Lessons Learned About Successfully Using Infiltration Practices

Eric H. Livingston
Stormwater/NPS Management Section
Florida Department of Environmental Protection
2600 Blair Stone Road (MS3570)
Tallahassee, Florida 32399-2400

Abstract

Infiltration practices are one of the most valuable urban stormwater BMPs because they not only help to reduce stormwater pollutants but, more importantly, help to reduce stormwater volume. Unfortunately, infiltration practices have gotten a bad reputation over the past 20 years because of their potential to fail. This paper will review the successes and failures of the use of infiltration practices in the United States. It will summarize the lessons that have been learned about the use of infiltration practices. This will include recommendations on when they should be used and how, and recommendations on when they should not be used. Finally, the paper will discuss what can be done to reduce stormwater volume when infiltration practices cannot be used successfully.

Introduction

To achieve the desired objectives of flood control, water quality protection, erosion control, improved aesthetics, and recreation, a stormwater management system must be an integral part of the site planning for every development site. Although the basic principles of stormwater management remain the same, each individual site and each specific project presents unique challenges, obstacles, and opportunities. The many variations in climate, soils, geology, groundwater, topography, vegetation, and planned land use require site-specific design.

The natural attributes of each site will strongly influence the type and configuration of the stormwater system. These features will suggest which particular combination of Best Management Practices (BMPs) can be successfully integrated into an effective system. Whenever site conditions allow, the stormwater management system should be designed to achieve maximum on-site storage of runoff by incorporating infiltration practices throughout the remaining natural and landscaped areas of a site. A stormwater management system should be viewed as a "treatment train" in which the individual BMPs are the cars. Generally, the more BMPs that are incorporated into the system, the better the performance of the treatment train. Inclusion of infiltrative practices as one of the cars should be a primary goal of stormwater system designers, even on sites where detention practices will be the primary BMP.

Infiltration practices (or retention practices) retain stormwater on-site, allowing it to soak into the ground or evaporate. There are a number of different infiltration practices that have been widely used throughout the United States, including basins, trenches, dry wells, pervious pavements, and swales. Often infiltration practices include vegetation with a wide variety of trees and shrubs. In 1987, Prince George's County, Maryland, began evolving this type of infiltration practice into "bioretention," which is a BMP that uses the soil matrix and vegetation to sequester pollutants within the terrestrial environment (PGC, 1993, 1997)

Infiltration practices are one of the few BMPs that can help to assure that all four stormwater characteristics (volume, rate, timing, and pollutant load) after development closely approximate the conditions which occurred before development. That is because infiltration practices help to maintain pre-development site perviousness and vegetative cover, thereby reducing stormwater volume and discharge rate, which further promotes infiltration and filtering of the runoff.

The benefits of infiltration include reducing stormwater volume and peak runoff rate; recharging groundwater, which helps to replenish wetlands, creeks, rivers, lakes, and estuaries; augmenting base flow in streams, especially during low flow times; settling and filtering of pollutants as they move through the system's vegetation and surficial soils; lowering the probability of downstream flooding, stream erosion, and sedimentation; and providing water for other beneficial uses.

Another benefit of infiltration practices is their ability to serve multiple uses since they are temporary storage basins. Recreational areas (e.g., ballfields, tennis courts, volleyball courts), greenbelt areas, neighborhood parks, and even parking facilities provide excellent settings for the temporary storage of stormwater. Such areas are not usually in use during periods of precipitation and the ponding of stormwater for short durations does not seriously impede their primary functions.

Longevity of Infiltration Systems

One of the problems with infiltration BMPs that has been consistently identified, either quantitatively or qualitatively, is their high rate of failure. Maryland's Stormwater Program produced one of the most comprehensive quantitative reviews of the longevity of infiltration systems (Pensyl and Clement, 1987; Lindsey et al, 1992). This information is summarized in Table 1, where it can be seen that the overall condition and functioning of infiltration systems declined over time. In 1986, about two-thirds of all surveyed facilities were functioning as designed, while in 1990, only about half were. Only 42% of the facilities were functioning as designed in both 1986 and 1990, while about 27% were not functioning as designed in both years. About 24% of the systems were functioning in 1986, but not in 1990; while only 7% of those not working in 1986 were working in 1990. Maintenance was needed at more facilities in 1990 (66%) than in 1986 (45%). Additionally, 38% of facilities that needed maintenance in 1986, still needed maintenance in 1990, while 32% of the facilities that did not need maintenance in 1986, did need it in 1990. Only 10% of the systems that needed maintenance in 1986 did not need maintenance in 1990. These data suggest that little effort is expended on maintaining the operational capabilities of stormwater management systems.

Additional quantitative information on the success and failure of infiltration systems was collected in the Puget Sound, Washington, area (Klochak, 1992; Gaus, 1993; Hilding, 1993; Jacobson and Horner, 1993). Of 23 infiltration basins evaluated, 12 did not comply with the region's guidelines for either infiltration rate or time for the basin to recover its storage volume. Interestingly, the authors found no relationship between lack of basin maintenance and failure, with examples of basins with and without maintenance that did not function properly. Some basins were functioning properly even though they had never been maintained, while 43% of the 23 basins had been scarified to enhance performance.

The above data, when combined with qualitative information from Florida and Delaware (Baldwin, 1999, personal communication), seem to indicate that infiltration basin failures are associated with:

1. Inaccurate estimation of infiltration rates
2. Inaccurate estimation of the seasonal high water table
3. Excessive compaction during the construction process
4. Excessive sediment loadings either from improper erosion and sediment control during the construction process or a lack of pretreatment BMPs
5. Lack of maintenance

Factors Influencing Successful Use of Infiltration Systems

Factors that influence the successful use of any stormwater BMP can be categorized as institutional, technical, and implementational. This section of the paper will examine the components of each of these categories that must be included in a stormwater program if the causes of infiltration system failure are to be minimized.

Institutional Components

The "BMP Golden Rule" states that stormwater BMPs should never be required unless the stormwater program includes components that will assure that the BMPs are correctly designed, approved, constructed, inspected, maintained,

Table 1. Results of Maryland Infiltration Practices Surveys

	Basins		Trenches		Dry Wells		Perv. Paving		Veg. Swale	
	1986	1990	1986	1990	1986	1990	1986	1990	1986	1990
# facilities	63	48	94	88	30	25	14	13	6	3
(% of total)	30%	27%	45%	30%	14%	14%	7%	7%	3%	2%
Facility Evaluations										
Functioning	30	18	75	47	23	18	7	2	3	2
	48%	38%	80%	53%	77%	72%	50%	15%	50%	67%
OM Needed	41	39	28	64	9	4	10	8	6	3
	65%	81%	30%	73%	30%	16%	71%	62%	100%	67%
Performance and Maintenance Criteria										
Buffer strip	20	4	65	35	24	0	14	3	1	0
inadequate	32%	8^	69%	39%	80%		100%	23%	17%	
Stabilization	12	23	11	13	1	3	1	1	3	1
needed	19%	48%	12%	15%	3%	12%	7%	8%	50%	33%
Sediment	24	28	32	58	0	2	9	9	4	1
entry	38%	58%	34%	66%		8%	64%	64%	67%	33%
Inappropriate	41	25	25	20	9	3	7	4	4	0
ponding	65%	52%	27%	23%	30%	12%	50%	31%	67%	
No observed	na	na	45	58	4	7	10	11	na	na
well			45%	56%	13%	28%	71%	85%		

and operated (Livingston, 1997). Specifically, the program must have stormwater treatment and management goals, performance standards, education, and an institutional framework that includes plan approval, inspections during and after construction, legal operation and maintenance entity requirements, effective compliance mechanisms, and dedicated funding mechanisms.

Program goals: Experience has shown that stormwater programs need to have multiple objectives that are important to the general public in order to gain the support of the community. Typically, these will include flood protection, erosion and sediment control during construction, water quality and habitat protection, and open space and recreation. Infiltration systems can help achieve all of these goals.

Performance standards: Nearly all stormwater treatment programs in the United States are technology-based, relying upon a performance standard (minimum level of treatment) and design criteria for various BMPs that assure that they achieve the desired treatment goal. A review of 32 stormwater programs around the country showed that the most common performance standard is removing at least 80% of the average annual loading of total suspended solids (WMI, 1997a). Some programs require higher levels of treatment for stormwater discharges to sensitive waters, such as Florida's requirement that discharges to Outstanding Florida Waters remove at least 95% of the average annual pollutant load. Technology-based performance standards such as these provide water quality goals for nonpoint sources that create equity with the minimum treatment requirements for domestic wastewater point sources (Livingston, 1988).

Institutional framework: The stormwater program must have a strong institutional framework that assures that all BMPs are (1) properly designed, (2) reviewed and approved, (3) inspected during and after construction, and (4) operated and maintained. The components of this institutional framework are set forth in Figure 1. One of the most important components especially for infiltration practices, is a feedback mechanism among system inspectors, plan reviewers, and designers about what is working and what is not. This information can then be used to revise the design criteria for infiltration BMPs and improve their potential for long-term success.

Technical Components:

Successful implementation of any BMP depends on a thorough understanding of the factors that determine the BMP's treatment effectiveness, a strong scientific basis for the BMP's design criteria, and an understanding of the site conditions that are required or that limit the utility of a specific BMP. Infiltration practices are also commonly called retention practices because they retain the runoff on-site and are designed to infiltrate a design volume (treatment volume) of stormwater. Factors that influence the treatment effectiveness and feasibility of infiltration practices include (1) precipitation patterns, (2) whether the system is designed as an on-line or off-line system, (3) whether pretreatment via the BMP treatment train is provided, and (4) site characterisitcs such as land use, soil type, geology, water table elevation, topography, and vegetation.

Infiltration areas, especially off-line ones, can be incorporated easily into landscaping or open space areas of a site. These can include natural or excavated grassed or landscaped depressions and recreational areas. Parking lots, with their landscape islands, offer an excellent opportunity for the use of this concept since even the infiltration of a quarter inch of runoff will greatly reduce sediments, metals, oils and greases. Placing storm sewer inlets within recessed parking lot landscape areas, raising the inlet a few inches above the bottom, and using curb cuts to allow runoff to enter this area represents a highly effective treatment train. If site conditions prevent the exclusive use of infiltration, then off-line retention areas should be used as pretreatment practices in a stormwater treatment train. This is especially true if detention lakes are the primary component of the stormwater system and the lakes are intended to serve as a focal point of the development.

Pollutant removal efficiency factors: Average annual pollutant removal efficiency is calculated considering the annual mass of pollutants available for discharge and the annual mass removed. The primary removal mechanism for infiltration practices is the volume of stormwater that is infiltrated, since this eliminates the discharge of stormwater and its associated pollutants. In addition, the system's vegetation and the surficial soils play an important role in binding and transforming pollutants as the water infiltrates. As with any type of stormwater management practice, actual field efficiency will depend on a large number of factors. For infiltration practices, such factors include:

1. Long-term precipitation characteristics; such as mean number of storms per year, their intensity and volume, and average inter-event time.

Figure 1. Stormwater Program Institutional Framework Components

Inspections
- Erosion/sediment controls
- Stormwater system construction
- Stormwater system operation

Stormwater system operation/maintenance
- Public facilities
- Private facilities
- Adopt a pond program

Plan review and approval
- Site plans
- Erosion control plans
- Stormwater plans
- Feedback evaluation process

Education programs
- General public
- Elected officials
- School curriculum
- Designers
- Developers
- Builders
- Practitioners
- Inspectors

Structural BMPs
- Design criteria
- Research/performance
- Proper construction
- Proper operation
- Maintenance

Performance standards
- Peak discharge rate
- Volume
- Treatment

Administration
- Lead agency?
- Separate agency?

Staffing
- Engineers
- Inspectors
- Planners
- Scientists
- Maintenance
- Clerical

Compliance/enforcement
- Stop-work orders
- Fines
- Civil or criminal

Nonstructural BMPs
- Site planning
- Source controls
- Land acquisition
- Street sweeping

Program Evaluation
- Citizen surveys
- Bldg. community surveys
- BMP monitoring
- Water body monitoring

Stormwater Retrofitting
- Watershed goal
- Targeting/prioritization
- Capital improvements
- Regional BMPs

Local land use plan

Stormwater master planning

Watershed planning

Integration with other federal, state, regional, and local programs

Adopt program laws/regulations

Adopt stormwater utility ordinance/fees

Legal | **Funding** | **Staffing** | **Public** | **Govt. Roles Responsibilities**

2. The occurrence of first flush, which is related to the amount of directly connected impervious area; type of stormwater conveyance system; and the pollutant of interest

3. Whether the system is an "on-line" or an "off-line" design

4. Cumulatively, the above three factors determine the minimum treatment volume and maximum storage recovery time

The U. S. Weather Bureau has measured weather statistics at many locations around the country. Long-term precipitation records, including such information as day and duration of event, intensity, volume, etc., are available from either the Federal government or private vendors. Statistical analysis of these records can develop probability frequencies for storm characteristics such as the mean storm volume and the mean inter-event period between storms.

"First flush" describes the washing action that stormwater has on accumulated pollutants in the watershed. In the early stages of runoff, the land surfaces, especially impervious ones like streets and parking areas, are flushed clean by the stormwater. This flushing creates a shock loading of pollutants. However, the occurrence and prevalence of first flush depends largely on precipitation patterns, the degree of imperviousness of the contributing drainage area, the size of the drainage area, and the type of stormwater conveyance system. Florida studies have determined that for highly impervious urban land uses with drainage areas under 100 acres, there is a first flush for many pollutants, especially particulates (Yousef et al., 1985; Miller, 1985). In areas such as Oregon and Washington, however, where rainfall consists of low intensity, long-duration "events," first flush is not very prevalent.

On-line stormwater practices store runoff temporarily before most of the volume is discharged to surface waters. These systems capture all of the runoff from a design storm. This mixes all stormwater within the system, thereby masking first flush and reducing pollutant removal. They primarily provide flood control benefits, with water quality benefits usually secondary--although on-line wet detention systems provide both.

Off-line practices are designed to divert the more polluted first flush stormwater for water quality treatment, isolating it from the remaining stormwater that is managed for flood control. In infiltration systems, the diverted first flush is not discharged to surface waters, but is stored until it is gradually removed by infiltration, evaporation, and evapotranspiration. Vegetation, such as grass in the bottom and sides of infiltration areas, helps to trap stormwater pollutants and reduce the potential for transfer of these pollutants to groundwater. Off-line retention practices are the most effective for water quality enhancement of stormwater.

Since an off-line retention area primarily provides for stormwater treatment, it must be combined with other BMPs for flood protection to form a comprehensive stormwater management system. Figure 2 is a schematic of an off-line system, commonly referred to as a "dual pond system." In these systems, a smart weir directs the first flush stormwater into the infiltration area until it is filled, with the remaining runoff being routed to the detention facility for flood control.

A more recent investigation of the influence of long-term rainfall characteristics on the efficiency of retention practices included inter-event dry periods, leading to the development of diversion volume curves for inter-event dry periods of varying length (Wanielista et al., 1991a). Figure 3 shows an example diversion volume curve for the Orlando area. It is important to note that first flush is not considered in these curves. If a first flush effect does exist, the design curves would be conservative in that the percent treatment efficiency of the infiltration system would increase. Furthermore, these curves are based on precipitation-interevent-frequency (PIF) curves that also include consideration of the probability that a storm greater than the design storm will occur. The PIF analysis looked at exceedance probabilities storms with a return period of 2, 3, 4, or 6 months, representing a chance that the storm will exceed the design volume 6, 4, 3, or 2 times per year. Other useful products from this project are Rate-Efficiency-Volume charts and curves that can be used to design wet detention ponds that reuse runoff and thereby help to balance pre- and post-development volume (Livingston et al., 1999).

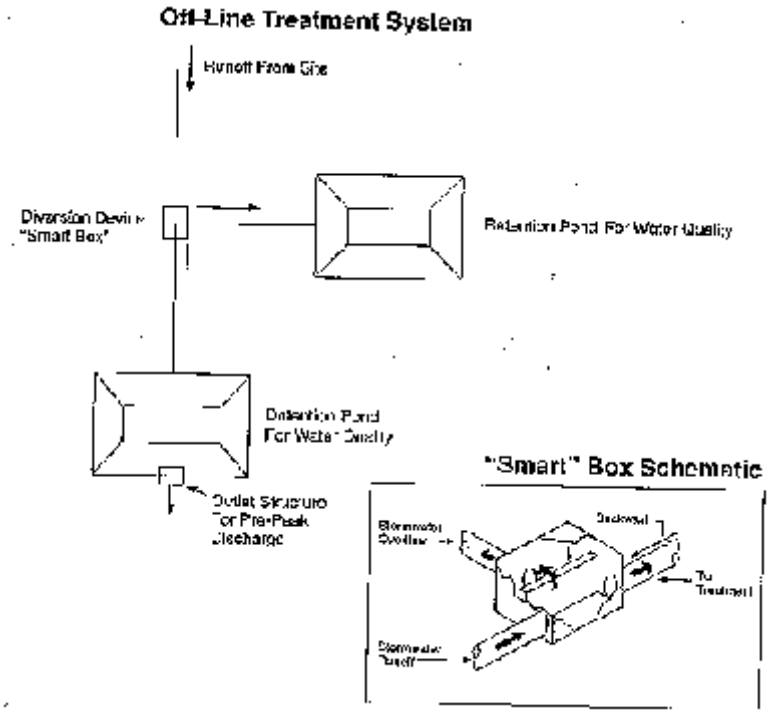

Figure 2. Schematic of an Off-line Stormwater System.

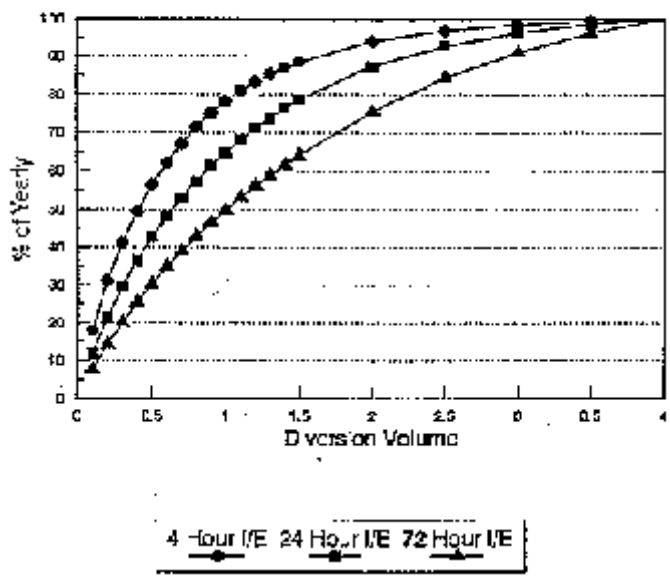

Figure 3. Diversion Volume Curve for Orlando, Florida.

Site Characteristics: The suitability of a site for using infiltration practices will depend on a careful evaluation of the site's natural attributes. Proposed infiltration areas should be evaluated for feasibility on any particular site or project by examining the following:

SOILS - Must be suitable for infiltration. Nationally, most states recommend that soil textures should not have more than 30% clay content or 40% silt content. Most importantly, they need to be able to percolate the diverted volume to infiltrate within 72 hours, or within 24-36 hours for infiltration areas that are planted with grasses. Therefore, soils that have been classified by the NRCS as HSG A are recommended for infiltration practices, although they can be successfully used with HSG B soil types.

INFILTRATION RATES - In recent years, the minimum permeability rate recommended for infiltration practices has been raised by implementing agencies. Shaver (1986) recommended a minimum rate of 0.25 inches per hour, but Maryland's regulations now recommend 0.52 inches per hour. One of the most difficult aspects of designing infiltration practices is obtaining reliable information about the actual infiltration rate of the soil where the practice will be constructed. Unfortunately, such information is not easily obtainable. Avellaneda (1985) conducted 20 hydrologic studies of vegetated swales constructed on sandy soils with a water table at least one foot below the bottom during dry conditions. Infiltration rates were measured using laboratory permeability tests, double ring infiltrometers, and field mass balance experiments. The field mass balance method measured a minimum infiltration rate of 2-3 inches/hour. This measured rate was much less than lab permeabilities, rates measured by double ring infiltrometer tests (5-20 in/hr), or rates published in the Detailed Soil Survey.

The following should be considered for determining the infiltration rate for retention practices:

1. Since the infiltration rate is the key to designing any retention practices, conservative estimates should be used, and safety factors incorporated into the design to ensure that the design volume will actually be percolated into the soil and not discharged downstream.

2. It is important that on-site infiltration measurements be taken at the locations where retention practices will be located. More importantly, since soil characteristics and infiltration rate change with depth, it is crucial that the measurements be made at the depth of the design elevation of the bottom of the retention practice.

3. Infiltration rates should be determined by mass balance field tests if possible. They provide the most realistic, accurate estimate of the percolation rate. If field tests are not possible, infiltrometer tests should be used, with lab permeability tests a third option. In either of these latter two tests, the design infiltration rate should be half of the lowest measured rate. As a last resort, information from Detailed Soil Surveys can be used to estimated the infiltration rate. However, the lowest rate should be used--as should a safety factor of two.

A recent assessment of infiltration practices in Carroll County, Maryland, quantified the infiltration rates for six basins and six trenches of differing ages (Nelson et al., 1999). They found that 64% of the systems had an average infiltration rate below the state's minimum recommended rate. However, 70% of the practices were still recovering their storage volume within the required 72 hours. Interestingly, for some facilities (mainly trenches), the infiltration rate met or exceeded the minimum state rate for a large percentage of the volume of water infiltrated, while the remaining water persisted for much longer periods of time before infiltrating. This may indicate that (1) the infiltration rate is related to the hydraulic head, where the higher depth of the stormwater in the BMP creates a higher pressure pushing water into the ground, or (2) the bottoms of the systems accumulate fines that impede percolation, while the sides of the systems are still infiltrating runoff rapidly.

WATER TABLE - The seasonal high water table should be at least three feet beneath the bottom of the infiltration area to assure that stormwater pollutants are removed by the vegetation, soil, and microbes before contacting the groundwater. Jacobson and Horner (1993) recommend a minimum of five feet if the seasonal high water table cannot be estimated accurately. When considering the groundwater elevation, it is important to remember that the retention area can cause a mounding effect on the water table, thereby raising it above the predevelopment level. The Southwest Florida Water Management District (SWFWMD) has developed a model that can be used to more accurately determine the seasonal high water table and the effects of mounding (SWFWMD, 1998).

GEOLOGY - Bedrock should be at least three feet beneath the bottom of the infiltration area. In those parts of the country where limestone is at or near the land surface, special precautions must be taken when using infiltration practices. The potential for groundwater contamination in such areas is quite high, especially in "Karst Sensitive Areas" (KSA) where sinkhole formation is common. In KSAs, solution pipe sinkholes may form in the bottom of infiltration areas creating a direct conduit for stormwater pollutants to enter the groundwater. Solution pipes often open in the bottom of retention areas because the natural soil plug capping the solution pipe is thinned by partial excavation to create the retention area and because the stormwater creates a hydraulic pressure which can wash out the plug.

In KSAs, a site-specific hydrogeologic investigation should be undertaken that includes geologic borings wherever infiltration areas are proposed and mapping limerock outcroppings and sinkholes on site. Infiltration systems in KSAs should (1) include several small off-site areas, (2) use swale conveyances for pretreatment, (3) be as shallow as possible, (4) be vegetated with a permanent cover such as sodded grasses, and (5) have flat bottoms to keep the stormwater spread out across the entire area.

TOPOGRAPHY - Infiltration practices should not be located on areas with slopes over 20% to minimize the chance of downstream water seepage from the subgrade. Sloping sites often require extensive cut and fill operations. Infiltration practices should not be sited on fill material, since fill areas are very susceptible to slope failure, especially when the interface of the fill/natural soil becomes saturated.

VEGETATION - To reduce the potential for stormwater pollutants to enter groundwater, and to help maintain the soil's capacity to absorb water, infiltration practices should be vegetated with appropriate native vegetation, especially grasses. However, this type of vegetation cannot tolerate long-term inundation, so the retention area must be capable of infiltrating all of its runoff within a relatively short time period (i.e., 24 to 36 hours). The design of “bioretention” systems incorporates soils and vegetation that are proficient in trapping stormwater pollutants within them and takes advantage of microbial processes that help transform and trap pollutants in the terrestrial environment.

SET BACKS - Infiltration areas should be located at least 100 feet from any water supply well and at least 12 feet down-gradient from any building foundations. Additionally, they should be set back at least 50 feet from on-site wastewater systems, especially drain fields.

LAND USE RESTRICTIONS - Certain infiltration practices can only be applied to particular land uses. For example, some sites are so small or intensively developed that space is insufficient for surficial practices (e.g., retention basin), but they may allow for infiltration or exfiltration trenches if pretreatment can be provided. A concern with any infiltration practice is the potential for hazardous or toxic wastes to enter the system and migrate into the groundwater. Land uses where such substances are used should implement comprehensive pollution prevention, spill containment, and emergency response plans that will prevent dangerous materials from getting into the infiltration system.

POTENTIAL FOR GROUNDWATER POLLUTION - A possible concern about infiltration practices is whether they simply are transferring the stormwater pollution problem from surface waters to groundwaters. Stormwater pollutants, especially heavy metals, quickly bind to soil particles and vegetation is effective in filtering pollutants, thereby minimizing the risk of groundwater contamination (Harper, 1985; Yousef et al, 1985b). However, groundwater beneath swales, and retention areas located in highly sandy soils with low organic content, did show elevated levels of heavy metals down to depths of 20 feet (Harper, 1988).

Design Criteria

Once all of the above factors have been quantified using state, regional, or local data as appropriate, specific design criteria can be established. Table 2 summarizes the design criteria for infiltration systems set forth in Florida’s stormwater regulations. St. John’s River Water Management District (SJRWMD, 1992).

Table 2. Florida's Design Criteria for Infiltration Practices

BMP	80% Treatment Effectiveness Diversion Volume
Swales	Infiltrate 80% of the runoff from a 3-yr, 1-hr storm (2.5 inches)
Retention - Off-line	Infiltrate the larger of 0.5 inches of runoff or 1.25" X % impervious
Retention - On-line	Infiltrate an additional 0.5 inches of runoff
DESIGN FACTOR	CRITERIA
Soil type	HSG A or B with < 30% clay or < 40% silt/clay
Treatment volume recovery time	72 hours, 24 to 36 hours if grassed
Water table or bedrock	At least 3 feet beneath bottom after mounding
Topography	On slopes < 20%, not on fill soils
Vegetation	Recommended to reduce potential for groundwater pollution and to maintain soil permeability
Land use	May not be appropriate at sites where hazardous materials spills may occur

Swales: Traditionally, swales are used primarily for stormwater conveyance and, as such, are considered an on-line practice. The removal of stormwater pollutants by swales can occur by infiltration or vegetative filtration. Investigations in Florida (Yousef et al., 1985a; Harper, 1985) have concluded that swale treatment efficiency largely depends on the volume of stormwater that can be infiltrated through the filtering vegetation and into the soil.

Avellaneda (1985) developed the following equation for a triangular-shaped swale to estimate the length of swale necessary to infiltrate the design stormwater treatment volume:

$$L = \frac{KQ^{5/8}S^{3/16}}{n^{3/8}i}$$

where:

L = swale length (m)
Q = average runoff flow rate (m3/S)
S = longitudinal slope (m/m)
K = constant which is a function of side slope that varies from 4,722 to 10,516
n = Mannings roughness coefficient
i = infiltration rate (cm/hr)

For most residential, commercial, and highway projects, the length of swales necessary to percolate the stormwater needed to achieve the 80% performance standard was found to be excessive, or at least twice the distance available. Thus, some type of swale block (berm) or on-line detention/retention may be more helpful. Swales make excellent pretreatment practices by providing for the infiltration of some stormwater and for some vegetative filtration. By using a raised storm sewer inlet, swales can provide water quality enhancement via retention and still serve as effective conveyances for flood protection. Swales can incorporate retention by using swale blocks, small check dams, or elevated driveway culverts to create storage; thereby reducing runoff velocity, reducing erosion, and promoting infiltration. In highway designs for high speed situations, safety must be considered; thus, a maximum depth of water equal to 1.5 feet and flow line slopes on the berms of 1 vertical/20 horizontal are recommended. Along lower speed highways or in some residential/commercial urban settings, steeper flow line berm slopes (1 on 6) are acceptable (Wanielista et.al., 1986).

Unlike Florida, investigations in Washington State (Horner, 1988; WPCD, 1992) indicate that swales can also act as a biofilter, with removal of particulate pollutants without infiltration of stormwater. The following recommendations were made to improve their water quality benefits:

1. Maximum design velocity should not exceed 27 cm per second.

2. A hydraulic residence time of at least 9 minutes is recommended for removal of about 80% of the total suspended solids. Longer residence times will provide higher removal effectiveness.

3. Swale width should be limited to 6 to 8 feet, unless special measures are provided to assure a level swale bottom, uniform flow spreading, and management of flows to prevent formation of low-flow channels.

4. Swale slopes should be between 2 and 4%.

5. Water depth should be limited to no greater than one half the height of the grass, up to a maximum of 3 inches of water depth.

6. Swale length will be a function of the hydraulic residence time, swale width, and stormwater volume and velocity.

Implementation Components

Even if effective design criteria have been established for an infiltration system, the design has been reviewed and approved, and the institutional framework to assure performance has been established, an infiltration system may still not work correctly. In fact, assessments of the success or failure of infiltration systems have determined that poor construction is a major factor in system failure (Pensyl and Clement, 1987; Lindsey et al., 1991). We will discuss five considerations that are essential to proper implementation of infiltration practices including (1) education, (2) erosion and sediment control, (3) construction, (4) inspections, and (5) maintenance.

Education: The stormwater program needs to include an extensive education program that targets BMP designers, plan reviewers, inspectors, contractors, and maintenance personnel. Each of these practitioners is an important part of the stormwater team. They must each understand their role in BMP design and implementation, as well as the technical factors discussed above. Additionally, a communication mechanism needs to be established among all of these practitioners so that in-the-field knowledge of what works, and what does not work, is transferred back to all other team members. With respect to BMP installation, the plan reviewers and inspectors should meet with the project engineers and contractors on-site to review the site plan, construction sequencing, erosion and sediment control plan and details, and the infiltration system's detailed standards and specifications.

Erosion and sediment control: Infiltration practices must be protected from sediment loadings, especially during the project's construction phases. Infiltration practices should never be used as part of the erosion and sediment control system, nor should they be put into operation until all contributing drainage areas are fully stabilized. Although sediment loads drop sharply after construction is completed, gradual clogging of infiltration practices can still occur. Pre-treatment practices such as swale conveyances or vegetated buffer strips can help to filter out sediments and extend the life of retention practices. Do not forget the treatment train concept.

Construction considerations: To prevent clogging of infiltration areas, special precautions must be taken during the entire construction phase of a project to prevent reduction of the system's infiltration capacity. In particular, two areas need to be stressed, including preventing sedimentation during construction and preventing compaction of the soil. Areas that are selected for infiltration use should be well marked during site surveying and protected during construction. Specifical construction recommendations are as follows (WMI, 1997b):

1. If possible, schedule construction so it does not occur during the rainy season but does occur during the vegetation growing season. For example, in Auckland, New Zealand, construction sites are shut down during the winter when long, prolonged rains make erosion and sediment controls ineffective and when vegetation does not

   grow well. Unfortunately, in the United States, these seasons often overlap and the economics of development dictate the time frame for starting construction.

2. Before the development site is graded, areas planned for use as infiltration systems should be well marked during site surveying, and all traffic and heavy equipment kept away from the area to prevent compacting the underlying soils.

3. Construction should be overseen by someone who is trained and experienced in the installation of infiltration practices, and who is knowledgeable about their purpose and operation.

4. The design team should inspect the exposed soil after excavation to confirm that soil conditions are as expected and are suitable for the approved design. If they are not, work should not proceed and the situation should be analyzed to determine whether or not design or construction changes should be made to the approved design.

5. Construction of the infiltration system should not begin until after the site has been completely stabilized. If this is not possible, then:

   a. Diversion berms should be placed around the perimeter of the infiltration area during all phases of construction to divert runoff and sediment away from it.

   b. Sediment and erosion control plans for the site should be oriented to keep sediment and runoff completely away from the area.

   c. The facility should not be excavated to final grade until after the contributing drainage area is stablilized. Leave at least two feet of native soil during the initial excavation.

6. Infiltration areas should never be used as a temporary sediment basins during the construction phase. Unfortunately, it is common for infiltration areas, especially basins, to be used as a sediment trap, with initial excavation to within two feet of the final design elevation of the basin floor. If the facility is to be used during construction, this soil can be removed in layers as it clogs. Once construction is completed, sediment that accumulated during the construction phase can then be removed when the basin undergoes final excavation to its design elevation. However, recent experience indicates that even with this type of construction practice, infiltration areas used as sediment traps have a higher rate of failure.

7. Infiltration areas/basins should be excavated using light earth-moving equipment with tracks or over-sized tires. Normal rubber tires should be avoided since they compact the subsoil and reduce its infiltration capabilities. For the same reason, the use of bulldozers or front end loaders should be avoided.

8. During construction, place excavated material at least 10-15 feet away from the infiltration area.

9. Since some compaction of the underlying soils is still likely to occur during excavation, the floor of the basin should be deeply tilled with a rotary tiller or disc harrow at the end of the excavation process.

10. Rock used in infiltration or exfiltration trenches should be washed clean of sediments. Rock should be placed in lifts and compacted after each lift.

11. Trenches should be clear of any protruding objects and carefully inspected before installing geotextile fabrics. The fabrics should have the proper permeability and be installed with at least a 12-inch overlap, in a shingle-like manner

12. Trenches should be covered and not put into operation until the contributing drainage area is completely stabilized and all pretreatment BMPs installed.

13. Pervious asphalt and concrete should be installed only by certified personnel who are specifically trained in their batching, pouring, and finishing.

14. The basin should be stabilized with vegetation within a week after construction. Use of low maintenance, rapidly germinating native grasses are recommended. The condition of the newly established vegetation should be checked several times over the first two months, and any necessary remedial actions taken (e.g., reseeding, fertilization, and irrigation).

Inspections: Like all stormwater treatment practices, infiltration systems need to be inspected during construction and on a regular basis after construction. Inspections during construction are needed to assure that the infiltration system is built in accordance with the approved design and standards and specifications. Five inspections are recommended: (1) pre-construction, (2) during excavation, (3) during construction of the embankment (if applicable), (4) after final excavation, and (5) after construction is completed. During this final inspection, the inspector should have a copy of the "As-built or record drawings." In addition, infiltration systems should be inspected semi-annually after construction (before and after wet seasons) to ensure that they continue to function. Two site trips are recommended: one during or immediately after a rainfall, so that conditions during operation can be observed, and a second from 24 to 72 hours after the rainfall, to determine whether the system is recovering its storage volume as designed. Inspection forms are highly recommended. Examples of inspection forms (WMI, 1997b) can be downloaded from the EPA web site located at http://www.epa.gov/owow/NPS/orderform.html.

Maintenance: All infiltration practices will require regular and non-routine maintenance to maintain their ability to infiltrate stormwater. The frequency and need for maintenance will depend primarily on the loading of particulates and whether pre-treatment practices have been employed. Routine maintenance includes revegetating eroding areas, removing materials that accumulate in pretreatment BMPs, and removing materials from inlets and outlets. Non-routine, restorative maintenance activities should be conducted whenever inspections reveal that stormwater remains in the system beyond the designed time. These may include structural repairs to the inlets or outlets and restoration of the infiltration capability of the system.

Additional Concerns and Recommendations

Concerns with Pervious Pavement: Local land development codes typically specify the type of material for a parking lot (i.e., paved, grass, gravel) and determine the number and size of parking spaces within a parking lot. These requirements should be reviewed carefully to ensure that they are necessary (is paving really required in every case) and that the number of spaces is related to actual traffic demands. After these requirements have been reviewed and verified, the use of pervious pavement within a parking lot should be examined. Pervious pavement materials include pervious asphalt, pervious concrete, turf blocks, and even Geoweb covered with sod.

Overall, experiences with pervious pavements have not been very good. Pervious pavements have been prone to clogging. Causes include poor erosion and sediment control during construction, unstabilized drainage areas after construction, improper mixing and finishing of the pavement, and poor maintenance. However, field investigations of pervious concrete that has been in use for up to 15 years in Florida indicate that these parking lots can continue to infiltrate rainfall and runoff if they were installed and maintained properly (FCMA, undated). Pervious concrete not only helps reduce site imperviousness, but also reduces hydroplaning and road noise.

Recommendations: Specific recommendations and other important information about infiltration systems that will help increase their successful implementation are summarized in Table 3. This table includes essential information about the advantages, disadvantages, maintenance, and other aspects of successfully using infiltration practice. To improve evaluation of site conditions for the suitability of infiltration practices, Jacobson and Horner (1993) recommended a quan titative rating system. The factors used in the system included: (1) soil till layer (presence and location), (2) location of seasonal high water table, (3) removal efficiency of the pretreatment BMPs, (4) degree of siltation protection, (5) soil type, and (6) infiltration rate. Different degrees of acceptability are possible: (1) disqualifying (characteristics that eliminate design or location from further consideration), (2) passable (characteristics that allow consideration but not ideal), and (3) ideal (optimum characteristics for design or siting of facility). Table 4 illustrates the proposed rating system factors.

Table 3. Additional Information About Infiltration Systems to Enhance Successful Implementation

Infiltration Bmp Type	Advantages	Disadvantages	Maintenance	Comments
Surface Basin (Typically recessed areas or, in Mid-Atlantic States, rock filled)	•Integrate into land-scaping, open space, parking lot islands •Use for recreation •Easier inspection and maintenance	•Land area required •Potential mosquito problem if not designed or maintained properly	•Vegetated basins should be mowed and clippings removed •Remove sediments when dry and cracked •Non-vegetated basins require annual disking	•Can serve larger drainage 3:1 or flatter side slopes, flat bottom •Bottom and side slope vege-tation recommended
Infiltration Trench (Typically a rock filled trench)	•Can be used where land or space is limited	•Easily clogged •Difficult to unclog •Difficult to monitor performance	•Removing sediments that accumulate in rocks	•Pretreatment essential •Use observation well •Keep covered until drainage area stabilized
Exfiltration Trench (Typically a perforated pipe with a gravel envelope)	•Can be used where land or space is limited	•Easily clogged •Difficult to unclog •Difficult to monitor performance	•Remove materials that enter pipe •High pressure wash perforated pipe •Removing sediments that Accumulate in rocks, replace rocks	•Pretreatment essential •Source controls useful •Geotextile is limiting infiltra-tion factor •Inf. rate 0.5"/hr if use sides and bottom •Inf. rate 1"/hr if use bottom
Pervious Pavement	•Reduces impervious-ness •Reduces hydroplaning and highway noise •Higher recharge rates	•Easily clogged •Lack of trained practitioners •Anaerobic conditions may develop in soils	•Regular vacuum street sweeping •High pressure cleaning •Drilling holes to restore infiltration •Replacement	•Proper batching and place-ment is crucial •Education programs needed for practitioners •Post signs to inform users and keep dir and mud out
Swale (Typically a shallow, grassed conveyance system)	•Can be incorporated into site ‘s landscaping/ open areas •Great car in BMP Train •Aesthetically pleasing	•Not for flood control •May “disappear” from residential back yards •May become depository for trash, yard wastes	•Mow and remove grass clippings •Hydroscope accumulated sediments and resod •Repair erosion areas	•Wet swales (wetland plants) work great too •Use swale blocks, raised driveway culverts to retain runoff

Table 4. Possible Rating System to Evaluate the Suitability of Infiltration BMPs

Factor	Disqualifying Characteristic	Passable Characteristic	Ideal Characteristic
Soil till layer	Impenetrable, thick layer near surface	Layer present but at >5' depth, or easily penetrable	No till layer present
Seasonal High Water Table	Close to surface, within 5'	At intermediate depth, at least 5' below BMP bottom	Very deep, well below BMP bottom
Pretreatment	None provided	Some,minimum 50% TSS removal	Pretreatment provides >80% TSS removal
Siltation Protection	None provided	Any silt or construction sediment removed before final BMP construction	Fully protected from silt during construction
Soils	Saturated or with >30% clay or >40% silt/clay content	Coarse, highly infiltrative soil that can be modified to produce proper inf. rate	Loam or loamy sand
Infiltration Rate	<0.5"/hr	>2.5"/hr but with very deep water table or modified to slower rate	0.5 to 2.5"/hr

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