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Module 4c Introduction: Infiltration as a Stormwater Control

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Introduction

Many stormwater control strategies rely on the use of infiltration to both reduce runoff quantity and to improve runoff quality. At the same time, infiltration can have significant benefits on reducing peak flow rates of benefit in drainage design, However, most infiltration devices have a much reduced benefit on flow rates and flooding as on the other benefits. This module describes some of the specific problems associated with increased runoff and how infiltration can reduce these problems. There are also some short discussions pertaining to some specific infiltration controls.

Receiving Water Impacts Associated with Increased Discharges

Urbanization causes profound changes in the hydrology of the area, specifically the timing of the runoff, the water use, runoff volume and flow rates, channel complexity, and especially pollution in receiving waters. Water quality problems increase with increasing imperviousness of the watershed. Impervious areas cause increased runoff and contaminated discharges from these areas and also contribute to receiving water contamination. Increases in urban population, and associated urban sprawl alters drainage basins and rivers. When watershed areas are urbanized, much of the vegetation and top soil is replaced by impervious surfaces (roads, parking lots, and roof tops) and much of the remaining soils are compacted. Population increases therefore cause increases in impervious areas which means less water will soak into the ground and more water will go directly to urban streams during the rains, along with faster rises in runoff. In addition to the high flows caused by urbanization, the increased runoff also contains increased contaminants. These increased flows are likely one of the major causes of stream degradation in urban areas (Burton and Pitt 2001). Increasing amounts of impervious cover are typically used as an indicator of these increased flows, and have therefore become an indicator in measuring the impact of land development on drainage systems and aquatic life (Schueler 1994). Impervious cover is one of the variables that can be quantified for different types of land development, although there are many different types of impervious surfaces and how they are connected to the drainage system. In urban areas, stream and lake impairment is also due to habitat destruction; but, in addition, physical and chemical contaminant loadings come from runoff from impervious areas (e.g., parking lots, streets) off of construction sites, and industrial, commercial, and residential areas. Numerous studies (such as May 1996) have examined the extent of urbanization with decaying receiving water conditions (Figure 1).

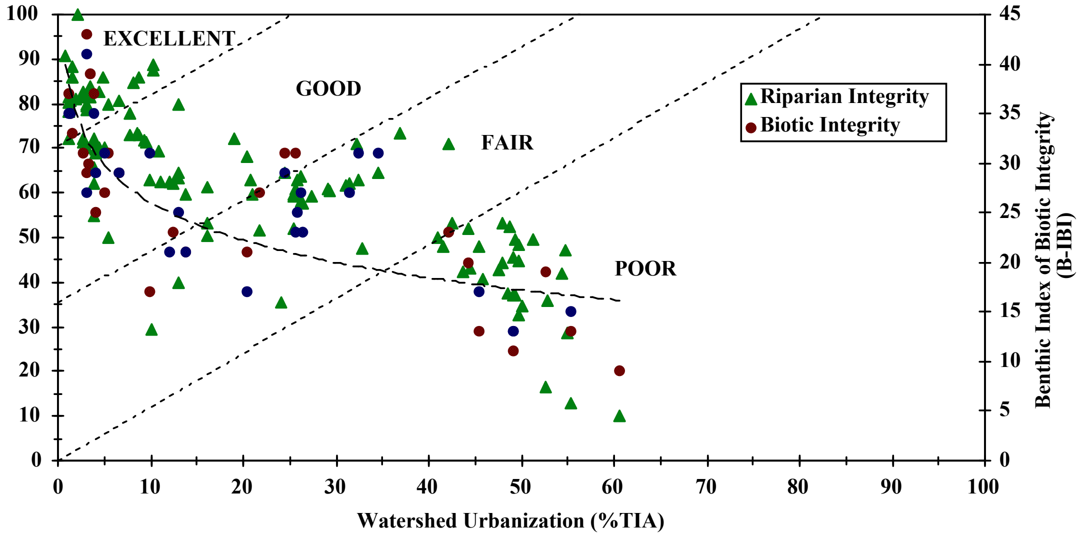

Figure 1. Relationship between basin development, riparian buffer width, and biological integrity in Puget Sound lowland streams (May 1996).

Urban pollutant loads in aquatic systems are directly related to watershed imperviousness. It is generally found that stream degradation occurs at low levels of imperviousness (about 10 to 15%), where sensitive stream elements are lost from the system. There is a second threshold at around 25 to 30% impervious cover, where most indicators of stream quality change to a poor condition (Schueler 1994). Bochis-Micu and Pitt (2005) have extensively examined land development practices in Little Shades Creek watershed in Birmingham, Alabama. Table 1 shows the amounts of impervious cover in these areas, along with the calculated volumetric runoff coefficients determined by WinSLAMM using a 43 year rain period. Overall, the watershed has a total impervious cover of about 35%, of which about 25% is directly connected to the drainage system and 10% drains to pervious areas. As expected, the land use with the least impervious cover is open space (parks, cemeteries, golf course), and the land uses with the largest impervious covers are commercial areas, followed by industrial areas.

Table 1. Little Shade Creek, Birmingham, AL: Average of Source Area Drainage Connections by Land Use (Bochis-Micu and Pitt 2005)

Land Use	Pervious Areas (%)	Directly Connected Impervious Areas (%)	Disconnected Impervious Areas (%) (draining to pervious areas)	Volumetric Runoff Coefficient (Rv) if Sandy Soils	Volumetric Runoff Coefficient (Rv) if Clayey Soils
High Dens. Residential	76.07	13.41	10.52	0.09	0.17
Med. Dens. Residential (<1960)	81.74	9.06	9.20	0.06	0.14
Med. Dens. Residential (1961-80)	81.24	8.80	9.96	0.07	0.15
Med. Dens. Residential (>1980)	81.59	14.09	4.31	0.09	0.17
Low Dens. Residential (drained by swales)	89.84	4.92	5.24	0.05	0.17
Apartments	57.79	15.86	26.36	0.09	0.17
Multi Family	65.19	27.38	7.43	0.13	0.14
Offices	38.67	56.77	4.57	0.41	0.43
Shopping Centers	32.53	63.83	3.64	0.43	0.47
Schools	79.12	16.03	4.86	0.12	0.17
Churches	44.24	53.64	2.12	n/a	n/a
Strip Commercial	7.90	87.80	4.30	0.60	0.61
Industrial	53.61	35.79	10.60	0.46	0.49
Parks	59.32	32.32	8.36	0.29	0.34
Cemeteries (drained by swales)	82.90	0.00	17.10	0.08	0.16
Golf Courses (drained by swales)	94.56	1.93	3.51	0.04	0.15
Freeways (drained by swales)	40.91	0.00	59.09	0.08	0.26
Vacant (drained by swales)	95.23	0.00	4.77	0.06	0.17

Figures 2 and 3 illustrate the relationships between the directly connected impervious area percentages and the calculated volumetric runoff coefficients (Rv) for each land use category (using the average land use characteristics), based on 43 years of local rain data. As expected, there is a strong relationship between these parameters for both sandy and clayey soil conditions. The fitted exponential equations are:

Sandy soils: $y = 0.062e^{0.031x}$ ($R^2 = 0.83$)

Clayey soils: $y = 0.15e^{0.017x}$ ($R^2 = 0.72$)

Where y is the volumetric runoff coefficients (Rv) and x is the directly connected impervious areas (%) for the areas. It is interesting to note that the Rv is relatively constant until the 10 to 15% directly connected impervious cover values are reached (at Rv values of about 0.07 for sandy soil areas and 0.16 for clayey soil areas), the point where receiving water degradation typically is observed to start. The 25 to 30% directly connected impervious levels (where significant degradation is observed), is associated with Rv values of about 0.14 for sandy soil areas and 0.25 for clayey soil areas, and is where the curves start to greatly increase in slope.

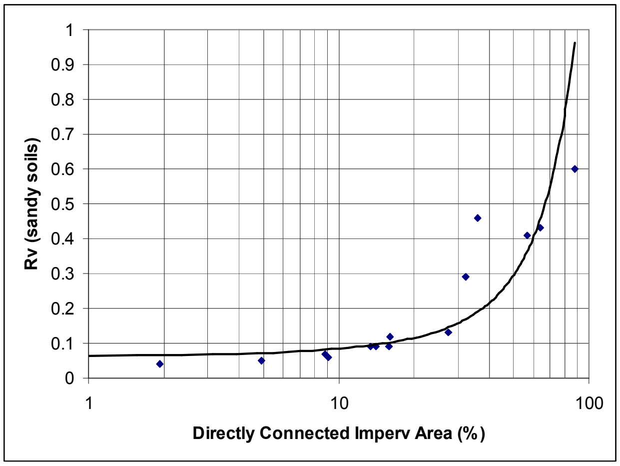

Figure 2. Relationships between the directly connected impervious area (%) and the calculated volumetric runoff coefficients (Rv) for each land use category for sandy soil.

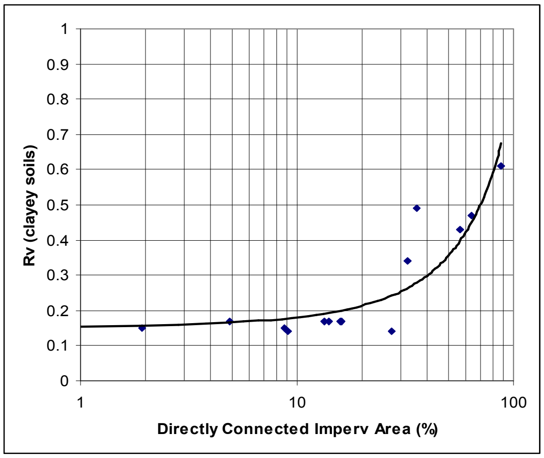

Figure 3. Relationships between the directly connected impervious area (%) and the calculated volumetric runoff coefficients (Rv) for each land use category for clayey soil.

These relationships are used in WinSLAMM to predict the relationship between the amount of impervious cover and the approximate expected receiving water biological condition (by using the calculated Rv values) affected by the study area. WinSLAMM calculates the Rv for the duration of the study period for various conditions, including with and without controls. These values are correlated to the expected biological conditions, weighted by the soil properties in the study area. This enables one to predict the expected benefits that may occur with the use of the stormwater controls, compared to no controls.

Stream Flow Effects and Associated Habitat Modifications

Some of the most serious effects of urban and agricultural runoff are on the aquatic habitat of the receiving waters. A major habitat destruction threat comes from the rapidly changing flows and the absence of refuge areas to protect the biota during these flow changes. The natural changes in stream hydrology will change naturally at a slow, relatively nondetectable rate in most areas where streambanks are stabilized by riparian vegetation. In other areas, however, natural erosion and bank slumping will occur in response to high flow events. This "natural" contribution to stream solids is accelerated by hydromodifications, such as increases in stream power due to upstream channelization, installation of impervious drainage networks, increased impervious areas in the watershed (roof tops, roadways, parking areas), and removal of trees and vegetation. All of these increase the runoff volume and stream power, and decrease the time period for stream peak discharge. The following summary is excerpted from Burton and Pitt (2001) and presents a few case studies describing habitat problems associated with increased urbanization and associated flows.

In moderately developed watersheds, peak discharges are two to five times those of pre-development levels (Leopold 1968, Anderson 1970). These storm events may have 50% greater volume which may result in flooding. The quicker runoff periods reduce infiltration thus interflows and baseflows into the stream from groundwater during drought periods are reduced, as are groundwater levels. As stream power increases, channel morphology will change with an initial widening of the channel to as much as 2 to 4 times their original size (Robinson 1976, Hammer 1972). Floodplains increase in size, stream banks are undercut and riparian vegetation lost. The increased sediment loading from erosion moves through the watershed as bedload, covering sand, gravel, and cobble substrates.

As an example, the aquatic organism differences found during the Bellevue Urban Runoff Program were probably most associated with the increased peak flows in Kelsey Creek caused by urbanization and the resultant increase in sediment carrying capacity and channel instability of the creek (Pedersen 1981; Perkins 1982; Richey, *et al.* 1981; Richey 1982; Scott, *et al.* 1982). Kelsey Creek had much lower flows than Bear Creek during periods between storms. About 30 percent less water was available in Kelsey Creek during the summers. These low flows may also have significantly affected the aquatic habitat and the ability of the urban creek to flush toxic spills or other dry weather pollutants from the creek system (Ebbert, *et al*. 1983; Prych and Ebbert undated). Kelsey Creek had extreme hydrologic responses to storm. Flooding substantially increased in Kelsey Creek during the period of urban development; the peak annual discharges almost doubled in the last 30 years, and the flooding frequency also increased due to urbanization (Ebbert, *et al.* 1983; Prych and Ebbert undated). These increased flows in urbanized Kelsey Creek resulted in greatly increased sediment transport and channel instability. The Bellevue studies (Pitt and Bissonnette 1984) indicated very significant interrelationships between the physical, biological, and chemical characteristics of the urbanized Kelsey Creek system. The aquatic life beneficial uses were found to be impaired and stormwater conveyance was most likely associated with increased flows from the impervious areas in the urban area. Changes in the flow characteristics could radically alter the ability of the stream to carry the polluted sediments into the other receiving waters.

In another study, Stephenson (1996) studied changes in streamflow volumes in South Africa during urbanization. He found increased stormwater runoff, decreases in the groundwater table, and dramatically decreased times of concentration. The peak flow rates increased by about two-fold, about half caused by increased pavement (in an area having only about 5% effective impervious cover), with the remainder caused by decreased times of concentration.

Bhaduri, *et al.* (1997) quantified the changes in streamflow and associated decreases in groundwater recharge associated with urbanization. They point out that the most widely addressed hydrologic effect of urbanization is the peak discharge increases that cause local flooding. However, the increase in surface runoff volume also represents a net loss in groundwater recharge. They point out that urbanization is linked to increased variability in volume of water available for wetlands and small streams, causing “flashy” or “flood-and-drought” conditions. In northern Ohio, urbanization at a study area was found to cause a 195% increase in the annual volume of runoff, while the expected increase in the peak flow for the local 100-yr event was 26% for the same site. Although any increase in severe flooding is problematic and cause for concern, the much larger increase in annual runoff volume, and associated decrease in groundwater recharge, likely has a much greater effect on in-stream biological conditions.

A number of presentations concerning aquatic habitat effects from urbanization were made at the *Effects of Watershed Development and Management on Aquatic Ecosystems* conference held in Snowbird, UT, in August of 1996, sponsored by the Engineering Foundation and the ASCE. MacRae (1997) presented a review of the development of the common zero runoff increase (ZRI) discharge criterion, referring to peak discharges before and after development. This criterion is commonly met using detention ponds for the 2 yr storm. MacRae shows how this criterion has not effectively protected the receiving water habitat. He found that stream bed and bank erosion is controlled by the frequency and duration of the mid-depth flows (generally occurring more often than once a year), not the bank-full condition (approximated by the 2 yr event). During monitoring near Toronto, he found that the duration of the geomorphically significant pre-development mid-bankfull flows increased by a factor of 4.2 times, after 34% of the basin had been urbanized, compared to before development flow conditions. The channel had responded by increasing in cross-sectional area by as much as 3 times in some areas, and was still expanding. Table 2 shows the modeled durations of critical discharges for predevelopment conditions, compared to current and ultimate levels of development with “zero runoff increase” controls in place. At full development and even with full ZRI compliance in this watershed, the hours exceeding the critical mid-bankfull conditions will increase by a factor of 10, with resulting significant effects on channel stability and the physical habitat.

Table 2. Hours of Exceedence of Developed Conditions with Zero Runoff Increase Controls Compared to Predevelopment Conditions (MacRae (1997)

Recurrence Interval (yrs)	**Existing Flowrate (m^3/s)**	**Exceedence for Predevelopment Conditions (hrs per 5 yrs)**	**Exceedence for Existing Development Conditions, with ZRI Controls (hrs per 5 yrs)**	**Exceedence for Ultimate Development Conditions, with ZRI Controls (hrs per 5 yrs)**
1.01 (critical mid-bankfull conditions)	1.24	90	380	900
1.5 (bankfull conditions)	2.1	30	34	120

MacRae (1997) also reported other studies that found that channel cross-sectional areas began to enlarge after about 20 to 25% of the watershed was developed, corresponding to about a 5% impervious cover in the watershed. When the watersheds are completely developed, the channel enlargements were about 5 to 7 times the original cross-sectional areas. Changes from stable streambed conditions to unstable conditions appear to occur with basin imperviousness of about 10%, similar to the value reported for serious biological degradation. He also summarized a study conducted in British Columbia that examined 30 stream reaches in natural areas, in urbanized areas having peak flow attenuation ponds, and in urbanized areas not having any stormwater controls. The channel widths in the uncontrolled urban streams were about 1.7 times the widths of the natural streams. The streams having the ponds also showed widening, but at a reduced amount compared to the uncontrolled urban streams. He concluded that an effective criterion to protect stream stability (a major component of habitat protection) must address mid-bankfull events, especially by requiring similar durations and frequencies of stream power (the product of shear stress and flow velocity, not just flow velocity alone) at these depths, compared to satisfactory reference conditions.

Urbanization radically affects many natural stream characteristics. Pitt and Bissonnette (1984) reported that the coho and cutthroat were affected by the increased nutrients and elevated temperatures of the urbanized streams in Bellevue, as studied by the University of Washington as part of the U.S. EPA’s NURP project (EPA 1983). These conditions were probably responsible for accelerated growth of the fry which were observed to migrate to Puget Sound and the Pacific Ocean sooner than their counterparts in the control forested watershed that was also studied. However, the degradation of sediments, mainly the decreased particle sizes, adversely affected their spawning areas in streams that had become urbanized. Sovern and Washington (1997) reported that, in Western Washington, frequent high flow rates can be 10 to 100 times the predevelopment flows in urbanized areas, but that the low flows in the urban streams are commonly lower than the predevelopment low flows. They have concluded that the effects of urbanization on western Washington streams are dramatic, in most cases permanently changing the stream hydrologic balance by: increasing the annual water volume in the stream, increasing the volume and rate of storm flows, decreasing the low flows during dry periods, and increasing the sediment and pollutant discharges from the watershed. With urbanization, the streams increase in cross-sectional area to accommodate these increased flows and headwater downcutting occurs to decrease the channel gradient. The gradients of stable urban streams are often only about 1 to 2 percent, compared to 2 to 10 percent gradients in natural areas. These changes in width and the downcutting result in very different and changing stream conditions. The common pool/drop habitats are generally replaced by pool/riffle habitats, and the stream bed material is comprised of much finer material, for example. Along urban streams, fewer than 50 aquatic plant and animal species are usually found. They have concluded that once urbanization begins, the effects on stream shape are not completely reversible. Developing and maintaining quality aquatic life habitat, however, is possible under urban conditions, but it requires human intervention and it will not be the same as for forested watersheds.

Increased flows due to urban and agricultural modification obviously cause aquatic life impacts due to destroyed habitat (unstable channel linings, scour of sediments, enlarging stream cross-sections, changes in stream gradient, collapsing of riparian stands of mature vegetation, siltation, embeddedness, etc.) plus physical flushing of aquatic life from refuge areas downstream. The increases in peak flows, annual runoff amounts, and associated decreases in groundwater recharge obviously cause decreased dry weather flows in receiving streams. Many small and moderate-sized streams become intermittent after urbanization, causing extreme aquatic life impacts. Even with less severe decreased flows, aquatic like impacts can be significant. Lower flows are associated with increased temperatures, increased pollutant concentrations (due to decreased mixing and transport), and decreased mobility and forage opportunities.

WinSLAMM presents a cumulative summary of all flows predicted over the complete study period. These are presented in graphical and tabular form and show the resultant conditions at the discharge from the study area for all the controls in place, and if the controls were not present. This comparison enables one to examine the benefits of the stormwater controls on the distribution and magnitude of the flows.

Local Area Soils and their Infiltration Capabilities

As described in a preceding module on hydrology, disturbed urban soils show little resemblance to the native soils mapped by the Soil Conservation Service (now the Natural Resources Conservation Service). During construction, grading operations may export soils from the site (exposing deeper subsoils that may be covered with a thin layer of top soil) or bring in fill. In addition, construction operations significantly degrade infiltration capacities of soils due to compaction from heavy equipment. Even so, the native soil characteristics in the area of concern are of interest, as the cut and fill operations are usually local and the soil texture in the area is likely indicative of the soil that will be exposed at the site. The reported infiltration rates for the soils will likely be a “best-case” estimate of conditions after development. It may require special amendments to the soil, or many years, before the soil can infiltrate at its capacity. However, significant stormwater runoff benefits can be expected with infiltration even in areas with reduced infiltration capacities, and these areas should be identified and targeted for infiltration.

As an example, Table 3 summarizes the soil characteristics along the main creeks in the Atlanta, GA, area as mapped on the SCS county soil maps. Most of the soils along the stream corridors in the Atlanta area have hydrologic soil type “B”, indicating excellent potentials for infiltration controls. There are some “D” type soils in the area which would not provide very successful infiltration locations. In all cases, local soil infiltration tests should be conducted in areas where large infiltration devices are being considered. Soils having infiltration rates greater than 0.27 inches per hour are preferred for infiltration devices, and soils having less than 0.17 in/hr are restricted from having infiltration devices in the City of Atlanta’s *Stormwater Management Design Manual* (1996). SCS hydrologic group C soils have infiltration rates of 0.17 to 0.27 in/hr, so C soils are marginal, while D soils are unsuitable (0.02 to 0.09 in/hr). Both B soils (0.52 to 1.02 in/hr) and A soils (2.41 to 8.27 in/hr) are clearly acceptable for infiltration controls, according to the City of Atlanta manual. In the Western Washington Stormwater Management Manual, soils having very high infiltration rates (>2 in/hr) are not considered adequate for “treatment.” Therefore, the B soils are preferred for sites for infiltration, without necessary modifications (discussed in a later module).

Table 3. Mapped Soils along Selected Atlanta Stream Corridors (from county SCS soil maps)

County	Creek/River	Soil Characteristics	Hydrologic Groups
Dekalb	South River	Urban land	
		Pacolet-Asher-Gwinnett: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Cartecay-Toccoa-Wehadkee: deep, somewhat poorly drained to well drained (loamy throughout)	B, C, D
		Gwinnett-Cecil-Madison: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
	Snapfinger Creek	Gwinnett-Cecil-Madison: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Madison-Pacolet-Gwinnett: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Cartecay-Toccoa-Wehadkee: deep, somewhat poorly drained to well drained (loamy throughout)	B, C, D
		Pacolet-Asher-Gwinnett: deep well-drained (loamy surface and clayey subsoil)	B, B, B
	Fowler Creek	Cartecay-Toccoa-Wehadkee: deep, somewhat poorly drained to well drained (loamy throughout)	B, C, D

		Pacolet-Urban land: deep, well-drained (loamy surface and clayey subsoil)	B
		Madison-Pacolet-Gwinnett: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Gwinnett-Cecil-Madison: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
	Doolittle Creek	Cartecay-Toccoa-Wehadkee: deep, somewhat poorly drained to well drained (loamy throughout)	B, C, D
		Madison-Pacolet-Gwinnett: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Urban land	
	Sugar Creek	Cartecay-Toccoa-Wehadkee: deep, somewhat poorly drained to well drained (loamy throughout)	B, C, D
		Madison-Pacolet-Gwinnett: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Pacolet-Urban land: deep, well-drained (loamy surface and clayey subsoil)	B
	Intrenchment Creek	Cartecay-Toccoa-Wehadkee: deep, somewhat poorly drained to well drained (loamy throughout)	B, C, D
		Madison-Pacolet-Gwinnett: deep, well-drained (loamy surface and clayey subsoil)	B, B, B
		Urban land	
		Cecil-Urban land: deep, well-drained (loamy surface and clayey subsoil)	B
Cobb	Chattahoochee River	Toccoa-Cartecay: well drained and somewhat poorly drained	
		Urban land	
		Madison-Louisa-Pacolet: well drained to somewhat excessively drained (clayey to loamy subsoil)	B, B, B
	Nickajack Creek	Cartecay-Toccoa: somewhat poorly drained and well-drained	
		Appling-Pacolet-Louisburg: well drained to excessively drained (clayey to loamy subsoil)	B, B, A
		Louisburg-Appling-Wilkes: excessively drained to well-drained (loamy to clayey subsoil, stony in places)	A, B, C
		Pacolet-Musella Louisburg: well-drained to excessively drained (clayey to loamy subsoil)	B, B, A
	Powder Springs Creek	Cartecay-Toccoa: somewhat poorly drained and well-drained	
	Sweetwater Creek	Cartecay-Toccoa: somewhat poorly drained and well-drained	
		Madison-Gwinnett-Pacolet: well-drained (clayey to loamy subsoil)	B, B, B
		Louisburg-Appling-Wilkes: excessively drained to well-drained (loamy to clayey subsoil, stony in places)	A, B, C
		Gwinnett-Pacolet-Musella: well-drained (clayey to loamy subsoil)	B, B, B
Douglas	Chattahoochee River	Wickham-Congaree: somewhat poor to moderately well-drained (alluvial land)	B,
	Sweetwater Creek	Madison-Louisa: deep and well drained	B, B
		Wickham-Congaree: somewhat poor to moderately well-drained (alluvial land)	B,
	Anneewakee Creek	Madison-Louisa: deep and well drained	B, B
		Wickham-Congaree: somewhat poor to moderately well-drained (alluvial land)	B,
	Bear Creek	Madison-Louisa: deep and well drained	B, B
		Wickham-Congaree: somewhat poor to moderately well-drained (alluvial land)	B,
	Dog River	Madison-Louisa: deep and well drained	B, B
		Wickham-Congaree: somewhat poor to moderately well-drained (alluvial land)	B,
	Hurricane Creek	Madison-Louisa: deep and well drained	B, B
		Wickham-Congaree: somewhat poor to moderately well-drained (alluvial land)	B,
Coweta	Chattahoochee River	Riverview: well drained (loamy throughout)	B
	Cedar Creek	Riverview-Chewacla-Roanoke: well drained to poorly drained (loamy or clayey subsoil)	B, C, D
		Pacolet-Wedowee: well drained (clayey subsoil)	B, B

		Madison-Pacolet: well drained (clayey subsoil)	B, B
	Wahoo Creek	Riverview-Chewacla-Roanoke: well drained to poorly drained (loamy or clayey subsoil)	B, C, D
		Madison-Pacolet: well drained (clayey subsoil)	B, B
		Cecil-Madison-Appling: well drained (clayey subsoil)	B, B, B
Heard	Chattahoochee River	Riverview: well drained (loamy throughout)	B
	Hilly Mill Creek	Riverview: well drained (loamy throughout)	B
		Appling: well drained (clayey subsoil)	B
	Centralhatchee Creek	Riverview-Chewacla: well drained to poorly drained (loamy throughout)	B, C
		Madison-Louisa: well drained and somewhat excessively drained (clayey or loamy subsoil)	B, B
		Pacolet-Wedowee: well drained (clayey subsoil)	B, B
Clayton	Reeves Creek	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B
		Pacolet-Gwinnett-Madison: well drained (clayey subsoil)	B, B, B
	Big Cotton Creek	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B
		Cecil-Madison-Pacolet: well drained (clayey subsoil)	B, B, B
		Pacolet-Gwinnett-Madison: well drained (clayey subsoil)	B, B, B
Henry	South River	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B
		Pacolet-Gwinnett-Madison: well drained (clayey subsoil)	B, B, B
	Walnut Creek	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B
		Pacolet-Gwinnett-Madison: well drained (clayey subsoil)	B, B, B
	Little Cotton Creek	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B
		Pacolet-Gwinnett-Madison: well drained (clayey subsoil)	B, B, B
	Big Cotton Creek	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B
		Pacolet-Gwinnett-Madison: well drained (clayey subsoil)	B, B, B
	Indian Creek	Cartecay-Toccoa: somewhat poorly drained and well drained (loamy throughout)	C, B

Types of Stormwater Infiltration Devices

There are many different types of infiltration devices, including roof drain leaders directed to lawns, soakaway pits (dry wells), seepage (infiltration) trenches, recharge (percolation) basins, and grass swales. These devices can be located throughout an area and can be incorporated into landscaped areas of all types of land uses. The use of infiltration devices can also significantly reduce the size, and therefore cost, of the storm drainage system. The most common method of upland infiltration uses trenches. Infiltration (or recharge) basins are also popular infiltration devices.

The following discussion examines a variety of infiltration control options, including general infiltration devices, grass filter strips, porous pavements, and grass waterways. The design procedures rely mostly on physical removal mechanisms, but it is recognized that biological processes, especially pollutant uptake by plants and biodegradation, along with chemical ion-exchange and sorption processes, have contributed to the pollutant removals noted during field studies. Therefore, special care must be taken to enhance these biological and chemical removal mechanisms (and to make them irreversible), such as in the selection of specific plants for use in grass waterways or grass filters, and the use of soil amendments to enhance infiltration and capture of pollutants in surface soils. The selection of plants for use in stormwater control practices must be carefully made in conjunction with knowledgeable specialists.

A major problem associated with many infiltration practices is the potential contamination of groundwaters. A few studies have investigated groundwater contamination associated with stormwater infiltration devices. These studies have identified limited problems. However, most of these studies have not been very comprehensive in scope. A major research need is a more through investigation of the groundwater contamination potential of infiltration (and other stormwater control) devices. It must be remembered that uncontrolled stormwater also has a groundwater contamination potential. Design procedures and guidance given in the following discussions should minimize serious groundwater contamination. It must be emphasized that special care is needed when planning and constructing infiltration devices.

There are many types of artificial stormwater infiltration mechanisms that have been used in urbanizing areas in order to decrease discharges of stormwater to surface waters and to help preserve groundwater recharge. These are described in many stormwater design manuals. The following infiltration techniques are most commonly used:

- surface infiltration devices (grass filters and grass-lined drainage swales; infiltration is usually dominant stormwater treatment mechanism; infiltration occurs through turf and surface soils, providing the most opportunities for pollutant trapping before the water reaches groundwater);

- french drains or soak-aways (small source area subsurface infiltration pits, most typically used for infiltrating drainage from roofs; usually simple gravel-filled dug holes, but can be an empty perforated container);

- porous pavements or grid pavers (replace impervious pavements, overlain on a relatively thick storage layer of coarse material; may include drainage pipes to collect excess water that cannot be infiltrated into underlying soil);

- drainage trenches (collect and infiltrate runoff from adjacent paved areas; generally long, moderately wide, and shallow in dimensions; filled with coarse gravel to provide storage);

- infiltration wells, or dry wells (deep, relatively small diameter holes allowing stormwater to be discharged to deep soil horizons, sometimes directly into saturated zones, commonly located at storm drainage inlet locations serving up to a few hectares of drainage area, with overflows discharged to storm or combined drainage system);

- percolating sewerage (conventional separate storm drainage, but with perforations through pipe or gaps between pipe segments; usually wrapped in geotextile fabric with coarse gravel used as trench backfill material);

- dry (percolating) basins (usually large storage areas typically located at end of drainage system before discharge into receiving water; commonly used as recreation facilities during dry weather; also provides infiltration through turf and surface soils).

All infiltration devices redirect runoff waters from the surface to the sub-surface environments. Therefore, they must be carefully designed using sufficient site specific information to protect the groundwater resources and to achieve the desired water quality management goals.

Beale (1992) described numerous methods to reduce problems in storm drainage. The traditional approach had been for the rapid removal of stormwater from a development to the nearest watercourse or sewer system. This approach cannot continue due to the high economic and social cost associated with upgrading existing sewerage and/or increased flooding in urban areas. Three main options are: 1) reduce flows entering the drainage system, 2) increase the capacity of the drainage system (the traditional approach), or 3) attenuate flows within the drainage system. The methods available to reduce incoming flows include:

- Diversion
- Infiltration (plane infiltration, basin infiltration, soakaways, infiltration trenches, or infiltration boreholes)
- Control flows entering drainage (rooftop detention, control in down pipes, control in gully outlets, control by gully spacing to attenuate flows in drainage:

- Attenuation in drainage (surface flooding, oversize sewer, on-line tank, off-line tank, storage ponds, or tank design)
- Attenuation in watercourse (on-line storage ponds, or off-line storage ponds)

Benefits and Problems Associated with Stormwater Infiltration

In most urban areas, stormwater is directed to subsurface drainage systems. In areas having combined sewer systems, such as in most of Europe, in the large cities of Asia, and in many older cities of the U.S., this additional water causes overflows of raw or poorly treated domestic sewage during periods of moderate to heavy rainfalls. Even in areas having separate sewerage systems, the use of conventional subsurface sewerage radically alters the receiving waters. The frequent and high flows in receiving waters causes detrimental biological conditions, causes increased erosion of channels, causes flood damage, and dramatically reduces the amount of rainfall that recharges the local groundwaters. This recharge reduction causes severe low flow problems in many areas during prolonged dry periods, further worsening the biological habitat, decreasing recreation benefits, and reducing the assimilative capacity for downstream wastewater discharges.

Infiltration techniques have been used for many years to control stormwater quality and flooding. They offer many advantages when integrated into conventional drainage systems (Azzout, *et al*. 1994; Novatech 1992; Novatech 1995):

- lower the costs of the sewerage systems;
- limited required maintenance;
- good integration in urban environment;
- preservation of the hydrological balance in the environment.

Upland infiltration devices are located at urban source areas and can significantly reduce both stormwater runoff volume and contaminant contributions from the treated areas to the receiving waters. All infiltration devices redirect runoff waters from the surface to the sub-surface environments. Therefore, they must be carefully designed using sufficient site specific information to protect the groundwater resources and to achieve the desired water quality management goals.

With development, natural groundwater recharge is reduced, with increased surface water flows during wet weather and significantly reduced surface water flows (that rely on groundwater discharge) during dry weather. The use of infiltration can help maintain the natural groundwater recharge in an urbanizing area and maintain adequate receiving water base flows during critical dry weather periods.

Stormwater Control Effectiveness of Infiltration Devices

Numerous recent papers describe the successful use of stormwater infiltration throughout the world. Musiake, *et al.* (1990) described the use of shallow infiltration facilities is Tokyo, and Stenmark (1990) described the use of infiltration facilities in cold climates. Other stormwater infiltration experience has been described by Wada and Miura (1990), Harada and Ichikawa (1993),Yamada (1993), and Duchene, *et al.* (1993). The Technical University of Denmark has recently conducted numerous research projects concerning the benefits of infiltration as a source area control to reduce combined sewer overflows (Geldof, *et al*. 1994; Mikkelsen, *et al.* 1994; Rosted Petersen, *et al*. 1994; and Jacobsen and Mikkelsen 1996). Rosted Petersen, *et al.* (1994), for example, found that the optimal solution for reducing CSO volumes by 40% required infiltrating 65% of the paved areas using infiltration trenches having total storage volumes of 3.6 mm. This corresponds to a return period of 0.04 years (about 2 weeks), in contrast to the commonly applied design return periods of 2 to 10 years.

An interesting example of a retro-fitted infiltration system in an intensively developed area is the Experimental Sewer System (ESS) in Tokyo. The ESS includes many infiltration components (infiltration inlets, infiltration trenches, infiltration curbs, and permeable pavements) and has significantly reduced the amount and frequency of urban flooding (Fujita 1993). The ESS has reduced the stormwater peak flows by 60% and runoff volume by 50%, compared to conventional storm sewerage systems. Furthermore, the cost of the ESS is about 1/3 of the cost of conventional detention facilities, and only about 1/10 of the cost of underground detention facilities that would provide similar benefits. The infiltration trenches used as part of the ESS have been easily installed in parks and alongside roads, with little interference to the intensive use of the land.

Infiltration also improves the receiving water quality in areas served by either combined or separate sewers (Geldof, *et al*. 1993). Decreased amounts, frequencies, and durations of overflows from combined systems have dramatically lowered the discharges of many pollutants. The number of overflows in combined sewers in Tokyo have decreased from about 36 per year to about 7 in areas served by the ESS. The resulting BOD discharges have also been reduced by about 45%. Phosphorus and heavy metals in separate sewer discharges can be substantially reduced with the widespread use of infiltration (Hvitved-Jacobsen, *et al.* 1992).

This radical alteration of the local hydrologic cycle has prompted the use of infiltration of stormwater to mitigate these affects. As an example, Krijci, *et al.* (1993) described the mandatory use of stormwater infiltration in Switzerland to decrease the burden on combined and separate sewerage systems. The 1992 Swiss Water Pollution Control Law requires that unpolluted wastewater must be infiltrated. If local conditions prevent infiltration, then special authorization is required and detention is used. A simple system is used to determine the suitability of stormwater for infiltration, depending on the area drained and the use of the groundwater. As an example, runoff from roofs, bike lanes, and walking paths must be infiltrated in all areas, even if the groundwater has high importance as a drinking water source. Surface infiltration is required (and subsurface infiltration is prohibited) for this runoff in most drinking water protection zones. The infiltration of roadway and parking area runoff is more restricted, where only surface infiltration is allowed for all areas. Any infiltration of highway and freeway runoff is only allowed in exceptional situations. In all cases, “clean” water (runoff from yard drainage, spring water, groundwater, and cooling water) is forbidden in combined sewers.

Conradin (1995) describes how Zurich is complying with the Swiss Water Pollution Control Law. The city has 50 to 100 year old sewerage, about 80% being combined sewerage and 20% being separate sewerage. Clean flows (fountain water, spring water, yard drainage, cooling system water, and possibly roof runoff) are required to be diverted from the sewerage. All other stormwater will be directed to the combined sewerage and newly renovated treatment plants. The city is converting its system to a partially separate system that collects the clean water and directly diverts it to the Limmat River. Zurich is building open brooks along streets and walkways to collect these waters. The open brooks provide natural water channels and aesthetically revitalizes the urban area. About 12 km of brooks have been built as of 1995, and as much as 30 km total are planned. The current brooks divert about 150 L/sec from the sewerage. The brooks are designed to carry about two to five times the dry weather flows, with excess diverted to the sewerage and the treatment plants.

Candaras, *et al.* (1995) describe an exfiltration and filtration demonstration project in Etobicoke, Ontario, near Toronto. The exfiltration system was developed to eliminate the discharge of stormwater for frequent rains, while improving the function of traditional drainage systems. The City of Etobicoke adopted a new stormwater management concept that promotes three levels of control:

1) Major drainage system (overland flow) designed to transport runoff from large and infrequent rains (such as the 100 year storm),
2) Minor drainage system (typical stormwater conveyance system) designed to transport the runoff from smaller and more frequent rains (such as the 2 and 5 year storms), and
3) Micro drainage system designed to eliminate runoff form the very frequent rains (such as rains of about 10 to 15 mm in depth).

The city developed two basic devices, currently being tested to accomplish these goals. The exfiltration system is a pair of small diameter, perforated PVC pipe that is installed below conventional storm drainage pipe. All three pipes run from manhole to manhole, but the perforated pipes are plugged at the downstream end to eliminate short-circuiting. The pipe trench is wrapped in a geotextile and back filled with 15 mm clear stone. If the storm exceeds the capacity of the stone, the excess water flows through the conventional pipe. The filtration system uses a perforated PVC pipe located above the conventional pipe, with both ends plugged. The catchbasin inlet has a lower outlet that directs runoff to the perforated pipe. The clear stone trench lining acts as a filter for the percolating water, which is picked up by another series of two perforated pipes located under the conventional pipe and connected to the lower manhole. If the filter capacity is exceeded, water flows out of the upper outlet from the catchbasin directly into the conventional pipe. Preliminary monitoring has shown that the test devices have performed better than expected.

Problems with Infiltration Devices

The following paragraphs describe some of the general problems encountered with infiltration devices.

Clogging

Mason (1982) reports that infiltration trench performance can be severely limited if the trench receives large amounts of oils and sediment. Extensive maintenance and reconstruction can be periodically required. Pretreatment of the runoff with silt traps or with grass filter strips can significantly reduce the required maintenance. Infiltration basins (percolation ponds) can be constructed with two different sections, with an initial small section to allow presettling of the particulates to minimize the area requiring dredging. Diffusion wells drilled through the basin bottom and breaking up the bottom material in the infiltration basin can also increase their performance and to help overcome premature clogging. There have been numerous accounts of infiltration trench failures associated with clogging (and compaction during site construction) and many areas are backing off from their use, unless pre-treatment can be assured (Schueler 1996). Clogging is not nearly as serious for grass swales, surface spreading areas, or disconnections of pavement and roof drainage. In these areas, clogging is localized and the water can flow around the clogged area with minimal loss of performance. Trenches are quite small and concentrate clogging problems in an isolated area that is difficult and expensive to correct.

Urban runoff from some source areas (such as roofs) can be relatively clean and does not require as much pretreatment to protect infiltration devices from clogging as runoff from other areas. However, runoff from parking lots or storage areas may contain large amounts of sediments and oils which may significantly reduce infiltration performance, if no pretreatment or maintenance is used.

Infiltration devices, especially rock filled trenches, must be protected from high sediment loads. This is usually done by lining the infiltration trench with an appropriate filter fabric before back-filling with rock. The filter fabric is then folded on top of the fill material and then further back filled with finer graded materials and finally either paved or covered with gravel or vegetation. This surface material can then be periodically removed and replaced as the infiltration capacity decreases. In addition, surface flows should be subjected to grass filtration before they enter an infiltration area to reduce the sediment being carried in the sheetflowing water. The Lake Tahoe Regional Planning Agency (Lake Tahoe 1978) recommended pretreatment of the runoff to remove the heavier suspended particles and trash even in their early manual. Vacuum trucks can be effectively used to remove accumulated sediment. A drop inlet or sedimentation box (with a sump volume of at least two percent of the gross volume of the infiltration trench) was recommended. They also required that all trenches be protected from surface traffic. They also found that it is better to use multiple infiltration trenches spaced throughout a source area instead of one large trench. This is especially important for parking areas in order to keep each device small and more easily maintained.

Maintenance inspections of infiltration devices (especially trenches and porous pavement) may be necessary after large rains or snowmelts.

Groundwater Contamination

One of the most important site constraints restricting the use of infiltration devices is the potential for contaminating groundwater with polluted urban runoff. Pitt, *et al.* (1994 and 1996) prepared a summary of the potential of groundwater contamination associated with stormwater infiltration. That material is summarized in a later subsection.

The fates of many potential pollutants in soils and groundwaters are not well known. The Fresno and Long Island NURP projects, (EPA 1983) examined the transport of urban runoff pollutants through soil, but mostly examined particulate metals, and did not thoroughly evaluate soluble organics. The particulate metals were found to be contained within the top few inches of most soils and did not penetrate to the groundwater.

Most of the information required to evaluate the groundwater contamination potential of specific project locations must be obtained through site investigations. Published information is typically not sufficiently accurate for this purpose (or to design infiltration devices). Factors that may indicate groundwater contamination potential are as follows:

- depth to water table less than 20 feet (the most important factor).
- depth to bedrock less than five feet and most types of bedrock (carbonate, sandstone, volcanic, igneous, and metamorphic), except shale.
- high permeability of unconsolidated material (the most suitable values for infiltration devices), such as found for most materials, except clay.
- soil permeability of greater than six inches per hour.

It must be realized that urban runoff currently contaminates shallow groundwaters in all urbanized areas by infiltration through the soils before the water reaches the drainage system, by exfiltration from leaking drainage systems, and by groundwater recharge from the receiving waters.

Reducing the Effective Impervious Areas Associated with Development

There have been numerous researchers that have identified relationships between percent imperviousness of a watershed and in-stream biological conditions. Schueler (1996) found that once a watershed area had more than about 10 to 15% effective impervious cover, noticeable changes in channel morphology occurred, along with quantifiable impacts on water quality, and biological conditions. MacRae (1997) also reported other studies that found that channel cross-sectional areas began to enlarge after about 20 to 25% of the watershed was developed, corresponding to about a 5% impervious cover in the watershed. When the watersheds are completely developed, the channel enlargements were about 5 to 7 times the original cross-sectional areas. Changes from stable streambed conditions to unstable conditions appear to occur with basin imperviousness of about 10%, similar to the value reported previously for serious biological degradation.

The following discussion presents examples of how the effectiveness of impervious areas associated with extensive development may be reduced significantly. The main control objectives will be to reduce runoff volumes, flow rates, and to provide a riparian buffer habitat. Further reductions in pollutant discharges beyond which would occur with runoff volume reductions may only be necessary at critical source or land use areas.

Runoff Volume Restrictions

The primary intent of stormwater management is to reduce water quality problems and to control urban flooding problems. Significant peak flow rate reductions can be expected for many storms as the runoff volume is reduced. When runoff volumes are reduced, similar peak flow rate reductions will also occur if the stormwater controls are carefully designed. Peak flow rate (flooding) criteria cannot be adequately developed without a detailed, basinwide, site-specific hydrologic analysis. If adequate hydrologic analyses have been conducted for an area, then specific peak flow rate criterion should be promulgated.

Simple criteria limiting predicted post-development peak flow rates to predevelopment values are very common nationwide. These flow rate criteria usually result in the use of many small dry detention basins scattered throughout an area. This approach can result in significant on-site drainage system construction cost savings to the developer by allowing smaller drainage system components between the on-site peak flow rate control device (such as a dry detention basin) and the municipal drainage system. In many cost analyses, this drainage cost savings has been shown to more than offset the cost of the peak flow rate control devices. Unfortunately, these criteria have resulted in few regional flood reduction benefits, and in many cases, they have actually increased downstream flooding. A stormwater management ordinance should require the disposal of runoff waters in order to reasonably prevent inundation, erosion, or deposit of floatable matter, sediment, or siltation onto property of others, or cause degradation of the waters of the watershed.

A flow volume criteria will result in system-wide drainage savings, even if no applicable hydrologic analyses are available. A runoff volume criteria can be developed to maintain post-development water balance conditions similar to those that occurred before development, and to permit achieving those conditions at reasonable costs related to development intensity. Low density residential developments, for example, are not expected to require any controls beyond typical grass roadside drainage swales. In contrast, a shopping center may be required to have an on-site wet detention basin (for pretreatment) and a relatively large infiltration system. In all cases, the added costs to meet stormwater criteria will be only a small fraction of site development costs and will be many times less expensive than the costs of retro-fitting controls into developed areas at a later time.

General water volume limitations could be based on U.S. Natural Resources Conservation Service (NRCS) "curve numbers" (CN) for different soil hydrologic groups (SCS 1986). Most engineers and planners are quite familiar with the NRCS curve numbers and their use for designing drainage facilities. The CN method is not applicable to small storms, but this is a general procedure familiar to many that can be used to indicate the magnitude of runoff that needs to be infiltrated. The curve numbers are highly dependent on land development and relate expected runoff volumes to different rain types. Higher curve numbers indicate more runoff than lower curve numbers for similar soil and rain conditions. As examples, undeveloped land has lower curve numbers than most residential land, and residential land has lower curve numbers than shopping centers.

According to the NRCS (SCS 1986), typical medium density residential areas, with curbs and gutters, located on sandy soils (A or B soil types) have curve numbers of about 75. Commercial areas have curve numbers of about 90, and industrial areas have curve numbers of about 85 for these same conditions. It is recommended that a runoff volume standard require that all developed areas having the same native soil type, irrespective of land use, have the same discharge volumes, expressed as an allowable CN. Areas having large curve numbers would therefore require greater efforts to reduce the CN values to acceptable values, compared to areas that have smaller curve numbers. Reducing the curve number from 85 to 70 (such as may be required for an industrial area) would result in a runoff volume (and therefore approximate pollutant yield and peak flow rate) reduction of about 50 to 90 percent, depending on the rain depth.

The general flow-limiting criteria are used to determine the allowable runoff flow volumes for applicable proposed land developments. The curve number criteria were selected to be sensitive to existing limitations in natural soil infiltration capabilities. If the undisturbed soils have a low infiltration capability (such as a type D soil), then the soil would naturally produce more runoff than a soil having a larger infiltration capability (such as a type A, B, or C soil). Thus, different curve number criteria were selected to produce resultant runoff volumes that would be somewhat greater than undisturbed conditions (to attempt to reasonably match the natural hydrologic cycle). This would allow some development without extensive stormwater management requirements. Stormwater management efforts for similar proposed developments in different soils would be similar. If highly intensive levels of development are proposed (such as a shopping center), then correspondingly greater stormwater management efforts would be required than for less intensive developments having larger amounts of pervious areas.

Possible runoff volume limitations, using an "allowable CN" approach, based on pre-development (pre-disturbed) soil conditions, are:

A (sand, loamy sand, or sandy loam soils): 54
B (silt loam or loam soils): 70
C (sandy clay loam soils): 80
D (clay loam, silty clay loam, sandy clay, silty clay, or clay soils): 85

These are the TR-55 (SCS 1986) values for 1/2 acre residential districts (for 25% effective imperviousness cover), and close to the TR-55 values for open space, lawns, parks, etc., in fair condition, "50 to 75% grass cover." However, the resulting runoff using these CN values may be larger than desired to offer adequate protection to the receiving waters. Composite curve numbers can be calculated to provide runoff volume estimates corresponding to other levels of imperviousness [using a CN of 98 for impervious surfaces and the following CN values for different soil conditions: 39 (A), 61 (B), 74 (C), and 80 (D)]. As an example, the following curve numbers correspond to percent imperviousness values in the range where receiving waters problems may be acceptable, but close to critical conditions (5 and 10% imperviousness):

	A	B	C	D
5% imperviousness	42	63	75	81
10% imperviousness	45	65	76	82

These are substantially smaller than the above listed CN values, but should provide significantly better receiving water conditions.

These values are irrespective of developed land use. Increased runoff by developing D soils to pavement is much smaller than if pre-existing soils were A type. The D soil situation would have to infiltrate much less runoff, corresponding to reduced available infiltration capabilities, etc. If soils or groundwater conditions restrict infiltration (for example if high groundwater pollution potential exists, such as for manufacturing industrial, or some commercial uses), then infiltration should not be allowed there, but they would have to treat the runoff (through sedimentation, etc.) and provide infiltration compensation elsewhere (watershed trading).

A more accurate method to determine the runoff volume reductions needed to meet receiving water beneficial uses is to use a more accurate continuous model to calculate runoff for alternative conditions over a long period of time. Typical urban hydrology methods (including the SCS CN method) were developed for, and are most suitable, for evaluating large rains used in drainage design. They can be quite inaccurate for predicting runoff volumes for small rains that are important for water quality evaluations (Pitt 1987). The Source Loading and Management Model (SLAMM) (Pitt 1986, Pitt and Voorhees 1995) was developed for water quality investigations, including examining the effects of multiple source are and outfall controls, along with alternative development characteristics. The following example illustrates how SLAMM was used to evaluate alternative controls and development conditions for a medium density residential area in Jefferson County, Alabama. Table 4 shows the general characteristics of recently developed residential areas, based on extensive local surveys. About 11 percent of the area is directly connected pavement and roofs, while another 7 percent is disconnected pavement and roofs. The landscaped area makes up about 82 percent of the area. The directly connected imperviousness (11%) is about twice the level desired that would cause minimal receiving water problems. Table 5 shows the results of SLAMM analyses for the 1976 Birmingham rain year (considered typical, with 55.2 inches of rain and 112 events, close to Atlanta conditions) for different development conditions. Table 6 lists the results of SLAMM analyses for different percent imperviousness conditions for comparison. For example, if all the roofs and driveways were disconnected, then the effective imperviousness would be reduced to desirable 6% levels. The use of grass swales would decrease the runoff volumes to even smaller values. Because of the large concentrations of suspended solids from unpaved areas in the southeast, and the low concentrations from pavement, the suspended solids concentrations and yield actually decrease with increasing amounts of pavement. However, the concentrations and yields of other pollutants, and water volume, significantly increase with increasingly amounts of pavement. Effective imperviousness is mostly related to habitat problems and associated receiving water problems, as noted earlier, and water volume reductions are one of the most direct ways of attempting to controlling these problems.

Table 4. Characteristics of Medium Density Residential Areas in Jefferson County, Alabama

Directly connected roofs	2.6%
Directly connected driveways	1.2%
Streets	7.2%
Total directly connected roofs and pavement	11.0%
Disconnected roofs	6.1%
Disconnected driveways	1.2%

Total disconnected roofs and pavement	7.3%
Landscaped areas	81.7%

Table 5. Effective Imperviousness for Different Development Conditions

	Effective imperviousness	Runoff Volume		
		ft^3/ac/yr	m^3/ha/yr	Rv
As built (18.3% imperviousness)	11%	46,900	3,240	0.23
All connected	18%	57,290	3,950	0.29
All disconnected	6%	39,590	2,730	0.20
Disconnected and with swales	Very small	12,700	880	0.06

Table 6. Runoff Discharges for Different Levels of Imperviousness

Imperviousness (%)	Runoff Volume		
	ft^3/ac/yr	m^3/ha/yr	Rv
0	31,000	2,140	0.15
1	32,500	2,200	0.16
3	35,400	2,400	0.17
5	38,200	2,640	0.19
8	42,500	2,930	0.21
10	45,400	3,130	0.22
15	52,600	3,630	0.26
20	59,800	4,130	0.29
25	67,000	4,620	0.33
30	74,200	5,120	0.36
40	88,600	6,110	0.43
50	103,000	7,110	0.51
60	117,000	8,070	0.57
70	132,000	9,110	0.65
80	146,000	10,100	0.72
90	160,000	11,000	0.78
95	168,000	11,600	0.82
100	175,000	12,100	0.86

One approach for sizing individual infiltration devices (especially grass filters, percolation ponds, and infiltration trenches) is to size the individual units to completely infiltrate incoming runoff associated with a specific series of storms. One criterion used is the family of 2-year storms. For Atlanta, these 2-year events are as follows:

Storm Duration (hours)	**Approximate Intensity (in/hr)**	**Corresponding Total Storm Depth (in)**
0.5	2.4	1.2
1	1.6	1.6
3	0.73	2.2
6	0.45	2.7
12	0.26	3.1
24	0.14	3.4

A reasonable goal for Atlanta area infiltration devices may be to size the individual units to infiltrate one-half of these above listed intensities and storm depths for the different storm durations. Spreading areas (such as grass filters) require relatively large areas for infiltration, as the peak rain intensity must be infiltrated without the benefit of short-term storage. When storage is provided, it is possible to use significantly smaller surface areas, as the high runoff rates associated from short periods of high rain intensities can be stored in the device until later times when the inflowing runoff rate decreases. Trade-off curves can be constructed to estimate these appropriate sizes.

The performance of the stormwater management program can be best estimated using a stormwater model calibrated and verified for the local area as it is otherwise difficult to estimate the collective benefits of multiple individual controls. Proposed stormwater management programs can then be compared to the overall performance goal for the watershed area. In most cases, multiple controls are needed to meet critical objectives. The following discussions summarize the performance and suggested design/sizing guidelines for many infiltration practices that can be used for newly developing areas in the Atlanta area.

Swales

Grass swale drainages can be used in place of concrete curb and gutters in most land uses, except possibly strip commercial, manufacturing industrial, and high density residential areas. Grass swales reduce urban runoff problems by a combination of mechanisms. Infiltration of the runoff and associated pollutants is probably the most important process. Filtering of particulate pollutants in grass waterways may also occur, but the flows are usually too deep to permit effective filtering by the grass and shallow flows are easily infiltrated. Groundwater contamination concerns are frequently raised whenever stormwater infiltration is proposed. Pitt, *et al.* (1996) reported that groundwater contamination is not a major concern for most stormwaters, if using surface spreading (such as occurs in grass swales). Lind and Karro (1995) also reported on the accumulation of stormwater pollutants in the surface soils of swales, minimizing groundwater contamination problems.

Several large-scale urban runoff monitoring programs have included test sites that were drained by grass swales. Bannerman, *et al*. (1979), as part of the International Joint Commission (IJC) monitoring program to characterize urban runoff inputs to the Great Lakes, monitored a residential area served by swales and a similar residential area served by concrete curb and gutters in the Menomonee River watershed in the Milwaukee area. This monitoring program included extensive flow and pollutant concentration measurements during a variety of rains. They found that the swale drained area, even though it had soils characterized as poorly drained, had significantly less flows and pollutant yields (up to 95 percent less) as compared to the curb and gutter area.

A project to specifically study the effects of grass swale drainages was conducted in Brevard County, Florida by Kercher, *et al*.(1983). Two adjacent low density residential areas, about 5.6 ha in area and having about 50 homes, were selected for study. One area had conventional concrete curbs and gutters, while the other had grass swales for roadside drainage. The two areas had very similar characteristics (soils, percentage imperviousness, slopes, vegetation, etc.). Thirteen rains were monitored in the areas for flow and several selected pollutants. The curb and gutter area produced runoff flows during all 13 events, while the grass swale area only produced runoff during three events. Estimated annual pollutant yields from the curb and gutter area were much greater than for the grass swale area. BOD_5 annual discharges from the guttered area were estimated to be about 130 times the discharges from the swale area. Yield increases from the guttered area as compared to the swale area for other pollutants were reported as follows: 160 times for total nitrogen, 450 times for total phosphorus, and 90 times for suspended solids. The grass swale system also cost about one-half the cost of the curb and gutter system.

In another large-scale urban runoff monitoring project, Pitt and McLean (1986) monitored a residential area in Toronto served about evenly by both swales and concrete curbs and gutters. The pollutant concentrations in both types of drainage systems were similar, but the area had annual flows (and therefore pollutant yields) about 25 percent less than if the area was served solely by curbs and gutters. For small but frequent rains (less than about 13 mm), very little runoff was ever observed in the grass swales. If the area had all grass swales, the flow and pollutant yields would have been even less.

Claytor and Schueler (1996) summarized grass swale performance literature as part of a manual for designing swales having water quality benefits (along with other stormwater filtering systems. The swales had appreciable concentration and mass reductions, mainly by enhancing infiltration through the swale bottom, widening the bottom width of the swale, providing a subsurface infiltration trench under the swale, or even by planting wetland plants in a swale that was in an area that has a high groundwater table. Larger drainage channels provided little concentration reductions, but some had significant mass reductions due to infiltration. In all cases, more care can be taken in designing swales to enhance their water quality performance, while still providing necessary drainage benefits.

Problems with Grass Waterways and the Need for Proper Design Guidance

The typical concerns with grass waterways are associated with maintenance, aesthetics, and safety. These are obviously important concerns, but can be overcome with appropriate designs. If the grass is not maintained (mowed to a moderate grass height), channel conveyance capacity can be significantly reduced. With frequent swale flows, mowing in the swale can be difficult. Grass survival in saturated soil is also a problem. Channel side slopes of less than 25 percent (1 to 4) with a flat bottom should make landscaping more attractive and the swale safer. Slowly growing grass that can withstand saturated and salt soils should also be used. Soil compaction and high water flows also limit swale performance in reducing stormwater problems.

Decomposition of the street pavement edge next to the grass waterway is also a recognized problem. Slotted curbs or other physical barriers can be used to keep vehicles off of the pavement edge and the grass. In special cases where curb and gutters are needed such as in strip commercial, downtown, or high density residential areas), it would be possible to install a slotted drain system with a perforated drainage pipe. Other ways to increase infiltration in the drainage system would include “open bottom” catchbasins.

Most of the information concerning grass waterways concerns their ability to carry water, with little information concerning their other beneficial uses. Novotny and Chesters (1981) calls grass waterways probably the cheapest and most effective means of conveying water. Their design is critical, however, in order to prevent the grass lining from eroding and to permit them to carry necessary water volumes. The grass is used to protect the permeable channel lining and to provide aesthetic benefits. Grass waterways can usually be designed to periodically carry water with velocities ranging up to 1.5 to 3 feet per second, depending on the grass selected and the waterway slope (Ontario 1984).

Grass Filter Strips

Grass filter strips may be quite effective in removing particulate pollutants from overland flows. The filtering effects of grasses, along with increased infiltration, reduce the particulate sediment load. Filter strips are extensively used in contour strip cropping systems in agricultural areas to reduce erosion yields associated with grain crop production. Grass filters can be used at urban runoff source areas to reduce the particulate pollutant yields to the storm drainage system. Specific situations may include directing roof runoff to grassed areas instead of pavement, planting grass between eroding slopes and the storm drainage system, and planting grass between paved or unpaved parking or storage areas and the drainage system.

Problems with Grass Filter Strips

Maintenance

As with all stormwater pollution control devices, grass filter strips must be maintained in order to perform as they were designed. If they are not adequately maintained, the deposited sediment can be easily scoured during subsequent rains. If the grass filter is large relative to the flow, sediment will slowly build up in the filter and grass can grow through the deposits, effectively anchoring the sediment, but changing the flow profile. Most of the sediment accumulation occurs near the entry location of the flow onto the grass and special care needs to be taken to ensure that the sediment accumulation doesn’t block the flowing water from entering the grass strip at the desired location. Grass cutting can also easily suspend the sediment into the air. If not maintained, the performance of grass filter strips would be very erratic, with some storms being very well controlled, and others possibly showing greater pollutant discharges than inputs from scouring that may occur.

Grass cutting should be carefully evaluated and only conducted when absolutely necessary. In order to speed up the incorporation of the deposited sediment into the soil, it may also be necessary to periodically plow up or remove the grass strip for replanting, especially near the flow entry location. Seeding could be a problem because of erosion damage before the plants become established, if subjected to high overland flows. Heavy mulching would reduce this problem, but planting with sod would be better. If obvious and large sediment accumulations of sediment occur, they should be periodically manually removed.

Grass Selection

The selection of grass to plant in the filter strip is very important. If the plants are not healthy, the stand population may decrease, substantially decreasing the filtering effectiveness. The plants will be subjected to much water and may remain water-logged for long periods of time. Plants near the flow inlet area may also be flattened during periods of high flows. The plants near the entry location will also be periodically covered with heavy loads of sediment. Water entry locations should be evenly spread across the filter strip by careful grading to decrease concentrated flow problems. Increased traffic due to required maintenance may also increase stress. Grass strips serving parking areas, sidewalks, or streets may also be subjected to high concentrations of deicing salts and other harmful pollutants.

Effects of Slope and Roughness

Changes in sediment carrying capacity of runoff water is usually based on the Yalin equation: water that is accelerating can pick up more and more sediment, while water flowing at a constant rate is in a state of equilibrium and neither picks up or deposits sediment. Water that is slowing down will usually deposit sediment, if it was at or near equilibrium before the water flow decreased. Some erosion models consider the effects of grass strips by examining how they slow down the water originating from a source area. This is done by comparing the effects of the source area and grass strip slopes and the Manning roughness coefficients (n) on the runoff water velocity as it passes from the source area to the grass strip. Therefore, if the source area and filter strip have similar roughness coefficients, the filter strip will only help in reducing the sediment load if it is of substantially less slope.

Porous Pavement

Porous pavement is a “hard” surface that can support a certain amount of activity, while still allowing water to infiltrate. Porous pavement is generally used in areas of low traffic, such as service roads, storage areas, and parking lots. Several different types of porous pavement exist. Open mixes of asphalt appear to be similar to regular asphalt, but only use a specific size range of rocks in the hot mix. The porosity of the finished asphalt is much higher than regular asphalt, if properly designed and constructed. Porous pavement blocks, such as concrete grids, have open holes up to several cm wide, possibly containing sand or gravel. It is possible to plant grass in the holes, if traffic is very light and if light and moisture conditions are adequate. The primary use of porous pavements is to mimic natural flow and infiltration conditions as closely as possible. They can be designed to eliminate all of the runoff from paved areas.

Performance of Porous Pavements as Reported in the Literature

Porous pavements can be effectively used in areas having soils with adequate infiltration characteristics. The infiltration requirements for porous pavements are not as critical as they are for other infiltration devices, unless runoff from other areas is directed towards the paved area. The infiltration rate of the soils underlying the porous pavement installation only needs to exceed the rain intensity directly. In most cases, several cm of storage is used in the asphalt base to absorb short periods of very high rain intensities. Diniz (1980) states that the entire area contributing to the porous pavement can be removed from the surface hydrologic regime.

Gburek and Urban (1983) studied a porous pavement parking lot in Pennsylvania. They found that infiltration below the pavement occurred soon after the start of rain. For small rains (less than 6 mm), no infiltration under the pavement was observed, with all of the rain being contained in the pavement base. Infiltration during large rains was equal to about 70 to 90 percent of the rainfall, resulting in similar runoff flow and pollutant reductions of 70 to 90 percent. The differences between the rain amounts and the observed infiltration quantities were caused by flash evaporation (not estimated) and storage in the asphalt base material.

Goforth, *et al.* (1983 and 1984) evaluated a porous pavement parking lot in Austin, Texas, over several years under actual traffic conditions. Infiltration rates through the pavement averaged about 1800 inches per hour (4500 cm/hr), while the two inch pavement base had an infiltration rate of about 70,000 inches per hour (180,000 cm/hr). The variation in measured infiltration rates over the whole area was quite large. The lowest infiltration rates were observed in areas where the hot pavement was rolled at a temperature greater than 180° F (80°C). The driveway area also had a lower infiltration rate due to traffic compaction and soil accumulation in the pavement pores.

Day (1980) conducted a series of laboratory tests using several different types of concrete grid pavements. The geometry of the grid was more important than the percentage of open space in determining the ability of the grid to absorb and detain rainwater. The volumetric runoff coefficients from the grids ranged from 0.06 to 0.26 (resulting in runoff volume and pollutant reductions from about 75 to 95 percent) depending on the rain intensity, ground slope, and subsoil type.

Research at the University of Guelph in Ontario (Thompson and James 1995) has found that porous pavement systems can also be effective filters to remove particulate pollutants from the runoff, even with an underdrain that captures the runoff after pavement infiltration. Runoff from typical pavement also had greater masses of pollutants than runoff from the porous pavements. Porous pavement research at the University of Essen in Germany (personal communication, Wolfgang Geiger 1995) also found significant water quality benefits from using porous pavement systems. However, Diniz (1993) measured the water quality of underdrain water from different porous pavement systems, gravel trenches located on the edge of an asphalt area, and conventional asphalt and concrete pavement during controlled sprinkler tests. Lead concentrations were about the same for all surfaces (12 to 25 μg/L, flow-weighted averages), while zinc (20 to 90 μg/L for porous pavements, vs. 7 to 12 μg/L for conventional pavements) and TKN (1.4 to 2.2 mg/L for porous pavements, vs. 0.5 to 1.3 mg/L for conventional pavements) were all higher for the porous pavement drain waters, compared to the conventional pavement runoff. Some, but not all, of the suspended solids and COD porous pavement drainage water concentrations were greater than for the conventional pavement runoff. The few data presented make conclusions uncertain, but it is likely that porous pavement may contribute some pollutants to the water, while removing others. In all cases, the amount of runoff diverted from the surface flows can be very large.

French experiments in Nantes, Bordeaux and Paris have shown that porous pavements (with substantial subsurface reservoir capacity) were very efficient in reducing the pollutant loads discharged into the receiving water (Baladès, *et al.* 1995a and 1995b). These French studies have shown that the pollutant removal efficiencies of suspended solids can be between 50 and 70%, between 54 and 89% for COD, and between 78 and 93% for lead. These reductions were associated with the large amounts of water being infiltrated through the pavements, and being diverted away from the surface drainage. These experiment and associated pollutants confirm results from previous studies in other countries (Hogland, *et al*. 1987).

Problems with Porous Pavement

Wear, deterioration, and strength are of concern when considering porous pavements. Diniz (1980) found that the surface of porous pavement is not easily clogged during normal use. Accidental spills could render porous pavement ineffective unless quickly cleaned-up. If the pavement is irreversibly clogged, drain holes can be drilled through the pavement, or it may need to be replaced. Goforth, *et al*. (1983) found that soil does accumulate in the pavement pores and recommended vacuuming to restore the surface.

Golorth, *et al*. (1983) inspected the pavement surface after eighteen months of moderate service and found the pavement to be in excellent condition, with no rutting, cracking, or scuffing. The weather during the test period was extremely cold with many freeze-thaw cycles. The strength of the pavement was determined to be capable of supporting between 3000 and 5000 vehicles a day, or sufficient for a light to moderate use roadway, and more than sufficient for most parking or storage lots. They concluded that conventional temperatures for placing the asphalt were appropriate (260 to 280 degrees F), but that compaction should be done at lower temperatures (180 degrees F) after some cooling.

Gburek and Urban (1983) found little leaching of polycyclic aromatic hydrocarbons (PAHs) in laboratory tests using columns o asphalt mix and concluded that porous pavement posed little threat to groundwater. Other tests with actual percolate in the field also showed little contamination. However, these tests did not include any automobile activity. Other source area sheetflow tests found parking lot runoff to be heavily contaminated (Pitt and McLean 1985; Pitt, *et al.* 1995). Particulate contaminants are not expected to be carried far into the soil, but soluble contaminants, such as some oils and gasoline, may pose a greater threat to groundwater.

Design Features of Porous Pavement

Much research has been directed towards determining appropriate design conditions for porous pavement. Porous pavement can have very high infiltration rates. In problem cases, the pavement base, or subgrade, is usually found to be restrictive. Grover, *et al.* (undated) shows an example where the subgrade soil must have a permeability of about 0.02 feet per day to remove two inches of rain from the asphalt base in ten days.

Cedergren (1974) stresses the need to install a suitable base under the asphalt. The possible range of permeabilities of base materials can range from a low of about 0.000003 feet per day for clays, to a high of about 100,000 feet per day for graded coarse gravel. This range is of the order of several billion, and when typical hydraulic gradients are considered, the range of potential seepage rates can be about 100 billion to 1 trillion times. The selection of base and subgrade materials must be carefully done. The permeability of the pavement bases should be at least several hundred times the permeability of the pavement itself. The maximum rains that standard bases can handle are light drizzles (0.01 inches per hour), while open graded bases can handle at least one inch per hour rains. Gravel about one inch in diameter is needed to obtain a high permeability of over 100,000 feet per day. Cedergren recommends maximum aggregate sizes of about 1 to 1-1/2 inches to minimize segregation during placement and other construction problems. The need to prevent fines from mixing with the coarser gravel must be stressed. Even five percent fines (passing through a number 200 sieve, or smaller than 75 microns) can reduce the permeabilities of sand and gravel bases to almost nothing.

Maintenance of Porous Pavements

Clogging of porous pavements is only a superficial phenomenon (typically extending to a depth of about 1 to 2 cm). Progressive clogging with time is caused by an increase of accumulated solids in the first few centimeters of the pavement and not to the moving of the clogging front within the pavement structure. The decrease in permeability in porous pavement may cause a drop by about 50% over three years. The mean diameter of the particles which are responsible for this clogging is about 300 µm. For sites where there is only a thin porous pavement layer above an impervious structure layer, it has been observed that the mean diameter of the clogging particles is finer, with about 30% of the particles responsible for the clogging being finer than 100 µm. Typical street dirt mean particle sizes are in the range of 200 µm, indicating that the particles responsible for the clogging are very common. Particles in these sizes are also suitable for effective removal by most conventional street cleaning operations. The masses of particles extracted from porous pavements depend on the use of the street, on the traffic intensity, on the cleaning equipment used and on the cleaning frequency. However, the amount of extracted particles is always very high: 0.2 to 1.5 kg/m^2. The highest value has been measured several times in residential streets which have not been cleaned during the last 2 or 3 years (Artières1987).

For porous pavements subjected to traffic below 100 vehicles/day, and especially for parking lots, Bertrand-Krajewski, *et al.* (1994) found that monthly cleaning by vacuuming is sufficient to keep an almost constant infiltration capacity. If clogging is already evident, a stronger cleaning technique using high pressure water jetting and vacuuming is necessary. Techniques which recycle the cleaning water are obviously preferred in order to avoid flushing of the pollutants to the receiving water. In all sites where measurements have been carried out, the extraction was very efficient and the porous pavement infiltration capacity was usually well restored. The following lists the improved infiltration rates through partially clogged porous pavements (cm/s enhanced infiltration capacity after cleaning):

- simple wetting and sweeping (<0.01 cm/s);

- sweeping and vacuuming (0.13 cm/s);
- vacuuming (0.28 cm/s); and
- high pressure jetting and vacuuming (0.80 cm/s).

Summary of Infiltration Devices as Stormwater Controls

Infiltration devices are unique in that they reduce stormwater volumes, in addition to peak flow rates and pollutant discharges. They discharge the stormwater to the groundwater and care must be taken to prevent groundwater contamination. Significant reductions in most pollutants occur in the vadose zone above the saturated layer. However, some stormwaters should not be considered for infiltration, including snowmelt water (especially in areas of de-icing salt use), industrial runoff (due to likelihood of high concentrations of filterable toxicants), and construction site runoff (due to clogging by sediment). The majority of stormwater flows can likely be safely infiltrated with significant reductions in surface water discharges and important equalizations of the hydrological cycle in urban areas. Pratt (1996) describes the current widespread installations of "soakaways" in the UK (tens of thousands per year), despite the extensive storm drainage systems available. Most are used for infiltrating runoff from small paved areas and roofs. Unfortunately, little systematic research has been conducted on their benefits and problems. Schmitt (1996) also described current German regulations favoring the use of infiltration controls for stormwater located at source areas to reduce combined sewer problems.

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