SOIL DRAINAGE AND INFILTRATION

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ABSTRACT--Soil infiltration and drainage is governed by the character of the soil pore system and the moisture content. Urban soils generally have less porosity and macropore space, which significantly reduces water movement rates as compared to similar forest or agricultural soils. Layering of soil material during construction creates hydraulic discontinuities in the profile that reduce water movement. Lateral runoff is enhanced and the soil can be at one time too wet, and at another time, too dry for optimum tree growth. Application of several techniques for solution of urban drainage problems is discussed, together with some lessons learned in the District of Columbia.

SOIL PORE NETWORK SYSTEM

Water moves in soils through a network of soil pores. During rainfall water enters the soil through larger, surface-connected pores under a positive hydraulic head. Water diffuses vertically and horizontally into a network of smaller pores by capillarity or soil moisture tension (SMT). The flow into the soil mass quickly becomes governed by the rate of flow into the smaller pores. Water flowing into the smaller pores is not primarily governed by a positive gravitational head rather by the SMT of the snail pores.

Water will move toward the pores having the greatest SMT. Once the flow into the larger surface-connected pores stops, then the water in the soil mass will redistribute toward the areas of greatest SMT, i.e., the smaller pores. Note Figure 5.1. The insert illustrates the indirect relationship between tube diameter and height of capillary rise (tension).

The rate at which water moves through soil is governed by the number, size, shape, continuity, and arrangement of the pore network system. Urban soils characteristically have less total pore space (less porosity, fewer and smaller macropores, less macroporosity), more irregular pore shapes, poorer continuity of pores and often considerable disorder in the pore network arrangement. Therefore, water movement rates in urban soils tend to be significantly less than those of similar soils in an agricultural or forest setting.

WATER MOVEMENT

In a saturated condition, water flows more rapidly through a coarse textured (sandy) soil, because a positive head occurs, transmitting water quickly through the larger pores. Once the source of the water is interrupted, the soil will soon move from saturated to unsaturated. In an unsaturated state, the water movement rate in the sand slows appreciably. Note the curve for sand in Figure 5.2. Since the sand has few smaller pores, which tend to govern unsaturated water movement, the flow rate is reduced. The sand curve is steep because of the pore size distribution, i.e., many larger pores and few smaller pores. Remember that, in an

Figure 5.1

SOIL MOISTURE TENSION RELATIONSHIP TO TUBULAR PORE SPACE

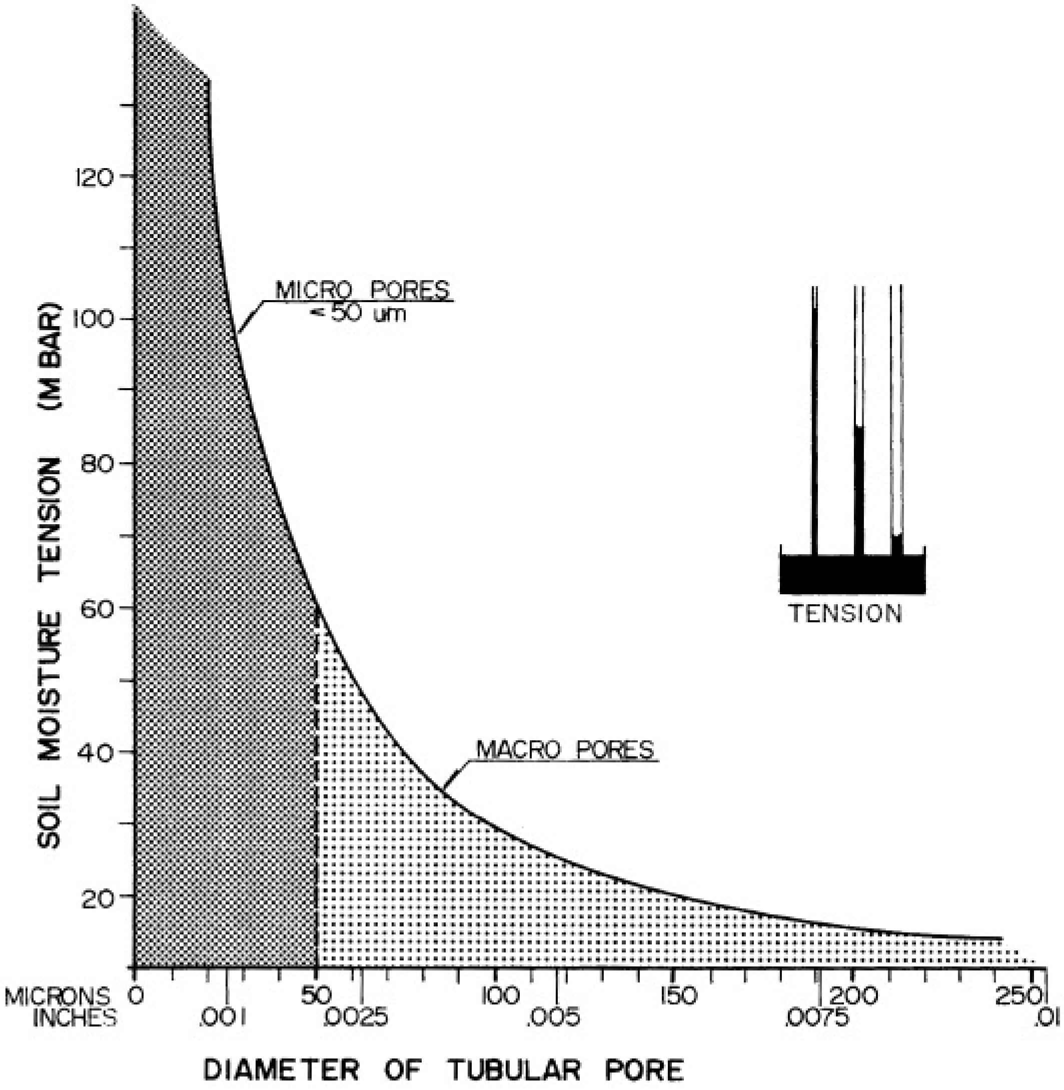
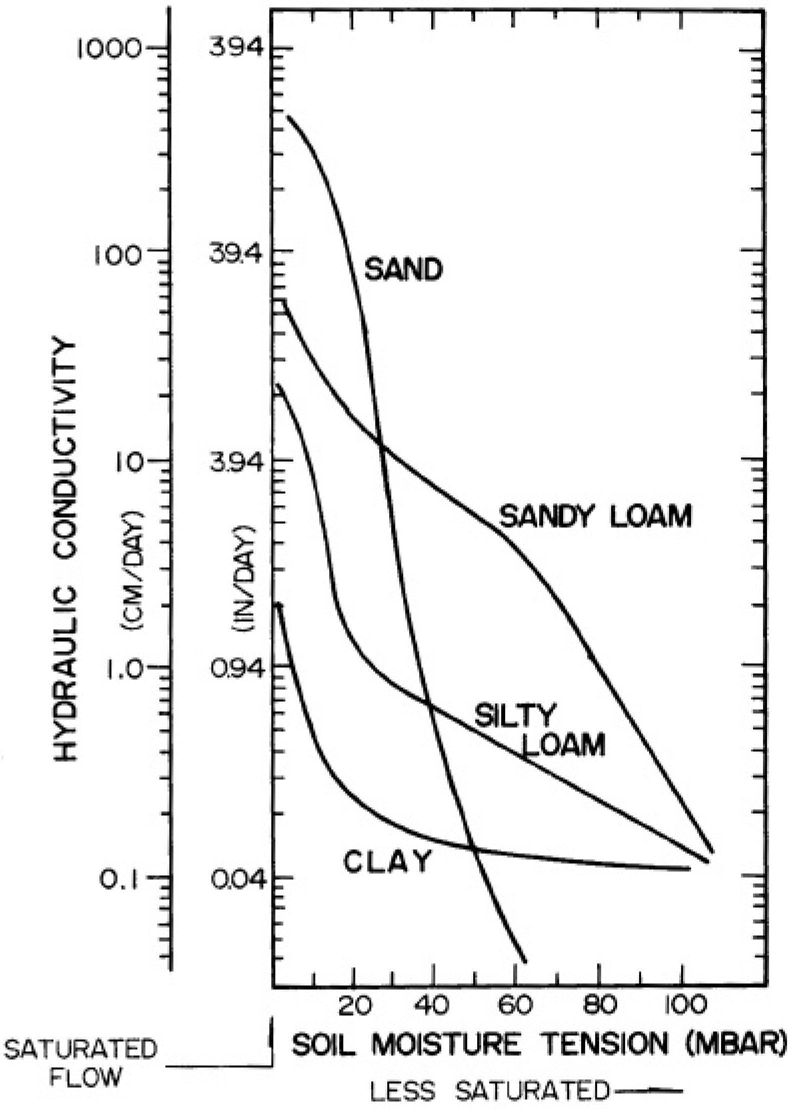


Figure 5.2

HYDRAULIC CONDUCTIVITY RELATIONSHIPS



unsaturated condition, the water will move through the smaller pores or along the side of larger pores (not filling the larger pores) this significantly reducing the water movement rate. If we assume flow in soil pores to be somewhat like flow of water in a pipe, one quickly realizes that a small increase or decrease in pore diameter dramatically alters the flow rate.

In contrast, to the sandy soil, a sandy loam soil will have a significantly lower saturated water movement rate (note Figure 5.2) because of fewer large pores, due to the greater amount of silt, clay and a difference in soil structure. However, the flow rate in an unsaturated condition will be greater due to the larger number of small pores. Figure 5.2 illustrates the basic differences in saturated and unsaturated water movement rates for four different soil textures. Obviously, there are numerous differences between sands and between clays, but this general pattern will still hold true.

An idealized soil would have a sufficient number of larger pores to transmit water rapidly under saturated conditions and would also have sufficient smaller pores to maintain good water movement rate under an unsaturated state. However, a silt loam soil would have a greater amount of available water than a sandy loam soil; therefore a silt loam soil would be optimum for tree growth.

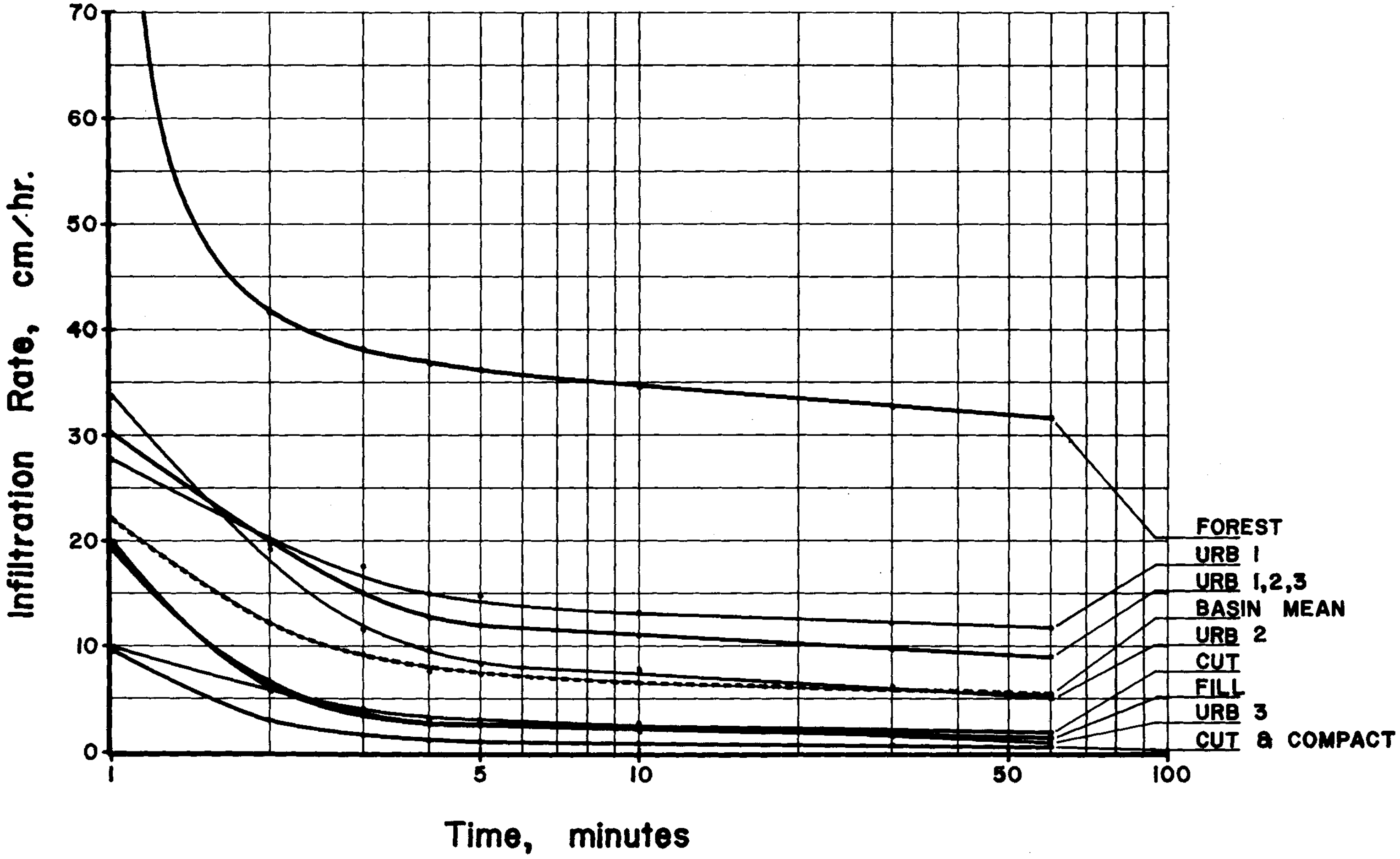
Water Movement in Layered Soils

Obviously, soils are not homogeneous, especially urban soils. Commonly a soil will have a coarse-textured sandy layer over a finer textured (loamy or clayey) soil layer. In this case, once the upper coarse layer is saturated, the flow rate would be governed by the saturated rate of the finer textured layer. This change in flow can occur rapidly. Note the curve transition within 2 to 3 minutes (in Figure 5.3).

However, the opposite situation, the finer textured soil over the coarse textured soil, has a more dramatic effect. In this case, the loamy soil would hold almost all of the water due to the smaller pores and greater SMT and, thus, would allow less water to ender the sand. Not until the loamy soil became nearly saturated would water begin to enter the sandy layer. Many people would believe this phenomenon could not occur, but it does. For example, this effect applies to the case of gravel and/or sand in the bottom of a planter. The addition of sand or gravel will do nothing to improve drainage except when a great amount of lateral drainage below the soil is required. Since a saturated or nearly saturated zone will often be maintained just above the sand or gravel, the main result or adding the sand or gravel will be to reduce the effective or aerobic rooting volume for the plant. A similar situation can occur with three layers: a planting bed of loamy material over sandy material, over a loamy subsoil kept saturated by ground water. In this situation, the sandy soil would block the

Figure 5.3

SUDBURY WATERSHED
AVERAGE INFILTRATION CURVES
WET ANTECEDENT CONDITIONS



Upward transmission of the moisture until the sandy layer became nearly filled with water and would also block the downward transmission of moisture until the loamy planting bed became saturated. Therefore the sandy subgrade will often cause the planting bed to be too dry or too wet at various times.

INFILTRATION AND WATER MOVEMENT IN URBAN SOILS

Infiltration rates are dependent upon texture of the soil material, but more important is the structural condition of the soil material. Soil in an undisturbed forest condition will have a high infiltration rate, compared to the same soil in an agricultural field. The infiltration rate is reduced still further under the highly disturbed urban condition where structure may be nearly obliterated. Infiltration rates for Cecil soils are given in Tables 5.1 and 5.2 and illustrated in Figure 5.3. A significant decline in infiltration rates is attributed to urban disturbances. A similar study in an Hawaiian urban area demonstrates a similar effect with the Wahiawa soil (Table 5.3).

A method exists for estimating infiltration rates. The SCS provides a classification of all soil series into one of four hydrologic soil groups (Table 5.4). However, this system does not indicate the wide range of values that were found in the North Carolina or Hawaiian studies. The hydrologic soil groups probably provide rates at the lower end of the scale, or are indicative of soils in poor condition. The Cecil and Wahaiwa soils both fall into the B hydrologic soil group.

EFFECTS OF THE URBAN MYSTICAL ENVIRONMENT ON DRAINAGE AND INFILTRATION

Soils in urban areas tend to exhibit extremes, either too wet or too dry. The wet extremes are often due to inadequate soil drainage. Buildings, paving and compaction tend to limit the lateral drainage of soils. Unusual man-made layerings of soil material (termed lithologic discontinuities) can limit water movement. The dry extremes are often due to increased surface runoff due to soil compaction and paving. Urban drainage systems discharge much of the rainfall into streams, rather than allowing for more natural soil water movement to slowly recharge the streams. Both wet and dry extremes can be found within one city and often on one given site. The lack of vegetation will reduce the amount of evapotranspiration and thus leave more water in the soil mass.

SOME PRACTICAL APPLICATIONS

Use of several practical examples best illustrates the application of some of the principals outlined above. These have been chosen from actual problems encountered in various projects, and should be prove useful to the practitioner.

Irrigation/Drainage Time Relationships

The frequency of irrigation or the time for adequate drainage will depend on the rate of water movement.

Example -

Clayey subsoil (1:1 clay)

Sandy loam topsoil – 4 inches deep

Topography – flat

Solve for –

Maximum irrigation amount – inches

Maximum irrigation rate – inches/hour

Maximum irrigation frequency – days

a. From Table 5.5, find -

Sandy loam topsoil has 18.6% large pores

4 inches x .186 = 0.74 inches

(i.e., 0.74 ac. In. of macroporosity in one acre of sandy loam topsoil at 4 inches deep)

Therefore, maximum irrigation amount is 0.74 inches. This is based on the premise that only a portion of the porosity should be filled with water. Therefore, fill the large pores, allow for redistribution into the smaller pores and then the large pore will be available again for air diffusion.

b. From all available sources, find –

Subsoil infiltration rates:

SCS hydrologic soil group 0.15-0.35 in/hr

On-site infiltration test 0.25 in/hr

Therefore, select 0.25 in/hr as maximum irrigation rate. Thus, we have chosen a sufficiently low irrigation rate to make sure no surface runoff occurs in areas where topsoil might not be as deep or may be compacted.

c. From Table 5.6 -

Drainage time	4 days
Re-aeration time	3 days

Therefore, use 7 days as minimum average irrigation frequency; however, actual frequency must be adjusted with rainfall and with actual observations of soil moisture conditions.

Design of Under Drains

An underdrainage system is used on a site to control the depth of the water table. Such a system is important to urban forestry when there is an inadequate aerobic rooting depth. Surface and subsurface drainage systems are covered in detail in Chapter 14 of the Soil Conservation Service, Engineering Field Manual.

The procedures for design of agricultural drainage in the field manual are generally applicable to urban sites. However, often due to the unusual soil conditions (unusual soil layerings, compacted fill soil materials, limited soil porosity, etc.) in the urban area, special care must be taken. Obviously detailed on-site soil investigations and laboratory permeability tests are warranted prior to design of an expensive subsurface drainage system.

Special attention must be given to determining reasonable soil permeability values for urban soils. The compaction of loamy or clayey soils can often reduce the soil permeability by one or two orders of magnitude; therefore, such a difference will have a major effect on the design of the under drainage system. For example:

Example #1

Clayey subsoil – not compacted
Water table depth – 1 foot
Desired water table depth – 3 feet
Subsurface barrier depth – 5 feet
Soil permeability – 1.5 in.hr
Depth of proposed drains – 4 feet
Desired water removal rate (drainage coefficient) – 0.5 in/day

$$S = \sqrt{\frac{4P\ (b^2-a^2)}{Qd}}$$

Where:

S = Spacing of drains (feet)

P = Coefficient of permeability (in/hr)

b = Distance from the draw down curve to barrier stratum. at midpoint between the drains (feet)

a = Distance from the drains to the barrier (feet)

Qd = Drainage coefficient (in/hr)

Therefore:

$$S = \sqrt{\frac{4(1.5)\ (2^2-1^2)}{0.021}}$$

S = 29.3 ft. (use 30 feet)

Example #2

However, if the clayey sols is compacted then assume:

Soil permeability – 0.15 in/hr (one order of magnitude reduction)

All other variables – hold constant

Therefore:

$$S = \sqrt{\frac{4(0.15)\ (2^2-1^2)}{0.021}}$$

S = 9.3 ft. (use 10 feet)

Example #3

Assume some severe compaction of clayey soil material:

Soil permeability – 0.015 in/hr (two orders of magnitude reduction)

All other variables – hold constant.

Therefore:

$$S = \sqrt{\frac{4(0.15)\ (2^2-1^2)}{0.021}}$$

S = 2.9 feet (use 3 feet)

Therefore, severe compaction can make a site exceedingly difficult and expensive to drain, saying nothing about the other problems of plant growth in compacted soils.

The site and soils investigator should take special note of lithologic discontinuities that could seriously impair water movement. It is also important to consider that lateral drainage through heavy loam, clay loam, heavy silt loam and clayey soils may be on the order of 1/10 of the vertical water movement rates for the same soil. If laboratory permeability tests are to be performed, make sure that the soil core samples are taken in the lateral rather than vertical position. Take samples from all important soil horizons and make sure to locate samples to search for spatial variability, i.e., seek out the most limiting horizons and locations. Also consider whether soil compaction from construction work on the site will occur after the drainage design is completed. If such compaction takes place, your design may be quite inadequate.

Design of Mound Planting Beds

An alternative method to managing a site with a high water table is by use of mounded planting areas. This approach can also be useful when for other reasons; the existing soil material is unsuitable for plant growth, e.g., due to expansive massive clay.

The approach is to mound suitable soil material above the existing grade and then plant in the mounds. However, provisions made me made for good positive surface drainage on the existing soil away from the mounds. If water accumulates around and under the mounds, it will move up into the mounds and thus nullify the mounding benefits. One method to counteract this accumulation is to crown the subsurface contour parallel to that of the finished surface contour.

The mounded soil material should consist of a sandy loam or silt loam soil material. The following quality criteria are provided.

Proposed Topsoil Textural Standards for Mounds

	Quality Rank			
Criteria	Excellent	Good	Fair	Poor
% Clay	<20	20-25	25-30	>30
% Expandable Clay[a]	<1	1-5	5-10	>10
% Silt	40-50	50-60	60-70	>70
	30-40	30-40	20-30	<20

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[a] percent expandable clay $\frac{CEC_{8.2}/100g}{230\ meg\ /\ 100g}$ x 100

The normal center depth of a mound should be about 3 feet. The wider the mounds the greater the depth, since a smaller water table may occur within the base of the mound. This is especially true if the existing soil material below the mound has a very slow permeability. The size of the mound should be based upon the selected plant species and their required rooting volumes.

Subsurface Sculpturing

In situations where mounding above the proposed grade is inappropriate, a technique has been used which we term "subsurface sculpting". This system is similar to the "crowning" of an athletic field to encourage lateral water movement off of a field during heavy rainfall events. However, at an urban site the existing soil - this soil is assumed to be heavily compacted and of rather poor quality - is contoured or crowned to allow for lateral drainage off of the site A prepared soil mix for the site is readied off-site and broadcasted over the "crowned" area to a uniform depth, usually a minimum of 18 inches. The finished soil surface (the prepared topsoil material) is then contoured such that it is parallel to the subsurface (existing compacted soil). Therefore a uniform soil material is provided with some provision for lateral subsurface drainage. Be sure to install subsurface drains and have positive outlets for these drainage systems.

Other Techniques Learned in Washington, D.C.

Surface Swales. Surface swales can provide an adequate means of removal of excess surface water during heavy rainfall events. This system is particularly useful where runoff from paved surfaces is directed toward plantings or in locations where beds are placed on side-slopes. A well-placed and properly engineered swale will intercept excess lateral runoff and carry it safely downslope away from the plantings.

For example, in Constitution Gardens in Washington, D.C. sod swales have been highly successful in removing excess water from areas where large walkways shed runoff. These swales are about 3 to 4 ft. across and about 6 inches maximum depth such that mowing equipment can provide necessary maintenance. The results are highly effective and affordable.

Planting Pedestals. Another planting technique implemented at constitution Gardens has been the use of "pedestals". This technique involves leaving a pedestal of existing compacted soil immediately beneath the root ball of the tree and excavating a “doughnut”-like hole for the planting. The hole in the doughnut is governed by the depth of the tree ball such that the tree ball rests securely upon the pedestal and remains about 4-6 inches above the surrounding surface.

The perimeter of the pedestal is then excavated an additional 12 to 18 inches and either prepared soil or a slight modification of existing soil is replaced into the hole. The purpose of using the pedestal is to maintain the crown of the ball at the desired elevation. Often, when a tree ball is placed within a planting hole or “prepared soil”, this prepared soil is generally the most porous and will tend to saturate. The tree ball will then tend to subside into the mud.

Homogeneous Soil. Total preparation of the soil is strongly recommended. By this we mean preparing of total soil profile – depths will be variable – of similar material or a homogeneous mixture. This practice must be accomplished prior to planting! A homogeneous soil system includes uniformity of the soil chemistry as well as the soil physic. Drainage and therefore aeration will be more favorable within this type of soil system, and is preferred for large area planting.

Avoid Soil Disturbance. Often prior to implementing an urban planting, the existing soils have undergone considerable disturbance. In Washington, some nearly natural soil profiles exist – these should be preserved. The O-horizon or organic horizon should be preserved as it will encourage deeper rooting, better infiltration and internal drainage, as well as, a reduction of impact upon plant roots due to use. Plan the entire construction program to avoid unnecessary soil disturbance. Fence areas to limit construction activities well beyond the tree drip lines. This is particularly important around larger trees that are to be preserved.

Mulching. Mulching is a sound concept provided it is geared to the soils existing at the site as well as the plantings. A mulch placed over a clayey soil is at best a poor situation. The soil will saturate and rapidly become anaerobic. However, if the proper soil and internal drainage is provided, a mulch will enhance the soil moisture regime. A word about plastic mulching - it should be avoided. Plastic sheeting used over the soil surface and beneath a mulch is detrimental to the planting. Roots tend to come up to the interface with the plastic, the soils tend to become anaerobic due to a sealing at the soil surface, and the planting is quickly susceptible to desication, wind throw (due to shallow rooting), anaerobic soils or a multitude of other problems (see chapter 2).

Restricting Use. Restricting use of an area is perhaps the next to last of the drastic maintenance techniques available to the urban plantsman. This system is widely practiced in Europe (England, Ireland, etc.) to control or limit access or parks and urban greenspace. The principal goal is to limit and restrict intense use so that the soils do not become compacted and the plants are given an added chance of survival. In Washington this system has not been widely practiced but at present certain areas are routinely closed to visitation to provide maintenance. Severe compaction and result improper soil aeration/drainage are a cause of plant decline. Often the last resort to maintenance of the urban planting is drastic, that of paving and/or channeling visitation through the area such that a portion of the planting might remain. The threshold of plant survival is such that it cannot tolerate continued abuse; therefore, this drastic alternative may be the last resort.

TABLE 5.1
Infiltration Rates by Land Types For Sudbury Watershed, Charlotte, NC – Residential Subdivision (4 d.u./ac.)

Land Type	Description	Percent of Watershed	Subsoil Bulk Density	Subsoil Macro Porosity	Mean Final Constant Infiltration Rate*
		%	g/cm^3	%	in/hr
Forest	Undisturbed Cecil Soils with medium aged Pine-mixed hardwood Forest with Al horizon And leaf litter intact	2.6	1.39	8.3	12.42
Urban 1	Slightly disturbed Cecil soils with lawn and large trees; roads and buildings at or near original grade	23.8	1.42	5.3	4.40
Urban 2	Slightly disturbed Cecil soils, previously cultivated field, lawns and few young trees	9.1	-	-	1.88
Urban 3	Slightly disturbed Cecil soils, previously cultivated field with plow pan, lawns and few trees	8.7	1.59	7.3	0.27
Fill	Highly disturbed fill soils, lawns and few young trees	7.1	1.62	3.7	0.49
Cut	Highly disturbed cut Cecil soils (cuts or more than 20cm or 8 in. below original grade), lawns & few young trees	15.1	1.42	6.0	0.26
Cut and Compacted	Highly disturbed cut and compacted Ceci1 soils, sparse grass, no trees	4.7	1.5	1.3	0.17
	Wet drainage ways, bottomland hardwoods	1.7	-	-	-
	Impervious surfaces	27.1	-	-	-

*Measured rates for sites with less than 5% slope.
After relationship of Soil Morphology, Soil Disturbance and Infiltration to Stormwater Runoff in the Suburban North Carolina Piedmont,” by Barrett L. Kays, 1979, Dissertation, Department of Soil Science, North Carolina State University, Raleigh.

TABLE 5.2

Infiltration Rates by Land Types for Raleigh, NC Sites[1]

Land Type	Description	Subsoil Bulk Density g/cm^3	Subsoil Macro-Porosity %	Mean Final Constant Infiltration Rate[2] in/hr
Residential Subdivision (4 d.r./ac.)				
Forest	Undisturbed Cecil Soils with mature hardwood forest with Al horizon and leaf litter intact	1.21	4.5	6.37
Cut and Compacted	Highly disturbed cut and compacted, Cecil soil, Lawn	1.31	4.5	0.14
Fill	Highly disturbed fill soils with lawn	1.28	5.0	0.05
Townhouse Development (10 d.u./ac.)				
Forest	Undisturbed gravelly Cecil soils with medium aged pine-hardwood forest with Al horizon and leaf litter intact	1.48	6.5	>4.00
Compacted	Highly disturbed Cecil soils in open space with grass and medium aged pine stand	1.19	3.3	0.07
Fill	Highly disturbed fill soils with lawn	1.48	5.5	1.08
Schenck Pasture Watershed				
	Cecil soils	1.53	11.2	3.65
Schenck Forest Watershed				
	Cecil soils	1.59	6.4	3.18

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1. Measured rates for sites with less than 5% slope.
2. After "Relationship of Soil Morphology, Soil Disturbance and Infiltration to Stormwater Runoff in the Suburban North Carolina Piedmont," by Barrett L. Kays, 1979, Dissertation, Department of Soil Science, North Carolina State University, Raleigh.

TABLE 5.3
Infiltration Rates by Land Types In an Hawaiian Urban Area

Land Type	Bulk Density g/cm^3	Mean Final Constant Infiltration Rate in/hr
Pre-urban land –		
Abandoned pineapple field	1.12	7.03
Urbanized land –		
Grubbed land	1.16	2.98
Cut & shaped lots	1.21	0.51
Non-recreational lawns		
Residences	1.08	.049
Sidewalk area	1.15	0.26
School yard	1.21	2.63
Recreational lawns		
Golf course	1.17	2.43
Swimming pool area	1.35	0.19
Recreational area	1.24	0.17
Baseball field	1.26	0.77
Baseball diamond	1.24	0.38

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1. After “Urbanization-Induced Impacts on Infiltration Capacity and On Rainfall-Runoff Relation in An Hawaiian Urban Area,” by Edwin T. Murabayashi and Yu-Si Fok, 1979, Technical Report 127, Water Resources Res. Center, Univ. of Hawaii, Honolulu.

TABLE 5.4
Hydrologic soil groups used by the Soil Conservation Service[1]

Hydrologic Soil Group	Sols Included[2]	Final Constant Infiltration Rate, (fc), in./hr.
A	(Low runoff Potential) Soils having high infiltration rates, even when thoroughly wetted, consisting chiefly of sands or gravel that are deep and well- to excessively-drained. These soils have a high rate of water transmission.	0.30 – 0.45
B	Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well-drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.	0.15 – 0.30
C	Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture and a slow infiltration rate. These soils have a slow rate of water transmission. (high runoff potential)	0.05 – 0.15
D	Soils having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay pan or clay layer at or near the surface; and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.	0 – 0.05

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1. After table by U.S.D.A.
2. Soils are classed in the next lowest category when a high percentage of stones is present.

TABLE 5.5
Hydrologic capacities of texture classes[1]

Texture Class	Storage Capacity %	Large Pores G %	Plant-Available Porosity AWC %
Coarse sand	24.4	17.7	6.7
Coarse sandy loam	24.5	15.8	8.7
Sand	32.3	29.0	13.3
Loamy sand	37.0	26.9	10.1
Loamy fine sand	32.6	27.2	5.4
Sandy loam	30.9	18.6	12.3
Fine sandy loam	36.6	23.5	13.1
Very fine sandy loam	32.7	21.0	11.7
Loam	30.0	14.4	15.6
Silt loam	31.3	11.4	19.9
Clay loam	25.7	13.0	12.7
Silty clay loam	23.3	8.4	14.9
Sandy clay	19.4	11.6	7.8
Silty clay	21.4	9.1	12.3
Clay	18.8	7.3	11.5

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1. After table by U.S.D.A

TABLE 5.6
Approximate Drainage and Reaeration Rates by Soil Textures[1]

Subsoil Soil Texture	Drainage Time (days)	Reaeration Time (days)
Clay (2:1 layer lattice)[2]	5	5
Clay (1:1 layer lattice)	3	3
Clay loam	3	3
Silt loam	3	3
Loam	3	3
Sandy loam	2	2
Loamy sand	1	2
Sand	.5	2

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1. Estimates assuming drainage and reaeration over 2 foot depth for soil with topsoil and uncompacted natural porosities; also assuming no water table or other restrictive barrier problems.

2. See text.