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Research Project GC 8286, Task 7
Construction Erosion Control-II

IMPROVING THE COST EFFECTIVENESS OF HIGHWAY CONSTRUCTION SITE EROSION AND POLLUTION CONTROL

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16. ABSTRACT

A comprehensive two-phase effort was conducted to improve the cost-effectiveness of erosion and pollution control at highway construction sites. This report covers both phases of the research. The initial work included laboratory model-scale testing of sedimentation pond designs and field monitoring of ponds to establish their effectiveness in pollutant removal. The laboratory models demonstrated that the following design features in concert maximize actual water residence time to promote sedimentation: (1) length/width ratio of 5:1; (2) series arrangement of two chambers rather than a single pond of equivalent size and shape; and (3) using a perforated riser outlet. To verify these results in a full-scale application, a sedimentation pond was designed according to the laboratory findings, constructed in a highway right-of-way, and monitored for pollution control performance. Another sedimentation pond without these design features was tested for comparison. A second pond based on the laboratory results was tested later. Monitoring consisted of flow measurement and water runoff composite sampling at pond inlets and outlets. Samples were analyzed for solids, metals, phosphorus, and organic content. Costs were also established for these ponds. Results demonstrated that the ponds designed according to the laboratory findings were both more efficient in pollutant removals and less costly (per unit area served) than the pond to which they were compared. The later phase of the work concentrated most on testing the ability of various mulches, blankets, and chemical products to prevent erosion on test slopes, as well as on the ability of silt fencing to contain erosion from such slopes. Runoff samples were collected at the bottoms of the slopes and analyzed as in the pond studies, and costs were again established. Overall, wood fiber mulch accompanied by grass seeding was the most cost-effective slope covering. This report is issued in conjunction with an erosion and pollution control manual, which is designed to implement the findings in highway construction practice.

17. KEY WORDS

highway construction, erosion control, pollution control, sedimentation ponds, slope coverings, silt barriers, environmental impact

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EXECUTIVE SUMMARY

A two-phase effort to improve highway construction site erosion and pollution control in Washington state has been completed. The work first involved laboratory testing of model water retention basins. Laboratory work was followed by the monitoring of full-scale sedimentation ponds at highway construction sites during three winter storm runoff seasons. Two ponds were designed on the basis of the laboratory findings ("designed ponds"). For comparison, a pond that had not been designed according to any specific engineering criteria ("non-designed pond") or guidelines was also monitored. The latter two winters of work featured the testing of slope coverings and filter fabric fencing on experimental plots. The purpose of this testing was to determine the relative effectiveness of the various options in reducing erosion and the release of potential water pollutants. Costs were estimated for the sedimentation ponds and slope treatments, so that an analysis of relative cost-effectiveness could be performed using indices devised for that purpose.

The laboratory scale modeling followed the dynamic similitude principle of fluid mechanics, using Froude and Reynolds numbers. The researchers determined actual water residence times by injecting sodium fluorescein dye and measuring light transmittance in the effluent. Tests were performed on basin shape, outlet type, series versus singular arrangements of chambers, baffles, and inlet position. The greatest benefit to water residence time was produced with a series of two chambers, rather than a single chamber of equivalent size. Elongation of the basin to a 5:1 length/width ratio and use of a perforated riser outlet was also beneficial when combined with the series configuration. Baffles were not advantageous, from the residence time standpoint, and inlet position made little difference.

The researchers monitored field-scale ponds by taking composite samples of influent and effluent and analyzing them for solids, organics, phosphorus, and metals.

The determination of flow volumes allowed calculation of pollutant mass loadings. All ponds captured virtually all of the settleable solids; more than 90 percent of the suspended solids; and majorities of the organics, phosphorus, and metals under most operating conditions, except for zinc in the case of the non-designed pond. This metal apparently was introduced by galvanized piping and silt fence support in the drainage system. The ponds, in general, did a relatively poor job of reducing turbidity in the effluents. Turbidity is influenced heavily by the finest particles and is frequently the basis of water quality standards. Overall, the designed ponds exhibited slightly better pollutant removal performance than the non-designed pond. Most significantly, the designed ponds were half the size of the non-designed pond per unit drainage area served. With pond construction costs at \$6.50 to \$7.50/ft^2 of pond surface area in the broad pond size range investigated, the designed ponds were substantially more economical and their cost-effectiveness indices higher than the pond to which they were compared.

The slope treatments investigated included straw mulches at three application rates and with and without manure mulching, fertilizing, and seeding; jute, excelsior, woven straw, and synthetic fiber mats; wood fiber mulch with fertilization and seeding, with various amounts of tackifier and without tackifier; a chemical agent; and a filter fabric fence. Duplicate test plots with these treatments were compared through a sample collection and analysis process to bare soil control plots in the rates of erosion (solids yield) and releases of organics, phosphorus, and metals. The wood fiber mulch without tackifier was the lowest cost option and exhibited the highest cost-effectiveness index. The most effective treatment in reducing erosion and pollutant releases overall was the wood fiber mulch with the maximum amount of tackifier (120 gallons/acre). Straw mulches were not as economical as the wood fiber alternatives but were close in overall effectiveness when manure mulching and fertilizing were excluded (higher phosphorus and organic releases accompanied these treatments). The most effective mat was the woven straw blanket, but relatively high cost caused its cost-effectiveness index to fall in about the middle of the set tested. Excelsior mat and the chemical agent used alone were relatively ineffective because they allowed rill erosion. Maintaining the filter fabric fence in good order produced intermediate pollution control benefits relative to other alternatives in all measures but settleable solids, which escaped the fence to a greater degree. Relative to the slope treatments, the sedimentation ponds were above the medians in effectiveness,but were relatively expensive per unit drainage area served.

CONCLUSIONS

The research results demonstrated that controlling erosion and pollution at the source, using certain slope coverings, is more cost effective than trapping eroded material later with filter fabric fences or sedimentation ponds. Source control also saves the costs of restoring eroded slopes, which were not included in the financial analysis. Another general conclusion warranted by the results is that erosion and pollution control objectives should be stated and considered in devising a strategy. For example, several different types of wood fiber and straw mulch applications can be cost-effectively used to reduce greatly the quantity of solids flowing from a slope. However, including manure mulch and fertilizer with these treatments can release relatively large quantities of phosphorus and degradable organic materials, at least until vegetation is well established. These releases should be avoided when the runoff discharges to a receiving water that is sensitive to nutrient increase or dissolved oxygen depletion. As another example, a woven straw blanket can provide a high level of erosion and pollution control even without grass, although at a rather high cost, and thus is a good strategy for a slope that is opened in the winter and requires immediate protection.

The many results and conclusions of the study are incorporated in an accompanying highway construction site erosion and pollution control manual, which is designed to be the implementation vehicle for the project. This manual provides selection, design, and operating criteria, guidelines, and specifications for slope coverings, filter fabric fences, and sedimentation ponds.

RECOMMENDATIONS

The erosion and pollution control manual contains numerous recommendations concerning the use of the various strategies. That manual should be incorporated into the various relevant Washington State Department of Transportation documents that guide Department construction and environmental protection policies and practices.

INTRODUCTION

BACKGROUND

Highway construction requires breaking large areas of ground, which frequently remain open and subject to erosion for a long period of time. Slope instability and erosion problems are aggravated by year-round construction. Both eroded soil particles and other pollutants transported by them can harm receiving water quality. Solids reduce light transmission in water bodies, cause abrasive damage to aquatic organisms, and degrade benthic habitats when they settle. Other pollutants of various types are commonly associated with eroded soil. Entering receiving waters, biodegradable organics can deplete dissolved oxygen, nutrients can promote eutrophication, and metals can be toxic to aquatic life.

The Washington State Department of Transportation (WSDOT) establishes contract specifications for the control of runoff quantity and water quality from construction sites (Washington State Department of Transportation 1988). WSDOT contractors typically rely on plastic sheeting to prevent erosion and on sedimentation ponds and such temporary measures as straw bales and silt fences to remove sediments from construction site runoff. WSDOT staff are dissatisfied with the expense of plastic sheeting (Strada, personal communication). Developing regulations and public interest, along with the high cost of restoring eroded slopes, are demanding more effective erosion control than in the past. Numerous products potentially satisfy this demand. However, there has been very little evaluation of the effectiveness of either traditional techniques or new products in relation to their cost, nor attention to the best design and operating techniques to maximize performance. Therefore, a research project was developed to study the performance and determine the costs of a selection of feasible erosion and pollution control measures in different design and operating configurations, with the goal of improving the cost-effectiveness of highway construction site temporary water pollution control.

SCOPE OF THE RESEARCH

The research investigated three types of control techniques: (1) slope coverings; (2) silt fencing, the most commonly used silt barrier; and (3) sedimentation ponds. The initial research task was a review of the literature pertaining to the three types. Findings from the literature review were instrumental in guiding subsequent phases of research. Some findings also contributed substantively to developing the criteria and guidelines presented in this manual.

The principal research tasks were experimental. First, well established principles of fluid mechanics were employed to design scale model sedimentation ponds that were dynamically similar to full-size systems. These models were used to test a host of design configurations in the laboratory. The objective was to identify configurations that are most effective in maximizing actual water residence times and will thus promote effective particle sedimentation. Beneficial design features identified through this analysis were then tested for pollution control performance at full-scale field sites and compared to a pond without these design features.

The literature review identified many potential slope covering techniques to reduce erosion at the source, as well as several silt barriers to interrupt eroded soil transport. A number of these techniques were selected for performance assessment at test plots. The selection was based on such considerations as expressed interest by WSDOT, the general extent of usage of the respective techniques, their potential suitability for highway construction applications, and their availability. The selected techniques were installed in duplicate on approximately 360-square foot test plots on a soil stockpile slope. These plots were monitored to determine erosion rates and yields of various pollutants. These data were compared with similar measurements from bare slopes that served as control sites in order to get measures of effectiveness.

The research was also concerned with obtaining the costs of the erosion and pollution control techniques assessed, so that their cost-effectiveness could be expressed. Sources of cost data included the literature review, erosion control product manufacturers, and WSDOT.

This final report is issued in conjunction with a Highway Construction Site Erosion and Pollution Control Manual (Horner et al. 1989), which is intended to implement the findings in highway construction practice. This document is termed the "Erosion and Pollution Control Manual" or "the Manual" in subsequent references in this report. The report and the manual are a complementary set; the report provides full documentation of the research results and the manual guides their application. An erosion control specialist would normally use the manual alone to select, design, and specify an operating plan for a technique. The user would only need to consult the final report if he or she desired or needed to obtain detail or justification concerning a manual provision.

LITERATURE BASIS

Construction site erosion and pollution control methods can be categorized as follows: (1) slope covering techniques, (2) silt barriers, (3) sedimentation ponds, and (4) other structural and nonstructural techniques.

Slope coverings prevent or reduce soil erosion at the source. Silt barriers interrupt the transport of eroded soil particles along the conveyance path between the source and a potential receiving water. Sedimentation ponds receive all the drainage from a catchment area and trap eroded material before it can pass into a surface water. This section summarizes the previous experience reported for each of these techniques in the literature.

Numerous additional structural and nonstructural (construction management) methods exist to prevent erosion or interfere with the transport of eroded soil. Investigation of these methods was beyond the research project's scope, and little quantitative information exists in the literature relative to their effectiveness and costs. Nevertheless, the Erosion and Pollution Control Manual lists them, along with their applications and purposes.

SLOPE COVERING TECHNIQUES

The subject of slope coverings was investigated during the research project with the aid of computerized literature search capabilities (Kortenhof 1988). The search covered six bibliographic databases and yielded 143 citations, 100 of which were sufficiently relevant to warrant detailed review.

Kortenhof (1988) synthesized and assessed the results of the literature review, which are summarized by Table 1. Ratings of effectiveness and service life were based on qualitative much more frequently than quantitative reports. Costs were expressed in terms of direct material and installation charges for a 1987 base year according to the Federal Highway Administration bid price index. See Kortenhof (1988) for further details on the methods used to construct Table 1.

TABLE 1. SLOPE COVERING EFFECTIVENESS AND COST DATA FROM THE LITERATURE REVIEW

(ADJUSTED TO 1987 DOLLARS)

			Cost (Dollars/Acre)[a]					
Method	Effectiveness	Life	Total	Material	Installation	Group	Notes	Reference[c]
Excelsior Mat	Best	1 season	6,135	4,200	1,935	High		1
			3,819	2,762	1,057			7
Jute Net	Best	1 season	5,915	4,918	997	High		1
			4,897	4,134	763			7
Plastic netting	Best	1 season	1,725	1,229	496	High?		7
Paper fabric	Best	1 season	5,291	4,512	779	High		7
Sodding	Best	indefinite	28,502	12,684	15,818	High		1
			10,166					5
Straw								
with tackifier	Best	3 to 6 months	1,295			Low	3 tons/acre straw	3
with punched			2,249	473	1,776		4 tons/acre	1
with tackifier			1,132	548	584		blown at 2 tons/acres	7
with tackifier			1,829	548	1,281		annual seed/straw at 2 tons/acre	7
with tackifier			1,634				asphalt	5
with tackifier			883				1.5 tons/acre	2
with tackifier			806				2.5 tons/acre	6
with tackifier			662				2.5 tons/acre	6
Straw without seeding	Good; short-term measure	1 to 2 months	373			Low	2 tons/acre mechanical anchors	5
			653				2 tons/acre; asphalt tackifier	5
Chemical soil stablizer	Good; significant product variability	1 to 12 months	2,524	2,010	514	High	Petroset SB	1
			4,497	3,195	1,302		Average of 6 products	4
Wood fiber mulch	Good; application rate strongly affects performance	1 to 3 months	1,109			Low	2000 lb/acre	3
			918	511	407		1500 lb/acre	7
			1,176	657	519		2500 lb/acre	7
			1,753	1,024	729		5000 lb/acre	7
			980					5
			698					2
			1,130					2
			858					6
Woodchips	Good; varies with thickness	> 1 year	6,017	1,157	4,860	High	3/4 inch thick	1
Hydroseeding	Poor alone; no control until grass is established		500	454	372		90 lb/acre seed; 450 lb/acre fer	3
			826	290	187			
			477				88 lb/acre seed;250 lb/acre fer	6
			291					
Plastic sheeting		1-3 months	2,161				Anchored with staked sandbags	8

[a] Includes hydroseeding, except as noted.

[b] High-->$2,500/ac; Low--<$2,500/ac

[c]
1. Ateshian (1976)
2. Goldman et al. (1986)
3. Goss et al. (1970)
4. Kibler and Bushy (1970)
5. Maryland Water Resources Administration (1983)
6. Missouri Highway and Transportation Department (1983)
7. White and Franks (1978)
8. Washington State Department of Transportation (personal communication)

The reported costs of some slope covering methods varied substantially, probably due in part to local variations and in part to inaccuracies in the procedure used to place all reports on a common basis. In light of this finding, efforts were made to establish the costs of the methods tested on the basis of local, up-to-date information.

Confirming the WSDOT experience, plastic sheeting was reported to be relatively expensive and to have a short service life. Natural mulches (straw and wood fiber) were identified as the least costly alternatives and thus became techniques of considerable interest for testing in the experimental research program. Other options (e.g., matting, netting, and chemical stabilizers) were found to be more expensive, but they are commonly used and may be the most appropriate methods in certain circumstances. Therefore, a selection of these options were also tested in the subsequent research.

SILT BARRIERS

Silt barriers are intended to reduce flow velocities and promote particle settlement, as well as to filter solids from the flow as it passes through. They include filter fabric fences, straw bale dikes, and brush barriers, which are filter fences made of materials removed during clearing and grubbing of a construction site. Straw bales have been widely used but have been found to be relatively ineffective in trapping sediments. Filter fabric fences offer the greatest flexibility and potential effectiveness among the silt barrier options.

Filter fabric fences are geotextiles made from polyester or polypropylene fibers that are used in a number of hydraulic and civil engineering applications besides construction site sediment control. Three main categories of geotextiles are used in sediment control: woven slit-film fabrics, woven monofilament fabrics, and non-woven fabrics (Municipality of Metropolitan Seattle 1988). The key characteristics in material selection are fabric strength and permeability of water. Strength is generally well defined by commercial suppliers, but permeability is inconsistently defined in the industry. Therefore, selection of characteristics to optimize both passage of water (to prevent pooling) and retention of solids in a given application is not entirely clear. For more effective use of this technique, greater industry standardization is needed. Also, users must become more informed about selection, rather than almost arbitrarily choosing products for distinctive applications.

A number of companies manufacture filter fabric fence, and most produce a number of grades. The Municipality of Metropolitan Seattle (Metro) (1988) has tabulated the properties of 16 materials from seven manufacturers. Metro considered effective opening size (EOS), which is based on U.S. sieve number equivalent, and slurry flow rate to be the best specifications on which to base material selection. However, manufacturers often do not provide data on the latter characteristic. In their absence, coefficient of permeability and water flow rate can be used as rough indicators of performance. Most promising are fabrics that have relatively high coefficients of permeability, water flow rates, and EOS values. Other important qualities by which alternatives should be compared are burst strength and ultraviolet stability (the ability to maintain performance with extended sunlight exposure).

Metro's assessment identified six among the 16 products considered to have these seemingly desirable characteristics (EOS = 40-120; coefficient of permeability = 0.10-0.20 cm/s; water flow rate = 100-470 gal/ft^2-min; tensile strength = 100-215 lbs.). All but one of these materials were in the non-woven category. Monofilament fabrics may provide better sustained performance than slit-film types because of their greater rigidity and lower tendency for pore distortion. However, the latter types are generally cheaper and are more widely used. On the other hand, the need for wire support to back relatively light slit-film fences, often required in ordinances, may offset the cost advantage.

Another consideration in filter fabric fence design is placement of posts, which must be close enough to maintain the fence under the force of water. Inspection is also required to check that posts are firmly in place. Filter fabric fences often sag to the point that sediment transport is unimpeded.

A fact that should be noted about silt barriers is that their pore sizes are always too large to contain clay- and many of the silt-size soil particles. Therefore, they serve much better to reduce the transport of settleable solids, along with a portion of the suspended solids, than to cut turbidity, which is a light-scattering measure that is disproportionately determined by the smallest particles. Being easier to measure, turbidity is more frequently the basis of standards than are the other quantities. Hence, erosion prevention at the source is a better strategy from the environmental and regulatory compliance standpoint than is interrupting the transport of sediments that have already been released.

SEDIMENTATION PONDS

Sedimentation ponds collect and store eroded particles before they can reach a water body or adjacent property. It is preferable to prevent erosion at the source, but ponds supplement source control. They usually serve until construction is complete. However, they can be adapted to permanent retention/detention pond service for the operating highway.

For some time detention ponds have been employed to regulate the rate of stormwater runoff released from urban catchments to receiving streams. Recently, these ponds have been recognized as potentially useful for improving runoff water quality by settling suspended soils as well. In this respect they are similar in principle to construction site sedimentation ponds. Some research on the pollution control performance of ponds in permanent urban runoff service has been accomplished and is relevant to the problem at issue here.

Among these reports, Whipple and Hunter (1981) quantified pollutant settling ability in laboratory water columns and applied the data to estimate detention basin pollutant removal capabilities. They concluded that a 32-hour residence time in an undisturbed pond 6 feet deep would reduce various stormwater constituents as follows: total suspended solids (TSS) — 70 percent; lead (Pb) — 60 percent; zinc (Zn) — 17 to 36 percent;

hydrocarbons — 75 percent; biochemical oxygen demand (BOD), copper (Cu), and nickel (Ni) — 20 to 50 percent. In a similar study, Randall et al. (1982) found that a 48-hour settling period removed 90, 86, and 64 percent of the TSS, Pb, and BOD, respectively, from parking lot runoff. In an actual pond, McCuen (1980) found sediment removal efficiency to vary between 2 and 98 percent over different storms, with the highest efficiencies associated with the smallest storms and longest detention times. One aspect of the U.S. Environmental Protection Agency's (1983) Nationwide Urban Runoff Problem involved detention basin effectiveness. This study established the following typical pollutant removal efficiencies for detention: TSS — 65 percent; Pb — 19 percent; Cu — 14 percent; total phosphorus (TP) — 25 percent. Dally et al. (1983) investigated the performance of two urban detention facilities and documented negative efficiencies due to resuspension of sediment; design flaws were to blame for this poor performance. Horner and Wonacott (1985) studied the performance of a detention pond serving a light-industrial site. They determined that the pond consistently removed the majority of the entering solids, nearly all of the lead, and 1/4 to 1/3 of the phosphorus. Reduction of other metals and nitrogen was variable.

These various reports lead to the conclusion that ponds can remove the majority of suspended sediments. However, the evidence is inconsistent for other pollutants. In recent years it has become clear that ponds that retain a permanent or semi-permanent water pool (wet ponds) yield better efficiencies than ponds that drain quickly because of the greater opportunity for physical, chemical, and biological mechanisms of pollutant removal to operate in the persistent pool (Schueler 1987).

Another recent advance is the formulation of design procedures that attempt to maximize pollutant capture. The procedures (e.g., National Cooperative Highway Research Program 1980; Goldman et al. 1986; King County Department of Public Works 1989) generally rely on several simplifying assumptions relative to the gravity settling of particles:

- particles settle separately with no interaction among them ("free" or "ideal" settling);
- soil particles are spherical;
- particles have relatively uniform specific gravities (meaning that weight is a positive function of size); and
- there is no horizontal component of velocity.

In reality these assumptions are untrue to varying degrees, but they are adequate for effective design if a sufficient detention time is allowed. In this situation, conventional engineering practice is to base pond design on the detention time required to capture particles with settling velocities greater than a selected design value. It should be noted that various contaminants, especially heavy metals and organic chemicals, are primarily in the particulate form in land runoff and are removed if the particles to which they attached settle.

In the ideal settling basin, the trajectory of a settling particle is a straight line extending from the water entrance to the bed as the water passes through. Several factors disturb this idealized pattern, including short-circuiting flow (water reaching the outlet in a period shorter than the theoretical water residence time), turbulence, bottom scour, riser design, and wind. Effective application of the technique is largely a matter of obtaining sufficient residence time to settle particles with given settling velocities and avoiding or reducing conditions that detract from idealized behavior. In this research project laboratory scale model testing was performed to determine the design features that best achieve these ends.

Application of the sedimentation pond design procedures relies on estimating a volume for sediment storage plus a particle settling zone volume. The sediment storage volume is the space required to contain the sediment yield to the pond over an annual or some other period. It is usually estimated with the use of the Universal Soil Loss Equation (McElroy et al. 1976). The particle settling zone volume is estimated with the continuity equation of fluid mechanics on the basis of a design storm of a selected recurrence interval and duration and the settling velocity of a selected design particle size.

A sedimentation pond can be formed by excavation, construction of a compacted embankment, or a combination. It can have one or more inlets introducing polluted runoff, but it should not intercept any significant amount of clean water, unless it is sized accordingly. Common features of a sedimentation pond include:

- baffles to check inlet velocity and spread flow throughout the basin;
- securely anchored riser pipe with an orifice designed for a selected dewatering time;
- emergency overflow;
- means of dewatering; and
- protection from channel erosion at the inlet and outlet.

Other advances in sedimentation pond design have concerned basin configurations that promote solids settling. Key recommendations are to maximize the basin surface area to volume ratio to the extent possible (Kathuria et al. 1976) and to maximize the length to width ratio and consider a series arrangement of more than one basin (Ellis 1985). The utility of these recommendations was a subject of interest in this research project.

RESEARCH METHODS

LABORATORY MODEL TESTING

The model test systems were constructed of Plexiglas to avoid leakage. They were made geometrically similar to full-size basins according to Froude Law scaling. The model scales were sufficiently large that the Reynolds numbers of the flows in the models were large enough for the essential features of prototype flows to be reproduced. Water was distributed to the models with a Cole-Parmer Masterflex peristaltic pump. Visual observations of flow patterns in the model basins were made with the aid of sodium fluorescein (a soluble, biodegradable dye) injections. To quantify the rate of dye travel, light transmittance in effluent samples was determined in a Bausch and Lomb Spectronic 20 spectrophotometer.

Laboratory tests were concerned primarily with observing the effects of basin geometries and hydraulics on performance. Of particular interest were configurations that prevent short-circuiting of the flow, which reduces residence time and causes low sedimentation efficiency. Sedimentation processes were not observed directly, since they cannot be scaled according to the Froude Law.

The flexibility and economy of laboratory testing permitted exploration of many more design and operating possibilities than were feasible in the field. The lack of ability to scale sedimentation processes was not a serious problem, since the solids removal efficiencies of sedimentation devices are governed principally by hydraulic considerations. While it was not possible to predict efficiencies directly from laboratory results, it was possible to identify the most efficient designs and thus inform the most critical decision. The field experiments at full scale then served chiefly to verify tentative laboratory conclusions and to provide estimates of actual pollutant removal efficiencies.

The following test sequences were performed in order:

1. shape sequence (length/width ratios of 1:1, 2.5:1, and 5:1 for constant volume)
2. riser outlet sequence
3. series sequence (two basins instead of one)
4. baffle sequence, and
5. inlet repositioning series

The most advantageous features of earlier tests were incorporated in latter ones. Scaling was based on a depth range in a full size sedimentation basin of 50 - 300 cm and an overflow velocity of $\leq 2 \times 10^{-3}$/cm/s (after Kathuria et al. 1976). These selections produced allowable Reynolds numbers in the range of 1 to 45 and Froude Numbers of 8.2×10^{-8} to 9.0×10^{-6}. In consideration of these scaling factors and pump capabilities, model chambers 32 x 125 x 40 cm high were constructed. Interior walls could be repositioned to reduce these dimensions when needed. Test overflow velocities were 4.5×10^{-4} to 5.8×10^{-4} cm/s.

FIELD MONITORING

Field Site Characteristics

Experimental work was performed at three field test sites: (1) a sedimentation pond constructed before the research project in the I-90 right-of-way in the First Hill area of Mercer Island, Washington; (2) a site in the SR-204 right-of-way in Snohomish County, Washington, just north of SR-2, where a truck-climbing lane was being added to the existing road; and (3) a fill stockpile located near the I-90 construction site area in Seattle, Washington. The Mercer Island pond was built to serve an active construction site without a formal design, as has been the usual practice (Conroy, personal communication) and will be referred to as the "Mercer Island non-designed pond." At SR-204 a pond was designed on the basis of the laboratory results. This pond will be referred to as the "SR-204 designed pond." The fill stockpile was used for two purposes. On one slope 16 plots were placed for testing slope covering and fabric fence materials. The remainder of the pile drained to a sedimentation pond that was also designed according to the laboratory results. This pond will be referred to as the "Seattle designed pond."

Table 2 gives the surface areas of the three sedimentation ponds and the catchments that drained them, area ratios and detention times. The Mercer Island non-designed pond was by far the largest and served the largest catchment, but its catchment area:pond area ratio was only about half of the ratio for the two designed ponds. Consequently, it had a much longer detention time. The Mercer Island pond was divided by filter fabric attached to chain-link fence. It was clay-lined and, therefore, had little exchange with groundwater. A permanent water pool had existed throughout the year before the monitoring, although the level dropped because of evaporation when intervals between storms were lengthy. The inlet and outlet were via 24-inch-diameter corrugated metal pipes.

Figure 1 illustrates the schematic plan and elevation views of the SR-204 designed pond, along with the monitoring equipment. The pond was designed to retain a 10-year storm event with the overflow velocity limitation suggested by Kathuria et al. (1976). It was constructed with earthwork and sandbags. Risers were 4-inch (inside diameter) polyvinyl chloride pipes that extended 16 inches below the water surface and had a series of 1-inch-diameter through-hole perforations on 3-inch centers. The pond's catchment area was more than half paved, existing road.

Table 2. Areas of Sedimentation Ponds and Their Catchments

Pond	Pond Surface Area (ft^2)	Catchment Area (ft^2)	Catchment Area: Pond Area: Ratio	Detention Time[a] (hours)
Mercer Island non-designed pond	7,900	331,000	42	11.5
SR-204 designed	980	78,400	80	1.6
Seattle designed pond	400	32,700	82	3.7

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[a] Estimated detention time of runoff from a 10-year, 6-hour storm.

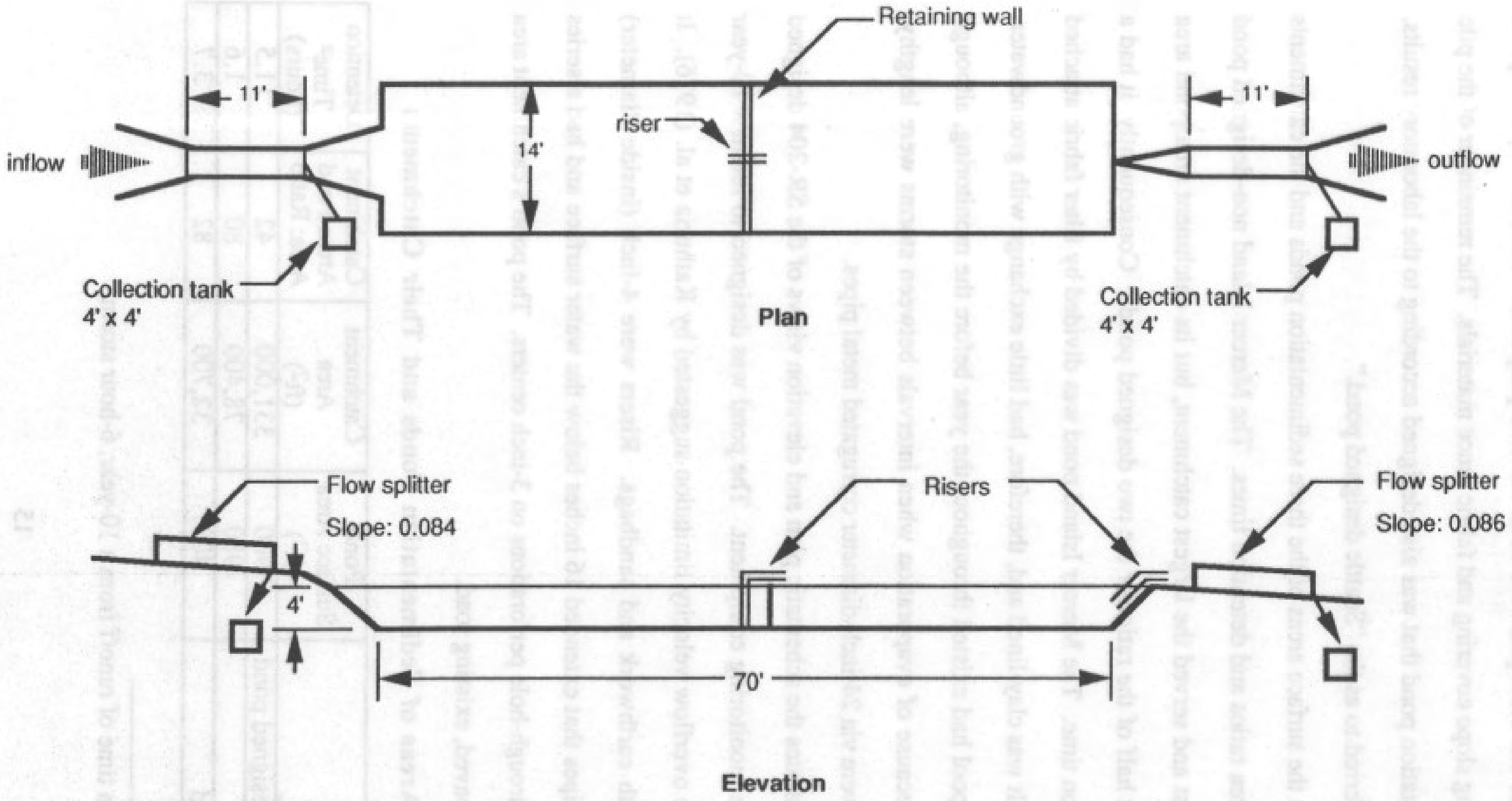

Figure 1. Schematic of SR-204 Sedimentation Pond

The Seattle designed pond was designed and configured in the same way as the SR-204 pond but had different dimensions because of the different contributing catchment characteristics. Its overall length and width were 40 and 10 feet, respectively (both bottom dimensions). Flow splitters were also slightly smaller than those at the SR-204 site.

The slope covering and fabric fence test plots were approximately 9 x 36 feet and lay on a 2.5:1 slope. During the first winter of operation (1987-88), the 16 plots were allocated as follows (each treatment was duplicated):

- Plots 1, 2 -- Straw mulch (4 tons/acre)
- Plots 3, 4 -- Straw mulch (4 tons/acre); manure-mulched, fertilized, and seeded
- Plots 5, 6 -- Straw mulch (2.75 tons/acre); manure-mulched, fertilized, and seeded
- Plots 7, 8 -- No treatment (bare soil control plots)
- Plots 9, 10 -- American Excelsior Curlex Mat (shaved wood mat)
- Plots 11, 12 -- North American Green S75 blanket (woven straw blanket)
- Plots 13, 14 -- Weyerhaeuser Silva-Fiber (wood fiber mulch) (1 ton/acre); fertilized and seeded
- Plots 15, 16 -- Weyerhaeuser Silva-Fiber (1 ton/acre) with Ero-Bond tackifier; fertilized and seeded

The duplicated treatments were changed to the following for the 1988-89 winter:

- Plots 1, 2 -- Straw mulch (1.25 tons/acre)
- Plots 3, 4 -- Belton Anti-Wash/Geojute (jute mat)
- Plots 5, 6 -- Phillips SuperGro blanket (polypropylene fiber blanket)
- Plots 7, 8 --Weyerhaeuser Silva-Fiber (wood fiber mulch) (1 ton/acre) with Ero-Bond tackifier; fertilized and seeded
- Plots 9, 10 -- Weyerhaeuser Silva-Fiber (1.5 ton/acre) with Ero-Bond tackifier; fertilized and seeded

- Plots 11, 12 -- Hoechst Celanese Curasol AK (chemical agent)
- Plots 13, 14 -- Exxon GTF100S filter fabric fence (installed perpendicular to the slope at the downslope end)
- Plots 15, 16 -- No treatment (bare soil control plots)

Each plot was isolated by berming covered with plastic sheeting so that only precipitation that fell on the plot contributed to runoff from the plot. At the downslope end of each plot, runoff was channeled by boards toward a central collection point, where it discharged through a 4-inch polyvinyl chloride pipe from which samples could be taken.

Table 3 presents soil textural data for the three study locations. The Mercer Island catchment contained sand and sandy loam soils, while gravelly sand prevailed in the SR-204 right-of-way. The Seattle fill stockpile was predominantly sandy loam, with some gravel.

Sedimentation Pond Monitoring

The general objectives of monitoring the sedimentation ponds were to determine their pollutant removal ability and to compare the performances of the designed ponds with the non-designed installation. The researchers accomplished these objectives by sampling flow to and from the ponds during storms and analyzing and comparing the quantities of pollutants entering and leaving.

At the SR-204 and fill stockpile sites, where the site configurations permitted, sedimentation pond sampling utilized the storm composite sample collection system developed in previous research (Mar et al. 1982, Clark and Mar 1980, Clark et al. 1981). The system consisted of a calibrated flow splitter, composite tank, and connecting piping. The flow-splitter was designed to direct a set proportion of the total runoff into the composite tank and was based on the specific site hydrology. Tank gaging and the calibration permitted accurate estimation of the total runoff volume. When a storm ended, the composite tank was stirred vigorously to resuspend any matter that settled between the

TABLE 3. SOIL TEXTURAL DATA FOR FIELD SITES

Mercer Island Site

	Sample 1		Sample 2		Sample 3		Sample 4	
	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight
Gravel (>2 mm)	7	2	6	1	0	0	0	0
Coarse Sand (0.4-2.0 mm)	153	37	317	49	186	66	248	66
Fine Sand (0.08-0.4 mm)	144	35	172	26	72	25	88	23
Silt (0.002-0.08 mm)	112	27	148	23	17	6	36	10
Clay (<0.002 mm)	5	1	13	2	7	2	6	2
Total	414		650		282		378	
Textural Classification[a]	Sandy Loam		Sandy Loam		Sand		Sand	

SR-204 Site (Composite sample)

	Weight (grams)	Weight (percent)
Gravel (> 2 mm)	569	28
Coarse Sand (0.4-2.0 mm	791	39
Fine Sand (0.08-0.4 mm)	477	23
Silt & Clay (<0.08 mm)	212	10
Total	2,049	
Textural Classification[a]	Gravelly sand	

Seattle Fill Stockpile Site (Composite sample)

	Weight (grams)	Weight (percent)
Gravel (> 2 mm)	212	10.4
Coarse Sand (0.4-2.0 mm	600	29.3
Fine Sand (0.08-0.4 mm)	601	29.4
Silt & Clay (<0.08 mm)	633	30.9
Total	2,046	
Textural Classification[a]	Gravelly sandy loam	

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[a] U.S. Bureau of Public Roads Classification System (Spangler and Handy 1973)

TABLE 4. WATER QUALITY ANALYSES AND ANALYTICAL METHODS

			References			
Constituent	**Type Sample**	**Method**	**American Public Health Association (1985)**	**U.S. Environmental Protection Agency (1983)**	**Equipment Specifications**	**Preservation**
Total Suspended Solids (TSS)	Unfiltered	Gravimetric	209C	160.2	Mettler Type H15 analytical balance	4°C refrigeration
Settleable Solids	Unfiltered	Imhoff Cone	209E	160.5	Standard Imhoff Cone	4°C refrigeration
Turbidity	Unfiltered	Nephalometric	214A	180.1	Hach Model 2100 Turbidimeter	4°C refrigeration
Chemical Oxygen Demand (COD)	Unfiltered	Dichromate reflux	508A	410.1	———	H_2SO_4 to pH < 2 4°C refrigeration
Metals (Pb, Zn, Cu)	Filtered and unfiltered[a]	SR-204/Mercer Island: Inductively coupled plasma (ICP) Fill stockpile site: Atomic absorption spectrophotometry (AA)	Section 300	Section 200	Jarrell-Ash ICP Instrumentation Laboratory 511 AA with 655 graphite furnace	HNO_3 to pH < 2
Total Phosphorus (TP)	Unfiltered	Ascorbic acid following persulfate digestion	424 C,F	365.2	Milton Roy Spectronic 1001 spectrophotometer	H_2SO_4 to pH < 2 4°C refrigeration

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[a] Filtered samples were analyzed for dissolved metals from the SR-204 and Mercer Island sites and from the fill stockpile site during the 1987-88 winter. Analysis for dissolved metals was eliminated during 1988-1989 because of the consistently very low (usually undetectable) concentrations.

entrance of runoff and the sample collection time. The composite tank was then subsampled for pollutant analyses.

At the existing Mercer Island sedimentation pond, where site configurations did not permit installation of the composite sampling system, an ISCO bubble-type flow meter was first used to determine runoff volume. When the meter proved unsatisfactory to measure low flows, they were estimated from Manning's equation and a depth measurement. Samples were collected manually and composited on a flow-weighted basis to provide a composite sample equivalent to that obtained with the composite sampling system.

At the SR-204 and Mercer Island sites, five storm events were monitored at each pond during the period April 1987-January 1988. Five events were monitored at the Seattle designed pond during the 1988-89 winter. On-site precipitation data were obtained from rainfall bucket collectors that were placed at all field locations.

Table 4 lists the water quality constituents that were measured in the runoff samples, the analytical procedures employed, equipment specifications, and preservation techniques. General sampling and sample handing provisions were according to the guidelines of the U.S. Environmental Protection Agency (1983).

Except for settleable solids and turbidity, pond pollutant removal efficiencies were computed by the following equation:

$$\% \text{ removal} = \frac{\text{Inlet loading - Outlet loading}}{\text{Inlet loading}} \text{ x } 100 \qquad \text{(Eq.1)}$$

Loading is the mass transport of contaminants per unit of time, and is the product of mean flow rate over the length of the storm event times the mean contaminant concentration (the concentration in the event composite sample). Loadings cannot be calculated for settleable solids and turbidity, but reductions in these quantities were expressed in terms of the units in which they are measured (mL/L and NTV, respectively).

Slope Covering Test Plot Monitoring

The general objective of the test plot monitoring was to determine the ability of slope coverings to prevent, or fabric fence to contain, soil erosion and its associated pollutants in comparison to bare soil control plots. The researchers accomplished this objective by measuring the flow rates and analyzing samples of runoff from the plots during storm events of several hours duration and expressing pollutant loadings from the treated plots with respect to those from the controls.

Flow measurement was accomplished by timing the rate at which a graduated cylinder filled from the plot discharge pipes. The runoff drained to buckets, which provided composite samples for analysis. Six and seven storm events were monitored inthis way in 1987-88 and 1988-89, respectively. Water quality analysis and loading calculations were the same as specified under Sedimentation Pond Monitoring. Except for settleable flow rate, settleable solids, and turbidity, the performance of the various slope coverings was expressed by a percentage reduction in pollutant loadings, in comparison to control plots, according to the following equation:

$$\%\ \text{removal} = \frac{\text{Control plot loading - Covered plot loading}}{\text{Control plot loading}} \times 100 \qquad \text{(Eq.2)}$$

Reductions in settleable solids and turbidity were expressed in the same way as described for sedimentation ponds. Flow rate reduction was calculated by an equation equivalent to Equation 2, in which the flow rate (L/h) replaced loading.

FINANCIAL ANALYSIS

Cost Estimates

All sedimentation pond, slope covering, and filter fabric fence costs were determined as direct material and labor expenses. These costs were estimated from unit material costs supplied by manufacturers and installation costs from WSDOT, whose contractors assisted with certain installation tasks, and from material suppliers. This system was preferred to reliance on the literature because of the difficulties experienced in converting literature-reported costs to a common basis during the preliminary review. The literature review made apparent that the various techniques offer different service lives. Therefore, the costs were normalized to a common service life (six months, the approximate length of the high runoff season in Washington, during which slope protection is most needed). They were also expressed per unit area served, and thus were reported in \$/(acre) served (6 months service).

Cost-Effectiveness Calculations

A series of indices was developed to express the relative costs, effectiveness measures, and cost-effectiveness of the various techniques investigated so that their erosion control utility could be quantitatively compared. These indices were defined as follows:

1. Relative economy index $= \left(\frac{\text{Cost - Minimum Cost}}{\text{Cost}}\right) \times 100$ (Eq.3)

Cost = \$/acre of catchment served — 6 month service life

Minimum cost = Lowest cost among all techniques compared

2. Relative effectiveness index$= \left(\frac{\text{Mean \% reduction}}{\text{Maximum mean \% reduction}}\right) \times 100$ (Eq.4)

Mean % reduction = average efficiency of removal of a given pollutant over all storm events monitored

Maximum mean % reduction = Highest average efficiency among all techniques compared

3. Relative cost-effectiveness index =

$$\left[1 - \left(\frac{\text{Cost-effectiveness - Best cost-effectiveness}}{\text{Cost-effectivness}}\right)\right] \times 100 \qquad \text{(Eq.5)}$$

$$\text{Cost-effectiveness} = \frac{\text{Cost}}{\text{Mean \% reduction}} \qquad \text{(Eq. 6)}$$

Best cost-effectiveness = High cost-effectiveness among all techniques covered

The first index was calculated for each technique tested. The second, third, and fourth indices were computed for five different effectiveness measures for each technique: (1) preventing erosion, (2) reducing phosphorus yield, (3) reducing metal yield, (4) reducing organic yield, and (5) overall. The erosion prevention measure was based on the mean percentage of total suspended solids mass flux in runoff relative to bare slope controls for slope coverings and silt barriers, or relative to the influent for sedimentation ponds. The phosphorus yield reduction measure was based on the mean percent reduction of total phosphorus mass flux in runoff on the same basis as erosion prevention. The metal yield reduction measure was based on the mean percent reduction in the total mass flux of three metals (lead, zinc, and copper) in runoff, also on the same basis as erosion prevention. The organic yield reduction measure was based on the mean percent reduction in the mass flux of volatile suspended solids and chemical oxygen demand fluxes in runoff, again on the same basis as erosion prevention. The overall measure was computed as the mean of the four individual measures.

A coding system was devised to express the indices in such a way that relative cost, performance, or cost-effectiveness would be immediately obvious to a user of the information. This system, which is used in the Erosion and Pollution Control Manual, is as follows:

A	(Highest)	Relative index = 81-100
B	(Moderately high)	Relative index = 61-80
C	(Intermediate)	Relative index = 41-60
D	(Moderately low)	Relative index = 21-40
E	(Lowest)	Relative index = 0-20

RESEARCH RESULTS

LABORATORY MODEL TESTING

Table 5 summarizes the results of all laboratory trials. Figure 2 illustrates key results. Elongating the shape with constant test chamber volume (2.5:1 or 5:1 length/width ratio) yielded only marginally longer water residence times, when no other special design features were incorporated. The riser outlet did not appear to be advantageous on the basis of the data in Table 5. However, starting with a full basin, some of the dissolved dye was detectable spectrophotometrically in the outlet stream in 1 to 3 minutes with surface outlets, but none was detectable with riser outlets after 23 minutes of operation. Therefore, risers offered an advantage in retarding short circuiting of inflow initially, if not in changing the average quality of the outflow after some time elapsed.

Comparison of the transmittance readings with a series of two basins to the results of preceding tests revealed a distinct advantage with the series arrangement. With this configuration, the most elongated basin also produced a slight advantage in water residence time. However, baffles did not yield nearly as good a performance as the series arrangement.

The horizontal position of the inlet (center versus offset) made very little difference in water residence time. Elevating the inlet suggested a possible advantage early in the test, but the advantage disappeared after the elapse of more time.

These results indicated that actual water residence time can be maximized by providing a sedimentation pond with a 5:1 length/width ratio, subdivided into two basins, and a perforated riser outlet. Other dispersed outlet designs should also yield the same advantage. The advantage of the series configuration was strong; thus the laboratory results suggest that this feature should be incorporated in every pond. It should be noted that subdivision of an actual sedimentation basin into cells could induce turbulence at the constrictions between cells, which could interfere with particle settlement. Therefore, field

Table 5. Summary of Laboratory Model Water Retention Basin Tests

Test Sequence	Special Design Features	Trial	Velocity (cm/s)	Test Duration (min.)	Length/ Width Ratio	Transmittance[a] (%)
Shape	Surface Inlet and outlet	1	4.5 x 10^{-4}	72	1:1	91.8
					2.5:1	96.3
					5:1	96.3
		2	5.8 x 10^{-4}	20	1:1	94.0
					2.5:1	93.0
					5:1	94.0
Riser outlet	Surface inlet	1	4.5 x 10^{-4}	60	1:1	92.0
					2.5:1	74.0
					5:1	89.0
		2	5.8 x 10^{-4}	26	1:1	92.0
					2.5:1	93.0
					5:1	92.0
Series	Surface inlet, riser outlet	1	5.8 x 10^{-4}	19	2.5:1	99.5
					5:1	99.7
				75	2.5:1	93.0
					5:1	95.0
				105	2.5:1	92.0
					5:1	92.0
		2	5.8 x 10^{-4}	20	2.5:1	100.0
					5:1	100.0
				70	2.5:1	92.0
					5:1	96.0
				100	2.5:1	90.0
					5:1	92.0
Baffles	Surface inlet, riser outlet	1	5.8 x 10^{-4}	19	2.5:1	98.0
					5:1	99.5
				75	2.5:1	87.0
					5:1	77.0
				105	2.5:1	81.0
					5:1	75.0
		2	5.8 x 10^{-4}	20	2.5:1	98.0
					5:1	98.0
				70	5:1	73.0
				100	5:1	72.0
Center inlet	Surface inlet, riser outlet, series	1	5.8 x 10^{-4}	30	2.5:1	96.0
					5:1	9.40
Offset inlet	Surface inlet, riser outlet, series	1	5.8 x 10^{-4}	30	2.5:1	94.0
					5:1	93.0
Elevated inlet	Riser outlet, series	1	5.8 x 10^{-4}	75	2.5:1	98.0
					5:1	97.0
				110	2.5:1	95.0
					5:1	87.0

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[a] Light transmittance in diluted dye sample taken at basin outlet, as measured by spectrophotometer. The lower the transmittance, the greater the presence of the dye and, therefore, the shorter the mean water residence time.

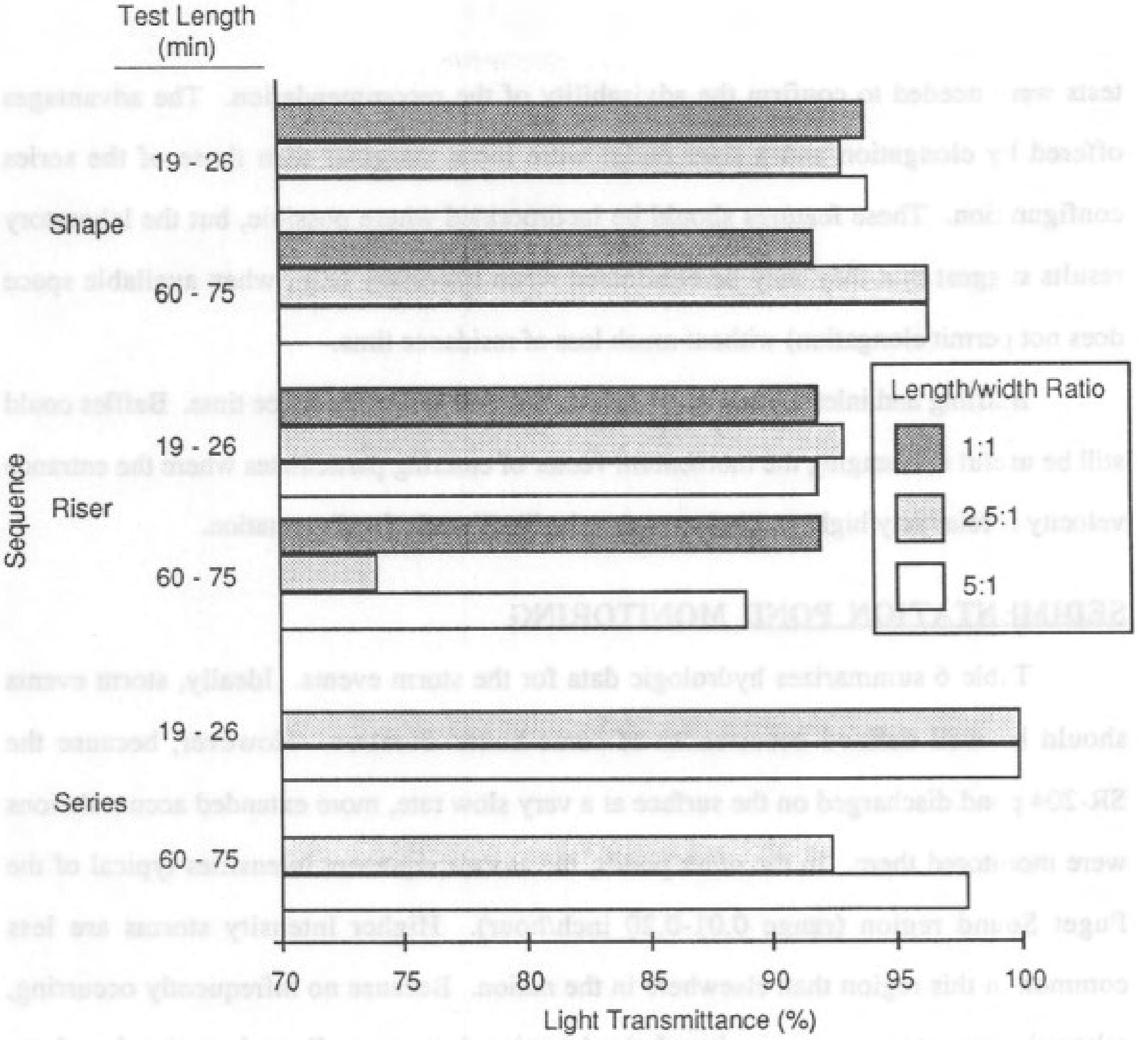

Figure 2. Laboratory Model Test Results for Shape, Riser, and Series Test Sequences, Each at Two Test Lengths

tests were needed to confirm the advisability of the recommendation. The advantages offered by elongation and a riser outlet were more marginal than those of the series configuration. These features should be incorporated where possible, but the laboratory results suggest that they may be eliminated when necessary (e.g., when available space does not permit elongation) without much loss of residence time.

Baffling and inlet repositioning did not increase water residence time. Baffles could still be useful in changing the momentum vector of entering particulates where the entrance velocity is relatively high, and in increasing the likelihood of sedimentation.

SEDIMENTATION POND MONITORING

Table 6 summarizes hydrologic data for the storm events. Ideally, storm events should be well defined occurrences of some hours' duration. However, because the SR-204 pond discharged on the surface at a very slow rate, more extended accumulations were monitored there. In the other ponds, the storms represent intensities typical of the Puget Sound region (range 0.01-0.20 inch/hour). Higher intensity storms are less common in this region than elsewhere in the nation. Because no infrequently occurring, relatively large storms were monitored, the detention times were all much greater than those for the design storm in Table 2.

Appendix A lists all water quality data for the storm events monitored in terms of both pollutant concentrations and mass loadings. Loadings were estimated by multiplying concentrations and total runoff volumes. The SR-204 pond received some exceptionally high pollutant loadings as a consequence of the extensive bare slopes in its catchment. For example, maximum TSS and TP at SR-204 were 37,165 and 18.6 mg/L, respectively. The equivalent maximums entering the Mercer Island pond were 4,140 and 0.787 mg/L, respectively, and for the Seattle designed pond were 7,577 and 3.23 mg/L, respectively.

Table 7 expresses pollutant reductions achieved by the sedimentation ponds. Three measures of solids reduction are reported: settleable solids, which reflect the volume of the

TABLE 6. SUMMARY OF STORM EVENT HYDROLOGIC DATA

Location	Storm No. (Date)	Precipitation (in.)	Event Duration	Antecedent Conditions	Runoff Volume (ft^3)	Detention Time[a] (hours)
Mercer Island non-designed pond	1 (4/3/87)	trace	4 hours	0.58 inch precipitation over preceding 9 days	180	1386
	2 (4/30/87)	0.39	2 hours	0.53 inch precipatation over preceding 14 days	2,700	17.8
	3 (12/1/87)	0.48	4 hours	1.23 inch precipitation over preceding 13 days	3,700	28.9
	4 (1/9/88)	0.06	4 hours	0.31 inch precipitation over preceding 1 day.	1,000	231
	5 (1/14/88)	0.21	4 hours	2.58 inches precipitation over preceding 3 days	5,900	65.5
SR-204 designed pond	1 (5/14-28/87)	0.27	14 days	Unknown	920	1047
	2 5/28-30/87)	0.67	2 days	0.27 inch precipitation over preceding 14 days	2,300	60.5
	3 (5/30-6/11/87)	0.48	12 days	0.67 inch precipitation over preceding 2 days	1,600	493
	4 (6/11-7/14/87)	0.69	33 days	0.48 inch precipitation over preceding 12 days	2,400	931
	5 (7/8-8/17/87	1.43	30 days	0.72 inch over preceding 37 days	4,900	419
Seattle designed pond	1	2.5	5 days	NA	300	52.9
	2	1.2	5 days	NA	500	111
	3	0.15	5 hours	1.1 inch precipitation over preceding 5 days	200	37.0
	4	0.20	4 hours	1.0 inch precipitation over preceding 5 days	300	22.2
	5	0.27	5 hours	1.4 inch precipitation over preceding 5 days	250	20.6

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[a] Estimated using the Rational Method for the storm conditions
NA -- not available

TABLE 7. POND EFFICIENCY DATA (POLLUTANT REMOVAL RATES IN PERCENT)

Mercer Island Non-Designed Pond

						Total Metals			Dissolved Metals		
Storm No.	Settleable Solids[a]	Turbidity[a]	TSS	COD	Total P	Cu	Pb	Zn	Cu	Pb	Zn
1	100.0	95.0	93.2	60.5	79.8	62.1	- - -	-17.4	76.3	- - -	-653.0
2	100.0	80.0	99.4	93.4	87.8	93.0	>78.0	84.7	79.4	- - -	-188.5
3	100.0	93.7	95.3	NA	91.4	66.7	>45.8	64. 0	18.2	- - -	65.1
4	100.0	93.1	94.7	NA	87.6	53.1	>56.0	46.8	60.0	- - -	-41.2
5	100.0	-21.4	-6.9	NA	-10.0	-38.9	-33.3	31.3	11.1	- - -	78.2
5 Storm Mean	100.0	68.1	75.1	76.9	67.3	47.2	>36.0	41.9	49.0	- - -	-147.9
Std. Dev.	0.0	50.4	45.9	23.3	43.4	50.4	- - -	38.6	32.3	- - -	301.9
4 Storm Mean (No. 1-4)	100.0	90.4	95.6	76.9	86.7	68.7	>60.0	44.5	58.5	- - -	-204.4

SR-204 Designed Pond

						Total Metals			Dissolved Metals		
Storm No.	Settleable Solids[a]	Turbidity[a]	TSS	COD	Total P	Cu	Pb	Zn	Cu	Pb	Zn
1	94.6	93.1	97.3	62.4	68.0	66.7	>78.0	73.7	38.5	- - -	67.6
2	100.0	-18.2	98.7	75.9	96.2	92.7	92.9	78.0	78.6	>45.0	-14.3
3	100.0	>84.5	98.4	NA	96.9	95.0	93.3	94.1	80.4	66.7	86.3
4	99.9	>82.0	99.4	NA	96.6	97.6	95.5	95.4	14.3	- - -	31.8
5	99.3	>85.0	99.2	NA	96.6	97.1	81.3	91.2	-50.0	- - -	50.0
Mean	98.8	>65.3	98.6	69.1	90.9	89.8	>88.2	86.5	32.4	>55.9	44.3
Std. Dev.	2.3	- - -	0.8	9.5	12.8	13.1	<8.0	9.9	53.8	- - -	38.5

Seattle Designed Pond

							Total Metals		
Storm No.	Settleable Solids[a]	Turbidity[a]	TSS	VSS	COD	Total P	Cu	Pb	Zn
1	92.2	0	69.2	55.3	44.9	59.5	46.4	32.1	14.6
2	99.1	0	85.3	80.7	NA	NA	NA	NA	NA
3	99.3	>79.2	86.3	80.9	69.7	76.1	70.6	60.0	71.2
4	NA	NA	96.9	88.8	82.3	91.2	89.1	82.4	88.8
5	NA	>83.9	92.7	89.9	60.5	86.6	60.0	85.7	86.2
5 Storm Mean	96.9	>40.8	86.7	79.1	64.4	78.4	66.5	65.1	65.2
Std. Dev.	4.0	- - -	10.6	14.0	15.7	14.1	18.0	24.8	34.6
3 Storm (No. 3-5) Mean	99.3	>81.6	92.0	86.5	70.8	84.6	73.2	76.0	82.1

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[a] Based on mL/L for settlable solids or NTU for turbidity; all others based on mass loading.

NA -- not analyzed; settleable dashes signify where values below detection limits prevented efficiency calculations.

most easily settled particles; turbidity, which is a light-scattering measure that especially depends on the quantity of the smallest, least settleable particles; and TSS, which reflects the mass concentration of all particles present in a sample. Sedimentation ponds are known to perform very well in capturing settleable solids, to be capable of removing the majority of TSS, but to be less reliable in reducing turbidity. These impressions are borne out by the results reported here. Turbidity decreases were often not proportionate to reductions of very high influent loads of solids as measured by settleable solids and TSS. It appears that those efficient removals were achieved through the relatively easy capture of the larger particles, while smaller particles, which contribute much less to volume and mass but very significantly to light scattering, were able to pass through the ponds. However, water quality standards are often based on turbidity. Therefore, sedimentation ponds are often not adequate to meet standards alone and require supplementation.

The three ponds removed virtually all of the settleable solids, and the SR-204 designed pond was consistently very efficient in TSS, total P, and total metals reductions, exceeding the non-designed pond in performance. That high level of apparent performance was achieved despite the fact that the SR-204 pond served a drainage area (relative to its surface area) about twice as large as the Mercer Island pond. However, ungagedgroundwater seepage entered the designed pond, diluted the sediment-laden surface water, and may have inflated the calculated efficiencies. Also, the Mercer Island results were heavily influenced by one storm (No. 5) that closely followed an extended rainy period. With a completely full pond, not reduced by evaporation as was the case with other storms, water residence time was short; and several removal efficiencies were negative (i.e., the pond was a source of pollutants). This pond was a consistent source of dissolved zinc, probably because of galvanizing on its inlet and outlet pipes and the chain-link fence used to support the filter fabric barrier.

Further testing was performed using the Seattle designed pond to attempt to resolve uncertainties remaining from the initial experiments with the other two ponds. This pond served a drainage area (relative to its surface) very similar in size to the catchment of the other designed pond, and again about twice as large as the non-designed pond. The first monitoring attempts at the Seattle pond were afflicted with various sampling difficulties, and there is some lack of confidence in the results from those attempts. The final three sets of samples were collected with a consistent, reliable monitoring system and provide a data subset in which there is considerable confidence. The mean efficiencies in this subset exceeded 70 percent for all water quality variables, and the mean TSS reduction was 92 percent. These results demonstrate that incorporating the recommended design features in a sedimentation pond can achieve performance that is at least equivalent to, and probably overall better than, the performance offered by a non-designed pond that consumes much more area (relative to its catchment size).

SLOPE COVERING AND FILTER FABRIC FENCE TEST PLOT MONITORING

Appendix B lists flow rates and water quality data in terms of both pollutant concentrations and mass loadings for the storm events monitored on the plots. Table 8 provides precipitation characteristics. The events were all approximately 1 to 4 hours long and represented precipitation intensities ranging over about one order of magnitude.

TABLE 8. RAINFALL INTENSITIES OF EVENTS DURING WHICH PLOT MONITORING OCCURRED

Winter	Storm No.	Intensity (inch/hour)
1987-88	1	0.044
	2	0.009
	3	0.039
	4	0.027
	5	0.013
	6	0.062
1988-89	1	0.026
	2	0.020
	3	0.047
	4	0.119
	5	0.114
	6	0.100
	7	0.051

Therefore, the two years of monitoring appropriately covered the range of conditions under which erosion and pollution controls serve.

Table 9 expresses the flow rate and pollutant reductions achieved by the various techniques tested, averaged over all storm events. For illustration, Figure 3 diagrams the effectiveness of the reflective methods in reducing erosion, as measured by TSS reduction, and overall pollutant loading. A number of conclusions can be drawn from these data, the most important of which are the following:

1. Slope coverings and filter fabric fences have varying abilities to reduce runoff flow rates, most likely by slowing flows and promoting infiltration into the soil. These flow reductions are partially responsible, along with pollutant concentration decreases, for reductions in contaminant loadings from slopes.
2. As with sedimentation ponds, slope treatments were, in general, more effective in reducing settleable and total suspended solids than in lowering turbidity, which is strongly influenced by the relatively small, easily eroded soil particles. However, a number of the slope treatments were substantially more effective in turbidity control than the ponds. This result helps to demonstrate the importance of pursuing erosion control at the source to the extent possible.
3. As measured by settleable solids and TSS reductions, a number of treatments achieved erosion control above 85 percent. The 1988-89 wood fiber mulch/tackifier/seeding treatments were the best in this regard. Straw mulch accompanied by seeding performed almost as well. Only these treatments achieved turbidity reductions over 90 percent. Even a light straw mulch without seeding was not much beneath these settleable solids and TSS performance levels, but turbidity release was higher with this treatment.

TABLE 9. MEAN FLOW RATE AND POLLUTANT REDUCTIONS (%) ACHIEVED BY SLOPE COVERING TECHNIQUES COMPARED TO CONTROLS AND FILTER FABRIC FENCE

Technique	Flow Rate[a]	Settleable Solids[a]	Turbidity[a]	TSS	Organics[b]	Total P	Metals[c]	Overall Loading[d]
Straw (4 T/ac)	29.3	89.9	~ 86.9[e]	88.9	43.1	78.2	81.4	72.9
Straw (1.25 T/ac)	48.8	93.2	~ 36.5[e]	94.8	81.9	89.9	86.8	89.7
Straw (4 T/ac), manure-mulched, fertilized, seeded (M,F,S)	15.9	99.6	~ 96.9[e]	97.6	17.6	3.3	84.7	50.8
Straw (2.75 T/ac), manure-mulched, fertilized, seeded	13.4	99.1	~ 94.6[e]	97.6	50.4	38.4	88.5	68.7
Jute mat	18.5	29.9	~ 2.8[e]	60.6	45.9	28.2	62.6	49.3
Excelsior	- 8.5	58.4	~ 51.6[e]	28.8	12.6	22.2	27.9	22.9
Woven straw blanket	1.2	95.1	~ 81.4[e]	92.8	53.1	87.8	78.0	77.9
Synthetic fiber blanket	24.8	47.7	~ 3.4[e]	71.2	53.9	62.3	66.6	63.5
Wood fiber mulch (1.25 T/ac), fertilized, seeded (F,S)	8.5	89.1	~ 77.1[e]	87.0	43.6	63.9	71.5	66.5
Wood fiber mulch (1.25 T/ac) with tackifier (50 gal/ac), fertilized, seeded (1987-88) (T,F,S)	0.0	85.9	~ 77.6[e]	86.1	23.6	63.7	63.0	59.1
Wood fiber mulch (1.25 T/ac) with tackifier (90 gal/ac), fertilized, seeded (1988-89)	62.2	99.1	~ 97.6[e]	99.5	82.7	38.0[g]	96.3	79.1
Wood fiber mulch (1.25 T/ac) with tackifier (120 gal/ac), fertilized, seeded	80.3	98.9	~ 96.0[e]	99.5	87.6	58.7[k]	96.2	85.5
Chemical agent	4.5	- 91.7	~ 7.3[e]	- 47.7	- 37.1	- 65.9	- 24.4	- 43.8
Filter fabric fence	51.2	25.7	~ 2.9[e]	85.7	74.1	74.0	70.5	76.1

[a] Based on L/h for flow, m/L for settleable solids, or NTU for turbidity; all others based on mass loading.

[b] Based on mean of VSS and COD reductions.

[c] Based on mean of total Cu, Pb, and Zn reductions.

[d] Based on mean of TSS, organics, Total P, and metals reductions.

[e] Approximation because of occurence of values that were too large to measure. Such values were set equal to the upper detection limit of 1,000 NTU.

[f] Wood fiber mulch (1 T/ac) with tackifier was retested in 1988-89, when there was an opportunity for better grass growth than in the first year.

[g] 88.6% reduction excluding first two events.

[h] 95.6% reduction excluding first two events.

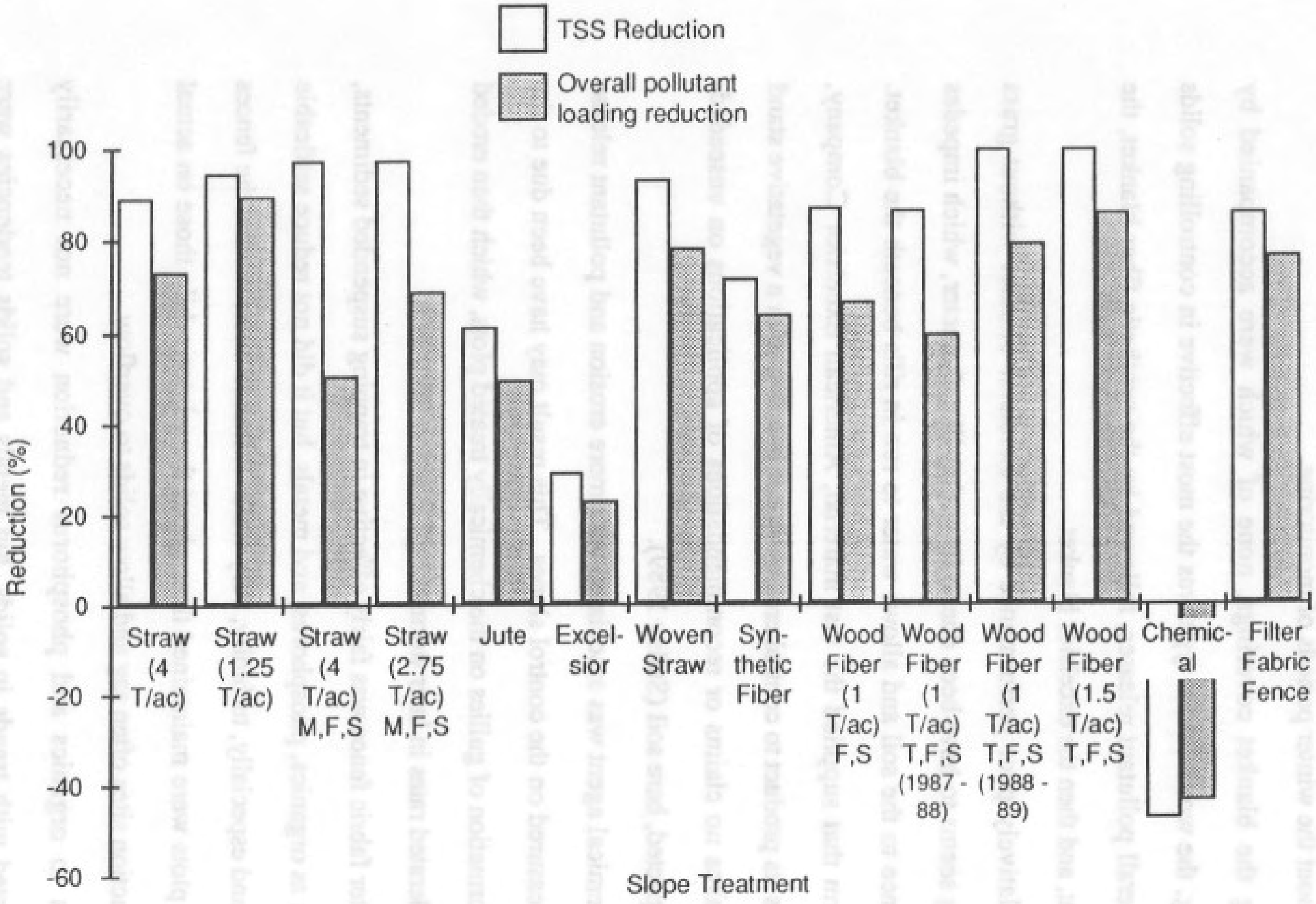

Figure 3. Mean TSS and Overall Pollutant Loading Reductions of Slope Treatments Relative to Controls

4. The straw treatments were all applied without tackifiers and still were stable throughout the winter periods of monitoring.

5. Among the blanket coverings, none of which were accompanied by seeding, the woven straw type was the most effective in controlling solids and overall pollutant releases, followed by the synthetic fiber blanket, the jute mat, and then the excelsior blanket.

6. The relatively poor performance by the excelsior blanket without grass seeding seems to have been due to its spring-like character, which impedes adherence to the soil and allows water to run in rills beneath the blanket. The firm that supplied the test material, American Excelsior Company, markets its product to control erosion in conjunction with a vegetative stand and makes no claims or recommendations of applications on unseeded, uncompacted, bare soil (Staley 1989).

7. The chemical agent was associated with more erosion and pollutant release than measured on the control slopes. This result may have been due to the early formation of gullies on the chemically treated plots, which then eroded at accelerated rates in later storms.

8. The filter fabric fence was fairly effective in trapping suspended sediments, as well as organics, phosphorus, and metals, but it did not reduce settleable solids and especially, turbidity, very well. It should be noted that the fences on the plots were maintained throughout the winter, while those on actual construction sites often sag and allow solids to overflow.

9. Trends to organics and phosphorus reduction were not necessarily associated with trends in solids, but metals and solids tendencies were generally aligned.

10. Straw mulches exhibited variable effectiveness in preventing phosphorus and organic releases. It was evident that manure mulching and fertilizing

were associated with less effective organics control and much reduced efficiency in stopping phosphorus release.

11. In 1988-89, the wood fiber mulch/tackifier seeding-treated slopes exhibited high P yields in the first two storms, but these yields decreased greatly as the grass became established.
12. Overall, the wood fiber/tackifier/seeding treatments in 1988-89 were the most effective measures tested. Increasing the tackifier application rate somewhat improved performance.
13. The lightest straw treatment actually had the highest overall loading reduction percentage, but, as pointed out earlier, allowed the escape of higher turbidities than did the wood fiber mulch.
14. The selection of an erosion and pollution control material and strategy should be considered with reference to the protection objectives. For example:
    - If a water body is to be protected against dissolved oxygen depletion and/or nutrient additions, avoid mulching with manure and fertilizing, or do so early enough that the manure can decompose and the fertilizer can be taken up by the grass before much storm runoff will occur.
    - Limit the fertilizer to plant requirements, especially when runoff will drain to a water that is sensitive to nutrient additions.
    - When immediate erosion control is needed before vegetation will develop, a woven straw blanket is a good choice to provide a relatively high level of interim protection.
    - When time is available to develop a fairly good grass stand before much runoff will occur, wood fiber and straw mulches can afford very good erosion and pollution control.

- Do not use a chemical alone as an erosion control agent but only as a tackifier to help secure mulches.

FINANCIAL ANALYSIS

Sedimentation Pond Costs

Table 10 summarizes the cost data, obtained from WSDOT, for the three sedimentation ponds considered in this research. The data exhibited substantial dispersion in the components of total cost, with labor ranging from about 30 to 85 percent of the total. The three ponds were very close in cost per unit surface area, with the largest pond exhibiting some scale economy. However, the two ponds designed according to the results of this research were considerably less expensive than the existing pond per unit drainage area served.

Slope Covering Costs

Table 11 summarizes the estimated costs of the slope treatments that were tested, including plastic sheeting and sedimentation ponds for comparison. The data are expressed as total material and labor costs per unit drainage area served over six months of service. Costs in $/acre were modified according to the approximate service life obtained from the cost survey to convert all data to a common service length basis. Note that a number of assumptions have entered this analysis, and variability of service lives is substantial. Therefore, the costs should be regarded as approximations that are at least useful for relative comparisons.

The filter fabric fence can be appropriately priced only in $/linear foot, rather than per unit area served. Therefore, the filter fabric fence was left out of the relative cost-effectiveness analysis that is reported in the next section.

The lowest cost technique reported in Table 11 is wood fiber mulch accompanied by seeding. Plastic sheeting appears to be the most expensive slope covering because of photochemical decomposition and cracking and its consequent short service life. Erosion

TABLE 10. SUMMARY OF SEDIMENTATION POND COSTS

Pond	Labor Total $	$/ft^2 Surface Area	$/Acre of Drainage Area
Mercer Island non-designed pond	0.85	7.20	7,483
SR-204 designed pond	0.48	7.54	4,105
Seattle designed pond	0.29	7.89	4,208

TABLE 11. SUMMARY OF ESTIMATED SERVICE LIVES AND COSTS (1988 BASE)

Technique[a]	Estimated Service Life (months)	Estimated Cost ($/(acre served) (6 months service)
Straw (4 T/ac)	3	3,200
Straw (1.25 T/ac)	3	2,500
Straw (4 T/ac) manure-mulched, fertilized, seeded	6	2,400
Jute mat	6	3,700
Excelsior	6	3,600
Woven straw blanket	6	4,100
Synthetic fiber blanket	6	3,300
Wood fiber mulch (1.25 T/ac) fertilized, seeded	6	1,300
Wood fiber mulch (1.25 T/ac) with tackifier (50 gal/ac), fertilized, seeded	6	1,900
Wood fiber mulch (1.25 T/ac) with tackifier (90 gal/ac), fertilized, seeded	6	2,100
Wood fiber mulch (1.25 T/ac) with tackifier (120 gal/ac), fertilized, seeded	6	2,300
Chemical agent	6	2,100
Plastic sheeting	6	2,300
Designed sedimentation pond	> 6	< 4,200
Non-designed pond	> 6	< 7,500

[a] The estimated cost of seeding where it was used is based on hydro-seeding (approximately $500/acre).

control actually becomes permanent if slopes are planted and not subsequently disturbed. Sedimentation ponds can be used indefinitely, perhaps with periodic sediment removal, and hence can have a service life greater than one wet season.

Cost-Effectiveness Calculations

Table 12 summarizes the calculations made according to Equations 3-6 to express the various performance and economy indices. The indices were numerical constructs that were all mutually relative to the techniques that were tested. Therefore, the values would change if any additional techniques were to be tested and introduced to the system in the future.

The Relative Economy and Relative Effectiveness indices and ranks are another expression of information previously presented in Tables 7 and 9-11. The various wood fiber mulch treatments were the most economical, differing in the costs associated with the tackifier application rate. Straw mulches as a group were the next most economical, followed by the various mats and blanks. Sedimentation ponds were the least economical option. The wood fiber mulch treatments applied in 1988-89 (with at least 90 gal/acre of tackifier and the opportunity to establish a good grass cover) ranked highly in all effectiveness categories. Otherwise, straw coverings generally rated relatively highly in effectiveness, when manure mulch and fertilizer did not raise phosphorus and organic yields. The woven straw blanket gave consistently good performance, and the designed sedimentation pond ranked relatively highly overall.

The Relative Cost-Effectiveness Index incorporates both considerations to provide a measure for designing erosion and pollution control programs on dual grounds. The wood fiber mulch treatment without tackifier was, overall, the most cost-effective alternative. Wood fiber treatments without tackifier ranked slightly lower in cost-effectiveness, but the most expensive of these treatments, which had the most tackifier, gained enough in effectiveness to rank in the top four in all cost-effectiveness measures. Straw treatments without manure mulching, fertilizing, and seeding were in the second tier in

TABLE 12. PERFORMANCE AND ECONOMY INDICES FOR SLOPE COVERINGS AND SEDIMENTATION PONDS TESTED IN THE RESEARCH PROGRAM

	Relative Economy		Effectiveness Measure	Relative Effectiveness		Relative Cost-Effectivness	
Technique	Index	Rank[a]		Index	Rank[a]	Index	Rank[a]
Straw (4 T/ac)	41	8/14	Reducing erosion	89	7/12	41	7/14
			Reducing phosphorus yield	87	7/14	50	5/15
			Reducing metals yield	85	5/13	46	8/14
			Reducing organics yield	49	11/15	34	8/14
			Overall	81	615	44	7/13
Straw (1.25 T/ac)	52	6/14	Reducing erosion	95	4/12	56	6/14
			Reducing phosphorus yield	100	1/14	73	2/15
			Reducing metals yield	90	3/13	63	5/14
			Reducing organics yield	93	3/15	83	4/14
			Overall	100	1/15	70	4/13
Straw (4 T/ac), manure-mulched, fertilized, seeded	50	7/14	Reducing erosion	98	2/12	56	6/14
			Reducing phosphorus yield	4	13/14	3	14/15
			Reducing metals yield	88	4/13	59	7/14
			Reducing organics yield	20	13/15	17	12/14
			Overall	57	12/15	38	8/13
Straw (2.75 T/ac), manure-mulched, fertilized, seeded	54	5/14	Reducing erosion	98	2/12	61	5/14
			Reducing phosphorus yield	43	10/14	32	10/15
			Reducing metals yield	92	2/13	67	4/14
			Reducing organics yield	58	8/15	53	5/14
			Overall	77	8/15	56	6/13
Jute mat	35	11/14	Reducing erosion	61	10/12	24	11/14
			Reducing phosphorus yield	31	11/14	15	12/15
			Reducing metals yield	65	10/13	31	12/14
			Reducing organics yield	52	9/15	32	10/14
			Overall	55	13/15	26	10/13
Excelsior	36	10/14	Reducing erosion	29	11/12	12	13/14
			Reducing phosphorus yield	25	12/14	13	13/15
			Reducing metals yield	29	12/13	14	13/14
			Reducing organics yield	14	14/15	9	13/14
			Overall	26	14/15	12	12/13
Woven straw blanket	32	12/14	Reducing erosion	93	5/12	34	8/14
			Reducing phosphorus yield	98	2/14	43	6/15
			Reducing metals yield	81	6/13	35	10/14
			Reducing organics yield	61	7/15	33	9/14
			Overall	87	5/15	37	9/13
Synthetic fiber blanket	39	9/14	Reducing erosion	72	9/12	32	10/14
			Reducing phosphorus yield	69	9/14	38	8/15
			Reducing metals yield	69	9/13	37	9/14
			Reducing organics yield	62	6/15	42	7/14
			Overall	71	10/15	38	8/13
Wood fiber mulch (1.25 T/ac), fertilized, seeded	100	1/14	Reducing erosion	87	8/12	100	1/14
			Reducing phosphorus yield	71	8/14	100	1/15
			Reducing metals yield	74	8/13	100	1/14
			Reducing organics yield	50	10/15	85	3/14
			Overall	74	9/15	100	1/13

TABLE 12. PERFORMANCE AND ECONOMY INDICES FOR SLOPE COVERINGS AND SEDIMENTATION PONDS TESTED IN THE RESEARCH PROGRAM (Continued)

Wood fiber mulch (1.25 T/ac) with tackifier (50 gal/ac), fertilized, seeded	68	2/14	Reducing erosion	87	8/12	67	3/14
			Reducing phosphorus yield	71	8/14	68	3/15
			Reducing metals yield	65	10/13	60	6/14
			Reducing organics yield	27	12/15	32	10/14
			Overall	66	11/15	61	5/13
Wood fiber mulch (1.25 T/ac) with tackifier (90 gal/ac), fertilized, seeded	62	3/14	Reducing erosion	100	1/12	71	2/14
			Reducing phosphorus yield	92	6/14	37	9/15
			Reducing metals yield	100	1/13	83	2/14
			Reducing organics yield	94	2/15	100	1/14
			Overall	88	4/15	74	2/13
Wood fiber mulch (1.25 T/ac) with tackifier (120 gal/ac), fertilized, seeded	57	4/14	Reducing erosion	100	1/12	65	4/14
			Reducing phosphorus yield	97	3/14	52	4/15
			Reducing metals yield	100	1/13	76	3/14
			Reducing organics yield	100	1/15	97	2/14
			Overall	95	2/15	72	3/13
Chemical agent	36	9/14	Reducing erosion	- 48	12/2	- 20	14/14
			Reducing phosphorus yield	- 41	14/14	- 42	15/15
			Reducing metals yield	- 25	13/13	- 12	14/14
			Reducing organics yield	- 42	15/15	- 26	14/14
			Overall	- 49	15/15	- 24	13/13
Seattle designed sedimentation pond	31	13/14	Reducing solids transport	92	6/12	> 33	9/14
			Reducing phosphorus transport	94	5/14	> 41	7/15
			Reducing metals transport	80	7/13	> 33	11/14
			Reducing organics transport	90	4/15	> 48	6/14
			Overall	90	3/15	> 38	8/13
Non-designed sedimentation pond	17	14/14	Reducing solids transport	96	3/12	> 19	12/14
			Reducing phosphorus transport	96	4/14	> 23	11/15
			Reducing metals transport	> 60[d]	11/13	> 14	13/14
			Reducing organics transport	88	5/15	> 26	11/14
			Overall	> 80[d]	7/15	> 19	11/13

[a] Given as index rank/total number of alternative techniques ranked; the total number varies as a result of tie values in indices. The highest ranking alternative for each comparison is designated 1.

[b] Based on performance means from Storm Nos. 3-5.

[c] Based on performance means from Storm Nos. 1-4.

[d] Uncertain because of undetectable metal concentrations.

cost-effectiveness. The designed sedimentation pond ranked intermediately in this respect among all options tested, but it was much more cost-effective than the non-designed pond. The relatively effective woven straw blanket ranked in the same area as a result of its relatively high cost.

APPLICATIONS

Applications of this research are recommended in the accompanying Erosion and Pollution Control Manual. This Manual provides detailed erosion and pollution control selection, design, and operating criteria, guidelines and specifications. The Manual is organized in four sections, as follows:

A. Slope Covering Techniques
B. Silt Barriers
C. Sedimentation Ponds
D. Additional Techniques

The first three sections present, as appropriate, the following aspects of each technique:

Characteristics	Design
Performance and Cost	Installation
Applications	Maintenance
Selection Criteria	

Section D lists a host of construction site erosion and pollution control measures that could not be included in the research and describes their applications and purposes. The Manual is organized so that new sections can be inserted, or existing sections revised, as additional information becomes available.

The provisions of the manual make direct use of the results of the research reported here and the literature review conducted in conjunction with it. Hence, they incorporate the economy, effectiveness, and cost-effectiveness information developed through the research in selection criteria. They also reflect the various application and design recommendations that arose from the research.

In addition to research findings, other published work formed a significant part of the basis for Sections B and C of the Manual. For filter fabric fences, the Municipality of

Metropolitan Seattle provided the general characteristics of the three types of materials used in sediment control. Detail on applications, selection criteria, design, and installation drew on the recommendations of Goldman et al. (1986) and the King County Department of Public Works (1989). The same sources were instrumental in developing the sedimentation pond procedures as well. In particular, charts and tables for computing sediment storage volume were adapted principally from Goldman et al. (1986), while the King County Department of Public Works (1989) was a primary source for the remainder of the design procedure.

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APPENDIX A

SEDIMENTATION POND WATER QUALITY DATA

APPENDIX A. SEDIMENTATION POND WATER QUALITY DATA

Mercer Island Non-Designed Pond

Concentration

							Total Metals			Dissolved Metals		
Storm No.	Stream	Turbidity (NTU)	Settleable Solids (mL/L)	TSS (mg/L)	COD (mg/L)	Total P (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)
1	Inlet	140	0.10	183.0	59.5	229	29	BDL	109	38	BDL	47
	Outlet	7	0.00	12.5	23.5	46	11	30	128	9	BDL	354
2	Inlet	90	4.00	4,140.0	297.0	670	128	100	307	34	BDL	52
	Outlet	18	0.00	25.0	19.5	82	9	BDL	47	7	BDL	150
3	Inlet	300	0.50	546.0	NA	787	27	40	89	22	BDL	169
	Outlet	19	0.00	25.5	NA	68	9	BDL	32	18	BDL	59
4	Inlet	275	0.14	347.0	NA	613	32	50	109	35	BDL	34
	Outlet	19	0.00	18.3	NA	76	15	BDL	58	14	BDL	48
5	Inlet	140	0.10	217.0	NA	404	18	30	160	9	BDL	220
	Outlet	170	0.00	232.0	NA	444	25	40	110	8	BDL	48
Mean:	Inlet	189	0.97	1,086.6	178.3	540	47	<48	155	28	——	104
	Outlet	47	0.00	62.7	21.5	143	14	<26	75	11	——	132

Mass Loading

					Total Metals			Dissolved Metals		
Storm No.	Stream	TSS (g)	COD (g)	Total P (g)	Cu (g)	Pb (g)	Zn (g)	Cu (g)	Pb (g)	Zn (g)
1	Inlet	932	303	1.20	0.1	- - -	0.6	0.2	- - -	0.2
	Outlet	64	120	0.20	0.1	0.2	0.7	0.0	- - -	1.8
2	Inlet	320,000	22,694	51.20	9.8	7.8	23.4	2.6	- - -	4.0
	Outlet	456	355	1.50	0.2	- - -	0.9	0.1	- - -	2.7
3	Inlet	57,000	NA	82.40	2.9	4.2	9.3	2.3	- - -	17.7
	Outlet	2,670	NA	7.10	1.0	- - -	3.4	1.9	- - -	6.2
4	Inlet	9,854	NA	17.30	1.0	1.5	3.2	1.0	- - -	1.0
	Outlet	519	NA	2.20	0.3	- - -	1.7	0.4	- - -	1.4
5	Inlet	36,000	NA	67.50	3.1	5.0	26.8	1.6	- - -	36.9
	Outlet	37,000	NA	74.30	4.2	6.7	18.5	1.4	- - -	8.1
Mean	Inlet	84,757	11,499	43.9	3.5	4.6	12.7	1.5	- - -	12.0
	Outlet	8,142	238	17.1	1.2	3.5	5.0	0.8	- - -	4.0

NA -- Not analyzed.
BDL -- Below detectable limit (1.8 ug/L for Cu; 16.2 ug/L for Pb; 2.1 ug/L for Zn).

Seattle Designed Pond

Concentration

								Total Metals		
Storm No.	Stream	Turbidity (NTU)	Settleable Solids (mL/L)	TSS (mg/L)	VSS (mg/L)	COD (mg/L)	Total P (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)
1	Inlet	>1,000	0.32	1,067	88	70	1,260	70	22	57
	Outlet	>1,000	0.01	605	52	52	710	37	9	38
2	Inlet	>1,000	4.50	4,702	237	78	3,230	129	33	153
	Outlet	>1,000	0.35	1,450	106	43	1,310	69	22	131
3	Inlet	>1,000	43.67	7,577	456	NA	NA	NA	NA	NA
	Outlet	>1,000	0.40	1,111	88	NA	NA	NA	NA	NA
4	Inlet	>1,000	13.50	2,420	136	56	2,000	121	18	184
	Outlet	208	0.10	331	26	17	480	35	7	53
5	Inlet	NA	NA	2,989	161	73	2,670	194	20	316
	Outlet	NA	NA	93	18	13	230	21	4	35
6	Inlet	>1,000	NA	2,255	139	43	2,100	42	30	153
	Outlet	161	NA	164	14	17	280	17	4	21
Mean	Inlet	>1,000	15.50	3,502	203	64	2,252	111	25	173
	Outlet	>674	0.22	626	51	28	602	36	9	56

Mass Loading

						Total Metals		
Storm No.	Stream	TSS (g)	VSS (g)	COD (g)	TP (g)	Cu (g)	Pb (g)	Zn (g)
1	Inlet	3,020	249	198	3.6	0.20	0.06	0.16
	Outlet	1,712	147	147	2.0	0.10	0.03	0.11
2	Inlet	39,926	2,012	662	27.4	1.10	0.28	1.30
	Outlet	12,312	900	365	11.1	0.59	0.19	1.11
3	Inlet	107,229	6,453	NA	NA	NA	NA	NA
	Outlet	15,723	1,245	NA	NA	NA	NA	NA
4	Inlet	13,699	770	317	11.3	0.68	0.10	1.04
	Outlet	1,874	147	96	2.7	0.20	0.04	0.30
5	Inlet	25,380	1,367	620	22.7	1.65	0.17	2.68
	Outlet	790	153	110	2.0	0.18	0.03	0.30
6	Inlet	15,956	984	304	14.9	0.30	0.21	1.09
	Outlet	1,160	99	120	2.0	0.12	0.03	0.15
Mean	Inlet	34,202	1,973	420	16.0	0.79	0.16	1.25
	Outlet	5,595	449	168	4.0	0.24	0.06	0.39

NA -- Not analyzed.

SR-204 Designed Pond

Concentration

							Total Metals			Dissolved Metals		
Storm No.	Stream	Turbidity (NTU)	Settleable Solids (mL/L)	TSS (mg/L)	COD (mg/L)	Total P (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)
1	Inlet	260	3.70	1,460.0	101.0	540	24	100	156	13	BDL	139
	Outlet	18	0.20	38.7	38.0	173	8	BDL	41	8	BDL	45
2	Inlet	55	15.10	3,780.0	135.0	8,196	150	280	296	28	40	35
	Outlet	65	0.00	50.6	32.5	308	11	BDL	65	6	BDL	40
3	Inlet	>1,000	18.50	12,345	NA	18,600	301	450	478	46	90	102
	Outlet	155	0.00	198.0	NA	574	15	30	28	9	30	14
4	Inlet	>1,000	170.00	37,165	NA	16,300	1,120	890	1,011	7	BDL	22
	Outlet	180	0.20	212.0	NA	550	27	40	47	6	BDL	15
5	Inlet	>1,000	70.00	32,440	NA	17,800	481	160	240	4	BDL	28
	Outlet	150	0.50	268.0	NA	605	14	30	21	6	BDL	14
Mean	Inlet	>663	55.46	17,438	118.0	12,287	415	376	436	20	<38	65
	Outlet	114	0.18	153.5	35.3	442	15	<28	40	7	<22	26

Mass Loading

					Total Metals			Dissolved Metals		
Storm No.	Stream	TSS (g)	COD (g)	Total P (g)	Cu (g)	Pb (g)	Zn (g)	Cu (g)	Pb (g)	Zn (g)
1	Inlet	38,000	2,630	14.1	0.6	2.6	4.1	0.3	- - -	3.6
	Outlet	1,008	989	4.5	0.2	- - -	1.1	0.2	- - -	1.2
2	Inlet	250,000	8,787	533.5	9.8	18.1	19.3	1.8	2.7	2.3
	Outlet	3,294	2,115	20.0	0.7	- - -	4.2	0.4	- - -	2.6
3	Inlet	560,000	NA	842.2	13.6	20.2	21.7	2.1	4.1	4.6
	Outlet	8,965	NA	26.0	0.7	1.4	1.3	0.4	1.2	0.6
4	Inlet	2,500,000	NA	1,107.1	76.0	60.3	68.7	0.5	- - -	1.5
	Outlet	14,000	NA	37.4	1.8	2.5	3.2	0.4	- - -	1.0
5	Inlet	4,500,000	NA	2,468.3	66.7	21.6	33.3	0.6	- - -	3.8
	Outlet	37,000	NA	83.9	1.9	4.5	2.9	0.9	- - -	2.0
Mean	Inlet	1,569,600	5,709	993.0	33.3	24.6	29.4	1.1	3.4	3.2
	Outlet	12,853	1,552	34.4	1.1	2.8	2.5	0.5	1.2	1.5

NA -- Not analyzed.

BDL -- Below detectable limit (1.8 ug/L for Cu; 16.2 ug/L for Pb; 2.1 ug/L for Zn).

APPENDIX B
TEST SLOPE DATA

Appendix B. Test Slope Data

1987-88 Concentrations

Storm No.	Plot	Flow Rate (l/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/L)	Dissolved Cu (µg/L)	Total Pb (µg/L)	Dissolved Pb (µg/L)	Total Zn (µg/L)	Dissolved Zn (µg/L)
1	1	7.0	0.10	49	86	32	0.517	133	20	13	5	0	44	11
1	2	0.7	0.20	71	148	28	0.268	38	14	6	7	1	56	8
1	3	4.2	0.01	10	42	26	1.584	103	11	9	1	1	89	91
1	4	6.5	0.01	14	34	24	2.702	148	11	8	3	0	16	7
1	5	5.2	0.05	37	50	14	1.805	89	14	10	3	1	44	40
1	6	4.6	0.01	18	36	12	1.276	75	9	9	3	1	53	32
1	7	13.9	9.50	>1,000	7,984	264	6.739	186	233	54	85	13	343	162
1	8	13.9	14.00	>1,000	11,920	3,064	6.723	183	248	46	133	4	481	136
1	9	11.9	3.50	248	2,536	124	3.326	111	85	10	36	2	148	81
1	10	11.9	2.00	318	1,300	80	1.810	104	78	14	35	3	132	59
1	11	11.1	0.40	230	280	30	0.418	71	29	7	11	1	68	23
1	12	11.1	0.30	168	168	22	0.230	64	14	7	8	3	65	50
1	13	11.7	1.50	245	538	44	0.788	86	27	7	13	1	93	30
1	14	11.7	1.00	245	532	246	0.723	143	24	9	11	1	96	61
1	15	11.8	1.50	273	816	50	0.950	91	34	9	11	0	99	75
1	16	11.8	1.10	195	230	26	0.598	240	42	9	7	0	71	72
2	1	4.1	0.00		5	2	0.459	158	23	16	2	1	37	66
2	2	1.3	0.00		96	13	0.184	81	26	11	13	2	114	51
2	3	2.4	0.00		23	17	2.903	182	13	9	3	1	47	266
2	4	3.8	0.00		23	18	3.381	212	16	10	2	1	31	10
2	5	0.9	0.00		20	14	1.602	73	11	6	2	0	50	14
2	6	4.3	0.00		26	18	1.828	127	13	8	2	1	22	5
2	7	5.9	0.80		286	26	0.957	34	46	7	17	2	77	58
2	8	6.5	0.90		976	82	0.879	32	48	10	13	2	65	61
2	9	8.9	0.10		232	26	1.542	44	20	7	10	1	40	15
2	10	8.1	0.40		1,160	90	1.026	62	62	20	16	4	96	74
2	11	6.5	0.01		74	18	0.117	36	13	5	3	0	19	31
2	12	6.4	0.01		46	16	0.129	39	14	6	3	5	50	29
2	13	5.5	0.10		92	18	0.331	39	11	5	3	0	40	7

Appendix B. Test Slope Data (Continued)

1987-88 Concentrations

Storm No.	Plot	Flow Rate (l/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/L)	Dissolved Cu (µg/L)	Total Pb (µg/L)	Dissolved Pb (µg/L)	Total Zn (µg/L)	Dissolved Zn (µg/L)
2	14	9.2	0.15		130	24	0.569	49	18	11	4	2	59	31
2	15	10.2	0.15		110	20	0.315	40	16	6	4	0	50	11
2	16	9.7	0.05		74	20	0.454	56	15	8	5	0	34	12
3	1	25.0	0.00	25	31	8	0.408	97	11	13	1	0	11	35
3	2	6.8	2.00	325	2,710	108	1.964	95	82	6	19	1	140	102
3	3	11.1	0.00	9	44	8	2.624	132	19	8	1	0	85	38
3	4	21.3	0.00	11	31	9	2.519	125	8	8	1	1	14	19
3	5	19.5	0.05	36	60	10	1.671	70	14	9	2	1	37	57
3	6	18.5	0.01	21	34	8	1.694	76	9	4	1	0	28	68
3	7	22.5	1.10	273	504	22	1.094	26	62	8	11	2	151	66
3	8	23.8	1.40	298	1,012	48	0.719	32	57	7	11	1	108	47
3	9	27.8	0.05	76	150	14	0.226	44	15	4	3	1	63	126
3	10	25.1	0.35	253	558	35	0.571	49	30	12	7	3	60	49
3	11	24.8	0.01	58	122	12	0.228	31	12	6	2	1	25	56
3	12	29.1	0.00	42	64	8	0.168	44	9	6	4	1	31	59
3	13	21.2	0.10	73	135	14	0.313	35	8	6	3	1	57	26
3	14	21.2	0.05	61	165	14	0.453	27	7	8	3	1	43	35
3	15	27.8	0.05	64	159	15	0.322	44	10	9	3	1	209	83
3	16	25.1	0.05	49	105	10	0.318	42	8	8	2	0	54	59
4	1	0.6	0.10	11	27	4	0.319	67	11	5	2		38	
4	2	0.9	0.15	20	51	4	0.290	33	7	4	2		32	
4	3	1.2	0.05	7	27	6	1.017	72	9	4	1		66	
4	4	1.1	0.05	7	28	7	1.177	75	9	3	1		20	
4	5	0.5	0.10	11	46	9	0.844	48	9	4	4		45	
4	6	1.1	0.05	6	21	6	1.457	56	7	3	2		32	
4	7	0.9	1.80	275	906	56	3.426	66	50	6	20		130	
4	8	1.4	4.00	290	2,590	124	2.390	128	118	3	50		237	
4	9	1.4	4.00	293	2,408	110	2.945	137	115	4	33		226	
4	10													

Appendix B. Test Slope Data (Continued)

1987-88 Concentrations

Storm No.	Plot	Flow Rate (l/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/L)	Dissolved Cu (µg/L)	Total Pb (µg/L)	Dissolved Pb (µg/L)	Total Zn (µg/L)	Dissolved Zn (µg/L)
4	11	0.5	0.50	46	165	15	0.435	48	17	5	6		36	
4	12	1.3	0.30	24	68	9	0.188	62	15	8	2		36	
4	13	1.3	0.30	35	125	12	0.479	50	15	7	5		38	
4	14	1.3	0.50	65	178	19	0.698	58	19	7	8		59	
4	15	1.3	1.20	56	319	27	0.676	50	21	4	14		63	
4	16	1.3	0.70	47	154	14	0.851	103	21	9	7		74	
5	1	1.2	0.50	33	59	7	0.392	84	15	10	1		74	
5	2	2.0	1.00	61	126	7	0.316	41	16	6	5		45	
5	3	1.6	0.01	14	46	7	1.396	77	16	10	1		38	
5	4	1.4	0.01	15	50	10	1.352	97	9	6	1		26	
5	5	1.0	0.05	34	124	10	0.859	68	17	4	5		47	
5	6	1.6	0.01	11	40	10	0.917	56	8	3	1		47	
5	7	2.0	2.00	250	959	61	1.216	62	49	5	23		137	
5	8	2.7	2.50	250	1,380	67	1.500	75	59	3	32		166	
5	9	1.9	1.50	225	1,003	50	0.946	32	45	6	18		109	
5	10	1.9	0.40	110	299	22	0.275	71	18	4	9		59	
5	11	1.2	0.30	76	189	13	0.405	44	15	5	8		63	
5	12	1.7	0.05	31	69	8	0.154	53	9	4	2		43	
5	13	1.9	0.30	54	181	19	0.469	66	13	7	4		40	
5	14	2.7	0.25	80	194	17	0.895	72	17	10	7		130	
5	15	2.0	0.55	63	205	20	0.478	65	13	5	6		49	
5	16	2.6	0.15	44	132	13	0.707	116	22	12	4		76	
6	1	38.6	0.01	40	35	6	0.471	32	10	7	1		49	
6	2	25.8	0.01	19	35	5	0.127	52	8	3	1		51	
6	3	41.7	0.01	15	61	6	0.801	46	8	4	1		47	
6	4	41.7	0.01	27	38	6	0.741	52	8	3	2		30	
6	5	41.7	0.01	30	40	5	0.546	31	7	4	4		9	
6	6	41.7	0.00	27	26	5	0.486	29	5	3	2		7	
6	7	34.7	0.65	258	950	46	0.624	40	37	4	9		66	

Appendix B. Test Slope Data (Continued)

1987-88 Concentrations

Storm No.	Plot	Flow Rate (l/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/L)	Dissolved Cu (µg/L)	Total Pb (µg/L)	Dissolved Pb (µg/L)	Total Zn (µg/L)	Dissolved Zn (µg/L)
6	8	37.8	0.90	275	1,248	66	1.389	48	46	2	9		68	
6	9	41.3	0.05	84	179	11	0.201	28	17	6	3		40	
6	10	37.8	0.10	118	236	15	0.285	36	22	7	5		45	
6	11	32.4	0.01	63	109	5	0.129	31	11	4	3		15	
6	12	37.1	0.01	38	68	7	0.111	36	19	4	2		57	
6	13	33.2	0.01	57	122	12	0.390	21	13	4	1		20	
6	14	31.6	0.05	42	105	6	0.276	29	9	3	2		22	
6	15	30.1	0.05	92	142	10	0.219	22	14	4	4		22	
6	16	31.6	0.01	50	73	7	0.363	31	8	4	3		9	

1987-88 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Dissolved Cu (µg/h)	Total Pb (µg/h)	Dissolved Pb (µg/h)	Total Zn (µg/h)	Dissolved Zn (µg/h)
1	1	601	224	4	928	139	89	35	3	304	79
1	2	111	21	0	28	11	4	5	1	42	6
1	3	176	109	7	432	47	36	6	3	374	382
1	4	221	156	18	963	70	52	18	1	104	48
1	5	258	72	9	460	74	53	16	3	225	204
1	6	166	55	6	346	42	41	14	4	243	147
1	7	110,959	3,669	94	2,589	3,241	747	1,175	176	4,773	2,258
1	8	165,660	42,582	93	2,544	3,449	634	1,842	49	6,687	1,888
1	9	30,210	1,477	40	1,321	1,017	124	424	27	1,758	970
1	10	15,486	953	22	1,233	926	170	412	40	1,576	701
1	11	3,099	332	5	784	320	74	120	7	753	250

Appendix B. Test Slope Data (Continued)

1987-88 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Dissolved Cu (µg/h)	Total Pb (µg/h)	Dissolved Pb (µg/h)	Total Zn (µg/h)	Dissolved Zn (µg/h)
1	12	1,860	244	3	712	160	82	84	33	719	558
1	13	6,289	514	9	1,006	312	85	149	13	1,081	354
1	14	6,219	2,876	8	1,674	277	106	124	9	1,117	716
1	15	9,629	590	11	1,073	401	109	128	5	1,164	886
1	16	2,714	307	7	2,835	497	112	78	5	839	854
2	1	20	8	2	646	93	66	10	3	153	268
2	2	129	18	0	110	35	15	18	3	153	68
2	3	56	41	7	443	33	22	7	3	114	648
2	4	87	68	13	808	59	38	7	2	119	39
2	5	18	13	1	66	10	5	1	0	45	13
2	6	112	78	8	549	58	36	9	4	95	22
2	7	1,675	152	6	201	267	39	99	9	452	339
2	8	6,318	531	6	204	310	64	85	15	421	397
2	9	2,057	230	14	387	180	62	87	12	359	129
2	10	9,387	728	8	501	504	164	131	31	773	596
2	11	484	118	1	239	82	32	18	2	125	205
2	12	292	102	1	249	86	35	18	31	315	187
2	13	509	100	2	217	62	30	19	2	224	41
2	14	1,202	222	5	453	168	98	40	16	544	286
2	15	1,119	203	3	406	165	63	42	5	505	110
2	16	719	194	4	542	149	75	53	2	334	112
3	1	788	200	10	2,417	276	338	21	11	275	875
3	2	18,546	739	13	651	561	41	132	7	958	698
3	3	488	89	29	1,469	212	92	16	5	949	426
3	4	660	202	54	2,669	165	169	26	18	295	404
3	5	1,157	195	33	1,369	263	166	32	11	715	1,109
3	6	630	139	31	1,416	171	81	14	8	522	1,258
3	7	11,333	495	25	584	1,384	187	246	45	3,404	1,491
3	8	24,096	1,143	17	750	1,354	156	253	30	2,581	1,129

Appendix B. Test Slope Data (Continued)

1987-88 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Dissolved Cu (µg/h)	Total Pb (µg/h)	Dissolved Pb (µg/h)	Total Zn (µg/h)	Dissolved Zn (µg/h)
3	9	4,168	389	6	1,214	406	104	84	21	1,738	3,507
3	10	14,026	880	14	1,238	758	294	182	84	1,501	1,228
3	11	3,036	297	6	774	304	157	60	16	627	1,376
3	12	1,863	233	5	1,284	268	184	118	22	904	1,718
3	13	2,846	296	7	738	180	121	62	18	1,203	547
3	14	3,491	296	10	580	138	176	69	21	899	741
3	15	4,404	417	9	1,226	266	242	93	16	5,798	2,319
3	16	2,639	264	8	1,056	195	204	44	11	1,357	1,489
4	1	16	3	0	41	7	3	1		23	
4	2	46	4	0	30	7	3	2		29	
4	3	32	7	1	86	11	5	1		78	
4	4	31	8	1	85	11	4	2		22	
4	5	21	4	0	22	4	2	2		21	
4	6	24	6	2	61	8	3	2		35	
4	7	795	49	3	58	43	5	17		114	
4	8	3,536	169	3	175	161	4	69		323	
4	9	3,288	150	4	188	157	5	45		309	
4	10										
4	11	84	8	0	24	9	2	3		19	
4	12	89	11	0	82	20	10	3		48	
4	13	165	16	1	65	20	10	6		51	
4	14	234	24	1	77	25	9	11		78	
4	15	420	35	1	66	27	6	18		84	
4	16	203	18	1	136	28	12	9		97	
5	1	71	8	0	101	18	12	1		89	
5	2	252	14	1	82	32	11	9		89	
5	3	74	10	2	124	25	16	1		61	
5	4	71	14	2	138	13	9	2		37	
5	5	120	10	1	66	17	4	5		45	

Appendix B. Test Slope Data (Continued)

1987-88 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Dissolved Cu (µg/h)	Total Pb (µg/h)	Dissolved Pb (µg/h)	Total Zn (µg/h)	Dissolved Zn (µg/h)
5	6	63	15	1	90	12	5	2		75	
5	7	1,894	120	2	123	97	9	45		270	
5	8	3,664	178	4	198	156	8	86		440	
5	9	1,869	93	2	59	84	10	34		204	
5	10	574	43	1	136	34	8	18		114	
5	11	228	16	0	53	18	6	10		76	
5	12	120	14	0	93	15	6	4		74	
5	13	335	34	1	122	24	13	8		75	
5	14	527	47	2	196	46	28	18		354	
5	15	406	39	1	129	27	10	11		96	
5	16	342	35	2	302	58	31	10		197	
6	1	1,364	219	18	1,224	385	280	57		1,884	
6	2	896	129	3	1,352	198	84	21		1,316	
6	3	2,557	250	33	1,914	325	167	61		1,948	
6	4	1,598	264	31	2,181	314	136	84		1,252	
6	5	1,682	195	23	1,308	283	173	150		381	
6	6	1,084	195	20	1,201	214	124	78		294	
6	7	32,999	1,598	22	1,381	1,275	149	314		2,276	
6	8	47,209	2,497	53	1,820	1,726	90	357		2,558	
6	9	7,394	475	8	1,174	685	244	110		1,672	
6	10	8,946	586	11	1,345	830	263	186		1,689	
6	11	3,533	162	4	1,017	360	139	108		500	
6	12	2,501	259	4	1,323	695	165	84		2,118	
6	13	4,066	415	13	689	419	133	31		650	
6	14	3,307	190	9	927	271	89	59		686	
6	15	4,274	316	7	666	419	125	116		652	
6	16	2,310	222	11	993	255	131	84		289	

Appendix B. Test Slope Data (Continued)

1988-89 Concentrations

Storm No.	Plot	Flow Rate (L/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/l)	Total Pb (µg/l)	Total Zn (µg/l)
1	1	2.8	0.10	61	86	9	0.360		27	5	123
1	2	4.2	0.05	52	61	7	0.196	29	16	1	54
1	3	24.7	1.30	333	1446	66	1.018	37	88	14	142
1	4	17.7	0.60	278	911	43	0.866	14	59	9	103
1	5	10.9	0.40	140	197	15	0.223	14	24	3	51
1	6	10.2	0.05	66	71	10	0.183	18	17	6	46
1	7	19.6	0.20	163	367	22	0.245	25	30	6	66
1	8	39.3	0.30	198	460	26	0.465		47	7	86
1	9	23.0	0.01	68	140	11	0.156	18	17	1	46
1	10	18.6	0.02	67	146	10	0.154	22	14	1	27
1	11	15.3	0.02	83	249	15	0.626	14	17	2	34
1	12	14.8	0.03	85	214	11	0.636	29	29	4	51
1	13	14.6	0.00	7	14	3	2.121	33	10	0	17
1	14	11.8	0.01	5	18	4	2.402	25	11	0	22
1	15	11.5	0.01	10	18	4	2.273	37	7	1	42
1	16	17.3	0.00	6	15	5	1.695	33	8	1	54
2	1	1.4	0.01	123	144	13	0.263	22	19	3	73
2	2	5.8	0.00	108	57	7	0.182	31	17	0	45
2	3	15.5	0.20	290	720	32	0.598	40	44	7	105
2	4	18.9	0.10	233	462	29	0.439	40	33	3	80
2	5	13.1	0.01	110	199	15	0.178	13	18	5	50
2	6	11.1	0.01	55	69	5	0.132	13	10	0	40
2	7	18.0	0.01	63	80	9	0.140	13	12	0	43
2	8	40.4	0.01	133	196	15	0.191	22	20	2	63
2	9	19.2	0.01	45	51	4	0.112	22	11	0	30
2	10	21.2	0.01	28	30	2	0.068	13	7	1	35
2	11	16.4	0.01	35	38	4	0.287	49	7	0	40
2	12	15.4	0.01	76	95	9	0.373	13	13	1	30
2	13	6.5	0.00	9	4	2	1.132	31	4	1	30

Appendix B. Test Slope Data (Continued)

1988-89 Concentrations

Storm No.	Plot	Flow Rate (L/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/l)	Total Pb (µg/l)	Total Zn (µg/l)
2	14	2.9	0.00	12	7	4	1.657	31	6	0	40
2	15	0.6	0.00	15	12	3	1.345	49	5	0	55
2	16	1.6	0.00	12	17	3	1.216	49	6	0	53
3	1	3.5	0.30	278	443	37	2.302	58	41	21	92
3	2	7.4	0.10	213	223	25	1.468	22	34	6	105
3	3	11.6	2.00	275	2058	114	41.303	49	124	33	259
3	4	10.1	9.00	318	1598	112	30.589	58	103	29	187
3	5	10.6	0.40	198	320	35	6.385	22	40	7	154
3	6	14.6	0.40	233	318	33	5.390	22	42	8	123
3	7	14.7	3.00	305	1738	98	10.287	49	102	38	195
3	8	19.7	3.50	200	2642	130	32.579	84	149	39	275
3	9	7.2	0.90	288	1118	61	10.364	40	68	10	177
3	10	17.8	1.80	258	1039	56	7.571	49	58	7	113
3	11	14.8	2.50	238	755	42	10.670	49	50	3	151
3	12	18.2	2.00	288	1059	57	19.111	58	60	5	298
3	13	1.3	0.00	5	13	12	1.047		14	0	46
3	14	0.5	0.05	17	40	18	1.162	22	11	0	71
3	15	0.7	0.10	34	59	17	0.772	22	12	0	259
3	16	0.7	0.05	10	20	11	0.703	40	10	10	100
4	1	24.6	4.00	200	2815	170	2.302	92	163	86	262
4	2	213.1	2.50	215	1610	125	1.468	53	93	37	172
4	3	250.2	135.00	1001	56190	1290	41.303	783	1449	701	2285
4	4	208.4	95.00	1001	36390	1090	30.589	623	1154	490	1677
4	5	83.4	40.00	1001	6605	255	6.385	142	378	79	1790
4	6	83.4	18.00	1001	4180	180	5.390	125	214	118	375
4	7	158.8	36.00	1001	17295	445	10.287	383	658	380	1211
4	8	250.2	81.00	1001	39510	875	32.579	588	1113	518	1579
4	9	125.1	31.00	1001	16580	455	10.364	267	472	187	722
4	10	101.9	25.00	1001	8440	265	7.571	160	356	46	571

Appendix B. Test Slope Data (Continued)

1988-89 Concentrations

Storm No.	Plot	Flow Rate (L/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/l)	Total Pb (µg/l)	Total Zn (µg/l)
4	11	125.1	28.00	1001	12040	275	10.670	240	439	95	660
4	12	125.1	48.00	1001	22255	505	19.111	347	563	136	835
4	13	18.2	0.00	7	24	12	1.047	9	11	0	22
4	14	19.8	0.20	28	83	18	1.162	9	12	0	19
4	15	8.2	0.30	57	124	16	0.772	36	15	1	47
4	16	8.2	0.30	27	80	17	0.703	45	15	0	42
5	1	64.8	0.80	1001	1192	126	0.908	45	81	38	145
5	2	94.9	0.10	1001	588	70	0.465	32	61	16	102
5	3	91.4	6.50	1001	9288	404	7.145	117	319	98	451
5	4	88.0	16.50	1001	11300	380	5.441	136	327	104	420
5	5	45.1	21.00	1001	2976	236	2.904	65	220	32	278
5	6	62.5	8.00	1001	1248	124	1.373	52	90	17	179
5	7	105.3	5.00	1001	6832	188	2.934	78	156	81	264
5	8	100.7	6.50	1001	5780	260	2.585	91	236	76	349
5	9	106.5	2.10	1001	2578	142	1.376	39	89	19	151
5	10	70.5	4.20	1001	2136	134	1.497	26	87	10	139
5	11	93.7	3.60	1001	2118	98	1.664		81	30	131
5	12	99.6	3.50	1001	2830	92	1.724	39	77	11	131
5	13	87.8	0.20	22	58	17	0.823	26	9	0	14
5	14	98.4	0.30	39	113	20	0.868	45	13	0	37
5	15	38.6	0.40	73	256	20	0.770	32	16	0	102
5	16	46.8	0.20	26	79	12	0.596	32	15	0	65
6	1	20.8	1.50	1001	1980	176	1.671	89	105	52	181
6	2	37.1	1.00	1001	1268	136	1.671	53	82	27	153
6	3	96.2	12.00	1001	15090	670	8.203	196	445	141	608
6	4	86.4	16.00	1001	10380	560	7.481	169	430	177	554
6	5	39.1	14.00	1001	2345	205	3.570	53	163	18	225
6	6	60.5	4.00	1001	980	80	1.382	36	74	15	122
6	7	83.7	6.50	1001	6510	220	2.719	89	194	100	297

Appendix B. Test Slope Data (Continued)

1988-89 Concentrations

Storm No.	Plot	Flow Rate (L/h)	Settleable Solids (ml/L)	Turbidity (NTU)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	COD (mg/l)	Total Cu (µg/l)	Total Pb (µg/l)	Total Zn (µg/l)
6	8	96.2	11.00	1001	10815	340	6.076	151	348	163	482
6	9	104.2	6.00	1001	4715	260	3.144	80	197	51	291
6	10	79.1	8.00	1001	3380	125	2.324	71	163	19	263
6	11	104.2	8.50	1001	4940	160	3.129	71	148	32	225
6	12	104.2	10.00	1001	7625	270	3.387	80	168	37	258
6	13	41.7	0.20	14	31	9	0.714	9	7	1	14
6	14	21.9	0.30	23	57	7	0.782	18	9	1	16
6	15	14.6	0.10	48	111	9	0.630	9	9	2	29
6	16	19.9	0.10	20	47	12	0.638	9	6	1	24
7	1	11.9	0.30	245	549	45	0.570	36	51	11	137
7	2	50.0	0.10	263	462	50	0.419	27	48	11	99
7	3	53.8	4.00	1001	6392	244	4.276	89	280	48	484
7	4	38.1	7.00	1001	5256	220	3.630	89	251	59	382
7	5	19.5	8.00	1001	968	82	1.063	27	91	6	145
7	6	51.2	4.00	1001	610	70	0.896	18	73	8	122
7	7	55.8	2.70	1001	5256	130	1.671	45	141	48	196
7	8	57.2	3.50	1001	4082	156	2.089	62	193	51	264
7	9	65.4	1.20	1001	1099	56	0.811		63	11	106
7	10	34.0	3.00	1001	1350	56	1.314	36	78	6	134
7	11	57.2	3.00	1001	1710	68	1.580		83	12	162
7	12	57.9	2.50	1001	1298	65	1.200	27	64	8	119
7	13	34.4	0.00	17	15	11	0.647	45	9	0	25
7	14	39.1	0.10	12	20	8	0.685		9	0	43
7	15	19.6	0.10	18	37	9	0.434	9	7	0	32
7	16	21.0	0.10	11	21	11	0.475	9	7	0	32

Appendix B. Test Slope Data (Continued)

1988-89 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Total Pb (µg/h)	Total Zn (µg/h)
1	1	241	25	1.0	0	77	14	346
1	2	256	31	0.8	123	66	4	225
1	3	35726	1631	25.2	920	2178	354	3516
1	4	16170	763	15.4	244	1049	153	1828
1	5	2155	167	2.4	150	261	28	561
1	6	732	102	1.9	181	169	58	476
1	7	7188	431	4.8	499	588	122	1295
1	8	18055	1021	18.3	0	1832	285	3368
1	9	3225	265	3.6	407	392	32	1071
1	10	2713	186	2.9	401	266	19	499
1	11	3805	229	9.6	210	253	26	523
1	12	3160	163	9.4	435	428	66	760
1	13	199	38	31.1	488	141	2	249
1	14	209	47	28.2	300	132	2	258
1	15	208	46	26.2	429	80	8	479
1	16	256	90	29.4	577	134	15	933
2	1	201	18	0.4	31	26	4	102
2	2	334	41	1.1	181	96	3	263
2	3	11177	497	9.3	622	689	102	1635
2	4	8715	547	8.3	756	614	62	1514
2	5	2602	194	2.3	175	241	66	657
2	6	767	58	1.5	148	108	5	445
2	7	1451	153	2.5	241	211	6	769
2	8	7943	606	7.7	900	819	76	2535
2	9	987	75	2.2	427	211	9	578
2	10	641	41	1.4	283	158	14	745
2	11	627	61	4.7	802	110	0	658
2	12	1464	141	5.7	205	198	13	463
2	13	26	16	7.4	203	29	9	197

Appendix B. Test Slope Data (Continued)

1988-89 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Total Pb (µg/h)	Total Zn (µg/h)
2	14	21	10	4.8	90	17	1	116
2	15	7	2	0.7	27	3	0	31
2	16	26	5	1.9	77	9	0	83
3	1	1559	130	8.1	202	145	74	324
3	2	1656	186	10.9	164	253	41	778
3	3	23819	1319	478.0	563	1435	380	3001
3	4	16102	1129	308.2	580	1037	296	1886
3	5	3386	370	67.6	234	424	70	1626
3	6	4629	480	78.5	322	613	112	1788
3	7	25574	1442	151.4	716	1502	559	2868
3	8	52013	2559	641.4	1655	2939	773	5409
3	9	8095	442	75.0	288	494	70	1281
3	10	18511	998	134.9	867	1033	131	2005
3	11	11191	623	158.2	721	745	51	2240
3	12	19245	1036	347.3	1045	1097	98	5414
3	13	16	15	1.3	0	17	0	57
3	14	20	9	0.6	11	5	0	35
3	15	41	12	0.5	16	8	0	184
3	16	14	8	0.5	28	7	7	71
4	1	69356	4188	56.7	2259	4023	2120	6456
4	2	343017	26632	312.8	11380	19873	7819	36573
4	3	14056378	322704	10332.2	195969	362529	175472	571527
4	4	7584258	227173	6375.3	129873	240498	102127	349597
4	5	550765	21263	532.4	11877	31510	6550	149292
4	6	348553	15009	449.4	10392	17866	9858	31272
4	7	2746570	70669	1633.7	60790	104476	60380	192372
4	8	9883743	218888	8149.9	146977	278535	129480	394885
4	9	2073810	56911	1296.3	33404	59084	23367	92282
4	10	859943	27001	771.4	16326	36267	4669	58176

Appendix B. Test Slope Data (Continued)

1988-89 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Total Pb (µg/h)	Total Zn (µg/h)
4	11	1505951	34397	1334.6	30063	54863	11894	82510
4	12	2783633	63165	2390.4	43425	70480	16999	104413
4	13	436	227	19.0	162	203	0	399
4	14	1646	347	23.1	177	240	0	380
4	15	1020	132	6.4	293	121	10	390
4	16	657	136	5.8	366	127	0	343
5	1	77224	8163	58.8	2938	5246	2450	9383
5	2	55820	6645	44.1	3076	5819	1499	9709
5	3	848989	36928	653.1	10661	29146	8995	41248
5	4	994118	33431	478.6	11971	28794	9145	36954
5	5	134357	10655	131.1	2925	9939	1423	12559
5	6	78049	7755	85.9	3242	5649	1080	11187
5	7	719554	19800	309.0	8189	16434	8484	27804
5	8	581948	26178	260.3	9133	23780	7682	35150
5	9	274627	15127	146.6	4141	9441	1978	16033
5	10	150665	9452	105.6	1828	6167	710	9815
5	11	198512	9185	155.9	0	7558	2798	12245
5	12	281783	9160	171.7	3871	7692	1057	13008
5	13	5091	1448	72.2	2275	791	0	1256
5	14	11123	1919	85.5	4465	1238	0	3643
5	15	9876	772	29.7	1250	603	10	3946
5	16	3700	562	27.9	1517	684	0	3063
6	1	41276	3669	34.8	1856	2180	1083	3770
6	2	46986	5039	61.9	1979	3040	1014	5654
6	3	1451879	64464	789.2	18843	42852	13593	58475
6	4	896498	48366	646.1	14608	37155	15259	47826
6	5	91763	8022	139.7	2090	6370	721	8788
6	6	59327	4843	83.7	2156	4465	889	7368
6	7	545067	18420	227.7	7454	16244	8374	24833

Appendix B. Test Slope Data (Continued)

1988-89 Loadings

Storm No.	Plot	TSS (mg/h)	VSS (mg/h)	TP (mg/h)	COD (mg/h)	Total Cu (µg/h)	Total Pb (µg/h)	Total Zn (µg/h)
6	8	1040561	32713	584.6	14561	33439	15669	46351
6	9	491456	27100	327.7	8351	20485	5356	30378
6	10	267392	9889	183.9	5634	12878	1501	20818
6	11	514909	16677	326.2	7423	15473	3298	23409
6	12	794773	28143	353.1	8351	17496	3842	26893
6	13	1313	354	29.8	371	310	53	571
6	14	1251	154	17.2	391	194	32	357
6	15	1616	132	9.2	130	134	27	426
6	16	936	239	12.7	177	117	18	478
7	1	6534	536	6.8	424	602	129	1630
7	2	23083	2498	20.9	1334	2411	540	4930
7	3	343691	13120	229.9	4787	15058	2564	26011
7	4	200300	8384	138.3	3392	9579	2247	14548
7	5	18829	1595	20.7	519	1779	121	2812
7	6	31223	3583	45.9	911	3711	400	6226
7	7	293507	7260	93.3	2486	7866	2692	10922
7	8	233517	8924	119.5	3565	11050	2940	15128
7	9	71865	3662	53.0	0	4097	718	6953
7	10	45922	1905	44.7	1211	2637	212	4571
7	11	97823	3890	90.4	0	4739	669	9292
7	12	75104	3761	69.4	1545	3698	482	6890
7	13	516	395	22.3	1531	320	0	850
7	14	801	313	26.8	0	370	0	1664
7	15	726	167	8.5	175	143	0	636
7	16	452	231	10.0	187	137	0	681