Field Evaluation of Permeable Pavement Systems for Improved Stormwater Management

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The contribution of impervious surfaces to the disrupted runoff processes in an urban watershed is overwhelming. Nearly all the problems ultimately result from the loss of the water-retaining function of the soil in the urban landscape. Traditional solutions for stormwater management have not been widely successful; in contrast, permeable pavements can be one element of a more promising alternative approach to reduce the downstream consequences of urban development. We report on a constructed experimental facility for measuring water quantity and water quality from four different permeable parking surfaces. Preliminary results demonstrate similar runoff performances of the surfaces relative to each other, and significant attenuation of runoff relative to traditional asphalt.

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Wherever grasslands and forest are replaced by rooftops and roads, the movement of water across the landscape is radically altered. Some of these changes are intentional and render the land more useful for the purpose for which it has been altered. Yet some changes are unintended and can have severe consequences, particularly as a result of disrupted runoff processes (e.g., Hollis, 1975; Klein, 1979; Saver, Thomas, Stricker, & Wilson, 1983; Steedman, 1988; Limburg & Schmidt, 1990; Booth & Reinelt, 1993). Such effects as flooding, channel erosion, landsliding, and destruction of aquatic habitat have been recognized for decades (e.g., Wilson, 1967; Seaburn, 1969; Hammer, 1972; Leopold, 1973) because of the loss of lives and damage to property that can result. With urbanization, stream channels expand catastrophically to consume adjacent land never before affected by either flooding or erosion, sediment inundates low-lying areas seemingly far away from active channels, stormwater facilities are overwhelmed by frequent flows far beyond their design capabilities, and populations of aquatic organisms are decimated. In small streams draining lightly to moderately urbanized watersheds, these environmental and ecological consequences of increased water *quantity* generally overwhelm the effects of impaired water *quality* (i.e., the chemical constituents carried by runoff; see Horner, Booth, Azous, & May, 1996).

Nearly all these water quantity problems result from one underlying cause: loss of the water-retaining function of the soil in the urban landscape.

This loss may be absolute, if the loose upper layers of the soil are stripped away to provide better foundations for roads and buildings. The loss may also be functional, if the soil remains but paving or rooftops block absorption of precipitation. In either case, a stormwater-runoff reservoir of tremendous capacity is removed from the stormwater runoff system. Water that may have lingered in this reservoir for a few hours, a few days, or many weeks now flows rapidly across the land surface and arrives at the stream channel in short, concentrated bursts of high discharge (Booth, 1991).

Traditionally, this change has been addressed by replacing the lost functions of the soil reservoir with a new, constructed reservoir (Dunne & Leopold, 1978; Whipple, 1979). To achieve this, a stormwater collection system routes the runoff from paved surfaces into an excavated "detention pond," designed to mimic the functions of the soil reservoir (Yrjanainen & Warren, 1973; U.S. Soil Conservation Service, 1975; Harbor, 1994). The pond accepts water at whatever rate it flows off the developed land surface but releases it at a much slower, presumably "natural" rate. This approach almost entirely separates the design of the development from the management of stormwater: The stormwater, displaced by human structures, is shunted to a point where "management" then takes over.

However, this strategy has proven surprisingly ineffective. The primary reason is one of *scale*—the volume of water retention in the soil that is lost, typically several inches to nearly a foot of depth over the developed area, is replaced by only a few tenths of an inch of volume in the detention pond. This represents a reduction in "reservoir" volume of perhaps 90% or more, so there should be little surprise that substantial downstream consequences result. Most detention ponds, unless designed to truly extraordinary (and thus no less costly) standards, have little or no effect on the quantity of runoff entering stream channels (Booth & Jackson, 1997).

This fundamental shortcoming is amply displayed by abundant empirical and hydrologic evidence of continued stormwater impacts downstream of detention facilities (e.g., Barker, Nelson, & Wigmosta, 1991; King County, 1990, 1993). Attempting to hold all runoff in a central facility, removed from the developed area itself, suffers from several additional drawbacks. First, construction and maintenance of stormwater facilities are distressingly erratic, with striking divergence between design targets and actual performance. Second, there are practical limits to applying drainage regulations to individual small-scale land developments. Jurisdictions typically set a minimum "threshold of concern" for nearly all development activities: above this threshold the drainage regulations apply, but below this level regulations are minimal or absent. For example, King County, Washington, stipulates a minimum 0.50-cubic-foot-per-second (cfs) increase in runoff, equivalent to about 0.5 acre impervious surface, before mitigation is required. Yet King County permit activity for 1987-1992 indicated that about one quarter of the impervious area added to the County's watersheds was in individual developments below this threshold and so was constructed without any detention facilities at all (Booth & Jackson, 1997).

In addition, almost all hydrologic models used to determine the size of detention facilities make the presumption that surface water exits a watershed at a single point discharge. After development this is invariably true: a constructed channel or a culvert outfall is generally quite identifiable. Before development, however, watersheds up to several tens of acres may have no discrete surface-water discharge point at all. Even if discharges were matched precisely in pre- and postdeveloped cases, the change from a subsurface to a surface flow regime renders the entire design analysis irrelevant and can lead to severe and entirely unanticipated channel incision (Booth, 1990). Other region-specific conditions, such as high water tables (McCann & Olson, 1994) or freezing (Oberts, 1994), can also pose substantial challenges to effective mitigation through the use of centralized stormwater facilities.

Finally, even the largest and best designed stormwater pond cannot transform precipitation during the wet season into runoff during the subsequent dry season; detention times are simply too brief. As a result, urban channels tend towards lower baseflow between storms and longer intervals of no flow (Klein, 1979; Simmonds & Reynolds, 1982). This relationship changes only if imported water, as from irrigation or septic systems, augments the dry-season flow (Ku, Hagelin, & Buxton, 1992). Otherwise, only a "reservoir" of sufficient volume (namely the soil column itself) can adequately mitigate this condition.

Our study of permeable pavements has evolved from a growing recognition of the limitations of traditional stormwater management (Schueler, 1995). To achieve the benefits of keeping water in the soil, we must allow access of water to that soil across much of the landscape, developed as well as undeveloped (Ferguson, 1995). This effort may raise new concerns; soils are not always suitable, and groundwater can be contaminated by runoff constituents. The first concern requires a preliminary, but by no means extraordinary, investigation of onsite soils. The second concern is legitimate but probably irrelevant in most applications, because the most common potential pavement-related pollutants are either rapidly sequestered during infiltration (e.g., heavy metals) or unaffected by *any* level of runoff treatment (notably chloride from road salt) before being discharged to the natural surface or groundwater system (Pitt, 1994; Novotny & Olem, 1994; Pitt, Field, Lalor, & Brown, 1995).

Project Objectives

The project reported here explored some practical implications of alternative stormwater management practices. Rather than attempt to describe and examine the entire range of stormwater infiltration (e.g., Ferguson, 1994), we focused on the use of manufactured permeable pavers in parking areas because the construction materials are readily available, because this land use typically accounts for a significant fraction of the runoff-generating area of urban development (City of Olympia, 1995), and because opportunities for relatively low-cost options appear to be great. This project was therefore developed around the following three tasks:

1. *Review existing information* on the types and characteristics of permeable pavements, to provide simple and readily accessible information to potential users of these systems.
2. *Construct and make operational a well-instrumented, full-scale test site* where parking occurs regularly and that permits evaluation of the durability, infiltratability, and water quality benefits of a representative sampling of permeable pavement systems.
3. *Evaluate the long-term performance* of these systems for maintenance needs, surface clogging, and the chemical quality of runoff being reintroduced to groundwater.

This article documents our efforts on the first two elements of this project, through which we can offer guidance on the following questions:

- What are the relative difficulties and costs of installing different infiltration systems?
- How well does each system infiltrate surface runoff in a site with intrinsically favorable soil conditions, both qualitatively and quantitatively?
- Are any special benefits and/or requirements imposed by grass, as opposed to gravel, as the surface filling?
- What are the initial water quality benefits of each system?

Types and Characteristics of Permeable Pavements

In the evolution of incorporating pervious areas into paving systems, concrete was the first widely used material. Permeable concrete paving comes in two forms: cast-in-place systems and precast modular units. Cast-in-place systems are monolithic and are made with reusable forms to create the voids needed for filling with gravel or planting with grass. This alternative is very strong when reinforced with welded wire mesh, which prevents the differential settlement sometimes experienced with modules. However, the installation is more labor-intensive than that of the precast modular pavers.

More recently, plastic products have been introduced to take advantage of their light weight and relative ease of installation. Most are composed of 50 to 100% post-consumer recycled materials. Flexible systems can be obtained in long rolls, which are positioned quickly; rigid modules, like their concrete counterparts, are laid in a running bond pattern and either interlock or are pinned in place. Plastic pavers, whether rigid or flexible, have less intrinsic strength than concrete pavers. With adequate base and subgrade preparation, any of these systems is fully capable of supporting heavy vehicular traffic loads, even when the ground is fully saturated with water. The compressive strength of a permeable paver system relies in large part on the strength of the underlying soils, particularly in the case of modular or plastic units where the "pavement" itself lacks rigidity. Although less intrinsically strong, flexible materials have a compensating advantage of being more easily laid over irregular surfaces. The shape and aggregate area of the openings (80-100%) vary among products, but these types of pavers are designed to be completely covered with grass or gravel and therefore are not visually intrusive.

Installation requirements and costs vary with the type of system. Plastic products can be moved and cut easily with hand tools, so they can fit into irregular spaces and around utilities with little or no special preparation or effort. Concrete systems require up to one-third more time to install because of their weight and rigidity. Either type of system is more labor intensive when infilled with grass than with gravel or stone, because of the added attention required for soil preparation, sodding (common for plastic systems) or seeding (generally mandatory for concrete systems), and initial irrigation until the grass is well established. Grass also requires a period of no traffic following installation, typically 1 or 2 months, to allow the root system to become established; even after establishment, the frequency of traffic on a grassed surface must remain low (typical recommendations are 1 to 2 trips per day).

Previous studies (e.g., Nichols, 1992; Sorvig, 1993) have suggested that permeable pavement is only modestly more expensive than traditional asphalt. We could not support this assertion, however. Based on manufacturers' quotes in early 1997, these systems generally cost substantially more to purchase and install than asphalt. Typical parking-lot asphalt paving over a prepared base course ranges from $0.50 to $1 per square foot (Smit, 1994); equivalent quoted costs for permeable pavement systems ranged from 25% to over 300% more, depending on the type of material used and whether volume discounts were assumed. Speculation is common that total project costs may actually be *lower* with permeable pavements if the expense of associated drainage facilities to manage impervious-surface runoff is included in the comparison. This requires the permitting jurisdiction to fully credit the anticipated stormwater management capabilities of these systems. To date, this has not been a common occurrence.

Full-Scale Field Evaluation of Permeable Pavements

The second element of this project involved the construction of a parking facility using permeable pavements with automatic runoff monitoring equipment. From the large variety of infiltration systems currently available, we selected four which span a wide range of impervious-surface coverage and include both grass and gravel surfaces:

- Grasspave^{2}®, a flexible system with virtually no impervious-area coverage by a plastic network (grass infilling)
- Gravelpave^{2}®, an equivalent plastic network with gravel infilling
- Turfstone®, a system with about 60% coverage by impervious blocks (grass infilling)
- UNI Eco-Stone®, with about 90% coverage by impervious blocks (gravel infilling)

Two adjacent parking stalls were constructed using each system, for a total of eight stalls (see Figure 1). A ninth stall of traditional, 100% impervious asphalt was also included as a control. A system of pipes, gutters, and gauges was installed to collect and measure the quantity and chemistry of surface runoff and subsurface infiltrate (see below).

The selected site, a portion of a new employee parking lot at the southeast corner of the King County Public Works facility in Renton, Washington, met three criteria: (a) intrinsically favorable soil conditions for infiltration, so the pavement system and *not* the local soil conditions were being evaluated; (b) good security for monitoring equipment; and (c) frequent use. The facility sits above the valley floor of the Cedar River on a glacial-age terrace underlain by several hundred feet of sand and gravel (Mullineaux, 1965). The area has been mined for coarse aggregate for decades; one of the most successful stormwater infiltration facilities in the region lies within 100 yards of the test site. The stalls are used consistently on a daily, once-in-and-out basis, with no cars parked overnight or on weekends. The entire facility is surrounded by a fence and is gated and locked during non-business hours.

Construction proceeded without unusual attention to installation details. Typical engineering plans were drawn up and manufacturers' specifications for subgrade preparation were duly noted. However, our intention was to determine the long-term function of these systems under typical conditions of installation as well as of use, so no extraordinary efforts were made to acquire highly select earth materials, or to prepare the subgrade with any more than the usual level of care given by a contracting pavement crew with a full set of plans and an on-site supervisor.

Whereas the gravel-filled systems are ready for immediate use after final compaction of the finished surface, grass-filled systems require 1 to 2 months for grass establishment. Irrigation was mandatory through the first year's dry season. The clean sand specified for the Grasspave^{2} topping was particularly susceptible to drought; our grass coverage has not yet exceeded about 80% after two growing seasons. Grass establishment in the Turfstone stalls was more readily achieved, probably because the growth medium is a sandy loam topsoil instead of clean sand; the Turfstone is only 40% open space, so the growing areas effectively receive over twice the actual rainfall; and the concrete grid provides some mechanical protection for the grass.

Our instrumentation was designed to measure the quantity and timing of both surface and subsurface runoff emerging from each of the pavement types. In addition, it needed to record rainfall and to allow collection of representative samples for water quality testing (see Figure 2). Each test area is 20 feet long and wide enough for two vehicles (the control area is wide enough for only one vehicle). Locations of the subsurface troughs are shown on Figure 2 by the dashed lines; locations of the concrete gutters for surface runoff are shown by the band across the head of each stall (nearest the instrument boxes) that routes water into the driveway drains. Arrows indicate the direction of surface and piped water flow.

Surface runoff was collected in the concrete gutter constructed across the head of each pair of stalls. The pavement surfaces were graded to slope 1 to 2% towards

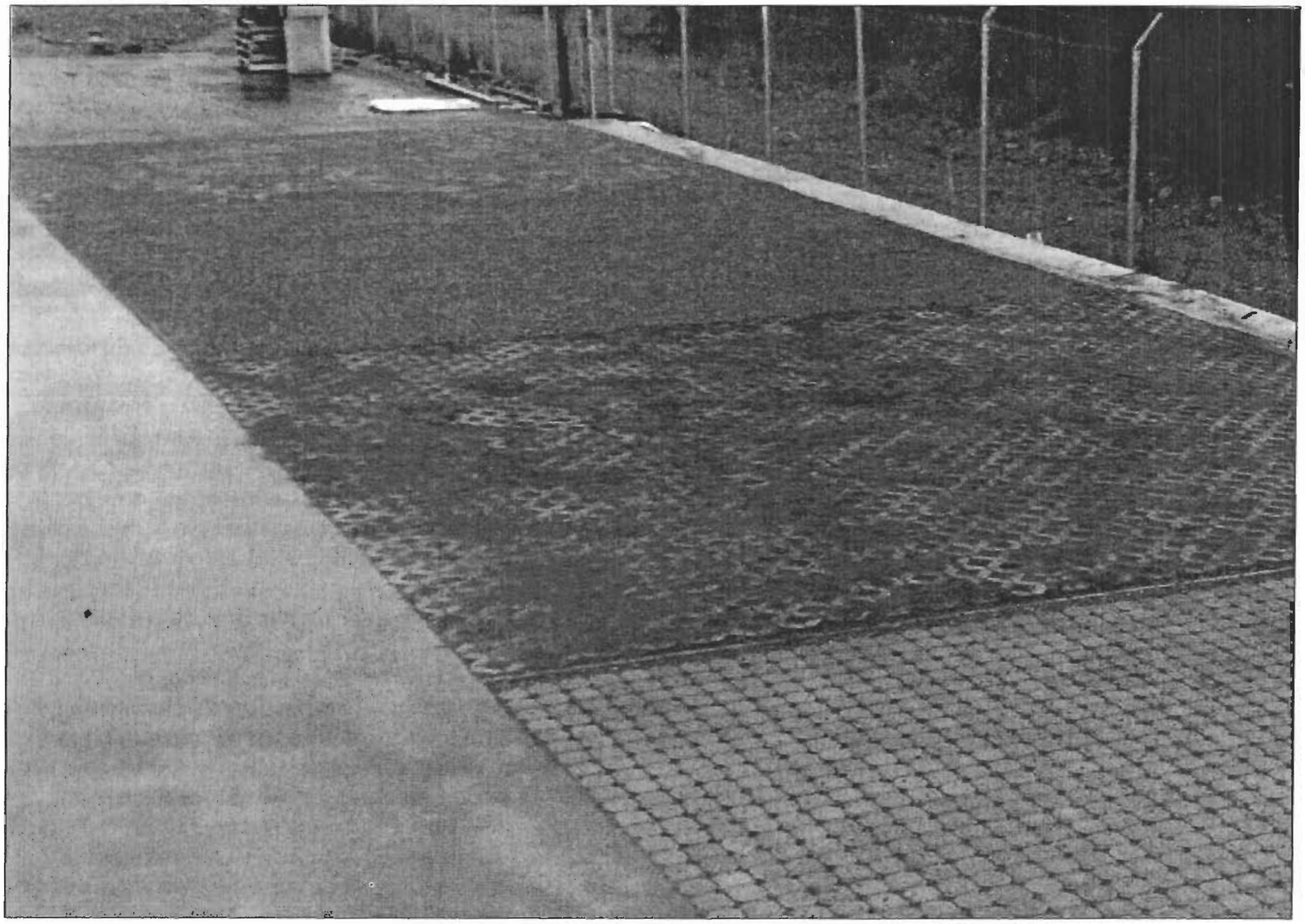

FIGURE 1. Test site shortly after construction and seeding (asphalt berm not yet installed).

the gutter, and wooden barriers were placed to block surface flow from moving laterally from one stall to another. A 2-inch-high asphalt berm surrounds the entire experiment area, so that the only water flowing over or through the surfaces originates from precipitation on the parking stalls themselves. The concrete gutter is partitioned so that surface flow from each pavement type is isolated and routed into a corresponding instrument bay and flow gauge. A sheet-metal lid over the gutter excludes nearly all the precipitation that would otherwise have fallen directly on the gutter and been erroneously recorded as runoff.

Collecting the infiltrated subsurface water required a different strategy, because any attempt to capture the entire volume of infiltrate would risk "backing up" water to the surface of the ground, affecting observed performance simply as a consequence of the monitoring system's presence. To avoid this, only a small fraction of the area of infiltrating runoff (about 1.8%) is collected in two subsurface troughs, embedded about 1 foot below the surface and extending down the middle of each stall (see Figure 2). The disadvantages of this collection system are the incomplete representation of the sampled water, which will be subject to proportionally greater oil and gasoline leaks because it is taken from directly beneath where vehicles park, and the absence of any collection when the stalls are occupied by vehicles (about 30% of the hours in a normal week). The critical advantage, however, is that the system does not affect the overall infiltration through the paving surface.

Both surface and subsurface water are piped to instrument bays at the head of each pair of stalls. There, two two-chambered tipping bucket gauges, with an approximate volume-per-tip of 0.1 liter, measure discharge. A magnetic reed switch mounted on the body of each gauge records the passage of a magnet on the tipping

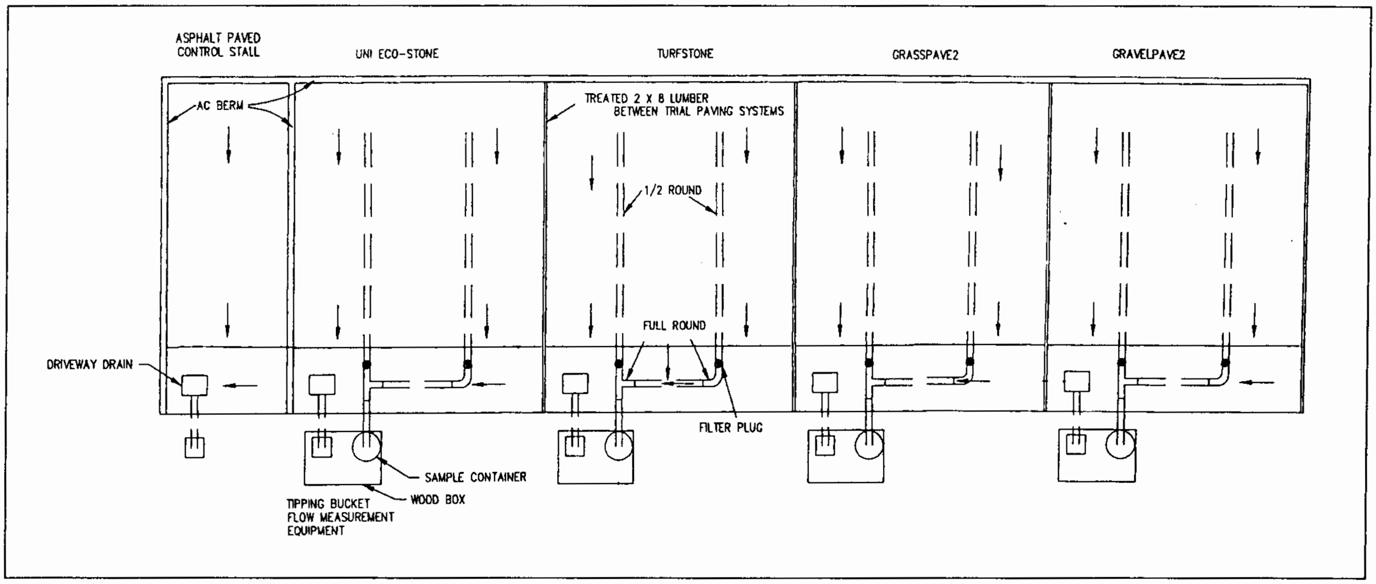

FIGURE 2. Plan view of experimental stalls.

bucket assembly as one side empties and the other side is brought into position. The asphalt parking stall, however, has no subsurface collection system or gauge at all, and the single (surface) flow gauge has a volume-per-tip about six times greater than the others. All the data collected by the flow gauges, plus an adjacent rain gauge, are recorded by an on-site datalogger.

Results of Initial Data Collection and Analysis

The site instrumentation and first sequence of data collection and analyses were designed to test three major hypotheses:

1. Replacing asphalt with pervious pavement dramatically decreases surface runoff and attenuates peak discharges.
2. Although different pavement systems have different mechanical properties and ranges of suitable applications, significant hydrologic differences among the different types of pavers do *not* exist.
3. Certain characteristics of intensity and duration of a storm, and weather conditions prior to a storm, may influence the hydrologic response of these pavers.

Based on the data collected throughout the autumn and early winter of 1996-1997, rain at the site commonly falls at rates of 5 to 10 mm per hour (0.2-0.4 in./hr) for periods of an hour or more during storms. Light rainfall of 1 to 3 mm per hour (0.04-0.12 in./hr) is also common. The most intense rainfall recorded during this period was 14 mm per hour (0.55 in./hr), limited to short bursts lasting no more than 15 minutes (the minimum time step recorded by our datalogger).

Comparison of Surface Runoff from Pervious and Asphalt Surfaces

The major purpose of this study was to evaluate the degree to which pervious pavers reduce surface runoff; the example shown in Figure 3 was chosen to illustrate this phenomenon directly. Using data collected from a storm on November 27, 1996, between 3:30 a.m. and 1:30 p.m., it compares the volume of surface runoff generated from the Turfstone stalls with the volume of runoff from the asphalt.

This storm had a maximum rainfall intensity of 4 mm (0.16 in.) per hour, a typical mid-point value for the range of storms recorded, with fairly uniform distribution throughout the duration of the storm. Rain falling on the asphalt mostly ran off the surface, as recorded by the sharp hydrograph peaks and high rates of discharge that approached the maximum rainfall intensity. In comparison, only about one tip per hour (0.03 mm/hr) was recorded from the surface of the Turfstone. This is equivalent to approximately 0.1% of the total rainfall and is more likely a result of observed leaks in the covering over the collection gutter than runoff from the Turfstone surface itself. The virtual absence of surface runoff

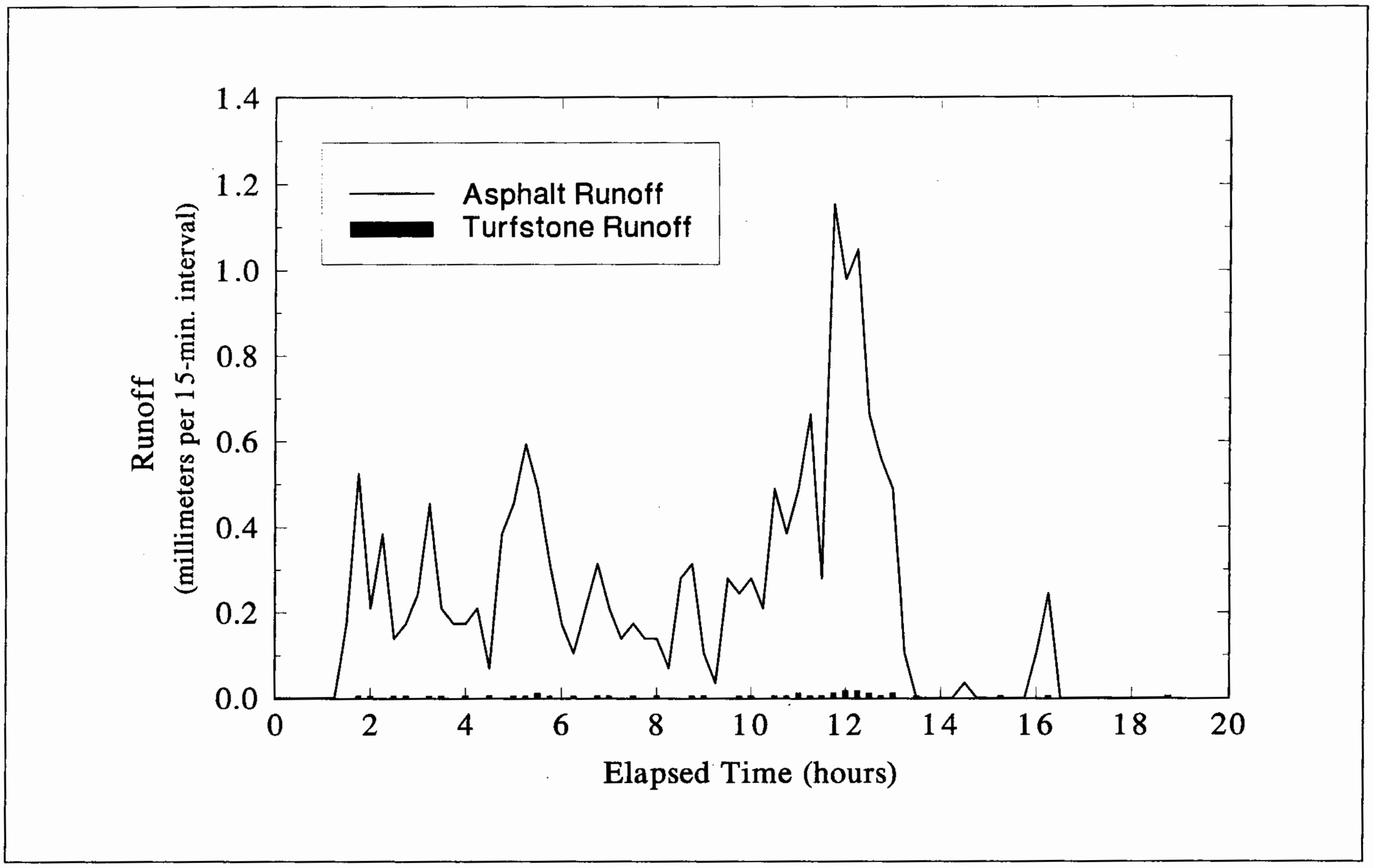

FIGURE 3. Comparison of asphalt and Turfstone runoff, storm of November 27, 1996.

was typical throughout our period of data collection and was supported by data from all of the gauges recording surface runoff from the permeable surfaces.

Comparison of Rainfall Rates and Subsurface Runoff

In contrast to the rapid response of surface runoff to rainfall, subsurface flow generally responds more slowly and more uniformly. Even at our field site, where the subsurface flow path is no more than 4 inches long before entering the collection trough, these differences are evident. The data of Figure 4 were recorded on November 12-13, 1996, between 8:45 p.m. and 5:00 a.m., from a storm of short duration with moderate-intensity rainfall. Individual peaks on the bar graph indicate rainfall rates as high as 14 mm per hour during single 15-minute intervals.

If surface runoff were to have occurred, similarly high peak discharges would be anticipated with very short time lags between rainfall and runoff spikes. However, the runoff gauges on all four pervious systems showed virtually no surface runoff at all. On average less than 0.03 mm of runoff (i.e., one tip) was recorded, again more likely due to leaks in the gutter covering than true surface runoff produced from the pavement surfaces. Thus the subsurface hydrograph shown in Figure 4 characterizes the *complete* runoff response of a pervious paving system, in this case Grasspave[2]. It displays characteristically attenuated discharge peaks and a lagged response to the rainfall inputs. The other pervious surfaces responded similarly, with virtually no surface runoff and a similar subsurface response.

Water Quality Results

Because of the relatively short period of time since the facility became operational, we anticipated little water quality information to emerge that would have significant long-term implications. Nevertheless, we wished to ensure that our sample-collection equipment and procedures worked well, and that we could start to identify the parameters of greatest potential use for a future long-term study.

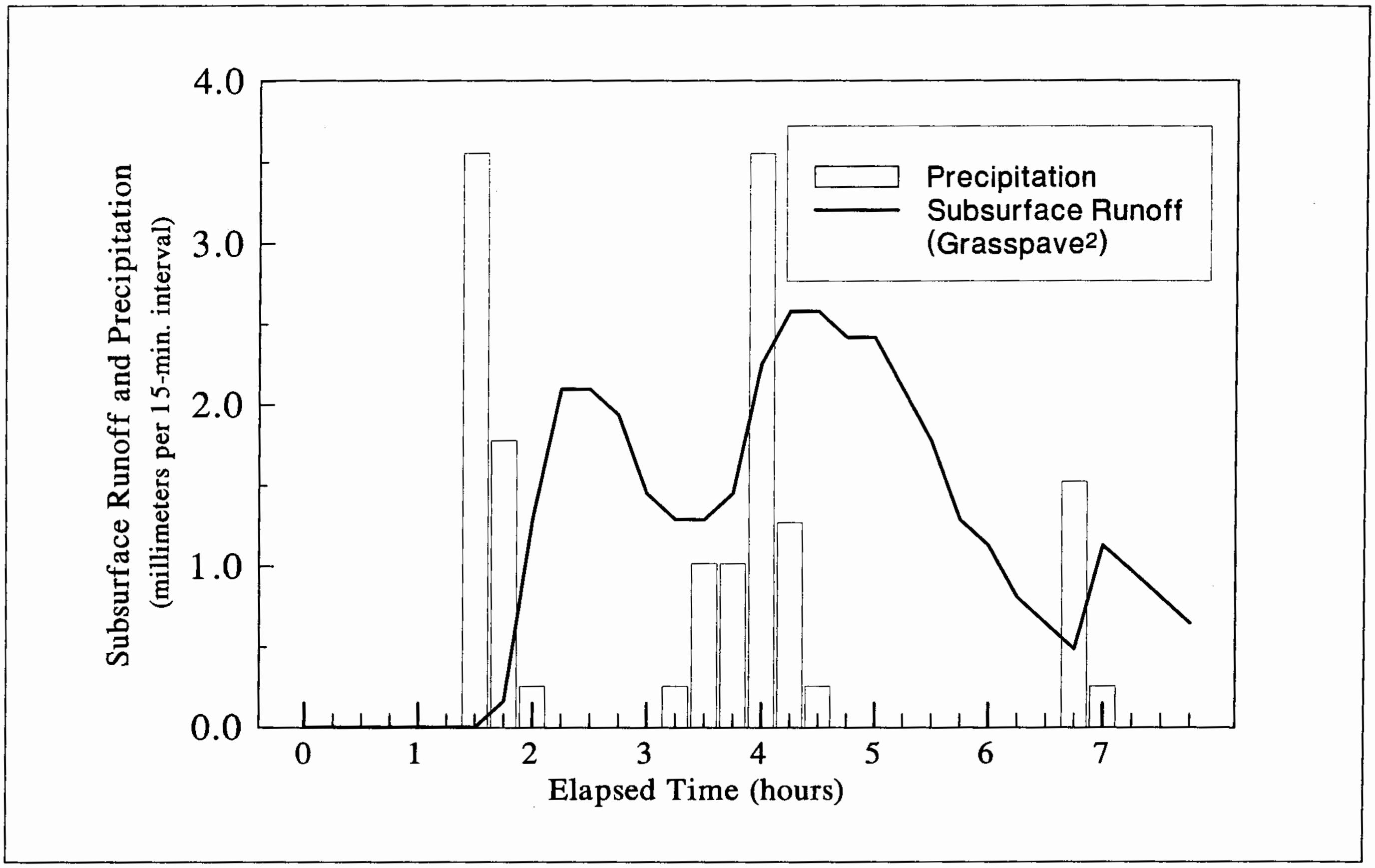

FIGURE 4. Comparison of subsurface runoff and rainfall, storm of November 12–13, 1996.

Based on these goals and the anticipated chemistry of the runoff and infiltrate, the water quality sampling was designed to meet the following criteria:

- Three storms in the autumn of 1996 to be sampled, with 24 hours or more of antecedent dry conditions
- Discharge-proportional sampling over at least a 12-hour period of rainfall
- Analysis for the primary constituents of concern in this setting: total petroleum hydrocarbons (gasoline and diesel), dissolved metals (copper, lead, and zinc, plus hardness), and conductivity

Samples were collected directly from the tipping bucket gauges. Because the permeable materials produced little or no surface runoff, only five samples—from the four subsurface collection troughs and the asphalt surface runoff flow gauges—were collected from each storm. Ideally, the required sample volume (about 1 to 2 liters) would be collected proportionally throughout the duration of a storm that delivered 13 mm (0.5 in.) of rain. This is the "water quality design storm" for the Seattle area; in an average year, 70% of the area's rain is delivered in storms of this size or smaller (Washington State Department of Ecology, 1990). Storms with greater rainfall may produce more severe drainage problems, but they actually contribute little to the total annual volume of runoff. Because 1 liter is only a fraction of the 8.9 liters of infiltrate that our subsurface troughs would ideally collect from 13 mm of rain, a splitter was designed to catch only a fraction of the water from each tip of the gauges. This yielded a proportional sample of the first 10–15 mm of rain before the sample bottle filled entirely.

Chemical analyses of the collected samples, performed by the Metropolitan King County Environmental Laboratory in Seattle, showed subdetectable levels for several of the constituents and relatively low levels for all tested compounds (Table 1). In particular, total petroleum hydrocarbons (gasoline and diesel) were not detected in any samples, and the measured concentrations of all the most common metals were low and substantially below the reported nationwide averages (Horner, Skupien, Livingston, & Shaver, 1994). This outcome is not surprising, given the relatively young age of the parking lot. Curiously, the subsurface samples showed slightly *greater* concentrations, on average, than the surface runoff; this may have resulted from sampling the "dirtiest" 2% of the subsurface runoff, immediately beneath where vehicles park. However, concentrations in even these "dirty" samples were one or more orders of magnitude *below* typical values seen in urban runoff, and thus they pose no apparent concern. From an inspection of the water quality results (but no formal statistical analysis), no significant differences have yet appeared between the water quality samples collected from the different permeable systems.

Limitations of the Recorded Flow Data

Collection of flow data has been reliable despite some intrinsic limitations of the site and the instrumentation. These limitations are few, but they help us establish reasonable expectations for the long-term utility of the experimental site.

First, to ensure that no data is overwritten between field visits, the datalogger compiles data over 15-minute intervals and the individual flow gauges require at least 0.03 mm of runoff to respond. Because light rainfall does not fill the gauges rapidly, the recorded data are not refined enough to accurately characterize the response of these pavers during low-intensity storms. However, since the focus of this study was on moderate to high rainfall, which is typically responsible for drainage problems, this limitation is not particularly severe. Performance of infiltration systems under very low rainfall intensities is generally optimal.

Second, the subsurface system is not capturing the full volume of rainfall over the area of the underground troughs, despite the absence of observed surface runoff. Possible explanations are that the filter fabric covering the top of the troughs sheds some water, that the system cannot accommodate the highest rates of surface infiltration, or that fine sediment may have reduced the permeability of the washed gravel filling in the troughs. We excavated two of the stalls in early 1998 and saw clear evidence that the overlying filter fabric "wicks" some moisture around the sides of the troughs. The consequences of these errors are not significant for our evaluation or conclusions.

Findings

The overall intent of this study was to remove some of the lingering uncertainties surrounding the use of permeable pavements and to disseminate more widely the information that is already well known and adequately proven in field applications. Although we report here on only a small-scale test site, several broader implications are clear:

- The differences in runoff responses from permeable and impermeable surfaces are quite

TABLE 1. Water quality results (detected constituents only; average of three storms 11/25/96, 12/8/96, and 12/25/96).

Material	Copper (μg/l)	Lead (μg/l)	Zinc (μg/l)	Aluminum (mg/l)	Barium (μg/l)	Calcium (mg/l)	Iron (mg/l)	Magnesium (mg/l)	Manganese (μg/l)	Sodium (mg/l)	Hardness Calc (mg CaCO3 per l)	Conductivity (μ mho s/cm)
Grasspave^2 (subsurface)	21.4	0.00	2.5	0.44	4.60	7.5	0.31	0.98	7.7	7.0	22.8	94
Gravelpave^2 (subsurface)	1.9	0.41	2.0	0.75	7.43	6.2	0.55	1.16	12.5	4.5	20.3	63
Turfstone (subsurface)	1.4	0.00	0.0	0.31	6.32	16.3	0.18	2.10	5.0	11.0	49.4	111
UNI Eco-Stone (subsurface)	14.3	0.62	7.9	0.78	7.12	7.1	0.68	1.27	22.3	7.6	23.0	44
Subsurface, average	10	0.3	3	0.57	6.4	9.3	0.43	1.38	12	7.5	28.9	78
Asphalt, average	9	0.2	12	<MDL**	2.7	2.3	0.02	0.12	9	1.5	6.1	17
Reported means, urban runoff*	34	140	160	means and thresholds not reported								
Limits for protection of aquatic life*	7	34	30									

*(Horner et al., 1994)

**<MDL=below minimum detectable levels

dramatic. At least where soil conditions are suitable, permeable pavements are quite successful at managing runoff from small and moderate storms.
- All permeable pavements, regardless of the type or brand, accomplish the basic hydrologic goal of infiltration quite well. They do differ, however, in how well they can handle high traffic volumes and in their appearance, which should guide their selection by architects and designers.
- Permeable pavement types vary widely in cost, and all are more expensive than asphalt. Life-cycle costs, including the potential savings in fewer stormwater facilities, may reduce this differential but is unlikely to justify their installation on economic grounds alone.

This investigation, however, cannot yet answer several questions about the widespread use of permeable pavements:

- Are any pavement systems particularly susceptible to clogging over time? We see little potential for this occurring if the system is backfilled with clean sand and virtually *no* chance if it is backfilled with clean gravel. Soil-filled systems may be slightly more susceptible, but several more years of testing will be necessary to determine this.
- How useful is permeable pavement where the native soils are fine grained and do not allow much infiltration? This condition may limit effectiveness, and it may require alternative construction techniques (e.g., overexcavation and/or underdrains), but some if not most of the benefits of permeable pavements should still remain.
- What is the long-term performance of these systems for mechanical durability,[1] infiltratability, and water quality?

Implications for Stormwater Management Planning

The use of permeable pavement reflects an effort to alter the seemingly inescapable relationship between new urban development and increased impervious surface area (Arnold & Gibbons, 1996; Schueler, 1994). Hydrologically, however, not all "impervious" surfaces are equivalent, which means that planners and designers have an opportunity to separate the human uses of impervious surfaces from their hydrologic consequences.

An important distinction exists between *total* impervious area (TIA) and *effective* impervious area (EIA). TIA is the "intuitive" definition of imperviousness: that fraction of the watershed covered by constructed, noninfiltrating surfaces such as concrete, asphalt, and buildings. It is the definition of imperviousness implicit in most planning applications, and it has important consequences for land use, automobile access, and visual appearance.

Yet this definition is incomplete for two reasons. First, it ignores nominally "pervious" surfaces that are sufficiently compacted or otherwise so low in permeability that the rate of runoff from them is similar or indistinguishable from that of pavement (Burges, Wigmosta, & Meena, 1998). In such situations, this contribution to surface runoff clearly cannot be ignored entirely. The second limitation of TIA is that it includes some paved surfaces that may contribute nothing to the storm-runoff response of the downstream channel. A gazebo in the middle of a park, for example, probably will cause no hydrologic changes except a very localized elevation of soil moisture below the drip line of the roof.

The first of these TIA limitations—the production of significant runoff from nominally pervious surfaces—is typically ignored in the characterization of urban development. The reason for such an approach lies in the difficulty in identifying such areas and estimating their contribution to runoff. Furthermore, the degree to which pervious areas shed water as overland flow should be related, albeit imperfectly, to the amount of *impervious* area: The more intense the development and the greater the fraction of the watershed that is paved, the more likely that the intervening green spaces have been stripped and compacted during construction (and only imperfectly rehabilitated for their hydrologic functions during subsequent "landscaping"; see Kolsti, Burges, & Jensen, 1995).

The second of these TIA limitations—inclusion of noncontributing impervious areas—is formally addressed through the concept of *effective impervious areas*, defined as the impervious surfaces with direct hydrologic connection to the downstream drainage (or stream) system (Alley & Veenhuis, 1983; Laenen, 1983; Prysch & Ebbert, 1986). Thus any part of the TIA that drains onto pervious (i.e., "green") ground is excluded from the measurement of EIA. This parameter, at least conceptually, captures the hydrologic significance of imperviousness, so EIA is normally used to characterize urban development in hydrologic models. Although values of TIA and EIA can vary by more than a factor of two for the same piece of ground (see Dinicola, 1990), many studies fail to note *which* type of impervious area is being reported. This renders any subsequent comparisons difficult and usually invalid (Schueler, 1994; see Booth & Jackson, 1997).

This hydrologic distinction underlies a fundamental planning strategy. Although urban and suburban developments require surfaces that can cover buildings and support vehicular loads, they need not all be *effective* impervious areas. To rely on simple measures of mere "imperviousness" for either assessment or regulations, therefore, will obscure some of the most promising avenues for reducing drainage impacts that might promote the use of "ineffective" impervious surfaces (Konrad, Kolsti, Streibe, Jensen, & Burges, 1995). The use of permeable pavements represents one such avenue, but there are other alternatives as well—constructing centralized stormwater infiltration facilities, for example, or encouraging site designs that separate impervious areas and so allow for widely distributed infiltration of relatively localized concentrations of runoff (Schueler, 1995). In each approach the underlying intention is the same, even if the techniques are different—decoupling of runoff-generating areas from the stream channel network. This is probably a necessary, and fundamental, change from the way stormwater has been traditionally managed if we are ever to achieve genuine protection of downstream aquatic systems in urbanizing areas.

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NOTES

1. Note added in press: Field inspection shows no surface rutting or displacement after 3 years (3/96–3/99) of regular passenger vehicle use.

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