Stormwater Infiltration and the Soil Landscape Connection

Russell L. Losco[1,2] and Joseph A. Valentine[1,3]

[1]Pennsylvania Association of Professional Soil Scientists, P.O Box 61035, Harrisburg, PA 17106-1035; www.papss.org <http://www.papss.org/>
[2]Lanchester Soil Consultants, Inc., 311 East Avondale Road, West Grove, PA 19390; PH (610) 869-3066; FAX (610) 869-8918; email: RLosco311@hotmail.com
[3]Del Val Soil & Environmental Consultants, Inc., Sky Run II, Suite A1, 4050 Skyrun Drive, Doylestown, PA 18901; PH (215) 345-5545; FAX (215) 345-8138; email: jvalentine@delvalsoil.com

Abstract

In recent years, the emphasis on stormwater management in this region has changed from retention/detention to infiltration. Municipalities are requiring stormwater infiltration wherever possible. This has led to a varied approach to stormwater infiltration, often ignoring the characteristics of the soils on the site. For stormwater infiltration to be successful, the morphology of the receiving soils and depth to seasonal, regional, and perched water tables must be considered. Proper utilization of the most suitable soils on the site can mean the difference between success and failure of infiltration systems. Site specific characterization of soils with consideration of landscape is vital to the decision-making process.

Introduction

In the past, the main concern with stormwater management had been with detaining or retaining stormwater and slowing it's release to surface waters to prevent flooding. Increasingly, the emphasis has shifted to infiltrating stormwater into the soil to recharge groundwater while also slowing the waters transport into surface water by making the groundwater the means of conveyance. This method of stormwater management presents a number of benefits coupled with a number of potential problems.

The benefits of stormwater infiltration include the usual benefits of stormwater management, the prevention of flooding and erosion, coupled with the benefit of groundwater recharge. Groundwater recharge, which is especially critical in the more arid regions, is also of increasing concern here in the northeastern United States. Expanded suburban development has caused an increase in impervious surfaces, limiting the normal infiltration of rainwater and limiting groundwater recharge. Use of on-site wells and sewage disposal systems (AKA septic systems) has traditionally provided a virtual zero-sum in groundwater use, where almost all of the water drawn for use from the aquifer through the well is returned via the septic system. This becomes a problem when septic systems are replaced by public sewerage and the water drawn from the aquifer is treated and disposed of by discharge to a stream or river. Public sewerage also presents a problem in urban settings if the source of drinking water is, in whole or in part, from wells. Constant withdrawal of water from an aquifer without recharge can lead to lowering of the water table and concentration of contaminants.

Infiltration of stormwater offers the advantage of increased groundwater recharge, thereby raising aquifer levels. It also offers the potential to limit non-point source pollution by introducing a filter medium, in the form of the soil mantle, between the stormwater runoff and the receiving waters, be they groundwater, or, ultimately, surface water. Soil has been shown to be a very effective filter medium which normally protects the groundwater from contamination by pollutants. Since soil is a living medium, supporting, under normal conditions, an extensive micro flora and fauna, it acts not only as a passive filter, but also as an active filter. Soil traps pollutants physically as well as chemically. Clay minerals in the soil have the potential of capturing cations through adsorption. The total potential ability of the clays to adsorb cations depends upon the type (there are hundreds) of clay minerals found as each type of crystalline structure has it's own particular Cation Exchange Capacity or CEC (Dixon & Weed, 1989). Nutrients trapped by the soil can be taken up by plants. This nutrient uptake is especially important in preventing groundwater contamination by nitrates and phosphorus.

While it could be postulated that a point could be reached where raising levels of water tables would be disadvantageous, such scenarios are unlikely in the northeastern United States. The disadvantages of stormwater infiltration are largely related to improper siting, design, construction, and maintenance. Failure in any of these aspects could easily result in the infiltration structure becoming no more than an elaborate detention facility.

Soil Basics

In order to understand water movement through soil, it is important to understand the characteristics of the soil medium itself. Soil is defined as the unconsolidated mineral or organic matter on the surface of the earth that has been subjected to and shows effects of genetic and environmental factors (SSSA, 1997). Soil formation is influenced by the five soil forming factors, parent material, climate, topography, biologic activity, and time (SSSA 1997, Brady 1990). Since management of the soil can have a tremendous impact on soil characteristics, a sixth factor could be added to this list, human activities. Obviously, soil that has been forested will have different characteristics than the same soil which has been cultivated regularly or been mechanically cut, filled, or compacted.

Most engineers and regulators are familiar with the NRCS (formerly SCS) County soil surveys. The soil surveys are a tremendous general tool, allowing rapid access to regional information on soils. It must be stressed, however, that the soil surveys are not, and were never meant to be, site specific. The soil surveys were compiled in order to give broad overviews of the soils and average, general information on the characteristics of the soil. In this they have succeeded and are a very useful tool. One must realize, however, the limitations of the soil surveys. The soil surveys were based upon field investigations by SCS soil scientists, who were allotted a time budget of mapping 500-1000 acres per day. Under the best of circumstances, this schedule does not allow for a tremendous amount of detailed field investigation. Factor into this inclement weather, hostile terrain and access issues and the detail decreases considerably. Obviously the site which is covered in dense bramble thickets is not going to receive the same attention at the open plowed field adjacent to it.

The soil surveys are further limited by the scale at which they are compiled. The soil survey maps were traditionally generated by drawing the soil series lines on aerial photographs. These rendered a scale of approximately 1”=1666’, an odd scale for transposing to other media. The current trend is to convert the soils maps to overlie USGS maps at the scale of 1”=2000’, which is easier to deal with but allows little resolution. At these scales, it is impossible to map all inclusions of other soil series within a mapped area. The mapped soil series can contain up to 35% inclusions of other series. Also, at this scale, the very lines themselves can scale out to be approximately 50 feet wide. Soil lines drawn in steep areas or areas approaching water may be so close together that definition is lost. It has been the practice in such cases to “lump” soil series together in these cases. In some areas, as drafts of the soil survey maps went to final stage, budgetary shortfalls required using prison labor as draftsmen, with the obvious problems which can result from having semi-skilled, unmotivated labor making drafting decisions (Mueller, 2003). For these reasons, it is often difficult, if not impossible, to make any kind of site-specific interpretations from the soil surveys.

The Catena Sequence

The Catena sequence is a somewhat outdated concept, but one which still has validity, especially in this discussion. The Catena sequence describes the variation of soils over a landscape going from a high topographic position to a low one (Brady, 1990). For example, in the soils derived from the crystalline bedrocks of the piedmont region of southeastern Pennsylvania, we see a typical Catena sequence as illustrated in figure 1, beginning with the excessively well drained Manor series at the summit of the hill, then, as you descend the slope the well drained Chester and Glenelg series, the moderately well drained and somewhat poorly drained Glenville as you approach the footslope, the poorly drained Worsham at the toeslope, and the sometimes flooded Wehadkee series within the floodplain and stream channel. As you can see, the water table becomes increasingly close to ground surface as you travel down-slope until it manifests itself as surface water within the toeslope or stream channel. This may seem intuitively obvious, but it is a concept which is often overlooked by designers and regulators.

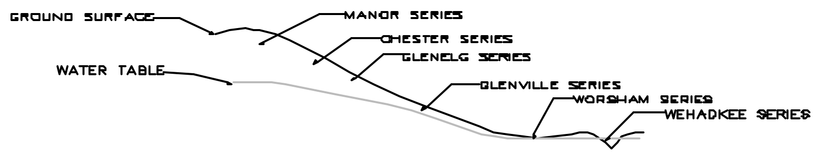

FIGURE 1

The obvious nature of this first catena sequence should not be considered universal. Take, for example a catena sequence from the Ridge and Valley province of Pennsylvania (figure 2). Here we see an unusual relationship between landscape position and drainage classification with the well drained Hazelton and Laidig series soils occurring at the summit and shoulder then the moderately well drained Buchanan series and poorly drained Andover series soils on the backslopes, then grading into the well drained

Murrill and Hagerstown series soils as we proceed downslope into the valleys. This is due to the fragipans which are typically found in these soils. A fragipan is a dense, brittle horizon with a high bulk density which acts as an aquitard, perching water above it. In this area, the fragipans occur shallower in the sandstone derived soils of the colluvial slopes than they do in the limestone derived soils of the valley. This causes the unusual catena sequence with wetter soils occurring higher on the landscape and drier soils in the lower topographic positions.

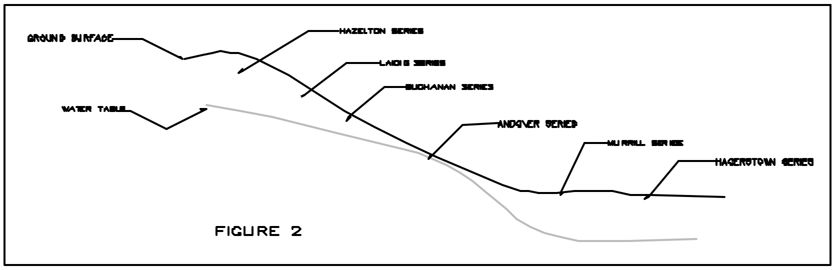

FIGURE 2

Another unusual catena sequence can occur in the coastal plain region where most of the soils are fluvial in nature. A common soil found in the coastal plain of Delaware is the Matapeake series, which consists mainly of wind deposited, fine textured loess overlying a sandy substrate which was deposited by moving fresh water. In these soils, the catena sequence tends to mimic that of the piedmont except the changes occur with more subtle variations in slope. In the piedmont, the shift from moderately well drained soil to somewhat poorly drained soil may require an elevation change of 10-20 feet, where in the coastal plain, 1 foot of elevation may signal that same shift. It is also possible in this region to encounter the heavier textured soils which were deposited in a marine environment, such as the Keyport series soils. In these soils the steady gradation which we have seen in the previous catena sequences is almost non-existent, instead, the gradation is between somewhat poorly drained to poorly drained as you traverse the landscape from high to low. Where these two types of soil meet, it is possible to find a somewhat poorly drained soil at a relatively high point on the landscape grading into a well drained soil downslope and then into a moderately well drained or somewhat poorly drained soil (figure 3).

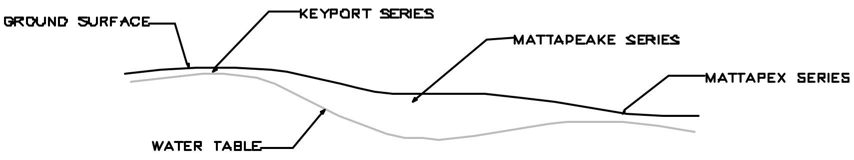

FIGURE 3

Another factor which can affect the validity of a catena sequence is depth to bedrock. In some cases, such as in limestone areas, the bedrock may actually have a higher permeability than the overlying soil, particularly if the soil exhibit's a fragipan. In other cases, such as the coastal plain, bedrock may be so deep that it is not of any concern. Elsewhere, bedrock may be so shallow and so dense that it is the aquitard and restricts water movement.

It must be stressed that the catena sequence is a general concept which attempts to describe the relationship between landscape position and drainage classification. It is possible to find any number of anomalies within a catena sequence in the real world. Localized aquitards and solution channels can turn the catena sequence, such as the typical one presented earlier in the piedmont, into an incredibly complex relationship which confounds the investigator. Almost none of these anomalies will be noted in the soil surveys, as the scale and intensity of the mapping preclude their inclusion. The only way to be certain of the nature of the soils on a site is by conducting site-specific testing.

Soil texture

Soil consists of five constituents sand, silt, clay, organic matter, and pore spaces. Since little construction occurs in North America in organic soils such as peats and mucks, we will omit them from this discussion. In mineral soils, organic matter content is greatest in the A horizon, commonly referred to as the topsoil, where it usually exists as approximately 5% by volume of the soil. The lower soil horizons contain smaller amounts of organic matter which are relatively insignificant for this discussion. The main constituents of mineral soil, for the purposes of this discussion therefore, are the sand, silt, clay, and pore spaces. The sand, silt, and clay represent the mineral fraction of the soil. Sand is composed of particles between 2 mm and 0.05 mm in diameter and are essentially small rocks. Silt is composed of particles ranging between 0.05 mm and 0.002 mm in diameter and are also essentially very small rocks. Clay is composed of particles less than 0.002 mm in diameter (Brady, 1990).

When soil particles are broken down to such small sizes, a change occurs in the crystalline structure and, in order to remain stable, clay minerals are formed. There are probably hundreds of clay minerals in existence, each with it's own range of physical characteristics. Due to their crystalline structure, clay minerals have electric charges and are capable of adsorbing varying amounts of cations. Some clay minerals, also owing to their crystalline structure, are hydroscopic and can trap water, causing them to expand. A very small percentage of certain types of expanding clays can cause a drastic difference in the porosity and therefore the permeability of the soil when water is present. Some of the smectitic clays occurring in the western United States, the so-called "gumbo clays" can change the elevation of ground surface by a foot or more between wet and dry periods. Ironically, the clays which are the most capable of adsorbing pollutants and are therefore qualitatively the best filters, are also the worst filters quantitatively since they swell and close off the soil pores (Dixon & Weed, 1989).

Water tables

The pore spaces found in soil may be filled with air or water, or may intermittently carry both. When the water table is encountered, the pore spaces are filled with water during normal periods. Many water tables found in the soil fluctuate in level depending on the seasons and the precipitation. This presents a problem when investigations are conducted during seasons of low water table. Luckily water tables leave behind a tell-tale signature which often indicates their seasonal extent. This signature consists of redoximorphic concentrations and depletions of iron and manganese, commonly referred to as mottles or redox mottles. These redox mottles are utilized to determine the drainage classification of a soil. Redox mottles form when soil is saturated with water for an extended period of time.

When soil is saturated with water for an extended period of time, a series of reduction reactions are triggered by the micro-fauna in the soil in which electrons are consumed. A number of conditions need to be present in order for these reduction reactions to occur. First, there must be organic matter present as a source of electrons, second the soil must be waterlogged to prevent the inflow of air, third the bacteria must be present and respiring and decomposing the organic matter, and fourth the soil must have a temperature sufficient to support the biological activity. These reduction reactions tend to occur involving existing elements and compounds in the soil based upon their reduction potentials. Typically this involves first reducing any remaining oxygen in the soil, then reducing nitrates (NO_3) to atmospheric nitrogen (N_2), then manganese oxides (MnO_2) to manganese (Mn^{2+}) then ferric iron oxides or hydroxides ($Fe(OH)_3$ to ferrous iron (Fe^{2+}). These reactions can continue to involve reduction of sulfates ($SO_4{}^{2-}$) to hydrogen sulfide gas (H_2S) and carbon dioxide (CO_2) to methane gas (CH_4) (Richardson & Vespraskas, 2001).

In a well drained soil, the soil color is usually a combination of yellows and reds yielding a brown or reddish brown color. This color is largely imparted by the individual grains of soil being coated by iron and manganese oxides, with the iron oxides being the most prevalent. If these coatings are removed, the background color of the soil grains are exposed. These colors are most often gray, blueish or greenish (Brady, 1990; Richardson & Vespraskas, 2001). Good examples of this can be found by observing the gray soil found in creek beds or beneath the organic surface soils in a wetland. Another excellent example is beach sand, which, due to constant contact with the water has had all coatings removed and is an even gray or tan color. Such extreme redox mottling is referred to as gley or gleyed soil. Often gleyed soil will contain streaks or reddish rust colored spots.

Redox mottles are formed when the commonly occurring ferric iron compounds found in the soil are reduced to the ferrous state. Ferrous iron is water soluble and can then migrate out of the soil leaving behind the gray matrix of the exposed soil grains. Sometimes it is possible along stream banks or adjacent to wetlands to observe water seeps which are rust colored. These seeps show the transport of the ferrous iron and it's re-oxidation upon contact with the air.

In an upland area, where a fluctuating water table or restrictive drainage causes an alternating wet/dry cycle, this process is exhibited in a more subtle fashion. The redox mottles in these areas occur as spots of gray, often surrounded by a reddish halo. Although these can occur in small pockets due to localized conditions, a general condition of a soil horizon exhibiting redox mottles is an indication of seasonal saturation which may indicate the highest extent of the seasonal water table. When the matrix soil color (50% or greater) is reduced (a chroma of two or less and a value of four or more), it is interpreted that the soil horizon is seasonally saturated with water. However, this condition could be perched due to a slowly permeable horizon and not due to a true or regional water table. When the saturated zone exists and continues to a depth of two meters, the condition is considered endosaturated. When the saturated condition is underlain by an unsaturated condition within two meters of surface, an episaturation exists. For the purpose of stormwater infiltration, end saturation should not be considered and should be treated as a true water table; however, episaturation <u>may</u> be considered. A qualified soil scientist who is familiar with the soil morphology to assess these conditions should make the determination.

Recognition of seasonal water table depths in soil is absolutely vital to the proper functioning of a stormwater infiltration structure. If infiltration is proposed in an area of even seasonal saturation, the infiltration structure may be completely or partially full of water during the portion of the year when precipitation is at the highest level, rendering the system useless during these periods. Soil surveys give typical depths to water tables, but these data are not specific enough to be applied to individual sites. Accurate water table depths can only be derived from site specific soil testing by qualified individuals.

Site Specific Testing

Site specific testing should involve mapping, description and characterization of the soil on the site by a qualified soil scientist. Soil can be investigated by using a soil auger, so long as the soil is not too rocky and bedrock is not a concern, but a soil auger is limited in it's ability to reach deeper depths. Backhoe pits are a preferred method of soil investigation as they open a sizeable window into the soil and can penetrate to considerable depths.

Site specific testing encompasses two aspects, soil profile description and interpretation and permeability testing. Accurate soil profile descriptions should be compiled by a qualified soil scientist. Descriptions should include such pertinent data as color, texture, structure, consistence, boundaries, redoximorphic features, coarse fragment content, mineralogy and any indications of bedrock, fragipan, plinthite (iron pan), or any other restrictive horizons. Interpretation of the soil profile should include drainage classification, taxonomic classification, depth to water table, soil series encountered, and use suggestions. The interpretation should recommend depth of installation/permeability testing of any stormwater recharge structures and any restrictions on use of the soil.

Permeability of soils can be estimated by an experienced qualified soil scientist or measured using appropriate permeability testing. Permeability testing should be conducted by qualified individuals at the depth of installation testing of any stormwater recharge structures or at the most restrictive horizon noted. It is a common failing of permeability testing to see it conducted within a relatively permeable horizon that overlies an aquitard without taking into account the hydraulic conductivity of the less permeable horizon. Another common failing of permeability testing is utilizing the wrong test. Percolation testing is often substituted for true permeability testing.

A percolation (perc) test is a method to determine septic system sizing in Pennsylvania. This test does not determine water movement in soil, or hydraulic conductivity (HC). For example, a 30 minute per inch percolation rate does not mean a 2 inch per hour HC. If it did, then a 30 minute per inch percolation rate would mean that the soil would “move” 48 inches of water per day. At this “rate”, we would never have stormwater runoff or the need for stormwater management structures. Therefore, the use of perc tests to assign a water movement value will greatly over-estimate the soil/site capability to infiltrate stormwater. An HC value must be determined by one of several methods as outlined in the ASTM Book of Standards, Volume 4.08 or the SSSA Methods of Soil Analysis, Part1 and utilizing Darcy’s Law to calculate the water movement potential.

Darcy’s Law

In his study of the rate of water flow through sand filters, Darcy, a French engineer working for the City of Paris, discovered over a century ago that the quantity of water Q flowing through water-saturated sand filters of length L and cross sectional area A during a time period t is proportionally related to the hydraulic gradient by

$$Q/(At) = v = K_{sat} \times \Delta H/L$$

Where K_{sat} is the saturated hydraulic conductivity of the medium and v is called flux density or flux. The above equation is known as Darcy’s Law and can be generalized by presenting it in differential form. For one-dimensional flow, this equation can be written as

$$V = K_{sat}\, dH/dx$$

Where H/dx is the gradient. (NOTE: The flux v is a vector, and similar to the gradient dH/dx, has a magnitude and direction. For our purposes, we take the value of v as positive at all times.) This law simply states that the rate of movement of water through a soil is proportionally related to the hydraulic gradient (the driving force acting on water) and the conductivity of the medium (a measure of the ability of the soil to transmit water). Darcy’s Law has been accepted as the physical law governing soil water movement and applies to both saturated and unsaturated flow under steady-state or transient conditions (Jury, Gardner & Gardner, 1991).

Water can move through the soil in all directions, but it always moves from a point at higher potential (higher total hydraulic head) to a point of lower potential. The direction of the flow depends on the direction of the gradient, and the rate of water movement depends on the magnitude of the hydraulic gradient and the hydraulic conductivity of the medium. For example, consider that water is applied to one end of a horizontal column of soil under a constant head, $H_{1,}$ and exits the other end of the column under a constant head, H_2. Knowing the K_{sat} and applying equation 1, one can determine the quantity of water that can pass through the column during a specified time period. Conversely, one can calculate a K_{sat} based on the flow rate through the column.

A number of methods are available for measuring K_{sat} in the field or in the laboratory. K_{sat} can be measured in situ or in the laboratory using intact or repacked soil cores using Single or Double-Cylinder (Ring) Infiltrometers or other devices.

Conclusions

Stormwater infiltration into the soil is a viable and practical method of stormwater management on many sites. The soil can provide an excellent filter medium to remove contaminants and protect groundwater from pollution while slowing the introduction of water into the water table and surface waters and providing groundwater recharge. The success of stormwater infiltration, however depends heavily on proper and accurate testing, description, and interpretation of the soils on each site to determine suitability. Furthermore, successful use of stormwater infiltration requires utilization of the proper method for each individual site. Careful testing, interpretation, design and installation of stormwater infiltration structures can make the difference between success and failure.

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The potential for storm water infiltration to pollute soil, seepage water and groundwater is investigated with long-term 3-D numerical water flow and chemical transport modelling in unsaturated and saturated zones over 50 years, which were already presented by Zimmermann et al. (Water Sci Technol 51(2):11â€“19, 2005). The recommendation is based on a comparison between modelling results and several guideline values prepared by several German authorities. The evaluation process leads to four hazard levels regarding the impact on topsoil (i.e. first 20 cm of the soil), on seepage water (1 m below This reduces infiltration through the soil surface and/or the percolation of water through the soil profile, with important consequences for crop yields, nutrient cycling and the hydrological response of catchments. This article describes a broad-scale modelling approach to assess the potential effect that improved agricultural soil management, through reduced soil structural degradation, may have on the baseflow index (BFI) of catchments across England and Wales.Â The magnitude of storm sediment production at different catchment scales will be examined and the potential links between hillslope sediment production and the stream sediment load explored in the context of catchment land use. Soils absorbing less water result in more runoff overland into streams. Soil saturation: Like a wet sponge, soil already saturated from previous rainfall can't absorb much more thus more rainfall will become surface runoff. Land cover: Some land covers have a great impact on infiltration and rainfall runoff. Vegetation can slow the movement of runoff, allowing more time for it to seep into the ground.Â Agriculture and the tillage of land also changes the infiltration patterns of a landscape. Water that, in natural conditions, infiltrated directly into soil now runs off into streams. Slope of the land: Water falling on steeply-sloped land runs off more quickly and infiltrates less than water falling on flat land.