University of Washington
Department of Civil and Environmental Engineering

ALTERNATIVES FOR LIMITING STORMWATER PRODUCTION AND RUNOFF IN RESIDENTIAL CATCHMENTS

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Principal Investigator:	**Stephen J. Burges** **Professor of Civil Engineering**

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We would like to acknowledge you individually; the risks of omission are high so we have chosen to thank you collectively.

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1. INTRODUCTION

1.1 Improved On-Site Residential Stormwater Management

The Improved On-Site Residential Stormwater Management project was conducted by the University of Washington Center for Urban Water Resources Management between September 1993 and September 1995. The project was funded through the State of Washington Centennial Clean Water Fund with King County Surface Water Management and the City of Redmond Storm and Surface Water Utility matching funds. This review summarizes scientific and technical literature relevant to managing stormwater on-site at the scale of individual residences, with particular emphasis on the Puget Sound lowlands of Washington State.

1.2 Stormwater

Stormwater, which is the excess rainfall that flows quickly over and through land to receiving water bodies, poses a challenging environmental problem in many areas. It has been traditionally viewed as an agent of flooding and erosion especially in growing urban and residential areas. Recently, stormwater's role in transporting pollutants and degrading riparian and stream habitat has been recognized and, in some places, may be more significant than flooding. As a result, public agencies and private landowners have increased their efforts to manage stormwater as a way to reduce flooding and to improve water quality.

Stormwater is an integral part of the hydrologic cycle. When precipitation falls on a landscape, it collects on trees, other plants, and buildings. As a storm continues, water infiltrates into soil through soil pores and fills up depressions and cracks in pavement and other impervious surfaces. If rainfall exceeds the storage and infiltration capacity of the land, stormwater can be generated through three different mechanisms. First, water that has infiltrated the soil can move laterally, for example, when it encounters less permeable soil layers. This is termed "subsurface flow". Subsurface flow contributes to storm flow only when its flow path is short, shallow, and terminates at a channel or seepage face. Second, if the rainfall rate exceeds the infiltration rate of the soil, excess rain will fill up depressions and flow over the land surface. Stormwater generated by this mechanism is called "Horton overland flow". Third, the water table can rise to the land surface such that rainfall cannot infiltrate into the soil and becomes stormwater or "saturation overland flow". Stormwater generated through any of these mechanism is commonly called quick-response storm flow or runoff.

Harr (1977) investigated steep forested slopes in the western Cascades in Oregon, and concluded that overland flow rarely results from storm events in these areas. Harr cited the results of Dunne and Black (1970a) as unindicative of mechanisms in the Western Cascades region, where although the saturated zones expand upslope from seepage faces (variable source area concept) no overland flow is evident and channels do not expand. The ability of the thin layer of permeable soil at the surface to retain moisture, coupled with the less intense rainfall rates in the Western Cascades, precluded the occurrence of Horton overland flow in steep forested slopes. In the Puget Sound region, subsurface flow is believed to take place just above a layer of compact glacial till, where the down-flowing water experiences a lower vertical conductivity and begins to travel laterally (Whipkey, 1965; Harr, 1977).

1.3 Hydrologic Changes Resulting From Urban Development

Harmful hydrologic effects of urbanization are well documented (Argue, 1988; Dunne and Leopold, 1978). For the Puget Sound region, important impacts include increased flooding, increased erosion from unvegetated soil and stream banks, gully formation, increased sediment deposition in low velocity waters, degradation of fish habitat, decreased groundwater recharge and stream flows during dry periods, and increased transport of pollutants from land surfaces to water. Generally, these impacts are a result of an increase in storm flow peaks and volumes (i.e., quick-response storm flow). Increased storm flow peaks and volumes result when there is:

(1) a decrease in the water storage capacity caused by removal of forests and associated loss of surface depressions and when permeable surface soils are removed or compacted,

(2) an increase in impervious and smooth surfaces which generate more stormwater in smaller storms and allow for higher velocity flows than natural landscapes,

(3) a decrease in stormwater storage capacity of natural streams because wetlands have been filled and swales and streams have been straightened and the channel cross-section modified, and

(4) an increase in the density of surface runnels and of drainage channels.

In addition to these changes which can inundate areas with stormwater, drainage problems are created when structures are located within or at the fringes of natural drainages.

Many of the common problems of urbanization are exacerbated in the Puget Sound region of Washington by the geological and climatic setting. The typical natural hillslope in Western Washington is heavily forested, with a dense understory and a permeable, absorbent layer of organic material (forest duff) and loam at the ground surface. The topsoil is shallow and underlain by Vashon Till, a "very dense, gray, silty to very silty, gravely, fine to coarse sand with scattered cobbles and boulders and a trace of clay." (Olmsted, 1969) Approximately 15,000 years ago this till was overlain by 1,000 m (3,000 ft) of ice, and is therefore highly compacted. Bulk densities range to 160 pounds per cubic foot (denser than Portland Cement Concrete) and hydraulic conductivities range from 10^{-6} to 10^{-4} mm/sec (0.034 to 3.4 m/year or 0.11 to 11 feet/year), making the till an "excellent material for dikes and dams" (Olmsted, 1969). Conversely, and for the same reasons, the till performs poorly as a stormwater storage medium.

While hydrologic changes are evident in cities, residential developments are likely to produce similar changes even if they appear to the casual observer to be more hydrologically benign. Residential development in the Puget Sound region usually begins by removing most trees and all of the forest understory at a site. The organic duff and top soil is scraped off leaving the till layer for foundation construction. Buildings are constructed with smooth sloping roofs which generate runoff even during light storms. In areas not occupied by buildings, driveways, or sidewalks, grass lawns are often established on a one- to two-inch layer of topsoil. Lawns constructed in this way have little capacity to store stormwater.

The difficulty in managing stormwater around Puget Sound, then, is designing and constructing systems to attempt to replicate the hydrologic functions of a forested landscape where buildings, roads, and lawns may occupy most of the land surface of a site. The rapid population growth in the Puget Sound region and the concurrent conversion of forested landscapes to commercial and residential developments have expanded the role of stormwater management from a site-by-site concern to the regional level because fewer sites are adjacent to forested areas which might be able to accommodate some of excess stormwater. As a result, more stormwater is concentrated in the fewer remaining swales, wetlands, and other surface depressions.

1.4 Stormwater Management

Stormwater has been viewed as "a form of refuse to be collected and disposed of as rapidly and as thoroughly as possible." (Argue, 1988). Stormwater management in the Puget Sound region historically has consisted of projects which increase the diameters of stormwater conveyance pipes, add or increase the size of detention ponds, and armor and channelize streams. Generally, the goals of these projects are to reduce peak storm flows, to increase the capacity of stormwater drainage systems, and to prevent erosion of and around drainage systems. Recent efforts have also focused on water quality issues through the construction of retention/detention ponds, wet pond, swales, and biofilters, Since many projects are constructed by private land developers to comply with local regulations, their influence is often limited to on-site concerns. Additionally, many of the projects are capital-intensive, dedicate large areas for only occasional use (i.e., when there are big, infrequent storms), fail to reduce storm flow volumes, and may only move the hydrologic and resulting ecologic problems downstream.

Fundamentally, stormwater management activities do not restore the hydrology of a developed basin to it pre-development condition even at local sites. As a result, current stormwater management in the Puget Sound region may only be marginally successful in achieving a broader range of objectives that include reducing regional stormwater flow (peaks and volumes), preventing degradation of riparian and stream habitat, protecting water quality, recharging groundwater, reducing demand for supplemental irrigation, and providing cost effective solutions. Stormwater management alternatives need to be considered at the scales of a single residence, the hillslope, and the catchment.

1.5 On-Site Residential Stormwater Management Alternatives

While stormwater management requires efforts at many levels ranging from regional planning to clearing debris from road culverts, on-site control of runoff from new developments is one area where public agencies around Puget Sound can effectively promote stormwater management and influence the design of many stormwater management systems. The work described here focuses on six stormwater management alternatives which can be implemented on-site at the scale of individual residences and on how those alternatives can be used to improve stormwater management. The six alternatives are:

1. Detention/retention systems;
2. Detention for use systems;
3. Roof down spout infiltration systems;
4. Soil amendments;
5. Alternative landscapes; and
6. Permeable pavements;

Examples of these systems can be found worldwide as well as in the State of Washington though their primary purpose is not always stormwater management. As a result, an extensive body of literature including government documents, conference proceedings, "gray" literature, and anecdotal reports describe many different aspects of these systems. We review here representative literature of the current state of knowledge regarding these systems as they are used for stormwater management. For each alternative, we provide:

1. an overview of the history, purpose, site application, and representative systems;
2. basic information regarding the construction and maintenance of systems;
3. a description of studies assessing the performance and reliability of systems; and
4. some of the costs of systems.

In some cases, the literature does not address each of these topics fully and the lack of information is noted.

Improved stormwater management may be possible by applying one or more of these alternatives in selected sites. The test for each alternative is in its performance and reliability in managing stormwater. Many studies have assessed the performance of actual or simulated systems. It is important to note, however, that most studies typically reduce system performance to a single measure (e.g., peak flow rate) and, as discussed, a single measure does not indicate how well an on-site system performs for a range of objectives especially those concerning habitat conditions or regional matters.

2. THE INFLUENCE OF SOIL ON THE HYDROLIC CYCLE

2.1 Physical and hydrologic characteristics of till

Glaciation produces soils by a number of processes, usually classified according to the portion of the glacier which drives the process. First the glacier erodes rock or mineral by scouring as it migrates. Then it transports the material either by grinding it along the base (basal transport), incorporating it into the glacial ice (englacial transport), or carrying it at the surface (superglacial transport) (Dreimanis, 1976). Finally it deposits the transported material by dropping it during retreat, where some of it may be washed away in melt water. Thus the materials which make up a glacial deposit are determined by the location from which they were plucked by the glacier, which can be many kilometers from the point of deposition. The structure is determined by the mechanism which resulted in deposition and weathering, fluvial effects, or other land-forming process which occur following the glacial deposition.

Because the mechanisms by which glaciers deposit sediment vary significantly, the term "till" encompasses a wide variety of soils. Dreimanis (1976) reviewed works by other authors and derived a general set of characteristics by which tills are identified:

1. glacial origin (making the term "glacial till" redundant)
2. presence of a variety of rock and mineral fragments
3. wide range of particle sizes (poorly sorted)
4. lack of stratification
5. compactness

This list is a general guide to identifying whether a given soil fits the broadest of all till types, and therefore is neither complete nor does it identify all tills precisely.

Our concerns deal with the hydrologic effects of a shallow layer of basal till upon which housing and landscaping (most typically sod) are placed. There are numerous sub-classifications of basal till, each fitting the 5-part description above, particularly the criterion of compactness. This high degree of compaction is attributed to the large pressures caused by the overlying ice combined with the wide range of particle sizes (Dreimanis, 1976). Additional common characteristics of basal till include a lack of structure, particularly if the till contains clay, and rounded and possibly striated clasts. As a result of the compactness and lack of structure, basal tills often display high bulk densities, high shear strength, low porosity, and low void ratios. It is these characteristics which also make basal till desirable from a geotechnical standpoint (Lutenegger et al., 1983), inducing developers to scrape down to shallow, dense till for building roads, houses, and commercial and industrial buildings. These characteristics produce undesirable runoff generation behavior from residential lawns grown on surface disturbed till.

2.2 Subsurface water storage and flux

The subsurface of a hillslope is divided into two general zones by the water table. Below the water table is the phreatic zone, where the soil is saturated and the pore water pressures are above atmospheric pressure. Above the water table is the vadose zone, where the soil is generally unsaturated with negative pore water pressures. These zones are also called the saturated and unsaturated zones, respectively.

Several parameters are used to characterize the storage behavior of a soil. Moisture content (θ) is defined as the volume fraction of water in a given volume of soil. Moisture content at saturation (θ_{sat}) occurs when a soil is saturated and is equal to the soil's active porosity *n*. (The active porosity does not include pores which are isolated from the flow paths and do not fill with water.) When the soil drains due to gravity a certain amount of water is retained in a film over the particles. The moisture content at this stage (θ_{fc}) is called the field capacity. The porosity available for storage during storms is equal to

(θ_{sat} - θ_{fc}) and is termed the "dynamic" or "effective" porosity. During long dry periods the vegetation will continue to draw water from the soil and transport it out of the soil through the roots and stems. The moisture content then falls below the field capacity. As water is withdrawn and suction heads increase, more energy is required to withdraw additional moisture. At moisture content θ_w; often called the wilting point, this energy exceeds that which the vegetation can muster and the plants may die. At the irreducible water content (θ_n) no more water can be removed from the soil unless it is oven dried.

The saturation of a soil, S, is the percent of the voids filled by water. Thus S is zero if no moisture is present (in an oven-dried sample) and equals 100% when the soil is saturated.

$$S = (\text{volume of water}/\text{volume of voids})*100 \quad (2\text{-}1)$$

The storage mechanism changes depending on the amount of water available. At low water content the water is bound to the soil particles as a film by electrical and molecular forces. As more water is introduced it is held in place between particles by capillary forces. Close to saturation non-bound free water is able to move more rapidly through the soil by passing through interconnected pores.

A soil structure is complicated further by biological activity, a process which is at least as significant as geological or morphological mechanisms. Hydraulic conductivity (a measure of the rate at which water moves through soil) has been shown to be at least as sensitive to structure as to particle size distribution (Nyborg, 1989). The field-scale properties of a soil mass can often vary by orders of magnitude due to root channels, earthworm and rodent burrows, etc. (Megahan and Clayton, 1983). Earthworms, for example, work the shallow soils and bring the digested dirt and organic materials to the surface at rates of up to approximately 18 tons per acre (4 kg/m^2) per year (Conniff, 1993). The biological activity in forests is credited for making the upper layers of soil highly permeable (Whipkey, 1965).

The heterogeneity of soil prompted research on the characterization of soil by a few parameters. Binley et al. (1989), investigated the effects of hydraulic conductivity variation on a simulated 150 m x 100 m hillslope on a slope of 6 horizontal to 1 vertical. Results indicated that in high-permeability soils (where most flow was subsurface) the soil parameters were effectively integrated over the hillslope, while in low-permeability soils the effect of spatial variability on the runoff hydrographs is more pronounced and cannot be represented by a spatially averaged quantity.

After reviewing a number of studies, Beven (1981) noted that vertical and lateral hydraulic conductivity decreased with depth. Though he provides no hypothesis for this phenomenon, one can assume that compaction due to overburden increases with depth, resulting in structural collapse of the soil matrix and producing a reduction of pore space with depth. This assumption is supported by an increase in bulk density with depth in three of the cases Beven reviewed (Dunne and Black, 1970; Harr, 1977; Whipkey, 1965). In addition, biological and chemical activities which break up the soil and enhance water storage and movement occur at shallower depths.

The difficulty in characterizing soil-water systems complicates the design of instrumentation and the analysis of data. Koide and Wheater (1992) performed a hydrologic study on a hillslope 18 meters long, 8 meters wide, and with a 25 degree slope. A network of tensiometers from 14 to 95 cm deep monitored soil moistures, a throughflow pit indicated flux at the lower slope boundary in each of five soil horizons, and tree throughfall and stemflow were monitored. Attempts to predict the response of the hillslope to rainfall with flow modeling were unsuccessful, illustrating the complex nature of the natural system. This work also exemplified the difficulty of examining hydrologic mechanisms, even on small, heavily-instrumented hillslopes.

Soil properties vary temporally as well as spatially. Gupta et al. (1992) measured hydraulic conductivities for three seasons in an agricultural field. Infiltrometer tests were performed every 5 m along a transect, and the results demonstrated that while saturated hydraulic conductivity varies with each season it remains spatially correlated.

2.3 Hydrology of small hillslopes in the Puget Sound region

The mechanical, chemical, and biological processes which take place after rain reaches the land surface are complex both in conceptual development and in experimental observation. However, these processes must be understood at least at an operational level if the response of a catchment to rainfall is to be investigated. The fundamental problem of hydrology is the water balance, or a study of the inputs, outputs, and storage of a given volume of land (the control volume). The water balance concept is summarized in the continuity equation:

$$dS/dt = I - O \qquad (2\text{-}2)$$

where dS/dt = rate of change of storage inside the control volume

I = volume flux into the control volume

O = volume flux from the control volume

Each term in (2-2) has dimensions of volume/time (L^3/T). If the control volume is defined for a small hillslope with a shallow soil, the water balance in terms of volumes over a given time step Dt can be formulated as

$$P + Q_{in} = DS + ET + R + Q_{sub} + Q_{surf} \qquad (2\text{-}3)$$

where P = precipitation

Q_{in} = inflow

DS = change in volume of water stored in the control volume

ET = evapotranspiration

R = recharge, or percolation downwards out of the control volume

Q_{sub} = subsurface runoff (by lateral flux through saturated zone)

Q_{surf} = surface runoff

In (2-3), all terms are in units of depth (average depth over the area of the catchment). The science of hydrology involves understanding the mechanisms which dictate the absolute and relative values of the terms in (2-3). In particular, hydrologists strive to predict the terms on the right side of (2-3) given the terms on the left. For a general review of hillslope hydrology processes see Freeze (1974), Chow et al. (1988), Dunne and Leopold (1978), or Linsley et al. (1982).

2.3.1 Precipitation

Winter storms in the Puget Sound basin are typically long-duration, low-intensity events. During spring the storms become more dynamic with shorter durations, more intense rainfall rates, and longer periods between storms. General climate and storm frequency statistics of the Puget Sound basin are described in detail in Chapter 4.

2.3.2 Storage of water

The principle medium of rain (or snowmelt) water storage on hillslopes is the soil. The soil water storage resulting from a storm depends on the ability of water to enter the soil through infiltration and the speed with which the soil transports and releases the water. These processes are dictated by the pore structure (including the presence of plants and effects of biological activity), porosity, particle size, and soil chemistry. The principle bulk parameters which characterize the soil's storage behavior are the porosity, field capacity, and saturated moisture content. The free water stored in the soil eventually leaves by a combination of lateral subsurface flow, percolation downwards to a deep aquifer, and vertically by surface evaporation or by vegetation through respiration processes.

Other mechanisms cause water to be stored temporarily by the hillslope. Interception occurs when rain drops (or snow) land on vegetation and can be significant up to the point where the leaves become wet and shed water. Thus interception is a storage mechanism which is significant only in small events or at the annual time scale (Linsley et al., 1982, page 235). In more significant rain events the vegetation is wetted quickly and no longer prevents rain from reaching the soil surface. Interception storage capacity is determined by the type of vegetation and the wind speed. In grasses, interception has been related to grass height and extent of grass cover (Dunne and Leopold, 1978). Intercepted rainfall eventually evaporates.

Depression storage occurs when water ponds but does not flow along the surface. Divots, rills, furrows, burrows, and other features of uneven topography cause depression storage. Depending on the atmospheric conditions and the ground surface properties, water stored in depressions will eventually infiltrate or evaporate. When a catchment is urbanized it is often graded to permit drainage, thereby eliminating a large amount of depression storage; the rain water which would have been stored in depressions becomes runoff.

2.3.3 Evapotranspiration

Evapotranspiration is the pathway by which water held on or within the land surface returns to the atmosphere. Because evaporation from foliage and soil and transpiration processes from vegetation are difficult to separate in practice, evapotranspiration encompasses both mechanisms. Water evaporates from the surface of vegetation, water-filled depressions, the soil, streams, and ponds. Transpiration is the release of water into the atmosphere by plants. The roots draw in the soil moisture, transport it through the stems, and expel it into the atmosphere through the stomata. Transpiration is the primary path by which moisture returns to the atmosphere from vegetated soil (Linsley et al., 1982). Evapotranspiration is primarily dictated by atmospheric conditions (Dunne and Leopold, 1978). Contributing factors include solar radiation, air (or leaf) temperature, air vapor pressure, and wind speed. The nature of the vegetation also affects evapotranspiration through the vegetation's albedo (tendency to reflect radiant energy), height above the ground, leaf structure and orientation and root structure.

2.3.4 Percolation and aquifer recharge

In areas with thin layers of permeable soils overlying hardpan till, most water travels laterally along and above the till layer. Some of the water seeps into fissures of the till and percolates downwards to the local (lower) water table. This water eventually reaches the outlet of the catchment along deep flow paths. While the fast surface and near surface hydrologic responses from storms are analyzed on the order of hours or days, deeply percolated water can take months or years to reach the outlet. Only in cases of large areal expanse (river basins) or long time scales does deep percolation become pertinent to local small-scale mass balance calculations except as a storm "loss." Water which percolates is important ecologically and is the source for natural streams which have their headwaters below till plateau regions in the Puget Sound lowlands.

2.3.5 Subsurface runoff

Subsurface runoff is the lateral flux of water through the upper horizon of the soil column to the catchment outlet. In forested non-mountainous slopes of the Puget Sound lowlands the typical soil column consists of a highly permeable layer of soil underlain by nearly impermeable till. Precipitation which is not intercepted, or throughfall, infiltrates into the unsaturated zone and travels downwards to the perched water table above the till. Most lateral subsurface flow takes place in the saturated zone just above the till layer (Whipkey, 1965; Harr, 1977). The high hydraulic conductivities of the shallow topsoil and steep hydraulic gradients are conditions conducive to significant hillslope response from subsurface flow (Beven, 1981).

Jamison and Peters (1967) investigated the effects of slope length on discharge hydrographs and concluded that recession flow is more significant in longer slopes. The slopes investigated were from 76 feet to 323 feet in length with a 3% grade. For long-duration or low-intensity storms, runoff per unit area decreased with longer slopes due to increased losses along the flow path due to evaporation and increased opportunity for deep percolation . In more intense storms, runoff per unit area increased with slope length due to return flow at the base of the slope.

2.3.6 Surface Runoff

Surface runoff is produced by three principal mechanisms: Horton overland flow, partial source areas, and variable source areas (Freeze, 1974). Horton overland flow occurs when the rainfall intensity exceeds the infiltration capacity of the soil. Often located in humid areas with relatively high-permeability soil, partial source areas are fairly fixed regions of a catchment which supply most of the runoff from the catchment while making up less than 10% of its area. In highly permeable soil, variable source areas likewise contribute the bulk of a catchment's runoff, but they are created by subsurface flow which saturates soil near channels (a result of seepage mechanisms and a rise in the water table following infiltration). The saturated areas are impervious to rainfall which is shed quickly into the channels. The resulting hydrographs are then directly related to the precipitation on the downslope saturated areas. The terms "partial" and "variable" are sometimes used interchangeably, according to Harr (1977).

On steep cleared slopes in humid Vermont, Dunne and Black (1970a) found that overland flow was produced only by surface runoff from direct precipitation onto areas saturated by a rising water table. The authors concluded for the hillslope studies that the storm runoff potential depended principally on the amount of overland flow produced. Only surface runoff substantially contributed to hillslope outflow.

Harr (1977) investigated steep forested slopes in the western Cascades in Oregon, and concluded that overland flow rarely results from storms. Harr cited the results of Dunne and Black (1970a) as unindicative of mechanisms in the Western Cascades region, where though the saturated zones expand upslope from seepage faces (variable source area concept) no overland flow is evident and channels do not expand. The ability of the thin layer of permeable soil at the surface to retain moisture, coupled with the less intense rainfall rates in the Western Cascades, precluded the occurrence of Horton (infiltration rate-limited) overland flow in steep forested slopes.

2.4 Amending Soils to Change Hydrologic Properties

Soil amendment has historically been viewed as a method for improving plant growth, with agricultural considerations motivating exploration. The studies listed in Table 2-1 had similar motivations, as indicated by the trends in their investigations. Soils were typically sandy, since sandier soils drain more completely, and ways were sought to add nutrients and improve moisture retention of the soil to support plant growth. Also, the most commonly studied amendments are sewage sludge and manure. Amendments were applied no deeper than the expected root zone (6 inches). The principal motivation for examining soil amendment with treated sewage sludge was for environmentally benign disposal.

Table 2.1: Summary of selected soil amendment studies

Study	Soil	Tillage	Treatment	Vegetation
Epstein (1976)	silt loam	rototilled	sewage sludge/compost	corn
Gupta (1976)	90% sand	rototilled 6 inches	sewage sludge	vegetables
Pagliai (1981)	sandy loam	"plowed in"	sewage sludge	corn
Tester (1990)	97% sand	rototilled 6 inches	comp. sewage sludge	fescue
			complete fertilizer	fescue
			comp. sewage sludge	vegetables
			beef manure	vegetables

There is little published in the literature concerning compost soil amendments and their influence on hillslope hydrology. Even with regards to basic soil properties the research scope has been narrow. Tester (1990) noted "there are limited reports describing the effects of sewage-sludge compost on soil properties." However, the results of these reports can be used to deduce likely effects of soil amendment on hydrologic processes.

According to the authors of the reports listed in Table 2-1, the amendment of a soil with organic matter such as compost generally increases water retention and saturated hydraulic conductivity, and decreases bulk density and unsaturated conductivity.

The major hydraulic characteristics of a soil mass are functions of its pore structure. Porosity is a simple measure of the highly irregular pore space in a soil matrix. However, this single parameter does not characterize the hydro-biologic nature of the soil pore structure. Pagliai et al. (1981) found the pore size distribution to be more of a controlling factor than porosity. Pore sizes are classified based on physical mechanisms they support (Pagliai credits Greenland, (1977)). Storage pores (0.5-50 mm) have the greatest agronomic function. Transmission pores (50 to 500 mm) control the flux of water and gases. Fissures (> 500 mm; i.e. 0.5mm) affect root structure as well as water/gas flux. A low fissure percentage is indicative of good soil structure. In their study, Pagliai et al. noted that while the pore size distribution varied little between different types and amounts (mass/area) of amendment, the drop in fissure proportion between the controls and the amended soils was pronounced. The resulting conclusion was that organic amendments improved the soil structure from an agricultural point of view.

Contrary to Pagliai et al. (1981), Tester (1990) and Gupta et al. (1976) found that the amount of compost applied affected the ultimate properties of the amended material. Tester concurrently conducted two studies on amendment with sewage sludge. In the first study, the more relevant study here, the soil was amended once; in the second study the soils were amended annually. After five years, the repeated amending of the soil in the second study led to reduced bulk densities, increased the soil water retention, and increased particle surface area. Likewise, Gupta et al. found that bulk density decreased and soil water content at a negative pressure of 15 bars (15 times normal atmospheric pressure) increased with the amount of amendment applied. The relationships were linear for the range of bulk density and water content investigated.

Organic material in compost will decompose over time. Gupta et al. showed that after one and two years, 58% and 50% of the mass (respectively) of the original sludge organic matter remained. Pagliai et al. credit other researchers for the conclusion that microbial activity, the regulator of organic decomposition, is generally greatest for a few weeks after amendment of the soil. Settlement of the soil due to loss of organic mass was not described.

2.5 Summary

In the Puget Sound lowlands, in the absence of wetlands and lakes, soil provides the largest component of stormwater storage in a natural forested catchment. High organic content, root channels from vegetation, and animal and insect action provide means for water to enter the soil where it is detained and slowly released. When a catchment is developed for pasture or urban or suburban infrastructure much of the upper soil is removed, effectively eliminating the primary stormwater storage reservoir. The remaining soil column fills with water after smaller volumes of rainfall and quickly generates surface runoff through overland flow processes. The flow production behavior is therefore altered, often to the detriment of the receiving streams and channels which now convey higher volumes of runoff.

To attempt to mitigate the hydrologic changes of urbanization, one needs to replace the storage and natural infiltration capacity of the soils which were removed during construction. Traditional stormwater management techniques such as detention ponds attempt to fulfill this role. Soil amendment could possibly provide an alternative means of managing stormwater throughout a catchment. Previous research indicates that amending a soil with organic material effectively alters the parent soil's water storage and flux behavior. Such practice on a catchment-wide basis could recreate a portion of the subsurface storage that was removed during construction, and more closely reproduce the catchment's hydrologic behavior prior to development.

3. INFILTRATION SYSTEMS

3.1 Introduction

Forests in the Puget Sound lowland region typically have layers of organic duff and top soil which store rain water temporarily where it is available for plants or will move vertically into deeper layers. When these porous materials are removed during residential and commercial development and replaced with roofs, roads, and lawns, rainfall quickly fills the available storage capacity of depressions and remaining thin soil. As a result, a larger proportion of rainfall flows overland as stormwater. To counter this effect of urban development, infiltration systems have been developed to promote infiltration and percolation of stormwater into the ground.

Infiltration systems cover a broad range of surface and subsurface structures. Surface structures include basins and open trenches which may be used for large volumes of stormwater or along the edge of impervious surfaces (e.g., parking lots). Subsurface systems (e.g., closed trenches and wells) employ perforated pipes to deliver water to an excavated area usually backfilled with free-draining rock.

Infiltration systems are used commonly for recharging aquifers, retaining storm runoff, or improving water quality of runoff (Geldof et al., 1993; Ishizaki, 1985). The specific purpose of an infiltration system will guide selection of appropriate sites, construction of the system including its size and materials, and the conveyance (and potentially pretreatment) of storm flow to the system. Duchene et al. (1994) note that the infiltration rate from a trench will depend on the depth of water in the trench, the saturated hydraulic conductivity of the surrounding soil, the distance to groundwater, and antecedent moisture conditions. Each of these factors should be accounted for when selecting a site and designing an infiltration system.

3.2 Sites

Governmental agencies have developed many site standards for infiltration systems. For water quality treatment, the State of Maryland (1984) recommends using infiltration systems in soils with infiltration rates at least equal to 6 mm/hr (0.24 in/hr). Stahre and Urbonas (1990) suggest that infiltration should be used for stormwater management only in soils classified in hydrologic groups A or B by the U. S. Department of Agriculture's Soil Conservation Service (also known as the Natural Resources Conservation Service) or in soils with field-tested saturated hydraulic conductivity greater than 60 mm/hr (2.4 in/hr).

The Maryland Department of Transportation sponsored a study of stormwater management infiltration structures for controlling peak storm flows (McBride and Sternberg, 1983). With regard to site criteria, the study recommends that sites be at least 3.8 m (10 ft) above the water table for water quality considerations and, to a lesser extent, to reduce the potential for surface ponding. Heavily traveled roads (>50,000 vehicles per day) are ruled out because of the potential for extremely high sediment loading. Moderately permeable sands and gravels are the preferred soil types. A site with an underlying aquifer used for domestic consumption is acceptable but not preferred.

3.3 Construction and Maintenance

Construction of stormwater infiltration systems generally involves determining the infiltration capacities of soils and designing an appropriately sized hole or trench (i.e., one that will infiltrate/store the runoff from a design storm or a design time slice of storm patterns). There is no widely accepted method for estimating the infiltration capacity of a soil. A survey of practice in Japan, Denmark, Sweden, Germany, the Netherlands, and the United Kingdom revealed that infiltration capacity at a site is estimated with constant head tests, falling head tests, and standardized values based on soil texture. There are conflicting standards over whether the bottom area of a trench should be considered a permeable surface when calculating the rate that water will drain from a trench as its bottom may clog (Petersen et al., 1993). Screens, either on collectors or inlet pipes, and/or settling basins should be used to keep debris and suspended sediment out of infiltration systems.

A recent United Kingdom design guidance calls for testing infiltration capacity in a long (3:1 ratio of length to width) pit at the depth of the planned trench. The test pit is filled and drained three times and the infiltration rate is calculated by using the longest time for the pit to drain from 75% to 25% of storage capacity. A second test pit should be used if the length of the actual trench will exceed 25 m (80 ft) to account for spatially variable infiltration capacity. To inspect infiltration trenches, two 225 mm (9 in) perforated pipes at either end of the trench are recommended as observation wells. (Pratt and Powell, 1993).

Danish researchers have developed standardized curves plotting the ratio of trench length over contributing drainage area versus hydraulic conductivity (K) for 1 m (3 ft) deep, 0.5 m (1.6 ft) wide infiltration trenches (Mikkelsen, 1993). Each design storm has a separate curve which, for a given K, will indicate the length of trench needed to store temporarily and infiltrate runoff from an area.

Schueler (1987) presents a design for a conventional infiltration trench as a 1 - 2.4 m (3 - 8 ft) deep trench filled with 40 - 60 mm (1.5 to 2.5 in) diameter clean stone. It is constructed on top of a sand filter. Runoff enters the trench as overland flow after passing across a 6 m (20 ft) wide grass buffer strip. Trenches should be designed to drain completely within 72 hours of the design event to maintain aerobic conditions and promote pollutant removal.

One design for infiltration wells consists of a perforated concrete or plastic cylinder placed inside of a hole filled with gravel. A minimum of 0.3 m (1 ft) of gravel is below the cylinder and 0.2 m (0.7 ft) between the cylinder and the hole's walls. Once the excavation has reached the base level for the well, a constant head infiltration test in the hole can be conducted to determine precisely how large the hole should be.

3.4 Performance and Reliability

Researcher workers have simulated the performance of infiltration systems using computer and laboratory models, considered the regional effects of infiltration systems, and monitored the reduction in infiltration capacities of systems over time due to clogging. Details of these performance measures and tests follow.

3.4.1 Infiltration trench analyses

A study in Japan indicated that a trench 0.3 m wide, 1.0 m deep (1 ft wide, 3.3 ft deep) with a pipe 0.3 m (1 ft) from the bottom of the trench had relatively constant outflow of 0.125 m^3/hr/m (10 gpm/1 ft) of trench whether they were backfilled with rough sand or Kanto loam (Ishizaki, 1985). A second set of experiments using four parallel trenches, 2.5 m (8.2 ft) apart, produced a constant infiltration rate of 0.15 m^3/hr/m (12 gpm/1 ft of trench) after 3 hrs. The two-year study of infiltration trenches also reported: (1) the infiltration capacity of the soil was not affected by groundwater when the water table is 2 m (7 ft) below the ground surface (1 m below the bottom of the trench); (2) the water contents of the soils above the bottoms of the trenches did not increase appreciably during infiltration periods; (3) infiltration capacity decreased 10% during the rainy season; and (4) the infiltration capacity of parallel trenches increased as the trenches were placed closer together until they were 1 m (3.3 ft) apart, where infiltration rates declined.

Kuo et al. (1989) developed a finite element model for studying infiltration trenches. After verifying the model's results with small-scale laboratory experiments, they performed parametric studies to assess the effect of soil properties, trench dimensions, and depth of water table on infiltration performance. They found that narrow, deep trenches had greater infiltration rates (per unit area of trench bottom) than shallow, wide trenches. For a given trench volume and length, however, shallow, wide trenches infiltrated a greater volume of water. Depth to the water table had a greater effect on infiltration rates in silty soils than sand. Simulated infiltration rates began to decline when the water table was 3 m (10 ft) below the surface for sand, 9 m (30 ft) for loamy sand, and 18 m (60 ft) for sandy loam.

Hydraulic analyses and laboratory tests were conducted to calculate delivery rates from perforated pipes discharging water into the trenches and, in particular, the depth of water in the pipes (Duchene and McBean, 1992). The results from the test were fit with a discharge equation: $Q = C_d A (2gH)^{0.5}$ where Q is the volumetric flow rate through the perforations, C_d is an orifice coefficient, A is the total area of the orifices, and H is the piezometric head at the center of the orifice. Where a pipe has multiple longitudinal lines of orifices, a term for each line must be included. The orifice coefficient for a 300 mm (1 ft) diameter smooth pipe with 12.7 mm (0.5 in) diameter orifices was 0.65. This method allows discharge to be calculated by measuring the depth of water in a pipe delivering water to an infiltration trench.

Duchene et al. (1994) developed a finite element simulation model of a two dimensional section of an infiltration trench to examine the effect of soil hydraulic properties, distance to groundwater, antecedent moisture, and clogging of the trench bottom. For a rise in the groundwater surface from 3 m (10 ft) beneath the trench to 2 m (6 ft), the model predicted a 20% decline in the infiltration rate of a sandy soil and a 8% decline for a loam soil. While water appeared to be infiltrating primarily through the bottom of the trench, doubling the width of trench increased modeled infiltration rates by only approximately 20%. Clogging was most pronounced for simulation of shallow depths of water in the trench. This suggested that narrow, deep trenches may perform better over time (Duchene et al., 1994). Higher antecedent moisture content in the soil adjacent to the trench reduced infiltration as expected.

A comparison of simulation results with those from a simple model (using only saturated hydraulic conductivity and the bottom area of the trench available for infiltration) indicated that the simple model consistently underestimated infiltration rates calculated by the finite element model: results from the simple model ranged between 24% and 54% of the rates calculated by the finite element model (Duchene et al., 1994). For engineering purposes, this suggests that use of a simple model of infiltration trenches has a factor of safety of approximately 25%.

The effect of cold temperatures on infiltration facilities has been studied. Constantz and Murphy (1991) found that surface infiltration rates for sand and loam soils increased 67% to 77% when water temperature was increased from 5 ° to 25° C. The increase in infiltration rate results from the decrease in water's viscosity at higher temperatures. A decrease in hydraulic conductivity and blockage due to ice was observed at -8.5° C in an infiltration system (Stenmark, 1993). Design hydraulic conductivies for infiltration systems should be estimated for the likely coldest water temperature corresponding to the time of year of the design storm or rainfall and snowmelt patterns that are likely to be critical.

3.4.2 Infiltration basin analyses

Ishizaki (1985) also compared flow from portions of an apartment complex served by conventional storm drains with a similar complex where infiltration facilities had been installed The infiltration facilities included trenches, connection boxes (i.e., French drains), and permeable asphalt pavement. Rainfall from roofs, 1.7 ha of a total 27 ha (4.2 acres of 67 acres) was piped to a detention pond which overflowed into infiltration trenches. The soil profile at the complex was: 100 mm top soil; 2 to 3 m loam, which was underlain by sand and gravel. The spatial average vertical hydraulic conductivity of the loam layer was 6 mm/hr and it ranged from 0.02 to 50 mm/hr.

Ishizaki (1985) used an outflow ratio (total storm flow/total rainfall) to compare the performance of four city blocks (two with infiltration facilities, two with conventional drainage systems) within the complex. For four storms with total precipitation ranging from 23 - 88 mm (0.9 - 3.5 in), the blocks with infiltration facilities had outflow ratios ranging from 0.01 to 0.05 while the blocks with conventional stormwater drainage had outflow ratios ranging from 0.39 to 0.54. These comparisons reflect the storm patterns for the Tokyo area.

In the Shirako River basin (northwestern Tokyo), 10 km^2 of a total of 25 km^2 (2,500 acres of 6,200 acres) area is served by an experimental storm sewer system which infiltrates runoff. It is estimated that this system has reduced peak flow of stormwater runoff by 40% and total volume of flow by 50% when compared with storm flows from conventional storm sewers (Geldof et al. 1993).

An experimental sewer system has been developed in Tokyo to control peak storm flow rates and nonpoint source pollution transported by those flows. The system includes infiltration trenches, inlets (wells), and porous pavement. Fujita and Koyama (1990) reported that the system was successful in reducing peak flows and pollutant loadings. The system reduced the frequency of storm sewer overflow from 50% to 19%. Overflow loading of suspended solids was reduced by 91% from 223.3 kg/ha (1,200 pounds/acre) to 19.2 kg/ha (100 pounds/acre). Wet weather loading of suspended solids was reduced 76% from 642 kg/ha (3,500 pounds/acre) to 156 kg/ha (848 pounds/acre). Annual loading of suspended solids was reduced 55% from 1075 kg/ha (5,800 pounds/acre) to 589 kg/ha (3,200 pounds/acre).

Fujita (1987) reported on capacity and clogging over time of the infiltration components of this system. Mean infiltration values for three types of infiltration structures were measured: inlets infiltrated 29.8 liters/minute; trenches infiltrated 16.2 liters/minute/meter; and curbs infiltrated 5.1 liters/minute/meter.

Infiltration capacities generally declined for three years. Experimental clogging reduced the infiltration capacity of inlets by 10%, trenches by 50%, and curbs by 50%. The permeable pavement infiltrated 10 mm/hr after application of sediment-laden runoff (Fujita, 1987).

3.5 Cost

Infiltration systems may be less costly to install and maintain than conventional detention systems. A infiltration basin was used for stormwater management at a parking lot in Woodbridge, VA (Higgs, 1978). The soils at the site had measured permeabilities of 25 - 100 mm/hr (1 - 4 in/hr) with groundwater more than 3 m (10 ft) below the surface. A large, 430 m^3 (15,000 ft^3 or 110,000 gallon) detention/infiltration basin was necessary to store the 10-yr., 2-hr. storm (76 mm or 3 in total precipitation) falling on the 0.8 acre site. The cost for the basin was $27,213 effectively doubling the construction costs of the parking area. Excavation was single largest cost ($19,500). Geldof et al. (1993) estimate that cost of infiltration trenches for housing complexes is 33% of the cost of open detention ponds, and 10% of the cost of underground detention.

4. MULTIPURPOSE DETENTION OF STORMWATER

4.1 Introduction

Detention and delayed release of stormwater at low flow rates is a widely used management strategy for mitigating drainage problems associated with urban development. It is used in many residential developments to compensate partially for the depression storage and soil storage lost when land is graded (Dendrou and Delleur, 1982). We discuss on-site residential detention systems which can be used to reduce quick-response runoff (i.e., single purpose detention systems). Multipurpose detention systems which provide a supplemental domestic source of the water by collecting and storing runoff are also described.

Single-purpose detention systems and multipurpose detention systems are similar in that they must collect rainwater, store it in a reservoir, and provide for the delayed release or use of stored water. As such, both systems have components to provide these functions. Roofs, parking lots, courtyards, and other impervious surfaces often form catchments which drain directly to detention systems. The stormwater is conveyed to a tank, cistern, or pond where it is stored. To release stored water, the systems must have outlet structures and, possibly, pumps.

Single-purpose detention facilities are frequently large impoundments, serving individual developments, designed and operated as part of a regional stormwater management system (Urban Water Resource Research Council, 1992). Typically, they collect stormwater from roofs and roads, store it in a pond, and, then, release it slowly to natural swales, engineered channels, or regional sewer lines. We found few examples of small systems that could serve individual residences.

In addition to single-purpose detention systems, there are opportunities for multipurpose detention where stormwater is captured and used at a residence thus reducing peak storm flows, storm flow volumes, and residential demands on water supplies. Stormwater collected for potable supplies must be analyzed for biological, chemical, and physical constituents and then treated appropriately. Specific technology for, and risks of, using stormwater as a potable supply (including uses such as drinking, cooking, and bathing) are not discussed here. While the stormwater systems described could be used for potable supplies if the water received adequate treatment, the systems should otherwise be dedicated to non-potable purposes (e.g., landscape watering, clothes washing, and supplemental water for fire fighting).

4.2 Purpose of Detention Systems

Single-purpose detention systems are designed to achieve different objectives than multipurpose detention systems. To control runoff, detention systems are designed to slow down the flow of stormwater from a site which reduces the volume of quick response flow from storms, reduces peak storm flow rates delivered to the drainage system, and, in some cases, to provide limited water quality treatment (e.g., settling of suspended solids).

For most residential and commercial sites, stormwater detention systems are constructed to comply with local governmental regulations to mitigate the deleterious effects of development on the production of runoff. Commonly, regulations limit post-development peak flows rates from design storms to pre-development levels or, in the case of water quality treatment, may require that detention systems have sufficient storage volume for the runoff created by a high frequency design storm (e.g., 1/3 of the 2-yr. 24-hr. storm) (King Co., 1990). In situations where water quality is a concern (e.g., large areas dedicated to motor vehicles, chemicals, or other potential sources of pollutants), detention facilities are typically designed with a permanent storage pool to store frequent storms (or the first flush from larger storms) for an extended period of time to allow for settling of suspended solids (King Co., 1990).

Systems designed to capture runoff for later use are often constructed to provide water for a specific purpose (e.g., landscape irrigation). If the stormwater is treated, it can provide or supplement the main source of domestic water for a residence. This chapter distinguishes "use systems" from "detention systems." A combined "use and detention system" is similar to a multiple purpose reservoir used for water supply and flood damage mitigation.

4.3 Sites

Given their different purposes, detention and supplemental supply systems are often found in different climatic regions. Detention systems are often used in areas where flooding and nonpoint source pollution are considered problems. For example, places where vegetation and soils have been removed from building sites or where swales and depressions are filled to be used for building. In contrast, supplemental supply systems typically are located in areas where rainfall patterns do not coincide with use patterns (e.g., Mediterranean climates with hot, dry summers and cool, wet winters or arid regions with periodic, intense storms) or where ground and surface water supplies are marginal in terms of quantity or quality (e.g., small estuarine and marine islands).

4.3.1 Single purpose detention

The locations of detention systems within a catchment are crucial to their performance at the regional or basin-scale. Detention "of flow volumes in sub-basins alone will not maintain the main channel in its pre-urbanization state due to the increase in peak flow rates and to substantially longer durations at these levels" (Hardt and Burges, 1976). Lakotas and Kroop (1982), using the Soil Conservation Service TR-20 single event rainfall runoff model, concluded that on-site detention reservoirs should not be located in lower areas of a basin because releases from the reservoirs can aggravate downstream flooding. Increased and sustained peak flow levels may result when the runoff from a site draining to a lower reach of a stream is detained and released as peak runoff from the upper basin arrive. This conclusion is supported by Hardt and Burges (1976) and Dendrou and Delleur (1982). Consequently, the response of a basin to storm patterns and the relationship of contributing sub-basins should be analyzed before selecting locations for detention facilities including on-site residential systems.

After determining that on-site detention is likely to be effective in reducing peak storm flows or in alleviating flooding for a basin, the actual sites for the detention facilities will depend on where land is available, how storm flows can be collected and conveyed, and structural considerations. Potential locations for storing water include on flat roofs, under driveways and paved areas, in water-tight vaults inside building foundations, in above ground or buried tanks, or in ponds or swales. While natural wetlands retain stormwater and constructed wetlands have recently been used to detain stormwater for water quantity and quality management, generally runoff should not be introduced to an existing wetland as it will change the hydrologic and nutrient fluxes and the ecological balance of the wetland (Loucks, 1990; Mitsch and Gosselink, 1993; National Research Council, 1991).

4.3.2 Multipurpose detention

Rainwater collection systems have been used to provide potable water, irrigation water, and water for fire fighting around the world for centuries. While an exhaustive review was not conducted on this topic, the literature that was reviewed here identified residential rainwater harvesting systems in Australia, Botswana, Brazil, China, California, Florida, Gibraltar, India, Jamaica, Japan, ancient Rome, Sudan, Swaziland, and Thailand (Jenkins and Pearson, 1978; Hofkes and Huisman, 1983).

In Washington State, Marrowstone Island has numerous examples of on-site, supplemental supply systems. The main purpose for these systems in to provide a supplemental water supply for domestic uses and any stormwater control is incidental. While Marrowstone Island's principal water supply is from small, brackish aquifers, it receives approximately 18 inches of precipitation during the wet season. Residents have constructed systems to capture the stormwater in reservoirs, ranging in size from 3,800 - 190,000 liters (1,000 - 50,000 gallons), to use through the year in a variety of applications. Large scale application of rainwater harvesting is not common, though U.S. EPA (1985) has assessed the potential for using stormwater in industrial facilities (e.g., for cooling water, irrigation, etc.)

Woods and Choudhury (1992) analyzed U.S. rainfall patterns to determine where a 200 m^2 (2200 ft^2) roof could provide total indoor water consumption requirements for a 2-person household based on mean annual precipitation. Their results indicate that on-site stormwater collection could be effective in meeting indoor water consumption for most of the West Coast and the Southeast U.S. provided sufficient storage capacity is available. If advanced conservation methods are practiced, Woods and Choudhury calculate that any residence in an area receiving 410 mm (16 inches) annually (i.e., all of the East, Midwest, West Coast, and Western mountain regions) could use stormwater "harvesting" systems to satisfy all indoor water needs.

4.4 Design and Construction

Detention and supplemental supply systems must provide three functions with regard to stormwater: collection; storage; release; and delivery. The main design and construction considerations apply to both systems, though there are some distinct differences.

4.4.1 Collecting stormwater

Large, impervious surfaces exposed to rainfall or snow are used to collect water. Any type of roof can serve to collect stormwater for detention systems. For supplemental supply systems, tile or metal roofs may be preferred to wood or composition roofs because they do not introduce debris into the water supply. Roofs with metal flashings containing lead or zinc and painted surfaces are unsuitable for collecting drinking water, though, they can provide a water supply for landscape irrigation or other non-potable and non-dermal uses (provided the concentration of metals is low). In addition to contaminants introduced by roofing materials, bird feces, tree leaves and seeds, and airborne pollutants may be the most significant sources of contamination for any roof collection system.

Courtyards, depression storage, ponds, parking lots (Malcom, 1982) and other ground-level surfaces also collect stormwater. These collection sites are more susceptible to contamination and, consequently, are not generally used for drinking water supplies unless the water is properly treated. Ground-level surfaces are acceptable for collecting stormwater that will be used in non-potable applications or that will be detained for flood mitigation purposes.

The first flush of stormwater (i.e., the first runoff after an extended dry period) should be diverted from systems used for drinking water. A simple jar-trap with a floating plug and siphon will capture the first flush, divert subsequent flow to the reservoir, and can be emptied manually with the siphon (Jenkins and Pearson, 1978). As the first flush may also contain debris that can clog water lines, any supplemental supply system could either divert the first flush or screen/filter all stormwater.

One of the problems with using detention to manage stormwater is that once the storage capacity has been used, there is no benefit from detention facilities. To improve the performance of detention systems in large, long-duration storms, the systems can be located "off-line" where they only receive a portion of runoff from a site or only receive stormwater flow when it exceeds a specific rate. Since off-line facilities delay the filling of the storage facility, they may be smaller than on-line facilities for equivalent peak flow rate control (Nix and Tsay, 1988).

4.4.2 Storing stormwater

Once collected from a small (e.g. roof) catchment, stormwater is stored in a reservoir, which may be the collector as well, until peak flows have receded or until the water is needed. A wide range of storage reservoirs are available including roof-top storage, above ground storage tanks, ponds, underground cisterns, and building foundations designed to accommodate water storage (Coyler, 1982; Brown). Covered reservoirs may be preferred for supplemental supply systems to limit evaporation and contamination. Storage containers should minimized hazards and be made from materials which will not contaminate the water they contain. Portland Cement Concrete, metal, plastic, and wood have all been used for containers to store water. Recently, large volume plastic bladders have been used to store water. While use of these bladders for stormwater storage is not documented, they may be usable in a crawl space of an existing building. The design of storage reservoirs must include consideration of safety issues, necessary storage volume, maintenance, and cost.

Storage reservoirs must be secured against intrusion by people (especially children), animals, and contaminants (particularly for potable supplies). While small tanks may be secured easily, larger tanks and ponds may require more extensive measures such as high fences. Large storage reservoirs should also allow an easy escape route should a person or animal enter the reservoir (e.g., open detention ponds should have low angle sides). Structurally, reservoirs must be able to bear the range of potential loads including the pressure of contained stormwater, active and passive soil pressures, and the weight of buildings or objects above the reservoir. Reservoirs must be equipped with a spillway to convey overflow to an appropriate drainage system. There should also be a way to drain the reservoir (e.g., a drain plug or siphon).

A storage reservoir must be sized appropriately for its purpose whether it is to reduce runoff from a residence or to supply water for a use. The reservoir volume depends on the collection area, local rainfall patterns, the pattern of release from the reservoir, and the tolerable level of risk of exceeding a targeted flow rate (i.e., spilling from a detention reservoir) or of not having water available for use. Typically detention systems used solely for stormwater management require less storage capacity than supplemental supply systems.

4.4.3 Storage for single purpose detention systems

Detention systems have been sized to detain the runoff resulting from one or more design storms (e.g., the 2-yr., 10-yr., and 100-yr. Of specific duration) while limiting releases to pre-development levels (King Co., 1990; Urbonas and Roesner, 1993). (Given the relative ease of modern computation it is now preferable to use continuous simulation rather than storm events to size such facilities and to simulate their operation). An example is given by Balmforth and Bailey (1985) who conducted a study of on-site detention for pitched roof residences in the hydrologically and meteorolically benign United Kingdom. They determined that storage tanks in the 300 - 500 liter (80 - 130 gallon) range would provide sufficient storage capacity for reducing peak storm flows without being so large that the tanks would be economically or socially unfeasible (Balmforth and Bailey, 1985). They installed a 340 l (90 gal) PVC storage tank to detain runoff from a 50 m^2 (540 ft^2) roof. With a 10 mm (0.4 in) outlet, outflow was limited to a maximum of 0.17 liters/sec (2.7 gpm). The tank would fill completely during a 2-yr., 15-minute design storm with longer duration storms causing overflow from the tank.

4.4.4 Storage for multipurpose systems

Few standards exist for sizing on-site storage reservoirs for supplemental supply systems, but any method must consider rainfall patterns and release patterns. For example, a supplemental supply system for a 230 m^2 (2500 ft^2) roof area in Oakland, CA with a 43,000 liter (11,300 gallon) tank could provide a reliable yield (i.e., 100% of the time) of 110 liters/day (30 gallons/day) based on 10 years of daily rainfall records. By comparison, a 7,600 liter (2000 gallon) tank would provide 75% of the 110 liters/day (30 gallons/day) demand in terms of either days that demand is met or volume yield of the system (82.5 liters/day) (Jenkins and Pearson, 1978). Because of the rainfall patterns in Oakland, CA, the storage for the system had to be increased by more than a factor of 5 to achieve 1/3 more reliability, (i.e., from 75% to 100%).

Four examples of residential stormwater use systems on Marrowstone Island, Washington provide another perspective on the size of systems used for various purposes (Brown, 1994). Generally, these systems have been designed to capture as much water as possible up to the average annual runoff that can be generated from a residential roof.

The four systems are:

- House and barn roof runoff is gravity-fed to two 19,000 liter (5000 gallon) above-ground swimming pools. After treatment (gravel filter, charcoal filter, chlorination, sediment filter, and solid charcoal filter), this water is used for potable purposes. The system has been operating for 7 years with a low yield well providing water for toilets and outside faucets.
- A 130 m^2 (1400 ft^2)metal house roof is connected to a 18,000 liter (4800 gallon) cistern which provides water for toilets, outside faucets, dish washing, and laundry. Overflow from the system runs to a fish pond and is used for dry weather watering.
- Water from a house roof and foundation drains is delivered to a buried 45,000 liter (12,000) gallon reinforced concrete cistern for use in lawn and garden watering.
- Rainwater fills a 32,000 liter (8,500 gallon) stabilized earth pond (soil cement) for irrigation use in summer with potential for reusing laundry water.

In all of these cases, the stormwater is conveyed through a distribution system separate from the primary domestic water supply (i.e., well water) and is dedicated to different uses. Depending on the quality of well water, stormwater provides a source of either higher or lower quality water.

There are design aids that have been developed to help individual home owners determine the storage size needed for supplemental supply systems. For example, Jenkins and Pearson (1978) developed a nomograph which is used to calculate the storage capacity of stormwater cisterns based on catchment area (e.g., roof area), annual precipitation, and reliable yield desired. More complete analyses are needed if the supplemental system is intended as a primary water supply.

The variability of rain patterns with-in a year, as well as year-to-year, need to be considered. For the Monterey Peninsula, California, the storage required to provide 380 liters/day (100 gallons/day) was calculated for estimates of within-year drought periods having increasing degrees of severity as indicated by average annual recurrence interval (Riley et al., 1981). Table 4.1 shows the storage requirements.

Table 4.1: Storage requirements for detention system providing 380 liters/day (100 gallons/day) during increasingly severe within-year droughts, Monterey Peninsula, California

Return period of drought	Storage (liters)	Storage (gallons)
2-yr	76,000	20,000
10-yr.	110,000	28,000
50-yr.	130,000	35,000
100-yr.	150,000	40,000

4.4.5 Release of stormwater

While any stormwater management system spills water when its reservoir is full, the controlled release of stormwater from detention systems is fundamentally different than release from supplemental supply systems. This section describes the goals or rules for operating detention and supplemental supply systems though actual mechanisms (e.g., valves) are not discussed. Complex operating rules can be developed to optimize the performance of stormwater management systems. Such rules, however, would be difficult to implement for individual residences. Hence, operational strategies should be kept as simple as possible.

4.4.6 Release from single-purpose detention systems

The release of stormwater from a large detention system must be controlled so that it does not exacerbate regional peak storm flow rates. Detention systems have been developed to limit post-development peak flows for design storms (i.e., storms of specified intensity and duration with recurrence probabilities that have been calculated) to pre-development levels (King Co., 1990, Urbonas and Roesner, 1993). Improved approaches take advantage of more complete information about storm patterns over many years rather than a "design storm."

Release policies applied uniformly through a basin do not assure flood control (Boyd, 1993; Dendrou and Delleur, 1982; Lakatos and Kropp, 1982). In fact, on-site systems designed for specific design storms can cause flood peaks during larger storms exceeding the peaks that would have occurred if no controls were present (Hardt and Burges, 1976). Additionally, stormwater detention can increase the duration of bankfull flows which, in turn, increases the sediment transport in a stream (McCuen, 1979). Sediment transport resulting from human altered catchment response to rainfall is associated with increased channel erosion, degradation of stream habitat, and increased pollutant transport.

A site-specific release rule for detention systems is suggested by Lakatos and Kropp (1982) to prevent on-site or sub-basin level detention from increasing peak flows downstream. They begin by identifying the time when the peak flow for the stream reach of concern (i.e., the peak flow some distance downstream) occurs for a design storm. The component of the peak downstream flow contributed by a specific sub-basin (e.g., an area slated for a new residential development) is calculated.

It is important to distinguish between the flow contributed by the sub-basin to the downstream peak flow (which is the basis for this rule) and the peak flow from the sub-basin (which is often the basis for stormwater detention regulations). Conventional hydrologic routing techniques can be used to determine a sub-basin's contribution to a downstream peak. The maximum release rate from the post-development sub-basin should be limited to the pre-development contribution of the sub-basin to the downstream peak flow even if this level may be much less than the pre-development peak flow from the sub-basin. This reflects loss of retardation of hillslope generated flow in the developed state relative to the pre-development state. The rule attempts to use a basin-level objective as the basis for release of on-site storedstormwater.

The problems with implementing this rule are practical limits on the number of design storms and the number of downstream locations that can be analyzed for each different release rate from a specific sub-basin. Because the rule relies on design storms, it does not account for sequential storm events which can create high and sustained peak flows. Instead of using design storms and single event models, continuous simulation models may be more effective for assessing the effect of various release rates for actual rainfall patterns. In particular, continuous simulation can be used to assess the efficacy of detention systems for long storms or when wet antecedent conditions influence storm flow generation (Ormsbee, 1987). We endorse and support the use of continuous simulation to assess local, sub-catchment, and catchment level efficacy of stormwater management.

4.4.7 Release from multipurpose detention systems

Supplemental supply systems convey stormwater to points of use (e.g., lawn sprinklers, garden drip lines, clothes washers, outdoor faucets) when water is needed. One example is provided by considering municipal and industrial water use in the Puget Sound lowlands which increases from April to July to nearly twice the level of winter use and decreases from August to October back to winter use levels (Seattle Water Department, 1992). To the extent that stormwater is collected for landscape irrigation and other outdoor uses, there may only be significant demand from early May to late September. While the water supply for maintaining landscaping is needed for only a few months, landscaping can consume a large volume of water. Based on Seattle Water Department recommendations, a 0.1 ha (1/4 acre) lawn requires approximately 26,000 liters/week (7,000 gallons /week) during the summer whether from natural storms or supplemental irrigation. As a result, the storage of water for many roof systems may be limited to meeting only days or weeks of demand. Since water demand is greatest in July and August when surface water supplies are historically low, stormwater use systems might be operated to provide water primarily during the height of summer. Actual release rates from storage will depend on the extent of uses for the stored stormwater.

4.5 Performance and Reliability of Single-Purpose Residential Detention Systems

Boyd (1993) reviewed 18 studies where on-site or sub-basin stormwater detention was modeled. In sum, these studies indicate that on-site and sub-basin stormwater detention can decrease or increase downstream peak flows depending on where the detention reservoirs are located and whether they are designed to control runoff from longer duration storms that cause downstream flooding even if sub-basin flows during these storms are not extraordinary. As a result, on-site stormwater detention will not necessarily be effective in reducing regional peak storm flows unless it is designed as a component of a basin-scale system.

Lakatos and Kropp (1982) note that "the criteria of effectiveness for stormwater management must clearly consider overall watershed impacts....It is not sufficient to measure the effectiveness of a stormwater management policy only in terms of peak flow reduction at the outlet of a given basin for a particular watershed." Consequently, the performance of on-site detention depends on the stormwater management objectives for the area, the location of the systems in a basin, and their size and release rate. Since the performance of an on-site detention system is highly site-specific, only a few situations have been documented. Two studies are reviewed below: one assesses the influence of detention on peak flow rate reduction and the other compares different detention techniques.

4.5.1 Storm flow simulation for a residential development

A computer simulation of a12 ha (30 acre) development in England with 19% of the area paved and another 13% of the area as pitched roofs was used to estimate the effect of small-scale storage on peak storm flows (Balmforth and Bailey, 1985). Each 50 m^2 (540 ft^2) of roof area was assumed to drain to a 340 liter (90 gallon) storage tank with release from the tank through a 10 mm (0.4 in) orifice. Considering storm intensities with a 2-yr. return period (actual intensities were not provided), tanks reduced peak flow rates by 37% for a 15-min. duration storm, 35% for a 30-min. duration storm, and 32% for a 60-min. duration storm. For a 15-min. duration storm, a 170 liter (45 gallon) tank provided only a 15% reduction in peak flow rates while increasing the tank size did not increase peak flow reduction above 37%. While these tanks appeared to reduce peak flow rates, the study only considered short-duration storms characteristic of England and assumed most runoff from the development produced on paved and roof areas.

4.5.2 Comparison of single-purpose detention and other stormwater management methods

Stormwater can be detained in a variety of structures. Colyer (1982) conducted a comparison of five stormwater management structures and ranked them according to their management efficacy (essentially the amount of rain water than could be stored):

1. detention tanks;
2. permeable pavement;

3. surface ponding;
4. rooftop detention; and
5. inlet (infiltration) chambers.

This ranking is limited to the specific stormwater management structures examined and it does not represent the potential for any one system to achieve a given level of stormwater control.

4.5.3 Performance of multipurpose detention systems

We were unable to locate any documentation for the actual performance of any small multipurpose detention systems.

4.6 Cost

Given the wide variety of systems that can collect and store stormwater, it is difficult to estimate the cost of on-site detention systems. One rule of thumb suggested by a distributor of prefabricated plastic tanks is that tanks cost slightly less than $0.25/liter (0.26 gallon) of capacity. In the Puget Sound area, a 190 liter (50 gallon) plastic rain barrel with an outlet valve that accepts a garden hose can be purchased for approximately $40.00 (Puget Consumers Cooperative, 1994). Other types of tanks may be less expensive (e.g., $0.10/liter) especially if they had been used previously.

On Marrowstone Island, Washington, an innovative homeowner uses two freestanding swimming pools to collect roof runoff at a cost for materials of $0.025/liter. The cost of a reservoir integrated into a building foundation is difficult to separate from the cost of the foundation itself, though it would increase construction costs. The material costs for an artificial pond may be very low (<$0.01/liter depending on the depth of the pond) but the construction and land costs may be fixed (i.e., independent of size) and quite high on a per liter basis unless the pond is very large. We do not have any information on life-cycle costs. We are limited to initial costs. The Marrowstone Island homeowner did not estimate the cost of his labor and operation and maintenance costs were not available.

5. ALTERNATIVE LANDSCAPES

5.1 *Introduction*

Vegetation has a strong influence on surface runoff generation, water use, and runoff quality. In the Puget Sound lowlands, natural forest lands produce cleaner streamflow, smaller storm flows, and more total evaporation than any other cover type except for uncommonly large floods (on the order of 50-year recurrence or larger) when forested and residential catchments produce similar flood magnitudes. This is partly due to the interception and evaporation from trees, and partly due to the high porosity, organic-rich soils generated by the forest biota. The forested landscape infiltrates most rainfall, stores relatively large amounts of water in its soil (which is released slowly to streams) and vegetation, and promotes groundwater recharge.

Clearing forests will reduce the interception of rainfall and evapotranspiration of soil moisture in the first few years while increasing storm flow production (Dunne and Leopold, 1978). Though these effects are associated with conversion of forest land to turf grass, it is difficult to separate out changes resulting from compaction, homogenization, or removal of soil (see Chapter 4) from the change in vegetation alone. In any event, the landscaping of new developments may affect the production of runoff from storms and alternatives to turf grass may help to restore some of the natural hydrologic functions to a developed site.

5.2 *Alternative Landscapes*

Alternative landscapes include a large variety of topographic arrangements and land covers. For example, leaving the existing forest cover around a building site is one alternative to current development practices where most of the forest vegetation and soil are removed. Construction of terraces, deep garden beds, surface depressions, ponds, and swales constitute structural changes to a landscape which will change its hydrologic response to storms. Even if the topography of a site is not altered, the diversity of plant species and their age may influence a site's hydrology through their leaf, branch, and root structures and seasonal water demands. While the possibilities for alternative landscapes are many, this chapter focuses on the hydrology of turf grass lawns and alternative landscape cover types. Five types of cover are considered:

1. Turf grass - lawns and other areas of mown grass. Turf grass typically consists of one or more grass species planted as seed or installed as sod. Seeding can be through broadcasting of dry seed or by hydroseeding. Sod is grown in a variety of soils ranging from sand to clay.
2. Mulch. Mulch may be organic in origin (bark, wood chips, compost) or inorganic (washed or unwashed gravel, river rock, quarry rock) and may be placed with or without a layer of plastic sheeting or breathable fabric underneath.
3. Living ground covers - low-growing plants intended to cover the ground surface within a few years of planting.
4. Undisturbed existing vegetation/forest - native plants in natural associations; usually second or third growth trees in urban and suburban settings. Such forests usually contain several of the following vegetation types: tree canopy (tallest dominant trees), understory (shorter trees), shrub layers, herb layers, and forest floor (litter, duff, dead plants and limbs).
5. Impervious surfaces - Portland cement concrete or asphaltic concrete pavement, roofs, gravel surfaces, and plastic sheeting.

The hydrology of turf grass and forests is better documented than the hydrology of mulch and other covers. Little information is available regarding runoff generation and water demand of ornamental plants, living ground covers, and mulches in urban and suburban settings. As a result, conclusions on the relative effectiveness of various ground covers for runoff control are difficult to draw.

5.3 Sites

There are several types of turf substrates and soil preparations which produce a range of runoff responses. For example, turf grown in clay, mulches with plastic barriers, and compacted mulch (gravel) driveways generate relatively high quantities of runoff. This conclusion has been demonstrated by Wigmosta et al. (1994) for a 17 ha (42 acre) development on the Sammamish plateau. Well maintained turf grown in sand and mulches without plastic liners will not produce as much runoff has "turf on till". The treatment of native and introduced soil and the addition of potentially impervious layers of plastic or clay soil are greater hydrologic issues than the issue of using turf or mulch.

Runoff peaks from commercial sites may not be very sensitive to the use of either turf grass or mulch because turf and mulch account for only about 20 percent of commercial sites. Runoff is predominately dictated by flow from the portion (80 percent) of the site that is impervious. Impervious surfaces in the Puget Sound lowlands generate substantially more runoff than any other cover type and undisturbed forests generate substantially less runoff than any other cover type.

5.4 Design and Construction

Several factors related to installation and management of turf can affect runoff generation and the associated movement of pollutants. Infiltration rates are low on land planted with grass grown on inadequately-prepared soil. When runoff is generated, pesticides and fertilizers may enter surface waters. Land cover plants which require no or low applications of fertilizers cause less water pollution than other turf covered land. Sediments are rarely generated from lawn areas, but turf grass is prone to erosion while roots are being established. The effects of ground cover plants and mulches on runoff quality is largely unknown. Runoff from mulched areas, particularly processed bark and unwashed gravel has poorer water quality than most naturally vegetated landscapes.

5.5 Performance

The land use changes brought by development typically increases surface runoff generation. As an illustration of this, the U. S. Soil Conservation Service (Natural Resources Conservation Service) has developed a system of runoff curves for indexing the amount of surface runoff generated by different land cover and soil types. Land cover/soil type combinations are assigned a runoff curve numbered from 0 to 100 with high curve numbers indicating large amounts of runoff (Sanders, 1986). Undisturbed forest land is assigned low curve numbers; paved areas are assigned the highest curve numbers.

5.5.1 Soil

Comparisons of the hydrology of different cover types are difficult because the hydrologic properties of soils in urban areas are highly variable. Hipp et al. (1993), testing the effects of alternative landscapes on runoff generation, found that even though the soil was undisturbed and appeared uniform, the infiltration rates of landscapes treated alike were highly variable. Craul and Patterson (1990) defined urban soil as soil that is disturbed or manipulated by human activity connected with construction and urbanization. Characteristics that differentiate urban soils from their natural counterparts are a high degree of vertical and lateral variability; a loss of structure resulting from compaction; poor aeration status and generally impeded drainage; and the presence of a hydrophobic crust on the bare surface.

Garbesi (1992) noted that compaction often limits infiltration on urban soils. The King County Environmental Division (1993), in a study of golf course development, concluded that for the rainfall rates in the Pacific Northwest (generally low compared with most other parts of the United States) the surficial infiltration rates for drained soils under natural conditions generally far exceed rainfall intensities. In spite of high surficial infiltration rates, compacted subsurface horizons (e.g., glacial till) may prevent deep percolation and cause saturation of soils during longer duration storms and, potentially, runoff in the form of saturation overland flow.

5.5.2 Cover

Calculated runoff from undisturbed forests, except for long-duration storms falling on wet ground, is substantially less than runoff from any other cover type and impervious surfaces connected to drains or streams generate substantially more runoff than any other cover type. Runoff can also be estimated for grass and gravel streets, but not specifically for turf with clay substrate or mulch with plastic liners that have been installed at a site. Grass in good condition produces less runoff than grass in fair condition; most grass surfaces produce more runoff than forests.

5.5.3 Turf grass

Gross et al. (1991), studying runoff and sediment losses from turf grass, found that a thick, dense and thatchy well-established home lawn may absorb and infiltrate all rainfall from light to moderate rainfall events. Beard (1993) noted that turf grass, even in a non-green dormant state, continues to function as one of the better covers for water entrapment. Petrovic (1990), reviewing the fate of nitrogenous fertilizers applied to lawns, found that surface runoff rarely occurred during storms for the hydro-climatic regions examined. Bannerman et al. (1993), studying sources of pollution in stormwater runoff in Wisconsin, found that not every storm produced lawn runoff. Long-duration rainfall was a condition that produced lawn runoff in this study.

Pinyuh (1994) reported that high-quality lawns do a good job of reducing runoff in the Puget Sound basin; however, neglected and older lawns, and lawns on slopes are not as effective. Collman (1994) concurs, stating that improperly managed turf cannot be expected to perform as well as the carefully maintained stands used in most trials.

Several factors affect lawn infiltration capacity. Shoot density may or may not be important. Cooper (1990) notes that several research studies have demonstrated that a well-maintained, dense turf area can reduce surface runoff to near zero (these studies do not account for interflow). The velocity of overland flow of water across a dense turf grass stand is sufficiently slow that, under most conditions, the vast majority of water will infiltrate into the turf/thatch/soil profile before it can move horizontally from a site as surface runoff. Gross et al. (1991), found that as the seeding rate (density of grass) increased, the runoff initiation time also increased. The increased runoff initiation time may be due to the effect of the turf stand on soil water infiltration, or may simply be attributed to increased hydraulic resistance of the turf stand to surface flow.

Hamilton et al. (1990) measured the infiltration rate, bulk density, tilled density, thatch depth, pore space, area of earthworm holes, and lawn quality of residential and experimental lawns. Rates were extremely variable on both types of lawns. Correlations between infiltration rate and all other measured characteristics were low. They noted that soil excavation during construction may be the most important factor affecting the lawn infiltration rates. This is consistent with the findings of Wigmosta et al. (1994) for an urban development on the Sammamish plateau near Seattle, Washington.

Grass height and maintenance practices influence the hydrology of turf. According to Karr and Schlosser (1978), increased vegetation height reduces surface runoff. Grey and Deneke (1986) noted that perforation of compacted lawns to improve water absorption and infiltration is one means of reducing fast runoff production. Robinette (1984) concurred, noting that lawn aeration and thatch control usually improves soil infiltration rates. Turf is another significant factor. Hipp (1994) found that established turf yields less runoff than new turf, likely because of the influence of root structure and ponding on infiltration.

As an index of the hydrologic importance of lawn quality in the U. S., SCS curve numbers for lawn areas in Washington State range from 68-92, depending on condition and underlying soil type. Lawns in good condition, with grass cover greater than 75 percent, have the lowest curve numbers, while the numbers increase for lawn areas in fair and poor condition.

5.5.4 Mulch

The effects of mulch on hydrology have received little attention in the literature, but it is generally thought to lessen runoff (American Horticultural Society, 1989; Price, 1986; Washington State, 1992). Mulches can increase the infiltration rate of the soil and prevent crusting and sealing of the soil surface. Organic mulch materials, such as straw, wood chips, bark, and wood fiber, have been found to be the most effective. Mulch with an impermeable barrier underneath (e.g., mulch over plastic), however, will actually result in substantial increases in runoff production; landscaping plastic creates just as much runoff as asphaltic or Portland Cement Concrete surfaces.

5.5.5 Planted landscapes - ground covers, shrubs, and trees

Trees, shrubs and ground covers provide many stormwater management benefits (Schueler, 1987). When mature, these plants form a canopy that intercepts rainfall before it reaches the ground. Rainfall that reaches the ground is more likely to be infiltrated in the spongy layer of organic matter that accumulates underneath the plants. Consequently, for a given storm, the volume, duration, and peak rate of stormwater runoff are reduced. He also noted that the amount of runoff generated from areas landscaped with naturalistic plantings of trees, shrubs and ground covers is 30 to 50 percent less than that produced from turf or lawns.

Soils generally have a higher infiltration rate when slightly moist than when wet. By maintaining low soil moisture conditions in landscapes, which is possible if "resource-efficient" plants are selected, it is possible to create a "reservoir" for water storage in the soil profile. This results in less runoff when rain falls onto the drier soil (Hipp et al., 1993). The authors, testing the runoff characteristics of alternative landscapes, found that efficient irrigation yielded essentially no runoff from plots containing resource-efficient plants. Thus, planting and properly maintaining native or adapted species is likely to reduce runoff production during some storms.

Biofiltration systems (grassed swales and filter strips) can restrict runoff and pollutant transport if they are properly designed. They have potential to preserve surface water quality when used as buffers between landscaped areas and watercourses. Biofiltration systems are increasingly used as "green infrastructure" in the landscaped areas of new developments. Life cycle costs of these systems have to be evaluated in terms of replacement time.

5.5.6 Undisturbed vegetation

Undisturbed forest generates less runoff than any other cover type except during long-duration, infrequent storms. Wigmosta et al. (1994) monitored a small, second-growth forest catchment (Novelty Hill) on the Sammamish plateau, King Co., Washington, and found that for a three year period the volume of runoff was equal to 17% of the rainfall. U.S. SCS curve numbers for forested land in Washington range from 42 to 81 depending on forest successional stage and soil type. While the rating of 81 for second growth on Group D soils is high, it is the lowest curve number assigned to any cover type in that soil group.

Forested lands in the Puget Sound lowlands produce runoff via interflow and, when the soil becomes saturated, via saturation overland flow. Near surface runoff through root holes, burrows of small invertebrates and so forth (macropore flow) is the dominant runoff producing mechanism in moderately-sloped forested lands during major storm events. Because of their high porosity, high organic content, and high water storage capacity, forest soils produce relatively small storm flow peaks and volumes and provide recharge to deep groundwater.

Dunne and Leopold (1978) noted that in humid regions (such as the Puget Sound lowlands), infiltration capacities are high because vegetation protects the soil from rain-packing and dispersal, and because the supply of humus and the activity of microfauna create an open soil structure. Under such conditions rainfall intensities generally do not exceed infiltration capacities, and Horton overland flow (overland flow that occurs when rainfall intensity exceeds the soil infiltration rate) does not occur on large areas of the landscape. Water that infiltrates the surface moves laterally and percolates downward.

5.5.8 Impervious surfaces

Impervious surfaces are assigned an SCS curve number of 98; they generate more runoff than any other cover type. The King County Surface Water Design Manuals defines impervious surfaces broadly, including all sealed pavements, gravel roads, and roofs (King Co., 1990).

5.6 Vegetation Water Requirements

Turf grass is generally a high water user, though low water use cultivars are available. Water use by ground cover species varies. In general, native and adapted species perform better with less water than introduced grasses and other plants. Native species are likely to require application of less fertilizer and fewer pesticides, and thus result in generation of less water pollution. In practical terms, user knowledge of plant needs is often the important factor in water use; landscape plants are often over-watered, because their water needs are not well understood. Undisturbed native vegetation is adapted to the local climate and does not need supplemental irrigation unless hydrologic pattern disruptions change water delivery to the site.

5.7 Summary

Good quality turf grass, planted in adequate top soil and with little compaction or removal of native soil, generates moderate runoff and effectively controls the movement of pollutants under most conditions. Grass planted on inadequately-prepared soil will lack the infiltration and storage capacity to decrease runoff quantities. Runoff produced from lawns that are not fully established, or those not properly maintained also suffer diminished infiltration functions.

Little is known quantitatively about mulches and living ground covers to assess their level of hydrologic function relative to turf grass. While Miller (1987) found that grass was a more effective filter of particulate pollutants in runoff than bark with shrubs or living ground covers, further study will be required to determine how different ground covers perform in terms of pollution and runoff generation. Undisturbed native vegetation generates less runoff and fewer pollutants than any other cover type, and impervious surfaces generate more. Organic mulches themselves may contribute to surface water pollution, by producing leachates and by disintegrating into particles that can be harmful to instream biota.

Construction, management, and cultural practices affect runoff characteristics. Runoff is a function of soil infiltration capacity, the depth of rain that can be stored in the soil column, and the ground cover's effectiveness in slowing runoff and enhancing infiltration. Soil preparation, plant stand age and condition, and the amount, frequency, and timing of chemical application can affect runoff quantity and quality. Site characteristics, including slope and soil type, are also factors. The entire landscape system, not just the cover type, determines runoff characteristics.

6. ALTERNATIVE PAVING SYSTEMS

There are many situations where it is not necessary to have a continuous impervious paved surface in urban, suburban, and industrial areas. We discuss here features of permeable paving systems.

6.1 Permeable Pavements

Large expanses of industrial, commercial, and residential areas are dedicated to or periodically used for vehicle traffic and parking. Typically, roadways consist of pavement made from asphaltic concrete, Portland Cement concrete, or gravel and clay surfaces which are relatively impervious or, in the case of gravel roads, become impervious from vehicle compaction (Reid, 1983). Pavement is often installed in other areas that receive heavy foot traffic (e.g., playgrounds, urban walkways). Since pavement offers only marginal depression storage for precipitation and has very low infiltration capacity, a high percentage of incident precipitation on pavement becomes quick response overland flow even in low-intensity, short-duration storms. Estimates of the percentage of precipitation on pavement that becomes runoff include 78% (Day et al., 1981), 46%-100% (Goforth et al.,1983), and 87% - 93% (Urbonas and Roesner, 1993). The lowest percentages of runoff correspond to light storms where rainfall minus evaporation (including vehicle spray) is not much greater than the depression storage in the surface. The highest percentages correspond to large rainfall depths. Depression storage for paved roads is on the order of 1 to 2 mm (0.04 to 0.08 in).

There are alternatives to traditional pavement which allow water to infiltrate the surface of the pavement. These permeable pavements can be divided into two broad categories: porous pavement, and modular pavement. Porous pavement consists of either asphalt or Cement concrete mixed with aggregate to form a porous concrete or macadam surface. Modular pavements span a range of materials including Portland Cement concrete, brick, and asphaltic concrete paving blocks, and concrete or plastic grids planted with grass.

The unifying characteristics of these materials is that they allow water to infiltrate through the surface while still supporting the weight of vehicle and foot traffic.

6.2 *Application of Alternative Pavements*

Porous asphaltic concrete and Portland Cement concrete pavements have been developed for managing stormwater flows and increasing vehicle traction under wet conditions. Open graded asphalt concrete mixes have been used in highway, forest road, and airport runway construction at least since 1947 when an open graded base course was used under a conventional asphalt concrete wearing course (i.e., a layer of large diameter aggregate with high porosity) in U.S. Highway 99 near Reading, California (Diniz, 1980). An experimental Portland Cement concrete pervious road was constructed in England in the mid-1960's (Paine, 1990). Permeable pavements have been used in Sweden where, by 1990, 7,000,000 m^2 (1700 acre) of permeable roads were in use (Niemczynowicz, 1990). Other installations include porous asphaltic concrete in Zurich, Swotzerland; Perth, Australia; Pennsylvania, and Texas (Diniz, 1980; Urban and Gburek, 1980; Goforth et al., 1983; and Cahill and Associates, 1993); and porous Portland Cement concrete in Florida (Paine, 1990).

After World War II, slotted steel sheets that previously served as temporary runways were reclaimed and used in Stuttgard, Germany as wear surfaces in parking lots and later replaced with perforated concrete slabs (Day et al., 1981). Grass grew on the lots and served to attenuate stormwater runoff and the heat island effect of urban development. Currently, three types of concrete grass pavers are common: lattice; castellated; and poured-in-place (Day et al., 1981). Plastic modular pavement is available as small modular blocks and large flexible sheets which range from 25 - 100 mm (1 - 4 in) thickness.

6.3 *Purposes for Pavement Alternatives*

Porous and modular alternatives to conventional pavement are used to reduce the flow of quick-response stormwater, direct stormwater runoff into soils where pollutants can be removed, recharge groundwater, increase the "landscaped" area of a development, and increase vehicle traction during rain storms.

Porous and modular pavements may better restore a site's pre-development hydrology than a detention basin and, potentially, better mitigate the hydrologic impacts of development (Cahill and Associates, 1993). In Sweden, porous and modular pavements have been installed to control runoff quantity and quality and to prevent ground subsidence that can accompany groundwater withdrawals (Niemczynowicz, 1990). Similarly, permeable pavements have been studied in Japan as a method for controlling stormwater quantity and subsidence (Wada and Miura, 1986; Fujita, 1993). In Florida, many water management districts accept porous pavement as a way to comply with stormwater retention storage requirements (Paine, 1990).

The purpose for using infiltration will determine many of the design characteristics of porous and modular pavement systems. Cahill and Associates note that for recharge purposes, porous pavement systems can be designed for 2-yr. storms (in Pennsylvania) without loss of much recharge performance. This may not be sufficient for controlling non-point source pollution, erosion, or flooding. Alternatively, Denmark has a regulation requiring 15% of industrial areas to be landscaped (Pratt, 1990) which would dictate the extent of a porous or modular installation used to comply.

6.4 *Application and Site Criteria*

For porous and modular pavement to function effectively with regard to its intended purpose, it should be applied only in limited situations and to sites meeting basic criteria. While careful design can expand the range of potential sites, there are many factors which must be considered before installing modular or porous pavements including: traffic volume and weight; proximity to construction sites or other sources of sediment (including wind-transported particulates); infiltration capacities of soils beneath and adjacent to an installation; depth to groundwater (or any perched water tables) and bedrock; the flow paths of the infiltrated water; and slope. All requirements are secondary to the structural capability of the underlying soil to support the pavement and traffic when the soil is saturated.

Research on porous pavement has been focused on applications to low traffic volume roadways and parking lots (Diniz, 1980; Field et al., 1982). Heavy use and, especially, heavy vehicles cause excessive wear on the surface, collapse pores, and introduce high sediment loads which will clog the surface (Diniz, 1980; Anacostia Restoration Team, 1992).

Soils beneath the pavement should be permeable with infiltration rates adequate for regional storm patterns and the desired level of attenuation of runoff. Schueler (1987) suggests a 1 m (3 ft) clearance between the bottom of a system and the groundwater table in Maryland. Slope should be less than 5%. Porous pavement should not be used in areas where sediment inputs to pavement could be high (e.g., if there is construction or exposed soils upslope of the paved surface or if it is an area with high wind erosion). Sanding and scraping by snow plows may damage these surfaces and, thus, limit the applicability of porous pavement in colder climates (Schueler, 1987; Anacostia Restoration Team, 1992).

Cahill and Associates (1993) assesses sites for porous pavement systems in terms of soils, depth to bedrock, depth to seasonally high water table, steep slopes, and proximity to certain structures. They recommend soil infiltration rates of at least 2 mm/hr (0.5 in/hr), though an infiltration rate as low as 1 mm/hr (0.25 in/hr) can be used under special circumstances. For a rapidly draining soil (e.g., coarse sand), its cation exchange capacity (CEC) should be at least 10 milliequivalents per 100 grams of soil to ensure pollutant removal unless the soil is deep or other circumstances render lower CEC appropriate. A minimum 1 m (3 ft) depth to bedrock and 0.6 m (2 ft) depth to seasonally high water table is recommended, though a 1.3m (4 ft) depth to ground water is preferred (Cahill and Associates, 1993).

Cahill and Associates also suggests that porous pavement is well-suited for large installations (e.g., 8 ha or 20 acre development) where the infiltration capacities of soils appear sufficient for draining the site given precipitation patterns and off-site runoff (if any). With large sites, clogging and local variation of the sub-base's infiltration capacity should not significantly affect drainage. Small areas (e.g., a 0.4 ha or 1 acre residence) may not be as appropriate because of the fixed cost of attempting new construction methods, which added to a larger project may not be substantial, and the potential for encountering a "pocket" of soil with lower than expected infiltration capacity.

6.5 Construction of Alternative Pavement

The major components of alternative pavements are (1) the sub-base which ultimately must allow water to percolate, (2) the base course which acts as a reservoir for stormwater and a structural base for the pavement, (3) filter layers which may be located below and/or above the base course and may provide stability for the surface layer, and (4) the permeable surface layer (i.e., either porous or modular pavement) (Diniz, 1980). The most important design considerations from a stormwater management perspective are the infiltration capacity of the surface of porous or modular pavement, the infiltration capacity of the sub-base, and the storage capacity of the base course. These capacities must be evaluated with respect to antecedent conditions and design storm patterns, to any additional runoff the pavement may receive, to saturated conditions, and to clogging that can be expected over the life of the pavement.

6.5.1 Porous Pavement Construction

Porous pavement must be constructed such that the strength and permeability are balanced. The thickness of layers, the amount of asphalt or Portland Cement and fine aggregated, and the construction methods will generally promote one property at the expense of the other. Diniz (1980), Field et al. (1982), Goforth et al. (1983), and Urban and Gburek (1980) provide detailed information on the construction of porous asphalt pavement installations. The Florida Concrete and Products Association (Paine, 1990) has produced a design manual for porous Portland cement pavement installation.

6.5.2 Asphalt Pavement

Porous asphaltic concrete pavement requires a specific asphalt-aggregate mix and rigorous construction methods. While a variety of organizations have developed or replicated asphalt mixes, they are in general agreement regarding the size distribution of aggregate, the penetration and viscosity of the asphalt, the thickness of layers, and the type of compaction and temperature at which the pavement is compacted.

Open graded asphalt concrete mix has a high percentage (35 - 50%) by weight of aggregate larger than #4 sieve (4.76 mm or 0.187 in.). The depth of the base course is determined by storage requirements (i.e., how much precipitation must be stored given the input from the design storm and the sub-base infiltration capacity) and the frost level (the base must extend below the frost line to prevent heaving). A typical section of porous asphalt paving consists of:

- the porous asphalt course, a 19 - 25 mm (0.75 - 1 in.) thick layer (16% porosity compared with 2%-3% for conventional asphalt concrete, AC-20 viscosity asphalt, 5.5%-6% asphalt by weight);
- a filter/stabilizing course (57 mm (2 in)) of crushed stone aggregate 13 mm (0.5 in);
- reservoir base course (large, angular aggregate, up to 40% porosity, deeper in low areas); and a

- a sub-base (must be able to drain so that structural strength is maintained).

A thick asphalt coating should be applied to limit photo-oxidation degradation of the porous asphalt. Except for drainage and frost adjustments, the usual thickness of base course and paving should provide adequate strength. Diniz (1980), Field et al. (1982), Goforth et al. (1983), Wada and Miura (1986), Pratt (1990), Urban and Gburek (1980) provide detailed description of construction standards for porous asphalt.

A design suggested by Schueler (1987) consists of: 60 - 100 mm (2.5 - 4.0 in) of porous pavement course; 25 mm (1.0 in) of gravel filter course; a stone reservoir (40 - 75 mm or 1.5 - 3.0 in. diameter stone) deep enough to store the intended volume of stormwater (e.g., 2 yr. storm); a second filter course (2 in. deep, gravel or 6 in. deep sand); and filter fabric. The design also has a reverse perforated pipe near the surface to collect subsurface flow from events larger than 2-yr. return period. Schueler suggests that the reservoir should drain in less than 48 - 72 hours.

A 0.14 ha (0.354 acres) porous asphalt study lot was constructed as part of an EPA project in Austin, TX. The lot consisted of a 64 mm (2.5 in) layer of asphaltic concrete (5.5 to 6.0 percent asphalt by weight); a 50 mm (2 in) stone filter course of 10 - 15 mm (0.4 -0.6 in) diameter aggregate; a 100 - 1070 mm (4 - 42 in) base course with 30 - 65 mm (1.5 - 2.5 in) rocks providing 35% void space ; and an impervious limestone bedrock base. An impermeable liner was added to collect subsurface flow. A 132 mm (5.2 in) storm (representing the 25-year 3-hour storm) was used for sizing the base course. The depth of the base course depends on hydrologic consideration except for steep slopes where structural concerns may take precedence. The depth of the base course should increase downslope to provide storage of subsurface as well as local precipitation which is infiltrated (Goforth et al., 1983).

The temperature of compaction was found to be an important parameter in the construction of porous asphalt. The open graded mix should be laid down at 127° to 138° C (260° to 280° F) but should cool to 82° C (180° F) before it is compacted. Light compaction equipment should be used to maintain at least 16% porosity in the asphalt surface (Goforth et al., 1983).

The percentage of asphalt in a mix will depend on the type of aggregate used and must balance strength of cementation with porosity. Ideally, the drainage characteristics of different mixes should be tested before selecting one (Goforth et al., 1982). A study of aggregates indicated a range of 5 - 7% asphalt was needed, dry aggregates should be avoided, loads of asphalt should be covered to prevent crusting during transportation, light weight rollers are preferable to heavy rollers, and a vibrating screen for applying the asphalt is preferable to a tamping screen (Galloway and Epps, in Goforth et al., 1983).

Thelen and Howe (1978) recommend using hard asphalt to prevent scuffing. The stone base course should consist of 38 - 63 mm (1.5 to 2.5 in.) diameter aggregates to provide 40% porosity (depth dependent on storage needed). Over the base course, 50 mm (2 in.) of 13 mm (0.5 in) diameter gravel provides a better surface for applying asphalt. The depth of the asphalt surface course need only be 63 mm (2.5 in).

Franklin Institute Research Laboratories examined the load bearing strength of different soils and developed minimum recommended thickness for porous paving depending on soil strength and level of traffic (Diniz, 1980). These are presented in Table 6.1.

Table 6.1: Recommended thickness (inches) for porous pavement as a function of soil and vehicular traffic level (Diniz, 1980)

Level of traffic	Highly granular soil	Granular soil with silt and clay	Sandy clay, sandy silt	Fine silt, clay
Light	5	7	9	9 + 2 crushed stone
< 1000 vpd	6	8	11	11 + 2 crushed stone
<3000 vpd	7	9	12	12 + 2 crushed stone

(vpd = vehicles per day)

An experimental porous asphalt facility was constructed by the US Department of Agriculture in Pennsylvania (Urban and Gburek, 1980). All soil (1 - 3.5 ft) was removed from the site including a clay subsurface horizon that might have inhibited infiltration. The underlying sandstone was ripped to form a level base for the installation and to increase the permeability and porosity of the rock (measured in-situ as 0.15 in/day and 20 to 45%, respectively). This installation consisted of two asphalt layers - an asphalt treated porous material layer and an open graded porous material layer (the wear surface). The specifications of the aggregate used in the porous asphalt are presented in Table 6.2.

Table 6.2: Aggregate specifications for base and wear courses in porous asphaltic concrete (Urban and Gburek, 1980)

Available aggregate size	Base course	Wear course
40 mm (1.5 in)	100%	100%
25 mm (1 in)	90 - 100%	100%
12 mm (0.5 in)	25-60%	100%
# 4 sieve	5%	10-30%
#8 sieve	2%	10%

The bitumen content for these two layers also varies: 1.8% by weight for the asphalt base and 5.5-6.5% for the wear surface (Urban and Gburek, 1980).

Cahill and Associates (1993) use the following design for asphalt porous pavement: a 60 mm (2.5 in) layer of aggregate/asphalt mixture; a 25 mm (1 in) choker course (uniformly-grade crushed stones less than 2 mm or 0.5 in diameter); a reservoir base course of variable depth (depending on storage and frost) consisting of 50-60 mm (2 - 2.5 in) diameter stones; and a layer of filter fabric. Cahill and Associates also includes a 2 ft. wide perimeter boarder drain consisting of large cobbles (76 mm or 3 in. diameter) over the reservoir base course to drain runoff from the edges of paved surfaces should they become clogged. They design the storage reservoir/recharge facility to drain within 72 hours of a storm ending.

Cahill and Associates emphasize a number of points regarding the construction of porous pavement systems. The sub-grade must not be compacted and vehicles should be restricted from driving on the sub-grade and limited from driving on the bed after the reservoir course material has been placed. Fine sediment should be prevented from entering the sub-grade (e.g., by using silt fences). The sub-grade should be scarified prior to filter fabric placement. Pieces of filter fabric should overlap a minimum of 400 mm

(16 in) and extend 1.5 m (5 ft) past the edges of the bed. This excess fabric can be folded over the bed edge to prevent sediment transport into the bed. The asphalt layer should be placed in one layer or lift at temperatures from 116° - 121° C (240 - 250° F) at air temperatures above 4° C (40° F). Compaction is completed with one or two passes of a 10-ton roller. Porous pavement with a storage reservoir course can be designed to receive runoff from off-site, though this runoff must not introduce sediment to the system.

6.5.3 Porous Portland Cement Concrete Pavement

Construction of porous Portland Cement concrete pavement requires attention to the same permeability porosity and strength details (i.e., size distribution of aggregate, thickness) as asphaltic concrete though the water/cement ratio and curing time are critical for porous Portland Cement concrete.

An experimental Portland Cement concrete pervious road was constructed in England in the mid-1960's. It consisted of a 200 mm (8 in) conventional wire-reinforced concrete pavement and 50 mm (2 in) pervious concrete surface. The surface consisted of Portland Cement and 10 mm (0.38 in) aggregate and compacted with 6 passes of a 300 mm (12 in) pipe roller. (Paine, 1990).

The Florida Concrete and Products Association published a design manual for Portland cement porous pavement (Paine, 1990). The design begins with initial calculations of the storage needed to meet State of Florida stormwater quality and quantity regulations. Test borings to locate impervious layers and the seasonal high water elevation and double ring (vertical) infiltration tests of the sub-grade are recommended. The manual estimates that Portland cement porous pavement with 0.375 in coarse aggregate will have from 15%-22% porosity. A procedure for testing void space, which is needed to calculate a system's storage capacity, is given in the Federal Highway Administration Report No. FHWA-RD-74-2.

Storage capacity is provided by the pavement and base course only if the system is curbed or outlets otherwise elevated. This can, however, lead to ponding in large storms. Thus, overflow systems and recovery time of storage capacity must be assessed during design. Additional drainage systems can be used with porous pavement. These include a 0.6 m (2 ft) deep sand trench with a perforated pipe serving as an under drain, a V-trench at the edge of the pavement, or a rock-filled trench or under drain. The minimum recommended width of porous Portland cement pavement is 1.8 m (6 ft).

Detailed information on Portland cement porous pavement is available in Paine (1990). Sub-grade preparation begins with consideration of the sub-grade material. If it is sandy, an additional open graded sub-base is not necessary. The sub-grade must be able to provide uniform support of the Portland cement porous pavement slabs. One option for a sub-grade is a layer of concrete with larger aggregate and less cement. A surface layer of 130 mm (5 in) thickness should provide adequate strength for light traffic. The pavement should be compacted, misted, covered no more than 20 minutes after it is placed, and allowed to cure for 3 to 7 days (Paine, 1990).

6.5.4 Construction of Modular Pavement

Modular pavements, in contrast to porous macadam surfaces, are generally prefabricated. Consequently, installation of modular pavement systems focuses on using proper materials for filling interstices, determining the infiltration capacities of soils at the site, and the design of the reservoir base course.

Most modular pavement manufacturers specify how their product should be installed. Generally, modular pavement requires a supportive base course (e.g., washed rock which also serves as a reservoir). The interstices of modular pavement are filled with a permeable material (e.g., sand), and covered with a porous top course (e.g., sand and grass). In heavier use areas, the interstices of concrete grid blocks can be partially filled with soil and planted with grass so that traffic does not compact or destroy the grass.

This technique also allows the interstices to provide additional depression storage (Goforth et al., 1983).

Concrete paving blocks used by Pratt et al. (1988) were 200 mm by 100 mm by 90 mm deep (8 in by 4 in by 4 in) and were configured in a pattern formed of holes 25 mm (1 in) in diameter. The blocks rested on a 50 mm (2 in) bed of 5 - 10 mm (0.2 - 0.4 in) gravel with a geotextile below the gravel, and a free-draining stone sub-base (Pratt, 1990).

6.6 Maintenance

For porous asphalt or Portland cement concrete pavements, the primary maintenance concern is clogging. Some have suggested flushing, pressure washing, vacuuming, or sweeping porous pavement if it becomes clogged (Diniz, 1980 and Paine, 1989), though others recommend only periodic vacuuming (twice a year or as needed) and advise against pressure washing (Cahill and Associates, 1993).

Where grass is used with modular systems, it must be watered and cut. Re-seeding or re-sodding may be necessary. If interstices become compacted or otherwise clogged, they can be excavated and re-filled. This can be a labor intensive and expensive activity.

6.7 Performance and Reliability

Performance and reliability of porous and modular pavement over time typically refer to measures of infiltration capacity, storage, clogging, structural strength, and water quality. Infiltration capacities of these systems generally decline with time. Clogging is especially a problem when installations are near construction sites or if the pavement was installed at the beginning of a construction project. Oils from vehicles clog the soil in modular pavement systems.

6.7.1 Performance of porous pavement

Field et al. (1982) in an U.S. EPA supported study in Rochester, NY indicated that a porous asphalt parking lot reduced peak runoff rates by as much as 83% with no observable structural degradation after 100 freeze/thaw cycles in winter. Initial clogging of the system was relieved by flushing from the top.

Wada and Miura (1986) reported that a permeable pavement in Japan showed that infiltration capacities between 40-50 mm/hr (1.6 - 2 in/hr) prevailed at one site, though some areas infiltrated less than 10 mm/hr (0.4 in) and created local ponding. The spatial variability of the infiltration rate may be particularly important for smaller lots and sloping surfaces.

Clogging was reported by Hogland et al. (1987) on a parking lot that had received vehicle traffic from an adjacent construction site. In a Swedish field test, clogging of a porous asphalt parking lot occurred shortly after installation when construction traffic transported fine particles to the porous surface (Niemczynowicz, 1990).

Niemczynowicz (1990) reported the initial infiltration capacity of a porous pavement lot in Sweden was 500 to 600 mm/min. After five years of intensive use, the mean infiltration capacity was reduced by 88% to 65 mm/min. with a range from 1 to 200 mm/min. The performance of porous pavement was compared with conventional concrete surfaces using simulations of a 0.2 km^2 (50 acres) urban catchment representative of the city of Lund. The catchment's soils were assumed to be impermeable, so porous surfaces detain runoff but do not reduce its total volume. If all paved surfaces were porous, peak storm flows would be reduced 75 - 90%.

Three sources of failure of porous pavements were identified in an assessment of urban stormwater best management practices: (1) clogging immediately after construction due to high post-construction sediment loads in stormwater; (2) gradual clogging due to oil and sediment; and (3) resurfacing of the porous pavement with non-porous pavement. This document also cited a 75% failure rate within 5 years for all porous pavement systems surveyed in Maryland (Anacostia Restoration Team, 1992, p. 58).

Goforth et al. (1983) compared the performance of five parking lot drainage systems in Austin, Texas. They included: porous asphalt; modular pavement (concrete lattice blocks); conventional asphalt with a gravel trench; conventional asphalt; and conventional concrete. The lots varied in size from 580 to 5,500 m^2 (0.143 to 1.364 acres) and vehicle traffic of 10 to 375 vehicles per day. For the porous asphalt, initial permeabilities (i.e., infiltration rates for periods less than 5 minutes after ponding) measured in-situ using a 150 mm (6 in) single-ring infiltrometer were lower in areas that had been compacted at temperatures greater than 82° C (180° F) and that received heavy traffic. Table 6.3, summarizes the results of hydraulic tests on porous asphalt, lattice block, gravel trench, asphalt, and concrete (Goforth et al., 1983).

Table 6.3: Runoff production from five pavement systems (Goforth et al., 1982)

Pavement system	Storm intensity (mm/hr)	Storm duration (hr)	Runoff /rain Ratio -surface flow	-subsurface flow
Porous asphalt	9.4	1.0	0	0.73
	4.8	1.0	0	1.28
	16.7	0.9	0	0.37
Lattice block	8.5	1.3	0.18	0
	10.8	1.0	0.36	0
	19.0	0.6	0.23	0
Gravel	4.1	1.6	0	0.76
	5.6	1.2	0	0.64
	6.5	1.0	0	0.77
Asphalt	4.4	0.8	1.18	0
	12.6	0.2	0.71	0
Cement	4.3	2.0	0.55	0
	10.4	0.6	0.48	0
	3.0	1.5	0.38	0

Runoff/rain ratios greater than one result when rainfall is underestimated and runoff is overestimated even if both estimates are within the accepted limits of precision. The actual effect of each paving system on peak storm flows or total storm flow volume depends on the surface and subsurface drainage systems installed. These results support the conclusion that porous pavement systems direct the flow of stormwater into the ground but retain the water near the surface in vegetated systems (e.g., modular pavement).

Gburek and Urban (1980) monitored the response to natural rainstorms of an experimental porous asphalt facility in Willow Grove, Pennsylvania. When rainfall was sufficient to percolate into the sub-base (> 10 mm or 0.3 in.), a rise in groundwater level was observed 2 hours after percolation began. The level generally reached a maximum 6 hours after a storm ended. After 74 mm (2.9 in.)of rain in 8 hours, the local groundwater level (6.7 m or 22 ft. initially) rose 1.8 m (6 ft) while under the pavement it rose 4.9 m (16 ft). Within a week, the mound had dissipated. While neither the local grass plot nor the porous pavement generated runoff, the grass appeared to hold moisture near the surface while the porous pavement recharged the aquifer.

A survey of Portland cement concrete porous pavement installations in Florida indicated variable results in the infiltration capacity. The oldest sites were impervious (0.2 mm/hr or 0.007 in/hr) because the surface had been sealed with cement at the time of placement. Three other sites had permeabilities of 120 - 160 mm/hr (4.8 - 6.3 in/hr). The sub-grade permeability did not appear to decline during the life of the installations (Paine, 1990).

Coyler (1982) found that porous asphaltic concrete can store approximately 4 mm (0.16 in) of rain though initially it may be able to store as much as 7.5 mm (0.3 in) in depressions that later fill with sediments.

Water-quality effects of porous pavement were studied in Sweden in a full-scale field test. A porous pavement system was found to filter 50% of the total solids, phosphorous, and heavy metals. Laboratory test, designed to investigate the long-term (the equivalent of 30 yrs. of stormwater) effect of clogging and pollution migration, indicate the pollutants migrate and concentrate at the geotextile layer below the asphalt and base course of gravel with relatively high concentrations also occurring at the pavement surface (Niemczynowicz, 1990).

The strength of open-graded porous asphalt was lower than for conventional dense-graded hot mix asphalt especially around 21° C (70° F). Between 21° and 38° C (70° and 100° F), the minimum tensile strength of porous asphalt cores was 4.2 kg/cm^2 (60 psi) compared with 6.0 kg/cm^2 (85 psi) for conventional asphalt at 38° C (100° F). In spite of its lower strength relative to conventional asphalt, the strength of open-graded asphalt is sufficient for its use (Goforth et al., 1982).

6.7.2 Performance of modular pavement

A laboratory study of three types of modular pavement and a conventional concrete surface was conducted at the Virginia Water Resources Research Center. Runoff from each surface was measured for 10 different storms ranging from 30 to 120 minutes in duration (Day et al., 1981). Results of this study are presented in Table 4.

Table 6.4: Runoff from four types of modular pavement (Day et al., 1981)

Pavement type	Mean storm intensity (mm/hr)	Mean storm duration (min)	Mean runoff/rainfall ratio
Monoslab	3.9	60	0
Grasscrete	4.7	60	0.004
Turfstone	4.2	60	0
Concrete	4.9	56	0.78

These coefficients only account for surface runoff. Since shallow subsurface runoff, especially in porous material can contribute to quick-response storm flow, these coefficients do not indicate the reduction in storm flow volume that would result from modular pavement.

Pratt (1990) reported on the hydrologic responses of concrete paving blocks which provided between 6.5 and 9.5 mm (0.25 - 0.37 in) of surface storage over the paved area. They discharged 16 and 42% of incident rainfall for events of 11 and 21.6 mm (0.4 and 0.9 in), respectively. The combined surface and subsurface discharge amounted to 43% of the 11 mm rain event.

Sztruhar and Wheater (1993) found that modular pavement had surface storage of up to 21 mm (0.8 in). The systems they examined delayed storm flow such that only 40-45% of the rainfall input was discharged during the first 50 minutes for loamy and gravely soils and 64-71% after 100 minutes. For comparison, conventional pavement might discharge 90% of rainfall during the first 50 min.

Day et. al. (1981) examined the changes in concentrations of 10 pollutants as water infiltrated modular pavement systems. Metal removal was high, phosphorous variable, and nitrate concentrations increased as stormwater passed through the grass and soil. Day et. al. (1981) emphasized the importance of soil texture for pollutant removal.

6.8 Cost

The cost of porous and modular pavement differs from the cost of conventional pavement because of differences in:

(1) aggregate and mix (i.e., asphalt or Portland cement) specifications;

(2) methods for placing the pavement;

(3) excavation for base course reservoir; and

(4) materials and construction of stormwater drainage system.

Generally, the cost of excavation is higher for porous pavement construction while stormwater drainage systems are more expensive for conventional pavement installations. In most cases, the difference in costs of conventional and porous pavement are close. Cost estimates must be accurate and precise to be able to identify real differences between conventional pavement and drainage system and comparably sized porous pavement systems.

An example is provided by The Florida Concrete and Products Association which estimates that a 3,300 m^2 (4,000 yd^2) porous pavement parking lot could cost $30,000 less than a convention parking lot when the cost of stormwater drainage (pipes, inlets, curbs, retention areas, etc.) are considered ($28.00/$m^2$ or $23.50/$yd^2$) (Paine, 1990).

6.9 Summary

There is little information available on the long-term drainage properties and durability of permeable pavements for the Puget Sound lowlands. Permeable pavements offer an alternative to traditional continuous, impervious pavements. Permeable pavements may reduce quick response runoff during small storms and provide water quality benefits by filtering sediments and adsorbing pollutants in stormwater. These benefits, however, require that the selected paving system is appropriate to the level of traffic an area receives and that the pavement is constructed and maintained for its intended use.

7. SUMMARY OF ON-SITE STORMWATER MANAGEMENT

Stormwater can be managed on-site in residential areas using a variety of alternative systems. The alternatives discussed here address all of the stormwater-producing parts of residential areas including roofs, roads, and landscaping. While there has been some research reporting on the efficacy of the different stormwater management alternatives, the results are often qualitative, theoretical, or anecdotal. Furthermore, the life-cycle costs and long-term efficacy are not known for on-site systems. In many cases, there is a lack of information on the hydrologic functions inherent in the alternatives and, consequently, on the stormwater management performance of the alternatives.

The lack of information is due, in part, to the site-specific nature of system performance. Each site has its particular climate, geology, topography, and vegetation which influence the natural production of stormwater. There are also physical changes imposed by development activities at sites that modify the hydrologic response of the land to storms. The performance of any stormwater management system relative to natural conditions, then, is influenced by a unique set of factors.

Another reason for the limited reports on on-site stormwater management techniques is the prevailing regional approach for stormwater management. Stormwater management efforts have emphasized large capital projects that detain or convey large volumes of stormwater. As a result, the performance of stormwater management systems traditionally has been described in regional terms and the on-site hydrologic effects of small systems have received limited attention.

The potential for on-site stormwater management remains to be determined. On-site stormwater management techniques offer ways to restore some of the natural hydrologic functions of land that is converted from forest to residential (or commercial) development. Applied over a large area, on-site techniques could reduce the volume and peak rates of runoff that regional stormwater facilities must manage. To fill in the information gaps, much research needs to be performed to identify the costs and effects of integrated on-site residential stormwater management.

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