Puls methods or unsteady flow models for the floodplain storage evaluation.

Although Nolensville and Brentwood require compensation storage, the revised hydrologic models, developed for this study, show the discharges within Williamson County are significantly higher than published FIS values. For example, the FEMA published 100-year discharge at the mouth of Owl Creek is 7000 cfs, which is equivalent to the revised 10-year discharge. The FEMA published 100-year discharge for Mill Creek in Williamson County is equivalent to the revised 50-year discharge in this study. Some of this increase is due to development but the majority of the increase results from more stream gage information that included recently observed frequent events and allowed better calibration. The Mill Creek at Nolensville and Mill Creek near Nolensville gages helped in this determination. FEMA recently updated the FIS mapping for Williamson County, but the update does not include revised discharges. The lower discharge results in a smaller floodplain.

The Mill Creek models are sophisticated enough to evaluate hydrologic and hydraulic impacts from reduction in floodplain storage. To accomplish this, the Muskingum-Cunge cross-section geometry and Modified Puls storage curves were modified to reflect the loss of conveyance and storage (Refer to Figures 2 and 3). The red line represents conditions where fill is placed to the floodway without compensation and the blue line represents natural conditions. The 25 percent impervious watershed (which represents full build out) results with and without compensation (fill to floodway) storage are compared to existing conditions in Table 10. The 50 percent impervious watershed is also shown for reference.

Providing compensation for fill in the floodplain significantly reduces flood discharges particularly with the less frequent events which have higher discharges. For 2-year floods on the main stem, build out would increase discharges an average of 10 percent with compensation and 15-20 percent without compensation, a reduction of 5-10 percent. On the tributaries compensation lessens the increases caused by build out by 10-15 percent. For floods with greater discharges like the 100- and 500-year events, compensation lessens the increases caused by build out between 7 and 33 percent. The reductions provided by compensation are even more dramatic when the impervious area increases to 50 percent. Table 10 also shows that loss of floodplain storage increases peak discharge sometimes more than the increased imperviousness alone.

Table 10: Watershed Sensitivity to Floodplain Storage

		2 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	12%	13%	24%	28%
Mill Creek Nr Antioch Gage	64.2	12%	24%	26%	41%
Mill Creek at Nolensville Rd	40.5	11%	21%	23%	34%
Mill Creek at County Line	21.0	8%	15%	17%	24%
Owl Creek at Mouth	13.2	7%	20%	16%	30%
Seven Mile at Mouth	17.5	4%	18%	12%	28%
Seven Mile at Blackman Rd	12.1	5%	15%	13%	24%
Sorghum Branch at Mouth	2.7	4%	20%	12%	29%
Whittemore Branch at Mouth	3.7	4%	5%	12%	13%

		5 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	5%	12%	12%	20%
Mill Creek Nr Antioch Gage	64.2	6%	26%	13%	34%
Mill Creek at Nolensville Rd	40.5	4%	16%	8%	20%
Mill Creek at County Line	21.0	3%	10%	6%	13%
Owl Creek at Mouth	13.2	1%	14%	3%	16%
Seven Mile at Mouth	17.5	2%	18%	5%	21%
Seven Mile at Blackman Rd	12.1	2%	13%	5%	16%
Sorghum Branch at Mouth	2.7	2%	18%	4%	20%
Whittemore Branch at Mouth	3.7	2%	3%	3%	5%

		10 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	4%	14%	8%	21%
Mill Creek Nr Antioch Gage	64.2	4%	25%	8%	30%
Mill Creek at Nolensville Rd	40.5	3%	14%	5%	17%
Mill Creek at County Line	21.0	2%	10%	4%	12%
Owl Creek at Mouth	13.2	1%	15%	3%	17%
Seven Mile at Mouth	17.5	1%	20%	3%	22%
Seven Mile at Blackman Rd	12.1	1%	16%	3%	19%
Sorghum Branch at Mouth	2.7	1%	17%	3%	18%
Whittemore Branch at Mouth	3.7	1%	5%	2%	7%

		25 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	2%	26%	5%	31%
Mill Creek Nr Antioch Gage	64.2	3%	25%	6%	29%
Mill Creek at Nolensville Rd	40.5	2%	15%	4%	17%
Mill Creek at County Line	21.0	1%	10%	3%	11%
Owl Creek at Mouth	13.2	1%	14%	2%	16%
Seven Mile at Mouth	17.5	1%	25%	2%	27%
Seven Mile at Blackman Rd	12.1	1%	19%	3%	21%
Sorghum Branch at Mouth	2.7	1%	17%	2%	18%
Whittemore Branch at Mouth	3.7	1%	7%	2%	8%

		50 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	2%	31%	5%	36%
Mill Creek Nr Antioch Gage	64.2	3%	26%	5%	29%
Mill Creek at Nolensville Rd	40.5	2%	15%	3%	17%
Mill Creek at County Line	21.0	1%	10%	2%	11%
Owl Creek at Mouth	13.2	1%	14%	2%	15%
Seven Mile at Mouth	17.5	1%	27%	2%	29%
Seven Mile at Blackman Rd	12.1	1%	20%	2%	22%
Sorghum Branch at Mouth	2.7	0%	17%	2%	19%
Whittemore Branch at Mouth	3.7	1%	8%	1%	9%

		100 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	1%	33%	5%	37%
Mill Creek Nr Antioch Gage	64.2	2%	26%	5%	29%
Mill Creek at Nolensville Rd	40.5	1%	15%	3%	17%
Mill Creek at County Line	21.0	1%	9%	2%	10%
Owl Creek at Mouth	13.2	1%	13%	1%	14%
Seven Mile at Mouth	17.5	1%	28%	2%	30%
Seven Mile at Blackman Rd	12.1	1%	20%	2%	21%
Sorghum Branch at Mouth	2.7	0%	17%	1%	18%
Whittemore Branch at Mouth	3.7	1%	8%	1%	9%

		500 -Year			
		Mill Creek Watershed			
		Peak Flow Increase above Existing Conditions			
		25% Impervious Grid		50% Impervious Grid	
	Drainage	With	Without	With	Without
Location	Area (Sq. Mi.)	Compensation	Compensation	Compensation	Compensation
Mill Creek at Thompson Lane	93.2	1%	32%	4%	35%
Mill Creek Nr Antioch Gage	64.2	2%	28%	4%	30%
Mill Creek at Nolensville Rd	40.5	1%	15%	2%	16%
Mill Creek at County Line	21.0	1%	8%	2%	9%
Owl Creek at Mouth	13.2	0%	12%	1%	12%
Seven Mile at Mouth	17.5	0%	33%	1%	34%
Seven Mile at Blackman Rd	12.1	1%	24%	1%	25%
Sorghum Branch at Mouth	2.7	0%	17%	1%	18%
Whittemore Branch at Mouth	3.7	0%	10%	1%	11%

Note: Percent impervious is distributed uniformily across each subbasin. Constant loss rate parameter (infiltration rate) is in the range of 0.06 to 0.10 inches per hour for the frequency rainfall-runoff simulation. Initial loss (deficit) parameter is is the same as used for existing conditions. Without compensation column based on loss of conveyance and storage to floodway.

Metro also asked the Corps to evaluate flood reduction benefits from floodway and water quality buffers and other impacts beyond their control (i.e., Williamson County buildout). The following floodplain management alternatives were evaluated for future land use conditions:

1. Both Davidson and Williamson Counties provide Compensation Storage

2. Davidson County – 1:1 compensation storage provided
   Williamson County – Fill to floodway with no compensation storage

3. Davidson County - Fill to 75 ft floodway buffer with no compensation storage
   Williamson County – Fill to floodway with no compensation storage

4. Davidson County - Fill to 50 ft floodway buffer with no compensation storage
   Williamson County - Fill to floodway with no compensation storage

5. Davidson County - Fill to floodway with no compensation storage
   Williamson County - Fill to floodway with no compensation storage

As mentioned previously, future land use is defined as a 50 percent impervious grid with 50 percent connected imperviousness (i.e., 50% x 50% = 25% impervious grid). Average Water Surface Elevation increases above existing conditions for 10- and 100-year results are shown in Tables 11 and 12 for Davidson County. 100-year discharges and travel times for floodplain management alternatives (1), (2), and (5) are shown on Maps 5, 6, and 7 for the major streams in the watershed.

Table 11: Floodplain Management Alternative: 10-Year Results

	Floodplain Management Alternative				
Stream	Average WSEL Increase Above Existing Conditions				
Name	(1)	(2)	(3)	(4)	(5)
Mill Creek below Harding	0.3	0.3	0.7	0.8	1.1
Mill Creek above Harding	0.1	0.4	0.7	0.8	1.0
Sevenmile Creek below Blackman Rd			0.3	0.4	1.0
Sevenmile Creek above Blackman Rd			0.1	0.1	0.3
Whittemore Branch					0.2
Sorghum Branch					0.1

Table 12: Floodplain Management Alternative: 100-Year Results

	Floodplain Management Alternative				
Stream	Average WSEL Increase Above Existing Conditions				
Name	(1)	(2)	(3)	(4)	(5)
Mill Creek below Harding	0.2	0.6	2.3	2.6	3.0
Mill Creek above Harding	0.1	0.5	1.1	1.2	1.4
Sevenmile Creek below Blackman Rd			0.7	0.9	1.5
Sevenmile Creek above Blackman Rd			0.2	0.2	0.3
Whittemore Branch					0.2
Sorghum Branch					0.1

The main conclusion from the floodplain management analysis is that compensation storage is vital in maintaining flood stages and discharges and becomes even more important for larger streams. As the drainage area approaches 10 square miles, the average increase without compensation storage is one foot or more for both the 10- and 100-year events. Maximum increases are as much as 2.5 feet and 6 feet for the 10-year and 100-year events on Mill Creek and as much as 3 feet and 5 feet on Sevenmile Creek. Tables 11 and 12 show more of an impact below Harding Place for the 100-year event. Main stem and tributary hydrographs are additive as they combine. The increased impact below Harding Place is due to the main stem hydrograph arriving at Sevenmile Creek, the largest tributary, three hours earlier than existing conditions. Typical hydrographs along Mill Creek for the middle (Antioch) and lower (Nashville) zones are shown in Figures 5 and 6. Hydrograph peak, shape and timing are significantly altered as floodplain storage is reduced.

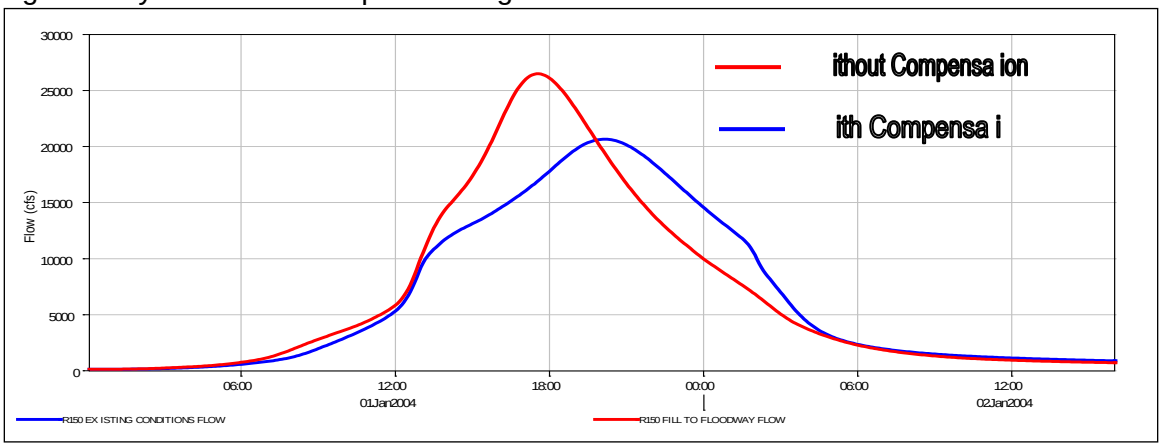


Figure 5: Middle (Antioch) Zone Typical Hydrograph

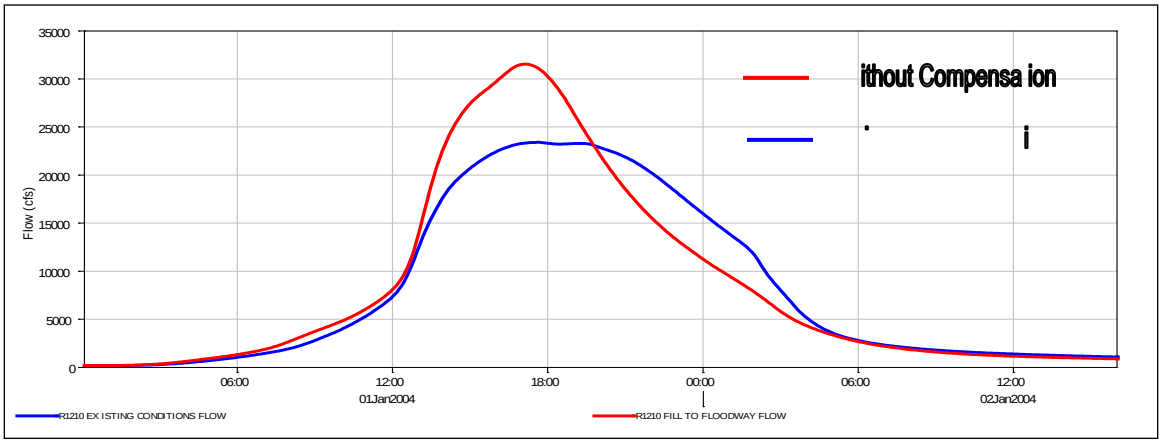


Figure 6: Lower (Nashville) Zone Typical Hydrograph

Flood damage reduction alternatives are compared to a future without project condition in Corps of Engineers' studies. The future without project condition for this study is based on watershed management alternative (2) which includes a continuation of existing policies in Davidson County and an assumption of no compensation in Williamson County because Metro does not regulate development within Williamson County and there is no plan to revise the discharges used in the FIS. The low discharges result in the regulatory flood plain being undersized and although Williamson

County does require compensation for fill in the floodplain, much of the area between the existing and potentially larger floodplain will fully develop without compensation before the new floodplains are defined. This is a rapidly growing part of the state.

Most flood damages along Mill Creek and its tributaries are a result of businesses and homes constructed before regulatory floodplains were established. Economic analyses determined Average Annual Damages (AAD) for existing conditions and each floodplain management alternative. Damages were computed for buildings within existing conditions 500-year floodplains in Davidson County. Existing condition AADs are present day and all floodplain management alternatives are 25 years in the future.

	AAD (in Millions)
Existing Conditions (Present Day)	$2.4 M
Floodplain Management Alternative	
(2) Future without Project Conditions (2031)	$3.6 M
(3) Fill to 75 ft Buffer No Compensation (2031)	$3.8 M
(4) Fill to 50 ft Buffer No Compensation (2031)	$4.0 M
(5) Fill to Floodway No Compensation (2031)	$4.6 M

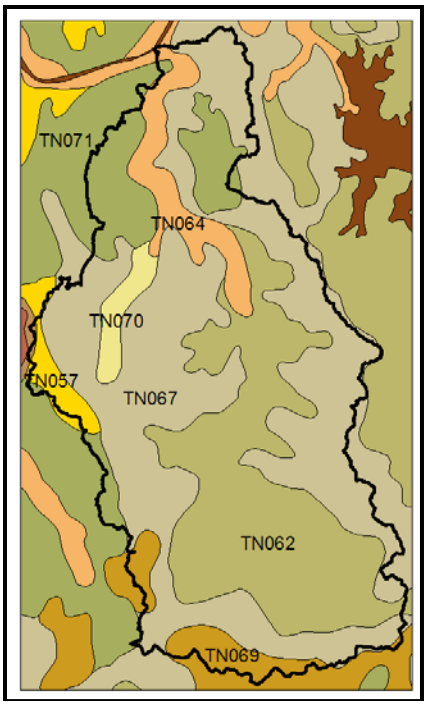
Future without project conditions result in a nearly 50 percent increase in AAD over 25 years. Providing no compensation storage or buffers nearly doubles AAD over 25 years. In other words, Metro is reducing AADs 50 percent by enforcing current stormwater regulations. They also plan to continue to remove repetitive loss residential homes from the floodplain, reducing damages even further. Currently, Metro does not remove non-residential structures from the floodplain.

5.0 INFILTRATION FOR ECOSYSTEM RESTORATION AND SUSTAINABILITY

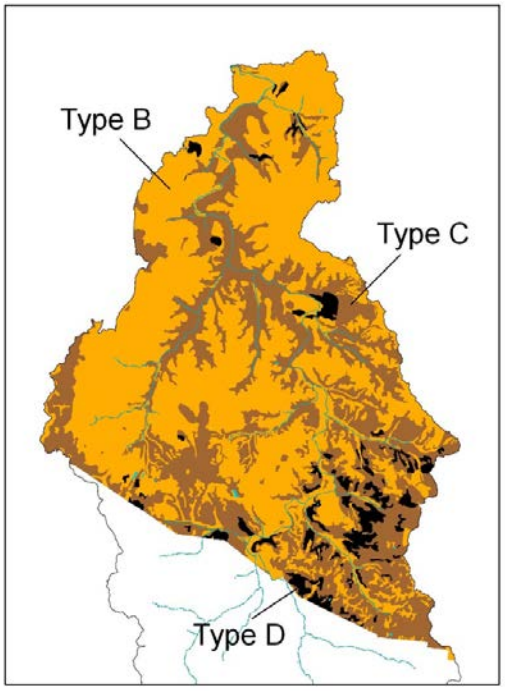
This section summarizes the infiltration and runoff characteristics of Mill Creek soils and discusses their suitability for infiltration measures for ecosystem restoration and environmental sustainability projects. These measures include infiltration ponds, rain gardens, and recharge, bio-retention, or seepage basins. They are designed to absorb stormwater by using the natural porosity and filtering ability of the soil and associated organic matter to infiltrate water and remove pollutants in runoff. This practice has high pollutant removal efficiency and recharges groundwater available to streams, thus helping to sustain aquatic life and maintain stream flow during critical periods.

5.1 Infiltration Characteristics of Mill Creek Soils

Soils data for the Mill Creek watershed was obtained from the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) database for Davidson County (Figure 7). Infiltration design guidelines recommend a minimum soil infiltration rate of 0.5 inches per hour, soil clay content of less than 30% and hydrologic soil groups A and B. A minimum of four feet from the infiltration basin bottom to the seasonal high water table and bedrock is also recommended to insure proper basin operation.



STATSGO



SSURGO

Figure 7: Soil Coverage for Mill Creek Basin

Mill Creek soils are shallow with low infiltration characteristics that present unique challenges to infiltration. They are predominantly type B, C, or D soils with Type B more abundant in Davison County and C and D in Williamson County. Type A and B soils have higher infiltration rates than type C and D soils. Saturated hydraulic conductivity was used to develop infiltration rates for the HMS model. The surface texture (SURFTEX) was found in the STATSGO database. Type B surface textures are mostly loams or silt loams. Type C soils are mixed clays, loams, silt loams, and silty clay loams. The percent saturation vs. hydraulic conductivity curves for different soil textures are presented in Figure 8. A loam has a saturated (100% saturation) hydraulic conductivity of 1 cm/hr that converts to 0.4 in/hr somewhat lower than recommended for optimum infiltration. Table 12 shows STATSGO characteristics for the upper 5 feet of soil. The lower percent clay value corresponds to the surface soil and the higher value corresponds to the soil at a depth of 5 feet. Bedrock is generally less than 5 feet and the water table ranges from 4 to 6 feet deep, which meet guidelines. While the Mill Creek Watershed does not meet optimum infiltration requirements, analysis revealed that it increases critical aquatic habitat during periods of low rainfall. It can help bridge the gap between rainfall events in the summer and fall.

Table 13: Mill Creek Soils Characteristics

Soil	Percent Clay	Depth to Water Table	Depth to Bedrock
TN057	18 to less than 60	4 to 6 feet	2 to 5 feet
TN062	15 to less than 50	4 to 6 feet	0 to 3 feet
TN064	20 to less than 35	4 to 6 feet	5 feet
TN067	20 to less than 50	6 feet	2 to 5 feet
TN069	8 to less than 60	4 to 6 feet	3 to 5 feet
TN070	12 to less than 60	3 to 6 feet	5 feet
TN071	12 to less than 60	6 feet	5 feet

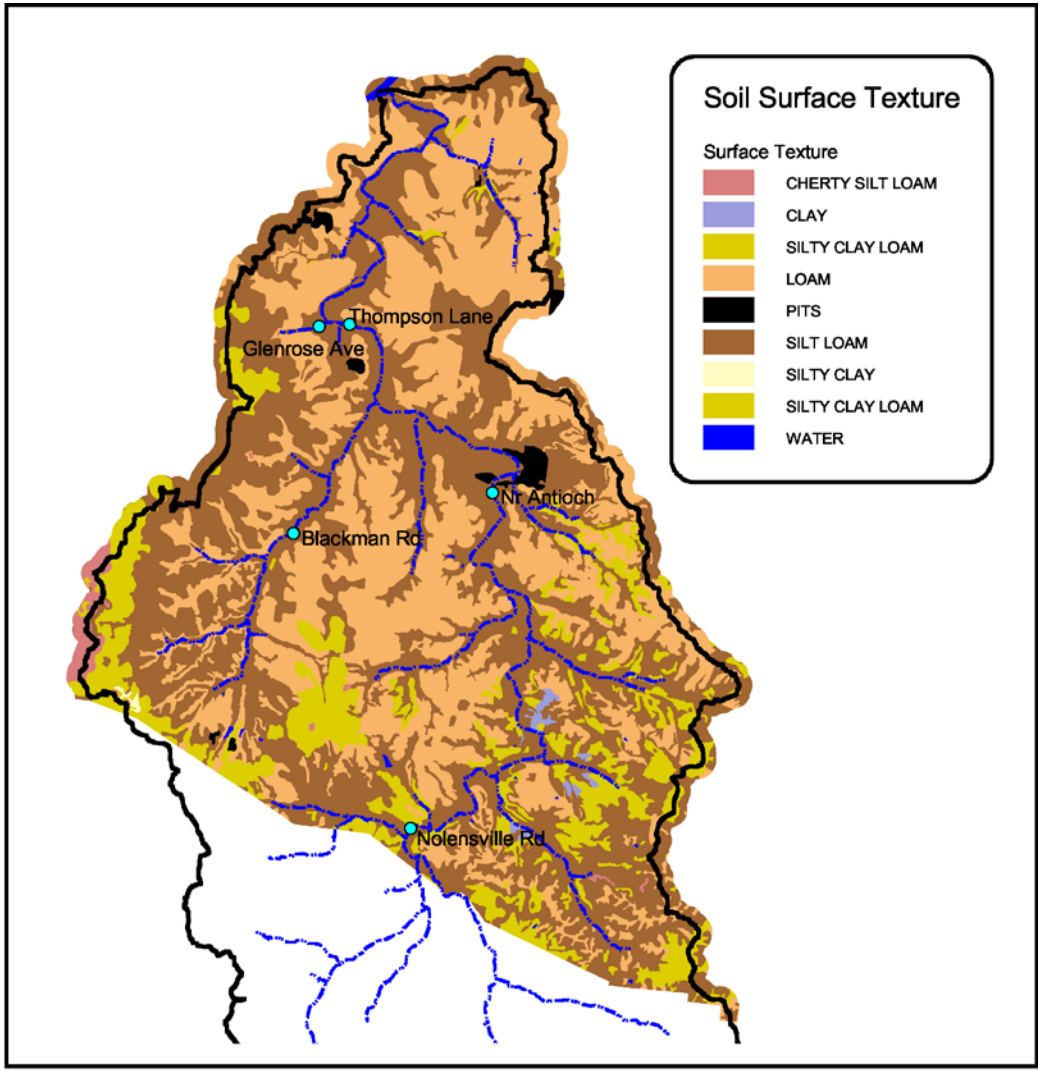
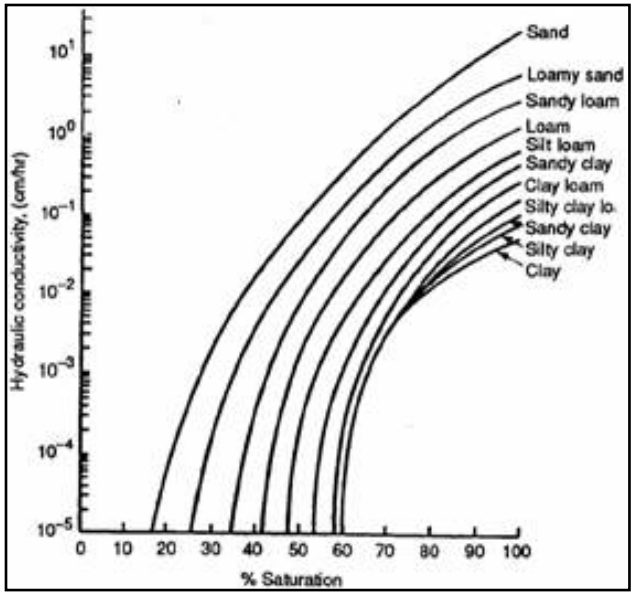


Figure 8: Soil Surface Texture



Saturated Hydraulic Conductivity

5.2 Continuous Simulation Hydrologic Model

A continuous simulation model was developed for Mill Creek to capture the potential benefits of ecosystem restoration measures. Unlike models used to define flooding and flood damage potential focus on maximum events, continuous simulation models capture the rainfall-runoff relationship over a longer, continuous period of time, such as a year. They capture seasonal variations, the wetting and drying of the soil and low flow events. They can be used to measure the effects of infiltration activities which capture a percentage of average annual runoff of the contributing drainage area. The infiltrated rainfall is expected to enter the water table or ground water and then reach the stream as baseflow overtime. Estimating baseflow (groundwater) and direct runoff is important to the design of the infiltration measure. Runoff, baseflow, and evaporation and transpiration are all important parts of the hydrologic cycle and a continuous simulation model. Evapotranspiration is the combination of water that evaporates from the land surface and water transpired by plants into the soil. In some areas of the country, up to 70 percent of precipitation is returned back to the atmosphere by evapotranspiration. It is one key to accurate, long term hydrologic simulation. Nine calibration periods were used to develop optimum model parameters for the Mill Creek continuous simulation model. Radar-rainfall data was used as the precipitation input. Other parameters from the HMS model developed for the stormwater analyses needed for the continuous simulation include the initial moisture conditions (initial deficit), maximum soil moisture conditions (maximum deficit), soil infiltration rate (constant loss rate), baseflow, and direct runoff from pervious and imperviousness surfaces. Initial deficit is dependent on antecedent moisture conditions or how dry the soil is at the beginning of simulation. An initial deficit of 1.5 inches is not unusual during summer months. Another way to consider the maximum deficit is the maximum amount of precipitation (measured in inches) that can fall on a watershed with no runoff. Calibration resulted in maximum deficits between 1 and 3 inches throughout the watershed. Soil infiltration rates ranged from 0.10 to 0.25 inches per hour for the watershed, which is about half the initial estimate of saturated hydraulic conductivity from Figure 8. When calibration data is not available, 0.5 times the saturated hydraulic conductivity of the surface soil layer would be a reasonable initial estimate of surface infiltration rate for Mill Creek soils.

Maintaining baseflow is important in sustaining a healthy ecosystem. HMS uses a linear reservoir method to route precipitation infiltrating into the soil as baseflow. It allows precipitation to infiltrate to baseflow only when the soil is completely saturated or the maximum deficit is reached. Precipitation that infiltrates into the soil is divided equally among two groundwater zones. A storage coefficient determines the rate at which water leaves the zone. A large storage coefficient results in water being released more slowly from the zone as compared to a small storage coefficient. For the typical Mill Creek one square mile sub-basin, one storage coefficient is set to a relatively small value of 10 hours to simulate the quicker responding “interflow” portion of a flood hydrograph. The other storage coefficient is set to a large value, 100 hours (approximately 4 days), to simulate the slower responding “baseflow” portion of the stream flow hydrograph. As shown in Figure 9, the baseflow hydrograph continues for days (possibly weeks) beyond the direct runoff portion of the hydrograph. Unfortunately, as a watershed develops, the length and volume of the baseflow hydrograph will diminish.

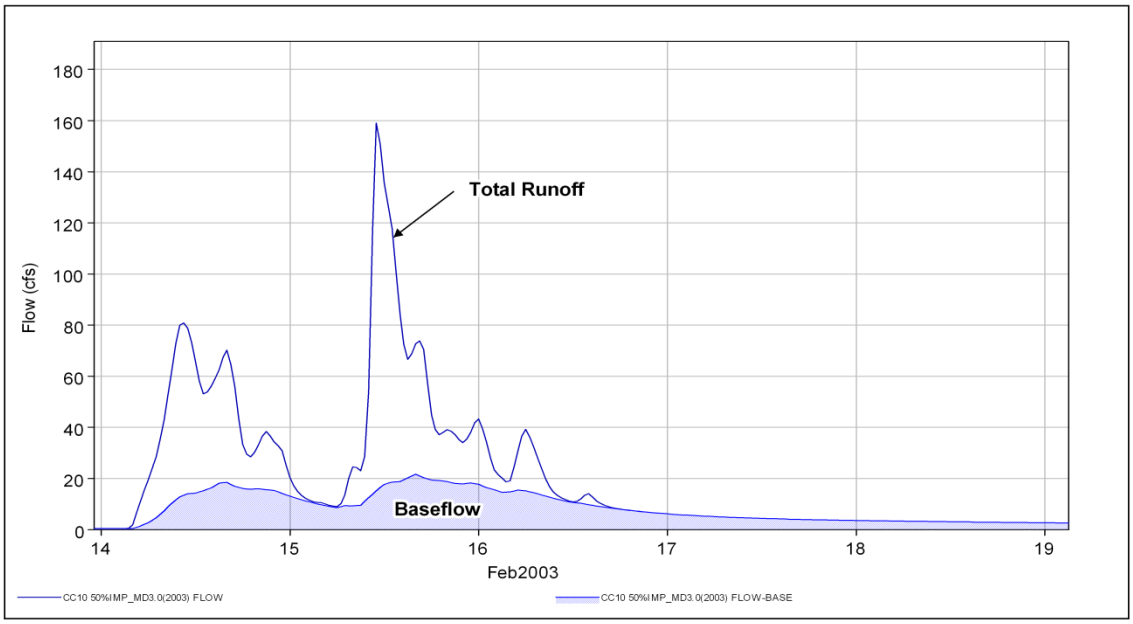


Figure 9: Runoff Hydrograph Depicting Baseflow

Figure 10 shows weekly potential evapotranspiration calculated in HMS using the Priestly-Taylor method and solar radiation and temperature. One week in July, up to 1.5 inches of precipitation was lost.

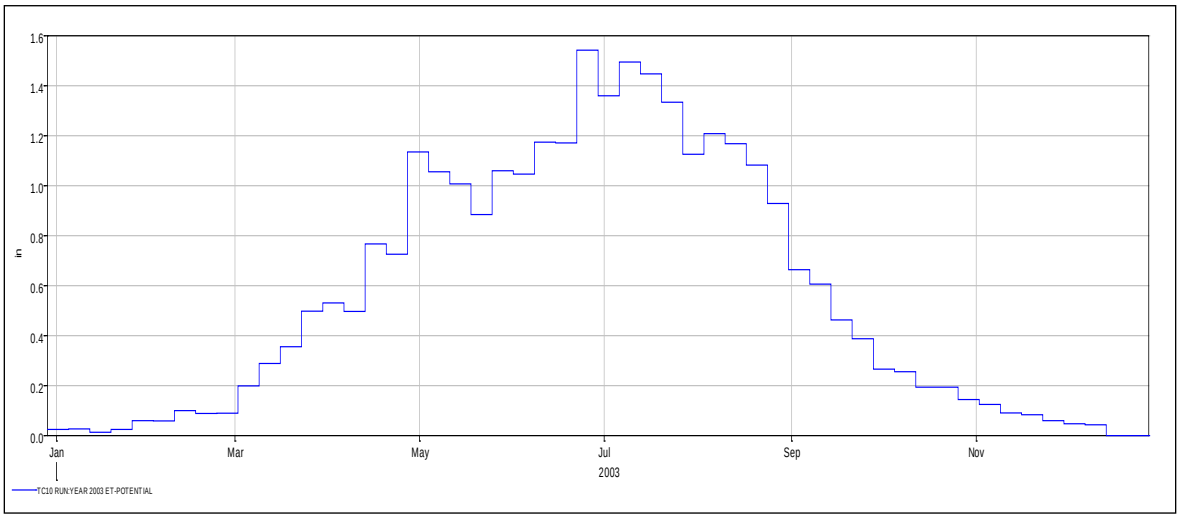


Figure 10: Weekly Potential Evapotranspiration in Inches

Figure 11 shows the cumulative observed rainfall and stream discharges during the summer of 2003 when between 6 and 7 inches of rain fell. Stream discharge at the Nolensville Road gage, with a drainage area of 40.5 square miles near the county line, is representative of runoff from Williamson County. Davidson County with its increased development and imperviousness is represented at the Thompson Lane gage just below Sevenmile Creek. The gage has a drainage area of 93.4 square miles. Davidson soils infiltrate more precipitation to groundwater than Williamson, but less than 10 percent returns to the stream as baseflow in both counties. About 50 percent of paved (impervious) surfaces were calibrated to directly connect to the drainage system.

Davidson produces twice the runoff with similar rainfall conditions compared to Williamson. Figure 11 demonstrates how little precipitation actually contributes to baseflow during hot, dry periods for watersheds like Mill Creek.

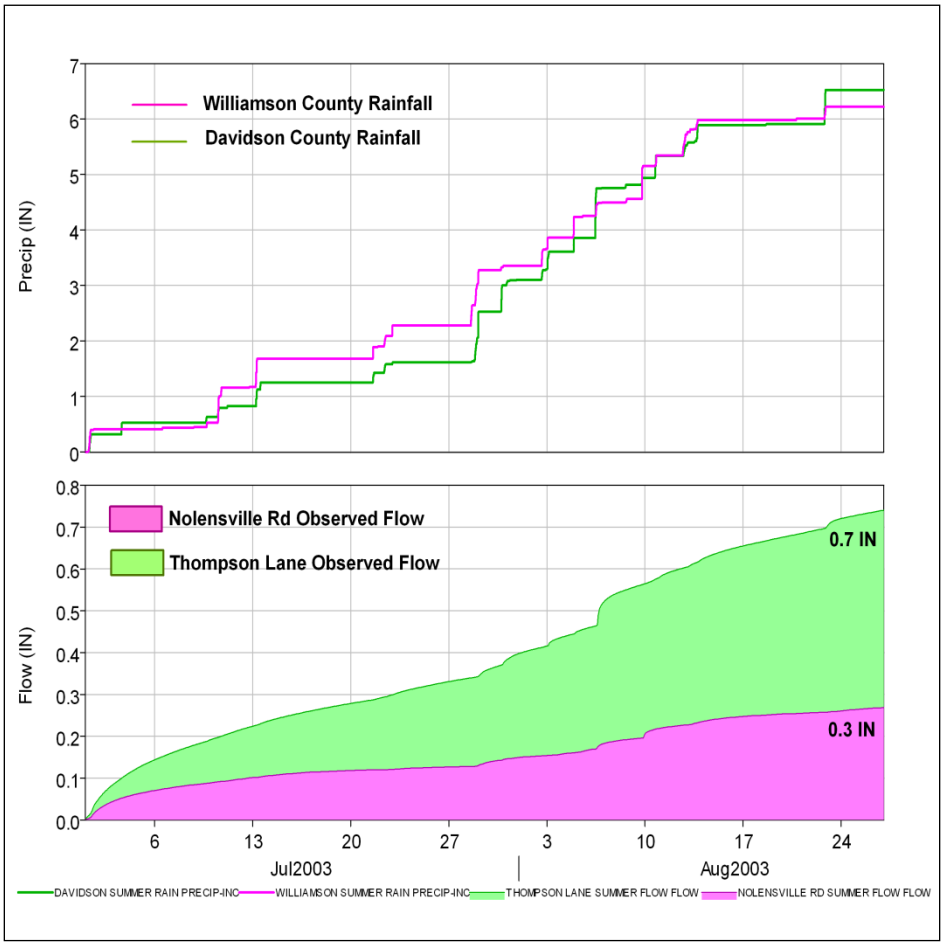


Figure 11: Observed Cumulative Rainfall and Discharge during summer 2003

Metropolitan Atlanta's rapid growth is associated with widespread degradation of aquatic habitats and water quality (Georgia Dept. of Natural Resources 1996; CH2M Hill 1998). Georgia State University and the USGS compared urban stream flow characteristics to those of less urbanized watersheds in the region. Other studies have shown that urban streams peak faster and higher during storms. This study determined that urban streams also recede faster which lowers summer baseflow.

Figure 12 demonstrates how HMS accounts for soil moisture. It shows calibrated results for a 1 year simulation for a Mill Creek soil having a maximum deficit of 2.5 inches. Saturated soil is 0 is on the y-axis. The simulation starts with an initial deficit of 1 inch (minus 1.0 inch on the y-axis). The soil continues to dry out to nearly 2 inches then precipitation occurs and the voids begin filling. When they are completely filled (i.e. moisture deficit is 0), precipitation can infiltrate to baseflow. Eevapotranspiration is different for each season. During winter months the change in moisture deficit is small (low ET). In the hot summer months, the change is rapid (high ET). In the example, the moisture deficit is not filled between June and October, thus, no precipitation infiltrates to

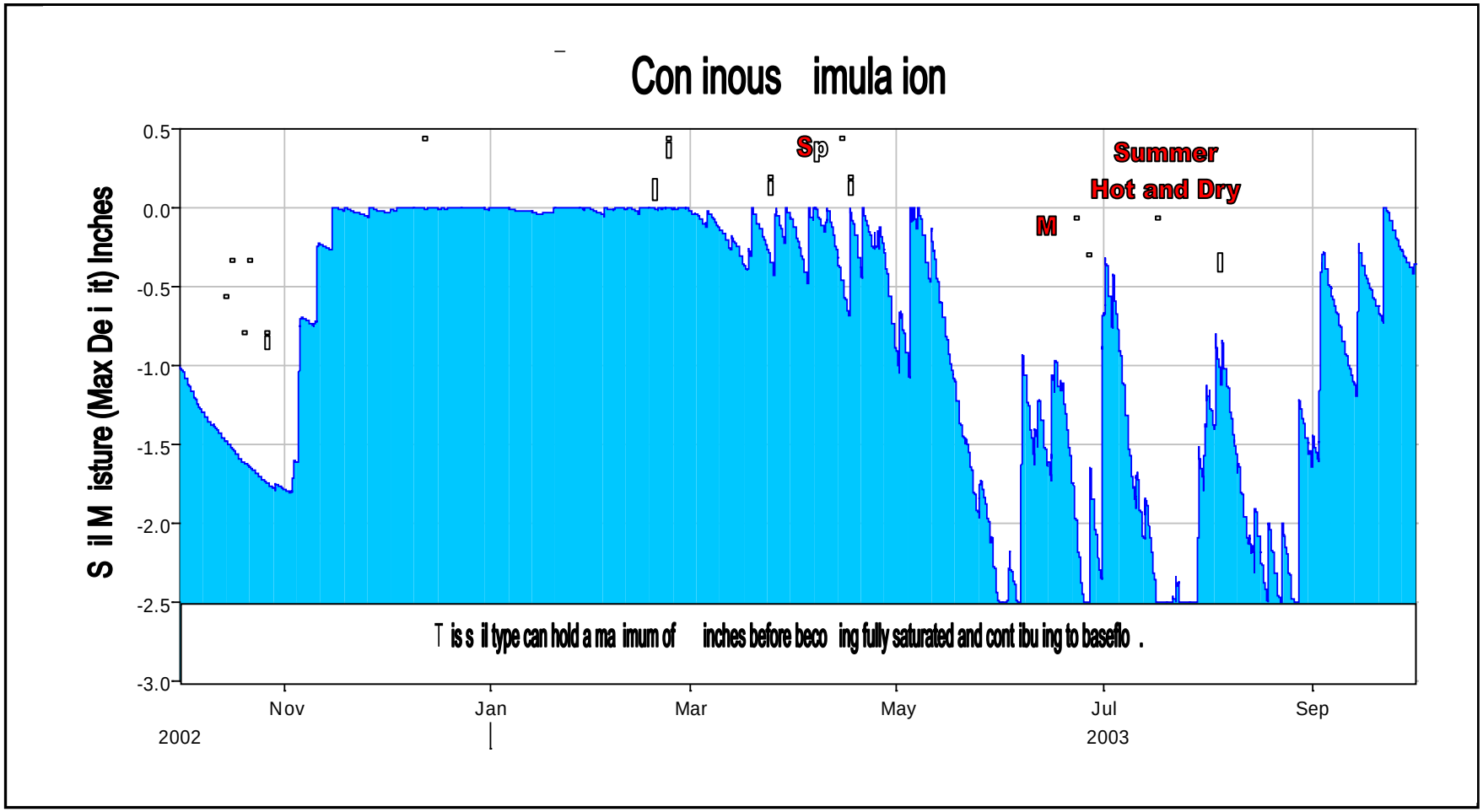


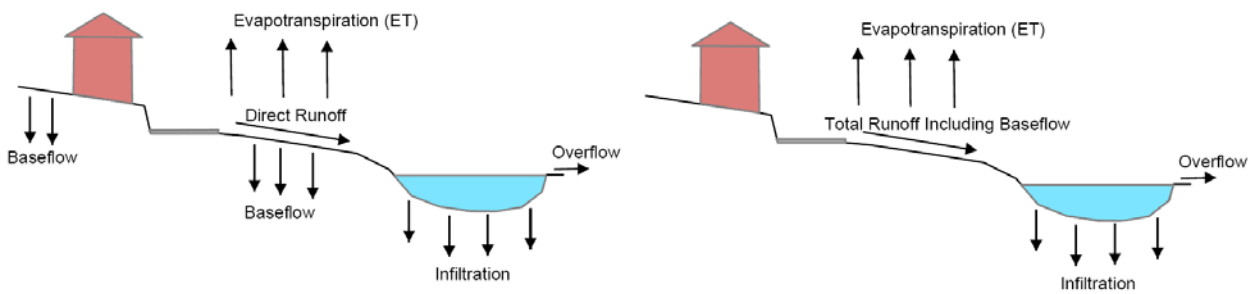
Figure 12: Soil Moisture Accounting in HMS

baseflow (i.e., no groundwater flow) during the summer months. This correlates with observed data shown in Figure 11.

5.3 Infiltration Demonstration Model

Davidson County's storm water quality regulations and guidelines include basic technical data for designing and sizing infiltration basins. For this study, an HMS model was developed for a 4-acre site. Runoff was routed through an infiltration basin based on the minimum design requirements. Typical Mill Creek soil and runoff characteristics were used for the contributing runoff development. The model encompassed an entire year to account for seasonal evapotranspiration and baseflow changes.

Infiltration rates of 0.1, 0.25, and 0.40 inches per hour were applied to the 4-acre watershed representing 2, 25, 50, 75 and 100 percent imperviousness. The 2 percent impervious watershed represents an undeveloped, natural condition. The 3 infiltration rates represent very low, low and moderate infiltration rates for soils. Both direct runoff (1) and total runoff (2) were routed independently through the infiltration basin.



Evapotranspiration and Infiltration

The infiltration basin was modeled as a simple storage area having the required water quality volume (WQv) and emptying time of 72 hours, the maximum time allowed by Metro's regulations. Runoff volumes exceeding the WQv overflow the basin and do not infiltrate to baseflow.

The following questions are evaluated:

Questions

1. What treatment volume (infiltration basin size) is required for a 25, 50, 75, and 100 percent impervious 4-acre watershed using Metro's new stormwater regulations?

2. How much evapotranspiration occurs during a typical year?

3. How much of the total runoff goes to baseflow for the different watershed conditions?

4. What is the annual stormwater runoff capture rate for the different watershed and infiltration conditions?

5. How do captured (treated) runoff volumes compare to that of natural baseflow?

6. How does baseflow change with Infiltration?

Water quality treatment measures are designed to capture 85% of the annual stormwater runoff, treat the runoff from the first 1.1 inches of rainfall, and detain water no longer than 72 hours. Water quality treatment volume (WQv) is based upon percent imperviousness of the contributing drainage area. Metro's water quality treatment volumes for the different watershed conditions are shown below:

$WQv_{(25\%\ Impervious)}$ = 3,920 cu. ft. ~ 36 ft x 36 ft x 3 ft deep
$WQv_{(50\%\ Impervious)}$ = 7,580 cu. ft. ~ 50 ft x 50 ft x 3 ft deep
$WQv_{(75\%\ Impervious)}$ = 11,280 cu ft. ~ 60 ft x 60 ft x 3 ft deep
$WQv_{(100\%\ Impervious)}$ = 14,940 cu. ft. ~ 70 ft x 70 ft x 3 ft deep

HMS model results for the yearly simulation are summarized in Table 13 and Figure 13. The annual precipitation for the simulation period is 55.9 inches, slightly higher than average for Nashville (48.1 inches). 26 inches (47 percent) was lost to ET for an undeveloped condition (2 percent imperviousness). There is no ET for the 100 percent impervious development. The 25, 50, and 75 percent developments had 20, 13, and 7 inches of precipitation going to evapotranspiration, respectively.

Baseflow for natural conditions ranges from 25 to 45 percent of annual precipitation for very low to moderate infiltration rates. Baseflow and ET combined account for 72 to 90 percent of annual precipitation for natural conditions. As development increases, baseflow drops accordingly. Also note that a development that is 50 percent impervious with moderate infiltration can produce as much baseflow as a natural condition with very low infiltration. This indicates that reducing the impervious area of a development or increasing infiltration at a site can prevent loss of baseflow. It also indicates that retrofitting and redevelopment can have an impact on the preservation of baseflow.

Because of the soils in the Mill Creek Watershed, an 85 percent capture rate cannot be achieved under any development or infiltration condition. Only 60 to 75 percent capture rates can be achieved using Metro's minimum guidelines. The low infiltration properties of Mill Creek soils produce more direct runoff, thus computed water quality treatment volumes may be low, especially for developments with lower imperviousness.

For all scenarios, baseflow plus treated runoff volume exceeds the baseflow for natural conditions which is encouraging. Separating the baseflow portion of the hydrograph (direct runoff vs. total runoff) does not have a significant impact on capture rates, but becomes more substantial as infiltration rates and drainage area increases.

Average daily and cumulative baseflow results are shown in Figure 13 for a one year simulation. The results show no baseflow between June and August. As expected, ET during summer months removes most of the moisture from the soil, thus eliminating baseflow. Precipitation must fill the soil moisture deficit before baseflow can occur. Infiltration increased days with baseflow from 159 to 276 days, mostly between June and September. Infiltration basins added nearly 10 weeks of baseflow during summer months. If only half of this is achieved, significant improvements in water quality and habitat survival would occur. The cumulative impacts to baseflow and water quality could be significant. Figure 13 shows the results for soils with very low infiltration rates. Benefits would further increase in watersheds with higher infiltration rates.

Table 13: Infiltration Model Results

4 ACRE DEVELOPMENT (Very Low Infiltration Rate = 0.10 in/hr)

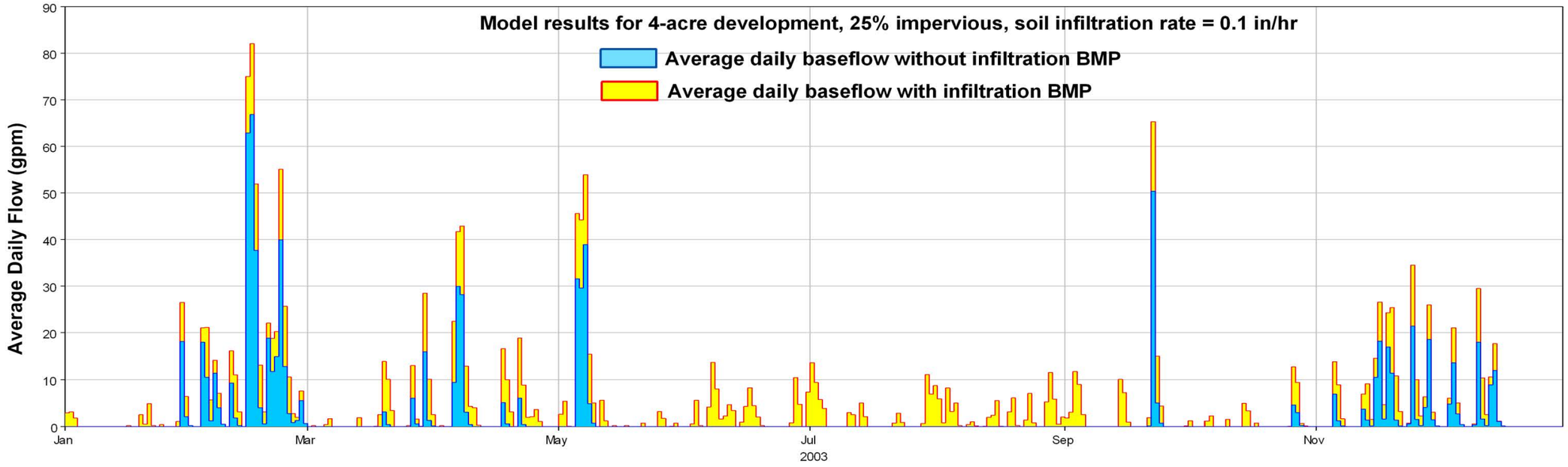
Development Imperviousness (%)	Total Precipitation (inches)	Total Precipitation Loss (inches)	Total ET (inches)	Total Baseflow (inches)	Total Direct Runoff (inches)	Total Flow (inches)	(1) Direct Runoff Capture (%)	(2) Total Runoff Capture (%)	Direct Runoff Treated (inches)	Total Runoff Treated (inches)
2	55.9	40.0	25.7	14.3	15.9	30.2	**N/A**	**N/A**	N/A	N/A
25	55.9	30.6	19.7	11.0	25.3	36.2	**50.0**	**45.0**	12.6	16.3
50	55.9	20.4	13.1	7.3	35.5	42.8	**64.0**	**61.0**	22.7	26.1
75	55.9	10.2	6.6	3.7	45.7	49.4	**72.0**	**70.0**	32.9	34.5
100	55.9	0.0	0.0	0.0	55.9	55.9	**75.0**	**75.0**	41.9	41.9

4 ACRE DEVELOPMENT (Low Infiltration Rate = 0.25 in/hr)

Development Imperviousness (%)	Total Precipitation (inches)	Total Precipitation Loss (inches)	Total ET (inches)	Total Baseflow (inches)	Total Direct Runoff (inches)	Total Runoff (inches)	(1) Direct Runoff Capture (%)	(2) Total Runoff Capture (%)	Direct Runoff Treated (inches)	Total Runoff Treated (inches)
2	55.9	47.2	25.7	21.5	8.7	30.2	**N/A**	**N/A**	N/A	N/A
25	55.9	36.2	19.7	16.5	19.8	36.2	**58.0**	**47.0**	11.5	17.0
50	55.9	24.1	13.1	11.0	31.8	42.8	**69.0**	**62.0**	21.9	26.5
75	55.9	12.1	6.6	5.5	43.9	49.4	**73.0**	**70.0**	32.0	34.5
100	55.9	55.9	0.0	0.0	55.9	55.9	**75.0**	**75.0**	41.9	41.9

4 ACRE DEVELOPMENT (Moderate Infiltration Rate = 0.40 in/hr)

Development Imperviousness (%)	Total Precipitation (inches)	Total Precipitation Loss (inches)	Total ET (inches)	Total Baseflow (inches)	Total Direct Runoff (inches)	Total Flow (inches)	(1) Direct Runoff Capture (%)	(2) Total Runoff Capture (%)	Direct Runoff Treated (inches)	Total Runoff Treated (inches)
2	55.9	50.4	25.7	24.7	5.5	30.2	**N/A**	**N/A**	N/A	N/A
25	55.9	38.6	19.7	18.9	17.3	36.2	**65.0**	**50.0**	11.3	18.1
50	55.9	25.7	13.1	12.6	30.2	42.8	**72.0**	**62.0**	21.7	26.5
75	55.9	12.9	6.6	6.3	43.1	49.4	**75.0**	**70.0**	32.3	34.5
100	55.9	0.0	0.0	0.0	55.9	55.9	**75.0**	**75.0**	41.9	41.9



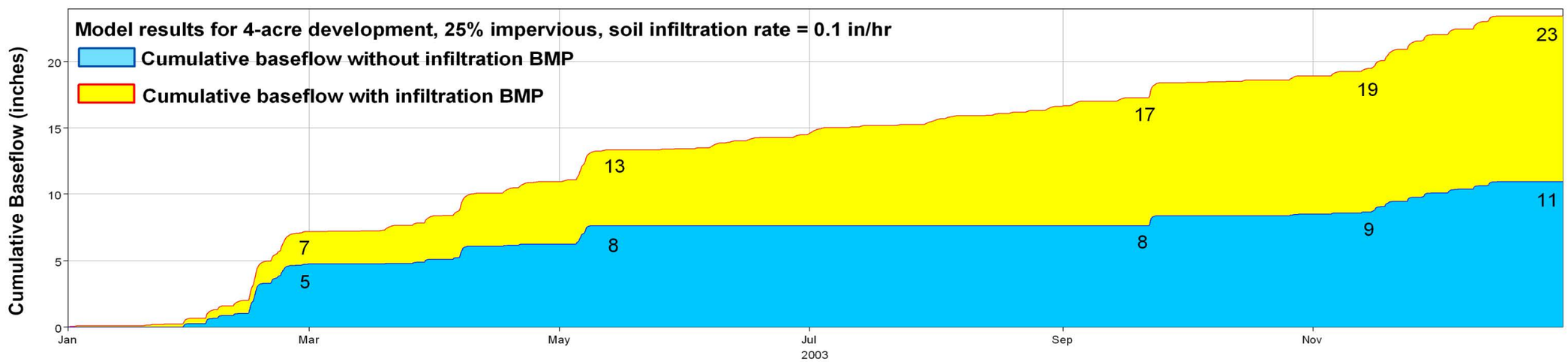


Figure 13: Average Daily and Cumulative Baseflow Results

5.4 Success Stories of Infiltration in the Mill Creek Watershed

Stormwater management measures like rain gardens are gaining acceptance at the state and local levels in Middle Tennessee. The Tennessee Department of Agriculture (TDA) along with watershed groups like the Cumberland River Compact, Mill Creek Watershed Association and Harpeth River Watershed Association have created educational programs about infiltration and low impact development (LID) practices. Metro has recently updated their stormwater regulations to encourage low impact development.

Dodd Galbreath, formerly with TDA, led efforts to implement demonstration Best Management Practices (BMPs) at the Ellington Agricultural Campus which is home to TDA and located along Sevenmile Creek. Sevenmile Creek, the largest tributary to Mill Creek, may offer the best water quality improvement opportunity in Tennessee. Ellington is also the home base for the state's "stormwater runoff" program. BMP construction at Ellington includes commercial and residential scale rain gardens, infiltration swales, pervious concrete parking lots, pervious paving strips and retention islands to intercept parking surface flow, rain barrels, land conversion projects, riparian buffer widening and stream and floodplain restoration projects. Ellington provides working examples of BMPs.

Stormwater monitoring was performed before, during, and after construction of infiltration BMPs at Ellington. In 2005, the initial monitoring equipment was installed by the Nashville District Corps of Engineers and TDA. The equipment included a continuous recording rain gage, flow measurement weirs, and instrumentation. Several wet weather events were measured during the spring of 2005 to determine infiltration and runoff characteristics of the campus. The soils at Ellington are predominantly B type soils in the Stiversville loam and Maury silt loam STATSGO groups. Average clay content for these soils is between 20 to 40 percent. The depth to the water table and bedrock is 5 to 6 feet. HEC-HMS models determined infiltration and runoff characteristics. Model calibration resulted in soil infiltration rates between 0.1 and 0.2 inches per hour.

The infiltration basin at Ellington included mixing sand and organic materials like mulch with native soils and planting native vegetation with root systems that absorb nutrients and stormwater runoff. Several of the Ellington rain gardens are shown below. Infiltration rates of the Ellington rain gardens vary but have exceeded 0.5 inches per hour. The infiltration rates have increased over time as the rain gardens mature. The volumes of the infiltration basins at Ellington are slightly larger than Metro's water quality volume requirements, but preliminary modeling resulted in annual stormwater runoff capture around 80 percent for conditions similar to those found at Ellington.

Residential Scale Rain Garden

Commercial Scale Rain Garden

The Mill Creek watershed is expected to reach 50 percent imperviousness in the next few decades and it is not ideal for infiltration based on soil characteristics alone. Soils are shallow having low moisture retention and infiltration properties. Even under natural conditions, baseflow contribution is low and the production of more direct runoff is part of the natural ecosystem. However, modeling shows that properly designed infiltration projects, including rain gardens, could significantly improve baseflow in Mill Creek during the summer and fall. They can significantly increase the number of days that rainfall contributes to Mill Creek's baseflow. To maintain a sustainable ecosystem both baseflow and runoff should be considered when designing stormwater measures. Projects like those at Ellington provide excellent examples in the Mill Creek watershed.

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