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MANAGEMENT FACILITIES FOR CONTROL OF URBAN RUNOFF BY INFILTRATION

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NWRI Contribution No. 98-044

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Management Perspective

Concerns about urban non-point sources of pollution led to the development of stormwater best management practices (BMPs), which serve to mitigate the impacts of urban developments on the hydrological cycle, including receiving waters. Stormwater infiltration practices represent a unique class of BMPs, which reduce runoff from urban areas by infiltrating it into the ground at special facilities. A review of such facilities is presented, with emphasis on their purpose, feasibility, design, and environmental benefits and impacts. Well-designed and maintained infiltration facilities can be used to infiltrate clean or pretreated runoff from urban areas and produce such benefits as enhanced groundwater recharge and baseflows in small streams, and reduced runoff volumes, peaks and pollution loads.

This report represents an invited paper which presented at the UNESCO and IWRA sponsored International Workshop on Non-Structural Flood Control in Urban Areas, Sao Paulo, Brazil, April 20-22, 1998. It should be of interest to water managers dealing with stormwater management in urban areas.

Sommaire à l'intention de la direction

Les inquiétudes suscitées par les sources de pollution urbaines non localisées ont suscité l'élaboration de meilleures pratiques de gestion des eaux pluviales, dont le but est d'atténuer les répercussions des aménagements urbains sur le cycle hydrologique, et notamment les eaux réceptrices. Les techniques d'infiltration des eaux pluviales constituent une catégorie à part des meilleures pratiques de gestion, en ce sens qu'elles permettent de réduire les eaux de ruissellement des régions urbaines en les faisant pénétrer dans le sol dans des installations spéciales. Les auteurs passent en revue ces installations, en insistant sur leur but, leur faisabilité, leur conception, leurs avantages pour l'environnement et leur incidence environnementale. On peut utiliser des installations d'infiltration bien conçues et bien entretenues pour injecter les eaux de ruissellement propres ou préalablement traitées en provenance des zones urbaines et obtenir divers avantages, par exemple une meilleure alimentation de la nappe souterraine et des débits de base dans les petits cours d'eau et une réduction des volumes d'eaux de ruissellement, des pointes et des charges polluantes.

Le rapport est le texte d'une communication sollicitée qui a été présentée à l'*International Workshop on Non-Structural Flood Control in Urban Areas* parrainé par l'UNESCO et l'Association internationale des ressources en eau (AIRE) à Sao Paulo, au Brésil, du 20 au 22 avril 1998. Il devrait intéresser les personnes responsables de la gestion des eaux pluviales dans les régions urbaines.

Abstract

Urbanization reduces infiltration of rainwater into the ground, and thereby increases the generation of surface runoff. Such processes can be reversed by infiltrating runoff into the ground at special infiltration facilities. Various types of such facilities are reviewed, with emphasis on their purpose, feasibility, design, and environmental benefits as well as impacts. Well-designed infiltration facilities can be used to infiltrate relatively clean or pretreated runoff from urban areas and produce such benefits as enhanced groundwater recharge and baseflows in small streams, and reduced runoff volumes, peaks and pollution loads. For larger areas or in cold climate, infiltration facilities should be combined with storage facilities for runoff detention. The main concerns in the design and implementation of infiltration facilities are their operating life and the prevention of contamination of groundwater and soils.

Résumé

En réduisant l'infiltration des eaux pluviales dans le sol, l'urbanisation augmente le ruissellement en surface. Il est possible d'inverser ces phénomènes en injectant les eaux de ruissellement dans le sol dans des installations spéciales. Les auteurs passent en revue différents types d'installations de ce genre, en s'attachant à leur but, à leur faisabilité, à leur conception et à leurs avantages écologiques, ainsi qu'à leur effet sur l'environnement. On peut utiliser des installations d'infiltration bien conçues et bien entretenues pour injecter les eaux de ruissellement assez propres ou préalablement traitées en provenance des zones urbaines et obtenir divers avantages, par exemple une meilleure alimentation de la nappe souterraine et une amélioration des débits de base dans les petits cours d'eau et une réduction des volumes d'eaux de ruissellement, des pointes et des charges polluantes. En ce qui concerne les secteurs plus étendus ou les climats froids, il y aurait lieu de combiner les installations d'infiltration à des installations de stockage des eaux de ruissellement. Les principaux problèmes que posent la conception et la mise en œuvre des installations d'infiltration sont leur vie utile et la prévention de la contamination des eaux souterraines et des sols.

Introduction

Continuing migration of population from rural to urban areas results in fast urbanization in most regions of the world. In this process, the natural environment and its water cycle are dramatically modified. Changes include increased volumes and peak flows of surface runoff (causing increased incidence of floods or water ponding in urban areas), increased discharges of pollutants and thermal energy into receiving waters, and reduced baseflows and groundwater recharge (Geiger et al., 1987). All of these adverse impacts are closely connected with the operation of urban drainage systems that provide for conveyance and disposal of surface runoff by open drains, storm sewers or combined sewer overflows. In the traditional approach to drainage, typical for municipal practice in most countries till the 1960's and still prevailing in some regions, the emphasis was placed on providing hydraulically efficient drainage of urban areas, without much concern for the impacts on receiving waters and downstream areas (Marsalek, 1998).

A considerable change in this attitude towards urban runoff has occurred during the last 30 years, with the advent of stormwater management. Advances in the understanding of urban runoff processes indicate that the cumulative impacts of increased flows, erosion and discharges of pollutants have led to severe degradation of many urban waters. Consequently, the needs for urban stormwater control have been promulgated in government policies, and a wide range of stormwater management practices have been developed in support of such policies (U.S. EPA, 1993).

Stormwater management practices attempt to reverse the impacts caused by urbanization, through application of non-structural, semi-structural and structural control measures, which may be also classified, depending on their physical setting, as source controls, collection system controls, and storage and treatment measures. More recently, another term was introduced – best management practices (BMPs). Most common BMPs include lot-level measures, grass filters and swales, infiltration facilities, porous pavement, water quality inlets, oil/grit separators, filters, stormwater management ponds, and constructed wetlands (Azzout et al., 1994; Geiger and Dreiseitl, 1995; MOEE, 1994; Schueler, 1987).

The selection of appropriate BMPs widely varies, because each urban setting is unique in terms of sources and characteristics of stormwater, the existing infrastructure, the receiving waters (type, quality, beneficial water uses), and the regulatory environment. Consequently, solutions to stormwater problems are also unique and should be designed to fit the local conditions. For this purpose, several BMPs can be combined to provide the desired control of runoff flows and removal of various pollutants (Schueler, 1987).

The selection of the design return period for BMPs is a compromise between the costs of protection and the costs of damages, and reflects an acceptable level of risk. In typical applications, BMPs provide the best performance for relatively common storms (return periods $\leq$ 2 yrs), but must be designed to convey much larger events (up to 100 yrs) with an acceptable peak flow control, but greatly reduced water quality benefits (Schueler, 1987). Finally, it should be emphasized that BMP performance has been so far documented mostly in temperate climate, and further testing in other climates is needed.

The purpose of this paper is to examine urban runoff control by infiltration and the potential of this approach for mitigating floods generated in urban areas. The topics discussed include the purpose and types of infiltration facilities, design procedures, environmental impacts, and conclusions.

Purpose of Stormwater Infiltration Facilities

Stormwater infiltration facilities have been in use for a very long time, with some of the early structures tracing back to antiquity (Geiger and Dreiseitl, 1995). They have been used opportunistically for groundwater recharge. Only during the last 10 years or so have the design and use of infiltration facilities been approached systematically with the objective of meeting the following specific goals of stormwater management (Mikkelsen et al., 1996):

(a) Reduce the volume and rate of surface runoff, and thereby the risk of on-site and downstream flooding

(b) Reduce the export of pollutants from urban areas by reducing pollutant mobilization and hydraulic transport.

(c) Recharge groundwater aquifers, while preserving their quality.

Reduction of runoff volume is achieved by infiltrating some fraction of the total stormwater volume into the ground. Furthermore, infiltration facilities contribute to runoff detention (e.g., by increased hydraulic losses and temporary storage), and thereby reduce the speed of runoff. Reduced runoff volume and speed then contribute to lower runoff flow rates along the entire stormwater transport route from the point of runoff generation to the receiving waters. However, as discussed later, only certain types of infiltration structures have sufficiently large capacities to provide effective runoff peak reductions for infrequent storms (Schueler, 1987).

Reduction of stormwater pollution by rainwater infiltration is a significant environmental benefit. Recognizing that entry of many pollutants into stormwater requires energy to mobilize (e.g., by erosion) or transport them hydraulically, and a medium for their transport (i.e., water transporting dissolved, suspended and bed loads), pollutant transport and export is significantly reduced by reducing the mass and energy of the transport medium.

Finally, with respect to sustainable development, unpolluted stormwater is a valuable resource which can be reused for recreational amenities, the creation of habitat, water supply, and groundwater recharge. The last two water uses are facilitated by stormwater infiltration, provided that the water quality of the groundwater is preserved. This imposes constraints on groundwater recharge by unpolluted stormwater, which either originated in clean urban areas, or was effectively pretreated.

Types of Stormwater Infiltration Facilities (SIFs)

A general classification of stormwater infiltration facilities is shown in Fig.1 and encompasses SIFs with small-to-intermediate detention as well as those with large detention storage. The former ones are designed either with full exfiltration of stored stormwater into the ground, or with partial exfiltration and return of some flow to surface runoff. Individual measures are described below.

Stormwater infiltration facilities with small-to-intermediate detention storage

SIFs with limited detention storage capture runoff volumes generated by storms with return periods of up to 10 years. Such SIFs effectively control runoff peaks for storms with shorter return periods, but are ineffective for rare flood producing storms. These facilities can be designed with full exfiltration of stored water into the ground, or with partial exfiltration and return of some flow to surface runoff.

SIFs with full exfiltration

These facilities drain the infiltrated stormwater fully into the underlying soils. The emptying of these SIFs has to be completed within some limited time period, usually in the range from 24 to 48 h, which represents the inter-event time between two consecutive storms of the design-level magnitude. Four types of these facilities are listed in Fig. 1, and they differ mostly by the size and geometry of the surface through which exfiltration takes place.

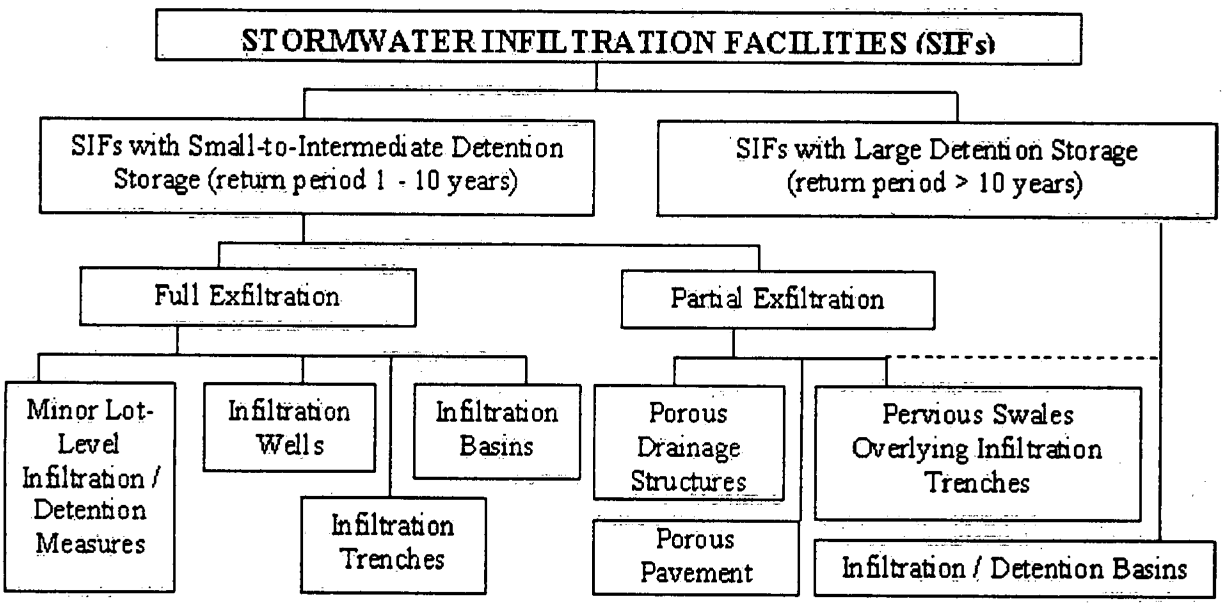

Figure 1. Classification of Stormwater Infiltration Facilities

Minor lot-level infiltration/detention represents small measures implemented at the lot-level, including reduced lot grading to slow down runoff and enhance infiltration on pervious areas, and redirecting roof leader discharges to pervious areas or soakaway pits (MOEE, 1994). While these measures contribute to the overall goal of stormwater management, their contribution to stormwater management at the catchment level is hard to assess and sustain. To reduce catchment runoff, these measures would have to be implemented and maintained throughout the catchment. Such goals are hard to achieve, because lot-level measures are generally implemented on a voluntary basis and their effectiveness in flow control can be dramatically reduced either through neglect of wilful interference.

Infiltration wells are small structures serving for exfiltration of runoff from one to several residential lots. The typical diameter of cylindrical wells is about 1 m and their depth depends on local hydrogeology, including the depth of groundwater table, permeability of individual layers, and the depth of bedrock. These wells can be used to penetrate low permeability layers and facilitate stormwater exfiltration into deep gravel deposits with high permeability (Mikkelsen et al., 1996). To achieve the required exfiltration capacity, a series of infiltration wells may have to be used. The design of these structures is similar to that for trenches, described later. The exfiltration area is the cylindrical well surface; the bottom area is neglected, because it will silt up.

Infiltration trenches are the most common SIFs currently in use. They are used in two versions, either as surface trenches (the top of the trench is exposed to open air) or as subsurface trenches located at some depth below the ground surface. The latter type is better protected against illicit discharge/disposal of wastewater into the trench or freezing temperatures.

A typical infiltration trench is shown in Fig. 2 and consists of a prismatic body of granular material enclosed in non-woven filter fabric, with several additional components, a (perforated) feed pipe, an observation well, and an optional sand filter on the bottom. Infiltration trenches are generally recommended for stormwater disposal from small areas (< 2 ha), with residential or comparable land use (low risk of toxic spills), native soils with fair hydraulic conductivity ($K > 4.2 \times 10^{-6}$ $m \cdot s^{-1}$), areas with water table and bedrock at least 1 m below the trench bottom, and locations with safe distances (> 10 m) from foundations and septic beds (MOEE, 1994).

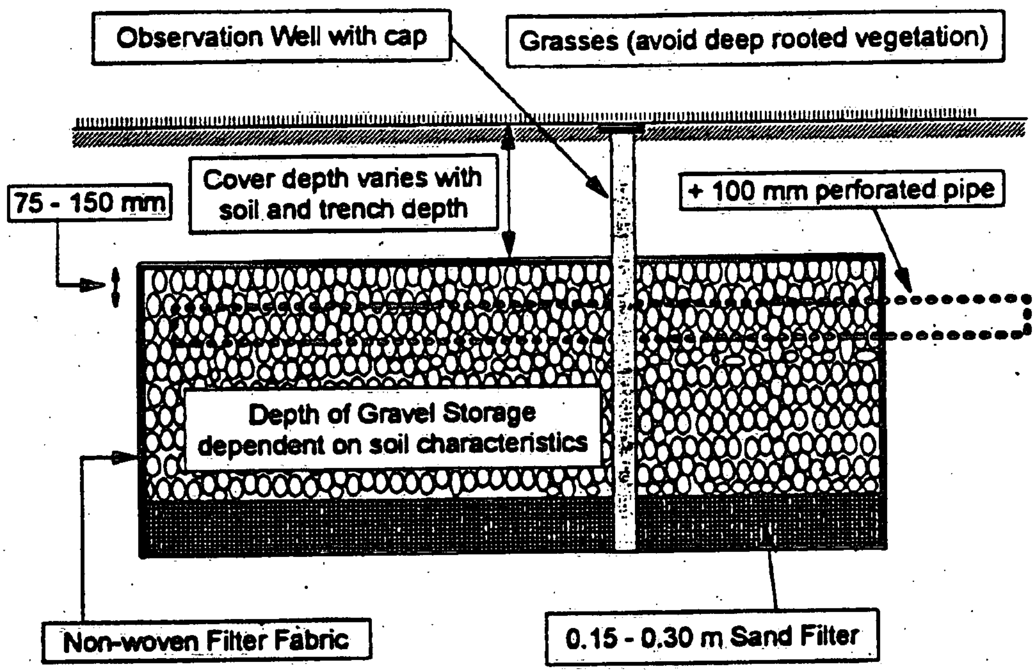

Figure 2. Subsurface Infiltration Trench (after MOEE, 1994)

Storage media should be clean stone (D ≈ 50 mm), wrapped in non-woven filter fabric, preventing migration of soil into the filter. Optionally, a sand filter or sand/peat filter layer is placed on the trench bottom, to enhance stormwater treatment. Addition of peat may help increase the sorption capacity of the filter.

Additional features of infiltration trenches include a proper water feed/drain system. The feed is provided by a perforated pipe (D ≈ 100 mm), located some 100 to 200 mm below the trench surface. Where feasible, a drainpipe is located close to the trench bottom and equipped with a valve. When necessary, the trench can be quickly drained through this arrangement. An overflow or bypass upstream from the trench allows to bypass excessive or polluted flows, particularly during the construction period.

Infiltration basins are built as shallow depressions which control stormwater runoff by storage and infiltration. These basins are often designed in conjunction with stormwater ponds, which provide the storage function. Infiltration basins are more prone to failure than other SIFs, because their bottom will become covered with fine deposits settled from stored stormwater and the permeability of the basin bottom will be reduced.

Infiltration basins are recommended for drainage areas up to 5 ha and soils with hydraulic conductivity greater than 1.7×10^{-5} $m \cdot s^{-1}$. Their shape and configuration are typically given by the terrain, but elongated shapes with the length to width ratio greater than 3:1, and an upstream flow spreader are recommended. The permeability of basin's bottom can be restored by suitable vegetation and proper maintenance (MOEE, 1994).

Other design features include overflow/bypass structures upstream of the basin, which serve several purposes: (a) for site protection during construction (flows with high solids concentrations are bypassed), (b) for potential protection during spills, and (c) as a safety outlet in cold weather, when soil infiltration capacity is seriously impeded (Oberts, 1994). Infiltration basins are planted with suitable vegetation, which should withstand temporary inundation and enhance porosity of the underlying soils. The fencing of these facilities is discouraged, except during construction. Once fully operational, explanatory signs around the facility should be sufficient and contribute to general awareness of stormwater management and support public education. The facility performance can be enhanced by subsurface drains which accelerate the dewatering of the basin (MOEE, 1994).

SIFs with partial exfiltration

Numerous structures were proposed for transport and enhanced exfiltration of collected stormwater. The terminology for these structures is not well established, and such adjectives as porous, permeable, perforated, and pervious are used interchangeably. Pratt (1997) attempted to clarify terminology in this field by defining porous pavements as those which allow water infiltration through pores across the total pavement surface area, and permeable pavements are those with inlets (openings) for water entry. SIFs with partial exfiltration include porous/permeable pavements, permeable drainage structures and drainage swales overlying infiltration trenches.

Porous/permeable pavements are perhaps the best researched and understood measures in this category and international experience with such pavements was recently summarized by Pratt (1997). Porous pavements are similar to conventional asphalt pavements, but by selection of suitable aggregate sizes, high infiltration of stormwater is achieved. Properly designed, installed and maintained porous pavement has similar load bearing strength and longevity as conventional pavements, but much lower rates of runoff; runoff peak flow and volume reductions of up to 80 % were reported. Permeable pavements (e.g., grass concrete tiles/blocks) perform in a similar way. Extensive research of permeable pavements also indicated other advantages – enhanced quality of stormwater percolating through the pavement and its stone storage reservoir, lower surface temperature and runoff heating in the summer, and heat storage in low or freezing temperatures (Pratt, 1997).

Typical porous/permeable pavement structures include the top water transmitting layer, filter layer, stone filled reservoir, lower filter course and a filter fabric preventing exchange of materials between the pavement and the underlying soil. In some cases, a drainage pipe is inserted into the stone reservoir and serves for dewatering the structure. The drainage effluent can be monitored with respect to water quality and where needed, further treated, or directly reused for water supply (in one case in the U.K., for flushing toilets; Pratt, 1997). Perhaps one of the best applications of these pavements is for commercial parking lots, as reported in France (Raimbault, 1997). In this case, 87 % of all rainwater was infiltrated and the quality of exfiltrated stormwater was improved by removing up to 60–80 % of some heavy metals (Pb, Zn and Cd). Porous/permeable pavements have been used widely in Tokyo, where more than 50 km^2 of such pavements exist (Fujita and Koyama, 1990).

Typical porous/permeable pavements possess very high hydraulic conductivities (up to 0.01 $m \cdot s^{-1}$) when new (Pratt, 1997). The main problem of these facilities is to sustain their satisfactory operation over extended time periods. This is achieved by proper design (e.g., in locations without high influx of sediment or plant debris, preventing compaction of deposits in inlets through surface) and proper maintenance. Porous pavements are maintained by frequent vacuum/jetting of surface to remove loose deposits and clear pores, and permeable pavements require regular stiff brushing and removal of loose deposits.

Permeable drainage structures have been incorporated in sewer systems in many jurisdictions. These structures have been typically built of permeable (perforated) concrete and include curbs and gutters, sewer inlets, manholes, and sewer pipes (Fujita and Koyama, 1990). These structures are generally viewed as management measures, which improve the performance of the overall system by reducing the quantity of transported stormwater. They are not subject to rigorous sizing/design procedures, but are designed on the basis of experience from other projects. While the effectiveness of individual structures in runoff exfiltration may be limited, a combination of many such components results in significant runoff reductions. As for practically all infiltration measures, these structures require good protection against influx of inorganic and organic debris, and regular maintenance by removal of materials blocking water passages (sediment, leaves).

The most extensive and systematic use of permeable drainage structures was achieved in the Experimental Sewer System installed in Tokyo during the last 10 to 15 years. This system comprises porous/permeable pavements, and hundreds of thousands of permeable stormwater inlets, manholes, and sewer pipes.

Pervious swales overlying infiltration trenches store, transport and treat stormwater, and enhance its infiltration into the ground in two stages, first from the swale into the underlying soil, draining into an infiltration trench, and partial exfiltration from the trench into surrounding soils. Grassed swales have been traditionally used to control stormwater quantity and quality by reducing runoff velocity (i.e., extending the catchment concentration times) and facilitating runoff infiltration into the ground. This concept has been further developed in Germany by placing an infiltration trench underneath these swales, and enhancing stormwater exfiltration from the swale into the trench, which is drained by a drainage pipe with a throttled outlet (Uhl and Harms, 1996). Runoff percolation through the active root layer of the swale bottom provides treatment by filtration and biological uptake of pollutants. Percolating stormwater is then further treated in the infiltration trench, and allowed to exfiltrate into surrounding soils. In soils with low hydraulic conductivity ($K < 10^{-6}$ $m \cdot s^{-1}$), the trench is drained by a small pipe ($d = 150$ mm) fitted with an orifice restricting the outflow discharge.

Grassed swales are built with low longitudinal slopes, and mild side slopes for easy maintenance. Where needed, runoff detention and retention is increased by permeable check dams placed across the swales at certain intervals. The German infiltration system presented above was used successfully in urban redevelopment and in small in-fill construction in the existing areas requiring high level of control of surface runoff (Uhl and Harms, 1996).

Stormwater Infiltration Facilities with Large Detention Storage

The infiltration measures discussed in the preceding sections were characterized by limited detention storage and low runoff control once their exfiltration capacity has diminished. To overcome these problems, particularly in connection with infiltration basins, modified designs with large detention storage were developed. A brief description of such facilities follows.

Infiltration/Detention basins

Infiltration basins pose a number of practical problems, including accumulation of solids and clogging of exfiltration beds, risk of solids washout, and the need to provide a back-up drainage system when the infiltration capacity is impaired, either by clogging of soil pores or winter freeze up. Most of these problems can be mitigated in a combined infiltration/detention basin design, which is shown in Fig. 3.

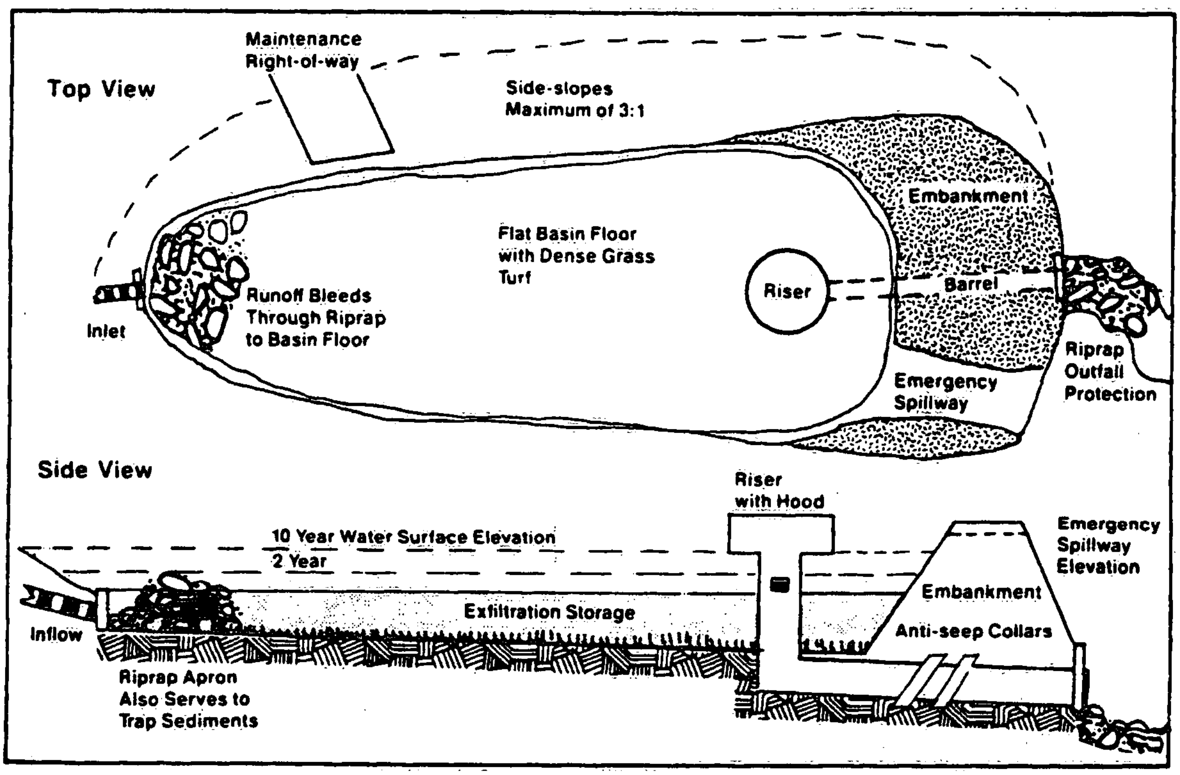

Figure 3. Infiltration/Detention Basin Design (after Schueler, 1987)

In this design, stormwater is first pretreated in a small sedimentation forebay and then spread over the basin area. The depth in the basin is controlled by a vertical riser, with a 2-year control orifice placed up to 1 m above the basin floor and creating dead exfiltration storage. This storage volume will be completely exfiltrated, or evaporated. The stormwater volume in excess of exfiltration storage drains through the low flow orifice, while larger event volumes (corresponding to 10 – 100 yr storms) are routed through the basin and discharged through the riser overflow or the emergency spillway, in the case of rare events. In soils with a marginal infiltration capacity, it is advisable to provide drainage of the basin underlying soils by perforated drainage pipes, which may be capped or opened up when needed.

Depending on hydrological conditions, these infiltration/detention facilities can be designed to provide flow control at practically any feasible flow level; with increasing return periods, the contribution of exfiltration to flow control will be reduced and the facility will work more or less as a detention basin.

Infiltration Design Considerations

With respect to stormwater infiltration design, much of the earlier work in this area has been done in support of the general stormwater management goals, but without striving for a specific performance. Only the recent contributions focused on developing systematic design guidelines (Mikkelsen and Jacobsen, 1996). Recognizing that soil permeability widely varies in time and space, all infiltration design procedures are rather approximate and should include safety factors for ensuring the required performance.

The first design task is to select a design rainfall event. This choice depends on the general design objective with respect to runoff quantity or quality control. In quality controls, the total stormwater volume captured and treated over an extended time period is of primary importance. Thus, it is adequate to store and infiltrate some selected water quality control volume (e.g., the first 12 mm of runoff) for all storms. For controlling runoff quantity, a different approach is used and requires capture of the whole runoff volume from a design event.

In the past, the quantity control volume was determined for combinations of rainfall intensities and durations. A more realistic approach was proposed by Mikkelsen and Jacobsen (1996), who used simulations of infiltration for a historical rainfall series and various drawdown times to develop charts of infiltration depths as a function of the drawdown time, for return periods ranging from 0.2 to 10 yrs. For Danish conditions, with typical drawdown times of 48 h and return periods ranging from 1 to 10 yrs, the infiltration depths (volumes) ranged from 20 to 50 mm over the catchment area.

The hydraulics of infiltration facilities can be described by a storage equation, in the form

$$I - O = \Delta S \qquad (1)$$

where I = stormwater inflow, O = outflow (exfiltration), and ΔS is change in storage. This approach would require routing various inflows through the infiltration facility and thereby determining the maximum volume required. In view of large uncertainties involved, a simplified, steady state calculation, with a constant exfiltration flow, is normally adopted in practice, as demonstrated below for infiltration trenches and basins.

In infiltration trench design, the trench volume, V_{it}, is set equal to the stormwater volume to be stored (V_{st}), which is either given by local stormwater management criteria (MOEE, 1994), or derived by the designer as the volume of runoff from a design or historical storm of selected frequency of occurrence (Mikkelsen et al., 1996). Using the simplified approach introduced by Jonasson (1984), two design equations can be written for trench geometric parameters:

$$V_{it} = V_{st} = n\ w\ h\ L \qquad (2)$$

$$t_e = (w\ n) / K \leq 24 - 48\ h \qquad (3)$$

where n is the trench medium porosity, the trench dimensions (width x height x length) are w, h and L, respectively, t_e is the maximum trench drawdown time (generally specified from 24 to 48 h) needed to drain the facility before next event arrives and to maintain aerobic conditions favouring pollutant removal by bacteria, and K is the hydraulic conductivity of the surrounding soils, which is either measured at the site, or derived from the literature (e.g., $K_{sand} = 6 \times 10^{-5}\ m \cdot s^{-1}$, $K_{loam} = 4.2 \times 10^{-6}\ m \cdot s^{-1}$). For practical reasons, trench height is limited to 0.9 to 2.5 m, and Eq. (2) imposes a limit on trench width, w.

Using the same approach and notation as for infiltration trenches, the bottom area A_{ib} of an infiltration basin can be determined as

$$A = V_{st} / (K\ t_e) \qquad (4)$$

where depth $d = K\ t_e$ should not exceed 0.6 m to minimize soil compaction (MOEE, 1994).

Some large sources of uncertainty remain: safe estimates of soil permeability and the operating life of infiltration structures. Soil permeability is either measured at the project site, or adopted from the literature. Field measurements are preferred and are often corrected by a safety factor increasing the design safety. Careful excavation of infiltration facilities is required, particularly the prevention of smearing soil surfaces which reduces the soil hydraulic conductivity.

Some authorities discourage the use of infiltration measures in soils with the hydraulic conductivity of less than $2 \times 10^{-5}\ m \cdot s^{-1}$. However, there are no physical reasons for this limit – it just follows from considerations of economic efficiency (Mikkelsen et al., 1996). At low soil permeabilities, infiltration facilities may become too large and therefore economically unfeasible. In SIFs with partial exfiltration and return flow, the minimum infiltration rate becomes less important, because the facilities can be dewatered by gravity into surface waters, after runoff subsides.

Recognizing the high variability of rainfall characteristics, stormwater pollution including suspended solids, and soil infiltration parameters, it is hardly surprising that the design of infiltration facilities suffers from many uncertainties. This becomes particularly obvious when estimating the operating life of these facilities. There are facilities which have operated well for over 50–100 yrs, but others become inoperable in only a few years (Schueler, 1987). The operating life of well-maintained porous/permeable pavements may be from 10 to 30 yrs (Pratt, 1997). It is difficult to develop similar estimates for other structures, because the older facilities are often poorly documented. The most common reasons for infiltration failure is hydraulic overloading with groundwater "mounding" around the facility, the blockage of storage medium by fine sediments, and root intrusions causing damage.

Well-designed infiltration facilities are effective in reducing runoff volumes, providing groundwater recharge, preventing stream-bank erosion, and controlling runoff peaks for events with return periods up to 10 yrs. For longer return periods, peak flow control can be achieved only in combination with detention in on-line or off-line facilities. Infiltration facilities also provide good pollution control, depending on the volume of runoff infiltrated. For most effective designs, all runoff from events up to a 2-year design storm should be infiltrated. Other benefits include the maintenance of low flows, some degree of stream-bank erosion control, prevention of thermal enhancement of receiving waters, and wide acceptance by local residents.

Feasibility Issues

The selection of stormwater management measures for a particular site is governed by a number of criteria, including performance, feasibility and cost-effectiveness. Among these factors, the feasibility is the most important, because suitable SIFs perform well in controlling runoff and are relatively inexpensive to construct and maintain. Thus, the discussion in this section focuses on SIF feasibility, including the site feasibility and prevention of environmental impacts.

Site Feasibility

The site feasibility is assessed with respect to the area served, soils, and minimum distances from certain structures or the groundwater table. SIFs are generally best applied in small areas, less than 2 ha in the case of infiltration trenches, swales and porous pavement, and perhaps up to 10 ha in the case of infiltration basins (MOEE, 1994). Larger areas require infiltration/detention basins or multiple facilities. Thus, SIFs are spatially distributed throughout urban areas. With respect to land use, areas with risks of chemical spills (i.e., industrial land) and groundwater contamination are not suitable for stormwater infiltration. Similarly, areas with high production of suspended solids are not acceptable because such solids would clog infiltration structures. SIFs are best applied in flat terrain; infiltration trenches become unfeasible on slopes > 2%, and porous pavement or swale slopes should not exceed 5%. With respect to soils, SIFs are feasible in highly permeable sands, loamy sands, sandy loams, and even loams with a minimum infiltration rate of $3x10^{-6}$ $m \cdot s^{-1}$ (Schueler, 1987).

The bottom of infiltration facilities should be at least 1.2 m above the seasonally high water table and 0.6 to 1.2 m above the bedrock. Finally, SIFs must be located at least 10 m from building foundations and 30 m from groundwater sources of drinking water. The former condition makes SIFs unfeasible at fully developed sites.

Prevention of Environmental Impacts

Stormwater infiltration into groundwater is acceptable only when the groundwater quality can be protected and excessive soil contamination is avoided. Thus, it is of interest to examine such impacts first and then discuss the means of prevention.

The impacts of stormwater infiltration on groundwater quality are relatively recent concerns in stormwater management and impede a more widespread use of infiltration. Such impacts depend on stormwater quality and its changes during stormwater transport through the infiltration facilities and the receiving soil.

<u>Observed infiltrated stormwater impacts</u> – Mikkelsen et al. (1996) reviewed some recent studies addressing infiltration impacts on groundwater quality and soil contamination. The findings of these studies should be approached cautiously in view of relatively short duration of these studies and the fact that future leaching of pollutants from the soil phase cannot be discounted. Within these

limitations, the list of pollutants posing risk to groundwater includes highly soluble compounds (road salt), heavy metals, hydrocarbons including polycyclic aromatic hydrocarbons (PAHs), simple aromatic compounds, polychlorinated biphenyls (PCBs), volatile chlorinated hydrocarbons, pesticides, and pathogens (Pitt et al., 1994). So far, soluble pollutants like chlorides have been barely addressed, but can be expected to readily enter groundwater aquifers. Hydrophobic pollutants are generally immobilized in a relatively thin soil layer next to the infiltration facility (Mikkelsen et al., 1996).

The findings about soil contamination by infiltrated stormwater indicate large uncertainties in such assessments. Computer simulations were used to estimate the period of stormwater infiltration required to exceed the established soil quality criteria and produced such estimates in the range from 10 to several hundred years (Mikkelsen et al., 1996). It should also be noted that such periods could be significantly extended with further advances in pollutant source controls.

Stormwater quality – with respect to stormwater quality, four sources can be recognized: (a) roof areas, (b) residential and public amenity land, (c) industrial land, and (d) roads and parking lots. Roof runoff, particularly in residential areas, is relatively uncontaminated, except for some metals from roofing materials in locations with acid rain.

The quality of runoff from residential and public amenity land is variable; besides common constituents found in rain or wet and dry deposition, traffic byproducts and household and garden chemicals can be found in such runoff. By proper source control, these sources of pollution can be controlled. The quality of industrial runoff depends on the type of industry, but it can be polluted, certainly in areas with petrochemical industry or steel production and heavy manufacturing. Finally, highway and parking lot runoff is significantly contaminated by hydrocarbons (including PAHs) and heavy metals (Marsalek et al., 1997). Thus, among these stormwater sources, only the first two are acceptable for infiltration, without much pretreatment (Mikkelsen et al., 1996).

The chemical assessment of stormwater suitability for infiltration is difficult in the absence of appropriate standards. The use of drinking water standards or soil quality standards (usually developed for agricultural soils) is obviously inappropriate, but alternative approaches are missing.

Transport and fate processes – stormwater chemistry changes during transport and these changes generally contribute to enhancement of stormwater quality. The most important transport and fate processes in soils include hydraulic transport (convection and dispersion), filtration, sorption, degradation, and volatilization. Sorption dominates the processes in the case of dissolved pollutants, such as trace organic contaminants and metals. Organic compounds are readily absorbed to the organic matter; other sorbents and soil properties are less important. Sorption properties of heavy metals vary, with common binding to organic matter, metal oxides and clay, and their mobility depends on pH, redox, and ionic exchanges.

With respect to fate processes, trace organics may be degraded chemically or microbiologically, but some degradation byproducts may be toxic. Soil parameters, such as temperature, pH, moisture, and supply of nutrients and air (oxygen), affect the compound stability and micro-organism activities and thereby the compound degradation. Finally, contaminants adsorbed to particles are removed by filtration. Indeed, it has been observed that solids caught in filtration devices are significantly polluted, often to the levels several times higher than in stormwater entering the facility.

Stormwater pretreatment – the quality of inflow to SIFs can be controlled in two ways, either by accepting only relatively clean stormwater (as discussed earlier), or by improving the stormwater quality by pretreatment. Several processes have been applied in pretreatment of stormwater entering SIFs. For this purpose, the emphasis is placed on simple methods with low demands on technology and maintenance. Such conditions can be met e.g., by oil and grit separators and vegetation filter strips (length > 15 m) or grassy swales (Schueler, 1987).

Conclusions

Stormwater infiltration is an important runoff management practice, which should be ideally applied close to the sources of relatively clean or pretreated runoff. Among infiltration structures, trenches, wells and porous drainage structures are preferred and can be designed using the available hydrologic and hydraulic criteria. The main design uncertainty is the operating life, which can be improved by conservative design and good maintenance. Infiltration measures must meet feasibility criteria with respect to the site and prevention of environmental impacts. Main benefits of infiltration facilities include reduced runoff volumes, peaks and incidence of flooding; reduced pollutant loads and receiving water pollution; and, enhanced groundwater recharge and baseflow in small streams. For significant flood risk reductions, infiltration facilities must serve a substantial part of the drainage area, and should include detention storage. Infiltration structures can be highly cost-effective, because infiltration structures are relatively inexpensive. Many examples of successful infiltration structures can be found in several European countries and in Japan.

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