THE UNIVERSITY OF WASHINGTON PERMEABLE PAVEMENT DEMONSTRATION PROJECT–

Background and First-Year Field Results

by

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INTRODUCTION

The Management of Stormwater Runoff

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 they render the land more useful for the purpose for which it has been altered. Yet some of the changes are unintended and can have severe consequences. Flooding, channel erosion, landsliding, and destruction of aquatic habitat are some of the unanticipated changes that can also result from these alterations, recognized by many decades of studies (*e.g.*, Wilson 1967; Seaburn 1969; Hammer 1972; Leopold 1973) because of the loss of both lives and property that sometimes 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.

Nearly all of these problems result from one underlying cause: loss of the water-retaining function of the soil in the urban landscape. This loss may be literal, in that the loose upper layers of the soil are stripped away to provide a better foundation for roads and buildings. The loss may also be functional, if the soil remains but precipitation is denied access to it by paving or rooftops. In either case, a stormwater runoff reservoir of tremendous volume is removed from the stormwater runoff system; water that may have lingered in this reservoir for a few hours or 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 problem has been addressed by replacing the lost functions of the soil reservoir with a new, constructed reservoir. A stormwater collection system routes the runoff from paved surfaces into an excavated “detention pond,” designed to mimic the functions of the soil reservoir by accepting water at whatever rate it flows off the developed land surface and releasing it at a much slower, “natural” rate. This approach almost entirely separates the design of the development from the management of stormwater: the runoff displaced by human structures is shunted to a point, where “management” then takes over.

However, this strategy has proven to be 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 to-be-developed area, is replaced by only a few tenths of an inch. This represents a reduction in “reservoir” volume of perhaps 90 percent or more, and 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, are of limited or virtually no effectiveness. In addition to this fundamental shortcoming, the stormwater-management strategy of holding all water in a facility removed from the developed area itself yields two additional problems: stormwater-facility construction and maintenance are distressingly erratic, with striking divergence between design targets and post-construction in-the-ground performance (*e.g.*, Billica and Booth, 1996); and a surprisingly high fraction of a developed area does not drain through stormwater facilities at all, because regulatory thresholds typically allow much of the development in a watershed to occur without any runoff mitigation at all (Booth and Jackson, in press).

> *“Water belongs in the soil. This principle is supported by the fundamental way landscapes maintain themselves, and by decades of experience in thousands of documented field installations. But it is astonishingly unrecognized in stormwater management conventions in large areas of the country.” (Ferguson, 1995)*

Our study of permeable pavements has evolved from a growing recognition of the limitations of traditional stormwater management. To keep water in the soil we must allow access of water to that soil across much of the landscape, developed as well as undeveloped. This will not be practical everywhere, but where previously undeveloped land is being consumed most rapidly, and thus previously high-quality aquatic resources are being threatened most immediately, the opportunities are particularly great.

This work was able to proceed only with the substantial support of Olympia’s broad-ranging Impervious Surface Reduction Study, which in turn was funded in part by a Centennial Clean Water Fund grant from the Washington State Department of Ecology. King County Department of Public Works also contributed generously and substantially to this project in both labor and funds.

Project Background

In 1994, staff from the Center for Urban Water Resources Management and King County Surface Water Management Division evaluated a variety of different vehicle surface products installed at various sites around King County. Typical applications included fire lanes, parking lots, road shoulders, and low-use roads and driveways, where traffic loads were not high but the amount of impervious area was nonetheless significant. Specific systems evaluated (and their locations, all in the greater Seattle area) were:

—Geoblock, a molded plastic (Veterans Administration Hospital, Boeing Credit Union, Microsoft)

—Grasscrete, a cast-in-place concrete block (Gilman Village, Museum of Flight)

—Geoweb, a plastic cellular confinement system (Richmond Beach Drive road shoulder)

—Grasspave^2, another plastic confinement system (Chelsea Square Apartments).

The most common problems associated with these systems included improper application or installation, differential settlement, and poor grass growth. Simple infiltration testing was performed on some of these systems and the results were promising, although more detailed information about the relative performance of different types of systems (*e.g.*, grass-covered vs. gravel-filled) and the longevity of good infiltration performance was not determined.

The current project has expanded the scope of this early effort to answer the following questions:

- What are the relative installation difficulties and costs of different infiltration systems?
- How well do each of the systems infiltrate surface runoff in a site with intrinsically favorable soil conditions, both qualitatively and quantitatively?
- What is the long-term performance of each system under normal, daily parking-lot usage, for both durability and infiltratability?
- What special benefits and/or requirements are imposed by grass, as opposed to gravel, as the surface filling?
- What are the maintenance costs, if any, of each of the systems?
- What are the water-quality benefits of each of the systems?

Scope of the Current Project

Based on the perceived values of stormwater infiltration and the scattered examples of promising yet ill-tested applications of permeable pavements in the Pacific Northwest, the Permeable Pavement Demonstration Project has been initiated. It has three elements:

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; and
3. ***Evaluate the long-term performance*** of these systems.

This report documents our efforts on the first two elements of this overall project.

TYPES AND CHARACTERISTICS OF PERMEABLE PAVEMENTS

In the evolution of incorporating grass into paving, concrete was the first material to be explored. Concrete grass paving comes in one of two formats: cast-in-place or pre-cast modular units. Cast-in-place systems, such as Grasscrete, are monolithic and are made with reusable forms to create the voids needed for planting 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 pre-cast pavers.

Modular systems, such as Turfstone, are laid out individually, commonly in a running bond pattern perpendicular to the flow of traffic.

More recently, plastic products have been introduced to take advantage of their light weight and relative ease of installation. Most are composed of 50-100 percent post-consumer recycled materials. They are classified as either "flexible," such as Grasspave[2], or "rigid," such as Geoblock. The flexible systems can be obtained in long rolls that are positioned quickly; the rigid modules, like their concrete counterparts, are laid out in a running bond pattern and either interlock or are pinned in place. Plastic pavers, whether rigid or flexible, have less intrinsic strength than the concrete pavers; yet any of these systems are fully capable of supporting even heavy vehicular traffic loads with adequate base and subgrade preparation, even when the ground is fully saturated with water. Although less intrinsically strong, more 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 between products, but all are designed to be completely covered with grass and therefore are not visually intrusive.

The bearing capacity and grass growth of any such system depends on the correct installation of the product. As with any pavement system, concrete and plastic pavers require careful preparation of the subgrade and base course before laying out the material. 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.

Installation costs vary with the type of system used. Plastic products can be moved and cut easily with hand tools, and so they can fit into irregular spaces and around utilities with little or no special preparation or effort. Concrete systems are slower to install by about one-third or more because of their weight and rigidity. Either type of system infilled with grass will be more labor-intensive than if infilled 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.

Summary Characteristics of Widely Available Permeable Pavement Systems

CRITERIA	PRODUCT (see below for codes)							
	Plastic				Concrete			
	GW	Gpv^2	GP	GB	CB	GC	TS	UES
Appearance at Surface Ratio of structure/filling:	<5%	<5%	<5%	18%	25%	50%	60%	90%
Rigidity of System[1]	M	L	M	M	H	VH	M	L
Traffic Frequency[2]								
Grass fill:	L	L	L	L	L	M	M	N/A
Gravel fill:	H	H	H	H	H	H	H	H
Installed Cost[3]/sq. ft.	L*	L**	L	M*	H***	H*	M	M*

NOTES:

Product codes (all registered trademarks of the following manufacturers):

GW = Geoweb (Presto Products, Inc.; 1-800-548-3424)
Gpv^2 = Grasspave^2 and Gravelpave^2 (Invisible Structures, Inc.; 1-800-233-1510)
GP = GRASSY™PAVERS (RK Manufacturing; 1-800-957-5575)
GB = Geoblock (Presto Products, Inc.; 1-800-548-3424)
CB = Checkerblock (Hastings Pavement Co.; 1-800-874-4717)
GC = Grasscrete (Bomanite Corp.; 1-209-673-2411)
TS = Turfstone (Westcon Pavers; 1-604-888-0555)
UES = UNI Eco-Stone (Concrete Paving Stones; 1-503-669-7612)

[1] (determines the ability to span irregularities in base course or subgrade without surface deflection under heavy loads) **VH** = continuously poured, reinforced concrete; **H** = interlocking concrete units; **M** = large non-interlocking concrete units *or* continuous or rigidly interlocking plastic units; **L** = flexible (plastic) units

[2] **H** = no restrictions; **L** = one pass daily or multi-day intervals between use; **M** = intermediate usage

[3] **H** = \$3-\$4/ft^2; **M** = \$2-\$3/ft^2; **L** = \$1-\$2/ft^2. Includes material cost, typical shipping, and installation on a fully prepared base course, based on distributors' phone quotes 2/97; does not include cost of gravel or soil & grass fill, which will add appx. \$0.10-0.25/ft^2 including labor. Equivalent total costs for asphalt surfaces are about \$0.50-\$1/ft^2 (Smit, 1994).

*Volume discounts of 10-30% may apply

**Volume discounts up to 50% may apply

***Proximity to manufacturing plants (in southern CA and eastern PA) will significantly reduce costs

Typical Applications

Although permeable paving systems have been available for several decades, their use has expanded only slowly. Typical applications have been for light-duty or infrequent-use parking areas or access drives, although the load-bearing capabilities of these systems allow for a much wider range of uses. Based on a review of available manufacturers' literature, appropriate potential applications include:

- Vehicular Access
  - Residential driveways
  - Service driveways
  - Roadway shoulders, crossovers, and medians
  - Fire lanes and utility access
- Parking
  - Church
  - Employee
  - Overflow
  - Event
  - Guest
- Bicycle trails
- Golf Courses
  - Cart paths
  - Cart parking
- Pedestrian Access
  - Approaches to monuments, statues, and fountains
  - Areas for outdoor special events
  - Picnic areas and highway waysides
  - Pathways and trails
- Equestrian Trails
- Slope Stabilization and Erosion Control

FULL-SCALE FIELD EVALUATION OF PERMEABLE PAVEMENTS

Study Design and Siting

The second element of this project involved the construction of an instrumented parking facility using permeable pavements. Out of the large variety of infiltration systems currently available, four were selected for evaluation to span the full range of impervious-surface coverage over the ground and to include both grass and gravel-surfaced systems:

1. Grasspave[2], a flexible system with virtually no impervious-area coverage by a plastic network (grass infilling);
2. Gravelpave[2] (an equivalent plastic network with gravel infilling);
3. Turfstone, with about 60 percent coverage by impervious blocks (grass infilling); and
4. UNI Eco-Stone, with about 90 percent coverage by impervious blocks (gravel infilling).

Two adjacent parking stalls were constructed in each of these systems, for a total of eight stalls. A ninth stall of traditional, 100-percent 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).

Field-Site Construction

The field testing site needed to meet several criteria:

- intrinsically favorable soil conditions for infiltration, so the pavement system and not the local soil conditions were being evaluated;
- good security for monitoring equipment; and
- frequent use.

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 each of these conditions. The facility sits high above the valley floor of the Cedar River on a glacial-age terrace underlain by several hundred feet of sand and gravel. 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, minimizing (and hopefully eliminating) any risk of vandalism.

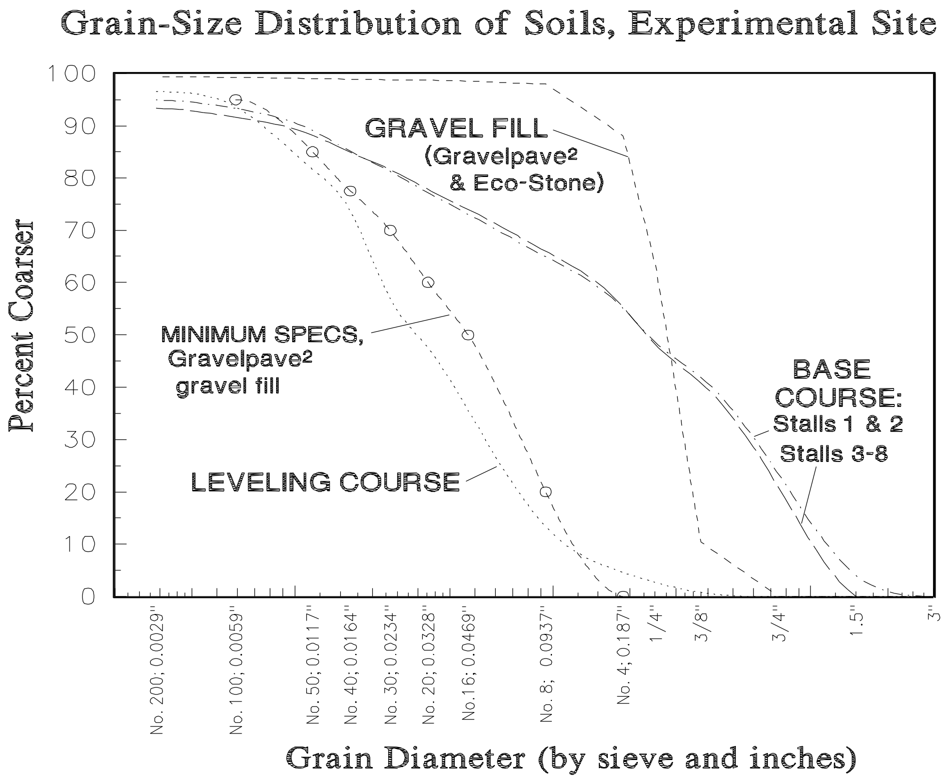
Having selected an intrinsically favorable site, construction was allowed to proceed *without* unusual attention to installation details. Typical engineering plans were drawn up, manufacturer's specifications for subgrade preparation were duly noted, and a member of the University of Washington experimental team was present constantly throughout the work. However, our intention was to determine the long-term function of these systems under typical conditions of installation as well as of use, and 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. The resulting quality of the installation was very high, given the skill of the King County crews that performed the work—but these conditions are entirely representative of what any other such crew would likely achieve, independent of the presence or absence of a research team hovering about the construction site.

The one atypical characteristic of the site design was imposed by the need to collect and measure surface and subsurface runoff. Conveniently, the overall gradient of the parking lot forced any surface runoff towards the head of the stalls, and so a concrete gutter was constructed along the entire length of the facility to intercept this flow, with individual drains collecting the entire volume runoff from each group of similarly surfaced stalls. 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 infiltrated water (about 1.8 %) is collected in two subsurface troughs, 10 feet long by 4¼ inches wide, extending down the middle of each stall and embedded into the subgrade about 6 to 8 inches below the surface. The disadvantages of this collection system are the incomplete representation of the sampled water, which will presumably be largely unaffected by wheel compaction but subject to proportionally greater oil and gasoline leaks, and the absence of any collection when the stalls are occupied by vehicles (about 30 % of the hours in a normal week). The advantage of this system, however, is that it does not affect the overall infiltration through the paving surface, and this consideration was judged to be critical.

Most of the site construction occurred in five days during the months of January and February 1996. By this time the remainder of the 35-stall parking lot had already been graded and paved with asphalt, leaving only the rough area of the experimental sites incomplete. The sequence of construction work for the experimental site was as follows:

- Trimming of existing pavement back to boundaries of the experimental site;
- Excavation of previously placed (noninfiltrative) subgrade to a depth of 10-14 inches below final grade;
- Placement of new pit-run sand and gravel in two lifts as a base course up to within 2-5 inches of final grade, followed by compaction with a vibrating-drum roller and vibrating-plate compactor, followed by rough releveling as needed with additional material;
- Excavation of trenches and placement of the subsurface troughs (and associated plumbing), which were then filled with ½- to 2-inch washed rock and covered with free-draining filter fabric (AMOCO 4545);
- Forming and pouring of the concrete gutter for surface-runoff collection;
- Placement of 2 x 8 pressure-treated lumber at the lateral boundaries of each pair of stalls on edge, with the tops of the boards at finish grade, to minimize lateral migration of surface or subsurface runoff from one pavement area to another;
- Spreading, leveling, and compacting of ½ to 1½ inches of medium sand as a leveling course below each of the pavement systems;
- Laying out of each pavement system following manufacture's specifications;
- Infilling with sand (Grasspave^2), pea gravel (Gravelpave^2 and UNI Eco-Stone), or soil (Turfstone);
- Installation of gauges, data logger, and associated wiring; and
- Grass seeding (Grasspave^2 and Turfstone).

Samples of the various earth materials used in construction were collected and sieved in the laboratory to better quantify their physical properties. They are graphed below:



The grain-size distributions of the soil materials were quite consistent with typically available materials. The subgrade was "pit run" sand and gravel, acquired from the quarry immediately adjacent to the field site and probably quite representative of the deep subsurface materials at the site as well. During construction the specific location in the quarry shifted from which the base materials were extracted, and so we tested each of the two batches ("Stalls 1 & 2," and "Stalls 3-8") but saw no significant differences. Fines (passing the No. 200 sieve) ranged between 6 and 7 percent. Although this is a few percent higher than the 5-percent limit typically specified for free-draining fill, we have seen no evidence of impaired performance as a result. Above this base material, a thin layer (½" to 1½") of leveling sand was spread with a fines content of about 4 percent. The minimum manufacturer's specifications for the surface topping (the "gravel fill") of the Gravelpave^2 system are also shown on the graph above, together with the measured grain-size distribution of the (substantially coarser) washed gravel that was used for this system and for the UNI Eco-Stone surface fill.

Installation times were difficult to quantify at this site and probably not representative of larger, more typical applications. Much of the effort was involved in the intricacies of subgrade preparation, particularly the installation and sloping of the subsurface drains. In addition, the small areas involved meant that start-up times and familiarization delays consumed an inordinate percentage of the total construction time. We have incorporated manufacturer's estimates of installation rates in the previous section (typically on the order of 100 square feet per person per hour, including surface filling), and our own experience suggested no glaring inconsistencies with their estimates. We did find that the plastic systems were particularly easy to move around the job site, being very lightweight; the concrete systems required mechanical transport of pallets for even short distances. Once positioned, however, the materials could be placed in final position at roughly equivalent rates. The UNI Eco-Stone was unique of the four surfaces used in that it could take full vehicular traffic as soon as it was placed (although we did subsequently infill with gravel and compact with a vibrating plate, in accord with manufacturer's specifications); the Grasspave^2 and Gravelpave^2 systems were more delicate and we allowed no traffic until the sand or gravel topping was spread over the surface. This led to some minor inconveniences in the sequencing of construction activities but no serious delays. Filling of the spaces in the Turfstone was surprisingly time-consuming; we used slightly damp soil, and as a result we had difficulty filling each void area uniformly without making multiple passes with assorted manual tamping devices (primarily tool handles). A drier soil fill would have reduced the magnitude of this problem.

Whereas the gravel-filled systems are ready for immediate use after final compaction of the finished surface, grassed systems require a suitable period (1-2 months) for grass establishment. During this period the prevailing rainfall will determine if irrigation is necessary, but we found (and the manufacturers strongly recommend) irrigation to be mandatory through the first year's dry season (summer, in the Pacific Northwest). The clean sand specified for the Grasspave^2 topping, in particular, was very susceptible to drought; our grass coverage has not yet exceeded about 80 percent, although we are anticipating virtually full coverage during the spring of our second year (1997) through reseeding and continued establishment of the turf. In modest contrast, grass establishment in the Turfstone has been more readily achieved, probably for three reasons: (1) the growth medium is a sandy loam topsoil, not sand, and so water-retention ability is greater; (2) the Turfstone is only 40 percent open space, and so the growing areas effectively receive over twice the actual rainfall; and (3) the concrete grid provides some mechanical protection for the grass while cars are parked. Part of this study is to determine the long-term performance of these different surfaces under our light-to-moderate parking frequencies, and we anticipate that any differences, if persistent, will be instructive.

Instrumentation

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. Surface runoff from these surfaces was collected in a concrete gutter constructed across the head of each pair of stalls. The slope of the pavement surfaces were graded to fall 1-2 percent towards the gutter, together with a slight lateral gradient in each pair of stalls (about 0.5-1 percent) that was unavoidable given the overall site topography. Lateral surface flow is blocked from moving from one pavement type to another by a length of treated lumber, installed flush with the surface and extending 7¼ inches below the surface, forming the lateral boundary of each pair of stalls. A low asphalt berm, about 2 inches high and 8 inches wide, surrounds the entire experimental area and isolates it from the remainder of the parking lot so that the only water flowing over or through the surfaces originates from precipitation on the surfaces themselves. The concrete gutter was partitioned so that surface flow from each pavement type was isolated and routed into a corresponding instrument bay and flow gauge (see below). The concrete gutter was subsequently covered with a low sheet-metal lid that excludes nearly all of the precipitation that would otherwise have fallen directly on the gutter and so produced unrepresentatively high rates of apparent surface runoff.

The subsurface water-collection system had to achieve the dual goals of collecting a representative sample of the infiltrating runoff and not disrupt the overall performance of the pavement systems. We judged the latter goal most important, and so only a scant fraction of the potential infiltrate (about 1.8 %) is intercepted by this system; the balance is allowed to percolate into the subgrade without interruption. The collection is accomplished by two troughs beneath each infiltrative pavement system, constructed out of molded plastic and designed for subsurface installation. Each trough is 4¼ inches wide and 10 feet long; they were positioned down the center of each parking stall, with the head of the trough placed about 1 foot back from the head of the stall. They were set at a depth no more than 6 inches below the underside of the pavement system, at a gradient between 1 and 2 percent (although subsequent compaction may have flattened this somewhat in a few cases), filled with washed ½- to 2-inch gravel to provide some additional strength, and covered with a free-draining filter fabric (AMOCO 4545) to minimize subsequent intrusion of fine material. Each pair of troughs were linked by lengths of 2” ABS pipe that subsequently drain into the same instrument bay as the corresponding surface drain and then measured by a separate (subsurface) flow gauge. By virtue of the troughs’ position, useful data can be collected only when the parking stalls are free of vehicles, which otherwise shield the entire area supplying water to the troughs. The troughs also sample a somewhat unrepresentatively “dirty” infiltrate, being directly under the drive train of parked vehicles.

The flow gauges were fabricated at the Department of Civil Engineering’s metal shop, using a design first developed on a previous project and further refined by our machinist. They are two-chambered tipping bucket gauges, with an approximate volume-per-tip of 0.1 liters. A magnetic reed switch mounted on the body of the gauge records the passage of a magnet on the tipping bucket assembly itself as one side empties and the other side is brought into position. The asphalt parking stall is unique of the systems, however, in that it has no subsurface collection system or gauge at all, and the single (surface) flow gauge has a volume-per-tip about six times larger than the others.

All of the data collected by the flow gauges were recorded by a CR10X datalogger, manufactured by Campbell Scientific Incorporated and purchased in early 1996. It was housed at one end of the experimental site, with wires from each of the gauges run to it through conduit. A rain gauge, also a tipping-bucket type calibrated to pulse every 0.01 inch of rain, was mounted nearby and similarly connected. The datalogger consists of a battery pack and a fully contained measurement and data-storage module, programmable to accumulate multiple input sources over discrete time steps from 1/64 second to 2.5 hours. For this application it was programmed to accumulate tips from each of the 10 gauges (4 subsurface, 5 surface, 1 rain) over 15-minute periods and then store the totals in permanent memory, with a maximum storage capacity of 62,000 data points (about two months’ worth of information at this rate of data accumulation). The data are downloaded with a laptop computer about monthly; batteries must be changed about quarterly.

In late October 1996, all of the gauges were calibrated to allow us to convert the number of tips recorded by the datalogger into a precise volume of runoff. This was done using a 1-liter bucket that released water at a constant rate through a valve outlet at its base. The flow rate selected for the calibration, 10.4 L per hour, was chosen to match the anticipated flow rates expected during an actual storm. This rate corresponded well to the range of maximum rates seen later during storms (between about 8 and 11 L per hour). However, these rates did not occur frequently under natural storm conditions, and the calibration rate was in fact several times greater than the most common flow rates of about 2 to 3 L per hour. We anticipate no significant error in the calibration from this divergence.

Water from the calibration bucket flowed through a hose directly into each gauge until twenty tips had occurred. The volume of water was calculated using the known flow rate and the duration of the test run. The small gauges, which measured runoff from the pervious surfaces had volumes per tip that ranged from 0.09 to 0.17 liters. The large gauge, which measured runoff from the asphalt, had a volume per tip of 0.65 L.

Results of Gauge Calibration

Gauge (location, runoff source, & pvmt. system[1])	Calibrated Volume per Tip (L)
1 (stall 1-2, surface, Gsp^2)	0.09
2 (stall 1-2, subsurface, Gsp^2)	0.10
3 (stall 3-4, surface, Gvp^2)	0.13
4 (stall 3-4, subsurface, Gvp^2)	0.17
5 (stall 5-6, surface, TS)	0.08
6 (stall 5-6, subsurface, TS)	0.14
7 (stall 7-8, surface, UES)	0.10
8 (stall 7-8, subsurface, UES)	0.11
9 (stall 9, surface, asphalt)	0.65

[1] Pavement systems: Gsp^2 = Grasspave^2, Gvp^2 = Gravelpave^2, TS = Turfstone, UES = UNI Eco-Stone

Because additional construction on the gauge enclosures occurred after initial calibration, the five gauges showing significant runoff (nos. 2, 4, 6, 8, and 9) were recalibrated in late December 1996. The second calibration was less precise but more rapid, estimating the volume of each gauge based on the number of tips resulting from a known volume of water. The smaller gauges were calibrated by pouring the water directly into them; the large gauge was calibrated by pouring the water onto the asphalt itself adjacent to the collection gutter.

The results of this second calibration were not conclusive, however, yielding values as high as two times greater than the initial measurements and suggesting that errors from using an unrealistically high flow rate obscured any possible changes in the gauge response from construction activities. Losses from cracks at the edge of the asphalt are also possible sources of error for gauge 9 (see below). The gauges will be recalibrated yet again in 1997.

Comparison of Calibration Results

Gauge (pvmt. system)	Calibrated Volume per Tip (L)	
	Calibration 1 (October 1996)	**Calibration 2 (December 1996)**
2 (Gsp^2)	0.10	0.19
4 (Gvp^2)	0.17	0.25
6 (TS)	0.14	0.23
8 (UES)	0.11	0.14
9 (asphalt)	0.65	1.24

RESULTS OF PRELIMINARY DATA ANALYSIS

Introduction

The site instrumentation and this preliminary data collection and analyses were designed to test three major hypotheses:

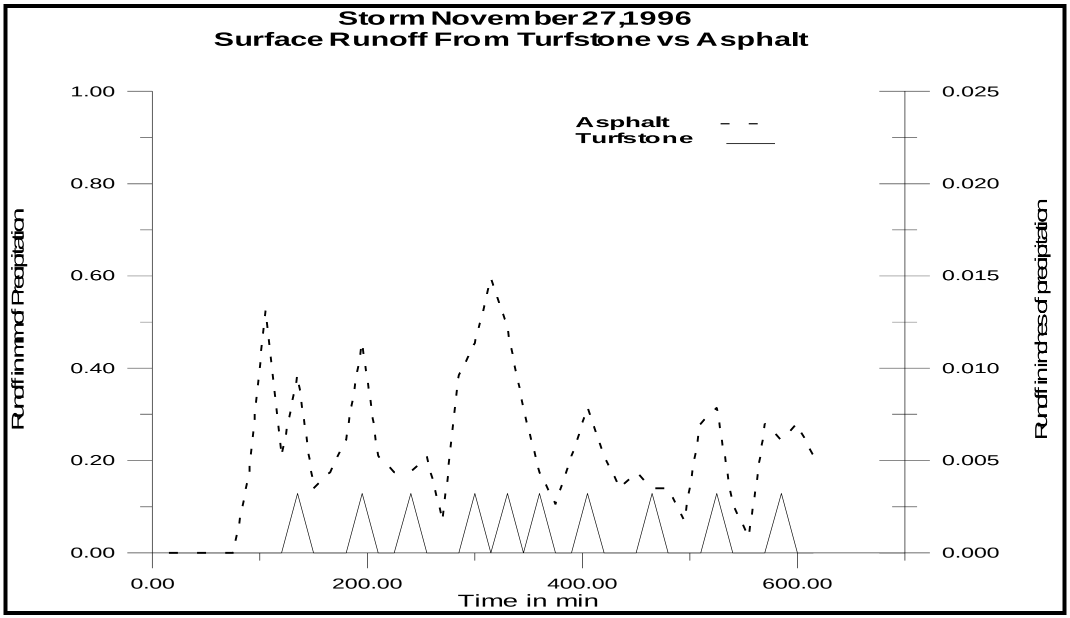
1. Replacing asphalt with pervious pavement dramatically decreases surface runoff and attenuates peak discharges.
2. Although different pavement systems have different mechanical properties and range of suitable applications, significant hydrologic differences do not exist between the different types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

Based on the data collected throughout the autumn of 1996, rainfall commonly falls at rates between 5 and 10 mm per hour for periods of an hour or more during storm events. Light rainfall, with rainfall rates between 1 mm per hour and 3 mm per hour, is also common. The most intense rainfall rates recorded was 14 mm per hour, limited to short bursts lasting no more than fifteen minutes (the minimum time step recorded by our datalogger).

The examples shown in the remainder of this section are selected from three different storms during the autumn of 1996. To provide a more complete perspective on hydrologic responses, the selected storms expressed a range of total durations and average rainfall intensities. Although we also evaluated the hydrologic response of the pavers to storms that were preceded by long dry periods in comparison to storms preceded by abundant rain, not enough data have been collected to demonstrate any systematic differences.

Example 1: Comparison of Surface Runoff from Pervious and Asphalt Surfaces

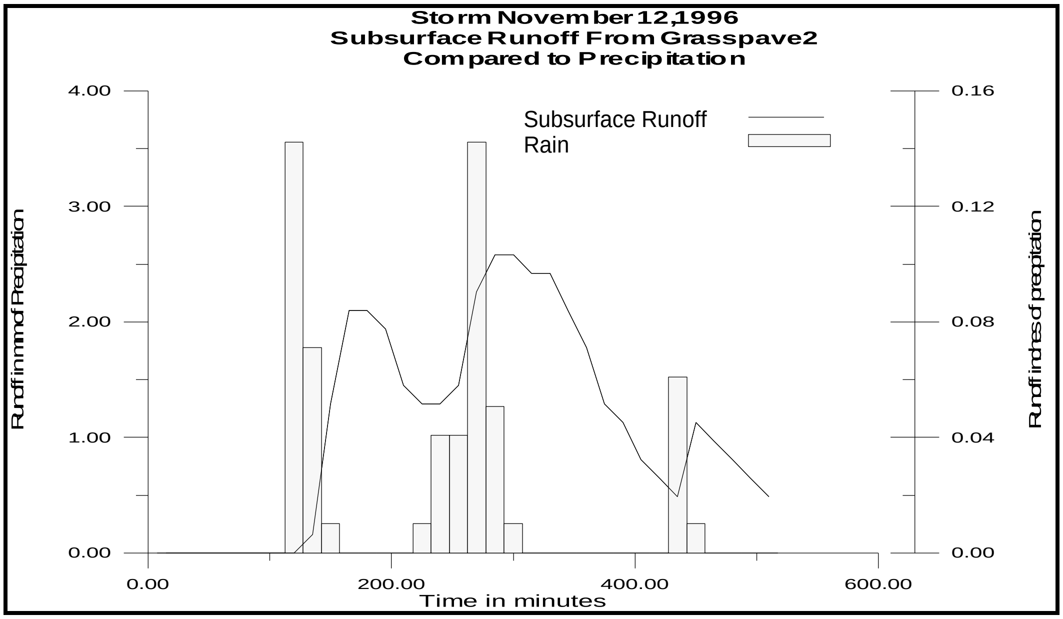
Because the major purpose of this study is to evaluate the degree to which pervious pavers reduce surface runoff, our first example is selected to illustrate this phenomenon. The graph below compares the volume of surface runoff generated from the Turfstone stalls with the runoff from the asphalt, using data collected from a storm on November 27, 1996, between 3:30 AM and 1:30 PM. This storm had a maximum rainfall intensity of 4 mm 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 total volumes of water. In comparison, only about one tip per hour (0.03 mm of runoff per hour) was recorded from the surface of the Turfstone. This is equivalent to approximately 0.1% of the total rainfall and is a more likely result of observed leaks in the covering over the collection gutter rather than by surface runoff produced from the Turfstone surface itself. The absence of surface runoff 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.



This response was also typical for the other storms measured in this study. Although we hope to eventually determine if a difference in lag time exists between surfaces that are already wet from light rain occurring prior to the storm event and runoff from surfaces that are dry, the data collected so far did not resolve this uncertainty. None of the storms had rainfall rates great enough to saturate the surface of the pervious pavers and produce surface runoff, and so the different types of storms all had equivalent responses.

Example 2: Comparison of Rainfall Rates and Subsurface Runoff Response

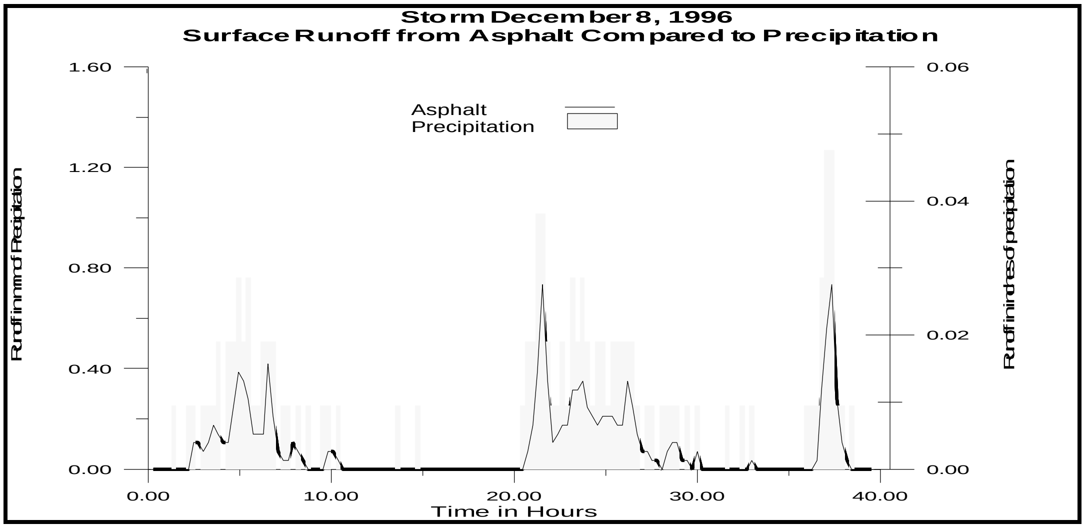
In contrast to the rapid response of surface runoff to rainfall, subsurface flow generally responds more slowly and more uniformly. Even at our field site, where the subsurface flow path is no more than 10 cm long before entering the collection trough, these differences are evident. The data below were recorded on November 12-13, 1996, between 8:45 PM and 5:00 AM, from a storm of short duration and moderate-intensity rainfall. Individual peaks on the bar graph indicate rainfall rates as high as 14 mm per hour but which only last for 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 rather than true surface runoff produced from the pavement surfaces. Thus the subsurface hydrograph shown in this figure 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. Although the volume of the subsurface gauge should equal the quantity of rain falling on the trough area of the subsurface, it actually measured a volume 40% less than estimated from the rain gauge. We believe this reflects some unavoidable inefficiency in the subsurface collection system (see below).

Example 3: Surface Runoff from Asphalt

Impervious surfaces such as asphalt generate large volumes of surface runoff during storm events. Because the instrumentation here independently measures both rainfall and the volumes of runoff generated during storm events, we can examine this relationship in detail. The precipitation and runoff data shown below, recorded during the storm beginning on December 8, 1996, were chosen because they display a precipitation pattern typical of storms in the Pacific Northwest. The storm has a long overall duration with commonly light or no rainfall, punctuated with relatively brief periods of moderately intense rain.



The volume of water running off the asphalt surface responded quickly to changes in the rate of rainfall, indicated by high peak flows followed abruptly by periods of no runoff. The recorded volume of water that ran off the asphalt was a substantial fraction of the total rainfall volume but nevertheless over half the anticipated runoff was “lost” (29.0 mm rainfall vs. 12.0 mm recorded runoff), particularly during periods of low rainfall intensities. Due to the imperviousness of the asphalt surface, these volumes should have been nearly equal. The presence of observed cracks at the edge of the asphalt pavement probably explain most or all of this difference, given the proportionally higher losses at low rainfall intensities.

Limitations of the Recorded Data

Data collection in this study has been reliable despite a few temporary setbacks and some intrinsic limitations of the site and the instrumentation. The intrinsic limitations are few, but they help us establish reasonable expectations for the long-term utility of the experimental site:

1. <u>Time Resolution</u>: To ensure that no data is overwritten between field visits, the datalogger compiles data over fifteen-minute intervals and the individual flow gauges require at least 0.03 mm of runoff to respond. Because light rainfall rates do 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, the focus of this study is to look at the moderate to high rainfall rates that are typically responsible for drainage problems, and so this limitation is not particularly severe.
2. <u>Inefficiency of the Subsurface Collection System</u>: Analyses of the data suggest that the subsurface system is not capturing the full volume of rainfall over the area of the trough, despite the absence of observed surface runoff. Plausible explanations are that the filter fabric covering the top of the trough sheds some water, the troughs have leaks where drainage pipes join, or the system “backs up” at high rates of infiltration. A test piece of the same filter fabric, covered by a sample of the subgrade sediment and exposed to rainfall for all of 1996, was reexcavated and showed modest reductions in permeability but a final infiltration rate that was still one or two orders of magnitude higher than any observed rainfall intensity. Plumbing leaks are possible, but the losses would then be most noticeable at low rainfall intensities

where presumably a greater fraction of the total infiltrate could be lost. This is not evident from the data.

The possibility of water backing up in the trough as a result of insufficient flow rates through the collection system appears to be most plausible, although this explanation is also not well supported by the evidence currently in hand. Using Darcy's Law we predicted the maximum discharge rate in the trough to determine the probability of them backing up during intense rainfall. The troughs were initially sloped at about one percent; for the permeability of the gravel-filled trough we used a value of 10 cm/s, a typical value for clean gravel (*e.g.*, Freeze and Cherry, 1979). These assumptions result in a maximum potential discharge of about 7 cm^3/s. Using the maximum measured rainfall intensities and the surface area of the trough we predict a maximum *inflow* rate of only about 1 cm^3/s, and so the likelihood of the troughs backing up appears to be low. Several conditions could change this conclusion, however:

1) the slope of the trough may have decreased during compaction of the overlying surface;
2) the surface slope of the water in the trough will be flatter than the gradient of the trough itself, because a greater volume of water must be present at the downstream end than at the upstream end; and
3) the permeability of the washed gravel filling the troughs may have decreased from the migration and infiltration of fines from the overlying subgrade material.

We will continue to look for explanations through continued analysis of the recorded data and some reexcavation and direct examination in mid-1997.

Other problems emerged during this initial period of construction and data collection and have been corrected. Prior to November 11, 1996, rain fell directly onto the concrete surface-collection gutter, resulting in unrepresentatively high recorded surface runoff from all of the parking surfaces. Ponding had also been occurring in some sections of the gutter that drained the asphalt and UNI Eco-Stone, reducing the amount of surface runoff that could reach their respective gauges. Periodically, we also had encountered salamanders in the buckets of the gauges, where they had been able to climb before the gauges were remounted in October. All of these problems have been corrected.

One remaining mechanical problem, however, has prevented collection of data from the subsurface gauge for the UNI Eco-Stone since mid-autumn. Based on the gauge record, the subsurface drainage pipe carrying the combined runoff from the two troughs became partly clogged sometime between November 12th and November 28th, most likely by a large piece of gravel. This will be cleared by the summer of 1997.

Water-Quality Results

Because of the relatively short period of time since the facility became operational, we anticipated little in the way of water-quality information to emerge in this first year 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 utility for a future long-term study.

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 Total Petroleum Hydrocarbons (gasoline and diesel), dissolved metals (copper, lead, and zinc, plus hardness), and conductivity.

All analyses were made by the King County Environmental Laboratory in Seattle, a state-certified public-agency facility. Full quality assurance/quality control procedures were followed for all samples.

Samples were collected directly from the tipping bucket gauges. Because little or no surface runoff was produced from any of the permeable surfaces, five samples only—from the four subsurface collection troughs and the asphalt surface runoff—were collected from each storm. About 1 to 2 liters of sample were required for a complete analysis; this represented only a fraction of the 8.9 liters of infiltrate that our subsurface troughs would ideally collect from 13 mm (0.5 inches) of rain (approximately the "water quality design storm" for the Seattle area, which includes about 90 percent of the total annual precipitation volume in an average year). A splitter was therefore designed to catch the water from each tip of the gauges, fabricated from a short length of ABS pipe with a slot cut lengthwise along the top to accept the water and a small hole drilled in the bottom where the accepted water could then drain out. Two such splitters were mounted on each of the gauge, one on each side; the splitters were designed to reject about 3/4 of the volume of each tip while allowing the remainder to drain to either of two 1-L collection jars positioned beneath each gauge. The asphalt surface was anticipated to produce about 250 L from the same amount of rainfall, and so our splitter design for that gauge sought to reject close to 99 percent of the water from each tip. The splitters for the small gauges worked very close to their design goal, typically accepting between 20 and 30 percent of the discharge; the splitter for the large gauge was somewhat less successful by proportion, accepting only about 2 percent (but still about twice what was intended, leading to a potentially disproportionate sampling of the first 0.25 inches of rain).

Chemical analyses of the collected samples showed sub-detection levels (<MDL) for several of the constituents and relatively low levels for all tested compounds. In particular, TPH gasoline and diesel were not detected in any samples, and the measured concentrations of all of the most common metals were low and substantially below the reported nationwide averages. 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 the preferential subsurface sampling of the "dirtiest" 2 percent of the runoff, immediately beneath where vehicles park. However, even these "high" concentration samples were one or more orders of magnitude *below* typical values seen in urban runoff and thus pose no apparent concern whatever. By inspection, there are no significant differences that have yet appeared between the water-quality samples collected from the different permeable systems. More formal statistical analyses would require collecting a larger number of samples, however, which was judged to be premature in light of the recent age of the facility.

WATER-QUALITY RESULTS (detected constituents only)
Storms of 11/25/96, 12/8/96, and 12/25/96

SAMPLE	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 $CaCO_3$ per L)	Conductivity (µ mhos/cm)
Grasspave[2] (subsf.)	59	<MDL	7.6	0.643	5.7	6.77	0.483	0.984	11.5	7.52	21	77.9
Gravelpave[2] (subsf.)	5.8	0.53	6.1	1.03	9.12	6.48	0.811	1.23	17.5	4.43	21.3	67.3
Turfstone (subsf.)	<MDL	<MDL	<MDL	0.3	6.65	16.9	0.18	2.04	5.1	13.6	50.5	166
UNI Eco-Stone (subsf.)	36.5	1.2	15	1.66	14.1	11.3	1.46	2.14	46.7	11.7	37.1	<MDL
Asphalt (surface)	5	<MDL	7.6	<MDL	1.8	1.62	<MDL	0.094	6.7	1.1	4.45	16.3
Grasspave[2] (subsf.)	<MDL	<MDL	<MDL	0.37	3.4	5.6	0.23	0.684	5.7	4.86	16.8	89.9
Gravelpave[2] (subsf.)	<MDL	0.69	<MDL	0.627	6.91	6.19	0.405	1.12	10.3	4.61	20.1	58.3
Turfstone (subsf.)	<MDL	<MDL	<MDL	0.33	6.38	15.6	0.18	2.05	5.1	10.2	47.3	22.3
UNI Eco-Stone (subsf.)	6.5	0.67	8.7	0.691	7.27	10	0.568	1.67	20.3	11	31.9	<MDL
Asphalt (surface)	<MDL	<MDL	8.1	<MDL	1.6	1.33	<MDL	0.077	7.1	0.71	3.65	19.4
Grasspave[2] (subsf.)	5.3	<MDL	<MDL	0.31	4.7	10.2	0.23	1.26	6	8.66	30.7	114
Gravelpave[2] (subsf.)	<MDL	<MDL	<MDL	0.599	6.25	5.92	0.436	1.14	9.7	4.36	19.5	63.4
Turfstone (subsf.)	4.1	<MDL	<MDL	0.3	5.92	16.5	0.18	2.2	4.8	9.26	50.3	144
UNI Eco-Stone (subsf.)	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	131
Asphalt (surface)	23.4	0.71	21	<MDL	4.7	3.82	0.074	0.175	11.9	2.75	10.3	15.1
Subsurface, average	**10**	**0.3**	**3**	**0.57**	**6.4**	**9.3**	**0.43**	**1.38**	**12**	**7.5**	**28.9**	**77.8**
Surface, average	**9**	**0.2**	**12**	**<MDL**	**2.7**	**2.3**	**0.02**	**0.12**	**9**	**1.5**	**6.13**	**16.9**
Reported mean, urban runoff;	**34**	**140**	**160**									
limits for protection of aquatic life (Homer and others, 1994)	**7**	**34**	**30**									

IMPLICATIONS AND FUTURE WORK

Long-Term Work Plan for the Experimental Facility

Although this report covers the significant efforts associated with the first year's worth of construction and operation of the test facility, the most useful information is not anticipated for several years. In that time, we expect to see any progressive effects of regular usage, particularly settlement, surface sealing, and/or incomplete grass growth. Regular maintenance of the instrumentation will be needed, but little or no attention to the parking systems themselves is anticipated besides spring and summertime mowing. We hope to conduct a more comprehensive water-quality analysis in the autumn and winter of 1998-1999, after the facility has been in continuous operation for three years. Conducting this work will depend on the continued interest of local and regional jurisdictions in the results of these investigations.

Impervious-Surface Reduction

The contribution of impervious surfaces to the disrupted runoff processes in an urban watershed is overwhelming (Hollis, 1975; Klein, 1979; Steedman, 1988; Limburg and Schmidt, 1990; Booth and Reinelt, 1993). As consequences of this disruption, downstream flooding, channel erosion, landsliding, and destruction of aquatic habitat have become ordinary parts of the urban and suburban landscape, and traditional efforts at mitigation that are applied only *after the impervious-area runoff has already been generated* have proven broadly ineffectual. We need a new paradigm for stormwater management, one that seeks to eliminate the runoff itself before it ever comes to exist. Part of that strategy should include reducing the gross area that is covered by constructed surfaces, be they rooftops, pavement, or compacted soils. A number of recent publications are available that cover aspects of this subject in detail (see Reference list), including the Center for Watershed Protection's *Site Planning for Urban Stream Protection* (phone 1-301-589-1890), the City of Olympia's (Washington State) *Impervious Surface Reduction Study* (1-360-753-8454), and the Center for Urban Water Resources Management's *Alternatives for Limiting Stormwater Production and Runoff in Residential Catchments* and *Stormwater Detention and Infiltration at the Scale of an Individual Residence* (1-206-543-7923).

However, significant portions of the urban and suburban landscape will continue to be covered, and a high fraction of those covered areas will be dedicated to vehicular traffic. Not everywhere will permeable pavement be suitable, but the scarcity of these systems in today's cities and towns in no way reflects their potential range of application and suitability. With a proper match of anticipated use to chosen system and care in installation, failures should be no more common than for asphalt; with total-cost accounting of not only installation and materials but also associated drainage systems and runoff-treatment facilities, the economics are competitive if not compelling. The intent of the present study is to remove some of the lingering uncertainties surrounding the use of these materials and to disseminate more widely the information that is already well known and more-than-adequately proven in field application. Resolving the problems surrounding urban stormwater runoff will require a tremendous effort, in many different arenas, to be successful. We are hopeful that this study will make a contribution in advancing one aspect of that work.

REFERENCES

Billica, K., and Booth, D. B., 1886, Evaluation of Filter Berms in Double-Cell Dry Detention Ponds, King County, Washington: Seattle, Center for Urban Water Resources Management, University of Washington, report to King County Surface Water Management Division, 25 p.

Booth D. B. 1991. Urbanization and the natural drainage system - Impacts, solutions, and prognosis. The Northwest Environmental Journal 7:93-118. City of Olympia, 1994 Impervious Surface Reduction Study

Booth, D. B., and Jackson, C. J., in press, Urbanization of aquatic systems—degradation thresholds, stormwater detention, and the limits of mitigation: Water Resources Bulletin.

Booth, D. B., and Reinelt, L. E., 1993, Consequences of urbanization on aquatic systems--Measured effects, degradation thresholds, and corrective strategies: Watersheds '93, Conference sponsored by U. S. Environmental Protection Agency, Alexandria, VA, March 21-24, p. 545-550.

Ferguson, B. K., 1995, Preventing the problems of urban runoff: Renewable Resources Journal, winter 1995-1996 issue.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: New York, Prentice-Hall, 604 p.

Hammer, T. R., 1972, Stream and channel enlargement due to urbanization: Water Resources Research, v. 8, p. 1530-1540.

Hollis, G. E., 1975, The effects of urbanization on floods of different recurrence intervals: Water Resources Research, v. 11, p. 431-435.

Horner, R. R., Skupien, J. J., Livingston, E. H., and H. Earl Shaver, H. E., 1994, Fundamentals of urban runoff management—technical and institutional issues: Washington DC, Terrene Institute, 302 p.

Klein, R., 1979, Urbanization and stream quality impairment: Water Resources Bulletin, v. 15, p. 948-963.

Konrad, C. P., Burges, S. J., and Jensen, B. W., 1995, An examination of stormwater detention and infiltration at the scale of an individual residence in the Sammamish Plateau of King County, Washington: Seattle, University of Washington, Department of Civil Engineering, Water Resources Series Technical Report No. 148, 1995, 105 p.

Konrad, C. P., Kolsti, K. F., Streibe, S., Jensen, B. W., and Burges, S. J., 1995, Alternatives for limiting stormwater production and runoff in residential catchments: Seattle, University of Washington, Department of Civil Engineering, Water Resources Series Technical Report No. 149, 1995, 86 p.

Leopold, L. B., 1973, River channel change with time—an example: Geological Society of America Bulletin, v. 84, p. 1845-1860.

Limburg, K., and Schmidt, K., 1990, Patterns of fish spawning in Hudson River tributaries--response to an urban gradient?: Ecology, v. 71, p. 1231-1245.

Schueler, T., 1995, Site planning for urban stream protection: Silver Spring, MD, Center for Watershed Protection, 232 p.

Seaburn, G. S., 1969, Effects of urban development on direct runoff to East Meadow Brook, Nassau County, Long Island, New York: U. S. Geological Survey Professional Paper 627-B, 14 p.

Smit, K. (ed.), 1994, Means site work and landscape cost data, 1995 edition: Kingston, MA, R. S. Means Co., 504 p.

Steedman, R. J., 1988, Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario: Canadian Journal of Fisheries and Aquatic Sciences, v. 45, p. 492-501.

Wilson, K. V., 1967, A preliminary study of the effects of urbanization on floods in Jackson, Mississippi: U. S. Geological Survey Professional Paper 575-D, p. D259-D261.