

Dumbarton Oaks Park Hydrologic Analysis Update, September-November 2011

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National Park Service Maps prepared by Joe Kish, Rock Creek Park

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Executive Summary

Dumbarton Oaks Park encompasses 27 acres of a sloping stream valley in the Georgetown area of Washington, District of Columbia. It is a naturalistic landscape designed by landscape architect Beatrix Jones Farrand during 1921-1940. The Dumbarton Oaks watershed is approximately 208.6 acres in size, draining to Rock Creek that drains to the Potomac River and Chesapeake Bay. Most of the Dumbarton Oaks watershed acreage has been developed with impervious surfaces covering 31% of the effective watershed. Development included the installation of sanitary and storm sewer piping, reducing the size of the area contributing runoff to the Dumbarton Oaks stream to 135.7 acres. The runoff from the Dumbarton Oaks Park neighboring properties causes flash flooding in the park that exceeds the flow capacity of the designed water fall structures, even for low precipitation events. This flash flooding has resulted in extensive erosion of soil/slopes and damage to the in-stream structures. Invasive plants have degraded much of the original designed landscape and continue to threaten the native trees, brush and plants that remain.

The objectives were (1) to update the Greenhorne & O'Mara, Inc. *Dumbarton Oaks – Phase I Hydrologic Study* (1999) for more recent development and (2) to evaluate the actual watershed response and runoff flow rates from precipitation. Re-development activities included stormwater improvements that significantly reduced runoff volumes from Jelleff and Safeway properties. Field observations indicate that no one property is the sole source of high flows, but collectively all of the surrounding properties contribute runoff into the Dumbarton Oaks Park. With regard to the second study objective, precipitation amounts were low and did not provide the 1.8 inches needed for the minimum 6-month storm water design volume. However, the precipitation was sufficient to document that stream flow of 2.4 cubic feet per second from 0.74 inches over 11 hours exceeded the flow capacity of 6 of the 18 park water fall structures. Stage and discharge data indicate runoff peaks approximately two hours for unsaturated soil conditions and 18-23 minutes for saturated soils after precipitation ends.

With sufficient precipitation, short-lived “voluntary tributaries” start flowing and follow the bare soil park trails where additional sediment is eroded from trail use during rain events. Some of the stream sediment comes from properties outside the park. Eroded sediment has accumulated in the pools and slower flowing sections of the stream, reducing stream water storage capacity. Optimum water storage capacity is critical to reduce flow velocities and to buffer flash flooding.

The time of concentration is the most significant difference between 1999 and 2011. If the stream results for the low observed precipitation events indicate the water collects faster than the estimates, the time will likely be even shorter for heavy rainfall.

During baseflow periods, the 30" headwaters pipe is most significant source of water into the Dumbarton Oaks Park, intermittently supplemented by low discharges from the Dumbarton Oaks 12" green pipe and the Georgetown University Building 18" pipe.

During the Fall 2011 precipitation events, the water sources in order of total volume would be the 30" pipe, the 12" pipe and its overland flow down the Pebble Stream, the stone-lined crossing, the Naval Observatory/Embassy of New Zealand runoff, and the 6" cast iron pipe. No storm event observations were made at the 18" pipe to include it in the above ranking due to its late discovery on 11-29-2011. Although no discharge measurements were made at the 12" green pipe, it is ranked higher than the stone-lined crossing because of the co-located overland flow (also too shallow to measure) and the longer flow duration.

Recommended actions for the Dumbarton Oaks Park and neighbors include the following: removal of accumulated stream sediment, repair and revegetation of eroded areas, trail hardening/separation of runoff flow from foot traffic, and storm water retention/treatment for all neighboring properties. Storm water retention solutions will require "overdesign" beyond regulatory requirements to protect the undersized historical waterfall structures. Storm water treatment will reduce the sediment load and improve stream water quality. Redesign of the historic water falls to increase their flow capacity should also be considered as such action would decrease storm water impacts.

Introduction and Purpose

Dumbarton Oaks Park (DOP) encompasses 27 acres of a sloping stream valley in the Georgetown area of Washington, District of Columbia (DC). It is a naturalistic landscape designed by landscape architect Beatrix Jones Farrand during 1921-1940 (Joseph et al, 2000). The Dumbarton Oaks watershed is approximately 208.6 acres in size, draining to Rock Creek that drains to the Potomac River and Chesapeake Bay. Most of the Dumbarton Oaks watershed acreage has been developed. Development included the installation of sanitary and storm sewer piping (Personal communication, Jessica Demoise, DC Water and Sewer). Impervious surfaces associated with development increase the rate and volume of runoff into streams, resulting in runoff peaks two to eight times higher than the pre-development peaks (Anderson, 2001). The runoff from the Dumbarton neighboring properties causes flash flooding in the park that exceeds the flow capacity of the designed water fall structures. This flash flooding has resulted in extensive erosion of soil/slopes and damage to the in-stream structures. Forest and grasslands cover the Dumbarton Oaks Park property and moderate some of this runoff. Invasive plants have degraded much of the original designed landscape and continue to threaten the native trees, bushes and plants that remain.

The purpose of this work is to update the Greenhorne & O'Mara, Inc. *Dumbarton Oaks – Phase I Hydrologic Study* (1999) for more recent development and to evaluate the actual watershed response and runoff flow rates from precipitation. The more recent re-development may have increased the amount of impervious surface and the volume of runoff entering the park. The re-development may have also included stormwater improvements that slow or reduce the volume of runoff. In addition, watersheds do not always behave/deliver runoff volumes and timing as predicted by stormwater models. The Greenhorne & O'Mara report used the United States Department of Agriculture (USDA) Soil Conservation Service (now National Resource Conservation Service) Hydrology Model TR-20 to predict runoff rates and maximum flow volumes for various amounts of precipitation. TR-20 is the standard model used for estimating flows for stormwater engineering designs. Basin-specific stage and discharge data will be collected to determine how the Dumbarton Oaks basin responds to precipitation events of differing conditions. Differing conditions can include unsaturated soils, saturated soils and rain events moving in different directions, as examples.

Background

Located in Washington, DC, the unnamed Dumbarton Oaks stream is one of the tributaries of Rock Creek. Its watershed elevation drops from a high of 370 feet (105 meters) at Fulton and 37th Street, NW down to less than 15 feet (5 meters) at the mouth with Rock Creek. Figure 1 presents the basin topography using a 5-meter contour interval relative to the pre-development and post-development watershed boundaries. A watershed boundary defines the

limits of surface water runoff collection; all area inside the boundary flows to the stream. The pre-development watershed boundary is based on the topography (the shape of the land surface). The post-development watershed boundary reflects the installation of storm sewer lines that direct some of the runoff out of the basin into other drainage basin piping and eventual discharge downstream (Personal Communication, Jessica Demoise, District of Columbia (DC) Water and Sewer, 2011). Figure 2 shows the post-development watershed boundary relative to the existing network of sanitary sewer and storm sewer piping throughout the Dumbarton Oaks watershed (DC Water and Sewer, 2011). The stormwater runoff for the triangular-shaped area north of Calvert Street/north part of Observatory Circle now drains out of the Dumbarton Oaks Park basin to piping in the Normanstone drainage basin. Likewise, the area west of Wisconsin Avenue, the Safeway property, the Jelleff Boys and Girls Recreation Center and a storm sewer line along S Street drain storm water into the Combined Sewer Overflow (CSO) pipe that runs under the Dumbarton Oaks stream and connects to the Rock Creek CSO (Personal Communication, Jessica Demoise, District of Columbia (DC) Water and Sewer, 2011). Heavy precipitation could exceed the piping capacity and in these rare situations, the piping could allow overflows to the land surface. Such events have occurred in the past, but if the manhole covers have been bolted down as reported to the author (Personal communication, Doug Curtis and Bill Yeaman, 2011), any such leakage would be minimal. The net result for the Dumbarton Oaks stream is a smaller effective drainage basin. This effective drainage area covers 135.7 acres of which 31% is covered by impervious surfaces (Personal communication, Joe Kish, Rock Creek Park, 2011).

Figure 3 shows the Dumbarton Oaks Park topography in greater detail using a one meter contour interval. The stream longitudinal profile has a gradient of 0.04 from the 30 inch headwaters pipe to Lover's Lane where the gradient increases to 0.06 down to its mouth with Rock Creek.

Basins respond to rainfall dependant on the soil type and thickness, slopes, basin size and shape, and the degree of development (Hayes and Young, 2005). The type of soil controls the infiltration capacity and water movement. Rainfall that drains into the soil (infiltration) can move laterally or continue moving vertically (percolation) to provide recharge to the water table zone. The water table (zone below which the soil is completely saturated) is the upper surface of groundwater. Runoff collects and reaches streams at different rates and volumes requiring an evaluation of basin-specific behavior response. The best way to demonstrate the response of a basin is through the development of a rating curve. A rating curve shows how a change in stage (surface water elevation) relates to change in discharge (flow or the quantity of water passing a specific point per unit time). Data on stage and discharge are collected concurrently at one location on a stream. Such data will reflect the nature of the stream channel and its floodplain (gradient, vertical sides versus sloped sides, etc). Because a

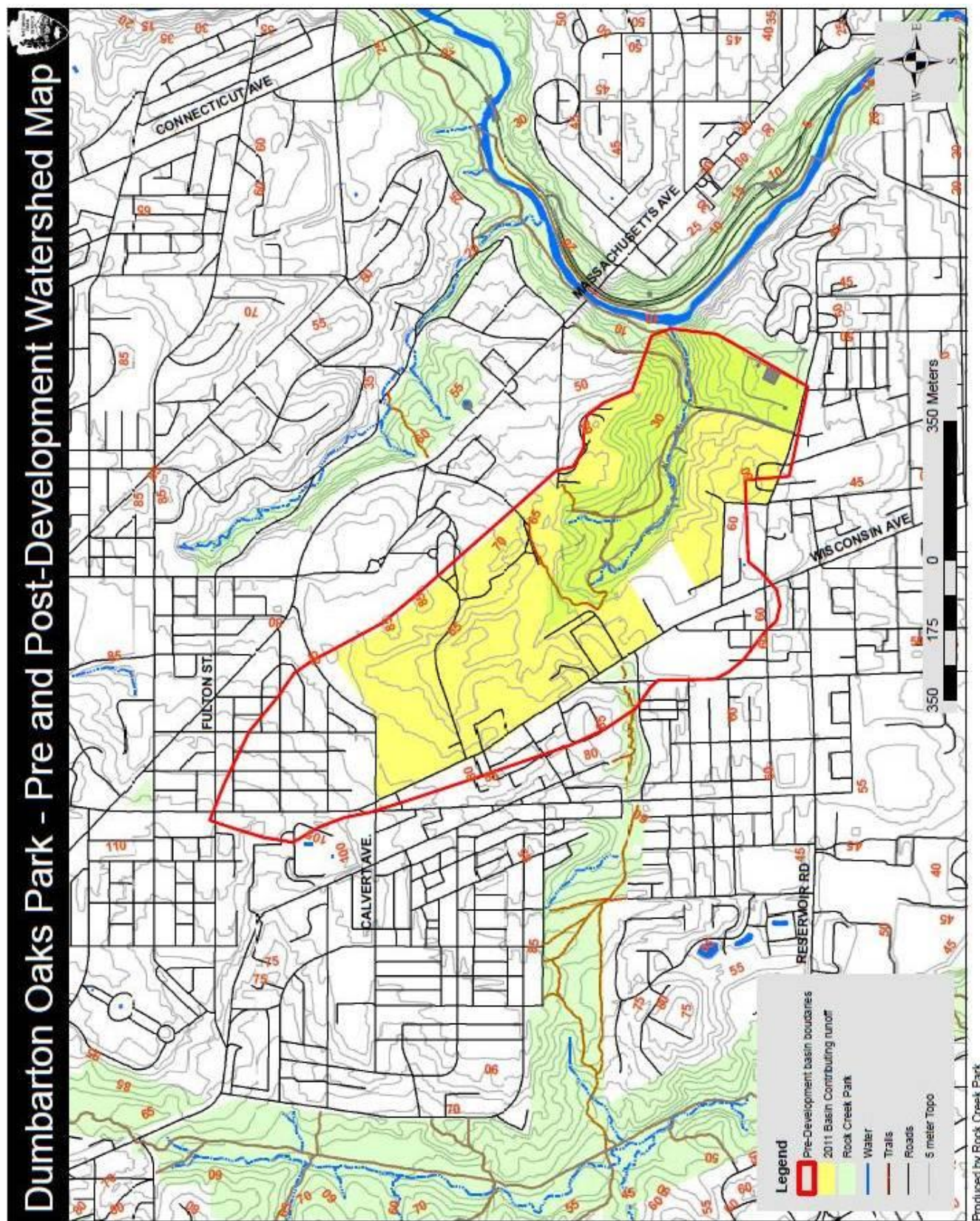


Figure 1: Dumbarton Oaks Park - Pre and Post Development Watershed Map

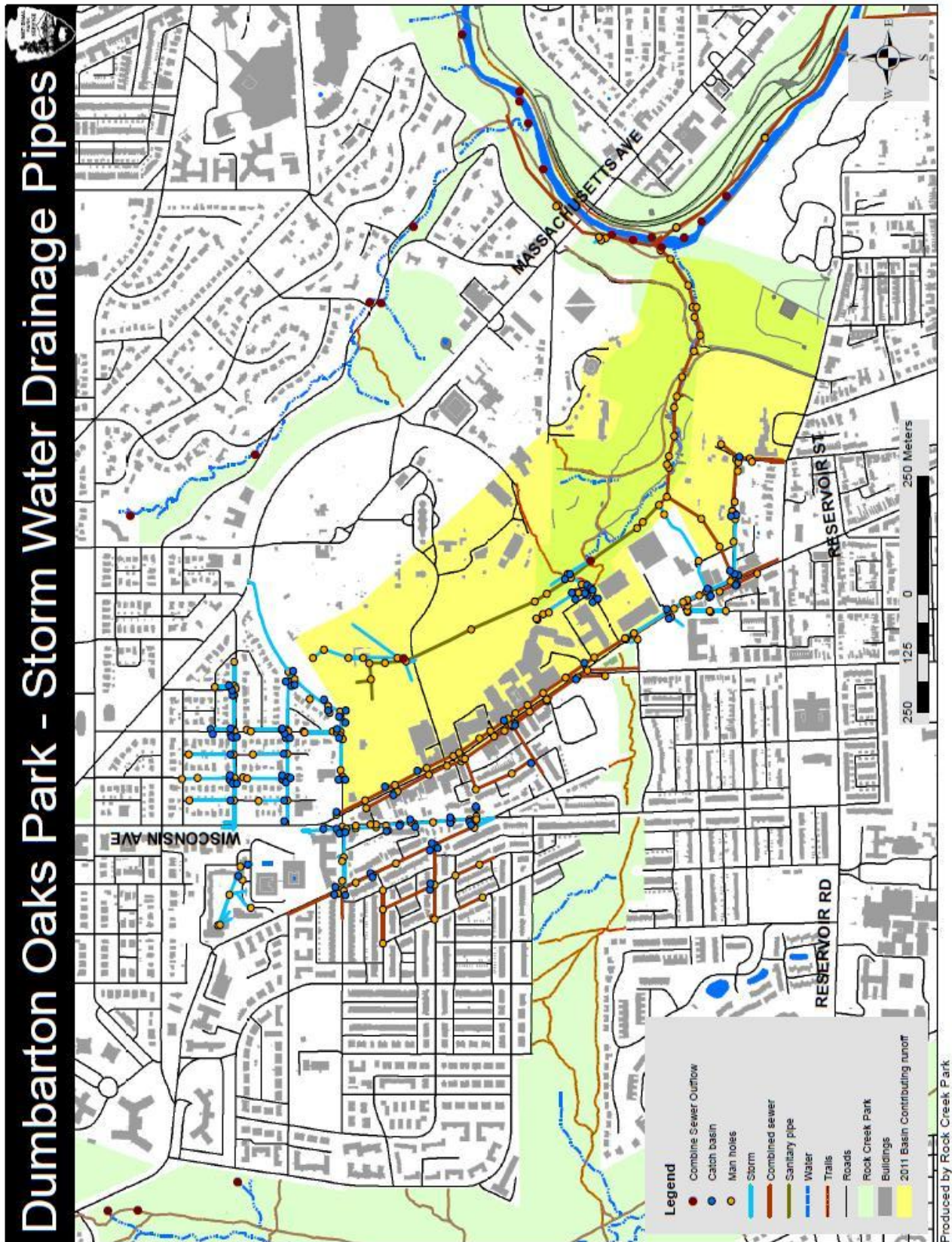


Figure 2: Dumbarton Oaks Park - Stormwater Drainage Pipes

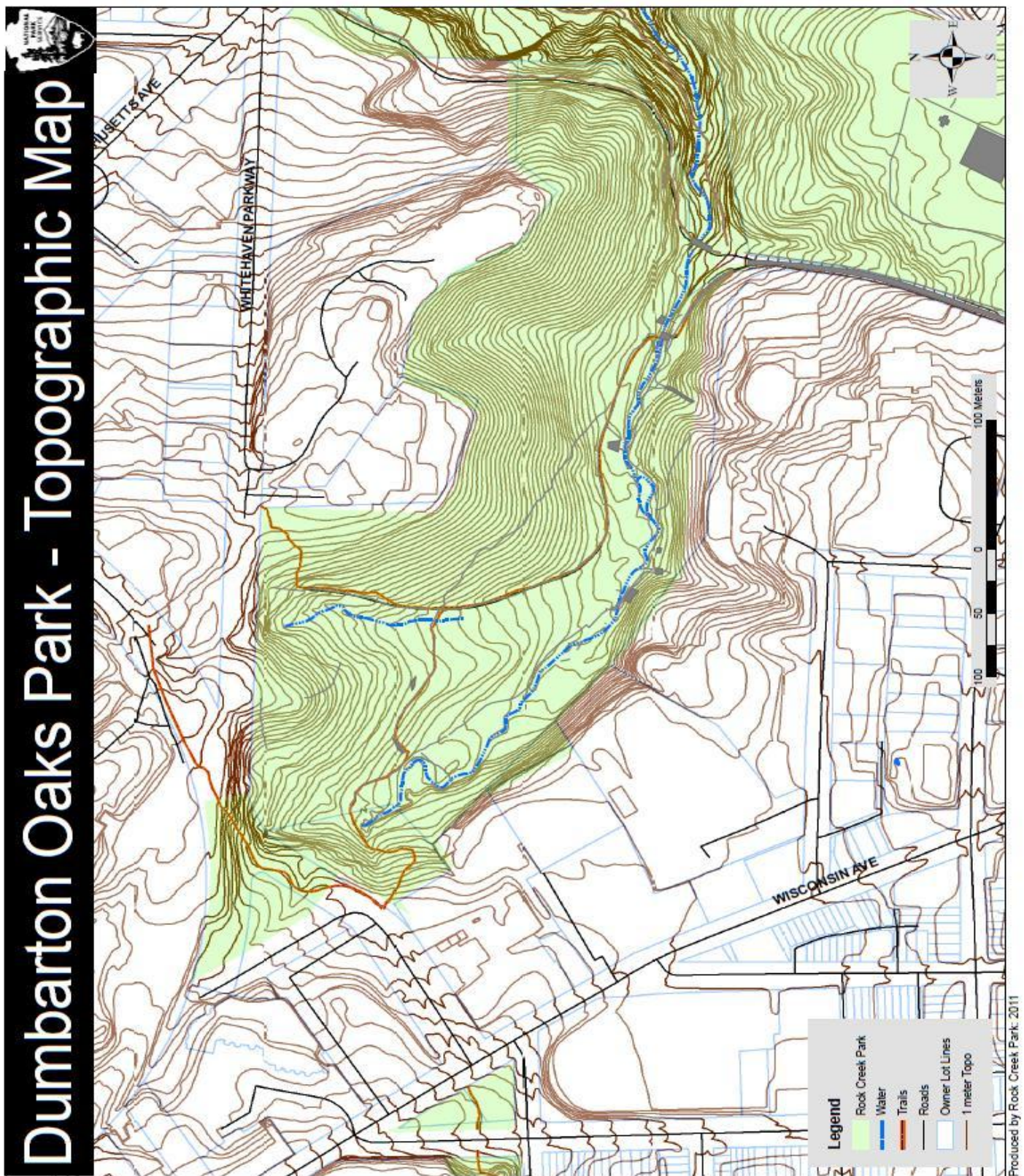


Figure 3: Dumbarton Oaks Park – Topographic Map

rating curve includes the basin response under many differing precipitation conditions, rating curves that include long-term data collected over several decades are the most useful.

Surface Water Quality

Surface water concentrations of nitrate, total phosphorus, fecal coliforms, and pesticides/herbicides exceeded their Montgomery County desired threshold for aquatic organisms and primary human contact. Montgomery County thresholds are used because their extensive data base allows identification of impact levels not discernible in the data bases for smaller regions like the District of Columbia (Personal communication, Marion Norris, 2011). Nitrate and total phosphorus are components of fertilizer and very soluble in water. The source of the nitrate and phosphorus is likely residential and commercial property fertilizer applications as well as aerial deposition. Paerl (1997) estimates that aerial deposition may account for 27% of new nitrogen delivered to the Chesapeake Bay. Figures 4 and 5 present monthly nitrate and total phosphorus data collected by the Center for Urban Ecology for the Dumbarton Oaks stream and the desired threshold. Fecal coliform bacteria are an indication of feces from warm-blooded mammals. While not harmful to humans, they are used as an indicator of whether digestive system pathogens (toxic protozoans, viruses or bacteria) might be present. Fecal coliforms are targeted because the analytical testing is less expensive than testing for each potential pathogen (U.S. EPA, 2011). If no fecal coliforms are present, then it is also likely that no pathogens are present. Fecal coliform sources can be determined using bacterial source tracking (BST) of DNA patterns (Hyer and Moyer, 2003). During the 2003 Bioassessment, the dominant aquatic species were those considered to be sewage-loving organisms. Table 1 shows fecal coliform densities per gram of feces for a few species. A gram is the approximate size of the tip of a pinkie finger.

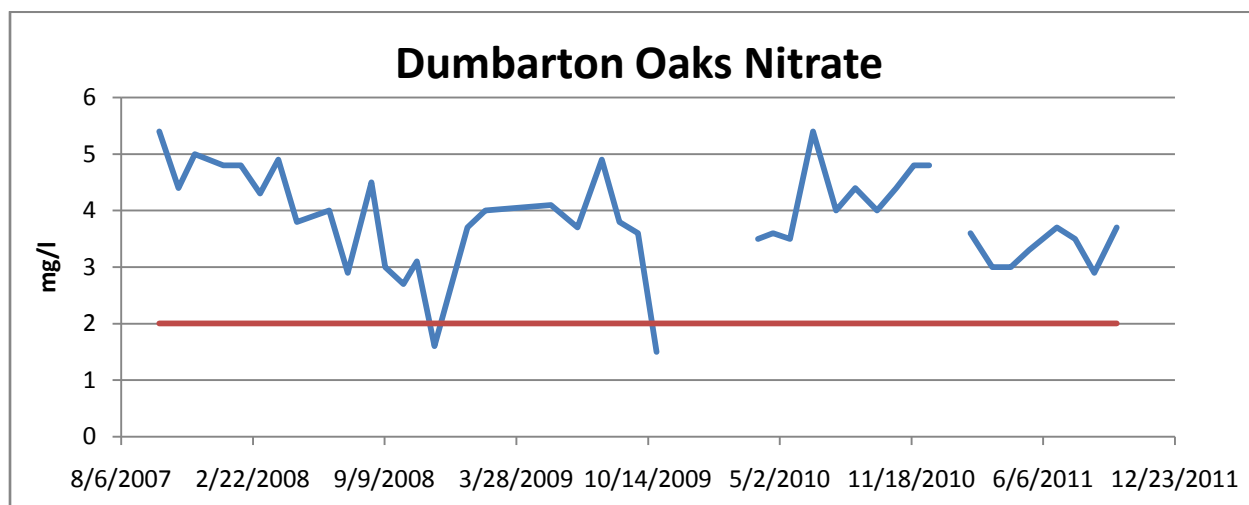


Figure 4: Dumbarton Oaks stream Nitrate Data collected by the Center for Urban Ecology

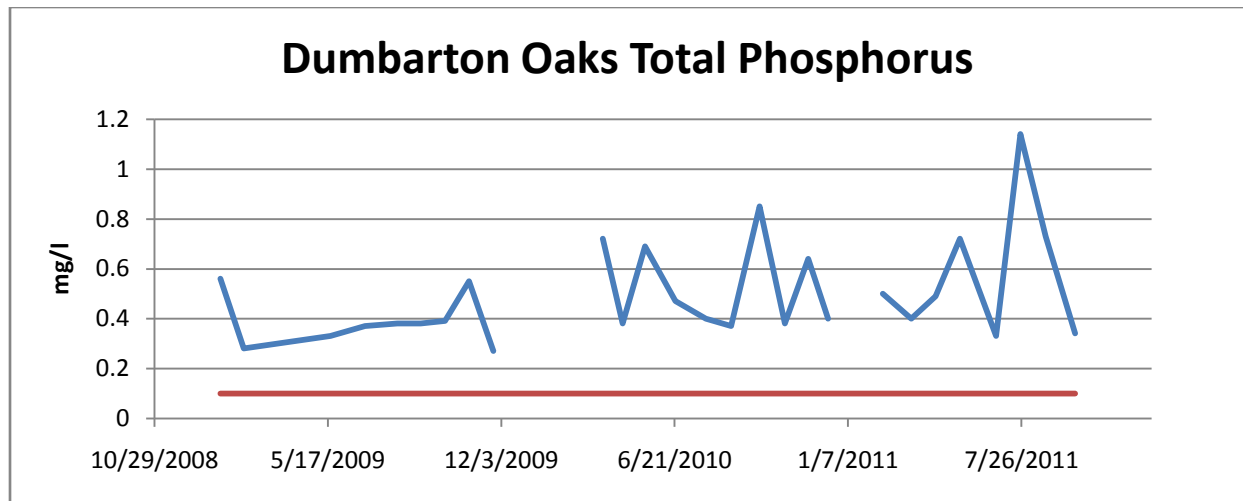


Figure 5: Dumbarton Oaks stream Total Phosphorus Data from the Center for Urban Ecology

Table 1: Bacterial Densities in Common Feces		
Source	Fecal coliform (Density/gm)	Reference
Human	13 million	Geldreich 1976
Cat	7.9 million	Geldreich et al, 1968
Dog	23 million	Geldreich 1976
Field mice	330,000	Geldreich 1976
Robin	25,000	Geldreich 1976
Sparrow	25,000	Geldreich 1976
Cow	230,000	Geldreich 1976
Horse	13,000	Geldreich 1976

All of the surface water contaminants are related to sediment (observed as turbidity) in the water column. These pollutants absorb to solid particles and when the soil is eroded, the contaminants are transported by runoff into the water column. Davis (1979) concluded that the most important factor for runoff fecal coliform concentration was the concentration of fecal coliforms in soil and that stream sediment could be 100-1000 times greater than the surface water concentration. For a Virginia stream, Simmons et al (2000) established that nonhuman species were the dominant sources of fecal coliforms and that underground piping contributed significantly to the fecal coliform problem. This study of Dumbarton Oaks Park included no surface water sample analyses and no work regarding this issue.

Geology

Rock Creek Park straddles the Piedmont and Atlantic Coastal Plain physiographic provinces (Southland and Denenny, 2005) separated by the Fall Line. Dumbarton Oaks Park is located on the southwest side of Rock Creek Park and contains characteristics of both provinces. The

Piedmont physiographic province is characterized by exposed metamorphic rocks, igneous intrusions, steep-sided valleys and rolling terrain, and rapid flowing streams (CH2M Hill, 1979). The Atlantic Coastal Plain physiographic province has a flatter terrain with meandering streams, no massive outcrops and unconsolidated beds of gravel, sand and clay (CH2M Hill, 1979). The Atlantic Coastal Plain sediments thin to the west and the remnants of these deposits are limited to the tops of ridges such as the ridge from Montrose Park westward along R Street and following Wisconsin Avenue on its west side. The ridge that forms the northern boundary of Dumbarton Oaks Park is also capped by Atlantic Coastal Plain sediments ranging in age from Holocene (Qc) to the Lower Cretaceous (Kps). Note that the USGS revised the age of these deposits because the unconsolidated ridge sediments lacked the systematic alignment of long-term contractural and extensional forces (Southworth and Denenny, 2005). The oldest Atlantic Coastal Plain layer, the Potomac Formation Sand-dominated lithofacies, underlies the Naval Observatory. See Figures 6a and 6b (lithology key) reproduced from Southworth and Denenny (2005) providing the specific formation/rock type names. The Atlantic Coastal Plain sediments, where present, overlie the weathered residuum (saprolite) of and the Piedmont igneous rocks of Paleozoic age (Southland and Denenny, 2005). The Dumbarton Oaks basin is underlain by the Georgetown Intrusive Suite, specifically biotite-hornblende tonalite and biotite tonalite members (Southworth and Denenny, 2005). Greene et al 2004 documented an extensive three-dimensional network of fractures in an outcrop of biotite-hornblende tonalite located on the north bank of the Potomac River. Their work also established that this three-dimensional network of fractures transmits groundwater (Greene et al 2004).

The Rock Creek fault and shear zone is oriented north-south along the District of Columbia channel of Rock Creek and has a width up to 1.9 miles (Southland and Denenny, 2005). See the three parallel lines on Figure 6a. Although the fault does not extend into the Dumbarton Oaks Park, the shear zone may.

The soils that have developed on the ridges of the Dumbarton Oaks Park are gravelly sandy loam, well to excessively drained, and where present on steep slopes, these sediments are easily eroded (USDA, 1976). The term loam means that the soil grain size is predominantly silt-sized. Water drains into the soils rapidly but is not retained so storage capacity is low. Within the Dumbarton Oaks basin, these soils are present over the high elevations and on some slopes.

Surface soils on the Dumbarton Oaks basin valley floor are the result of extensive in-place weathering of the Georgetown Intrusive Suite bedrock. This weathered bedrock residuum is called saprolite. Chemical and physical weathering processes destroy the majority of igneous rock minerals leaving clay and quartz. These resulting silty to sandy loams have moderately slow permeability and rapid runoff (USDA, 1976). Water capacity is high, but where the slopes

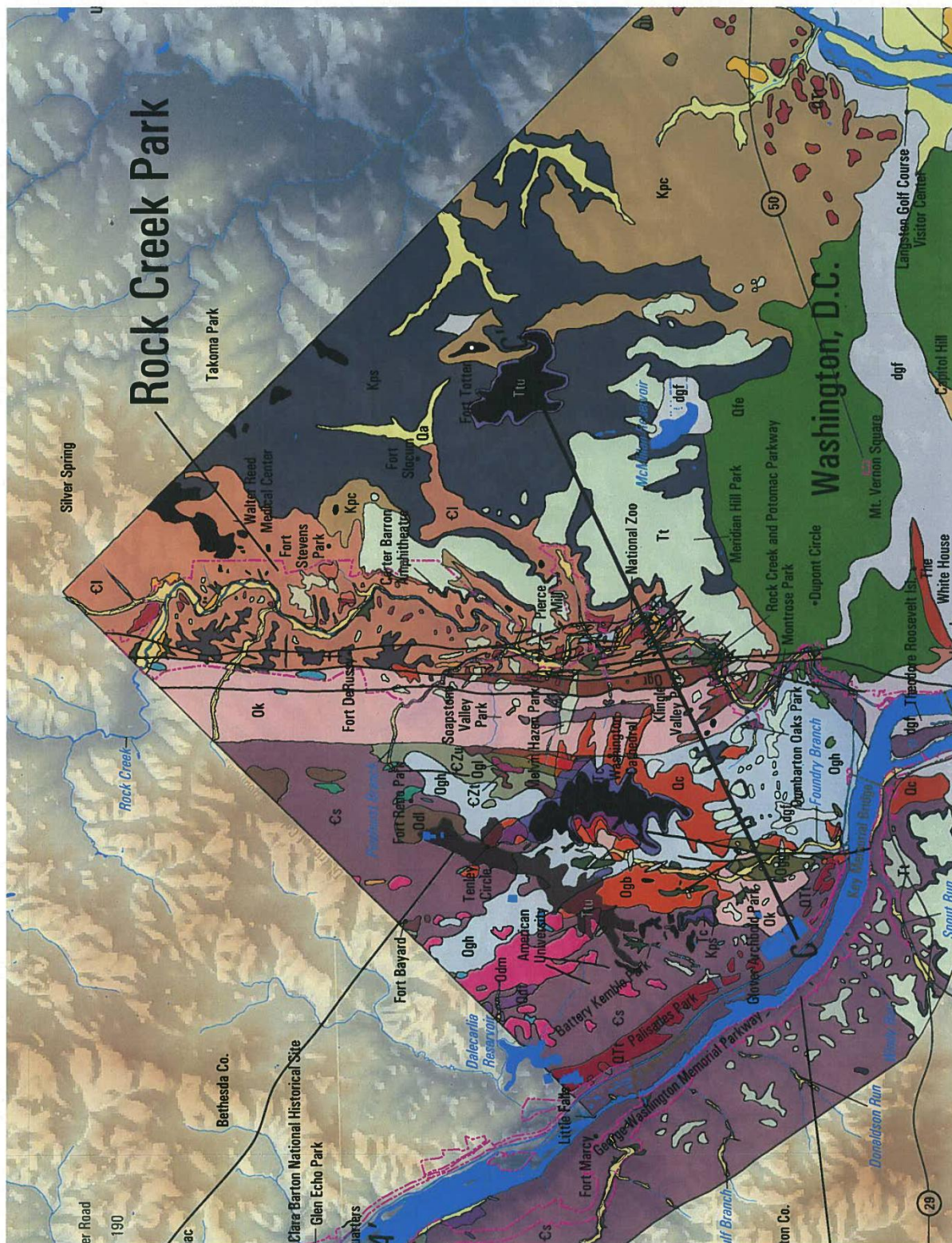




Figure 6b: Geologic Map Legend from Southworth and Denney, (2005)

are greater than 8%, the hazard of erosion is high. The combined thickness of the Atlantic Coastal Plain deposits and the weathered bedrock residuum is estimated to range from 50-100 feet over the Piedmont bedrock (USDA, 1976) in the Dumbarton Oaks Park basin area.

Hydrogeology

Groundwater occurs in the saprolite and the Atlantic Coastal Plain deposits as the water table aquifer. Engineering Consulting Services, Ltd. (1999) documented the depth to groundwater as 2-5.8 feet below land surface for the west part of Dumbarton Oaks Park. Although water tables typically fluctuate in response to rainfall, Greene et al (2004) showed that the water table aquifer is very slow to respond to precipitation and may be limited to a 2-3 foot annual fluctuation range. With depth, the saprolite transitions to less weathered bedrock, and eventually to the fractured bedrock itself. Groundwater is also present in the bedrock and although the two layers are interconnected and capable of recharging the other, they should be considered two separate aquifers. Greene et al (2004) slug testing of the saprolite (using an air-pressure slug to push the water level down and record the rate of water level rise) determined a hydraulic conductivity of 1 ft/day (foot per day), transmissivity of $10 \text{ ft}^2/\text{day}$ (feet squared per day), and storativity of 10^{-6} . The fine grain size of the clays gives the saprolite high porosity (20-30%) and high water storage capacity but because of the very small pore sizes, this water table aquifer yields water slowly and would not be a good candidate for water supply. The high water storage capacity provides recharge to the deeper and more permeable bedrock aquifer. The bedrock has low porosity (0.01-2%) but the hydraulic conductivity of the bedrock aquifer is controlled by the three-dimensional network of connected fractures (Greene et al 2004). The low storage and low porosity of the bedrock results in a strong response to precipitation with an eight-foot fluctuation range in the potentiometric surface. (A potentiometric surface defines the hydraulic pressure surface for wells installed into that aquifer. It is used to understand the direction of flow and the rate of flow for the aquifer.) The vertical direction of flow is downward from the saprolite to the bedrock aquifer (Greene et al 2004). Fluid-injection packer tests on four bedrock wells gave a transmissivity range of $10^{-4} \text{ ft}^2/\text{day}$ to $10 \text{ ft}^2/\text{day}$.

Methods

Precipitation

Historical and recent precipitation data for the Washington Reagan National Airport was obtained from the National Climatic Data Center (NCDC) at the following website: <http://www.nws.noaa.gov/climate/index.php?wfo=lwx>. This website provided historical monthly data extending back to 1871 and daily data for September through November 2011. Daily precipitation did not provide sufficient detail to relate stream stage/discharge measurements to rainfall. Hourly observations of precipitation data for Washington, DC were

downloaded from <http://www.wunderground.com/history> to correlate with the observed rapid rise/decline in stream stage.

Field Procedures and Analysis

A field reconnaissance was conducted of the Dumbarton Oaks Park and surrounding area to document existing conditions, pipes, and runoff entry points. This effort included examination of the topography, health and nature of vegetation cover, potential groundwater seeps, and anthropogenic alterations such as piping and erosion.

A staff gage was installed in the Dumbarton Oaks Park stream between the Stone Bridge and East Falls to track surface water elevation changes during precipitation events. This location was selected because (1) it was downstream of a relatively straight section of uniform flow velocity, (2) the stream bed was relatively uniform and free from large rocks and aquatic growth, (3) it was a wide channel section to handle high flow velocities with minimal depth increase, and (4) had slopes supporting fast exit if needed for dangerous flash flooding conditions. It was also downstream of most waterfalls with East Falls being the exception. Downstream of East Falls, the stream flows through a rocky stream course that is not optimum for discharge measurements. The staff gage is divided in tenths of a foot, with 0.00' set at the sediment surface and extending to a height of 3.34'.

Discharge (the volume of flow passing a point per unit time) was measured at the staff gage location (East Falls), at the 30 inch Headwaters pipe, downstream of the 30 inch pipe (low flows only and this location includes discharge from the 18 inch Headwaters pipe), the stone-lined path crossing along the western park trail, downstream of Arbor Falls, and Dumbarton Oaks mouth. These locations are shown on Figure 7. At each stream transect location a tag line was set up perpendicular to stream flow across the stream width. The tag line was marked every foot. At each foot marking, the depth of the water was determined using the wading rod and recorded. All water depths were less than 2.5 feet, so the wading rod was adjusted to record the flow velocity at the depth equal to 0.6 of the total depth following USGS recommended procedures (Rantz and others, 1982). Pictures of the four major discharge transect locations are presented in Appendix D from two directions, including landmark features to allow the same sections to be re-established for continued data collection. Discharge was calculated using the following equation:

$Q=D*W*V$ where Q is discharge (cfs), D is water depth (ft), W is the width of the measurement section (1 foot in most cases), and V is velocity (ft/s).

Velocity measurements were made using a SonTek FlowTracker Handheld ADV flow meter (Acoustic Doppler Velocimeter). A keypad was used to designate location, water depth, enter commands, and view results as collected. The Flow Tracker measures velocity in two

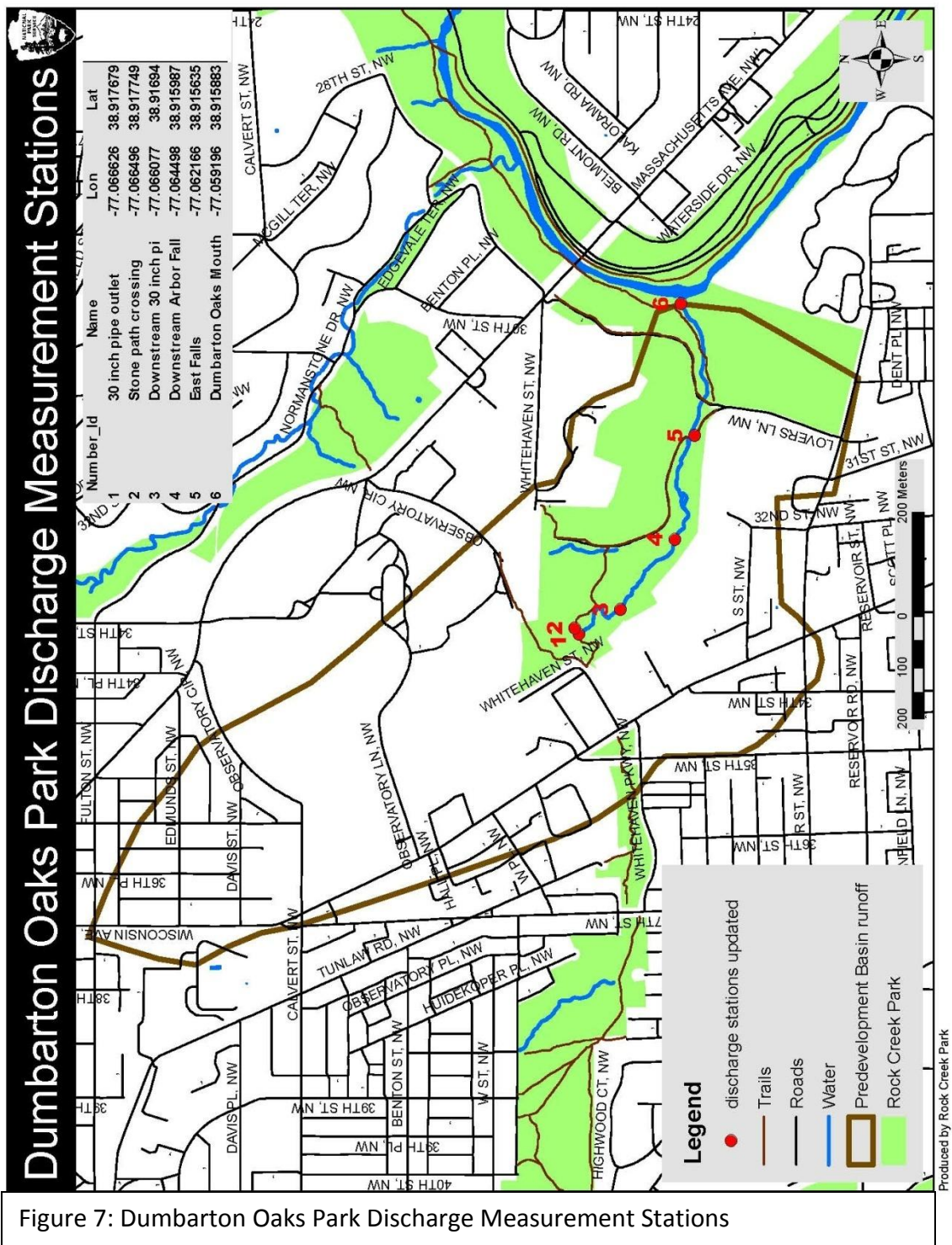


Figure 7: Dumbarton Oaks Park Discharge Measurement Stations

dimensions (x and y), records acoustic signal scatter and attenuation (Signal-to-Noise Ratio), includes built-in quality control checks, and computes discharge (SonTek/YSI, 2007). The unit stored data for later download to a personal computer for further processing.

Pipe measurements included the diameter of the pipe and for each visit, the depth of the water at the deepest point. If possible the velocity of the water exiting the pipe was measured. For the 30 inch pipe, the flow meter was set at the lowest point in the pipe where the water would be the deepest. Because the FlowTracker flow meter makes the velocity measurement 10 centimeters (4 inches) away from the acoustic transmitter, the 30 inch pipe velocity measurements do not represent the maximum velocity in the pipe center as desired, but a slower velocity towards the pipe wetted edge. A slower velocity than actual velocity means a lower calculated discharge than actual. This is the reason the 30 inch pipe discharge measurements were lower than expected based on visual observations. The velocity data were used with an online open-channel pipe flow calculator (http://www.hachflow.com/support/flow_calc.cfm) to calculate discharge.

Discharge calculations were also performed using the 30-inch pipe water depth data and pipe slope (Beacon online calculator <http://www.freecalc.com/fluid.htm>) to (1) determine what discharge rates should be for the concrete pipe and (2) to compare with both the FlowTracker discharge data and other Dumbarton Oaks Park discharge data.

Data analysis, calculations, and graphing were performed using Microsoft Excel (2007).

Park Features such as water falls, pipe locations, inflow sources, a Department of Interior monument, and eroded areas were surveyed using a Trimble Ranger to document their Ground Positioning System (GPS) locations (Travis Moore, Rock Creek Park, 2011). The equipment utilized Terrasync software version 5.0. The locations are relative to the North American Datum 1983 (NAD 1983, State Plane of Maryland) with an accuracy of +/- 1 meter (Personal Communication, Joe Kish, 2011). These positions and the longitude and latitude coordinates for each location are presented on Figure 8. Vertical elevations were not determined.

SonTek claims FlowTracker can measure velocities in shallow water at 2cm (less than 1 inch), but National Capital Region Network (NCRN SOP#11) states neither the FlowTracker nor the top-setting rod work below 0.2 feet. The FlowTracker reported velocities appeared reasonable for the flow rates observed at 0.1-0.2 feet, but this may be an additional reason the 30 inch pipe velocities give discharges that are lower than downstream measurements. Velocity measurement was not attempted if water depth was less than 0.1'. SonTek software evaluation of uncertainty and the raw data can be located in the "Discharge Data" folder of Rock Creek Park, Dumbarton Oaks Park electronic library.

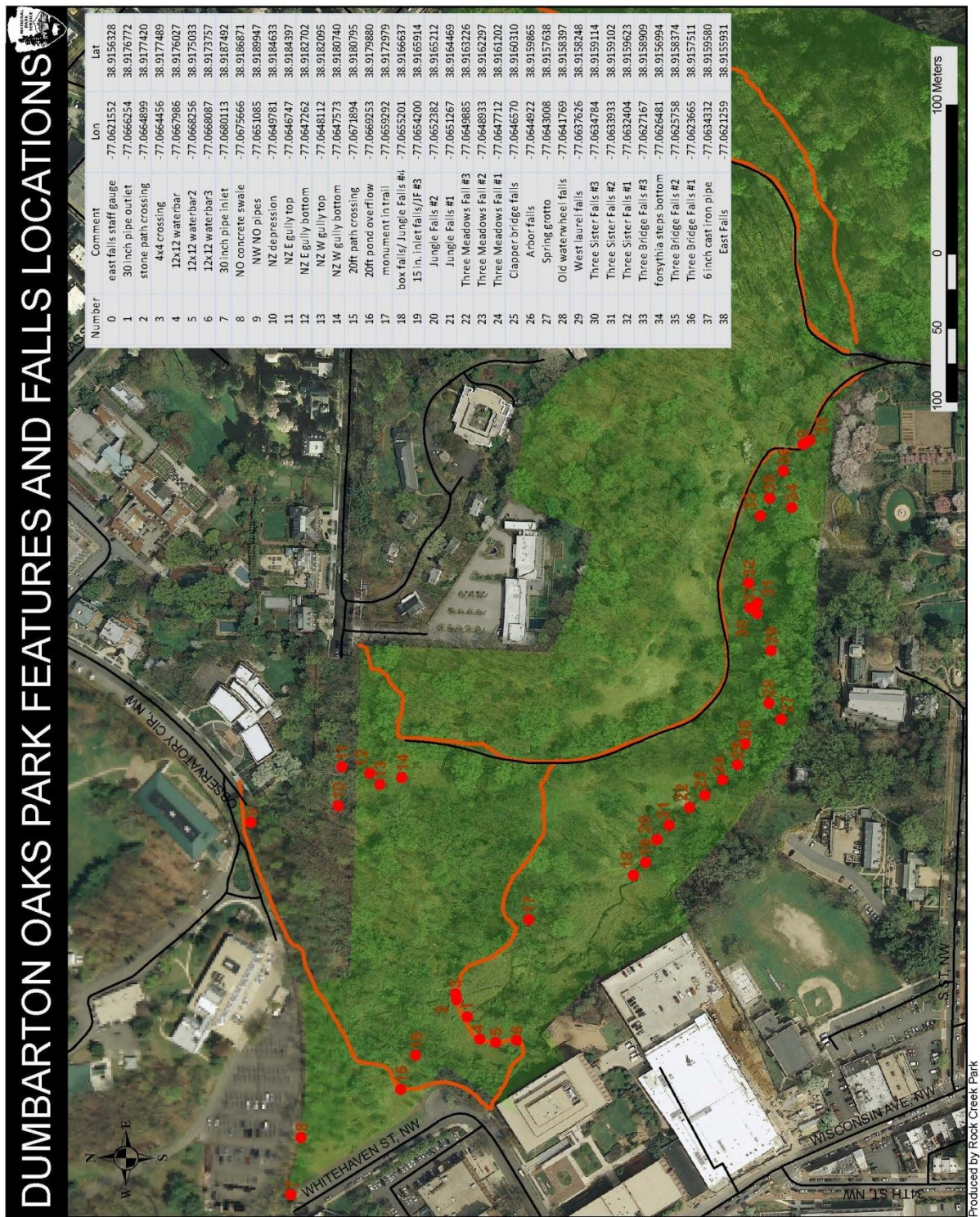


Figure 8: Dumbarton Oaks Park Features and Falls Locations

Results

Existing Conditions

Figure 9 summarizes field observations on the Cultural Landscape Report (2000) base map of existing conditions, piping, and volunteer stream entry locations for the Dumbarton Oaks Park area. Existing conditions included areas where runoff has eroded soil and vegetation, gullies, and areas where corrective measures are successfully controlling erosion. Appendix B provides photo documentation of erosion from runoff leaving Dumbarton Oaks down their north slope and into the park. Appendix C provides photo documentation of runoff sources into Dumbarton Oaks Park. The Figure 10 photos document two areas along the stream path where temporary fencing allows the accumulation of fallen leaves and re-establishment of vegetation. A poorly maintained storm water pond, with a possible uphill facility (to the northwest of Figure 8, GPS Location 15 where 6"X 6" posts lie on the land surface to control direction and rate of runoff), is located outside park property on Federal property identified as Reservation 357. These two areas are severely overgrown with porcelain berry covering the possible uphill facility and understory brush in the storm water pond. No flow for any precipitation event was observed exiting the flex pipes, the 2" cast iron pipe, the two southwestern-most Naval Observatory 6-inch PVC pipes, or the abandoned 15 inch concrete inlet structure. The exit location for the 2" cast iron pipe is unknown. The flex pipes and 6-inch PVC pipes may discharge water during higher precipitation events.

The only constant source of flow into the park is the 30 inch Headwaters pipe (GPS Location 1). It provides the stream baseflow and receives discharges from an unknown source that emits a fan blower sound with a surge in flow observed 5 seconds later emerging from the 30 inch pipe. The 18 inch Headwaters pipe from the Georgetown University Building (Parsons 2003) has intermittent flow that appears unrelated to precipitation events. The pipe had no discharge the day after precipitation (0.41 inches on 11/29/11) and then a sudden discharge that lasted at least 10 minutes. The velocity of this flow was significantly less than that observed at the 30 inch pipe. It is possible that de-chlorinated swimming pool bottom drain water and non-contaminated chiller water may be the intermittent sources of either pipe (Personal communication, Jessica Demoise, DC Water, 2011). The location of the 18-inch pipe is not shown on Figures 8 and 9 because it was discovered 11/29/2011 after the maps had been prepared. Considering water depth and concurrent conditions at the 30 inch pipe on 11/30/2011, the 18 inch pipe discharge was about a fourth of that observed at the 30 inch pipe. The 12 inch green pipe (GPS Location 27-28 area) draining Dumbarton Oaks also exhibits intermittent flow with higher flows occurring during precipitation events. Tropical Storm Lee

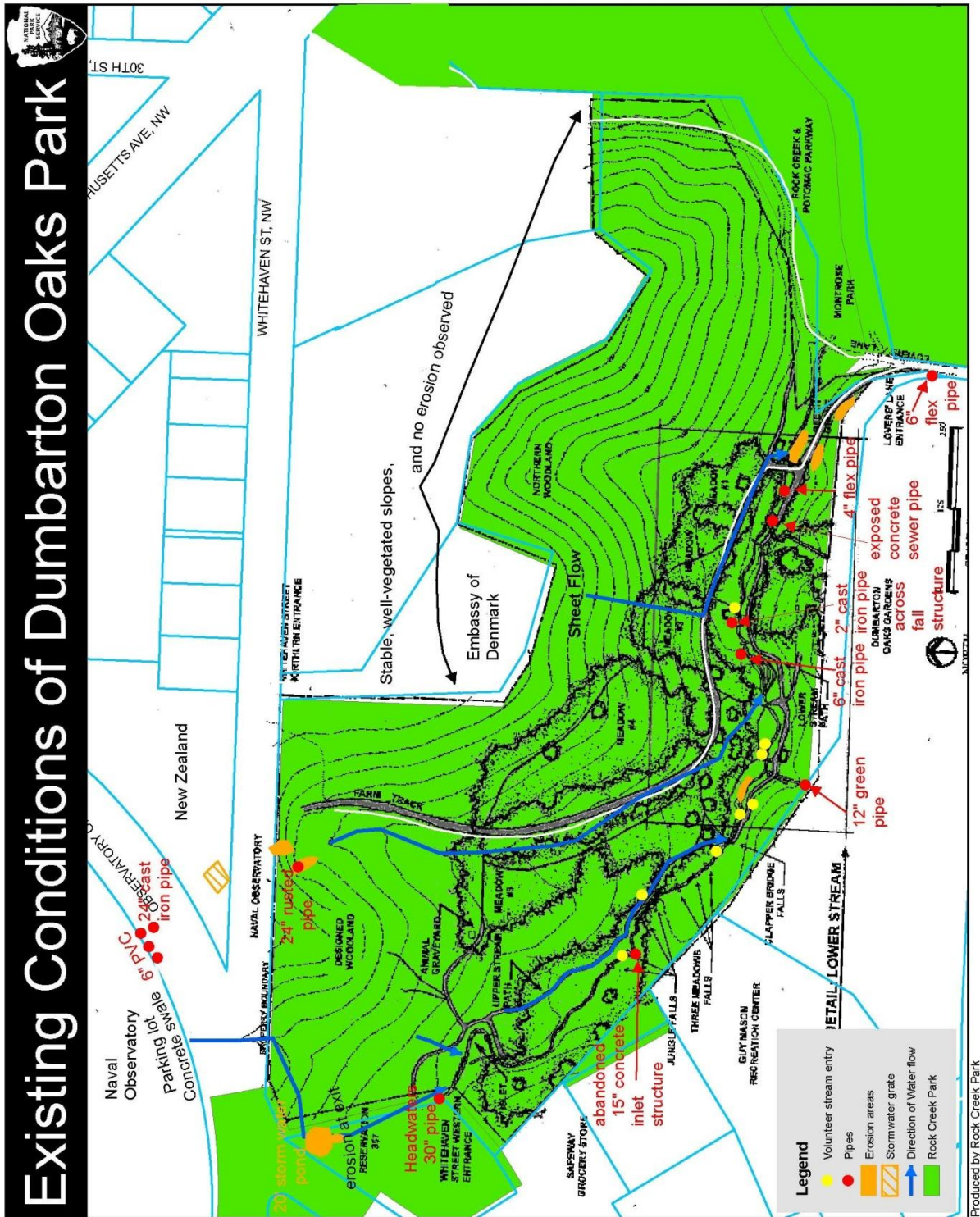


Figure 9: Existing Conditions of Dumbarton Oaks Park



Figure 10: Benefit of Temporary Fencing - These photos taken along the Stream Path show the benefit of temporary fencing for re-vegetation, accumulation of leaves, and slope erosion control.

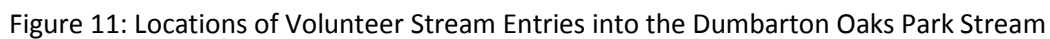
produced a high-flow pulsating discharge documented by video (Personal communication, Lou Slater, 2011). No velocity measurements were made at the 12-inch green pipe as flow was either too shallow or vertical up the left side of the pipe due to pipe turns, including a pipe turn of ninety degrees. The stone-lined path crossing near the 30" headwaters pipe contained short duration flow that visibly declined. The Naval Observatory/ Embassy of New Zealand flow was too shallow to measure the velocity. There is a 6-inch cast iron pipe (GPS Location 37) that discharges only during precipitation events downstream of the western most Three Sisters Falls. The Fall 2011 measured/documentated discharge range of these water sources is presented in Table 2.

Table 2: Fall 2011 Discharge Ranges

<u>Pipe</u>	<u>Discharge Range (cfs)</u>
30-inch	0.014-4.4
18-inch	0-?
12-inch green	0-pulsating high flow
Stone-lined crossing	0-0.458
NO/NZ runoff	0-?
6-inch cast iron	0-0.015

Other flow paths that drain into the park include (1) the runoff leaving the Naval Observatory Building 52 parking lot (GPS Location 8) that appears to drain into the 20-foot diameter stormwater pond (GPS Location 15-16 area), (2) the runoff leaving the Naval Observatory (GPS Location 9) and joining flow from the Embassy of New Zealand that drains into a storm grate/pipe that daylights in the park (GPS Location 13) with flow following the south side of the Farm Track, (3) multiple overland flow paths along the shared boundary with Dumbarton Oaks, (4) overland flow from the Embassy of Denmark, (5) overland flow down the grassed slope behind the properties that front Wisconsin Avenue from the Meridian to the Holiday Inn that drains into the 30-inch inlet pipe (GPS Location 7), and (6) runoff down the north slope behind the Jelleff Boys and Girls Club, Safeway, and Georgetown University. See Appendix C for photos of these runoff sources.

With sufficient precipitation, short-lived "voluntary tributaries" start flowing and transport eroded sediment into the Dumbarton Oaks Park stream. Figure 11 shows the locations where volunteer tributaries enter the stream and the sections where deposition of sediment has occurred. These volunteer tributaries follow the bare soil park trails where additional sediment is eroded from trail use. Some of the sediment comes from properties outside the park, but in-park areas of bare soil also contribute. The park trails are used heavily, even during rain events, resulting in additional erosion. Vegetation is absent on many stream banks primarily from



canine traffic, but also from the volunteer tributary entry points. Eroded sediment has accumulated in the pools and slower flowing sections of the stream. This sediment reduces the stream water storage capacity. Optimum water storage capacity is critical to reduce flow velocities and to buffer flash flooding.

Precipitation

Historical precipitation data was collected for the entire period of record (1871-2010) for Washington, District of Columbia (DC), Reagan National Airport from the National Weather Service, Sterling, Virginia (VA). The Reagan National Airport is located approximately 5 miles south of Dumbarton Oaks Park. Ideally, precipitation would be collected for the specific watershed being evaluated, but it is reasonable to assume the Washington National Airport precipitation approximates rainfall amounts and timing for the Dumbarton Oaks Basin. Rainfall data for the District of Columbia, Virginia, Maryland, and West Virginia areas are similar (Schmit 2011) and Dumbarton Oaks is a very small basin in comparison. Figure 12 shows the annual precipitation record. The climate of the study area is humid subtropical with an average annual temperature of 53.8°F. Heavy precipitation may occur from summer thunderstorms, frontal systems or tropical storms such as hurricanes.

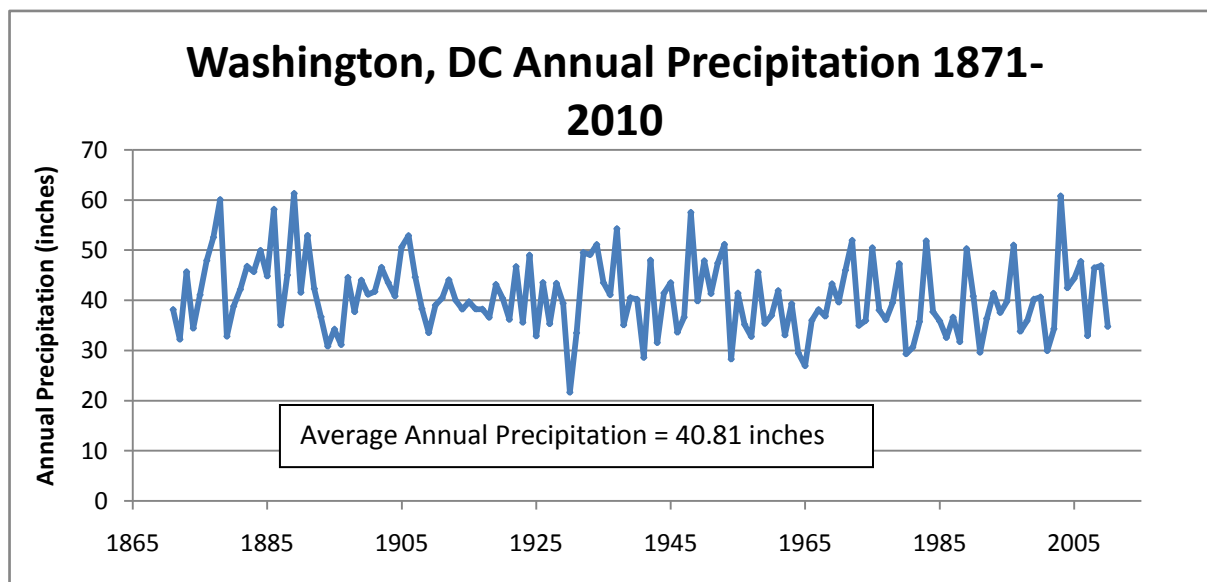


Figure 12: Washington, DC annual precipitation data from the National Climatic Data Center

The precipitation range for the entire 1871-2010 period of record varies from 21.66 inches (1930) to 60.83 inches (2003) with an average of 40.81 inches. Each year of total precipitation can be more (surplus) or less (deficit) than the average precipitation. If the surpluses (+) and deficits (-) are added year by year, a cumulative departure from average curve is developed. Such a curve will show general precipitation trends for the period of record. See Figure 13.

The period 1870-1890 was a period of increasing precipitation (small increases every year show as an upward slope on the plot from 12 inches below to 92 inches above the average), followed by a relatively stable period 1890-1950, and decreasing precipitation 1950-2000 (a downward slope from 100 inches above to 30 inches below the average). The precipitation of the most recent 20-year period has been relatively stable ranging from a low of 29.62 to a high of 60.83 inches, with an average of 40.36 inches. The cumulative departure curve validates the common perception that recent rainfall has been increasing as an increasing slope is observed since 2002, but this slope is insignificant when the entire precipitation record is considered. Overall, the precipitation record indicates a wide range of annual precipitation values is normal for the Washington, DC area.

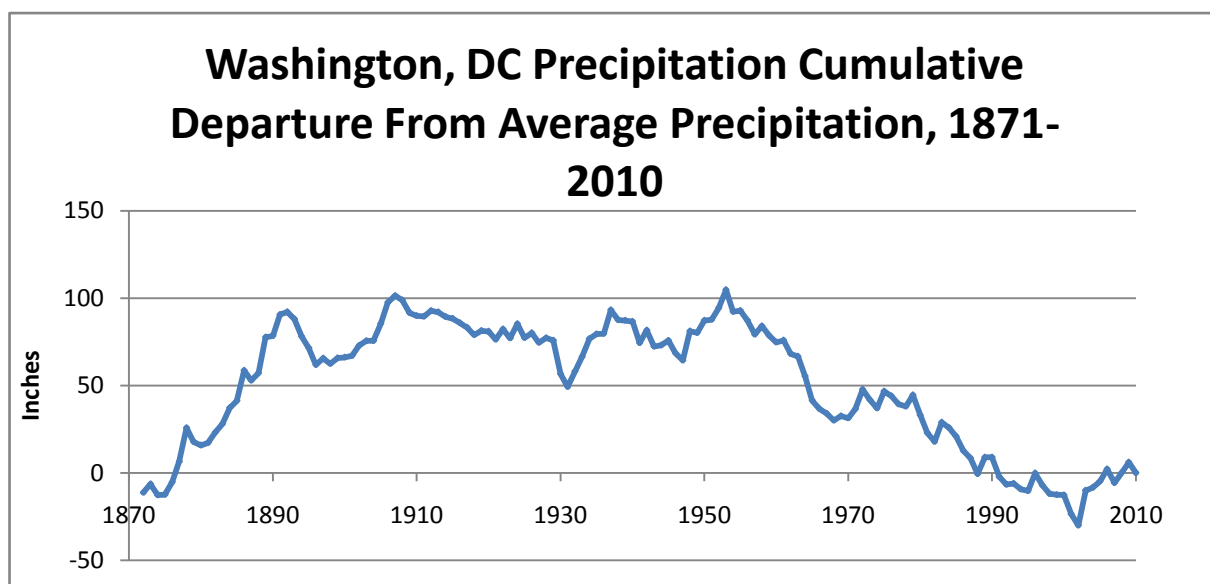


Figure 13: Cumulative Departure from Average Precipitation

During the years 1921-1940 that Beatrix Jones Farrand created the Dumbarton Oaks Park in-stream structures, precipitation was relatively stable ranging from a low of 21.66 inches to a high of 54.29 inches, with an average of 41.09 inches, slightly higher than the average of 1991-2010 (40.37 inches). The year 1930 was a dry year as shown in Figure 14 by the monthly precipitation totals relative to the decade years 1920 and 1940. A similar plot for the last 3 decades (1990-2010) is also presented for comparison (Figure 15). Precipitation varies widely naturally and this is the reason that long-term data is needed to evaluate any trends. Still, the annual precipitation amounts are very similar between the 1921-1940 landscape construction period and the conditions of today.

The storm damage called an “unholy mess” by Harry Thompson was probably the result of 11.62 inches of rain in August 1942. Damage occurred to the stream pools, the plantings by the stream, the stream course and included erosion of various piles of unprotected fill into the

park. The in-stream structures were not designed to accommodate high rainfall events from the beginning. In addition, the Cultural Landscape Report: Part I aerial photo on page 29 shows the original stream course extended across the southern part of the Naval Observatory as a vegetated flow path. Storm water piping has now replaced some sections and potentially the Naval Observatory portion of the stream. Stormwater piping removes the “roughness” of the vegetation resulting in the runoff collecting faster and arriving as a slug into the Dumbarton Oaks Park (DOP) basin.

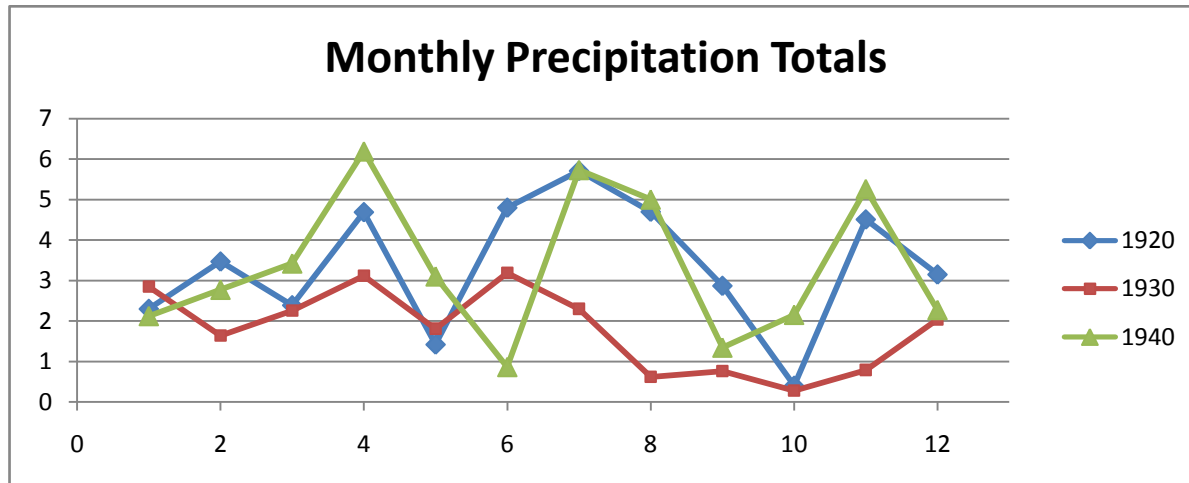


Figure 14: Monthly precipitation totals for the years 1920, 1930, and 1940 showing that 1930 was a dry year.

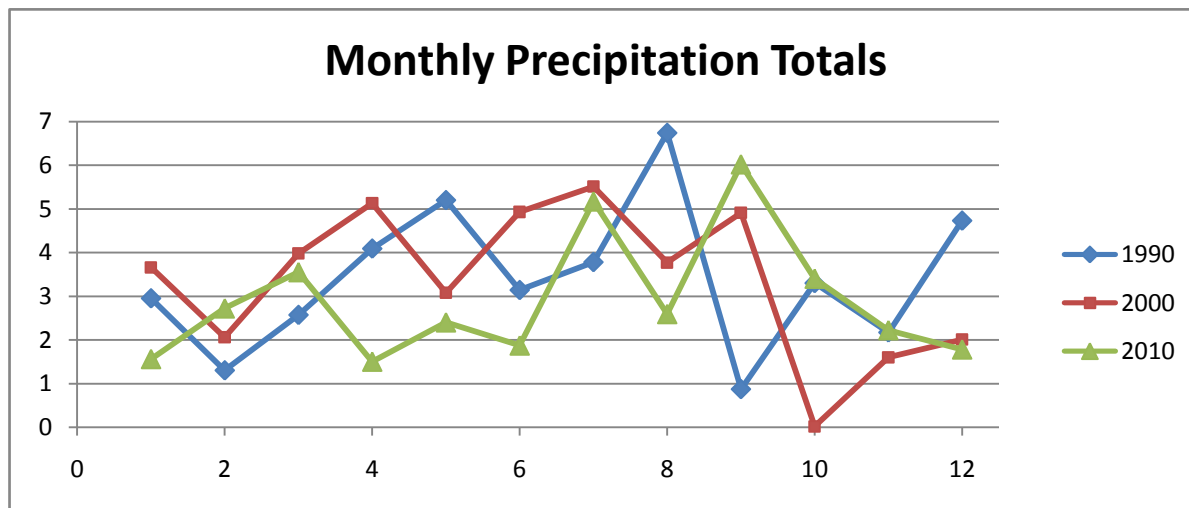


Figure 15: Monthly precipitation totals for the years 1990, 2000, and 2010

Annual changes in precipitation are not apparent but seasonal changes are. Schmit (2011) documented that precipitation in the spring (March-May) has been significantly increasing ($p=0.048$) for the Washington, DC region when the long-term precipitation trend was evaluated

seasonally. His work also indicated an increase in fall (September-November) precipitation, but this was not statistically significant ($p=0.29$). If the effect of climate change is to reduce the precipitation variation during the year, stream discharges should also reflect less variation. Instead, Rock Creek discharges show trends toward higher variability: higher high discharges and lower low discharges that are generally a result of increasing urbanization. In this case the effects of urbanization mask any potential effects of seasonal changes in regard to stream discharges. The Dumbarton Oaks stream has no long-term discharge data to evaluate for climate or urbanization changes.

Figure 16 presents the rainfall record for September 1 to November 30, 2011 and the amounts potentially reflected by Dumbarton Oaks Park discharge data. Many of the rain events occurred at night, but if the rain contributed to saturated soils still present for daytime rain, the night precipitation has been included. All of the observed rain events for September 19 through November 29, 2011 were considered low rainfall events and none met the six-month return frequency rainfall of 1.8 inches used by Greenhorne & O'Mara, (1999).

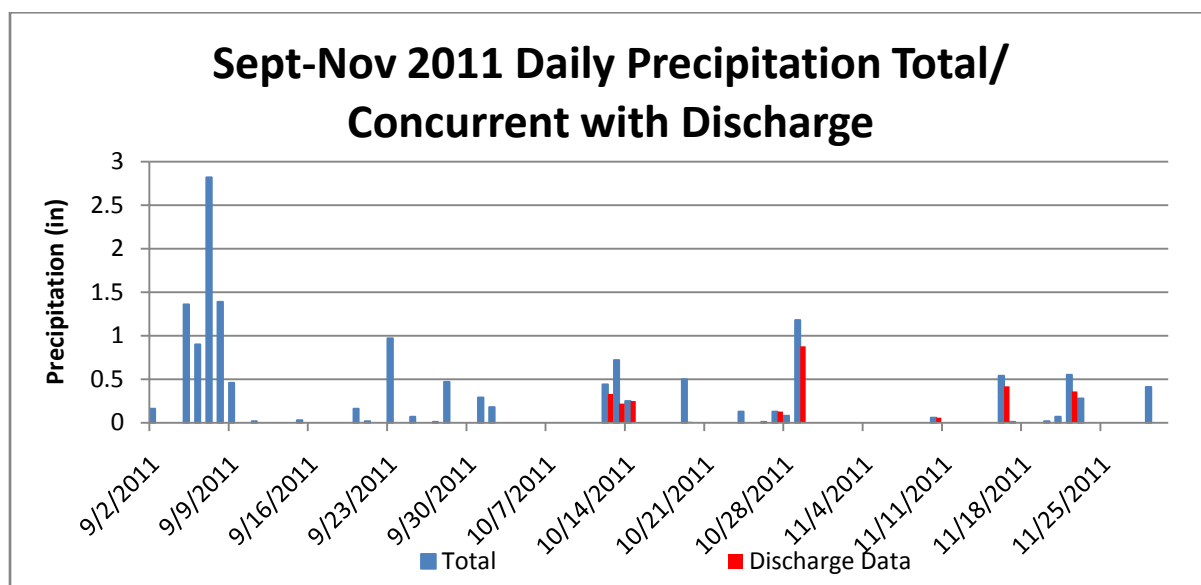


Figure 16: September-November 2011 Daily Precipitation Total/Concurrent with Discharge

Baseflow

Stream baseflow is the groundwater contribution to flow, but for the Dumbarton Oaks stream it includes the flow surges of unknown sources. Flow measurements were made along several locations of the Dumbarton Oaks stream on November 4, 2011 to evaluate the stream for baseflow conditions and the possibility of rising/falling discharge along the stream channel. Stream discharges can increase or decrease along their stream course due to recharge coming

in from or going out to groundwater as well as receiving/losing discharge from/to underground piping. No precipitation had occurred since the “trace” amount on October 31, 2011, eliminating the potential influence of stormwater runoff. The East Falls stage (surface water elevation) remained constant at 0.66 feet during the 5-hour measurement period. Discharge results are presented in Figure 17 and summarized in Table 3. Note the East Falls discharge range of 0.0874-0.153 cfs for one stage (0.66’). The arrow on Figure 17 shows the direction of surface water flow for the three stations from upstream to downstream.

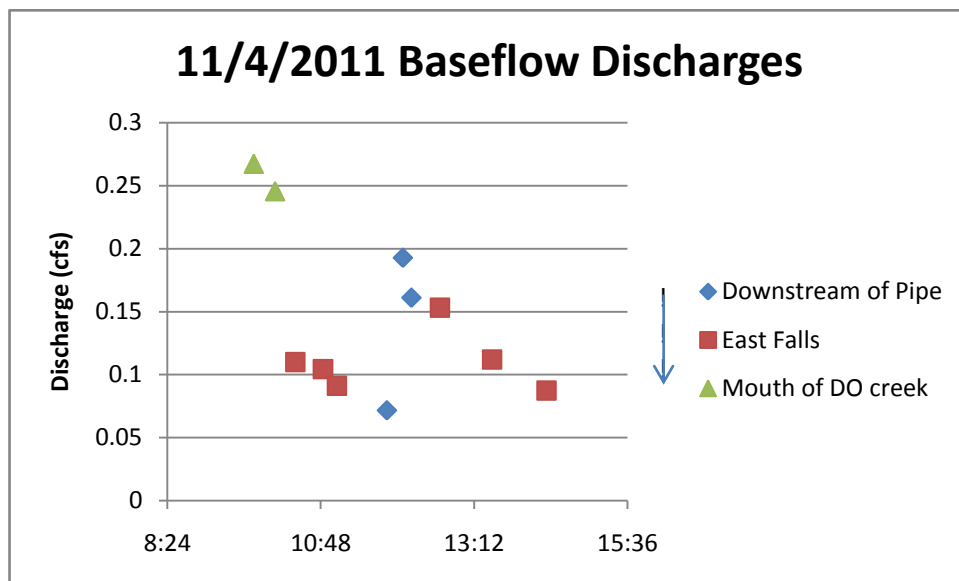


Figure 17: 11/4/2011 Dumbarton Oaks Park Baseflow Discharges

Flow in the stream starts at the 30 inch-discharge pipe located in the southwestern part of Dumbarton Oaks Park. Flow discharging from this pipe is variable with flow surges observed following the sound of a blower. The depth of water exiting this pipe was 0.05 feet; too shallow for a velocity measurement, but existing data can be used as a rough estimate. Velocity measurements for this pipe have ranged from 0.32 to 6.92 feet per second (ft/s) with an average of 3.43 ft/s. Discharge calculated with this average velocity and the 0.05 foot water depth is 0.08 cubic feet per second (cfs). (The sound of the blower coming on was heard while leaving the area.) The water depth on the discharge pad was also too shallow for measurement so a location was selected approximately 150 feet downstream (but up stream of the western-most Jungle Fall structure). This location (DS30”) was downstream of both the 30-inch and 18-inch Headwaters pipe discharge locations. The three discharge measurements along this section of the stream ranged from 0.07-0.19 cfs (including two measurements of the flow surge) with an average of 0.14 cfs. If the 18-inch Headwaters pipe was flowing at this time, it did not add significant flow.

The East Falls staff gage location is approximately 900 feet downstream of the DS30" location. Three discharge measurements were made twice; following the downstream mouth discharge measurement and following the downstream 30-inch/18-inch headwaters measurement. The initial three measurements averaged 0.102 cfs before the 30 inch-discharge blower came on to increase the flow. The last three measurements show the declining discharge from this flow surge with a range of 0.087 to 0.15 cfs and an average of 0.11 cfs.

Table 3: 11/4/2011 Baseflow Discharge Conditions

<u>Time</u>	<u>Stage</u>	<u>Discharge (cfs)</u>	<u>SNR (db)</u>	<u>Location</u>
9:20	0.66			East Falls
9:45		0.2673	21.2	DO mouth
10:05		0.2455	30.6	DO mouth
10:24	0.66	0.1099	16.6	East Falls
10:50	0.66	0.1044	12.7	East Falls
11:03	0.66	0.0912	14.3	East Falls
11:29	0.05			30" pipe
11:50		0.0715	22.2	Downstream 30"
12:05		0.1927	19.3	Downstream 30"
12:13		0.161	21.7	Downstream 30"
12:40	0.66	0.153	16.1	East Falls
13:29	0.66	0.112	17.3	East Falls
14:20	0.66	0.0874	25.6	East Falls

The two discharge measurements at the mouth of Dumbarton Oaks stream (before discharge into Rock Creek) were 0.2455 and 0.2673 with an average of 0.2564 cfs. The higher discharge at the mouth with Rock Creek (approximately double that detected anywhere upstream) could be explained by (1) the end of a previous blower flow surge, (2) by groundwater recharge to the stream or (3) by leaking fluids from the combined sewer piping running through the park. Discharges of 0.218-0.296 cfs have been measured for East Falls stage of 0.65-0.68 feet, supporting the possibility of flow surge with a volume greater than the event captured. The stream valley drops in elevation from 85 feet at East Falls to 20 feet at the mouth with Rock Creek. The Geotechnical Investigation by ECS in 1999 observed groundwater 2-5.8 feet below land surface in the southwestern area of the park now overgrown with porcelain berry and other invasive plants. If groundwater is shallow in the headwaters area (30'/800' or a gradient of 0.0375), it is also likely close to the land surface downstream where the stream gradient steepens (65'/1000' or a gradient of 0.065). The elevation drop of 65 feet between the two stations makes groundwater recharge a strong possibility. The possibility of leaking sewer pipes is very high unless the pipes have been lined. The direction of flow from a sewer pipe depends on the height of the water table relative to the fluid level inside the pipe, controlling flow into

or out of the pipe and into the stream. Park staff recalls the lining of the sewer pipe from the Laurel Pool area upstream to the Rock Creek sewer pipe, eliminating the sewer line as a possible source of the flow increase (Personal communication, Bill Yeaman, 2011).

The Signal-to-Noise-Ratio (SNR) values reflect the scattering and attenuation of the sound waves by sediment and other particles in the water column. USGS Technical Memorandum 2004.04 comments that solid boundaries can cause an increase in the SNR. Boundary effects within the measurement volume were reported by the FlowTracker at the 30" pipe, DS30" and at the Dumbarton Oaks stream mouth. In addition, SNR is affected by particle shape, particle size distribution, and particle concentrations. Such variations require more data than collected during this 2-month period of study. The SNR data has been included in this report, but due to the limited amount of data and boundary effects, no evaluation or conclusions will be offered with regard to these results. Landers, 2010 summarized scientific literature regarding continuous turbidity data collection methods. The water clarity (per visual observations – no turbidity or total suspended solids data were collected during this effort) is generally good during baseflow conditions permitting a clear view of leaves on the sediment surface. During storm events, the water clarity is poor resembling the appearance of coffee with cream.

On November 23, 2011, similar measurements were made the day following 0.41 inches of rain, adding a new station on the downstream side of Arbor Falls. Figure 18 does not indicate any significant groundwater influence on the flow between East Falls and the mouth with Rock Creek. Both flow measurements at the downstream Arbor Falls transect had a section with visible flow, but the water depth was too shallow to measure and these discharges are on the low side. The last discharge measurement of the day at East Falls reflects declining discharge and is the probable lowest measurable discharge at East Falls at this stage (0.77) as East Falls is essentially a pool at the staff gage location. The "DS 30 Inch Pipe" station is located about 300 feet (90 meters) southeast of the 30" headwaters pipe (also downstream of the 18 inch headwaters pipe). The four measurements show variable discharge, but the average discharge (0.363 cfs) agrees with the initial East Falls (0.368) and the Dumbarton Oaks stream mouth discharges (average 0.375 cfs). Since the average discharge at the downstream 30 inch pipe location agrees with East Falls and the mouth with Rock Creek, and there are no known additional flow inputs, this is probably equal to the discharge from the 30 inch pipe. However, the depth of water in the 30 inch pipe was 0.5 inch and using the average velocity, 1.37 ft/s plugged into an online flow calculator, this gives a discharge of only 0.0687 cfs. (The average velocity was for a water depth of 0.1' and because velocity declines with water depth, this velocity gives a high end estimate for a 0.5 inch water depth.) Velocities typically vary and average velocities are used for calculating discharges. Velocity variation applies to the Dumbarton Oaks stream, but the velocity data for the 30" pipe does not represent the pipe center velocity range because the FlowTracker makes the measurement four inches from the acoustic transmitter. Figure 19 shows the discharge

differences calculated from the 10/27/2011 30" pipe water depths and the average SonTek FlowTracker velocities (for each specific depth) or the pipe slope using an online flow calculator (Hach or Beacon). The pipe slope-based discharges show greater variation with pipe water depth increase than the velocity-based discharges. Figure 20 compares the discharge differences relative to 10/29/2011 water depth at the 30" pipe for: (1) average SonTek, (2) high SonTek, (3) expected discharge from a pipe with a 3 percent slope, and (4) approximately concurrent East Falls measured discharges. Average discharges are used to describe variable flows. The high discharges reflect the highest SonTek discharge recorded for that specific depth. The 3 percent slope is used for comparison because it is close to the 0.026 slope measured at the pipe and it is the common engineering design slope to maintain flow velocities for self-cleaning of leaves and debris. The East Falls peak discharge relative to the 30" pipe 0.4' water depth was missed due to the one hour travel time/photo documentation of stream conditions on 10/29/2011. The Figures 19 and 20 discharge discrepancies apply only to the 30" pipe measurements; measurements at other locations appear valid and agree with typical variations.

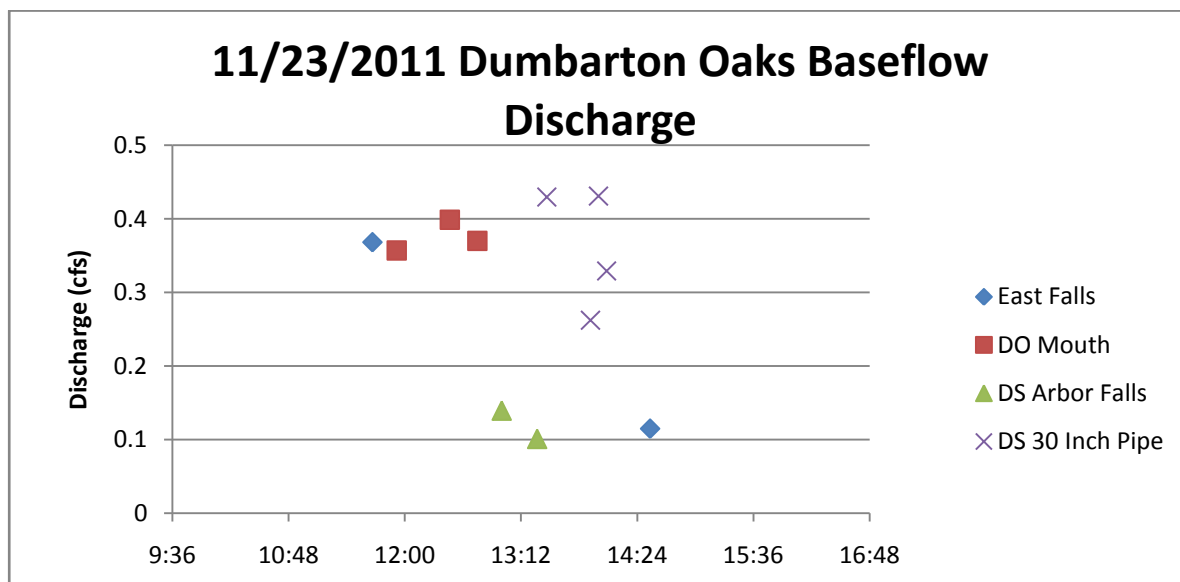


Figure 18: 11/23/2011 Dumbarton Oaks Park Baseflow Discharges – the initial East Falls, Dumbarton Oaks mouth, and Downstream 30" pipe discharges are similar and likely represent the concurrent 30" Pipe discharge.

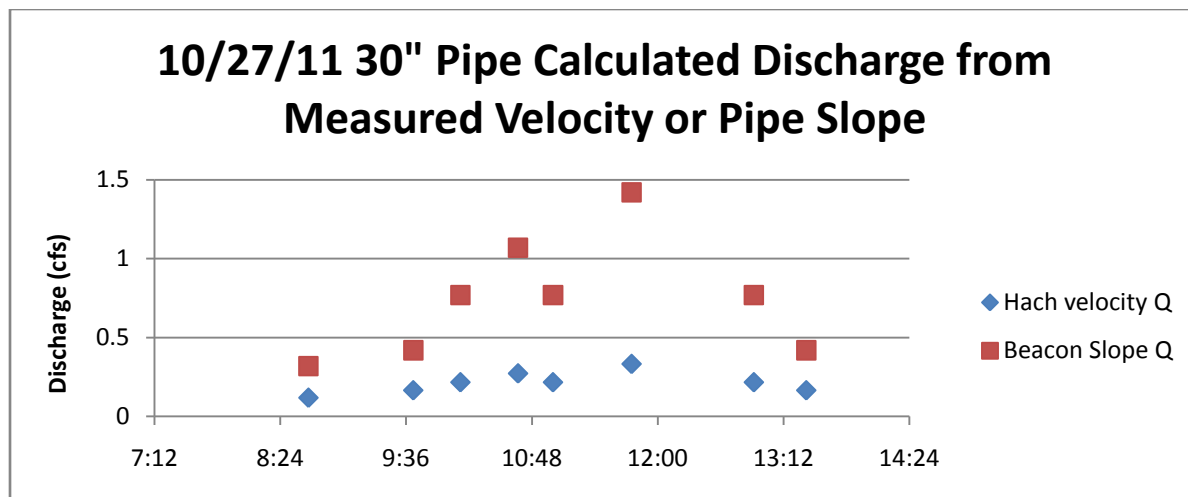


Figure 19: 10/27/11 30" Pipe Calculated Discharge from Measured Velocity or Pipe Slope - The pipe slope-based discharges (correctly) show greater variation with pipe water depth increase than the FlowTracker velocity-based discharges.

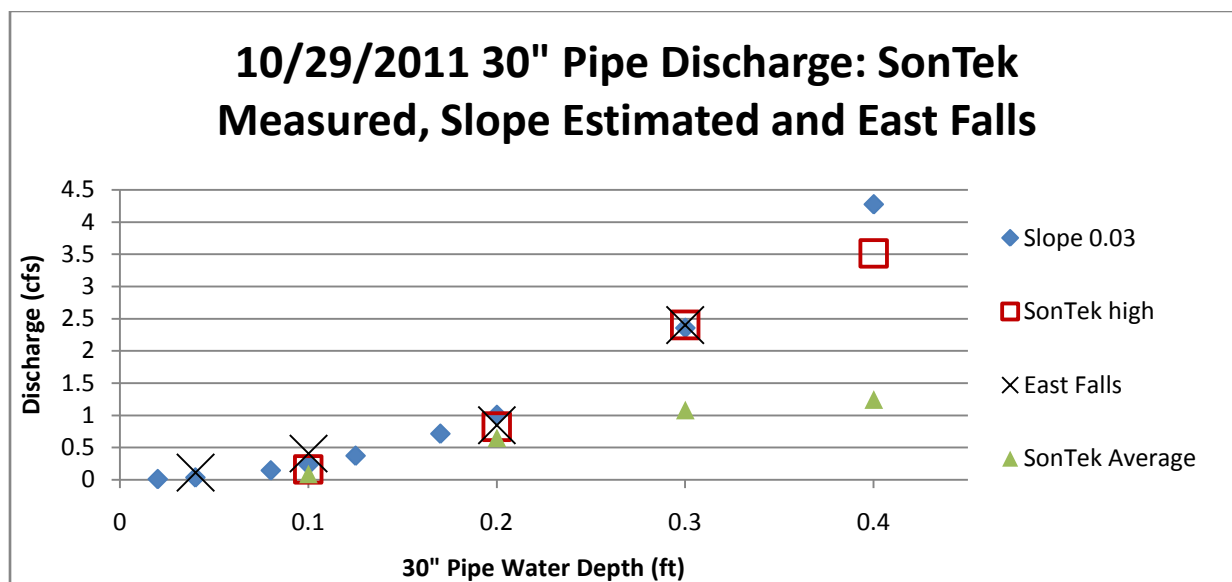


Figure 20: 10/29/2011 30" Pipe Discharge: SonTek Measured, Slope Estimated and East Falls

Storm Water

Precipitation on 10/12 and 13/2011 included soil infiltration, and at least for the daylight hours did not include flowing volunteer streams. Runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil. Figure 21 shows the hydrograph and cumulative precipitation for 10/13/2011. The 10/13/2011 peak hour of precipitation ended at 7:52 (0.17"), but the data show constant stage and declining discharges, indicating data collection missed the peak discharge as stage had already dropped to baseflow at the time of first measurement at 9:41.

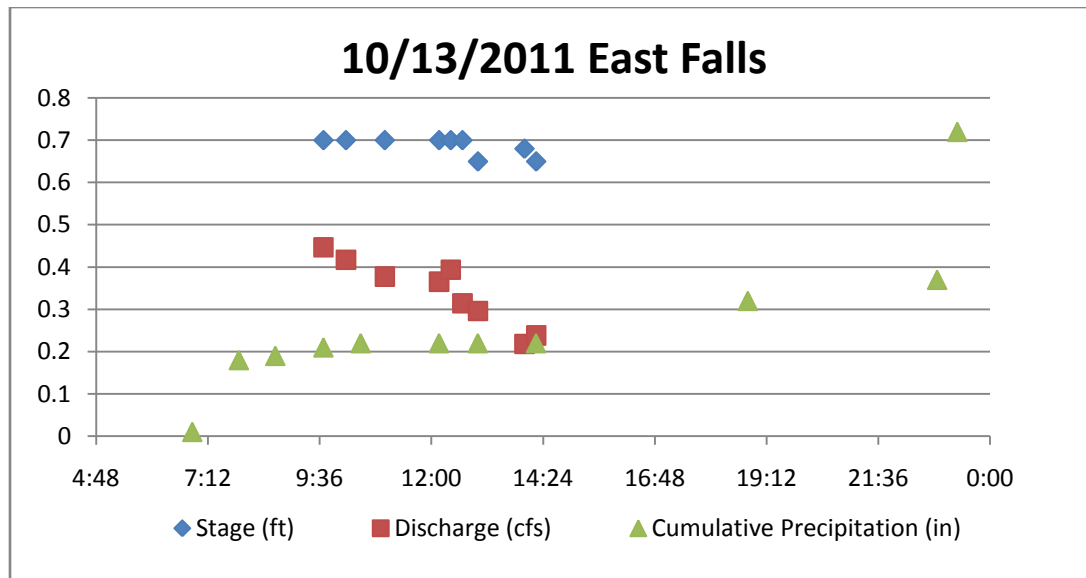


Figure 21: 10/13/2011 East Falls Stage, Discharge, and Cumulative Precipitation

Complete soil saturation may have occurred the evening of 10/13/2011 from the heavy rain of 0.50 inches. Evidence of higher stage was observed the following morning (absence of water line marker, removal of all fallen leaves along the stream flood plain, and new snags of branches, twigs and leaves). The volunteer streams were flowing with each rain event on 10/14/2011 and saturated soil conditions have been assumed. Pictures were taken of the volunteer flow entering upstream of East Falls. The flow was very turbid, with turbidity declining as each rainfall event ended. Stream water clarity declines as discharge increases from storm water runoff. Figure 22 shows the East Falls stream hydrograph for stage and discharge with cumulative precipitation on 10/14/2011. Two stage/discharge peaks were captured with peak discharge occurring 33 and 23 minutes, respectively after precipitation. The first peak of 10/14/2011 was the only hydrograph curve with enough data to visually determine the inflection point (defined as the time that the runoff portion of the hydrograph ended and stream discharge source became predominantly storage, interception and groundwater recharge). This time is 11:25, an hour after the discharge peaked. Figure 22 also shows the rapid rise and fall of stage and that the entire event is over in 2 hours.

On 10/29/2011, a cold front dropped 1.18 inches of precipitation that included sleet and snow. Figure 23 shows the hourly precipitation amounts and discharge data for East Falls and the 30" pipe. Peak discharge for East Falls and the 30" pipe were not obtained. After measuring a high discharge of 2.4 cfs at East Falls and discovering that the flow exceeded the capacity of some water falls, photo documentation of conditions took an hour. (See Appendix A for the 10/29/2011 photo documentation.) Higher discharges were measured at the 30" pipe (4.4 and 3.5cfs), but considering the 18-33 minute basin response time, it is likely higher discharges occurred before arrival. A large number of measurements were made to obtain good velocity data for the flow exiting the 30" pipe and just beyond the hydraulic jump on the discharge pad.

Figure 24 presents the discharge data and shows the variability associated with the discharge and compounded by the use of the FlowTracker acoustic flow meter in a pipe. (Sontek does not include velocity measurement in pipes and culverts as a suitable use for the FlowTracker.) The discharge pad had backflow (water moving upstream toward the 30" pipe) and this added to the uncertainty of the flow rate. Each location is essentially measuring the same flow and should show similar discharges.

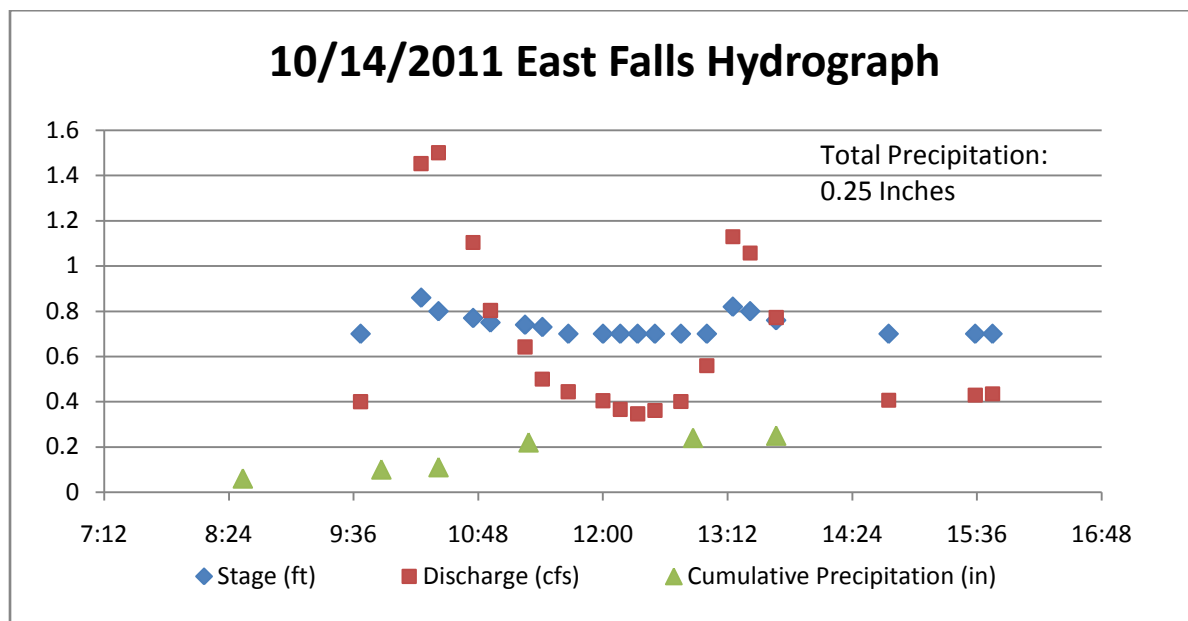


Figure 22: 10/14/2011 East Falls Hydrograph: shows the stage and discharge of two runoff peaks.

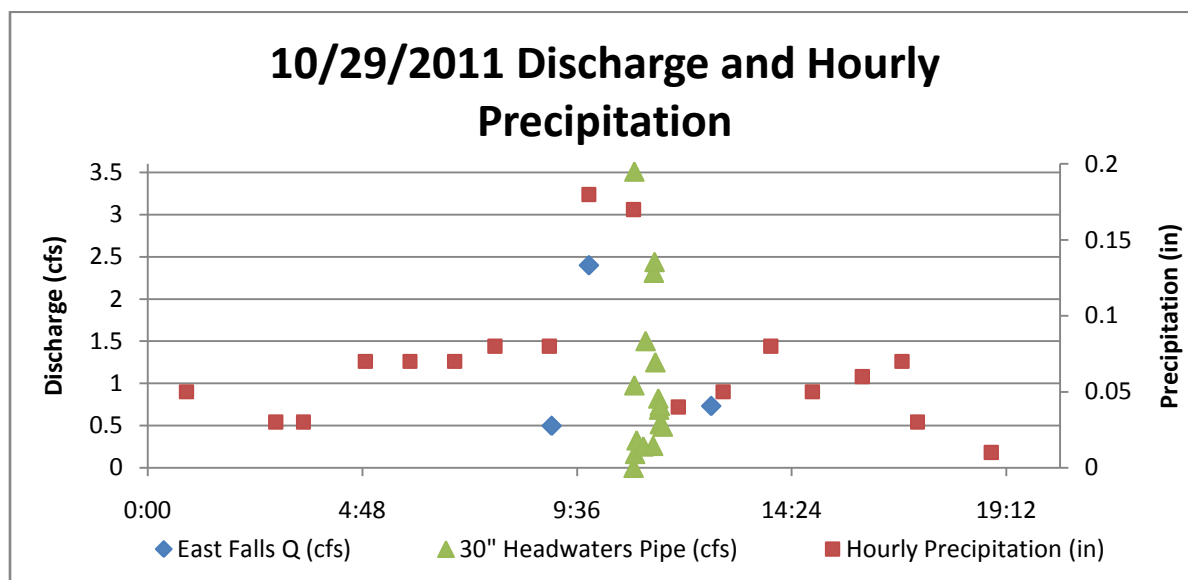


Figure 23: 10/29/2011 Discharge and Hourly Precipitation: East Falls and the 30" Pipe

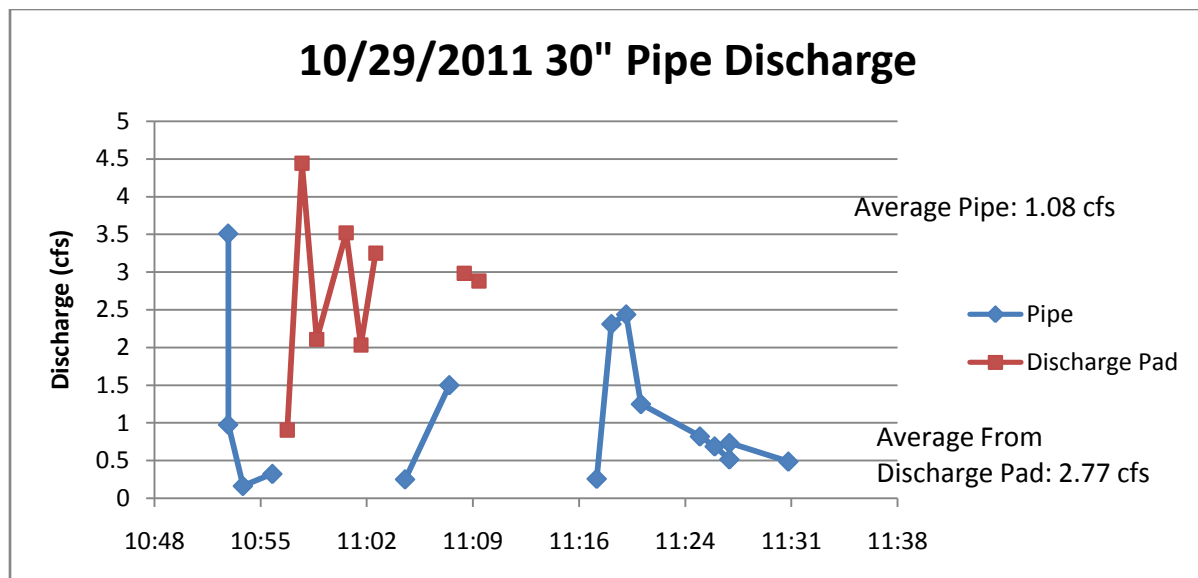


Figure 24: 10/29/2011 30" Pipe Discharge – these discharges reflect measured velocities for the pipe exit and on the discharge pad beyond the hydraulic jump. Neither location was ideal, but the discharges should be similar.

Figure 25 shows that the 11/22/2011 discharge data captured two peaks at East Falls (one at 13:15 and the other at 14:00), with Time-of-Concentration (T_c) of 23 and 18 minutes, respectively for rain ending 12:52 and 13:42. The discharge at the mouth is higher than that at East Falls due to runoff from additional watershed acreage. Cumulative precipitation is presented, showing that the heaviest rainfall occurred between 12:00 and 13:42. Only the East Falls volunteer tributary was active beginning at 11:55.

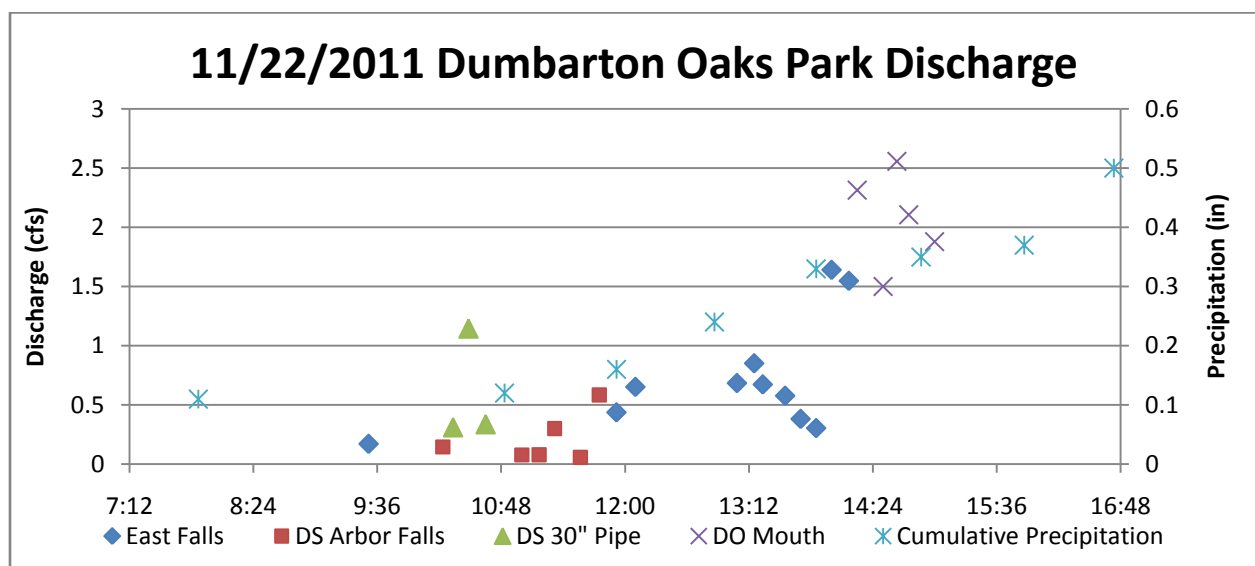


Figure 25: 11/22/2011 Dumbarton Oaks Park Discharge

Figure 26 summarizes the stage-discharge data of this study as a rating curve to show how the Dumbarton Oaks stream discharge (flow rate) changes with increase in stage. It reflects the

nature of the stream channel and its floodplain (nature of development, gradient, vertical sides versus sloped sides, soils, etc). Because a rating curve includes the basin response under many differing precipitation conditions, rating curves that include long-term data collected over several decades are the most useful. High stage/discharge data control the shape of the curve and are lacking for the Dumbarton Oaks stream.

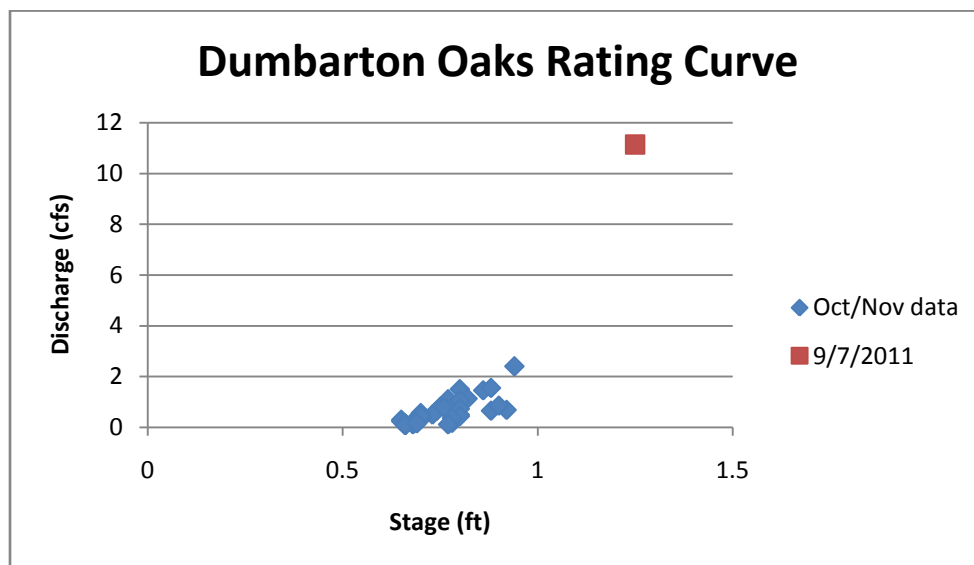


Figure 26: Dumbarton Oaks Stage-Discharge Rating Curve

Time of Concentration

Time of concentration (T_c) is defined as the time it takes water to travel from the most distant point of the basin to the point of measurement. (It is also defined as the time between the mass of excess rainfall and the inflection point of the stream hydrograph. The inflection point separates runoff discharge from baseflow discharge on the recession part of the hydrograph.) Peak discharge and Time of Concentration occur at the same time in the Dumbarton Oaks stream. Using a nomograph (Appendix E) to determine the time of concentration for the Dumbarton Oaks watershed requires the distance and the elevation differences between the most distant point and the point of measurement. These locations are the intersection of Fulton Street and 37th Street, NW (360 feet/105 meters) and the East Falls stage (90 feet/20 meters) having a drop in elevation of 270 feet/85 meters. These points are approximately 5600 feet/1707 meters apart along the water flow path. Plotting the distance and elevation values in meters and connecting the two points gives a time of concentration of 0.3 hours or 18 minutes. Stage and discharge measurements made at East Falls for the Dumbarton Oaks stream were evaluated for time of concentration. Data must show the time of peak flow. Table 4 shows the East Falls Time of Concentration data. The Dumbarton Oaks Park data show a response of 18-118 minutes (2 hours) for saturated soil conditions, but high precipitation events did not occur during this study. Short travel times are typical for urban areas whereas longer travel times occur in forested, undeveloped basins.

The data for 10/14/2011 captured peak flow and two complete rise/recession curves. The first peak precipitation occurred at 9:52 (0.11") with peak discharge (1.506 cfs) following at 10:25, giving a time of concentration of 33 minutes. The second peak precipitation occurred at 11:17 (0.11") with peak discharge (1.13 cfs) following at 13:50, giving a time of concentration of 1 hour and 58 minutes. Additional data is needed to understand why the second peak has a lower discharge and a longer Tc for the same amount of precipitation. Possibilities include additional infiltration (reducing runoff volume) and less water in storage available for release.

Table 4: East Falls Time of Concentration

Date	Time of Peak Precipitation	(in)	Time of Peak Discharge	(cfs)	Tc	Time of Peak Stage	Soil Condition
14-Oct	9:52	0.11	10:25	1.506	0:33		saturated
14-Oct	11:17	0.11	13:15	1.13	1:58		saturated
27-Oct	11:52	0.05		0.8	2:03	13:55	unsaturated
16-Nov	10:52	0.37	?	?	1:08	12:00	unsaturated
22-Nov	12:52	0.08	13:15	0.8507	0:23		saturated
22-Nov	13:42	0.09	14:00	1.6404	0:18		saturated

The time of concentration is used for the duration value in the Intensity-Duration-Frequency graph to determine the rainfall intensity based on the design return frequency storm of interest. As the time of concentration gets longer, the rain intensity for each design storm return frequency decreases to a lower precipitation amount. The Intensity-Duration-Frequency graph reflects the historical precipitation pattern for the area of interest. The preliminary time of concentration observations of this study differ from those used in the 1999 Greenhorne & O'Mara Study, but again high precipitation events did not occur and the data are insufficient to understand the timing differences.

Infiltration Estimate

Although the observed Fall 2011 events were low precipitation events, saturated soil conditions occurred and the 10/14/2011 event has sufficient data to estimate soil infiltration rates using the following equation:

$Q = 1/2 q_p(t_p + t_r)$, where Q is the total volume of water (cubic feet), q_p is the peak discharge (or the baseflow discharge) in cubic feet per second, t_p is the time to peak from peak rainfall (minutes), and t_r is the time of recession (minutes).

Table 5 shows the 10/14/2011 hydrograph results. (The 10/29/2011 event only has three discharge values for East Falls, and the maximum discharge value is not the peak. The 30" pipe discharge data can't be used to supplement the 10/29/2011 East Falls data because of the moderating effect the stream storage has on the observed East Falls discharge.) The second

peak of 10/14/2011 has a lower ratio likely because the pre-event water (water in the basin before rain begins) was released during the first peak. If there are no differences between surface soils and sub-surface soils, the infiltration rate equals the percolation rate after soil becomes saturated. Soil infiltration is controlled by the extent of soil saturation, the root network, the depth to the water table, and the permeability of sub-surface soil layers. These results should be considered preliminary because of the limited data events. An extensive data base is needed to calculate engineering design quality values.

Table 5 Hydrograph Runoff Versus Soil Infiltration

Date	Total Q Volume	Runoff Volume	S/I/GW Volume	Cumulative Rain (in)	Runoff/discharge Volume ratio	
10/14/2011	5783	4247	1536	0.11/3 hours	0.73	first peak
10/14/2011	7046	4550	2496	0.24/5.75 hrs	0.65	second peak

Genereux and Hooper (1998) used oxygen and hydrogen isotopes to determine the amount of pre-event water and event water in the volume of storm runoff. Their analysis of 41 events concluded that pre-event water was the source of over half of the runoff volume.

None of the 10/14/2011 individual precipitation events (or any of the events October – November 2011) had the intensity or extended long enough to evaluate whether the basin soils meet the 0.5"/hour infiltration rate needed for recharge to groundwater stormwater alternatives.

Hydrologic Analysis Update and Conclusions

The engineering plans for re-development of the Safeway (2009) and Jelleff Boys and Girls Recreation Center (2010) properties indicate that the re-development included stormwater capture, treatment and discharge into the stormwater sewer system. This significantly reduces the volume of stormwater runoff from both properties able to reach the Dumbarton Oaks Park stream. Precipitation that falls on the north slopes of the Safeway and Jelleff properties still drains to the stream. Likewise, a storm sewer line along S Street drains storm water into the Combined Sewer Overflow (CSO) pipe that runs under the Dumbarton Oaks stream and connects to the Rock Creek CSO (Personal Communication, Jessica Demoise, District of Columbia (DC) Water and Sewer, 2011). These improvements have altered the effective runoff collection area for the Dumbarton Oaks Park watershed from that reported in 1999 (Greenhorne & O'Mara). Re-development activities have not increased the percentage of impervious surfaces in the watershed. See Figures 1 and 2 for detail and the Table 6 summary of differences between 1999 and 2011 for the East Falls/Lovers Lane stream location.

Field observations and discharge results show that 6 of 18 park water fall structures did not have the capacity for a discharge of 2.4 cfs from 0.74 inches of rainfall (cumulative over an eleven hour period). These six water falls were each of the Three Bridge Falls, the east and middle Three Sister Falls, and Old Water Wheel Falls had flow through the water fall structure (this flow path is observed for low flows also). The actual flow capacities are lower than the 1999 estimates and document that some of the water fall structures are undersized for minor precipitation events. There are two potential reasons for the differences. (1) Additional damage to the fall structures removing critical stones may have occurred since 1999 that reduced the water depth capacity. (2) The 1999 calculated velocities ((1.91-2.46 ft/s) are higher than 2011 measured velocities. Measured velocities ranged from 0.0264-1.08 feet per second for the observed low precipitation events. However, velocity increases with water depth and even the 9/7/11 East Falls event represents a depth of 0.57' relative to the 0.83' used in 1999 for water fall flow capacity.

Table 6: Hydrologic Analysis Summary

	1999 estimate	2011 update
Watershed Acreage	124.9 acres	135.7 acres
Percent Impervious Area	31%	31%
Water Fall Flow Capacity	4.3-18.9 cfs	less than 2.4 cfs for 6 of 18 falls
Baseflow	0.06 cfs	0.07-0.44 cfs
Time of Concentration	25.2-27.6 minutes	18-123 minutes
Storm Return Frequency Precipitation		
6-month	1.8"/33 cfs	maximum precipitation was 1.18":
1-year	2.7"/107 cfs	too low to compare discharge
2-year	3.3"/167 cfs	estimates
10-year	5.3"/396 cfs	Minimum discharge for 9/7/11
100-year	7.4"/659 cfs	picture is 11 cfs for 0.9" rain

The 30 inch Headwaters pipe is the only perennial source of water into the park. Although this work provided more detail regarding the baseflow variation, it is unlikely that there have been any significant changes to the groundwater component of stream flow. The 2004 Dumbarton Oaks Gardeners' Court construction/storm water detention system with disposal by infiltration to groundwater is too small to produce a measurable stream recharge change.

The stage and discharge data in conjunction with hourly precipitation data show a range for the time for runoff to collect and produce a peak discharge. This property, called "time of concentration" is controlled mostly by land use and ground cover (the amount of impervious surface) followed by slope, shape and size of the drainage basin. The 1999 time of concentration range reflects the sub-basin flow routes added for two different flow paths (sub-basins 2+4 and 1+4: sub-basin 3 didn't add additional travel time when the path length of sub-basin 4 was

considered). The 2011 Dumbarton Oaks Park basin rainfall response had time of concentrations of 18-123 minutes, typical of urban and forested/undeveloped watersheds. These results are preliminary as all events had low precipitation amounts, below engineering design Storm Return Frequency amounts. The low observed precipitation prevented validation of maximum flow rates for the Storm Return Frequencies.

The time of concentration is the most significant difference between 1999 and 2011. If the stream results for the low observed precipitation events indicate the water collects faster than the estimates, the time will likely be even shorter for heavy rainfall.

During baseflow periods, the 30" headwaters pipe is most significant source of water into the Dumbarton Oaks Park, intermittently supplemented by low discharges from the Dumbarton Oaks 12" green pipe and the Georgetown University Building 18" pipe. The East Falls discharge data is a good estimate of the 30" pipe discharge during baseflow periods in spite of the surging flows. With the addition of storm water, the 30" pipe discharge becomes highly variable. Other storm water sources into the park flow for very short periods of time. The resulting discharge at East Falls is a composite of all the source waters moderated by the pool/stream storage and travel distance. During the Fall 2011 precipitation events, the water sources in order of total volume would be the 30" pipe, the 12" pipe and its overland flow down the Pebble Stream, the stone-lined crossing, the Naval Observatory/Embassy of New Zealand runoff, and the 6" cast iron pipe. No storm event observations were made at the 18" pipe to include it in the above ranking due to its late discovery on 11-29-2011. Although no discharge measurements were made at the 12" green pipe, it is ranked higher than the stone-lined crossing because of the co-located overland flow (too shallow to measure) and the longer flow duration.

If Farrand divided the meadow spaces by placing lines of trees in the ravines, (p96) she was also using a vegetated barrier and plants to reduce flow velocities. By allowing the northern woodland to develop where the land was too steep for mowing, she was increasing the land surface roughness (Manning's "n"), increasing runoff infiltration, and slowing the flow velocity. This has been very effective as no erosion of these slopes was observed and runoff occurs as overland sheet flow (very shallow water moving as a continuous surface instead of collecting into channels).

Recommendations

Each of the following lists of recommendations is provided in the order of suggested priority; that is the highest priorities are listed first, followed by decreasing priorities. Figure 27 shows the suggested locations for stormwater control actions.

Recommendations for Dumbarton Oaks Park

The following National Park Service actions are needed in consideration of the nature of the degraded water fall structures, the high traffic volume in the park, and in addition to any actions implemented by neighboring properties to retain their runoff.

1. Remove sediment in-fill from stream pond sections. If at all possible, this removal should be completed before the invasive plants are removed from the park slopes to provide the greatest protection for the in-stream structures. Removal of the invasive ground cover will increase the volume of runoff, the flashiness of the runoff arrival and its magnitude (higher water levels and volume), and add the potential erosion of soil. The downside to the early removal is that if a high precipitation event occurs before the replanted native vegetation becomes established, sediment removal may need to be repeated sooner than anticipated, but this one action restores the stream to best handle high flow volumes until off-property runoff rehabilitation actions have been completed. The CLR: Part I (page 47) states that Beatrix Jones Farrand and Robert Woods Bliss recommended pool dredging every three years. If the turbidity sources are eliminated, a direct benefit would be the need for a less frequent dredging schedule. Not only will sediment removal restore part of Beatrix Jones Farrand's original design, but it will increase in-stream water storage in the pools, reduce flow velocities, and most importantly, moderate the flash flooding stage. A greater volume of water in each pool has the benefit of decreasing water velocity and erosion potential by spreading the energy into a higher volume of water. The lower pool water velocities will cause the coarser sediment fraction (sand and silt) to settle out of the water column. Clay fractions will stay suspended for long periods of time, but this size fraction has significantly less erosive power. Each pool also decreases the stage flashiness via the water storage component. Normally sediment removal would be scheduled after complete revegetation and trail hardening so that rainfall during those construction periods will not add additional sediment, but in consideration of the continuing impact of runoff that exceeds the water falls flow capacity; it is recommended that this item be scheduled as soon as possible to minimize continued damage. Sediment removal should proceed from upstream to downstream to maintain designed pool depths and contain removal related turbidity to sections not yet addressed.
2. Revegetate all slopes and isolate from all foot traffic with temporary fencing, especially those slopes adjacent to the stream. Some slopes will need repair and recontouring to restore eroded soil and the original contours. Temporary fencing alone may be adequate to restore vegetation and leaf litter accumulation in some areas. This action has the benefit of reducing stream turbidity by protecting the soil closest to the creek from traffic and raindrop impacts, preventing erosion of the soil, and increasing runoff

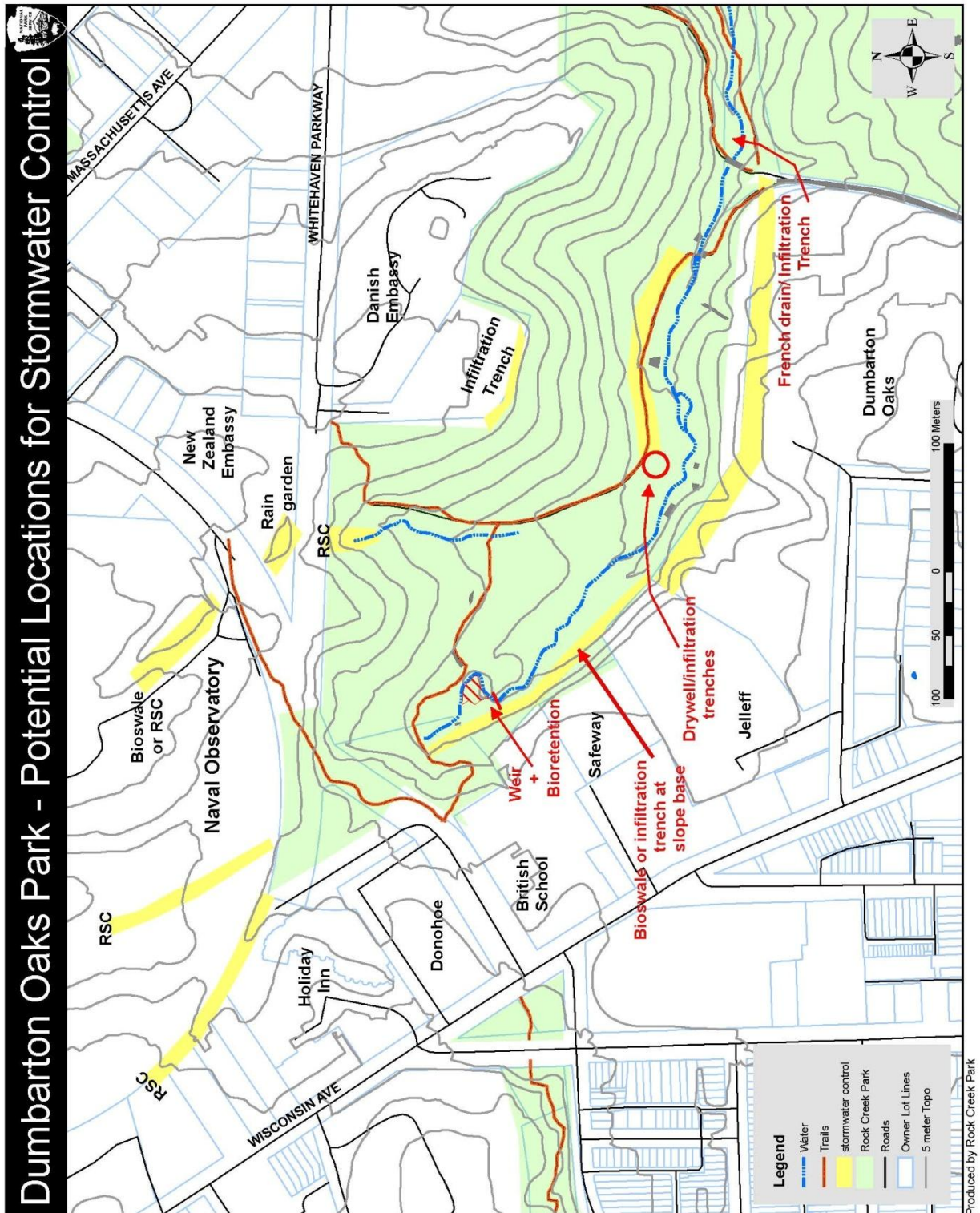


Figure 27: Dumbarton Oaks Park – Potential Locations for Stormwater Control

infiltration from dense root networks. Roots create connected pathways that water can follow to drain to the water table, increase soil porosity, and increase infiltration rates (Wilder and Kiviat, 2009, <http://www.epa.gov/reg3esd1/garden/pdf/stormwater.pdf>). A multi-tiered canopy protects the soil best with canopy storage of rain (up to a third of an inch depending on time of year and species), water storage in bark/downed trees and ground organic matter, and softening of rain drop impact (bushes and ground cover). The best way to protect stream water quality from turbidity and pollutants is to keep a vegetated buffer between the stream and all sources /flow paths. The vegetation slows runoff velocities, traps the sediment, promotes infiltration into the developed soil profile, and allows plant uptake of nutrients. Alternatively, temporary fencing could be installed between the entire stream path and the creek to allow all banks to naturally revegetate, accumulate leaf litter, and develop a soil profile without initial repair of erosion.

3. Harden the Stream Path and Farm Track (from its intersection with the Clapper Bridge trail east to the Old Stone Bridge) to add a drainage layer capable of carrying heavy precipitation runoff while the surface for foot traffic is raised above the surface water drainage layer topped with a permeable erosion resistant surface. Turbid water collects on both the Stream Path and the Farm Track and flows to the stream during minor precipitation events. Major precipitation events will generate higher volumes of runoff and additional active volunteer tributaries as indicated by erosion at the stream entry points. Consider widening the Stream Path to encourage all visitors to stay on the path (particularly upstream of Clapper Bridge Falls along the Meadow Falls, Jungle Falls, and the trail to the 30 inch headwaters pipe). People and their pets are using the trails in the rain when the soil is most fragile and most likely to be disturbed/washed into the stream, adding to stream turbidity and the ongoing erosion. At a minimum, a gravel/pebble surface would provide greater protection of the soft sediments and minimize erosion.
4. Re-route the creek by the islet rock wall back to its designed course to lengthen the stream flow path and reduce the gradient. A longer flow path serves to reduce flow velocities. Alternatively, this area could be used to create a bioretention pond to take advantage of the wide floodplain by installing a weir to control the elevation of outflow. Because a bioretention facility would cover a bigger area than the downstream pools, it would also be more effective in reducing the peak stage of the flash flooding. A weir would simplify discharge calculations to just require water depth measurements.
5. To the immediate west of the Old Stone Bridge on the Stream Path is a shallow depression with poor drainage at the base of the slope with the Dumbarton Oaks formal gardens. During the observed precipitation October-November 2011, flow collects on the Stream Path and flows east to collect in this low area. The routine soggy path (that

is a direct flow path to the stream during heavy precipitation events) could be addressed by installing a linear infiltration trench under the path and raising the path elevation. This trench topped by a hardened trail and permeable base would hold the runoff until it could percolate to groundwater and provide slow recharge to the stream.

6. Invasive plant removal should be closely followed by replanting of desirable species to minimize erosion and stream turbidity. This is a critical point especially for the easily eroded slopes on the western end of the park property as invasive plant removal will increase runoff volumes, velocities and flash flooding.
7. The last waterfall structure to the west, labeled “18” on the Features and Falls Locations Map, “box falls/Jungle Falls #4” certainly needs repair to restore the south side of the structure. This water fall structure height and width could also be expanded to increase the water storage upstream and create an herbaceous wetland. The size would need to be large enough to handle heavy precipitation events and reduce flow velocities so that plants would remain rooted.
8. The thick bamboo growth in the Meadow Falls area serves to reduce flow velocities and erosion potential when the stream stage rises over the stream banks. The park slopes hidden to the south of the bamboo should be planted with hardwood trees to slow flow velocities and maximize infiltration.
9. Preserve the meadows with thick native vegetation to continue to absorb runoff and slowly release it to the stream. The meadow vegetation is keeping the runoff in shallow sheet flow and runoff velocities low, preventing the collection of concentrated flows to cause erosion and turbidity. Discourage any walk paths through these areas. This situation changes on the down slope exit side of the meadows where the sheet flow concentrates into volunteer streams, but can be eliminated/managed with a drainage layer/ hardened permeable surface of the Farm Track and foot paths.
10. Reduction in the nitrate and phosphorus loading may be achieved with a public education campaign to include residential and lawn maintenance businesses. This same campaign could address the need for keeping dogs leashed in the park (public safety, protection of the vegetation for others to enjoy, dog poop has more fecal coliform bacteria than any other species, the poop from one dog isn’t the problem but the collective poop load is on the stream water quality, poop needs to be discarded in the garbage or flushed down a toilet, natural areas need the same protection as a city street or someone’s yard, etc.).

Recommendations for Neighboring Properties

Considering that the Beatrix Jones Farrand water fall structures are undersized for the larger precipitation events of 0.74 inch and more, uphill stormwater rehabilitation projects need to be “over-designed” to handle the larger precipitation events. There are many stormwater

alternatives allowing site specific considerations (soil type, space and cost as examples) to select one or more as needed. Alternatives such as green roofs and cisterns capture the water where generated for site reuse for irrigation. Bioretention ponds use plants and subsurface filters to remove pollutants and replenish groundwater supplies. Rain gardens also use plants tolerant of variable moisture conditions for pollutant removal and infiltration. Specific areas to target for stormwater volume attenuation are:

1. Runoff from Dumbarton Oaks during heavy precipitation events is currently causing erosion of soil and plant cover on the south slopes of Dumbarton Oaks Park. The volume of this runoff is sufficient to collect along certain flow paths with sufficient velocities to erode the soil and remove any plants within these flow paths. Examples of areas so impacted include the south slope within the Beech Grove, the former Iris Path, the south slope and the stream slope at East Falls, adjacent to Laurel Pool, and Hazel Walk. Along the stream to the immediate west of the Stone Bridge, high flows down the slope combined with eastward flows along the Stream Path are responsible for the erosion resulting in the visible sewer pipe. In addition, the Gardeners' Lodge stormwater system needs expansion of the length of the infiltration pipe so that the soils can dissipate the volume of water and recover for the next storm event. The perforated pipe slope also needs modification so that flow is not directed to the west end of the pipe where overflow is causing soil erosion. The young trees planted in this area are ideal for stabilizing the slope soils, increasing soil porosity, increasing infiltration capacity, and increasing retention of runoff. When full grown, each tree will remove 20-40 gallons per day from the soils. Understory vegetation would increase the volume of canopy storage and increase root density. The best option for Dumbarton Oaks Park would be for the entire north slope of Dumbarton Oaks to have an east-west French drain/infiltration trench with excess flows delivered to the Dumbarton Oaks stream channel downstream of Lover's Lane. An infiltration trench would increase the recharge surface area (sides and bottom of the trench) and with perforated piping at the top of the trench backfill, trench water storage would be maximized before excess water would drain and be released to the stream on the east side of Lovers Lane. Such a system could also capture the flow now released to the green pipe, allowing the green pipe to be removed and the Pebble Stream to be restored. These actions would eliminate the high flows from entering the creek in the section where the in-stream structures have limited capacity. Volume attenuation for Dumbarton Oaks is critical due to its proximity to the stream and the under-sized water fall structures.
2. Runoff collecting at the northern end of Whitehaven Street/ Naval Observatory/ Embassy of New Zealand could be managed using bioswales, rain gardens, or a bioretention pond combination providing slow release to the Dumbarton Oaks Park

basin. Repair and revegetation of the existing gullies down slope within the park property is also needed. This repair could include the installation of a Regenerative Stream Conveyance (RSC) to prevent heavy precipitation events from re-eroding these fragile slopes. As this runoff drains to the Meadow #5 area, reduction of this flow component would deliver less water and less turbidity to the volunteer tributaries that enter the stream on the downstream side of Old Water Wheel Falls and the upstream side of Laurel Pool.

3. The existing small 20-foot diameter storm water detention facility downhill of the Naval Observatory parking lot needs to be maintained, including repair of the overflow point that has a young gully. There also may be another “pond” in this area now over grown with porcelain berry upstream of this observed facility on the immediate opposite side of the trail (see GPS location #15). The potential additional “pond” includes posts installed on the ground to control the direction and level of flow draining to the 20-foot diameter pond. Redesign of this facility to retain and treat all runoff (including the heavy precipitation events) from the Naval Observatory parking lot (perhaps as a RSC winding down the slope) would be the best option for the Dumbarton Oaks Park. This area also has a minimum number of property owners (Federal and District of Columbia) and might be the most expedient off site runoff volume and turbidity source to reduce.
4. The grassed drainage area extending west of the end of Whitehaven Street NW parallel to Wisconsin Avenue, north of the Holiday Inn to the Meridian and to Observatory Lane NW collects water that drains into the 30” inlet pipe that provides the Dumbarton Oaks stream headwaters. This flow path is suitable for a bioswale or a RSC system of small pools, subsurface sand drainage, overflow grassed swales, rocks, and trees to slow the flow velocity, provide stormwater storage, and enhance ground infiltration of runoff. The use of dry wells/infiltration trenches below the surface can store some of the runoff and recharge groundwater for later arrival as groundwater recharge of stream base flow. The low precipitation events of this study produced no observed runoff, but the long drainage area needs slope breaks to slow the flow down, delay arrival to the 30” inlet pipe, and encourage recharge.
5. The 18” pipe draining the Georgetown University building needs additional monitoring to understand its discharge pattern and flow contributions. Attenuation of this flow source may be needed.
6. Runoff from the Embassy of Denmark is currently attenuated where Dumbarton Oaks Park is thickly vegetated by forest or meadows. The land surface slopes are stable and lacking erosion. The runoff from this direction becomes a problem where the runoff reaches the Farm Track and collects to flow down the Farm Track and discharge to the stream between the Old Stone Bridge and the Old Stone Pump House. Soil along the Farm Track is eroded, adding turbidity to the flow along this flow path. Capture and

retention of this runoff component on the Embassy of Denmark property perhaps using a bioswale or an infiltration trench along the south property line would reduce the runoff volume and improve park conditions.

7. The steep slopes of the Jelleff Recreation Center, Safeway and Georgetown University should be reforested to slow flow velocities, and to maximize infiltration and retention of the runoff generated on these slopes. This slope, from Georgetown University/British school to the Jelleff Recreation Center is covered with solid waste debris that will need to be removed before the slope can be revegetated. Alternatively, this slope could be modified into a meandering slope of terraces (each terrace providing recharge) to allow American Disabilities Act (ADA) access to the park experience. An executed example of this would be the Andropogen and Associates All Hallows Amphitheater design at the Washington National Cathedral (see Appendix E), incorporating storm water capture/infiltration terraces at multiple levels down the slope.
8. If it is confirmed that the Naval Observatory has an outfall for stormwater piping on their property, the resulting water course would likely be part of the original stream path. An RSC would be an effective way for runoff to be treated and retained until percolation occurs, slowing its arrival in the park.

Contingency Recommendations

If the above park actions and those of the neighboring properties do not completely address adverse events from heavy precipitation, there are several areas where water naturally collects that would be suitable for rehabilitation projects. These areas are:

1. Where the Farm Track curves at Meadow #4 and meets the Clapper Bridge trail, the volunteer tributary separates to flow to the upstream side of Laurel Pool. The ground is eroded, and soils are highly saturated for minor rain events in this area. Many alternatives would work here from hidden infiltration trenches (perpendicular to flow directions, potentially curved) and French drains to a visible bioswale or rain garden compatible with the vistas of Beatrix Jones Farrand's landscape.
2. The south side of Meadow #3 (near the Gray Memorial) may need a bioswale or French drain on the north side of the Farm Track to control the runoff that creates the volunteer stream that enters the creek to the east of the Old Stone Bridge.
3. Alternatively, if the Farm Track surface is hardened with a drainage layer separating high precipitation runoff from land surface foot and vehicle traffic, the seepage/runoff from Meadows 1-4 could be allowed to collect in a cobble-lined drainage feature to run along the north edge of the Farm Track. Such a cobble-lined drainage feature is used on both sides of the National Cathedral Pilgrim's Path in Olmsted Woods (Olmsted Woods

Restoration by Andropogon Associates) and in Oak Hill Cemetery to the east of Dumbarton Oaks.

4. If the reforestation of the steep slopes of the Jelleff Recreation Center, Safeway and Georgetown University properties requires further park action, an infiltration trench or a bioswale along the base of the slope would be the best way to capture this runoff and slow its discharge to the stream.

Recommendations for Dumbarton Oaks stream Rehabilitation

Beatrix Jones Farrand used rock walls along the creek to stabilize banks where high velocities occurred. See the south stream bank (1) downstream of Old Water Wheel Falls leading into Laurel Pool, (2) the upstream pool of Clapper Bridge Falls, and (3) downstream section to Arbor Falls. The eroded north bank upstream of Old Water Wheel Falls could be protected by mimicking her stone walls. Other options: (a) let the stream continue to meander to the north (allow the erosion to continue, accepting the eventual loss of more bulb plantings and landscape trees/designed vista) or (b) flatten and widen the stream bed and armor the north bank with boulders and the stream bed with cobbles. This would increase friction associated with the creek bed, slowing the velocity down for the high flow events. A wider stream channel makes the water shallower and more affected by friction, thus reducing flow velocities. The area downstream of Old Water Wheel Falls is a good example of this option: a broad, shallow section with a constant gradient.

The north bank of the Laurel Pool has experienced erosion that is threatening the structural integrity of the tulip poplar. If the original shape of the pool as a laurel leaf were recreated, the north bank will likely need reinforcement (a wall or continuous line of boulders would be most compatible with the landscape design) to retain the soil because the water takes a straight path from the pool inlet to West Laurel Falls. With removal of the accumulated pool sediment, water storage volume alone may not be adequate to protect the restored laurel leaf shaped north bank from high runoff volumes.

The park needs to consider modification of the in-stream structures to expand capacity for higher flow volumes. Many of the existing structures do not have the needed flow capacity for routine precipitation events and water flows through and under the structures. Such alternate flow routes increase the likelihood of future high runoff causing substantial damage. Re-design of the structures to expand capacity while keeping with the historical and cultural aesthetics and original design is possible.

If expanded capacity to accommodate the high precipitation runoff is eliminated as an option, the only other ways to protect the cultural resource is to (1) route the runoff around the stream structures or (2) add a retention pond to the park. Both would require a change in the designed

landscape aesthetics: the re-routing option from the removal of trees along the selected pipe path or new stream run and the retention pond from the area to be periodically flooded and its berm to provide the storage volume.

Recommendations for Future Data Collection

Considering the lack of significant rainfall events to compare to the stormwater design runoff requirements, it is recommended that stage/discharge data continue to be collected at East Falls to build the rating curve for the Dumbarton Oaks stream. Continuous stage monitoring would be the best way to capture high flow events using a pressure transducer (in the water) or a sonic water level indicator (on a post above the high water elevation) especially since many events occur at night. This continuous stage data would be correlated with daytime stage/discharge measurements. Note that removal of the sediment infill in the pools will likely alter the stream response to rainfall and the developed rating curve. The pre-removal stage/discharge data may no longer be valid and if so should be removed from the valid rating curve data. A basic rating curve will require at least 7-9 moderate to high precipitation events. The best rating curves are generated from long-term data because they include responses from various soil saturation conditions, different rain event arrival directions and rain intensities.

High precipitation discharge data is needed for the 30 inch headwaters pipe, the 18" pipe, the Naval Observatory parking lot at the Stone-lined crossing and 4X4 crossing, the Naval Observatory/Embassy of New Zealand flow into Meadow #5, the Embassy of Denmark flow into Meadows 3 and 4, the Dumbarton Oaks infiltration slope, the green pipe/overland flow, and the various flow pathways down the south slope adjacent to Dumbarton Oaks. A Hach Marsh McBirney flow meter would be the best instrument to use for pipe flow velocity measurements. The 30 inch headwaters pipe discharge needs additional data to understand the water source(s). The remaining locations need flow quantification for precipitation events exceeding 1 inch to produce enough flow to be measured. If the discharge for each of the sources is concurrently determined, the contribution for each source can be expressed as a percentage of the total East Falls discharge. Because of the rapid flow changes and the distances between the runoff entry locations, a team approach to concurrent data collection would be best to quantify relative contributions.

Ongoing surface water quality monitoring needs to add Suspended Solids Concentration (SSC) /Total Suspended Solids (TSS)*, turbidity, fecal coliforms, and Dissolved Organic Carbon (DOC) to the existing list of analytes. Not only will such data permit trend evaluation (are concentrations increasing, decreasing, or staying the same?), but such data is critical to evaluate the progress of rehabilitation efforts. Consider phased actions as an example; the water quality after the installation of temporary fencing could be compared to the pre-fencing water quality. Was keeping traffic off the stream slopes sufficiently successful in reducing

turbidity and pollutant levels below the desired threshold levels? What water quality and discharge improvements in the Dumbarton Oaks stream occur after a neighboring property addresses their stormwater contribution? Finally such data can reduce future costs and delays (for other streams) by identifying those alternatives that provide the best cost/environmental benefit for the subject soils. The Dumbarton Oaks basin is small (smaller scale means a lower implementation cost) and receives high use making it an ideal test location for potential fixes that may be effective in other watersheds.

*A USGS study (Gray et al 2000) of the standard methods for Total Suspended Solids (TSS) and Suspended Solids Concentration (SSC) concluded that SSC produces relatively reliable results for natural waters whereas TSS was unreliable. Results from the two methods are not equal to quantify sediment load. If TSS is currently the form being collected, consult with the data users to see if change to SSC would pose any long term evaluation problems.

Surface water sampling within Dumbarton Oaks stream is recommended (1) to determine what pollutants contribute to the Flow Tracker Signal-To-Noise-Ratio (SNR) variations (does it correlate only to suspended sediment or does it also correlate to dissolved concentrations/fecal coliforms?) (2) to determine the water quality differences between the 30 inch pipe baseflow and the water released five seconds after the blower comes on (such data may help track down the source of the discharge surges), and (3) to evaluate the source areas of the fecal coliform, nitrate, and total phosphorus stream loading. Multiple sampling locations will be needed to separate headwaters sources from runoff and from the potentially leaking sewage piping. At a minimum the following locations are suggested: the current sampling location at the mouth with Rock Creek, the 30 inch, 18 inch, and 12 inch pipes, the stone-lined crossing, the Naval Observatory/ Embassy of New Zealand flow into Meadow #5, and above East Falls. If the nitrate, total phosphorus, and fecal coliform are positively correlated with suspended sediment, rehabilitation actions that focus on preventing erosion and reducing turbidity will also improve water quality.

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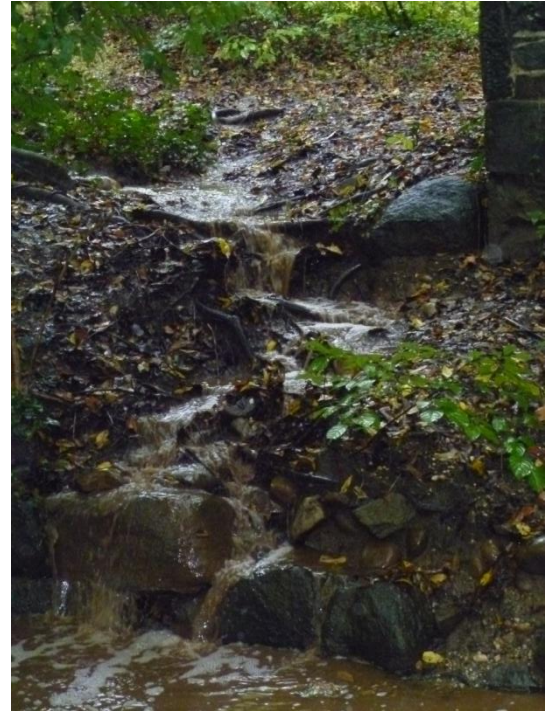
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Appendix A – Photo Documentation of October 29, 2011 Precipitation

On 10/29/2011, a discharge of 2.4 cfs was measured at East Falls at 9:52A. This was likely not peak flow, but as the stage had risen quickly, it was decided to document conditions for all the Dumbarton Oaks Park falls heading upstream. No picture was taken of East Falls but it handled the flow and had additional capacity. At all flows, East Falls has flow passing under the waterfall structure outside the south wing wall. The East Falls volunteer tributary started flowing into the stream at 9:15A. At this time 0.74 inches of rain had fallen (total rainfall for the day- 1.18"). Below are pictures of the East Falls volunteer tributary taken on 10/14/2011.



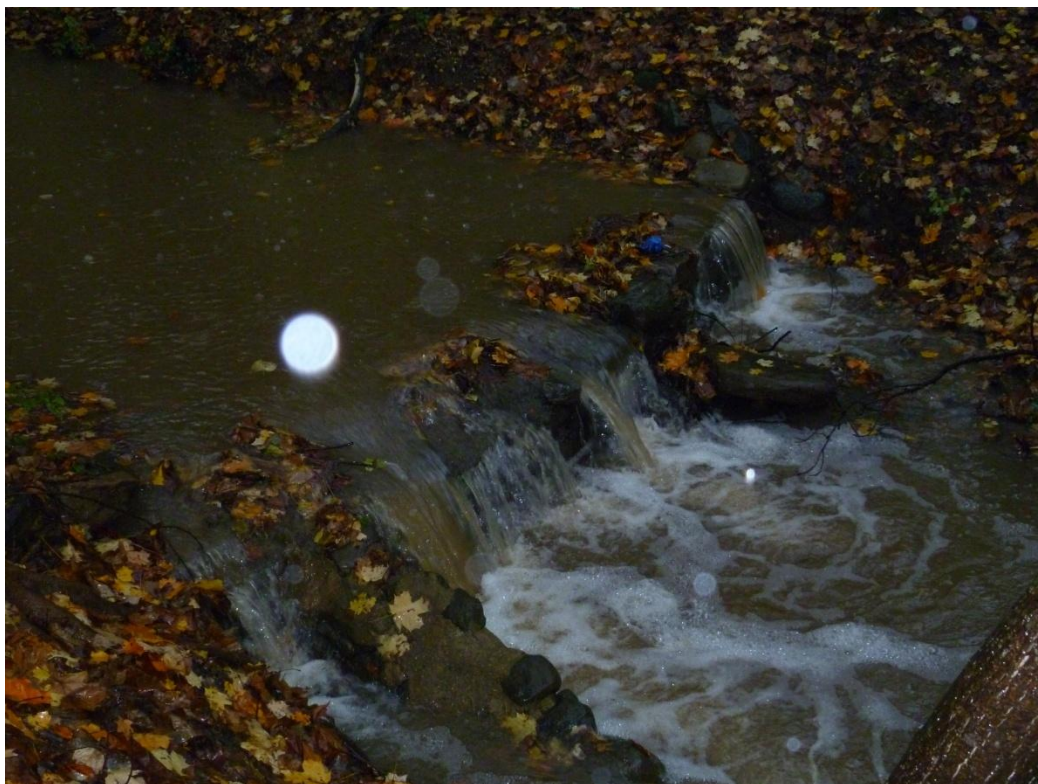
The following picture shows a wet area on the Stream Path below the slope with Dumbarton Oaks and to the immediate west of the Stone Bridge (9:58A). Water collects in this naturally low area that would be an appropriate place for a rain garden (the objective is to create a thick root mass to improve soil permeability and increase water infiltration using plants tolerant of a wide range of soil moisture conditions) on the south side of the path. Although not observed during any precipitation events during this assessment period, it is obvious from the eroded soil that once covered the now exposed sewer pipe in the stream channel that high flows into the creek do occur in this area. Raising the path elevation with a drainage course and a hardened permeable surface for traffic could increase the water storage of this naturally low area and decrease the turbidity contribution to the stream.



Three Bridge Falls (E) at 10:01A – water volume exceeds the capacity on the south side of the structure.

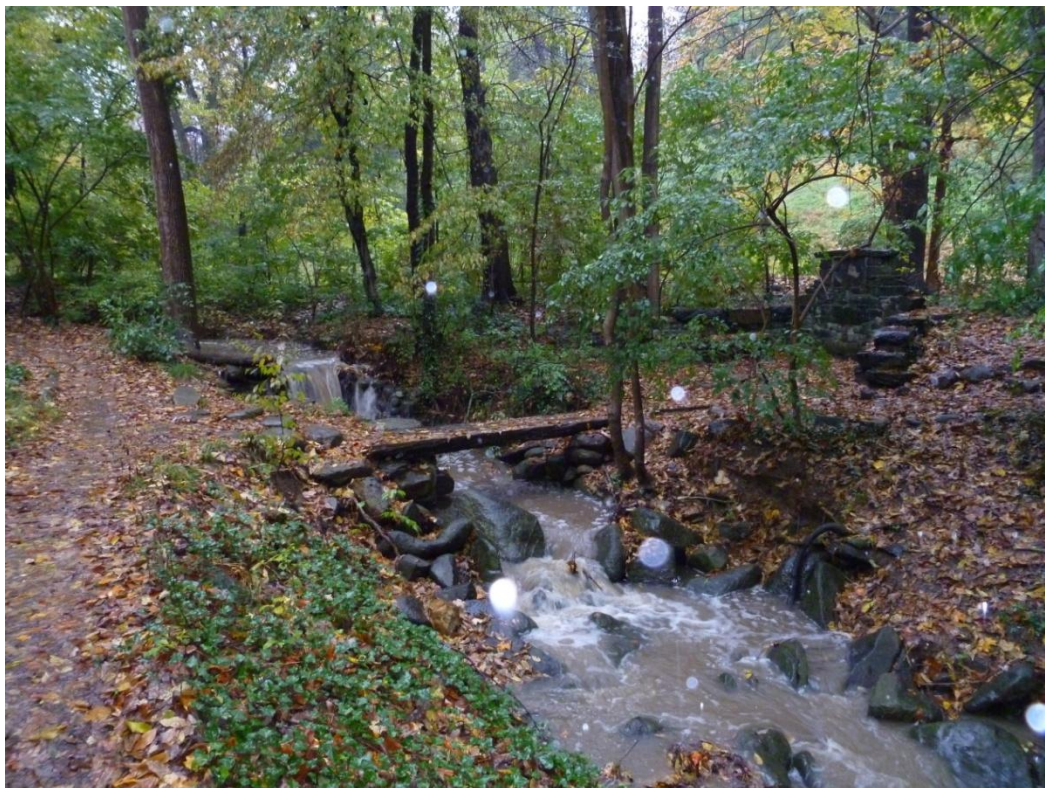


Three Bridge Falls (M) opposite Forsythia Way at 10:01A – water volume exceeds the capacity on both sides of the fall structure. A more detailed photo taken at 10:02A follows below.





Three Bridge Falls (W) at 10:04A – water volume exceeds the capacity on both sides of the structure.



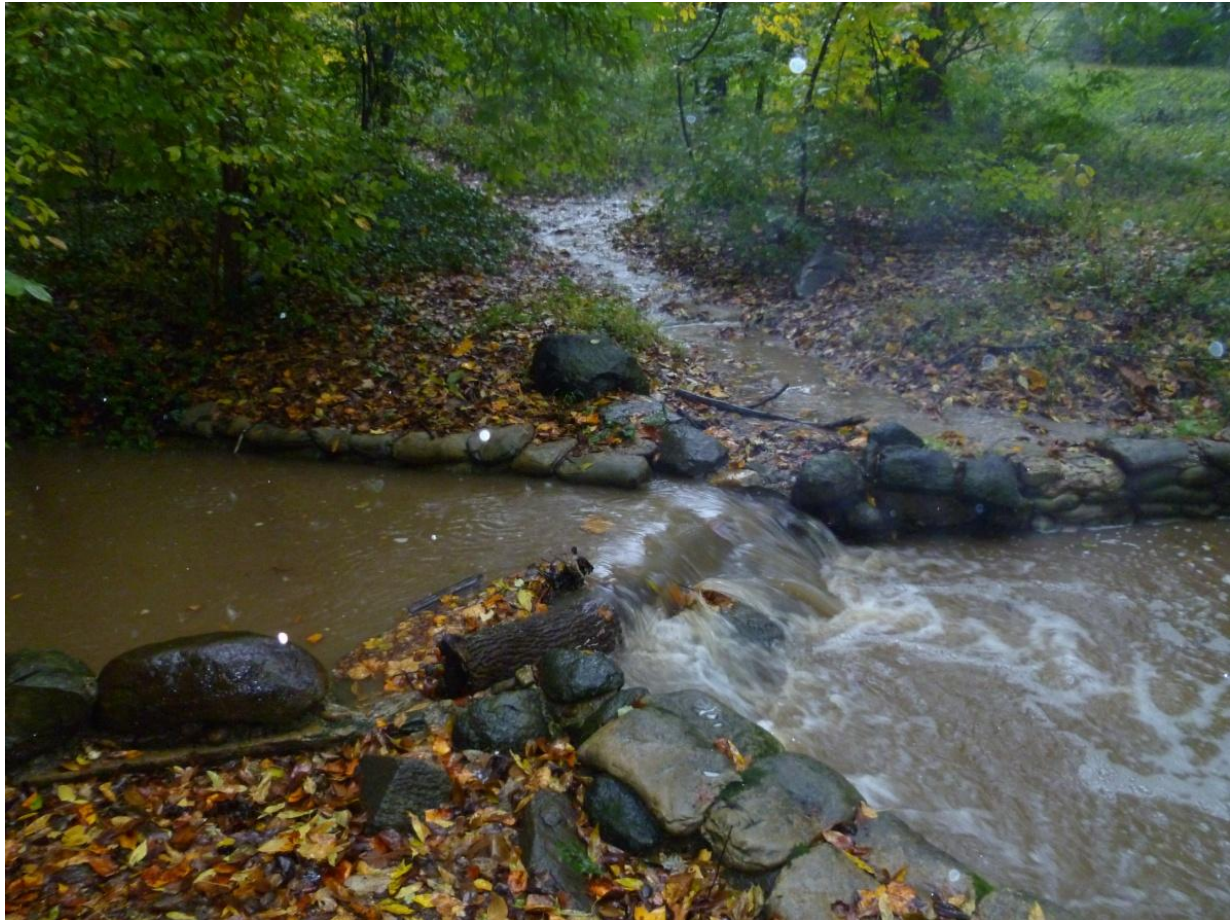
(Above) Gray Arbor Memorial with the first of the Three Sisters Falls at 10:06A. The boulder lined stream section is handling the flow fine but the eastern most Three Sisters Falls has flow bypassing the structure on the north side as shown in detail in the following photo.



In spite of the humidity/raindrop compromised photo above, it is clear that the middle Three Sisters Fall has flow leaving the south side channel (10:07A). The Three Sisters Falls (W) handles the discharge but has past erosion from a volunteer tributary outside its north wing wall. Both waterfalls are below.



(Above photo) Laurel Pool at 10:08A is full and providing water storage. The eroded pool banks are not visible. Note that the incoming flow to Laurel Pool takes the shortest flow path along the north shore to the water fall. This is the cause of the north bank erosion. Any pool rehabilitation to fix this situation will require a hardened north bank (boulders or a stone wall). The following picture shows West Laurel Falls at 10:12A discharging into Laurel Pool (no capacity problems at this volume). The log damming the stream channel serves to increase creek storage by causing the upstream water to pool, but needs to be removed for higher flows. The volunteer tributary from the Farm Track drainage path was actively discharging on the north side of the north wing wall.





Old Water Wheel Falls at 10:15A has leakage through the fall structure on the south side. This leakage occurs during lower stage conditions also and should be repaired. Note the erosion on the north side of the fall structure from a volunteer stream that was not active on this date.

The following picture shows flow exiting the 12 inch green pipe in the pebble stream area at 10:17A. The pipe contains a bend forcing the higher flows to exit up the interior pipe wall. No note was made whether the overland flow down the pebble stream was also active as it was on October 13 and 19; dates that had less rainfall than 10/29 (0.72", 0.5", and 1.18", respectively). The overland flow on October 13 was observed to be approximately double that observed to be exiting the pipe (flow was too shallow to measure velocity either for the green pipe or the overland flow).

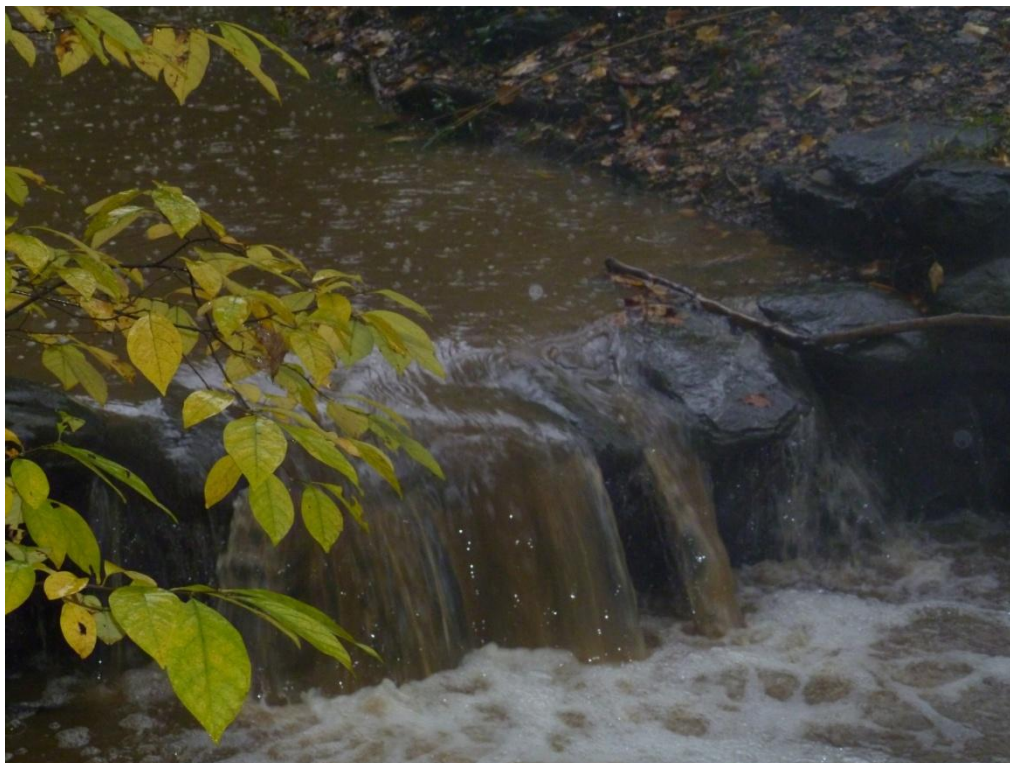


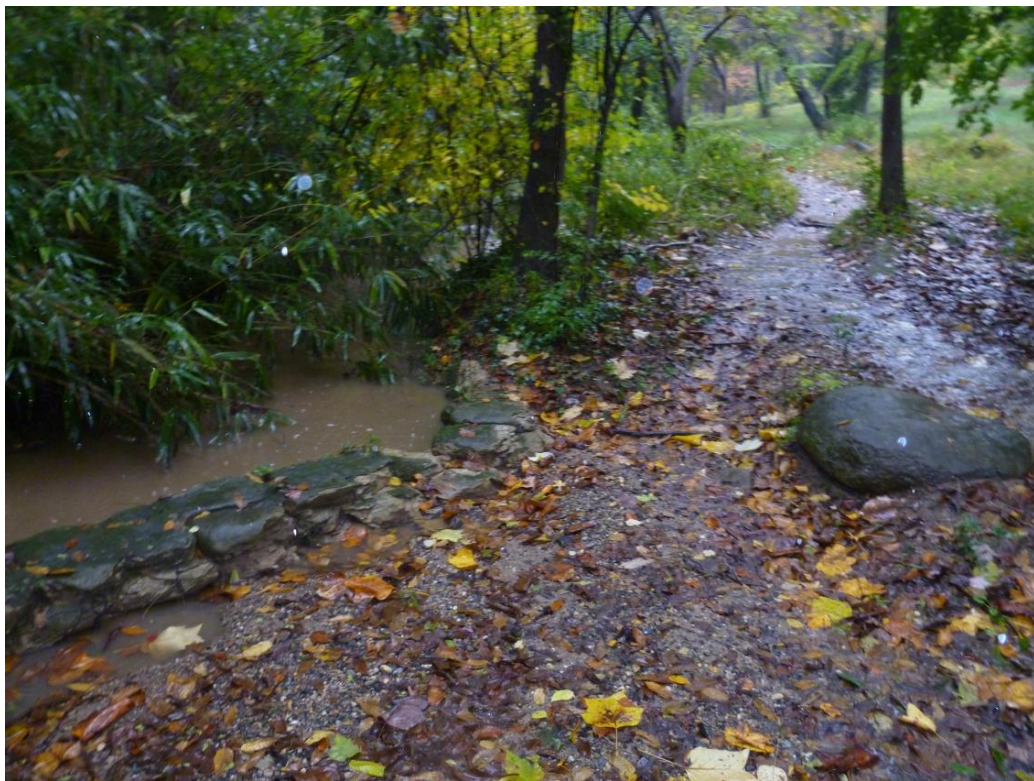


The stream channel (10:17A) between the Spring Grotto/Pebble Path and Arbor Falls has migrated north and is eroding the north bank exposing the roots of the remaining trees and plants. Bulb plantings on the top of the north bank are being eroded with every rain event. Alternatives to fix this situation include (1) the installation of a rock wall similar to those used by Beatrix Farrand for high velocity stream sections (2) the removal of sediment, followed by the addition of cobbles to create a wide, gently-sloping cobble-lined stream course, and (3) the armoring of the north bank with boulders to force the flow south. The channel is steep enough in this section to concentrate the flow into a narrow width (increasing the flow velocities) and even the armoring option should include a widening of the stream base to increase friction and slow the velocity. The following photo (10:18A) shows the upstream section and the beginning of the eroded section.



Arbor Falls and Clapper Bridge Falls had sufficient capacity with the observed discharge as the photo below and the photo on the following page show (both photos taken at 10:18A).





Upstream of Clapper Bridge Falls at 10:24A, the falls structure is providing storage and slowing the flow down by forcing the water to pool. This area is one of the pools needing sediment removal.



Water collecting on the stream path that may drain to Old Water Wheel Falls (10:24A).





Pictures taken 10:25 and 10:28A of falls in the Meadow Falls area that have sufficient capacity.





Pictures of the upper stream at 10:28A and the western-most Jungle Fall at 10:29A show how the thick invasive plant cover is protecting the soil and minimizing any potential erosion in spite of the high velocities.

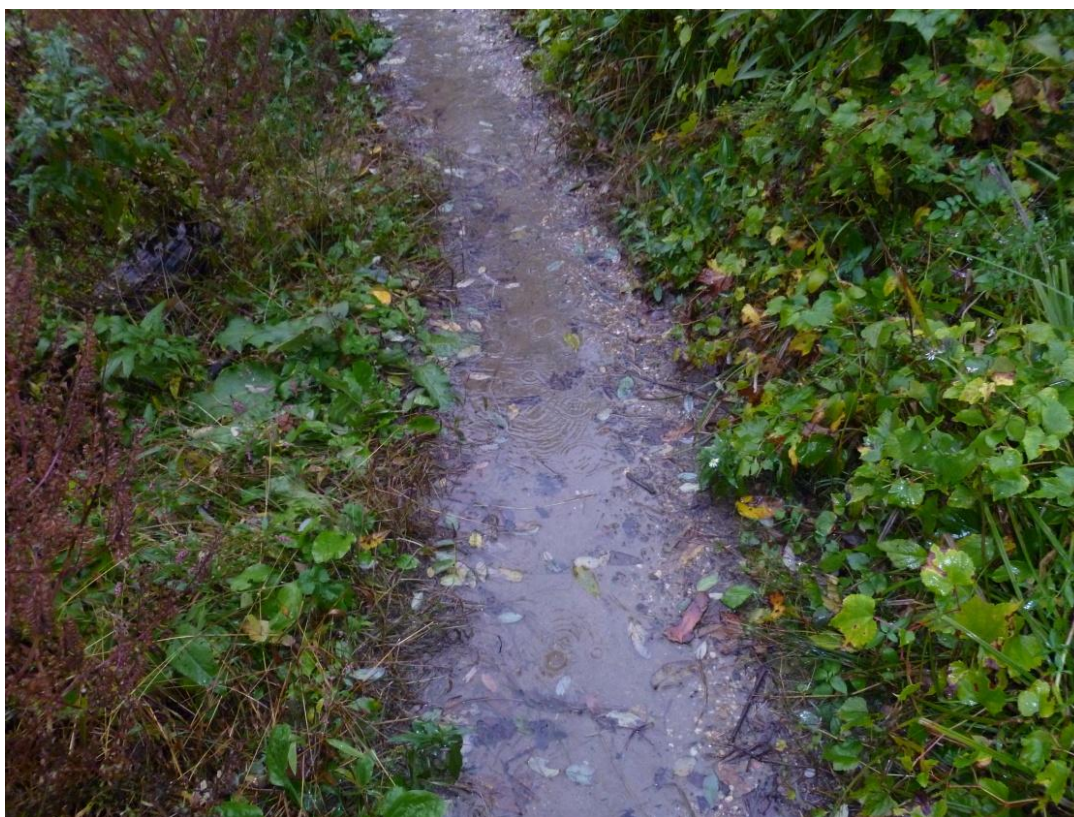


(Above photo) Looking east towards Clapper Bridge Falls, this picture (10:29A) shows that water follows the park trails and is transporting turbid water. The following pictures (10:31A and 10:32A) show the same trail to the west (but looking east and west, respectively).





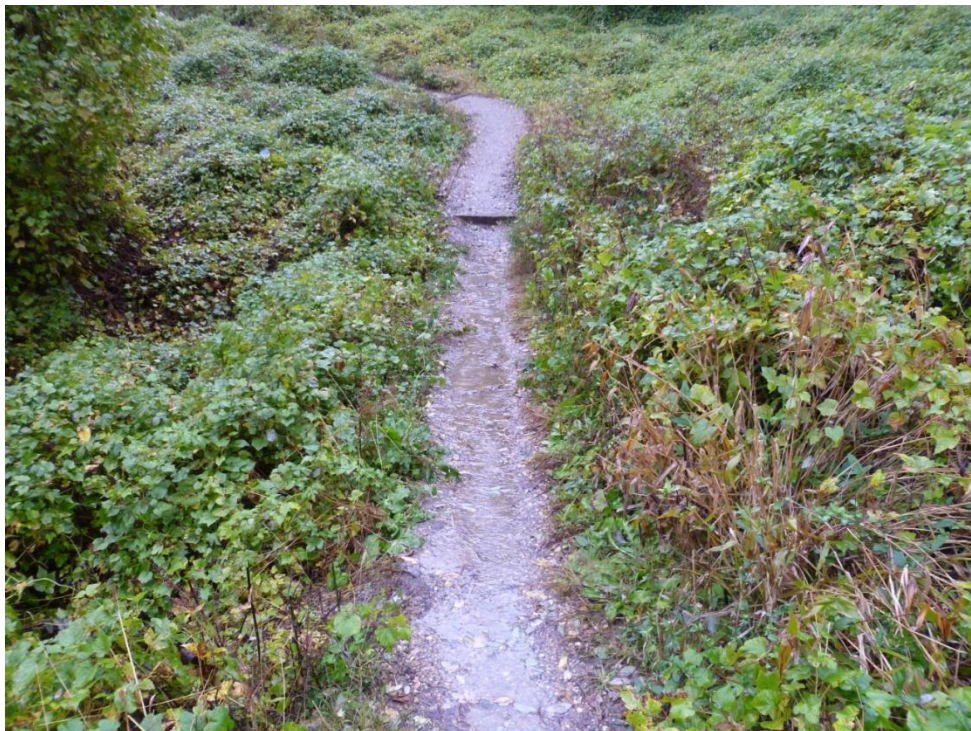
This picture shows two path crossings on the west side of the park at 10:35A for water that leaves the Naval Observatory/Building 52 parking lot. Water was collecting (but not flowing) in the 4X4 channel and flowing in the stone-lined channel to the south. The following picture shows the stone-lined channel where decreasing flow was observed/measured from 1.05 to 0.36 cfs (five measurements made 10:44-11:54A).



This picture shows water on the trail looking to the south (10:35A).



This photo shows the 30 inch headwater discharge of the Dumbarton Oaks stream (10:36A). Numerous flow measurements ranged from 0.253 to 4.47 cfs (the blower was on during the entire measurement period 10:53-11:31A). The 18 inch headwaters pipe was unknown at this time but is located on the south side of the stream (to the right in this photo) across from the vine-covered fence. The following picture (10:36A) shows some water on the trail to the south of the 30-inch pipe.



Appendix **B** – Photo Documentation of Erosion from Runoff leaving Dumbarton Oaks

Erosion observed during Fall 2011 along the shared boundary with Dumbarton Oaks starting at the Lover's Lane entrance gate:





The top photo is a second photo of the same erosional area with vegetation (10-6-2011). The bottom photo shows another eroded slope including the Iris Path stones now visible.



From East Falls looking south toward the slope down from Dumbarton Oaks.



Looking east from East Falls and showing the erosion that created higher elevation “ivy islands” between the runoff flow pathways.



Note the difference in the vegetation coverage difference between the north and south slopes at East Falls. A closer view follows.



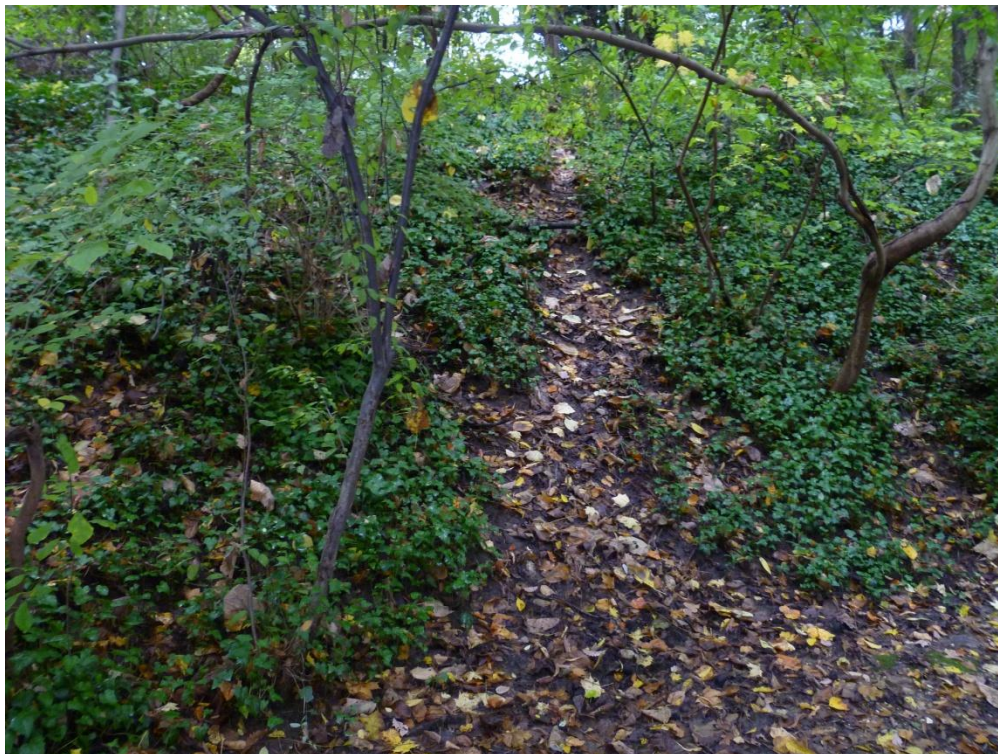


The concrete sewer pipe is exposed because runoff collects on the stream path, flows east to the low spot at the base of the south slope with Dumbarton Oaks and joins flow from Dumbarton Oaks during higher rain events. The high flows removed soil that originally covered the sanitary sewer pipe.





Notice how the water appears to go around the areas with thick vegetation.



Adjacent to Laurel pool, one of the flow pathways down the slope from Dumbarton Oaks.



East of Old Water Wheel Falls on the south park slope.



Picture (above) of the Gardeners Lodge east and west overflow caps of the stormwater infiltration piping that is located uphill of the bamboo forest adjacent to Clapper Bridge Falls. Note that the west end is lower in elevation than the east end. The following picture shows the rock fill on the west end used to return the eroded grade back up to the fence bottom.



Appendix C – Photo Documentation of Runoff Sources into Dumbarton Oaks Park

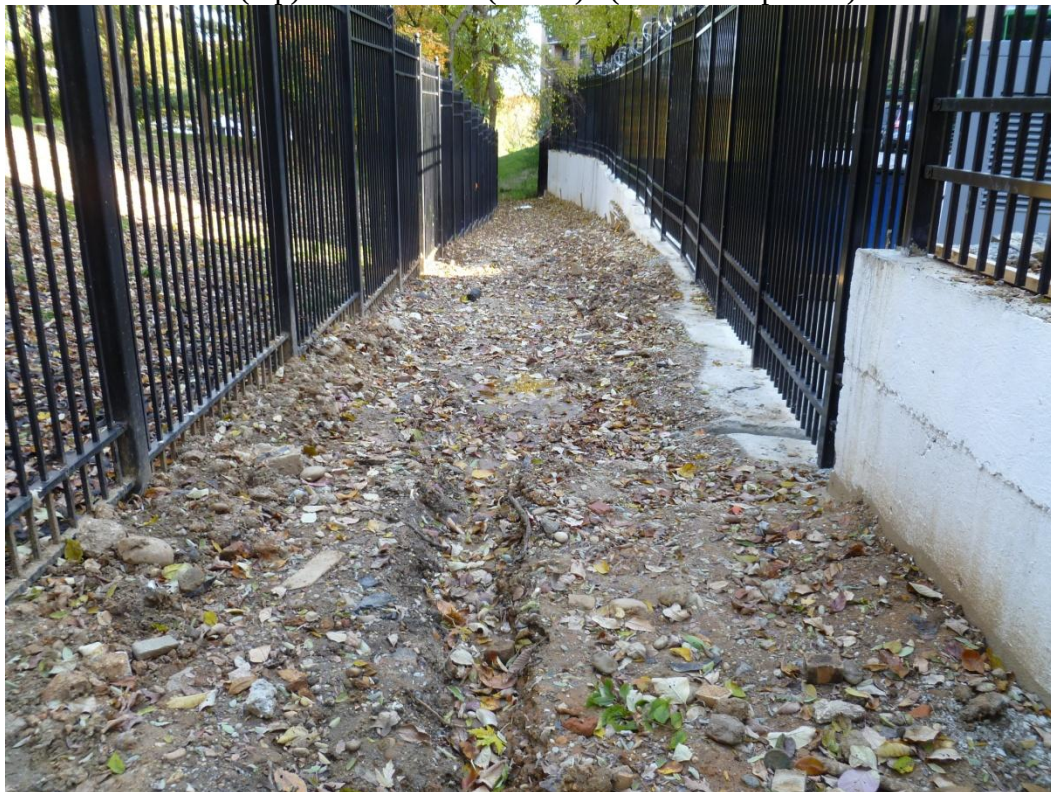


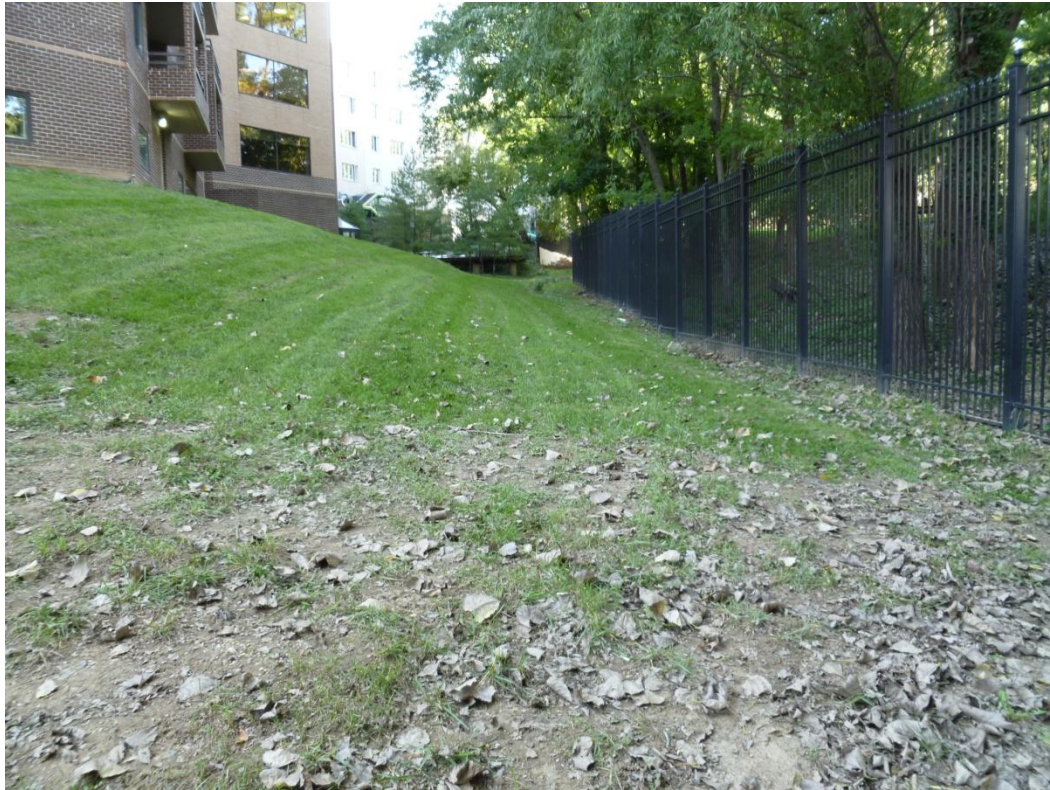
Above and below are photos of the overgrown 20 foot diameter stormwater pond located close to Whitehaven Street outside the Dumbarton Oaks Park. West and uphill of this pond is a porcelain berry overgrown area that has 6"X6" posts laid down to control flow. (10-6-2011)





Sloped drainage area behind the Wisconsin Avenue development and the Naval Observatory from the west end (top) to the middle (below). (11-4-2011 photos)





(above) Grassed area between the Holiday Inn and the Naval Observatory that drains to the 30" inlet pipe shown below (the pipe is top center). (10-6-11).





Drainage from the Naval Observatory Building 52 parking Lot enters the Federal Reservation 357, flows overland (picture below with Whitehaven Street in the background), and eventually enters the Dumbarton Oaks Park. (10-27-2011 photos)





Flow exits the Naval Observatory on its northeast side from a 6" PVC pipe located above a 24" cast iron pipe, flows in this channel into the Embassy of New Zealand property where it joins New Zealand runoff and drains into a storm grate/piping (this low area and grate are shown below) that discharges into the Dumbarton Oaks Park. (October 27 and 1, 2011 photos)





The Naval Observatory/Embassy of New Zealand combined flow leaves the Woodland area into Meadow #5 where the flow follows the west side of the Farm Track. (11-16-2011)



The above photo shows a gully from runoff leaving the Embassy of New Zealand property leaving the park fencing horizontal (visible at the top of the 10-1-2011 photo).



Sewer manhole located down slope of Jelleff. In spite of the solid waste debris used to minimize erosion, the soil upslope of the manhole has been eroded. If the round disc leaning against the manhole is the cover, this manhole may still be discharging into the park, i.e. this cover may not be bolted down to prevent discharge. (11-20-2011 photo)

Appendix D – Photo Documentation of Dumbarton Oaks Park Discharge Measurement Stations

Figure D1: Two views of Mouth of Dumbarton Oaks (DO Mouth) stream transect: perpendicular to flow and looking upstream



Figure D2: Two views of East Falls (EFALL) stream transect: looking upstream and perpendicular to flow.



Figure D3: Two views of Downstream of the 30" pipe (DS30INCH) stream transect: (top photo) perpendicular to flow with the northwest corner of the Safeway garage in the background and (bottom photo) looking downstream.



Figure D4: Two views of Downstream of Arbor Falls (ARBFALL) stream transect: (top photo) perpendicular to flow and (bottom photo) looking upstream.



Appendix E - Miscellaneous Information: Nomograph, Olmstead Woods, Photos, and Data

Figure E1: Dumbarton Oaks Park Nomograph for Time of Concentration (T_c)
 (Input: $L=1707$ meters and $H=85$ meters for $T_c=0.3$ hours or 18 minutes)

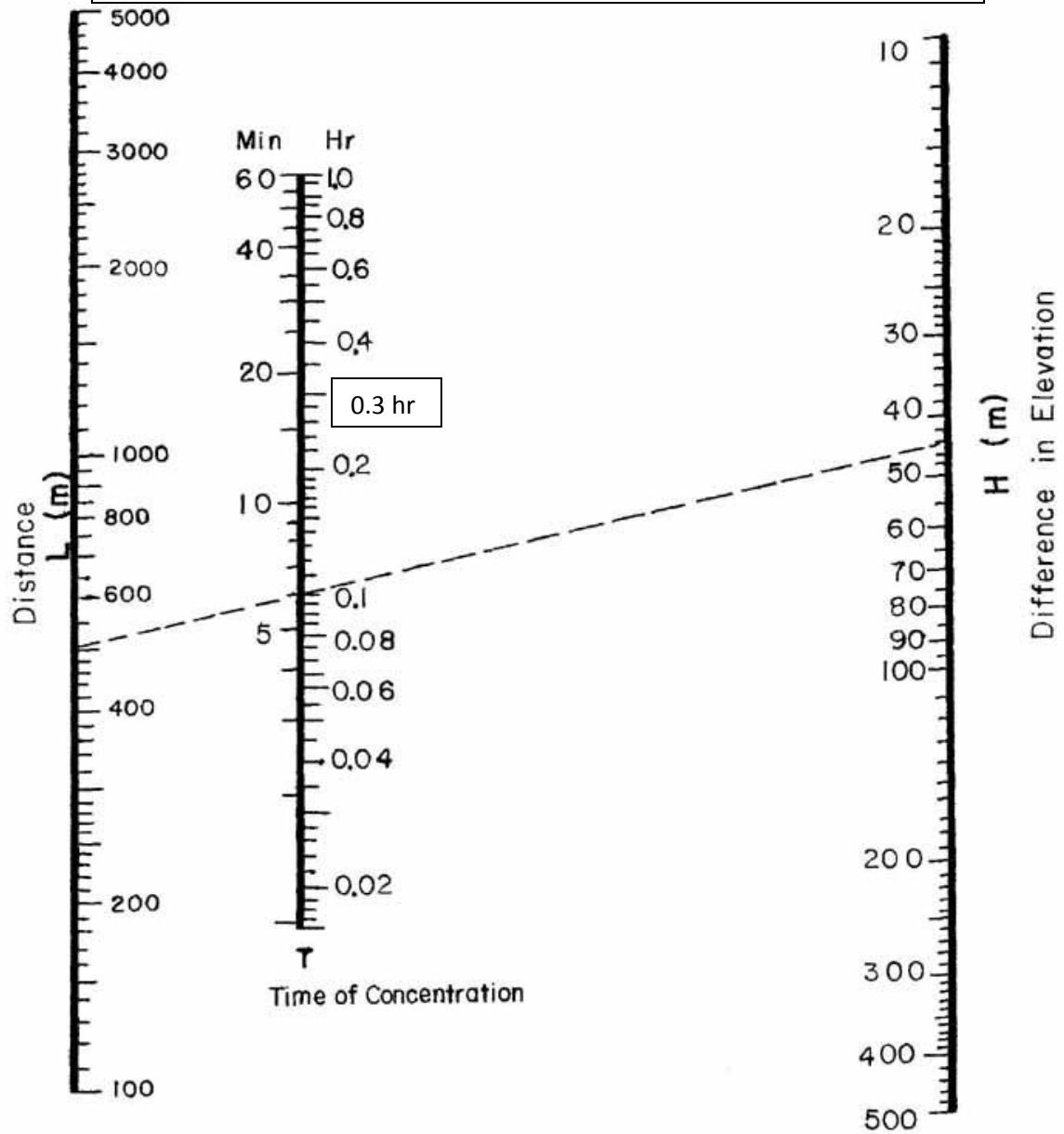


Figure E2: Washington National Cathedral Olmsted Woods and All Hallows Amphitheater restoration project to correct stormwater erosion using stone gutters, collection systems and infiltration to groundwater. (Andropogon Associates and Michael Vergason Landscape Architects)





Figure E3: This multi-use amphitheater design meshes stormwater collection/infiltration with entertainment and supplements the two uphill infiltration trenches. The design slows the runoff velocity with infiltration in the grassed areas between the seat rows and temporary storage below the front stage. Pebbles below each seat row minimize soil erosion from runoff cascading over the benches (photo below).

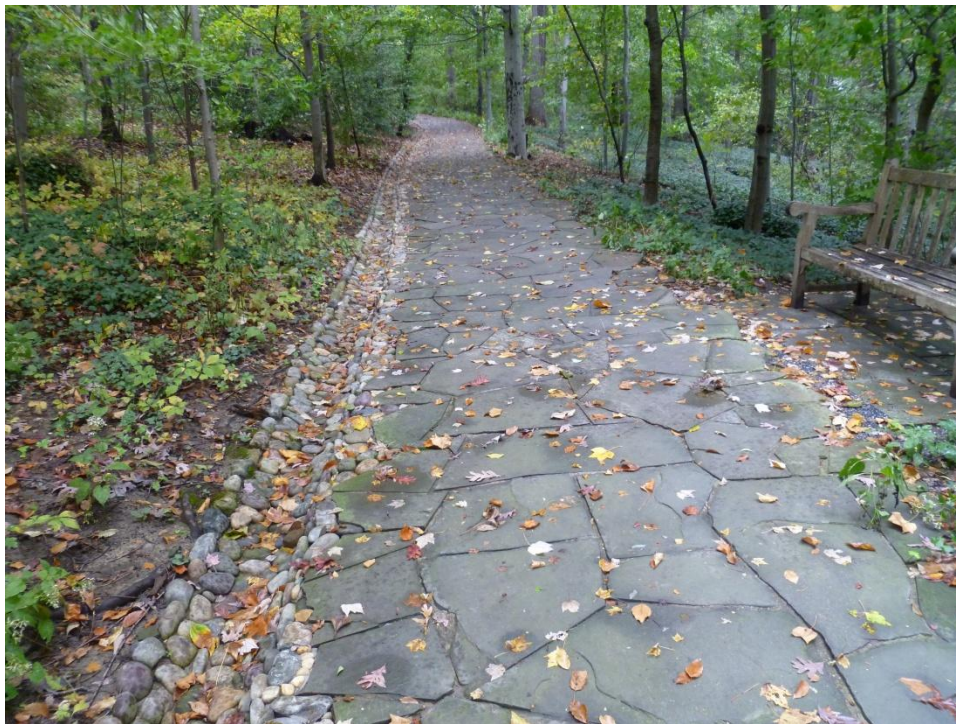
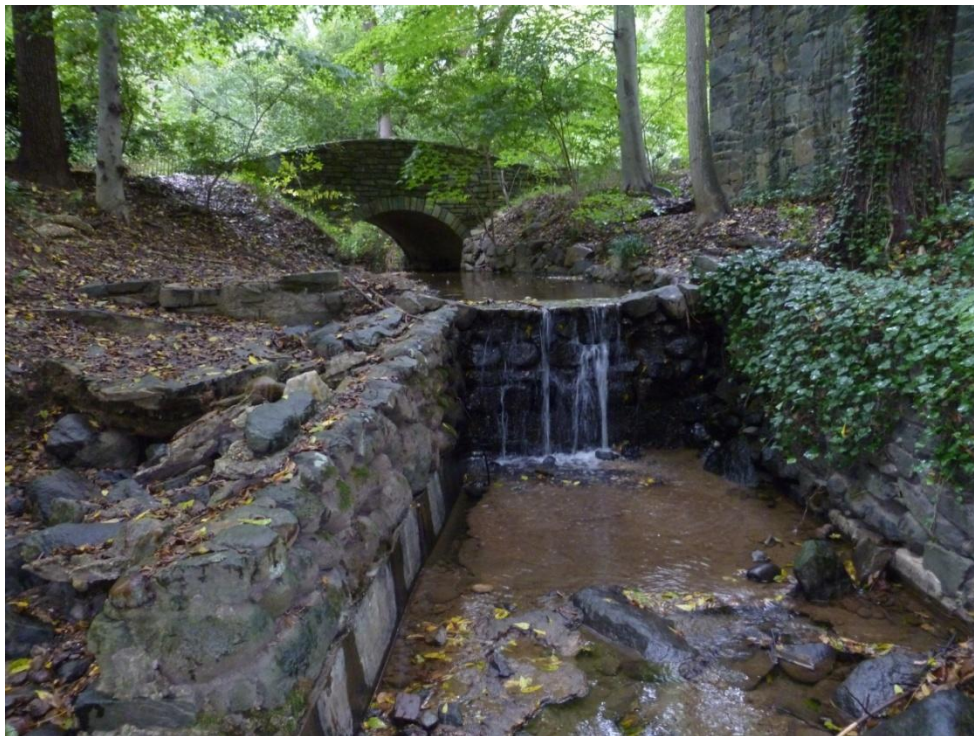


Figure E4: Cobble stone gutter along Pilgrim Way to direct the water along but off the walkway. Below is a hardened, but still permeable path.



10-1-2011 photo of Dumbarton Oaks Park East Falls and the Stone Bridge. The left side of the photo shows the opening where underground flow bypasses the waterfall and exits beyond the south wing wall. The following photo (10-13-2011) documents erosion that has left patches of ivy higher than the surrounding East Falls slope.



The following photos (10-6-2011) show (1) the eroded north bank of Laurel Pool that threatens the stability of established landscaping and (2) the upstream view of Laurel Pool of sediment that if removed would provide greater water storage capacity. High velocities of stormwater will require boulders or a rock wall to protect the north bank from continued erosion.





(Above) This photo provides an example of a rock wall near the Stream Arbor designed by Beatrix Jones Farrand to protect soils and Stream Path from high stream velocities. The 30" headwaters pipe is shown below. (10-6-2011 photos)



The above photo shows the 18" headwaters pipe connected to the Georgetown University Building. This pipe does not provide a continuous discharge. (11-30-2011 photo)



Runoff collects on the Farm Track (above) and flows to the east to drain into the stream at East Falls (below 10-20-2011 photos).



The bottom of the above photo is the area where flow from Meadow #5 merges with flow from the Farm Track to flow to the stream (10-27-2011). Below is a picture of the 12" green pipe, Pebble Stream (under the leaves), and the Spring Grotto (11-16-2011).



Table E1: Precipitation, East Falls, and 30" Pipe											
		Total	Hourly	East Falls	East Falls	East Falls		30" Pipe	30" Pipe	30" Pipe	30" Pipe
Date	Time	Precip (in)	Precip (in)	Stage (ft)	Discharge (cfs)	SNR (db)	Sontek ID	Depth (ft)	Velocity (ft/s)	Discharge (cfs)	SNR (db)
10/12/2011	3:49		0.01								
	10A-12			0.7							
	12:36		0.05								
	15:52		0.21								
	16:42		0.06								
	17:00			0.78							
	17:20										
	17:40							<0.08			
	18:00			0.72							
	18:56		0.06								
	19:40		0.03								
	20:47	0.44	0.02								
10/13/2011	6:52		0.01								
	7:52		0.17								
	8:39		0.01								
	9:41		0.02	0.7	0.4464	28.1	EFALLS				
	10:10			0.7	0.4171	28	EFALLS2				
	10:29		0.01								
	11:00			0.7	0.3772	26.7	DOPEF3				
	11:15						302 .WAD	0.1	1.17	0.077	47.8
	11:25						302 .WAD	0.1	0.955	0.063	
	12:10		0	0.7	0.3653	27.8	EFALLS4				
	12:25			0.7	0.3936	27	EFALLS5				
	12:40			0.7	0.3143	27.9	EFALLS6				
	13:00		0	0.65	0.2962	27	EFALLS7				
	14:00			0.68	0.2182	25.3	EFALLS8				
	14:15		0	0.65	0.2381	21.2	DEFALLS9				
	18:48		0.1								
	22:52		0.05								

	23:18	0.72	0.35								
10/14/2011	7:29		0.01								
	8:32		0.05								
	9:40			0.7	0.4	47	DOPEFAL1				
	9:52		0.04								
	10:00										
	10:15			0.86	1.4524	37.4	EFALL2				
	10:25			0.8	1.5006	26.7	EFAL3				
	10:45			0.77	1.1037	33.4	EFALL4				
	10:55			0.75	0.8032	33.6	EFALL5				
	11:15			0.74	0.6417	32.3	EFALL7				
	11:17		0.11								
	11:25			0.73	0.4996	31.9	EFALL8				
	11:40			0.7	0.4437	31.9	EFALL9				
	12:00			0.7	0.4042	31.4	EFALL10				
	12:10			0.7	0.3657	31.4	EFALL11				
	12:20			0.7	0.3458	32.3	EFALL12				
	12:30			0.7	0.3611	31.8	EFALL13				
	12:45			0.7	0.4003	34.8	EFALL14				
	12:52		0.02								
	13:00			0.7	0.5591	32.6	EFALL15				
	13:15			0.82	1.1292	31.9	EFALL16				
	13:25			0.8	1.0571	33.2	EFALL17				
	13:40		0.01	0.76	0.7716	31	EFALL18				
	13:50						30IN4X4				
	14:00						30INPIPE	0.1	2.4259	0.16	32.3
	14:02						30INPIPE	0.1	1.4544	0.096	
	14:04						30INPIPE	0.1	0.7799	0.051	
	14:06						30INPIPE	0.1	1.5085	0.099	
	14:08						30INPIPE	0.1	1.313	0.086	
	14:45			0.7	0.406	27.3	EFALL19				
	15:02						EOFCLAPP				
	15:06						EOFCLAPP				

	15:10						EOFCLAPP				
	15:14						WOFGRAY				
	15:35			0.7	0.4289	25.6	EFALL20				
	15:45	0.25		0.7	0.4345	25	EFALL21				
10/15/2011		0									
10/16/2011		0									
10/17/2011		0									
10/18/2011		0									
10/19/2011	2:52		0.01								
	3:52		0.08								
	4:52		0.12								
	5:27		0.09					1.25	2.37/6.9	5.8/16.9	
	8:52		0.02								
	13:30			0.68							
	14:30			0.68							
	14:52		0.01								
	15:35			0.67							
	15:50							0.021		0.014	
	15:55							0.042		0.042	
	16:20			0.67							
	17:52		0.06								
	18:52		0.13								
	19:52		0								
	20:52		0								
	21:52	0.5	0.02								
10/20/2011		T									
10/21/2011		0									
10/22/2011		0									
10/23/2011		0									
10/24/2011		0.13									
10/25/2011		0									
10/26/2011		0.01									
10/27/2011	5:52		0.01								

	6:52		0.01								
	7:52		0.01								
	8:15			0.74							
	8:40						0.08		0.119		
	9:10			0.74							
	9:40						0.1		0.166		
	9:52		0.01								
	10:07						0.125		0.217		
	10:27			0.72							
	10:40						0.146		0.273		
	11:00						0.125		0.217		
	11:35										
	11:45						0.17		0.333		
	11:52		0.05								
	12:05										
	12:10										
	12:20			0.74							
	12:52		0.03								
	12:55						0.125		0.217		
	13:25						0.1		0.166		
	13:50			0.74							
	13:55		0.01	0.75							
	14:00			0.73							
	14:15			0.71							
	14:40			0.7							
	15:26	0.13		0.68							
10/28/2011	23:59	0.08									
10/29/2011	0:52		0.05								
	2:52		0.03								
	3:29		0.03								
	4:52		0.07								
	5:52		0.07								

	6:52		0.07								
	7:46		0.08								
	8:35			0.8		33.2					
	8:59		0.08								
	9:02			0.8	0.4957	35.3	EFALL1A				
	9:15			0.8							
	9:37			0.81							
	9:52		0.18	0.94	2.4	23.5	EEALL2				
	10:44						304X4				
	10:45						304X4				
	10:52		0.17								
	10:53						30PIPE	0.4	6.9212	3.509	28.6
	10:53						30PIPE	0.4	1.9268	0.977	7.3
	10:54						30PIPE	0.4	0.3261	0.165	8.2
	10:56						30PIPE	0.4	0.6411	0.325	2.2
	10:57						30PIPEpad	0.6	1.0069	0.90621	44.7
	10:58						30PIPEpad	0.6	4.935	4.4415	47
	10:59						30PIPEpad	0.7	2.0072	2.10756	41.3
	11:01						30PIPEpad	0.7	3.3511	3.518655	43.6
	11:02						30PIPEpad	0.6	2.2589	2.03301	42.5
	11:03						30PIPEpad	0.6	3.6099	3.24891	45.3
	11:05						30PIPE	0.3	0.7585	0.253	9.5
	11:08						30PIPE	0.3	4.4977	1.501	44.5
	11:09						30PIPEpad	0.6	3.3153	2.98377	47.5
	11:10						30PIPEpad	0.6	3.2024	2.88216	46
	11:18						30PIPE	0.3	0.7789	0.26	1.1
	11:19						30PIPE	0.3	6.9262	2.311	43.6
	11:20						30PIPE	0.3	7.3071	2.438	
	11:21						30PIPE	0.3	3.7454	1.25	18.5
	11:25						30PIPE	0.2	4.4633	0.821	
	11:26						30PIPE	0.2	3.7474	0.689	
	11:27						30PIPE	0.2	2.8127	0.517	
	11:27						30PIPE	0.2	3.9915	0.734	

	11:31						30PIPE	0.2	2.6506	0.488	17.8
	11:50						304X42				
	11:52		0.04				304X42				
	11:54						304X42				
	12:25			0.8							
	12:36			0.8	0.7306	29.6	EFALL3				
	12:52		0.05								
	13:00			0.78							
	13:18			0.78							
	13:56		0.08								
	14:52		0.05								
	15:59		0.06								
	16:52		0.07								
	17:13		0.03								
	18:52		0.01								
	20:52	1.18									
10/30/2011		0									
10/31/2011	9:22			0.68							
	9:40										
	11:20	T		0.67							
11/1/2011		0									
11/2/2011		0									
11/3/2011		0									
11/4/2011	9:20			0.66			E. Falls				
	9:45						DOmouth				
	10:05						DOmouth				
	10:24			0.66	0.1099	16.6	EFALLS1				
	10:50			0.66	0.1044	12.7	EFALLS2				
	11:03			0.66	0.0912	14.3	EFALLS3				
	11:29						30"pipe	0.05			
	11:50						DS30IN				
	12:05						DS30IN.2				
	12:13						30IN3.3				

	12:40			0.66	0.153	16.1	EFALL4				
	13:29			0.66	0.112	17.3	EFALL5				
	14:20	0		0.66	0.0874	25.6	EFALLS6				
11/5/2011		0									
11/6/2011		0									
11/7/2011		0									
11/8/2011		0									
11/9/2011		0									
11/10/2011	13:52		0.03								
	14:11			0.68							
	14:22			0.68	0.1386	13.6	EFALL				
	14:40			0.68	0.1166	16.9	EFALL2				
	14:55			0.67			E. Falls				
	15:15			0.66	0.109	16.5	EFALL4				
	15:30			0.66	0.0945	20.9	EFALL5				
	16:00		0.02				30" pipe	<0.08			
	16:13			0.69	0.1559	14.9	EFALL7				
	16:28	0.06		0.7			E. Falls				
11/11/2011	4:00	0		0.69							
11/12/2011		0									
11/13/2011		0									
11/14/2011		0									
11/15/2011		T									
11/16/2011	0:52		0.01								
	1:40		0.02								
	2:18		0.01								
	3:52		0								
	4:52		0								
	5:52		0.02								
	6:52		0.02								
	7:52		0.03								
	8:47		0.05								

	9:52		0.1								
	10:16		0.03								
	10:30			0.71							
	10:45			0.72							
	10:52		0.06								
	11:17							0.17		0.6498	
	11:38		0.02								
	11:40			0.78							
	11:44			0.8							
	11:52			0.8							
	12:00			0.82							
	12:10			0.82							
	12:20			0.81							
	12:40			0.79							
	12:46							0.08			
	12:52		0.01								
	13:14			0.76							
	13:40							0.08			
	13:52		0.02								
	14:30			0.72							
	14:52		0								
	15:52		0								
	16:52		0								
	17:52		0								
	18:35		0								
	19:30		0.05								
	20:52		0.02								
	21:52		0.02								
	22:52		0.03								
	23:52	0.54	0								
11/17/2011		0.01									

11/18/2011		0									
11/19/2011		0									
11/20/2011		0.02		0.72							
11/21/2011		0.07		0.75							
11/22/2011	0:52		0								
	1:52		0.01								
	2:52		0.03								
	3:52		0.01								
	4:52		0.04								
	5:52		0								
	6:52		0								
	7:52		0.02								
	8:52		0								
	9:31			0.78	0.17	7.6	EFALLS1				
	9:50		0	0.78							
	10:14						DSArbor1				
	10:20						DS30IN1				
	10:29						DS30IN2				
	10:39						DS30IN3				
	10:50		0.01					0.08		0.119	
	11:00						DSArbor2				
	11:10						DSArbor3				
	11:19						DSArbor4				
	11:34						DSArbor5				
	11:45						DSArbor6				
	11:55		0.04	0.8	0.4361	14.3	EFALL2				
	12:06			0.88	0.6513	22.5	EFALL3				
	12:52		0.08								
	13:05			0.92	0.6835	24.9	EFALL4				
	13:15			0.9	0.8507	22.9	EFALL5				
	13:20			0.88	0.6721	25.7	EFALL6				

	13:33				0.5764	22.2	EFALL6B				
	13:42				0.3809	24.4	EFALL7				
	13:51		0.09		0.3031	18.3	EFALL9				
	14:00			0.9	1.6404	26.4	EFALL9B				
	14:10			0.88	1.5477	25.8	EFALL10				
	14:15						DOM1				
	14:30						DOM2				
	14:38						DOM3				
	14:45						DOM4				
	14:52		0.02								
	15:00						DOM5				
	15:06			0.86							
	15:52		0.02								
	16:44		0.13								
	17:52		0.04								
	18:52		0								
	19:41	0.55	0								
11/23/2011	2:39		0.07								
	2:59		0.03								
	3:52		0.13								
	4:52		0.02								
	10:52		0.02								
	11:20			0.78							
	11:40			0.78	0.368	21.8	EFALL1.5				
	11:55						DOM15				
	12:28						DOM16				
	12:45						DOM17				
	12:50			0.78							
	13:00						DSARB15				
	13:22						DSARB16				
	13:28						DS30IN15				
	13:37						DS30IN16				

	13:46						DS30IN17				
	13:55						DS30IN18				
	14:00							0.04			
	14:10			0.77							
	14:32	0.28		0.77	0.115	18.2	EFALL19				
11/24/2011		0									
11/25/2011		0									
11/26/2011		0									
11/27/2011		0									
11/28/2011		0									
11/29/2011	2:00	0.41		0.76							
11/30/2011	12:30	0		0.72							
	13:12							0.1			

Table E2: DO Mouth, Downstream 30" Pipe, and Downstream Arbor Falls							
		DO Mouth		DS30inch		DS Arbor	
		Discharge (cfs)	SNR (db)	Discharge (cfs)	SNR (db)	Discharge (cfs)	SNR (db)
11/4/2011	9:20						
	9:45	0.2673	21.2				
	10:05	0.2455	30.6				
	10:24						
	10:50						
	11:03						
	11:29						
	11:50			0.0715	22.2		
	12:05			0.1927	19.3		
	12:13			0.161	21.7		
	12:40						
	13:29						
	14:20						
11/22/2011	0:52						
	1:52						
	2:52						
	3:52						
	4:52						
	5:52						
	6:52						
	7:52						
	8:52						
	9:31						
	9:50						
	10:14					0.145	21.4
	10:20			0.3116	37.7		
	10:29			1.1466	37.3		
	10:39			0.3375	42.1		
	10:50						
	11:00					0.0773	12.8
	11:10					0.0779	30.9
	11:19					0.3004	21.7
	11:34					0.0564	36.6
	11:45					0.5848	36.6
	11:55						
	12:06						
	12:52						
	13:05						
	13:15						
	13:20						

	13:33						
	13:42						
Table : DO Mouth, Downstream 30" Pipe, and Downstream Arbor Falls - continued							
		DO Mouth		DS30inch		DS Arbor	
		Discharge (cfs)	SNR (db)	Discharge (cfs)	SNR (db)	Discharge (cfs)	SNR (db)
11/22/2011	13:51						
	14:00						
	14:10						
	14:15	2.3144	29.3				
	14:30	1.5015	40.6				
	14:38	2.5563	45.9				
	14:45	2.1061	44.8				
	14:52						
	15:00	1.8787	40.6				
	15:06						
	15:52						
	16:44						
	17:52						
	18:52						
	19:41						
11/23/2011	2:39						
	2:59						
	3:52						
	4:52						
	10:52						
	11:20						
	11:40						
	11:55	0.3569	21				
	12:28	0.3987	21.8				
	12:45	0.37	29.8				
	12:50						
	13:00					0.1394	19.1
	13:22					0.1011	21.2
	13:28			0.4297	34.9		
	13:37			0.2623	33.7		
	13:46			0.4308	34.3		
	13:55			0.3293	31.7		
	14:00						
	14:10						

Table E3: Miscellaneous Flow Data								
		Sontek ID	Discharge (cfs)	SNR (db)	velocity (ft/s)	max depth (ft)	width (ft)	Notes
10/13/2011	11:05					0.02		12" green pipe, pebble stream overland flow double that exiting pipe
10/14/2011	13:50	30IN4X4	0.157	-0.4	0.6276	0.2	1.25	Stonecrossing
	15:02	EOFCLAPP		15.2	0.3156	0.05		no data
	15:06	EOFCLAPP			0.3743	0.15		no data
	15:10	EOFCLAPP			0.5492	0.15		no data
	15:14	WOFGRAY		31.9	1.248	0.25		no data
10/19/2011	13:30							12" green pipe and pebble stream overland flow discharging
10/27/2011	11:10							NZ flow starting to enter storm grate
	11:15							NO top 6" PVC is flowing but 25 feet from NZ fenceline
	11:26							NO parking lot draining: trib is 2' wide and 0.04-0.08' deep
	11:35							30" inlet receiving no flow
	12:05		0.015		1.5	0.04		12" green, estimated velocity
	12:10		0.015		0.5	0.1		6" cast iron pipe, estimated velocity
	13:45		0					6" cast iron pipe no longer flowing
10/29/2011	10:17							12" green pipe water depth 1" up left side
	10:44	304X4	0.458	42.8	1.0459	0.35	1.25	Stonecrossing flow was visually dropping
	10:45	304X4	0.368	42.8	0.8406	0.35	1.25	
	11:50	304X42	0.113	42.8	0.3602	0.25	1.25	
	11:52	304X42	0.115	42.8	0.3678	0.25	1.25	
	11:54	304X42	0.113	42.8	0.3622	0.25	1.25	
	12:05		0.015		1.5	0.04		12" green pipe, approx velocity
	12:10		0.015		0.5	0.104		6" cast iron pipe on the N side, DS Laurel Pool, approx velocity
11/10/2011	16:13							low discharge from green pipe
11/16/2011	10:45		0.015					6" cast iron pipe is active with same flow rate as before
	11:09		0.015		1.5	0.04		12" green, estimated velocity
	11:38		0.015					6" cast iron pipe is still discharging
	12:25							6" cast iron pipe is still discharging, at a dimenished flow rate
	12:35							green pipe flow has dropped, low flow at 6" cast iron pipe
11/22/2011	11:00							6" cast iron pipe is discharging at a low velocity
11/23/2011	12:55		0.015		1.5	0.04		12" green pipe, approx velocity
11/29/2011	2:00							Found new pipe DS of 30 inch pipe.

11/30/2011	12:30					0.04		No flow at 18" Headwaters pipe. Then flow at velocity less than 30"
	13:12					0.1		30" pipe

