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# The Washington Water RESOURCE

*The quarterly report of the Center for Urban Water Resources Management*

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Volume 13 ♦ Number 3 ♦ Summer 2002

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## CONTENTS

2

Restoration of Puget Sound Rivers

3

Accuracy of Stream Temperature  
Estimation from Thermal Infrared  
Images

5

Permeable Parking Lot  
Demonstration Project—  
The Six-Year Follow-Up

11

Civil and Environmental  
Engineering Professional  
Development Opportunities

## Message from the Director

This issue of the Newsletter marks the last publication of the Center for Urban Water Resources Management. Our merger with the Center for Streamside Studies, to form the Center for Water and Watershed Studies, is now complete. The celebration and open house of the new center was held on September 6, with a fine turnout of past and present participants and supporters of both centers. The time is now before us to show whether the promise and the opportunities of this new entity can achieve the goals for research, student education, and professional outreach that we have set before us.

The merger has also made some changes to our interaction with subscribers and other supporters:

**Directors:** The co-directors of the new center are the two directors of the previous centers, professors Susan Bolton and Derek Booth. For the 2002-03 academic year Dr. Bolton is on sabbatical leave, and so her co-directorship role is being handled by Dr. Clare Ryan from the College of Forest Resources (cmryan@u.washington.edu).

**Contacting the Center:** The previous office of the Center for Streamside Studies will be the administrative home of the new center. Leslie Wall is our program manager, the same role she held in CSS; she can be reached at 206-685-6920. The Center's email is cwws@u.washington.edu.

**Web page:** The URL of the new center is at <http://depts.washington.edu/cwws/>. As you might imagine, this site is still under construction—shortly, we expect to have the content of both existing centers' web sites transferred here, but until that time (and no doubt for some time thereafter) the original centers' sites will continue to function in their present form (<http://depts.washington.edu/cuwrw/> and <http://depts.washington.edu/uwcss/>).

**Newsletter:** We are expanding the newsletter options to support the 4000-person distribution of CSS while continuing to offer more comprehensive reports to subscribers. Beginning in 2003, you will have three options:

1. A quarterly 8- to 12-page newsletter, similar in scope and detail to the issue you are now reading but spanning a broader range of projects covered by the new center. This will be sent to all current CUWRM subscribers as your last issue of 2002. If you wish to continue receiving printed copies of the newsletter in 2003, or you wish to continue providing financial support for the center, this option will remain—we will check in with you for your preference early next year.

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*Continued on page 2*

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*The Washington Water Resource* is the quarterly publication of the Center for Urban Water Resources Management at the Department of Civil and Environmental Engineering, University of Washington, Box 352700, Seattle, WA 98195.

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**MESSAGE FROM THE DIRECTOR**

*(FROM PAGE 1)*

2. An electronic version of the newsletter, posted on the Center's web site. For those who prefer a paperless version, this option will be available free of charge to all digital visitors.
3. A quarterly 4-page digest of the newsletter, sent to all individuals, agencies, and companies on both the CSS and CUWRM mailing list, also free of charge.

We believe that the value of broadly disseminating the work of the Center, by making current issues of the Newsletter freely available over the web, is most consistent with our mission, and that this consideration outweighs the potential loss of financial support. For some of us, however, "on the web" means "never read," and so we will continue to make a full print version available to those who can help defray the cost. We also hope that many existing subscribers will continue in their current role, not simply out of habit but because our work continues to provide research results, and well-educated graduates, to the community at large.

Derek Booth ❖

## Restoration of Puget Sound Rivers

A forthcoming book edited by

*David R. Montgomery, Susan Bolton, and Derek B. Booth*

The recent listings of salmon as endangered species have led to substantial interest in river restoration in the Pacific Northwest (PNW). Millions of dollars in state and federal funding are already programmed for habitat restoration efforts, presuming a widely accepted role of habitat change and loss in salmon population declines in the region. This emphasis on habitat restoration programs, however, assumes that such efforts will be based on a solid understanding of fluvial processes and aquatic ecology, and that these scientific disciplines can yield accurate prediction of both river and salmonid response to restoration projects. Yet much of our fundamental understanding of river processes and dynamics comes from regions outside the PNW, and regardless of geographic region we are still learning about the processes that create habitat and river structure, as well as how those processes influence aquatic ecosystems and how to gauge the response of river systems to both land use and restoration efforts. The onset of a regional program of river restoration here in the PNW provides an opportunity to evaluate the state of river restoration in general through a focused examination of efforts for restoring Puget Sound rivers.

*Restoration of Puget Sound Rivers* draws from regional experts on river processes, restoration, ecology, history, and management. The volume examines scientific and policy issues involved in creating regional river restoration projects, and it includes case studies that illustrate river restoration successes and failures. While the contents are regional in scope, they have broad applicability in other regions as well and it should be of interest to geomorphologists, aquatic biologists, civil engineers, planners, and those interested in the interface of science and policy in addressing one of the fundamental environmental challenges of the twenty-first century.

*Continued on page 3*

## RESTORATION OF PUGET SOUND RIVERS

(FROM PAGE 2)

The book is being published by University of Washington Press and will be available in late fall 2002. Please contact the Center in writing with your name and contact information if you would like to reserve a copy in advance or receive notice of its availability.

## TABLE OF CONTENTS

- Puget Sound rivers and salmon recovery – *Montgomery, Booth, and Bolton*
- The geology of Puget Lowland rivers – *Booth, Haugerud, and Troost*
- Fluvial processes in Puget Sound rivers and the Pacific Northwest – *Buffington, Woodsmith, Booth, and Montgomery*
- Reconstructing the historic riverine landscape of the Puget Lowland – *Collins, Montgomery, and Sheikh*
- Anthropogenic alterations to the biogeography of Puget Sound salmon – *Pess, Montgomery, Beechie, and Holsinger*
- Scientific, political, and individual constraints on restoring Puget Sound rivers – *Ryan and Jensen*
- The politics of salmon recovery in Lake Washington – *Lombard*
- Role of watershed assessments in salmon recovery planning – *Beechie, Pess, Beamer, Lucchetti, and Bilby*
- Putting monitoring first: Designing accountable ecosystem restoration and management plans – *Ralph and Poole*
- Restoring floodplain forests – *Berg, McKee, and Maki*
- Opportunities and constraints for urban stream rehabilitation – *Konrad*
- Monitoring and evaluating fish response to instream restoration – *Roni, Liemann, and Steel*
- Establishing a standard of practice for natural channel design using design criteria – *Miller and Skidmore*
- Reference conditions for instream wood in western Washington – *Fox, Bolton, and Conquest*
- Stream enhancement projects: A King County perspective – *Bethel and Neal*
- Use of long-line cabled logs for stream bank rehabilitation – *Nichols and Sprague*
- Integrating engineered log jam technology into river rehabilitation – *Abbe, Pess, Montgomery, and Fetherston*
- Restoration of Puget Sound rivers: Do we know how to do it?—*Bolton, Booth, and Montgomery*



## Accuracy of Stream Temperature Estimation from Thermal Infrared Images

*Rebecca N. Hancock, Jennifer E. Kay, Keith A. Cherkauer, Nir Naveh, Alan Gillespie, Stephen J. Burges, and Derek B. Booth, University of Washington*

## INTRODUCTION

The ecological integrity of many rivers and streams in Washington State is threatened by elevated temperature. According to the state Department of Ecology, "By far, temperature is the most prominent water quality problem for the water bodies listed" as water quality impaired in the state. The National Water Quality Assessment Program (NAWQA) has selected summer stream temperature as a focal point for regional water quality assessment in the Puget Sound Basin. Stream temperature is a vital concern in the Pacific Northwest where cold-water refugia are essential for the survival of threatened and endangered salmon and where warm water can be lethal. Regionally extensive assessments are needed for monitoring water temperature because it is a spatially distributed condition that cannot be represented by single regional values. The causes of elevated water temperature also need to be analyzed regionally because this parameter is influenced by spatially distributed conditions, including anthropogenic activities, both near to and distant from stream channels.

Regional temperature assessments, however, are limited by sparse sampling in both space and time, given the area (or length of stream) of concern. In the Puget Sound region, for example, the State of Washington relies on periodic data collected at 76 stations to assess water quality conditions of 12,721 km of streams and rivers (i.e. one station for each 167 km of stream). If critical watersheds are to be properly managed it is necessary to have spatially extensive temperature measurements. They must also be of known accuracy.

The principal goals of the current work are to develop efficient methods for regional assessments of stream temperature and to demonstrate how the methods can be applied to assess effects of land use on stream temperature. This project is evaluating the utility of remotely sensed thermal infrared (TIR) and visible images of streams and stream corridors for increasing the data coverage for regional stream temperature analysis and assessment. We have selected water temperature to illustrate and explore methods for regional water quality assessments, because water temperature is biologically important, it is affected by anthropogenic activities, and surface (skin) temperature (i.e. the top 0.1 mm) can be measured from remote instruments that detect TIR signals. Rapid, spatially extensive remote measurements of other water-quality parameters, although also potentially important, are likely to prove even more challenging.

Continued on page 4

**ACCURACY OF STREAM TEMPERATURE**  
 (FROM PAGE 3)

Remotely sensed TIR imagery can be used to derive spatially distributed estimates of the skin temperature of streams. TIR imagery has long been used to estimate skin temperatures of the ocean, where split-window techniques have been used to compensate for atmospheric effects. Streams are a more complex environment, however, because 1) most are unresolved in typical TIR images of relatively coarse resolution, and 2) the near-bank environment of stream corridors may consist of tall trees or hot rocks and soils that irradiate the stream surface (Figure 1). Additionally, small-scale characteristics of the stream surface, such as evaporative cooling due to wind and water-surface roughness, will affect measurements of radiant skin temperatures with TIR devices.

We are assessing the effect of these factors on stream temperature estimates made using three resolutions of data: fine resolution (5-25 cm) TIR imagery from ground-based forward-looking infrared (FLIR) radiometers, medium resolution (5-15 m) data from the airborne MASTER sensor, and coarse-resolution (15-90 m) data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) which is mounted on the Earth Observing System (EOS) Terra-ASTER satellite (see Figure 2). Extensive measurements of the kinetic and radiant temperatures of streams and the near-bank environment within the Green River and Yakima River watersheds in Washington State are being used to validate analysis results. Aspects of this study are also being supported by the Center's regional stream-temperature survey (see the Winter 2002 issue of the *Newsletter*).

Obtaining accurate estimates of stream temperatures is a multi-step process. Using remotely sensed measurements of TIR made from satellite, air-borne, or ground-based platforms requires image-processing corrections made to TIR data (e.g. atmospheric correction, spectral-unmixing, emissivity correction) and validation of remotely sensed estimates using concurrent ground truth. Yet, in practice, even field measurements of stream temperature are confounded by surface effects (such as wind) that are hard to remove, different temporal and spatial scales between the ground-based measurements and the remotely sensed measurements, and by typically lower body temperatures of water relative to the remotely sensed skin temperature (because of wind-driven surface evaporative cooling).

Based on the work to date, several conclusions are apparent:

- 1) Atmospheric correction using high-quality estimates of concurrent atmospheric conditions is critical because using a standard atmospheric model may not adequately capture concurrent atmospheric conditions. The potential errors so introduced can impose significant (>1 °C) errors in remotely sensed temperatures (Figure 3).

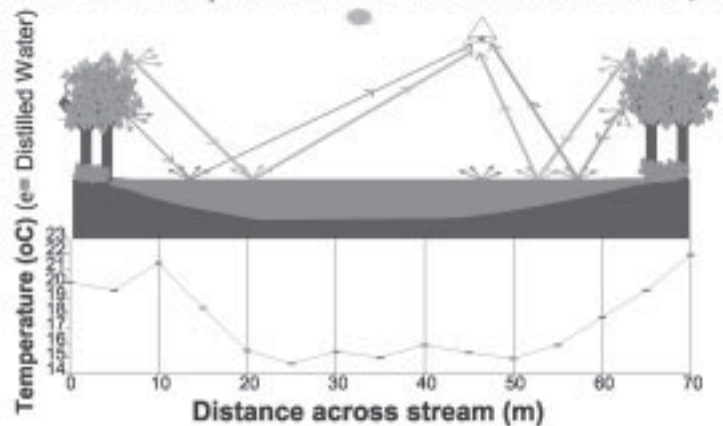
- 2) Ground validation of water temperatures must be well-designed with consideration to spatial and temporal constraints, and with regard to surface temperature effects.
- 3) When water pixels are not fully resolved at the resolution of the sensor, sub-pixel analysis becomes critical. It may not be possible to unmix some stream pixels.
- 4) Frequency bands that are greatly affected by atmospheric conditions are not used in the calculation of surface temperatures but they should be useful in assessing how well alternative atmospheric corrections perform.

Additional information on this project is available at <http://depts.washington.edu/strmtmp/>

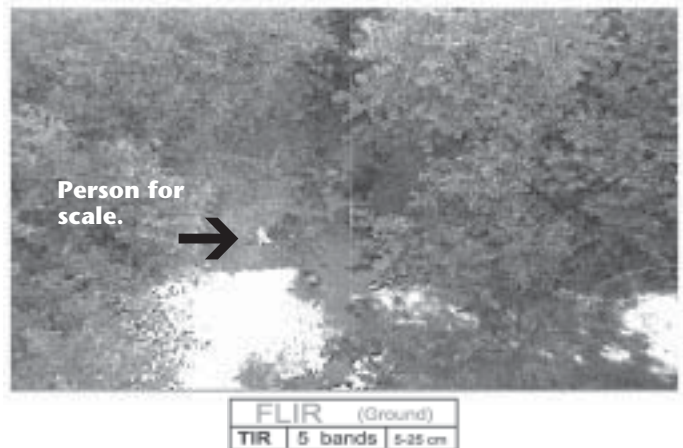


A well mixed stream should be isothermal across its width. Increased temperatures in the near-bank environment may be due either to sub-pixel mixing or multiple scattering from the near-bank environment (e.g. vegetation). Removing both of these effects is critical to accurately determining  $T_k$

**Cross-Stream Temperatures from MASTER. Green River, WA**



**Figure 1.** This figure displays some of the complications of measuring stream temperature remotely. Although a well-mixed stream should be isothermal across its width, increased temperatures near the banks may be a result of subpixel mixing or multiple scattering from vegetation or rocks. Removing both of these effects is critical to accurately determining temperature.



**Figure 2.** Sample resolutions for FLIR and ASTER imagery.

Continued on page 5

ACCURACY OF STREAM TEMPERATURE  
(FROM PAGE 4)

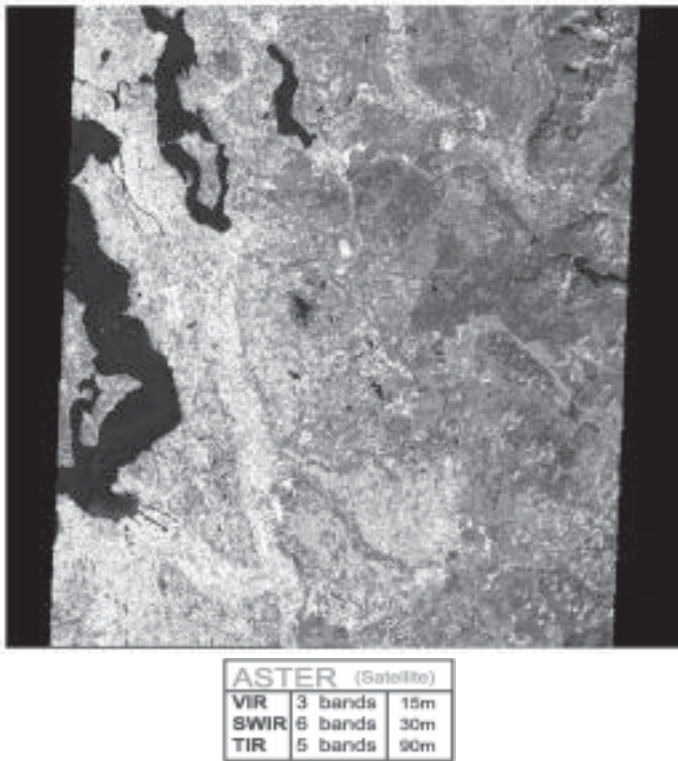


Figure 2. Continued.

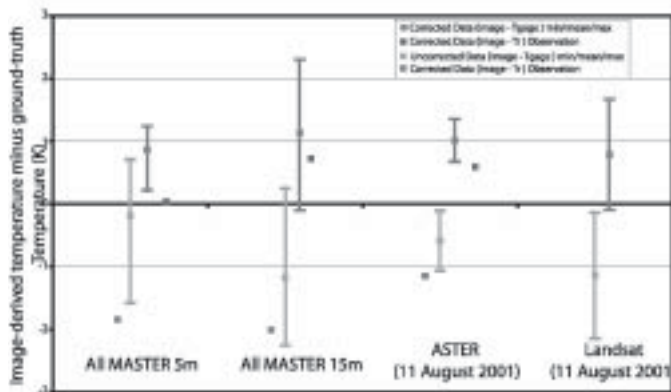


Figure 3. Example of the range of measured temperature differences (remotely sensed minus ground truth) for three sensors. Typical values are about  $\pm 1$  °C, with some errors more than twice as great.

## Permeable Parking Lot Demonstration Project—The Six-Year Follow-Up

Ben Brattebo and Derek Booth, Center for Urban Water Resources Management, University of Washington

### INTRODUCTION

Impervious surfaces have long been implicated in the decline of watershed health in urban and urbanizing areas (e.g., Klein 1979, Schueler 1994, Booth and Jackson 1997). A major portion of these impervious surfaces are built for automobile travel and parking, but much of these areas, particularly parking lots, driveways, and road shoulders, experience only minimal traffic loading while making up a significant percentage of total impervious areas (City of Olympia 1995, Washington State Department of Transportation 2001). Parking lots are typically sized to accommodate peak traffic usage, which may rarely occur, leaving most of the area unused during a majority of the time (Willson 1995, Albanese and Matlack 1998). Other large parking areas, such as for businesses and schools, may be used to full capacity nearly every day but with only once-in and once-out traffic that imposes little long-term wear.

Permeable pavements offer one solution to the problems of increased stormwater runoff and decreased stream water quality associated with automobile usage. Systems are commonly made up of a matrix of concrete blocks or a plastic web-type structure with voids filled with sand, gravel, or soil. These voids allow stormwater to infiltrate through the pavement into the underlying soil, which in turn can play a significant role in mitigating the impacts of stormwater runoff caused by urban development.

Although permeable pavement systems display good initial performance for both infiltration and durability, questions are less readily addressed about their long-term performance, notably those of durability, delivery of pollutants to groundwater, and loss of permeability due to surface clogging. If permeable pavements can infiltrate stormwater over the long term without creating a new set of water-quality problems, they could be used in conjunction with or in place of current structural requirements for stormwater management.

### STUDY PURPOSE

The purpose of this study was to evaluate the long-term effectiveness of permeable pavements. We accomplished this task by evaluating the water-quality and water-quantity performance of four permeable pavement systems in an intensively monitored parking lot after six years of constant use. Our intention was to address some commonly raised questions about permeable pavement:

- Is permeable pavement structurally durable, relative to typical asphalt paving?
- Do permeable pavements remain permeable after several years of use, or does deposited particulate matter or grease cause clogging and significantly reduce infiltration over time?

Continued on page 6

**PERMEABLE PARKING LOT**  
(FROM PAGE 5)

- What is the water quality of the infiltrate through permeable pavement, and how does it compare to runoff from asphalt?

**METHODS**

The field site used for these studies was constructed in 1996. It is located in Renton, Washington, 20 km south of Seattle, and was chosen for several reasons. It has very deep permeable soil that is well suited for infiltration, good security for monitoring equipment, and frequent use. A site with intrinsically good infiltration properties was selected to ensure that any evaluation was of the permeable pavements systems themselves, without hindrance by the underlying soil. The site was used for employee parking at the King County Public Works facility, with once-in, once-out daily usage. Stalls were presumed clear of cars at night and on weekends, although this was directly verified only sporadically during the study. Occupancy of the nine stalls during working hours was regularly observed to be 90-100 percent.

At the site, eight parking stalls were covered, in pairs, with four types of commercially available permeable paving systems. The ninth stall was covered with asphalt and used as the control (Figure 1). The permeable pavement systems used in this study were:

- Grasspave<sup>2</sup>®, a flexible plastic grid system with virtually no impervious area, filled with sand and planted with grass.
- Gravelpave<sup>2</sup>®, an equivalent plastic grid, filled with gravel.
- Turfstone<sup>®</sup>, concrete blocks with about 60% impervious coverage, filled with soil and planted with grass.
- UNI Eco-Stone<sup>®</sup>, concrete blocks with about 90% impervious coverage, with the spaces between blocks filled with gravel.

Each test parking stall was 3 meters wide by 6 meters long (10 ft x 20 ft). A series of gutters and pipes were used to collect and measure both surface runoff and subsurface infiltration water. The volume of both surface runoff and subsurface infiltration were measured for each of the four types of permeable pavements with tipping-bucket gauges. For the impervious asphalt stall, only surface runoff was measured. A rain gauge was also installed at the site. Precipitation and runoff rates were recorded in a data logger at 15-minute intervals.

During rainfall events, composite samples were collected from surface runoff from the asphalt and infiltrated water at each of the four pairs of instrumented stalls. Following the guidance of the Washington State Department of Ecology, a "rainfall event" for this study was defined as a 24-hour dry period, followed by at least 13 mm of precipitation in 24 hours. Flow splitters at each tipping bucket were adjusted to yield about 2 L of sample for 10 to 15 mm of rain for both the permeable (subsurface) and asphalt (surface) runoff collectors. Stormwater samples were analyzed for indicator water-quality parameters: hardness, conductivity, dissolved metals (lead, copper, and zinc), diesel fuel, and motor oil. Samples were collected from the field and held for less than 24 hours before being taken to the laboratory.

Assessing the durability of the permeable pavement systems was done by qualitative visual comparison with the asphalt control stall. No attempt was made to quantify these results.

**RESULTS**

**Durability**

Visual inspection of the permeable pavement systems showed varying, but generally minor, signs of wear and tear after six years. In two small areas, the interlocking sheets of the Grasspave<sup>2</sup>® and the Gravelpave<sup>2</sup>® plastic matrix had shifted slightly and partly lifted out of the soil in the area where the rear wheels of the parked cars typically rest. The Turfstone<sup>®</sup> and UNI Eco-Stone<sup>®</sup> showed no areas of rutting, settling, or shifting. Grass was growing uniformly across the Turfstone<sup>®</sup> surface, but more spotty (and quite sparse in the wheel ruts) in the Grasspave<sup>2</sup>® stalls.

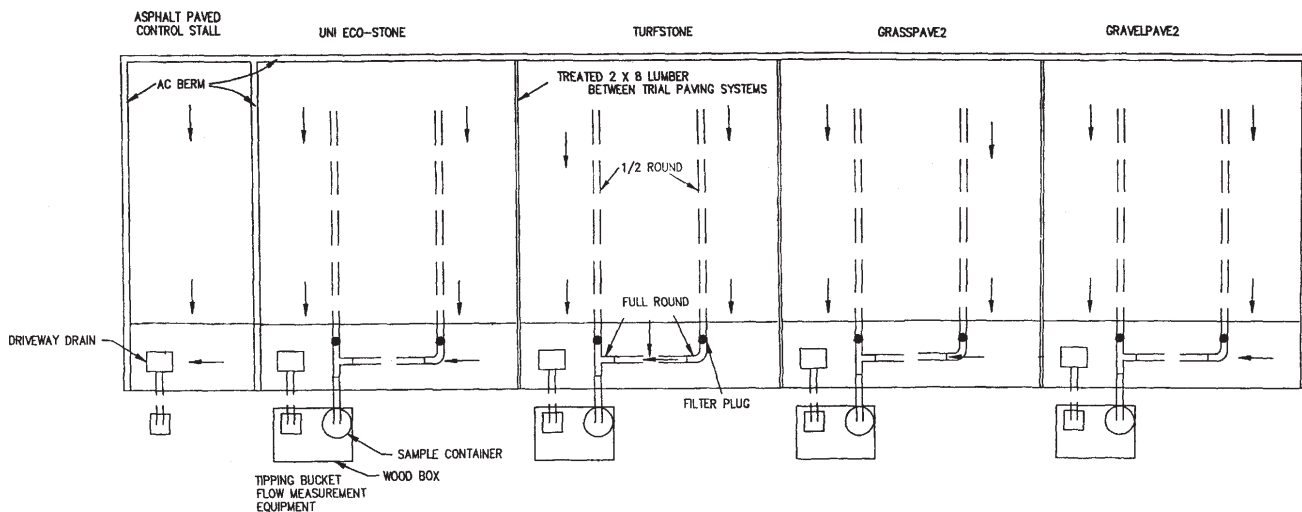


Figure 1. Plan view of the nine test parking stalls. Each permeable pavement type had two parking stalls paired into one instrument station.

Continued on page 7

## PERMEABLE PARKING LOT

(FROM PAGE 6)

**Runoff and Infiltration**

Surface runoff and infiltration rates were measured at the site throughout November 2001 and from the beginning of January until early March 2002. During the period of measurement, rainfall at the site totaled 570 mm, comparable to the 460 mm of rainfall measured at the National Weather Service's station at the Seattle-Tacoma International Airport 15 km to the west. A total of 15 distinct precipitation events were observed during the study period.

Runoff from the asphalt stall closely followed precipitation rates during all rain events (Figure 2). Any delay between the onset of rainfall and the runoff of water was less than the 15-minute time step of the data logger, and there was no measurable continuation in runoff after precipitation stopped. This response was dramatically different from any measured "runoff" (see below) from the permeable stalls.

For the permeable stalls, virtually all water infiltrated for every observed storm. Measurable surface runoff did occur during several of the precipitation events, but this resulted primarily from observed leaks through the cover of the troughs used to capture surface runoff. These leaks typically resulted in one to three tips (200 to 600 ml) of the gauge per hour; during the same interval, rainfall events delivered up to several hundred times this volume onto each pair of stalls. These results were therefore judged insignificant.

During six of the 15 distinct precipitation events, however, surface runoff from a single pair of stalls was greater than could be attributed to leakage into the trough (see, for example, Figure 3). Five of these six cases occurred from the Grasspave<sup>2</sup>® surface (the 6th event with surface runoff was from the Gravelpave<sup>2</sup>® surface). In four of the six cases, surface runoff occurred during working hours and so cars almost certainly covered the pavement area. Presumably, water sheeting off the roofs and hoods of the cars temporarily saturated the exposed permeable areas, resulting in local surface runoff.

In two cases, substantial surface runoff occurred from the Grasspave<sup>2</sup>® surface during non-business hours when parked cars were unlikely. One of these runoff events occurred during the most prolonged period of high-intensity rainfall seen during the study (Figure 3, hours 21-24). In that storm, 42

mm of rain fell in 14 non-business hours and yielded 1 mm of surface runoff from the Grasspave<sup>2</sup>® surface during that period. The entire storm lasted 72 hours, produced 121 mm of rainfall, and yielded 4 mm of surface runoff in total, the most voluminous example of surface runoff (3% of total precipitation) during the entire study.

Measured infiltration in the permeable pavement stalls followed the trends of precipitation but with a significant lag-to-peak due to subsurface flow rates (Figure 4). Though the flow path was quite short (<10 cm through soil, plus a few meters along the gravel-filled buried gutter) it did impose delays of up to about an hour.

**Water Quality**

Composite water samples for entire storms were collected from the runoff from the asphalt parking stall and the infiltrated water passing through each of the pervious pavement systems. Because surface water from the permeable pavement was extremely limited and overwhelmingly due to leakage, water quality was not tested for this fraction.

Nine storms were sampled for water quality (Table 1 and Figure 5). Of the nine, seven fully met the Washington State Department of Ecology definition of a "rainfall event" (13 mm of rain within the first 24 hours following at least 24 hours of no precipitation). Though two sets of samples did not meet these storm criteria, they were included in the water quality analysis because they "failed" only by duration: in one case, more than 30 mm of rain fell in 36 hours; in the second case, 12.4 mm fell in 48 hours.

Overall, surface runoff from the asphalt showed significantly higher concentrations than the infiltrated water of most measured constituents, namely motor oil, copper, and zinc (Table 1 and Figure 5). Hardness and conductivity were lower in the asphalt runoff than in the infiltrate, and no samples from any surface had detectable diesel fuel or lead.

Student t-tests were used to compare the quality of the infiltrated water with the asphalt runoff, pairing individual storms and combining them by type of paving material. In samples where concentrations were below detection levels, a concentration of one-half the detection level was used for data analysis purposes (Gilbert 1987, Kayhanian et al. 2002). For all storms, both hardness and conductivity showed significantly higher concentrations in the subsurface infiltrate than in the asphalt runoff samples ( $P < 0.01$ ). Among the permeable systems, these parameters were also significantly higher

2001-02	Hardness (mg CaCO <sub>3</sub> /l)	Conductivity (µmhos/cm)	Copper (µg/l)	Zinc (µg/l)	Motor Oil (mg/l)
<b>Infiltration Samples</b>					
Gravelpave2®	23.4	48	1.29 (6)	10.8 (2)	<MDL
Grasspave2®	14.7	38	<MDL	14.3	<MDL
Turfstone®	47.6	114	1.88 (4)	12.2 (3)	<MDL
Uni Eco-Stone®	49.8	113	1.7 (7)	8.6 (3)	<MDL
<b>Surface Runoff Samples</b>					
Asphalt	7.91	14.1	9.07	22.2	0.183 (1)

Table 1. Average concentrations of detected constituents from storm samples in 2001-2. Nine storms sampled. In parenthesis is the number of samples that fell below detectable levels. Lead was not detected. <MDL= all samples below minimum detectable level

Continued on page 8

**PERMEABLE PARKING LOT**  
(FROM PAGE 7)

from the concrete-based systems (Turfstone® and UNI Eco-Stone®) than from the plastic systems (Grasspave2® and Gravelpave2®).

Concentrations for zinc and copper were significantly lower in the infiltration samples than in the asphalt runoff ( $P < 0.01$ ). In all cases, the asphalt samples had measurable concentrations of copper and zinc, with highest measured concentrations of 12.1 mg/l and 34 mg /l, respectively. Moreover, all samples from asphalt runoff exceeded Washington State surface water-quality standards for copper at both acute and chronic toxicity levels (Washington State Department of Ecology 1997). For zinc, asphalt runoff exceeded the surface water-quality standard in all but one case at both the acute and chronic toxicity levels.

In contrast, 72% (copper) and 22% (zinc) of the infiltrated water samples from the permeable systems were below the minimum detectable limit. Only one sample (from UNI Eco-Stone®) exceeded state levels for chronic toxicity for copper. Zinc concentrations were exceeded once for acute toxicity and three times at the chronic level. Note that metal toxicity is determined not only by the concentration of the constituent but also by hardness—as hardness increases allowable concentrations for copper and zinc also increase (Washington State Department of Ecology 1997).

**DISCUSSION**

Surface durability, infiltration capacity, and water-quality performance of the tested permeable pavement systems all compared well, and in several aspects extremely well, with their asphalt alternative. Structurally, all permeable pavement systems in this study have held up to six years of daily usage. Visually, there were no differences between the concrete pavers (Turfstone® and UNI Eco-Stone®) in comparison

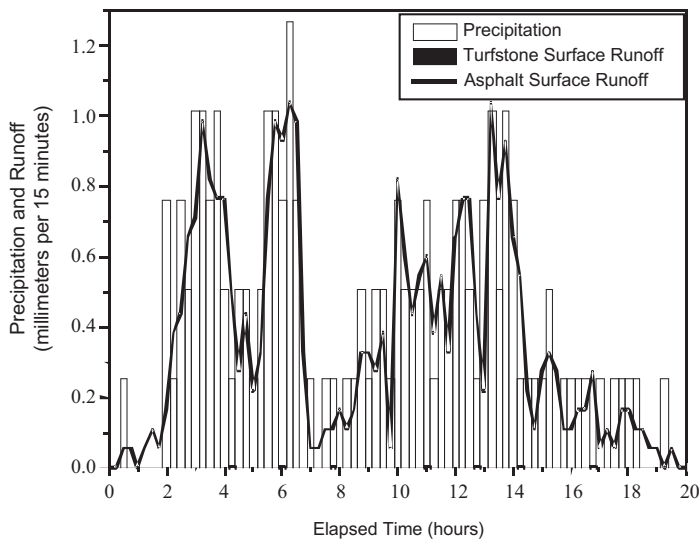


Figure 2. A comparison of precipitation rates and surface runoff from a permeable pavement stall and the asphalt stall during a storm beginning at 16:00 on 6 January 2002. Notice the surface runoff from the permeable Turfstone® stall occurring around 4, 6, 8, 11, 13, 14, and 17 hours. This runoff was attributed to leaks in the piping used to capture water.

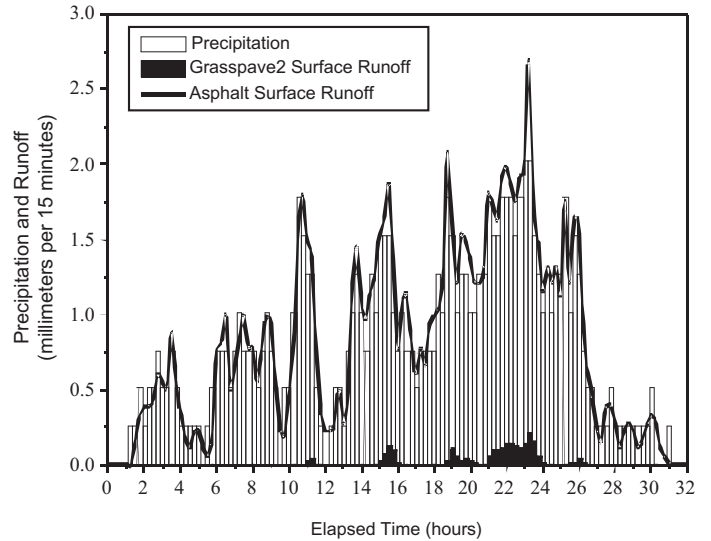


Figure 3. A comparison of precipitation rates to surface runoff from a permeable pavement stall and the asphalt stall during a storm beginning at noon on 13 November 2001.

to the asphalt stall, with neither rutting nor signs of differential settling. These systems are apparently as durable as the asphalt surface under at least this magnitude and frequency of loading. The flexible plastic systems (Grasspave2® and Gravelpave2®) showed some wear and tear, and under heavier or more frequent loads they may have required additional maintenance. Under the conditions here, however, the wear was minor and presented no impediment to use of the parking areas.

All four permeable pavement systems infiltrated virtually all precipitation, even during the most intense storms experienced during the study period. A larger parking area covered entirely by permeable pavement would almost certainly have sufficient uncovered areas to make up for any local saturation that we inferred to occur around individual cars.

While this study showed long-term success in infiltration, it does not assure uniformly good performance everywhere. The Pacific Northwest has generally low rainfall intensities, and so our extremely positive results may not apply equally well in all other locales. The site itself was specifically chosen because of good underlying drainage characteristics; infiltration during extended storms would not be as successful in areas with significantly less permeable substrate. This is a critical consideration in the use of permeable pavements, even if the performance of the surface itself is exemplary. We also made no attempts to quantify any decreases in permeability due to particulate matter deposited off cars. There is no doubt that as automobiles are parked in the stalls, sediments will be washed off and deposited. We observed such deposits, and over a very long period they could have a cumulative negative impact on infiltration. There was nothing found by this study, however, to indicate that infiltration capacity had been reduced to a value anywhere approaching the rainfall intensities experienced (typically 1-10 mm/hour).

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**PERMEABLE PARKING LOT**  
(FROM PAGE 8)

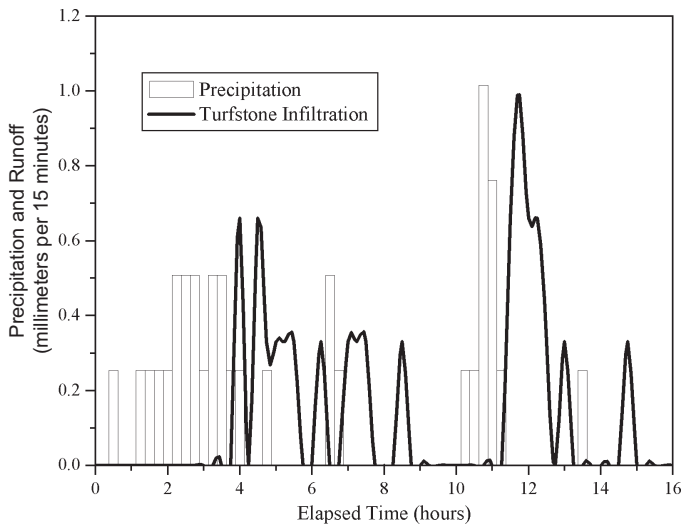


Figure 4. A comparison of precipitation and subsurface infiltration during a storm beginning at 2 pm on 20 November 2001

The water quality results from this study demonstrate clear differences between the subsurface infiltrate and direct runoff from asphalt. For nearly all storms and constituents, water quality of the infiltrated water was significantly different from the surface runoff from the asphalt parking area. Of greatest interest to this study is the apparent sequestering of pollutants within or just beneath the permeable pavement systems. For

both copper and zinc, infiltration of the stormwater had a dramatic effect on water quality (Table 1). Instead of reaching toxic concentrations as in 97 percent of the asphalt runoff samples, in 31 of 36 samples they fell below toxic levels and in a majority of samples below even detectable levels.

These data also address whether or not water-quality performance of permeable pavement systems degrades over time, which could lead to a greater potential for leaching pollutants into the groundwater. Comparison of the water-quality results from this study with those from Booth and Leavitt (1999) suggest that this may be a modest, but not problematic, phenomenon (Figure 6). Zinc concentrations in the infiltrated water from all permeable pavement stalls, as well as the asphalt runoff, exhibited statistically significant increases over the original testing in 1996. On the other hand, two of the systems, Grasspave<sup>2</sup>® and UNI Eco-Stone<sup>®</sup>, showed large decreases in copper concentrations. Lead, present in one-third of the 1996 samples, was not detected during the current survey. Conductivity and hardness remained relatively constant between the two studies.

These results suggest both positive and negative changes in runoff water quality after six years. Subsurface flow paths for this experimental system, however, were less than 10 cm, a far shorter path to groundwater tables than would occur in most field installations. With longer flow paths would presumably also come greater attenuation of pollutant loads and a corresponding decrease in the potential for long-term groundwater impacts.

**CONCLUSIONS**

This study evaluated the performance of four permeable pavement systems from the perspectives of mechanical durability, infiltration, and water quality after six years of daily use. We found generally positive, and in several aspects very positive, performance in comparison to a traditional asphalt surface. All permeable pavement systems have held up to six years of daily usage as a parking lot, with no rutting or signs of differential settling. Two of the systems were particularly robust, suggesting that even heavier or more frequent loads could be handled; the other two systems would probably require some amount of light maintenance under more intense use.

Runoff performance was also very good. All four permeable pavement systems infiltrated virtually all precipitation, even during the most intense storms experienced during the study period. The water quality of the resulting infiltrate was significantly different from, and generally much better than, the surface runoff off the asphalt parking area. For both copper and zinc, the infiltrated stormwater had concentrations mainly below detectable levels and, in all but five samples, below toxic levels; in contrast, these constituents had near-uniform toxic concentra-

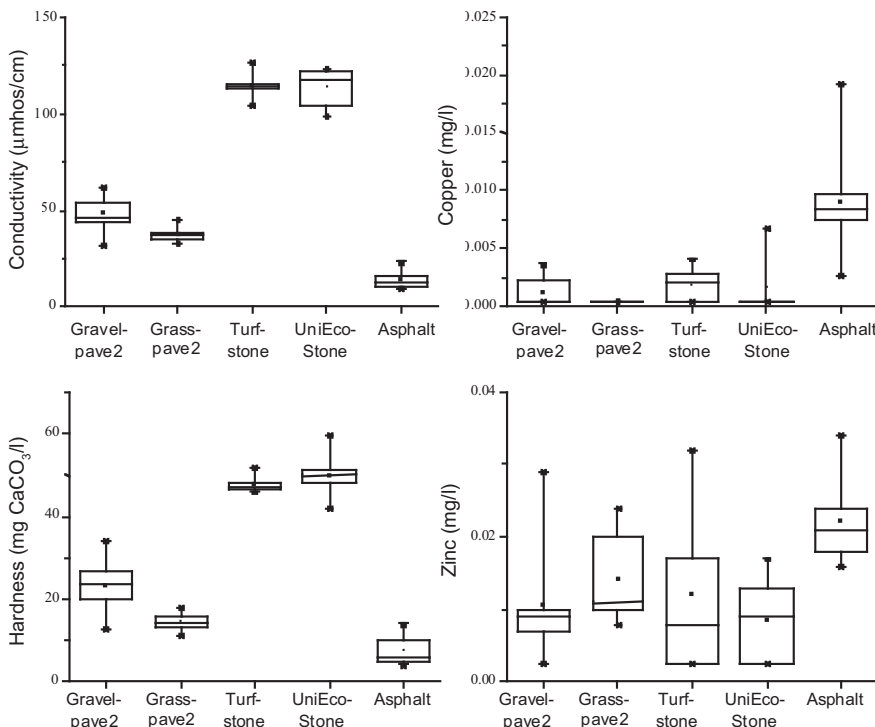


Figure 5. Box-and-whisker plots for 9 storms sampled in 2001-02. Samples from permeable pavements were infiltrated water. Samples from asphalt were surface runoff.

*Continued on page 10*

**PERMEABLE PARKING LOT**  
(FROM PAGE 9)

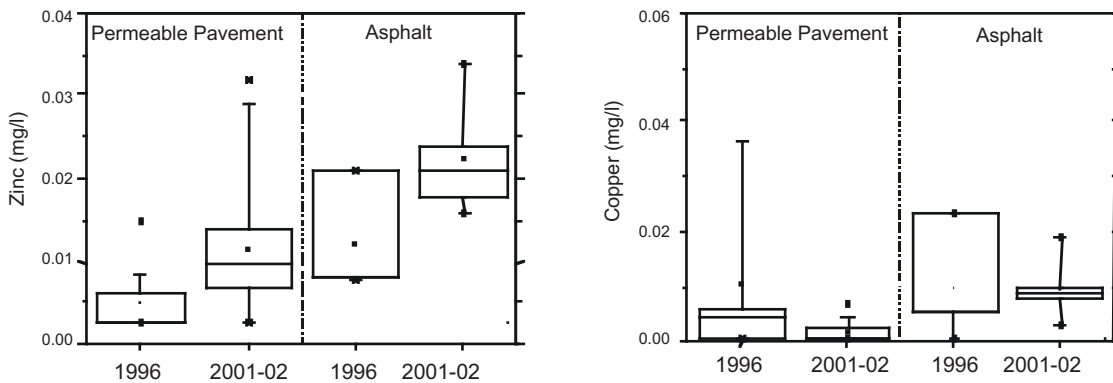


Figure 6. A comparison of zinc and copper concentrations between water infiltrated through permeable pavement and direct asphalt runoff collected in 1996 and 2001-02. Concentrations for permeable pavement are averages of infiltrated samples from all four paving systems. For 1996, 12 samples were collected from the permeable pavement and three from the asphalt runoff. For 2001-02, 27 samples were collected from permeable pavement and nine from asphalt runoff.

tions in the asphalt runoff. Motor oil was also consistently much lower in the infiltrate than in the surface runoff; hardness and conductivity were generally higher, and both lead and diesel fuel were not detected in any sample.

Over the six-years period of this study, concentrations of some infiltrated constituents have increased while others have stayed the same or even decreased. Zinc concentrations in both infiltrated and surface runoff exhibited marked increases; however, two of the infiltrating systems showed large decreases in copper concentrations. Lead was detected in one-third of the samples in 1996 but not in the present study; conductivity and hardness were relatively constant.

Despite these generally quite favorable results, uniformly good performance cannot be guaranteed everywhere. The experimental site has particularly favorable soil conditions, and Pacific Northwest rainfall intensities are typically quite low, masking any potential consequences of reduced infiltration of the surfaces over time. We have experienced no weather conditions requiring snow removal or extended periods of sub-freezing weather, and so this study is not a comprehensive evaluation of the suitability of such systems for all climate zones. Furthermore, this study made no attempt to quantify either the cost increment of permeable pavement systems over traditional asphalt, nor the potential cost savings from reduced stormwater management facilities. We anticipate that either factor could have a dominant influence on the financial attractiveness or feasibility of any given project. Despite these acknowledged limitations, we believe that these results provide clear indication of the value of permeable pavement systems and their long-term suitability for broad expanses of the built environment.

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