Article 36

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The Compaction of Urban Soils

Many professionals have an interest in the compaction of urban soils. For example, a structural engineer may need to increase compaction to provide a stable foundation for a road or building. Conversely, an urban forester or landscaper may want to decrease or prevent compaction in order to improve root growth and plant survival. A stormwater engineer must understand soil compaction to accurately model the runoff from lawns and landscaped areas, to identify suitable locations for stormwater treatment practices, or to stabilize an embankment or slope. Soil compaction is also an important issue for managers involved in land conservation, erosion and sediment control, watershed education and watershed planning. In this note, we examine how soil compaction increases in response to watershed development and the implications it has for watershed professionals.

What distinguishes soil from dirt? One of the major factors is the amount of "fluff" within a soil. Undisturbed soils have a lot of pore space. Indeed, air comprises from 40 to 55% of the soil volume (unless it has recently rained, in which case the pore spaces are filled up with water). Scientists and engineers frequently measure bulk density to indicate how much fluff is present in a particular soil. Bulk density is defined as the mass of dry soil divided by its volume, and is expressed in units of grams per cubic centimeter (gms/cc). Bulk density is a useful indicator of the structure of a soil, and can help predict its porosity, permeability, infiltration rate and water holding capacity. In general, as the bulk density of a given soil increases, it will produce more surface runoff and allow less infiltration.

The surface bulk density of most undisturbed soils ranges from 1.1 to 1.4 gms/cc, depending on the type of soil present (Table 1). Soils that are predominately sands or clays are on the lower end of the range, whereas silts and silt loams are on the high end of the range. Glacial tills, which were compressed by thousands of feet of ice in the last ice age, can have a bulk density ranging as high as 1.6 to 2.0 gms/cc, depending on how much they have weathered. Highly organic soils, like peat, can be as low as 0.3 gms/cc. In general, bulk density increases with soil depth, reflecting the compression by the overlying soil, and the decline in the abundance of soil fauna and organic matter.

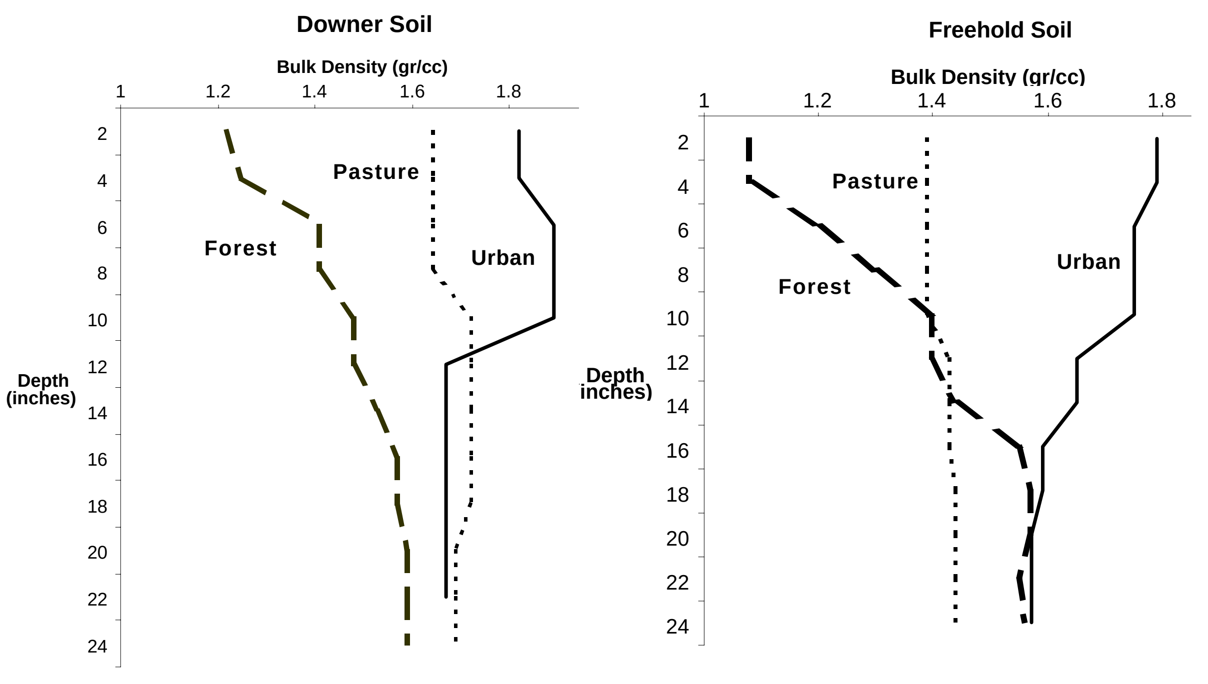

Figure 1: Change in Bulk Density in the Soil Profile as a Function of Land Use

Figure 1 shows a typical profile of how bulk density changes with depth for soils of different land use (Smith, 1999).

In contrast, many urban soils and surfaces have much higher bulk densities (Table 1). The highly disturbed soils of urban lawns range from 1.5 to 1.9 gms/cc, while athletic fields and fill soil typically range from 1.8 to 2.0 gms/cc. These bulk density values approach the density of concrete (2.2 gms/cc). Soils adjacent to building pads and along the road rights of way are intentionally compacted to meet engineering specifications, and can range from 1.5 to 2.1 gms/cc, depending on local compaction standards and the compressibility of the underlying soil.

The Consequences of Compaction

The extensive compaction of urban soils has many adverse hydrologic impacts on a watershed. The primary impact relates to the change of porosity within a soil. Figure 2 illustrates how soil porosity diminishes as bulk density increases. Porosity is important because it governs the soil's capacity to hold water, infiltrate runoff and allow roots to penetrate. As porosity declines, compacted urban soils can produce much more surface runoff than is normally expected for grass or meadow cover. While pervious areas are not generally thought to contribute much stormwater runoff, when urban soils become highly compacted, their runoff response more closely resembles that of an impervious surface, particularly during large storm events.

For example, Wignosta *et al.* (1994) found that compacted soils produced from 40 to 60% of the annual runoff for a small developed catchment, and that the soils had an effective runoff coefficient as high as 0.5. Other researchers have also noted that compacted urban soils can have effective runoff coefficients in the 0.2 to 0.45 range (Pitt, 1992, and Legg *et al.*, 1996). While these runoff coefficients are still lower than those commonly reported for completely paved areas (0.50 to 0.99), they are very significant since lawns can comprise as much as 50 to 70% of residential cover. Thus, from a practical standpoint, soil compaction increases watershed runoff and creates drainage problems such as surface ponding, since soils no longer have their water-holding capacity.

The second key concern with soil compaction relates to its impact on the roots of trees, shrubs and ground covers. Generally, once bulk density exceeds 1.6 gms/cc, roots are no longer able to penetrate through the soil, and growth is limited. The critical bulk density for root penetration for different kinds of soils is indicated in Table 2. The practical consequence of the lack of root growth is that trees, shrubs and grass cover are extremely difficult to establish without extensive soil preparation or planting pits. Since compacted soils hold little water, plants are more prone to drought, and may require supplemental irrigation to survive even in humid climates. Likewise,

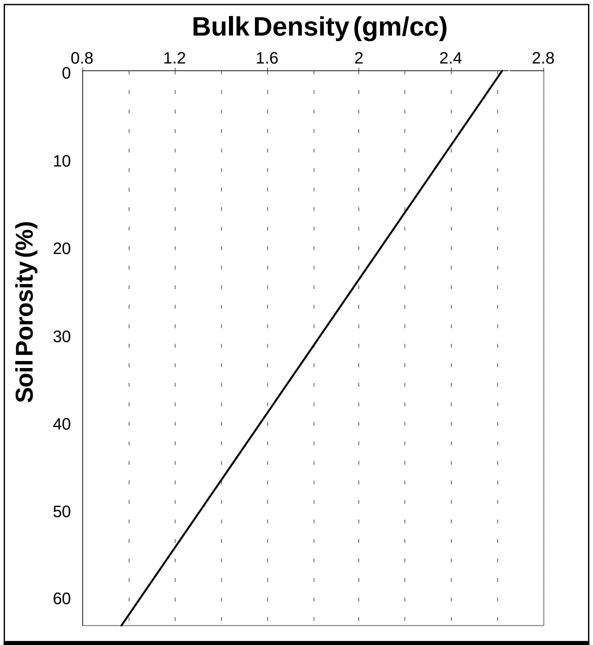

Figure 2: Relationship Between Soil Bulk Density and Soil Porosity

Table 1: Comparison of Bulk Density for Undisturbed Soils and Common Urban Conditions (Compiled from various sources)

Undisturbed Soil Type or Urban Condition	Surface Bulk Density (grams/cubic centimeter)
Peat	0.2 to 0.3
Compost	1.0
Sandy Soil	1.1 to 1.3
Silty Sands	1.4
Silt	1.3 to 1.4
Silt Loams	1.2 to 1.5
Organic Silts/Clays	1.0 to 1.2
Glacial Till	1.6 to 2.0
Urban Lawns	1.5 to 1.9
Crushed Rock Parking Lot	1.5 to 2.0
Urban Fill Soils	1.8 to 2.0
Athletic Fields	1.8 to 2.0
Rights of Way and Building Pads (85% Compaction)	1.5 to 1.8
Rights of Way and Building Pads (95% Compaction)	1.6 to 2.1
Concrete Pavement	2.2
Quartzite (Rock)	2.65

Table 2: A Comparison of Root Limiting Bulk Density for Different Soil Types (Morris *et al.*, 1988)	
Soil Texture	**Critical Root Limiting Bulk Density (grams/cubic centimeter)**
Sand *	1.8
Fine Sand *	1.75
Sandy Loam	1.7
Fine Sandy Loam	1.65
Loam	1.55
Silt Loam	1.45
Clay Loam	1.5
Clay	1.4

* only soil types which do not limit root growth after 85% compaction by proctor test

Table 3: Comparison of Bulk Density in New Jersey Soils Average Bulk Density in First Foot of Soil (gms/cc) Computed From Database Provided by Smith (1999)				
NRCS Hydrologic Soil Group	**No. of Samples**	**Forest Soils**	**Pasture Soils**	**Cultivated Soils**
A Soils Very low runoff potential	17	1.35 gms/cc	1.48 gms/cc	1.61 gms/cc
B Soils Low runoff potential	92	1.30	1.45	1.53
C Soils Moderate runoff potential	73	1.27	1.39	1.55
D Soils High runoff potential	28	1.20	1.46	1.65

This table provides a comparison of the bulk density for different hydrologic soil groups (HSGs), as classified by the Natural Resources Conservation Service. Hydrologic soil groups are frequently used to define curve numbers to characterize runoff potential within various hydrologic models. The HSG classification, is not strictly based on the porosity of the soil, but also includes other soil properties that govern runoff potential, such as the infiltration rate, depth to watertable and the presence of confining layers such as hardpans and fragipans. More information on HSG can be found in the National Resources Conservation Service, National Engineering Handbook, Chapter 2.

Notes: pasture category includes grassland, hay and grazed lands.

compacted soils have lower oxygen transfer, extreme summer soil temperatures, less nutrient retention, less soil fauna (such as earthworms) and less mycorrhyizal fungi compared to uncompacted soils (Bethenfalvay and Linderman, 1992 and Craul, 1994). Consequently, urban trees and ground covers tend to be very sparse, short-lived, and disease-prone, unless they are provided with significant irrigation, soil amendments, fertilization and other inputs.

Bulk Density Increases in Response to Watershed Development

We do not walk very lightly on the earth. Nearly every kind of watershed development compacts the soil and increases bulk density. Soil compaction begins with grazing, as the weight of livestock tramples soils of the pasture. A modest increase in soil bulk density of 0.12 to 0.20 gms/cc has been observed in pasture soils, compared to forest ones (See Table 3). Soil compaction, however, is largely confined to the surface, and does not extend more than a few inches into the soil profile.

Compaction becomes much more severe when crops are cultivated. As heavy farm machinery passes over the field, soils are compressed up to two feet below the surface. In addition, as topsoil is eroded, more compacted subsoils are exposed. The common practice of tilling the fields does relieve compaction in the upper few inches of the soil profile, but the effect is seasonal and does not extend more than six inches to a foot below the surface. Overall, the effect of cropping is to increase bulk density by an average of 0.25 to 0.35 gms/cc, compared to forest soils, depending on the hydrologic soil group (Table 3).

Compaction becomes even more dramatic during the urbanization of a watershed. Soil structure is compacted in three different ways during the construction process. First, grading equipment works over the site to cut and fill and achieve the desired elevations for building. As a consequence, existing top soil is stripped, stockpiled or even removed from the site, and compacted subsoils are exposed at the surface. Second, as construction equipment and vehicles work the site, their tracks and tires compress the remaining soils several feet below the new surface.

Lastly, certain portions of the site are intentionally compacted with vibrators or rollers to meet soil engineering standards for bearing structures or traffic loads. This intentional compaction usually occurs along the right of ways for roads, a 10-foot envelope around building pads, and around stormwater ponds. Other areas of the site are also frequently compacted as the equipment moves from lot to lot. Local development standards typically require that soils be compacted to within 90 or 95% of their maximum bulk density within these zones.

Table 4: Reported Land Use or Activities That Increase Soil Bulk Density

Land Use or Activity	Increase in Bulk Density (gms/cc)	Source:
Grazing	0.12 to 0.20	Smith, 1999 (Table 2)
Crops	0.25 to 0.35	Smith, 1999 (Table 2)
Construction, mass grading	0.34	Randrup, 1998
Construction, mass grading	0.35	Lichter and Lindsey, 1994
Construction, no grading	0.20	Lichter and Lindsey, 1994
Construction traffic	0.17	Lichter and Lindsey, 1994
Construction traffic	0.25 to 0.40	Smith, 1999, Friedman, 1998
Athletic fields	0.38 to 0.54	Smith, 1999
Urban lawn and turf	0.30 to 0.40	Various Sources

Taken together, construction increases the bulk density of surface soils on the order of 0.35 gm/cc over the predevelopment land use, whether it is forest, pasture or crops (Table 4). The compaction can extend up to two feet down in the soil profile, according to Smith (1999). One of the best studies on the impact of construction on soil compaction was performed by Randrup (1998), who examined 47 Danish construction sites and adjacent undeveloped soils. He reported an average increase in bulk density from 1.60 gms/cc to 1.94 gms/cc, with the greatest compaction found more than a foot below the soil. Lichter and Lindsay (1994) found a similar increase in soil bulk density at several California construction sites. They also noted that bulk density increased by 0.2 gms/cc at a construction site whose soil was not mass graded nor compacted to meet engineering standards. Clearly, mass grading and the passage of construction equipment are both important factors leading to soil compaction on most construction sites (see Table 4).

According to recent research, soil compaction continues after turf and landscaping are established at the site, at least for the first few years. Bulk density values typically remain about 0.30 to 0.40 gms/cc above predevelopment levels after development (Table 4). A few urban areas continue to become more compacted. Most notable are athletic fields, park areas, pathways and unpaved parking lots that continue to experience extensive foot and/or vehicular traffic after development. Surface bulk densities for these compacted soils often range from 1.9 to 2.1 gms/cc, which is almost equivalent to the bulk density for impermeable concrete surfaces.

Implications of Soil Compaction for the Watershed Manager

The compaction of urban soils has many implications for the watershed manager. As soil compaction appears to be virtually unavoidable once clearing begins and the site experiences construction traffic and activity, site planners must physically exclude any construction equipment from portions of the site where undisturbed soils are required or desired. Many stormwater practices utilize the soil to treat or infiltrate stormwater runoff, and are designed under the assumption that the underlying soil is uncompacted and relatively undisturbed (infiltration, filter strips, grass swales, disconnection of rooftop runoff, some forms of bioretention and even septic systems). As a result, these practices should be located outside the limits of construction disturbance. Otherwise, they may require extensive soil amendments to restore their intended function.

The second key implication of compaction relates to the objectives for local erosion and sediment control plans during construction. From a watershed standpoint, these plans should not only focus on preventing soil loss, but go further to prevent soil compaction. Any reduction in clearing, grading and construction access will provide a stormwater management benefit. Uncleared and ungraded portions of the site represent an important “hydrologic reserve area,” and erosion and sediment control plans should clearly demarcate the limits of disturbance over as much of the site as possible to retain these. Hydrologic reserves can include wetlands, conservation areas, buffers, setbacks, open space, and even portions of individual lots. However, drawing the limits of disturbance on a plan is much easier than actually enforcing them in the field, so increased contractor training and fencing are essential. Communities should also carefully reevaluate their current compaction requirements and grading standards to ensure that they only compact those areas of the site that are absolutely necessary, and otherwise promote the retention of undisturbed soils.

The third implication of urban soil compaction is that severe soil compaction fundamentally alters the hydrology of a site, and makes many pervious areas function more like impervious ones. This suggests that engineers will need to explicitly incorporate the effects of soil compaction into their models that predict the changes in runoff as a result of development. The challenge is that while it is relatively easy to predict the increase in bulk density caused by construction, it is much harder to predict precisely how much this increase in bulk density will increase the runoff coefficient or curve numbers for pervious areas. More research is urgently needed to characterize runoff from lawns and landscaped areas on compacted urban soils.

Until better data are available, it seems prudent to model the runoff from pervious areas differently. For example, it may be advisable to adjust runoff coefficients upwards for compacted pervious areas (by approximately 0.1 to 0.15) or, when using the NRCS TR-55 model, to automatically shift curve numbers (CN) upward by at least one hydrological soil group (HSG) when a site is cleared (i.e., if the original pervious area was a B soil, model it as if it were a C soil). An even larger shift is probably justified if the area is planned to be an athletic field or a new lawn.

In summary, watershed managers should bear in mind that the quality of soils is inextricably linked to the quality and quantity of water. Greater efforts to prevent or reduce the compaction of soil quality that results from construction are an important element of any urban watershed protection strategy. ***–TRS***

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