The Washington Water RESOURCE

The quarterly report of the Center for Urban Water Resources Management

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Contents

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Annual Review of Center Research

On *October 17th, 1997*, faculty and students affiliated with the Center will summarize the results from this last year's research. The presentations will take place from 9:00 AM until 12:00 noon at the Waterfront Activities Center (WAC) on the University of Washington campus. The WAC is a low building on the shore of Union Bay, southeast of Husky Stadium and northeast of the Montlake Bridge. To get there drive on SR 520 (Evergreen Point Bridge) towards the University from I-5 or I-405 and take the Montlake Boulevard NE exit northbound, cross the Montlake Bridge, continue north a few hundred yards through the major fork in the road at the Pacific Street traffic light and turn right at the next light, 0.1 mile beyond, immediately opposite the stadium (a large sign, "West Plaza," will be on your right). Double back to the south to the parking kiosk ($6.00 for the day, pay as you enter). The WAC is at the rear of parking lot "E12" south of the stadium; we will be on the upper (parking-level) floor. Metro buses 43 and 44 also stop nearby.

The schedule of presentations is still being confirmed as this newsletter goes to press, but the following reports are anticipated:

- Large-scale development monitoring
- Infiltrative parking lot surfaces
- Duwamish corridor groundwater investigations
- Urban stream rehabilitation
- Maintenance of failed biofiltration swales
- Water-quality pond performance
- Puget lowland urban corridor geology and geologic hazards
- Soil amendments to improve infiltration
- Stormwater environmental indicators
- Maintenance practices for water-quality facilities and road ditches

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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 Engineering, University of Washington, Box 352700, Seattle, WA 98195.

Message from the Director

The rather broad range of projects running here at the Center are beginning to crystallize into four distinct sets of activities. The first is the *outreach and technology transfer*, which provided much of the initial motivation for the Center's formation in 1990; it is responsible for this Newsletter, for the mail-order publication distribution service run by Stephanie Strom in Engineering Professional Programs, and for the several dozen phone and mail inquiries I receive every month from both regional and national professionals in search of information on water resources management in urban and urbanizing areas.

The second set of activities focuses on the *effects of development*, particularly upland watershed urbanization, *on natural aquatic systems* lying downstream. Our interests here are most directly on the physical and biological processes that are affected by these watershed changes; they reflect our judgment that the best path to solutions is via the most complete understanding of what has been altered through land-use changes. We are fortunate to have support to work on this problem from a variety of levels: from an analysis of altered processes at the watershed scale, through the detailed characterization of single developments' effects on the downstream system, to assessment of the most effective ways to measure (and to communicate to the public) the magnitude and the importance of those changes.

The third set of activities is based on long-standing efforts to *elucidate the geologic framework of western Washington*, which in turn has important implications both for surface-water management and for groundwater use and contamination. This focus has been developing only slowly; historically, our "water-resources management" center here has primarily addressed surface water, notably stormwater runoff. However, the local expertise in unraveling the geologic history and the sequence of subsurface deposits, coupled with the skills and resources of the US Geological Survey with whom we are working most directly, are starting to produce results of both general and quite immediate interest.

The fourth set of activities acknowledges the growing reliance on both *engineered and non-engineered facilities* to achieve management of development-related impacts to aquatic systems, particularly through treatment of stormwater. Several completed projects have evaluated some of the "classic" approaches for water-quality and water-quantity control; one of these projects completed several years ago has now become the basis for King County's recently proposed revision to their stormwater regulations for detention pond design. However, we are also looking to more innovative techniques, and also to some of the less prominent (but no less important) components of the constructed urban and suburban drainage system to understand what functions they play and how those functions can be best enhanced. I am particularly committed to maintaining a rigorous but very realistic and directly applicable thrust to these investigations, because the needs of our subscribing agencies seems to be greatest and most immediate in this area. Some if the research findings of our recent work is highlighted later in this Newsletter, notably some preliminary results on the maintenance of water-quality facilities and road ditches from a study identified and wholly financed by our Advisory Board this last summer.

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MESSAGE (from page 2)

Just in time, a new group of graduate students is joining those of us already here at the Center. They include Dalius Gilvydas, entering with a B.S.C.E. from the University of Illinois; Marit Larson, a past Fulbright Scholar with a M.S. from UC Berkeley in Forestry and Resource Management and several years of consulting in Massachusetts; and Erin Nelson, a geological engineer from the Colorado School of Mines with seven years of geotechnical consulting experience in the Seattle area (and recruited here after one year in the graduate program in Oceanography). Chris Konrad, with a M.S.C.E. from the University of Washington and two years of subsequent consulting work in California on restoration-related projects, has been with us since April.

Second only to my delight at having this new group of already-established professionals coming to work with us, I am happy to see substantial progress in several of our upcoming research projects. Our $297,000 project with King County as co-participants, "Evaluation of Environmental Indicators for Stormwater Management" from the Water Environment Research Foundation, is poised to begin almost immediately; we are experiencing first-hand some of the problems that large institutions can have in arriving at mutually acceptable contractual agreements, but I anticipate resolution shortly and have of necessity begun some of our planning for this project already. We also appear nearly certain to begin multi-year work on the intensive monitoring of two very large developments on the uplands east of Redmond, at the urban fringe of King County. This will present us with the unequaled opportunity to watch the total conversion of mature second-growth forest to urban land uses, with some of the most extensive stormwater mitigation yet attempted in this region (and under some of the closest public and political scrutiny yet experienced as well!).

At this time, I am still looking to some changes in the structure of the Center in order to better accommodate the range and magnitude of work before us. In particular, I reported in the last Newsletter some discussions with the Center for Streamside Studies in the colleges of Forestry and Fisheries that reflected the desire from all parties to improve the breadth and the interdisciplinary character of *all* of the aquatic and watershed-related research being conducted on the University of Washington campus. In true academic style the pace of those conversations has slowed (but not stopped entirely!) over the course of the summer, and so there is still nothing to report in the way of tangible alternatives or proposed integration of our respective efforts. However, I still anticipate that some changes beneficial to both groups will likely emerge this fall, and I look forward to keeping you abreast of those developments in the next issue of this Newsletter and at our annual presentation of research findings on October 17th. Please see the accompanying article for your personal invitation to that meeting!

Derek Booth ❖

Current Projects at the Center

- Maintenance of Failed Biofiltration Swales (see Spring 1997 Newsletter)
- Stormwater Environmental Indicators (see Spring 1997 Newsletter)
- Soil Amendments to Improve Infiltration (see Summer 1995 Newsletter). As part of the Professional Engineering Practice Liaison (PEPL) continuing education program, a two-day course is being offered September 23-24, 1997, that covers on-site stormwater management techniques (including soil amendments). We look forward to seeing some of our readers in attendance! (Also see publications K1 and K10)
- Eastgate Water-Quality Pond Performance (see accompanying article, this Newsletter)
- Puget Lowland Urban Corridor Geology and Geologic Hazards (see Spring 1997 Newsletter). Last month, Kathy Troost (graduate student in Geological Sciences) and Derek Booth co-led a field trip and evening discussion forum as part of the "2nd Symposium on the Hydrogeology of Washington State," sponsored by the Department of Ecology and attended by several dozen agency and consulting geologists.
- Hydrogeologic Pathways, Duwamish Corridor (see Fall 1996 Newsletter)
- Urban Stream Rehabilitation in the Pacific Northwest (see Summer 1996 Newsletter)

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CURRENT PROJECTS (from page 3)

- Environmental Benchmarks in Citizen-Based Watershed Planning (see Summer 1996 Newsletter)
- Lakemont Boulevard Construction Oversight: As part of an ongoing, multi-year contract with the City of Bellevue to review designs, permits, and monitoring results for the construction of Lakemont Boulevard at the south end of Lake Sammamish, professors Brian Mar and Richard Horner and student Owen Reese have been evaluating all water-quality aspects of the construction work. The following tasks are presently being covered under this project:

1. The University of Washington reviews and evaluates weekly water quality report, the main function of which is to estimate the extra phosphorus load to Lake Sammamish generated by the project. The project is under a requirement to reduce the expected uncontrolled P load by 75% through erosion prevention and sediment control measures and to have a contingency plan capable of 90% reduction if the worst-case loading expectation seems to be developing. Thus far, the reduction is well above 90%, despite rainfall of 167% of the average for the period since construction began.
2. The University of Washington reviews and evaluates the independent inspection of the erosion and sediment control best management practices. We have expressed some dissatisfaction with BMP execution, in spite of the success in reducing P, because we believed that some bad precedents were being set for winter. We have contributed recommendations for improvements to selected BMPs and for better options and are working constructively with Bellevue to implement them.
3. The University of Washington has reviewed and evaluated the testing done to develop a procedure for adding flocculating chemicals to the wet pond effluent (the project's discharge point to the lake after September, when the stormwater system will be fully constructed), if necessary to meet P reduction criteria.

In addition to this oversight work, the University group has been continuing to perfect low-cost water-quality sampling equipment (see publication E13). The basic design being used is a needle attached to tubing that leads to a sample bottle. In order to generate the head necessary for flow through the needle, the sample bottle is located in a PVC tube dug into the bottom of the stream. The needle is set above base flow so that as water rises during a storm the needle begins to sample. This equipment has been used to collect samples from four storm events during the summer. Three composite samplers are currently installed in the tributaries and one sampler is in Lewis Creek.

The advantages of the sampler are that it takes a continuous composite sample (albeit a brief one), reduces the need for being in the field during the storm, has no moving parts, and costs under $40. The main problems encountered have been needle clogging, occasional inability to start sampling, and a slightly too rapid fill rate. To solve these problems we are working on increasing the sample bottle volume and installing upstream screens to collect leaves. ❖

Evaluation of Wet Ponds for Phosphorus Reduction

This study has been in progress for the last year here at the Center to investigate the magnitude of phosphorous removal from urban stormwater runoff occurring through two detention/retention ponds of alternative designs. Phosphorus was the focus of the study because of the detrimental effects it can have on urban lakes and streams. The study was initiated by the Department of Ecology and managed by the City of Bellevue in conjunction with King County. The City of Bellevue conducted the first year of the study, and the University of Washington's Center for Urban Water Resources Management conducted the second year. Karen Comings, a graduate research assistant in the Department of Civil Engineering, collected the majority of the data and has performed the analyses that follow. A preliminary description of the project appeared in the last issue of the Newsletter.

The two wet-pond facilities ("Pond A" and "Pond C") included in this study are located in the south end of the Phantom Lake watershed in southeastern Bellevue. The size of the sub-basin served by the ponds is approximately 100 acres. Impervious surface area in the basin ranges between 65 to 85 percent. In the southern-most portion of the basin, Pond C receives runoff from about 12 acres. After receiving initial treatment by passing through Pond C, the water is routed via underground pipes to the inlet of Pond A. Pond A also receives runoff directly from the remaining 88 acres of the

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EVALUATION *(from page 4)*

sub-basin in addition to the water from Pond C. After receiving the additional quality treatment and flow control that Pond A provides, outflow from Pond A is discharged into Phantom Creek, which then flows into Phantom Lake. Lake Sammamish ultimately receives the water flowing from Phantom Lake.

In order to collect data for the study, sampling/monitoring stations were set up at the inlet and outlet of each pond. Stormwater samples were collected over a period of six months from October through March. These six months typically represent 71% of the annual rainfall for the Bellevue area. Storm events were sampled during this interval that represent a broad range characteristic of western Washington rainfall patterns. Events sampled had a range of precipitation totals from 0.22 to 1.94 inches, while intensities ranged from 0.015 to 0.088 inches per hour. The majority of the sampled storms followed a dry period of at least 48 hours; several were greater than one week.

Removal of pollutants from stormwater runoff by the ponds generally ranged from one-quarter to three-quarters of the measured constituents. Of those measured, total suspended solids (TSS) exhibited the greatest removal efficiency. Figure 1 shows the loading through each pond for the period studied as well as the percent removal for each constituent measured.

Figure 1. Removal of Constituents

The removal efficiencies for soluble reactive phosphorus (SRP) are quite a bit higher than have been seen in similar studies. Another study that compared the removal efficiencies of several dry ponds indicated a range of SRP removal from –12% to 26% (Stanley 1996). Another study investigating the performance of older wet ponds and found SRP removal efficiencies as poor as –50% (*i.e.* net export of SRP; Maristany 1993). The removal of SRP is primarily due to two mechanisms: adsorption by soil or sediment at the bottom of the pond and up take by photosynthesizing organisms living in the pond. Because the study took place during fall and winter months, it is unlikely that large amounts of SRP removal can be attributed to biological uptake. Thus, the removal rates are more likely attributable to interaction with the pond sediments.

The results of this study indicate that wet ponds can provide a significant benefit toward improving the water quality of urban runoff. Both of the ponds studied in this investigation work well, given their design criteria. For all constituents, Pond C was more effective at removing pollutants than Pond A. This was an anticipated but still welcome result, because Pond C was designed specifically for the purpose of water quality improvement. This study supports the value of having new developments install retention/detention ponds that follow a design such as that of Pond C in cases where water quality is the primary issue. Where space allows, older developments should also be encouraged to install ponds of this design.

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Vegetation Maintenance of Bioswales, Wetponds, and Roadside Ditches

Overview

This last summer, the Center's Advisory Board identified the vegetation maintenance of bioswales, wetponds, and roadside ditches as a very high research priority. Member agencies of the Board funded a preliminary review of past research findings and current practices, with the anticipation of a more intensive project being developed in the year to come. Dan Schultz, graduate research assistant in the Department of Civil Engineering, has conducted this preliminary work, compiling the empirical information on different management practices and their effects on the pollutant removal capabilities of these facilities.

The results of the survey have documented a general and significant *lack* of such empirical data on the mowing practices or the vegetation types that provide the greatest impact on the quality of the water leaving these facilities. Current BMPs ("Best Management Practices") provided by design manuals for vegetation maintenance and mowing have been established through general observation and on the plausible assumption that higher grass densities remove more pollutants. Depending on the pollutant of concern, however, some research results actually appear to conflict with these assumptions.

Current vegetation management practices are being implemented to the maximum that agency budgets will allow. Those practices are commonly not in line with design standards, primarily in the lack of removal of the clippings after mowing.

Several opportunities for research are available on this subject that could have significant impacts on the effectiveness, and the budgets, of current vegetation-management programs. The need to maximize stormwater treatment opportunities at all points in the conveyance system is becoming more apparent, but achieving this outcome is hampered by the limitations in current data on how to optimize the pollutant removal capabilities of these bioswales, wetponds, and roadside ditches.

Methods

A literature search was conducted of databases including; Water Resources Abstracts (1967-April 1997), GeoBase (1980-present), GeoRef (1986-present), National Technical Information Service (1983-present), Aquatic Sciences and Fisheries Abstracts (1978-present), Environmental Science and Pollution Management Database, and the Cambridge Scientific Abstracts Database. Searches were conducted for a number of keywords:

- vegetation maintenance
- biofiltration swale
- biofiltration, wetpond
- roadside ditch
- nutrient removal
- phosphorus removal
- detention pond.

Current surface water design manuals were referenced to establish current BMPs in terms of vegetation management and mowing of wetponds, bioswales, and roadside ditches. Personal contacts were made with both locally and nationally recognized professionals on the subject of stormwater management, to confirm the findings of the literature search and as a resource for information on any current projects being undertaken in the area of vegetation management.

In order to establish actual current practices on mowing of wetponds, bioswales, and roadside ditches, individuals from local agencies charged with their maintenance were then contacted and interviewed. Information was gathered on a variety of aspects of current management practices including the frequency of mowing, types of equipment used, miles of ditches mowed, number of sites maintained, and the cost of maintenance per mile and per stormwater management facility.

Results

The results of the literature search were minimal—few studies have been conducted specifically on the vegetation maintenance of stormwater management facilities. A significant amount of research has been undertaken on the design aspects of bioswales and wetponds, but none of them have attempted to establish the effects of various types of vegetation maintenance or mowing practices on the efficiency of the structures. When there is reference to the vegetation and the properties it

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should have, there is contradiction in some studies between the types of vegetation that need to be present for different types of pollutant removal.

Van Dijk et al. (1995) refer to a 1967 paper by L.G. Wilson that stated that suitable filter grass species should "(a) have a deep root system, (b) have a high stalk density, (c) be insensitive to submergence and droughts and (d) be able to grow through sediment coverage." These conclusions were reached in a study focused on sediment removal. A study conducted in Florida by Yousef et al. (1984) was the primary reference of several papers on the removal efficiency of heavy metals by roadside swales. They came to the conclusion that earthen, *unvegetated* swales were more effective than grassed swales in the removal of heavy metals due to the higher surface area available for adsorption (Harper et al., 1984). They also conclude that the removal of nitrogen, phosphorus, and heavy metals is "directly related to infiltration" and that retention of waters in the swale is the key to reducing contaminant transport to receiving waters (Yousef et al., 1985). They suggest that increasing contact and residence times can be achieved through several processes including planting a cover vegetation for erosion control that is kept viable through removal of clippings and planting a slow-growing species with low maintenance needs if possible (Yousef et al., 1985).

Researchers conducting a biofiltration swale study for King County and the cities of Seattle and Mountlake Terrace made several conclusions about characteristics and maintenance needed in the vegetation of bioswales through general observation. They suggest that regular mowing is important for several reasons: it encourages higher density grass, it keeps the grass from getting too long and so laying over, thereby channeling the flow; it provides for removal of vegetative litter such as leaves that can hinder grass vitality; and, at the end of the growing season, it permits removal of the grass clippings to avoid the return of the nutrients to the aquatic system that have been taken up by the plants. The conclusions also emphasized the need to remove the clippings for the purpose of preventing clogging of outflow structures.

The King County Surface Water Design Manual states, as a typical maintenance standard:

> "Grass should be mowed to maintain an average grass height between 4 inches and 9 inches, depending on the site situation. Monthly mowing is needed from May through September to maintain grass vigor. If the swale is not mowed at least annually, trees and brush will invade the swale and inhibit grass growth, compromising the swale's performance for water quality treatment."
>
> "Grass clippings should be removed from the swale and composted on site or removed from the site and disposed of properly."

It also notes that maintenance of privately managed open ditches should be undertaken when vegetation "reduces free movement of water through ditches" but does not address specifically what that action should be. No specific reference was found regarding vegetation maintenance of roadside ditches. Similarly, the Stormwater Management Manual for the Puget Sound Basin, published by the Washington Department of Ecology, states that biofiltration swales must be "mowed regularly during the summer to promote growth and pollutant uptake" and that they must not be mowed to a height below the design flow, with cuttings removed from the site. For the maintenance of ponds, this Manual uses the same guidelines as the King County Design Manual. As a guide for maintenance of roadside ditches it states that practices should be undertaken "in a manner that insures that the vegetation will be reestablished by the next wet season thereby minimizing erosion of the ditch as well as making the ditch effective as a biofilter." Yet how, exactly, to achieve these objectives is not specified.

Results of the survey of local and regional agency managers were summarized and tabulated. The results are somewhat inconsistent between jurisdictions but they do indicate trends in current management practices. Most agencies mow bioswales, wetponds, and roadside ditches two to three times per year, primarily during the growing season. Counties are the most active in vegetation maintenance because their jurisdictions encompass the unincorporated areas, which are the major portions of the land-base and road infrastructure with ditches. The cities do not have as many ditches or facilities and tend to pipe stormwater runoff into receiving waters. In some cases, no maintenance is being performed at all, or it is performed only in an emergency or

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Professional Engineering Practice Liaison (PEPL) Program

The PEPL (Professional Engineering Practice Liaison) Program, in cooperation with the Center for Urban Water Resources Management, offers a continuing education program in urban water resources management.

As part of the benefits extended to supporters of the Center for Urban Water Resources Management, member organizations submitting five or more registrations for the same course may deduct $30 per registration for a 1-day course, $35 for 1.5-day, $45 for a 2-day course, $50 for a 2.5-day course, and $60 for a 3-day course.

For further information on the *Urban Surface Water Management Continuing Education Program* or on any of the courses on the next page, please contact:

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as a direct result of a public complaint. All of the counties and most of the cities use tractor sidearm mowers of either the rotary or flail type that have a swath of five to six feet and do not allow for collection of clippings. Some of the work involves hand work by weed-whackers. For mowing on their wetponds and bioswales the City of Lacey contracts with a local lawn maintenance company that uses push-mowers and does remove clippings. Federal Way uses riding mowers on their wetponds and bioswales.

Due to the vast differences in accounting procedures, and different management procedures at the different agencies, an exact average cost per facility or cost per mile of roadside ditch is difficult to calculate. The most reliable and recurring figures range from $200-$300 per wetpond or bioswale per mowing, and an average in the same range for cost per mile of mowing the roadside ditches. The variations for wetponds and bioswales arise from the different sizes of facilities, the different types if activities performed, and the number of facilities that are maintained. The figures for roadside ditch mowing are more difficult because of the differences in practices undertaken over the course of the year. Mowing the shoulders with a sidearm rotary mower can cost one tenth that of mowing the backslopes of the ditches so the figures may represent a full ditch mowing, or just the mowing of the shoulder which is the only practice undertaken during the heaviest growing season by some agencies. This is shown, for example, by the data from Thurston County: specific costs per mile are $54.25 for shoulder mowing and $542.64 for back-slope mowing. There was also a difference in reporting of total mileage that obscured whether the numbers represented total road miles, total ditch miles (which may or may not equal twice the road miles), or total pass miles (which represent how far the tractor has to travel in the course of mowing regardless of how many passes it may take to mow one section of ditch).

Analysis

There is a significant deficiency of empirical knowledge on the effects of different types of maintenance practices on the pollutant removal performance of bioswales, wetponds, and roadside ditches. Studies have been conducted on the effectiveness and efficiencies of the different design aspects of bioswales and wetponds. Conclusions that have been drawn on the most desirable types and characteristics of vegetation for optimizing pollutant removal performance have been made through observation and professional judgment. These observations have been the *only* information available on this particular aspect of maintenance and therefore have become the sole basis for standards now incorporated into the design manuals. With these manuals dictating the direction that current mowing practices should take, it is apparent that additional research should be conducted in this area. Horner (1988) identified this need in his report on biofiltration systems, and this review has not identified any investigations conducted since that time.

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Actual current practices are not consistent with design manual and Washington State guidance. Current budgets generally do not allow for the specified type or level of intensive maintenance over the course of the growing season. Removal of clippings, in particular, would require hand-raking in most cases. Only one of the cities contacted is performing the maintenance as prescribed and they are achieving this through contracting with a lawn maintenance company. Specific research on the need to remove the clippings from the swales and ponds could justify, or alternatively eliminate, the requirement for this aspect of the maintenance and establish whether this practice would be of practical benefit in roadside ditches to increase their pollutant removal capabilities.

Conclusion

Maintenance of roadside ditches, bioswales, and wetponds is a significant portion of many public works' department budgets. Justification appears necessary (but presently lacking) for increasing or decreasing the intensity of the current management practices. Pierce County is undertaking a study analyzing several types of low-maintenance vegetation and alternative maintenance practices with a focus to reduce the costs of maintenance of roadside ditches. There are several areas where no information is available and offer several opportunities for research. These include pollutant uptake capabilities of various types of vegetation, movement of those pollutants through the system as a consequence of leaching after clipping and transport to receiving waters, root and vegetation densities of various plants and how they perform in erosion control, enhancement of infiltration through different types of vegetation, and how frequency and height of mowing affects density health of vegetation. Some of these questions are already being addressed with an ongoing Center project, "Maintenance of Failed Biofiltration Swales" (see Winter 1997 Newsletter), but far more needs have been identified through this investigation here.

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1997–1998 Professional Engineering Practice Liaison (PEPL) Courses

December 3 and 4
Design and Retrofit of Culverts in the Northwest for Fish Passage

December 11 and 12
Stormwater Treatment by Media Filtration

January 12, 14, 21, 26, and 28, 1998
Effective Writing for Technical Professionals

January 14 and 15, 1998
Fundamentals of Urban Surface Water Management

March 4 and 5, 1998
Achieving Real Success as a Project Manager

March 25 and 26, 1998
Biofiltration for Stormwater Runoff Quality Enhancement

June 10 and 11, 1998
Infiltration Facilities for Stormwater Quality Control

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Evaluation of the Effects of Forest Roads on Streamflow in Hard and Ware Creeks, Washington

The following Master's thesis was recently prepared by Laura Bowling in the Civil Engineer ing Department under the supervision of Dr. dennis Lettenmaier. Although not a direct study of the "urban" environment, its conclusions are relevant to understanding amplification of stream discharges that occur whenever a road network exists. The thesis is available through the University of Washington library system.

Road networks in mountainous forest catchments may increase peak streamflow by replacing subsurface flow paths with surface flow paths. Forest roads affect runoff generation via two mechanisms: capture of subsurface water by road incisions, and generation of infiltration excess runoff from road surfaces. The quantity of runoff intercepted by the road network was monitored in two small Western Washington catchments, Hard and Ware Creeks (drainage areas 2.3 and 2.8 square km, respectively). Road densities in both catchments are approximately 5.0 and 3.8 km/square km, respectively. Observations indicate that the highest peak culvert discharges in Hard and Ware Creeks are associated with subsurface flow interception rather than road surface runoff.

A total of 111 culverts in the two catchments were located using GPS. For each of the road segments defined by the culverts, road widths, slopes and the fraction of the road surface draining to the culvert were measured, and each of the culvert outlets was field checked to determine whether the culvert was hydraulically connected to the channel system. Based on the field study, the effective channel network density was found to have increased by 64% in Hard Creek and 52% in Ware Creek due to road construction. The Distributed Hydrology-Soil-Vegetation Model (DHSVM) is an explicitly distributed hydrological model that simulates the land surface water and energy balance at the scale of a digital elevation model (DEM). DHSVM represents water movement through the unsaturated zone and the vegetation canopy in one dimension, as well as subsurface and surface lateral flow. It accounts for interception of precipitation as both rain and snowfall in the forest canopy. A new scheme represents the effects of forest roads on runoff generation in DHSVM via two mechanisms: capture of subsurface water by road incisions, and generation of infiltration excess runoff from road surfaces. Runoff produced by both mechanisms is routed through an expanded (roads plus pre-existing channels) channel network using a Muskingum-Cunge scheme. DHSVM-simulated flows with and without roads were compared to continuous recording gauges at the outlets of each of the basins, and to crest-recording gauges installed on 12 culverts for selected storms during the winter of 1995-96. Simulated basin conditions indicate that the roads redistribute soil moisture throughout the basin, resulting in drier areas beneath the road right-of-way relative to the simulation without roads. Based on retrospective simulations using eleven years of data, the mean annual floods in Hard and Ware Creeks were predicted to have increased by 11%, and the mean of 4 peaks over threshold were predicted to have increased by 8 and 9%, respectively. ❖

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