The relative effects of tree canopy on water balance and nutrient loading rates from turfgrass and impervious surfaces

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Water Balance Modeling Approach

Trees modify the fate and transport of water, nutrients, and sediment in natural and developed landscapes due to their unique physical structure compared to other plant species, basic physiological processes, and long lifespan. The additional surface area of leaves and branches adsorbs, retains, and delays precipitation from reaching the ground (**interception**), and ultimately decreases the erosive forces of surface water by extending the duration and reducing the total volume of stormwater runoff. For trees growing in open space, the growth and death of tree roots improves soil physical structure and increases infiltration rates that enhance the benefits of delayed water movement by tree leaves and branches. Lastly, trees draw in water from the soil and return it to the atmosphere (**transpiration**), which increases the water holding capacity of soil in between storms.

Water balance is a quantitative mathematical framework used to account for water that enters, is stored, and is lost from ecosystems. A general mass balance equation is shown below where I is inputs, O is outputs, and ΔS is the change is storage. Water balance equations for two existing Chesapeake Bay Program land uses and those land uses with tree canopy are also shown. In the water balance equations, inputs include precipitation (P), and/or laterally flowing subsurface water (T, throughflow). Outputs include runoff (R), evapotranspiration (ET), gravitational soil water that drains beneath the plant rooting zone (L, leaching), evaporation (E), and throughflow (T).

General mass and water balance equations:

General	$I = O + \Delta S$
Turfgrass	$P = R + ET + L + \Delta S$
Canopy over Turfgrass	$P = R + ET + L + \Delta S$
Impervious	$P + T = R + E + T + \Delta S$
Canopy over Impervious	$P + T = R + ET + T + \Delta S$

Precipitation is assumed to be the only input of water to areas mapped as tree canopy over turfgrass because riparian forest buffers are a stand alone BMP. This restricts areas mapped as tree canopy over turfgrass to upland sites where the water table is below the plant rooting zone (~2 ft. deep). This assumption likely underestimates the hydrologic benefit of trees in developed areas as trees on residential property have been shown to access water below this depth, uplift, and redistribute it into shallow soil horizons (Day, Wiseman et al. 2010). For tree canopy over impervious surfaces, we had to introduce a source of shallow, subsurface water (T, throughflow) that trees can access and use to meet basic physiological needs because water and nutrients cannot infiltrate through impervious surfaces.

For water quality purposes, we are ultimately interested in the proportion of precipitation that becomes stream/surface flow (*J*, water yield). Water yield from turfgrass with tree canopy relative to turfgrass without canopy is described by Equation 1, and water yield from impervious surfaces with tree canopy relative to impervious surfaces without canopy is described by Equation 2.

Relative water yield equations:

Equation 1: $$\frac{J_{gc}}{J_g} = \frac{\sum R_{gc} + \sum L_{gc}}{\sum R_g + \sum L_g}$$

Equation 2: $$\frac{J_{ic}}{J_i} = \frac{\sum R_{ic} + \sum T_{ic}}{\sum R_i + \sum T_i}$$

The subscripts in Equations 1 and 2 are used simply to identify the underlying land use (*g* is turfgrass and *i* is impervious) and whether or not that land use is covered by tree canopy (*c*). The role of tree canopy in modifying water yield varies with the severity of precipitation and the quality of vegetation (Keim, Skaugset, and Weiler 2006). The ∑ symbol in Equations 1 and 2 indicates that the volume of runoff and soil leachate will be estimated daily using local weather data, and the final results based on the cumulative total over the course of a year.

For each of the four land use types, we estimated runoff using the Soil Conservation Service Curve Number Method, where *R* is runoff, *P* is precipitation, and *CN* is the land use curve number (USDA 1989).

$$R = \frac{\left(P - 0.2 \cdot \left(\frac{1000}{CN} - 10\right)\right)^2}{P + 0.8 \cdot \left(\frac{1000}{CN} - 10\right)}$$

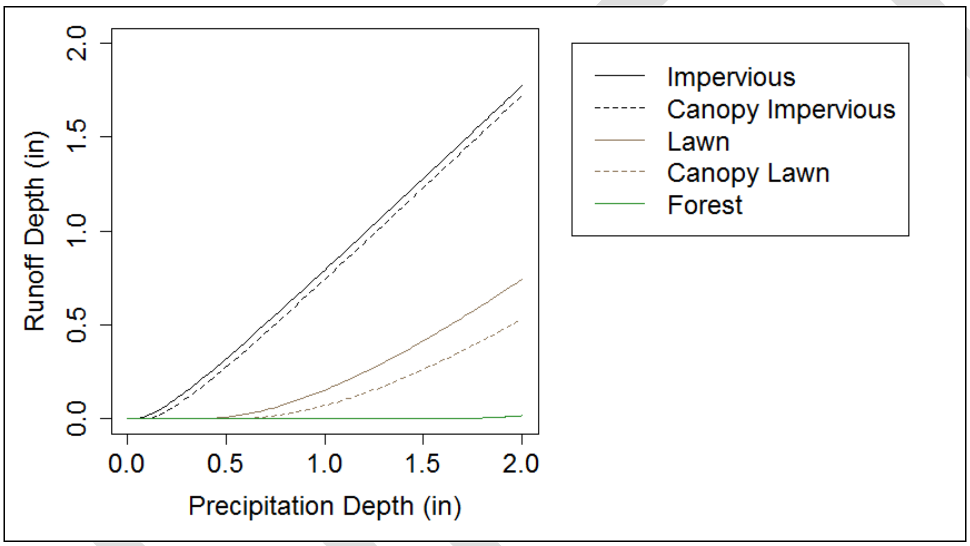
CN is a factor ranging from 0 to 100 that accounts for the physical attributes of the land surface as well as the hydrologic properties of the underlying soil that affect infiltration. Following recommendations in USDA Technical Release 55, *Urban Hydrology for Small Watersheds*, we used a *CN* of 98 for impervious surfaces and 84 for turfgrass (open space in fair condition with hydrologic soil group D). We used a *CN* value of 80 for tree canopy over turfgrass to account for the temporal effects of canopy interception and improved soil physical structure by tree roots. The difference between a CN value of 84 and 80 is modest, and is equivalent to turfgrass in fair versus good condition with hydrologic soil group D, or to turfgrass in fair condition and hydrologic soil group C versus D.

We added the variable C_i (interception capacity) into the SCS Curve Number Equation to account for the amount of water adsorbed to leaves and branches after throughfall stops. In other words, C_i is the amount of rainfall that never reaches the ground. We used a fixed value of 0.05 inches (per rain event) that is similar to the credit given for canopy interception by the Minnesota Pollution Control Agency for trees in tree trenches and boxes (USDA 1989) that is based on a synthesis of published plant values (Breuer, Eckhardt, and Frede 2003).

$$R = \frac{\left(P - C_i - 0.2 \cdot \left(\frac{1000}{CN} - 10\right)\right)^2}{P - C_i + 0.8 \cdot \left(\frac{1000}{CN} - 10\right)}$$

Figure 1 shows the relationship between precipitation and runoff depth for the four land uses of interest using the Curve Number Method with runoff for forested land (*CN* = 55; hydrologic soil group B) shown for reference.

Figure 1: Precipitation vs. runoff depth estimated using the SCS Curve Number Method



Using the water balance equations, the remaining volume of precipitation after interception and runoff infiltrates (*I*) into soil.

$$I = P - C_i - R$$

All or a portion of this water is temporarily stored in the soil. The maximum amount of water that can be stored in the soil and is available for evapotranspiration is equal to the soil's water holding capacity down to two feet. Water holding capacity varies with soil texture (lowest in both very sandy and very clayey soils) and ranges from 1 to 2 inches per foot of soil (Brady and Weil 1996). For this analysis, we used a soil water holding capacity of 2 inches per foot, and a total soil volume based on the typical rooting depth of trees (2 ft) and one square meter of land – the minimum mapping unit of tree canopy. The actual volume of soil water will vary over time as a function of the initial soil water volume after rainfall minus the amount of water transpired in between precipitation events. Tracking changes in soil water over time also has the advantage of placing an upper limit on the amount available for transpiration. During initial model testing, the soil water volume at the end of the year was almost always equal to the maximum water holding capacity. For this reason, the water holding capacity at the beginning of the year was set to zero.

Any rainfall that is infiltrated in excess of the available water holding capacity is assumed to leach (L) below the rooting zone and be lost as groundwater.

$$L = I - S$$

In between rainfall events, evapotranspiration by turfgrass and trees will reduce the soil water volume allowing more infiltration to be stored the next time it rains.

$$S_t = S_{\max} - S_{t-1} \cdot ET$$

Total annual evapotranspiration is similar between turfgrass and broadleaf trees ranging from 15 to 24 inches per year, or 0.043 to 0.064 inches per day, and slightly higher for conifers. For turfgrass beneath tree canopy we assumed that it's ET was half as effective as non-shaded turfgrass, and net rates of ET for turfgrass, canopy over turfgrass, and canopy over impervous surfaces were set to 0.05, 0.08, and 0.05 inches per day, respectively.

There is no straightforward way to determine the volume of throughflow available to trees with a canopy that extends over impervious surfaces. Tree root are extremely advantageous and often grow into broken stormwater pipes and culverts, and there is likely a high degree of spatial variation. We choose to estimate daily thoughflow by dividing the annual flux of soil leachate from turfgrass by 365, which is roughly 0.08 cubic feet per day. Trees and grass were only allowed to transpire on days without rain during the growing season (April through March), and ET for turfgrass in the non-growing season was assumed to be half the rate under favorable conditions. Table 1 shows preliminary water yield results using rainfall data from 8 locations around the Chesapeake Bay Watershed region using this approach. A timeseries of model results for Baltimore, MD can be found in the Appendix 1, and the table of results for each of the 8 locations is provided in Appendix 2.

Table 1. Model results for the average annual percent reduction in water yield by tree canopy relative to impervious and pervious land covers based on 2015 rainfall data from eight regional locations.

Land Use	Precip. (in)	Runoff Red. (%)	Leaching Red. (%)	Throughflow Red. (%)	Total (%)
Canopy over Turfgrass	43.6	39.1	23.3	NA	26.0
Canopy over Impervious	43.6	7.1	NA	22.7	15.5

Interactions between water yield and nutrient cycling processes:

Runoff, soil water leachates, and throughflow directly impact water quality by transporting nitrogen, phosphorus, and sediments from upland areas to aquatic ecosystems. Atmospheric deposition and fertilizer are the primary sources of nitrogen, phosphorus, and sediment in developed areas. Total atmospheric deposition (i.e., wet and dry deposition) is well documented and varies regionally over the Chesapeake Bay watershed (Linker, Dennis et al. 2013), but can be elevated in densely developed areas (Lovett, Traynor et al. 2000). Atmospherically sourced phosphorus is generally deposited as dust or aerosol forms (Correll 1998). Nitrogen oxide gases and ammonium nitrate (NH_4NO_3) particles can be deposited as both dry deposition and wet.

Lawn fertilizer inputs as well as the fate of these inputs to the Chesapeake Bay Watershed Model are similarly well-characterized and documented (Aveni, Berger et al. 2013). This additional source of nutrients is one of the primary reasons that nutrient loads from turfgrass are elevated in the Chesapeake Bay Watershed Model (beta Phase 6 loading ratios) relative to open space (5.0x and 1.7x for N and P, respectively) and forests (7.1x and 12.0x for N and P, respectively). Fertilizer added will undergo the same fate as atmospheric deposition – via transport and biogeochemical processes. For this reason, potential interactions between water and pollutant loads will be discussed on a nutrient basis.

In this analysis, we assumed that grass clippings and tree leaves from pervious surfaces remained onsite and are not considered a new source of nutrients that impact water quality. Grass clippings and tree leaves can help maintain nutrient levels in lawns and build soil carbon stocks (Raciti, Burgin et al. 2011, and Pouyat, McDonnell et al. 1997). Similarly, the annual flux of nutrients in leaves from tree canopy over impervious surfaces were considered to have a net flux of zero, as nutrients contained in biomass balance with changes in throughflow; that is the nutrients provided in litterfall are assumed to provide the nutrients delivered via throughflow. This assumption provides a placeholder for future research that may better quantify the impact of leaf litter on the impact of tree canopy on nutrient loads. For example, quantifying the amount of nutrients exported from the system via leaves that are blown onto impervious surfaces is an emerging field of study (Baker et al., 2014, Selbig 2014, Stack et al, 2013) . Various possible fates of nutrients from litterfall include being added to Bay loads via storm drains that connect directly to the Bay thereby contributing to stream nutrient webs, or swept up via street cleaning and catch basin cleanouts and added to municipal landfills or compost systems. The amount and form of nutrients (soluble and particulate) that becomes available hinges on the ability to estimate the amount of tree biomass leaf litter that falls on impervious surface, entering local waterways or removed by street sweeping and catch basin cleanouts is highly time dependent given decomposition of leaf litter in-situ and movement through the storm drain system.

The potential direct benefits (at the parcel scale) of tree canopy over turfgrass are high because increased infiltration provides greater opportunity for nutrient cycling, storage, and volatile loss. In theory, nutrient concentrations in runoff could increase if (1) nitrogen and phosphorus are leached from the canopy, or (2) delayed runoff dissolves more fertilizer. Nitrogen and phosphorus display different leaching potential from tree canopy with canopy being a net sink of ammonium, a small but potentially insignificant source of nitrate (but nitrate release < ammonium uptake), and a source of phosphate (Leininger and Winner 1988; Schrijver et al. 2007). From our current literature review, we do not know if prolonged interaction between runoff and the ground surface results in increased concentrations of nutrients in runoff. However, the reduced risk of particulate fertilizer transport via runoff likely exceeds potential increases in dissolution. Trees have been shown to increase trapping of particles when compared to grass, a difference attributed to the trees greater ability to decrease overland flow, allowing particles to settle out via sedimentation (Leguedois, Ellis et al. 2008). As the water that is infiltrated in each scenario is retained, the majority of sediments in that water are likely to be retained as well and added to soil stores via adsorption onto organic matter and soil surfaces (Leguedois, Ellis et al. 2008).

Compared to rainfall and throughfall chemistry, the concentration of nutrients in soil leachates are high near the soil surface and decrease with increasing soil depth. Nitrogen is leached from the system as nitrate-N, a form that is easily transported by groundwater flowpaths (Wakida and Lerner 2005). Organic N and ammonium-N in soil can also transformed to nitrate-N, which can be then leached from soil and contributed to groundwater sources. Conversely, nitrate-N can undergo denitrification in urban systems (Groffman, Law et al. 2008), a process augmented by increased soil moisture and warm temperatures given available carbon sources (Raciti, Burgin et al. 2011).

Denitrification, the ultimate sink for nitrogen, requires a carbon source and saturated soil conditions. Trees, and in particular the root system, enhance soil organic matter by incorporating organic matter, adding plant litter to carbon stores, exuding carbon from the roots, and root die-off (Day, Wiseman et al. 2010). Carbon cycling, in turn, drives N retention via uptake and microbial utilization (Lovett, Weathers et al. 2002). Soil under urban trees has been shown to have a higher carbon content than bare soil or soil under grass (Takahashi, Amano et al. 2008), therefore allowing greater potential for nutrient uptake and cycling. Denitrification potential has been shown to decrease downward through the urban soil profile, with high rates in upper layers of soil where soil organic matter and moisture were greatest (Zhu, Dillard et al. 2004, Gift, Groffman et al. 2010).

Removal of nitrate-N via denitrification is also strongly influenced by soil moisture (Kaushal, Groffman et al. 2008). Trees promote greater soil moisture by creating preferential hydrologic flow paths and absorbing water via root systems (Day, Wiseman et al. 2010). In urban areas in particular, it is assumed that as the root zone of grasses is likely not reaching the groundwater, therefore there are no water inputs from groundwater sources. Deeper-rooted trees may re-distribute soil moisture from farther underground to closer to the surface (Day, Wiseman et al. 2010). This would assist the greater plant community by providing soil moisture and so promoting greater growth and nutrient utilization. The increase in moisture to the soil regions where carbon and nitrate are also concentrated may therefore increase denitrification processes in tree plus grass scenarios (Gift, Groffman et al. 2010). Trees can therefore add moisture (and potentially utilize nutrients) to the upper soil profile both by increasing infiltration and the process of hydrologic lift (Day, Wiseman et al. 2010).

Phosphate is generally not a major component in groundwater because it is in forms that will be bound to soil particles and therefore will not be leached to groundwater (Correll 1998). Phosphorus leaching processes are not likely to contribute P to groundwater as most P has been shown to remain in the top three feet of soil (Daniels et al, 2010).

In contrast, the potential direct benefits (at the parcel scale) of tree canopy over impervious surfaces are limited. While the presence of trees delays the transport of water, nutrients, and sediment across impervious surfaces, these surfaces provide little to no opportunity for long-term storage or volatile losses. Therefore, it may not be reasonable to assume that nutrient loads from this land use are directly proportional to water yield.

Reductions in runoff can also be expressed as an *indirect* benefit to water quality, when moving beyond the parcel scale to the watershed scale. Runoff is particularly problematic in developed areas because impervious and compacted surfaces deliver more water over shorter periods of time to surface waters that erode stream banks (Walsh, Roy et al. 2005). Indirect benefits are obtained when reductions in runoff limit the erosive power of surface waters. To be clear, this is different from the direct benefits of reduced water yield that transport nutrients and sediment from upland areas to surface water. The potential *indirect* (watershed-scale) benefits of tree canopy over turfgrass are limited because the volume of runoff generated by turfgrass even in poor condition is relatively small compared to inputs. The volume of runoff generated by turfgrass with tree canopy is likely even smaller due to the greater ability of the tree to intercept water and promote infiltration (Leguedois, Ellis et al. 2008, Asadian and Weiler 2009). Extreme storm events may generate runoff from turfgrass and tree canopy land uses, adding to erosion and sediment loads downstream.

The potential *indirect* (watershed-scale) benefits of tree canopy over impervious are high, when compared to impervious surfaces without tree canopy. Trees reduce rainfall intensity, volume, and slow runoff rates by intercepting precipitation on leaves and branches (Nowak and Wang 2007, Asadian and Weiler 2009). Tree canopy, even when limited by surrounding impervious surfaces, decreases rainfall intensity and runoff volumes (Wang, Endreny et al. 2008). The effect of impervious surfaces in urban areas has been linked to increased frequency of strong overland flows that wash deposited nutrients and sediments into storm sewers, greater erosive flow increasing downstream sediment loads, greater magnitudes of high flows, and a shortened storm hydrograph (Walsh, Roy et al. 2005). Water quality can be impaired both by infrequent, large storm events as well as by more frequent, smaller events that deliver quick pulses of nutrients and sediments to receiving waters (Walsh, Fletcher et al. 2005). Trees reduce runoff during more frequent, smaller storm events, and therefore help downstream water quality (Xiao, McPherson et al. 1998). Decreasing rainfall intensity and runoff volume can thereby mitigate some of the delivery of sediment and nutrients to downstream loads indirectly.

The characterization of these indirect benefits is important to quantify because of the limited direct benefits to water quality by tree canopy over impervious surface. Tree soil pits, surrounded by impervious surfaces, may not be of size to infiltrate a significant amount of captured rainwater or slow water movement enough to filter out sediments and nutrients. The resulting drier soils in the root region will promote less processing of nutrients via processes such as denitrification and sorption onto soil organic matter. We are currently consulting the scientific literature for relationships between stream hydraulics and erosion that may be used to refine the loading rate recommendations for tree canopy over impervious surfaces.

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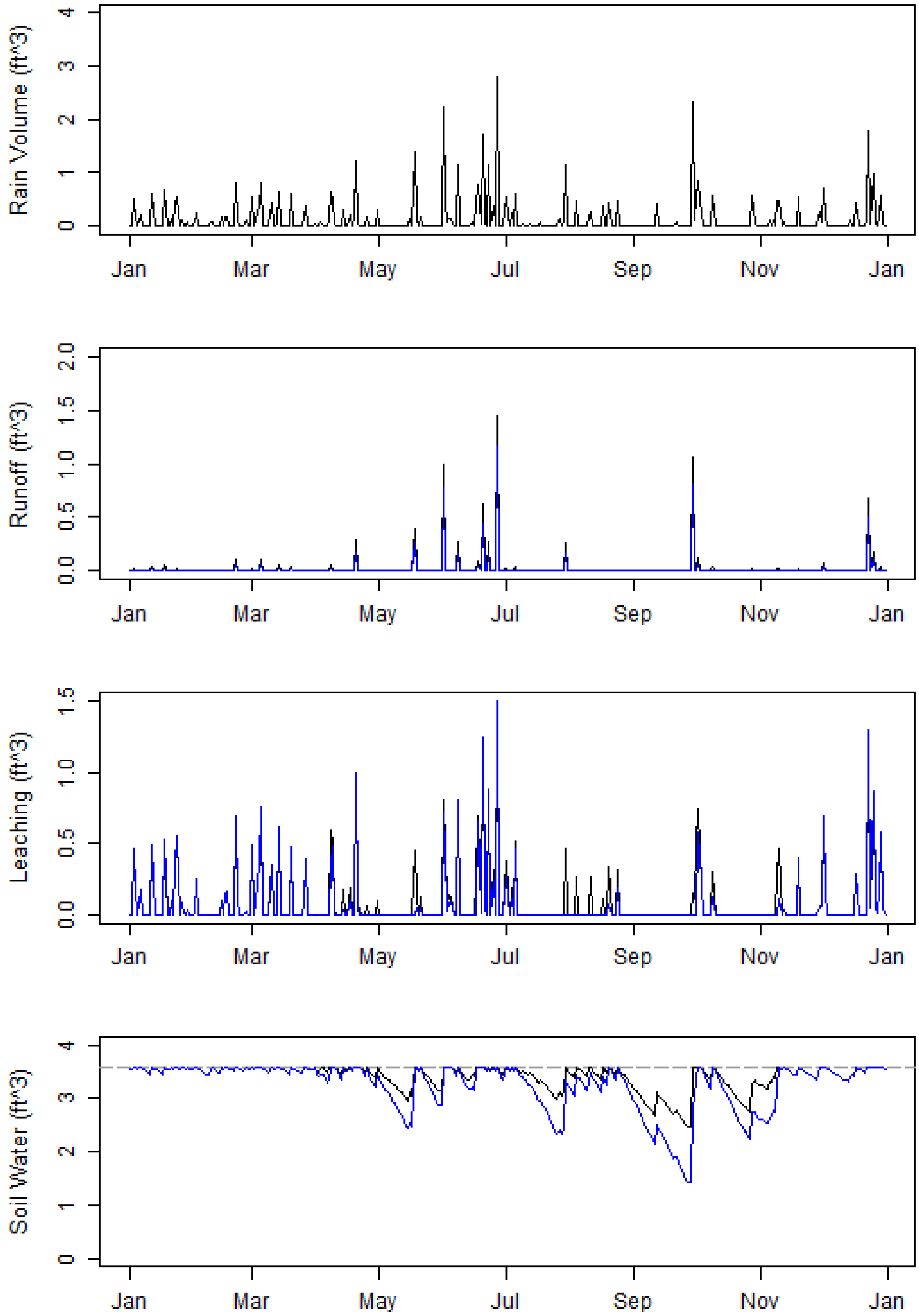
Appendix 1: Time series of water balance results for Baltimore, MD (2015)

Blue lines indicate tree canopy over turfgrass and **black lines** indicate turfgrass only.



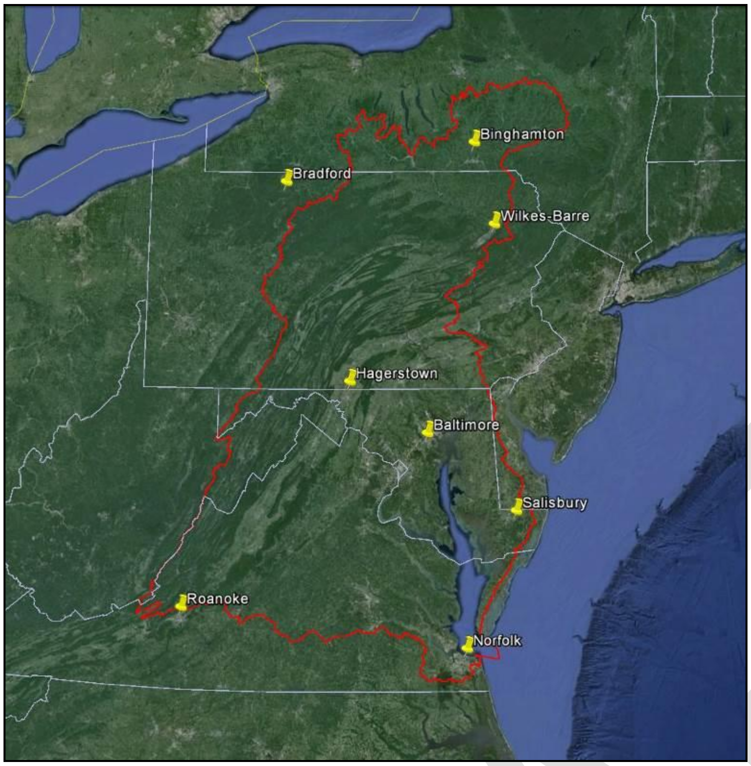
Appendix 2: Water yield results from individual cities based on rainfall data from 2015 (Map below)

Canopy over Turfgrass

City	Precip. (ft^3)	Runoff Red. (%)	Leaching Red. (%)	Total (%)
Baltimore, MD	45.9	33.4	15.9	**19.5**
Hagerstown, MD	25.4	45.9	44.0	**44.0**
Salisbury, MD	46.1	36.9	15.0	**19.3**
Binghamton, NY	25.4	39.5	20.9	**23.5**
Bradford, PA	35.0	48.0	24.7	**26.7**
Wilkes-Barre, PA	28.0	41.9	37.3	**37.9**
Roanoke, VA	48.9	35.9	12.4	**17.5**
Norfolk, VA	45.0	31.6	16.0	**19.7**

Canopy over Impervious

City	Precip. (ft^3)	Runoff Red. (%)	Throughflow Red. (%)	Total (%)
Baltimore, MD	45.9	5.2	24.3	**14.5**
Hagerstown, MD	25.4	9.5	23.8	**19.2**
Salisbury, MD	46.1	5.0	23.8	**14.1**
Binghamton, NY	38.3	8.2	20.2	**14.9**
Bradford, PA	35.0	10.0	18.3	**15.1**
Wilkes-Barre, PA	28.0	9.0	23.5	**18.4**
Roanoke, VA	48.9	5.2	22.8	**13.3**
Norfolk, VA	45.0	4.8	24.5	**14.4**


Binghamton
Bradford
Wilkes-Barre
Hagerstown
Baltimore
Salisbury
Roanoke
Norfolk