

USING TURBIDITY TO DETERMINE TOTAL SUSPENDED SOLIDS
IN URBANIZING STREAMS IN THE PUGET LOWLANDS

James J. Packman¹

Karen J. Comings²

Derek B. Booth²

Published as: J. J. Packman, K. J., Comings, and D. B. Booth, 1999, Using turbidity to determine total suspended solids in urbanizing streams in the Puget Lowlands: *in* Confronting Uncertainty: Managing Change in Water Resources and the Environment, Canadian Water Resources Association annual meeting, Vancouver, BC, 27–29 October 1999, p. 158–165.

¹ College of Forest Resources, University of Washington, Box 352100, Seattle, WA 98195, U.S.A. 206/543-5506. jpackman@u.washington.edu

² Center for Urban Water Resources Management, University of Washington, Box 352700, Seattle, WA 98195, U.S.A. 206/543-7923. kcomings@u.washington.edu and dbooth@u.washington.edu

ABSTRACT

The replacement of forestland with impervious surfaces during urbanization can have significant effects on watershed hydrology and the quality of stormwater runoff. One component of water quality, total suspended solids (TSS), is both a significant part of physical and aesthetic degradation and a good indicator of other pollutants, particularly nutrients and metals that are carried on the surfaces of sediment in suspension. We investigated whether turbidity could produce a satisfactory estimate of TSS in urbanizing streams of the Puget Lowlands. A log-linear model showed strong positive correlation between TSS and turbidity ($R^2 = 0.96$) with a regression equation of $\ln(\text{TSS}) = 1.32 \ln(\text{NTU}) + C$, with C not significantly different than 0 for 8 of the 9 sampled streams. These results strongly suggest that turbidity is a suitable monitoring parameter where water-quality conditions must be evaluated, however logistical and/or financial constraints make an intensive program of TSS sampling impractical.

INTRODUCTION

The replacement of forest with impervious surfaces during urbanization can have significant effects on watershed hydrology and riparian functions. One such concern is a decrease in water quality, which is generally reflected by an increase of particulate matter in streams (Mulliss et al., 1996; Webb and Walling, 1992). The composition and concentration of particulate matter in the aquatic environment is affected by the source and pathway of sediment input (Eisma, 1993; Webster et al., 1990). In the Puget Lowlands where the population is expected to double in by the year 2050 (DNR, 1998), linkages have been shown between increased imperviousness and increased peak flows (Booth, 1991) as well as between basin urbanization and stream habitat degradation (Olthof, 1994). These changes can potentially affect the type and quantity of suspended solids input to the riparian environment. Long-term changes in the composition and concentration of suspended solids can have potential cumulative effects on aquatic ecosystems in a multitude of ways (Newcombe, 1991). Stone and Droppo (1994) suggest suspended solids probably act as the primary transport mechanism for pollutants and nutrients in streams through flocculation, adsorption and colloidal action. Examples of effects on fish include reducing spawning habitat (Slaney et. al., 1977), limiting ability to find food (Sigler et. al. 1984), increasing susceptibility to predators (Gradall and Swenson, 1982) and increasing gill abrasion (Goldes, 1983). Especially susceptible are anadromous fish, some species of which have seen sufficient decline in their populations to warrant listing under the Endangered Species Act (Federal Register, 1999). Therefore, quantifying and monitoring changes in suspended solids is critical.

The measurement of TSS (APHA, 1995) is time consuming, and much research has been done to correlate secondary parameters to TSS, such as discharge (Webb and Walling, 1982; Williams, 1989), turbidity (Gippel, 1995; Sidle and Campbell, 1985) and water density (FISP, 1982). Each surrogate has limitations in statistical certainty, predictive power and logistical coordination. As one of the least expensive and easiest to measure methods, turbidity has been utilized extensively in many environments

including streams (Gippel, 1989), lakes (Halfman and Scholz, 1993; Paul et al., 1982), wetlands (Mitsch and Reeder, 1992) and tidal saltmarshes (Suk et al., 1998). As a measurement of the attenuation or scattering of a light beam by particulate and dissolved solids and sediment in the water column, turbidity has the potential to provide the most direct measure of particulate concentration. Lewis (1996) obtained runoff load estimation with continuous remote turbidity data collection that had significantly lower root mean square errors than estimation by discharge. However, turbidity is affected by more than just particle concentration. Water color due to dissolved solids (Malcolm, 1985) and temperature, as well as the shape, size and mineral composition of particles (Clifford et al., 1995; Gippel, 1988) can significantly affect a turbidity reading. In addition, comparison of turbidity readings between studies is confounded by a lack of a universal method of turbidity instrumentation. For example, infrared turbidimeter beams are unaffected by light absorbance of particles (usually dissolved organic compounds), whereas visible light turbidimeters are more sensitive to scattering from fines (Gippel, 1989).

The purpose of this study was to evaluate whether turbidity could produce a satisfactory estimate of TSS in urbanizing watersheds of the Puget Lowlands. Although turbidity has become the standard for forest stream monitoring in Washington state (TFW, 1993), little work has been done to assess the accuracy of correlating TSS to turbidity.

SITE DESCRIPTION

Nine streams were sampled in King County, Washington (Figure 1). Five streams were located in rural or forested areas in Redmond, Washington where impervious surfaces will increase significantly over the next decade in conjunction with a 5 km² urban planned development (UPD). Sampling stations on four of the five forest/rural streams were located where flumes and remote data loggers have been installed by King County Department of Natural Resources that record stage, turbidity and temperature (figure 2). UPD sampling stations were near the headwaters of the streams, and impacts upstream of those stations were minimal at the time of this study. Therefore, those streams provide a “pre-urbanization” picture of a TSS/turbidity relationship. Four additional streams were located in more urbanized settings in or near Seattle, Washington. Sampling stations on these streams have substantially more urbanized upstream drainage areas.

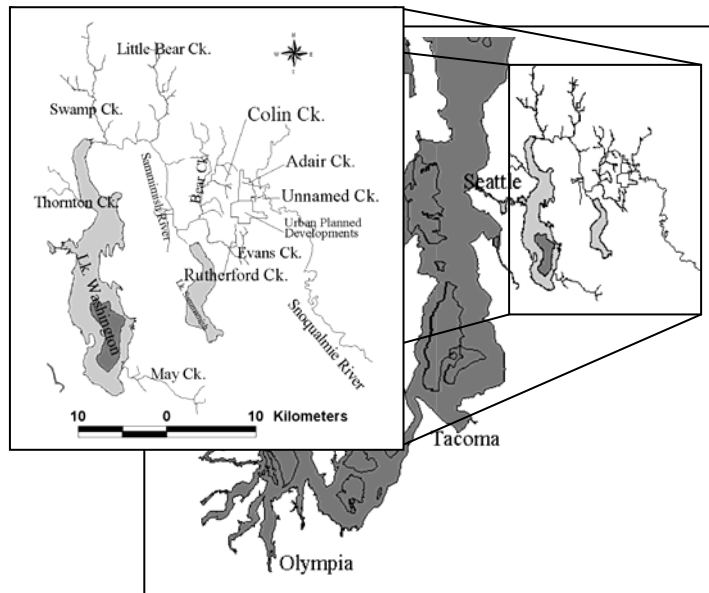


Figure 1. 9 streams in the Puget Lowlands were sampled. Five streams were located in rural or forested areas in Redmond, Washington where a 5km² urban planned development will occur over the next decade. Four additional streams are located in more urbanized setting with somewhat different land use, geology and rainfall.

METHODS

Sampling

1-liter water samples were hand-collected from 9 streams during storm events from September 1998 to March 1999. Samples were drawn from approximately mid-depth of flow. Bottles were rinsed with stream water, shaken vigorously and emptied before refilling for analysis.



Figure 2. Sample station with flume and gauge on Adair Creek.

A Hach 2100P portable attenuation turbidimeter (trade names are used for information only and do not constitute an endorsement by the authors or the University of Washington) was used to measure turbidity on samples within 4 hours of collection. Bottles were shaken thoroughly before filling turbidimeter sample cells once and then refilled for an immediate turbidity measurement. Values used represent the mean of 3 turbidity measurements following this procedure.

Filtration

Filtration procedure followed Standard Methods (APHA, 1995). Whatman 934AH glass microfiber filters were fired in aluminum cups at approximately 550°C in a Lindberg Model 810 Muffle Furnace for 24 hours as dry weight preparation. Dry weight was recorded and up to 850ml of sample was filtered using a graduated cylinder, Nalgene hand pump, Millipore filter tower and erlenmeyer filter flask. The graduated cylinder and filter tower were thoroughly rinsed using deionized water to ensure the entire sample was washed through the filter. Filters were then dried at 105°C for 24 hours in a Blue M Stabi-therm® Oven and reweighed. All masses were measured using a Mettler H31AR analytical balance accurate to 0.0001 grams.

Statistical Analysis

Statistical analysis was done using SPSS (version 8.0) and plots were generated using SPSS and Microsoft Excel (version Office 97). Differences between streams were tested using indicator variables in least squares simple linear regression. Normality tests were analyzed on quantile plots, standardized residuals were examined for independence and constant variance, and the influence of potential outliers was determined by comparing Cook's distances to F-values.

RESULTS and DISCUSSION

Stream data are plotted (Figure 3) along with data from a stormwater retention/detention (R/D) pond also in the Puget Lowlands as a comparison (Booth and Billica, 1997). Data is split into three groups on Figure 3: forested and rural streams, urban streams and R/D stormwater pond. It is evident the streams follow a different relationship than the R/D pond; specifically, the streams tend to have more TSS for a given turbidity than the pond. The tight cluster of stream data near the origin and wider spread higher on

the axes is typical of stream data in other studies on streams and rivers from around the world: Gilvear (1988) for the River Blithe in England; Grayson et. al. (1995) for the Latrobe River in Victoria, Australia, and; Lewis (1996) for Caspar Creek in northern California, USA.

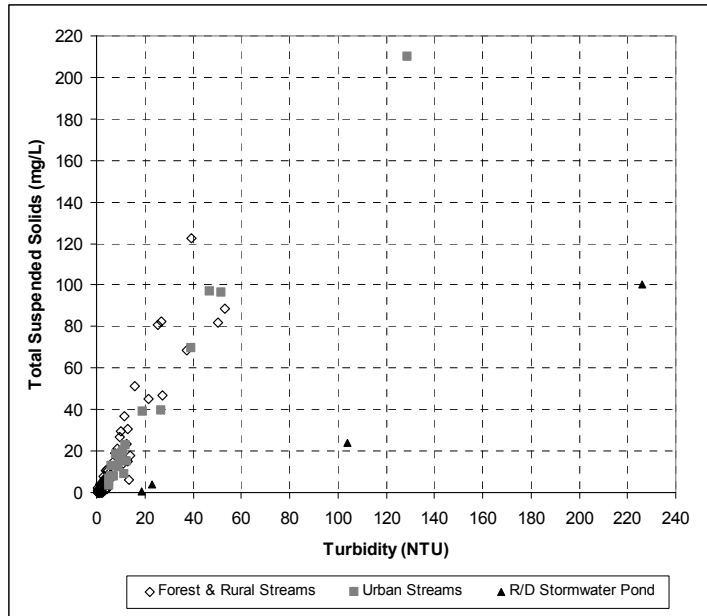


Figure 3. Turbidity and TSS data plotted for all 9 sampled streams plus stormwater retention/ detention pond also from Puget Lowlands. Notice that data from the R/D pond lies well apart from the trend suggested by the streams.

The higher TSS for a given turbidity for the stream data versus the R/D pond may be explained by higher concentrations of fine particulate organic matter (FPOM) in streams and higher concentration of suspended fines in R/D ponds. Gippel (1995) found mineral particles can cause lower turbidity levels for a solution of the same overall concentration with higher percentage FPOM. This is not a consistent relationship, though, as Gilvear and Petts (1985) found the opposite - lower turbidity readings from FPOM versus the same concentration of fines. This points to the influence of particle shape, size and amount of surface area which can cause variation in reflection, refraction and absorption of light. These variables were not measured in this study, and further understanding of the difference in TSS/turbidity relationships between streams, R/D ponds and other water bodies would require more detailed study.

Figure 4 plots natural log-transformed data for all streams (n=113), excluding the R/D pond data, with a simple linear regression model inset. The model shows a strong positive, log-linear relationship between turbidity and TSS with a correlation coefficient of $R^2=0.96$. Indicator variables were used to determine inter-stream variation in reference to Colin Creek, one of the least impacted streams of those sampled. This is not to say Colin Creek was used as a statistical control stream, rather since there was no control stream in the study, Colin Creek was randomly chosen as the reference which is required when using indicator variables without a true control stream. 1 regression analysis produced 2 models that

encompass all streams (Table 1) with the only variation of the intercept value for Rutherford Creek significantly different from the reference stream (p-value 0.006), which was not significantly different than 0. All slope coefficients were not significantly different from the reference stream value of 1.32 at the 99% confidence level.

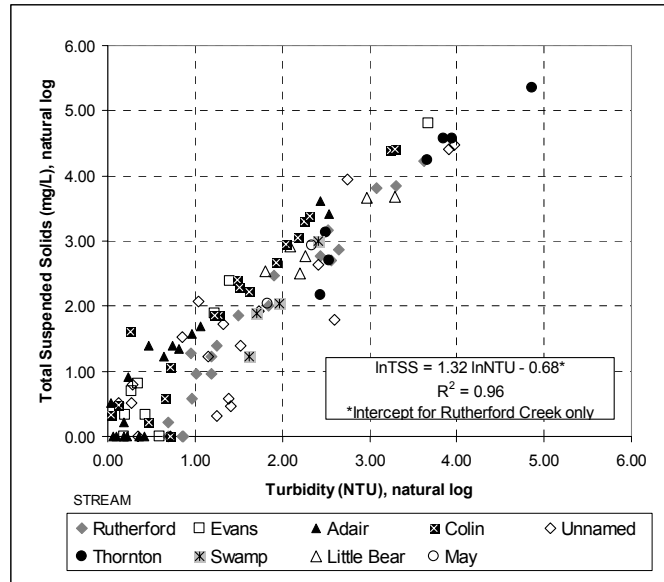


Figure 4. TSS and turbidity data, natural-log transformed, with simple linear regression analysis results. A strong relationship is evident for all streams together, regardless of different lithology, drainage area and land use upstream of sampling station.

Table 1. TSS/turbidity linear regression models

STREAM	REGRESSION MODEL
Rutherford Creek	$\ln(TSS) = 1.32 \ln(NTU) - 0.68$ (12.13)*** (2.85)***
All others	$\ln(TSS) = 1.32 \ln(NTU) + 0.15$ (12.13)*** (0.82)

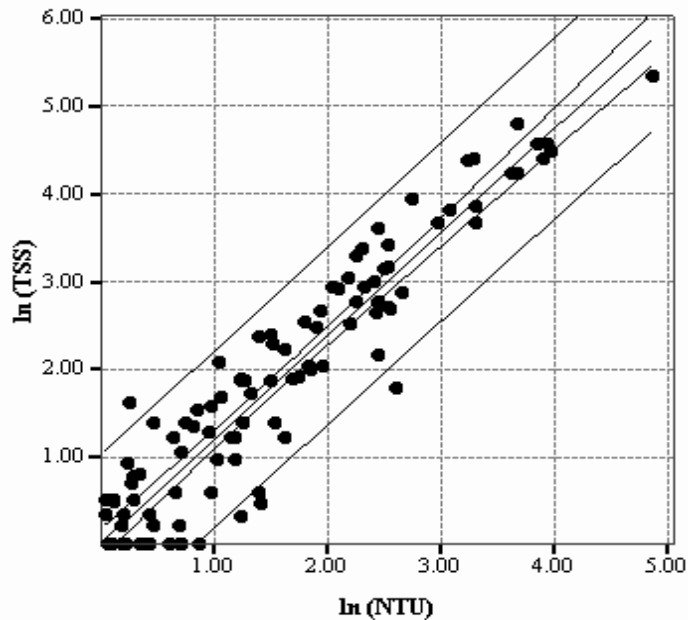
*** t-values in parentheses below coefficients indicate significance at 0.01 confidence level

The intercept difference for Rutherford Creek may be due to the sampling station choice, a weir pool. Samples from all other sites were drawn from in-stream running water. The weir pool may have caused some settling of particles, thus producing lower values and shifting the relationship down. Another factor is the influence of water color which can range from yellow-brown to black (Malcolm, 1985). A TSS turbidity relationship can be affected by water color from dissolved organic compounds which can absorb more light than inorganics. Although water color was noted empirically on each sampling trip, we did not account for water color quantitatively.

Residuals most closely followed a normal distribution when natural-log transformed, and a plot of standardized residual and standardized predicted value showed a mostly constant and independent variance of the error term. Although 1 outlier was identified on a plot of standardized vs. deleted residuals, the Cook's distance (0.088) was significantly less than the F-value (0.94, $\alpha=0.50$, $p=10$, $n=93$).

Figure 5 shows the regression best fit line bounded by 95% confidence and prediction intervals (CI and PI) for the model of all streams except Rutherford Creek. Although the data fit tightly around the regression line, the model does not provide very precise prediction capability. From the mean $\ln(\text{NTU})$ value of 1.57, the model yields a TSS value of 9.3 mg/l with a 95% confidence interval from 3.9 to 21.9. Such a wide CI is likely due to the log-linear relationship which indicates that changes in TSS concentration have a logarithmic effect on a turbidity reading.

Figure 5. Regression best fit line with confidence intervals (tighter) and prediction intervals (wider)



CONCLUSION

The results of this study indicate turbidity is potentially a viable surrogate measurement for determining total suspended solids (TSS) concentration in Puget Lowland streams. Data collected from 9 streams with both urbanized and forest/rural drainage areas show a strong positive log-linear relationship ($R^2=0.96$) between turbidity and TSS. The utility of these models will be in predicting TSS levels (e.g., storm event runoff suspended load estimates) from continuously measured turbidity in a given stream or region.

However, due to the logarithmic relationship, slight changes in TSS concentration have large effects on a

turbidity reading. This is probably due to natural variability in suspended solids size, shape and composition as well as water color.

Despite these complications, adequate relations between turbidity and TSS have been determined in many water bodies in regions around the world. This pattern is repeated in our pilot study from western Washington as well. However, the relationship between these parameters can display a distinctly different trend for different water bodies. For a given turbidity, data from a stormwater retention/detention pond have a markedly lower TSS concentration. The factors causing such differences in the TSS/turbidity relationships have not been investigated. They may prove to be important in light of the known effects of turbidity on fish, especially given the recent listing of several anadromous fish populations as threatened and/or endangered in the Puget Sound region.

Further research is warranted to determine the mechanisms that control the TSS/turbidity relationship in Puget Lowland streams so more useful and representative characterization of stream conditions can be made within the ordinary constraint of time and budget and the inescapable variability of water-quality parameters.

ACKNOWLEDGEMENTS

We would like to thank Dr. Susan Bolton and Dr. Rick Edwards at the College of Forest Resources, University of Washington for consultation and assistance with instrumentation. Thank you also to Dave Funke and Kate O’Laughlin, King County Department of Natural Resources for support with the flumes and remote data loggers. Funding provided by King County Department of Natural Resources.

REFERENCES

American Public Health Association. 1995. Standard Methods for the Examination of Water and Wastewater. 19th Ed. Topic 2540 Solids. APHA, Washington D.C.

Booth, D.B. and Billica, K. 1997. Evaluation of Filter Berms in Double-Cell Dry Detention Ponds, King County, Washington. Center for Urban Water Resources Management, University of Washington. Report K13. 25 pp.

Booth, D. B. 1991. Urbanization and the Natural Drainage System--Impacts, Solutions, and Prognoses. Northwest Environmental Journal. 7: 93-118.

Booth, D.B. 1990. Stream Channel Incision Following Drainage Basin Urbanization. Water Resources Bulletin. 26(3): 407-417.

- Clifford, N.J., Richards, K.S., Brown, R.A. and Lane, S.N. 1995. Laboratory and Field Assessment of an Infrared Turbidity Probe and Its Response to Particle Size and Variation in Suspended Sediment Concentration. *Hydrological Sciences*. 40(6): 771-791.
- DNR. 1998. *Our Changing Nature: Natural Resource Trends in Washington State*. Washington State Department of Natural Resources, PO Box 47001, Olympia, Washington, 98504. 75 pp.
- Eisma, D. 1993. *Suspended Matter in the Aquatic Environment*. Springer-Verlag, Berlin, Germany.
- Federal Interagency Sedimentation Project. 1982. A Fluid Density Gage for Measuring Suspended Sediment Concentration. St. Anthony Falls Hydraulic Lab, Minneapolis, MN. Interagency Report X.
- Federal Register. 1999. Endangered and Threatened Species: Threatened Status for 3 Chinook Salmon ESU's in Washington and Oregon, and Endangered Status of 1 Chinook Salmon ESU in Washington. Federal Register, Part II, Department of Commerce. 64(56): parts 223 and 224.
- Gilvear, D.J. 1988. Suspended Solids Transport in the Regulated River Blithe, Staffordshire, UK. *Regulated Rivers: Restoration and Management*. 2(2): 117-129.
- Gilvear, D.J. and Petts, G.E. 1985. Turbidity and Suspended Solids Variations Downstream of a Regulating Reservoir. *Earth Surface Processes and Landforms*. 10: 363-373.
- Gippel, C.J. 1995. Potential of Turbidity Monitoring for Measuring the Transport of Suspended Solids in Streams. *Hydrological Processes*. 9: 83-97.
- Gippel, C.J. 1989. The Use of Turbidity Instruments to Measure Stream Water Suspended Sediments Concentration. Department of Geography and Oceanography, University College, Australian Defense Force Academy. Monograph Series No. 4.
- Gippel, C.J. 1988. The Effect of Water Colour, Particle Size and Particle Composition on Stream Water Turbidity Measurements. Department of Geography and Oceanography, University College, Australian Defense Force Academy. Working Paper 1988/3.
- Goldes, S.A. 1983. Histological and Ultrastructural Effects of the Inert Clay, Kaolin, on the Gills of Rainbow Trout (*Salmo Gairdneri*). Master's Thesis, University of Guelph, Ontario, Canada.
- Gradall, K.S. and Swenson, W.A. 1982. Responses of Brook Trout and Creek Chubs to Turbidity. *Transactions of the American Fisheries Society*. 111: 392-395.
- Grayson, R.B., Finlayson, B.L., Gippel, C.J. and Hart, B.T. 1995. The Potential of Field Turbidity Measurements for the Computation of Total Phosphorous and Suspended Solids Loads. *Journal of Environmental Management*. 47: 257-267.
- Halfman, J.D. and Scholz, C.A. 1993. Suspended Sediments in Lake Malawi, Africa: A Reconnaissance Study. *Journal of Great Lakes Research*. 19(3): 499-511.
- Lewis, J. 1996. Turbidity-Controlled Suspended Sediment Sampling for Runoff-Event Load Estimation. *Water Resources Research*. 32(7): 2299-2310.
- Malcolm, R.L. 1985. Geochemistry of Stream Fulvic and Humic Substances. In: *Humic Substances in Soil, Sediment and Water*. Ed: Aiken, G.R., et.al. John Wiley and Sons, Inc., NY. 181-209.

- Mitsch, W.J. and Reeder, B.C. 1992. Nutrient and Hydrologic Budgets of a Great Lakes Coastal Freshwater Wetland During a Drought Year. *Wetlands Ecology and Management*. 1(4): 211-222.
- Mulliss, R.M., Revitt, M., Shutes, R.B. 1996. The Impacts of Urban Discharges on the Hydrology and Water Quality of an Urban Watercourse. *The Science of the Total Environment*. 189/190: 385-390.
- Newcombe, C.P. and MacDonald, D.D. 1991. Effects of Suspended Sediments on Aquatic Ecosystems *North American Journal of Fisheries Management*. 11: 72-82.
- Olthof, J. 1994. Puget Lowland Stream Habitat and Relations to Basin Urbanization. Master's Thesis, Department of Civil Engineering. University of Washington, Seattle, Washington.
- Paul, J.F., Kasprzyk, R. and Lick, W. 1982. Turbidity in the Western Basin of Lake Erie. *Journal of Geophysical Research*. 87: 5779-5784.
- Sidele, R.C. and Campbell, A.J. 1985. Patterns of Suspended Sediment Transport in a Coastal Alaska Stream. *Water Resources Research*. 21(6): 909-917.
- Sigler, J.W., Bjornn, T.C. and Everest, F.H. 1984. Effects of Chronic Turbidity on Density and Growth of Steelheads and Coho Salmon. *Transactions of the American Fisheries Society*. 113: 142-150.
- Slaney, P.A., Halsey, T.G. and Tautz, A.F. 1977. Effects of Forest Harvesting Practices on Spawning Habitat of Stream Salmonids in the Centennial Creek Watershed, British Columbia. British Columbia Ministry of Recreation and Conservation, Fish and Wildlife Branch. Fisheries Management Report No. 73, Victoria, British Columbia.
- Stone, M. and Droppo, I.G. 1994. In-Channel Surficial Fine-Grained Sediment Laminae (Part II): Chemical Characteristics and Implications for Contaminant Transport by Fluvial Sediments. *Hydrological Processes*. 8(2): 113-124.
- Suk, N.S., Guo, Q. and Psuty, N.P. 1998. Feasibility of Using a Turbidimeter to Quantify Suspended Solids Concentration in a Tidal Saltmarsh Creek. *Estuarine, Coastal and Shelf Science*. 46: 383-391.
- TFW. 1993. Ambient Monitoring Program Manual (Eds: Schuett-Hames, D., Pleus, A., Bullchild, L. and Hall, S.). TFW-AM9-93-001. Northwest Indian Fisheries Commission, Olympia, WA.
- Webb, B.W. and Walling, D.E. 1992. Water Quality II: Chemical Characteristics. In: *Rivers Handbook: Hydrological Ecological Principles* (eds: Calow, P. and Petts, G.E.). Blackwell Scientific, Oxford, UK.
- Webb, B.W. and Walling, D.E. 1982. The Magnitude and Frequency Characteristics of Fluvial Transport in a Devon Drainage Basin and Some Geomorphological Implications. *Catena*. 9: 9-23.
- Webster, J.R., Golladay, S.W., Benfield, E.F., D'Angelo, D.J. and Peters, G.T. 1990. Effects of Forest Disturbance on Particulate Organic Matter Budgets of Small Streams. *Journal of the North American Benthological Society*. 9(2): 120-140.
- Williams, G.P. 1989. Sediment Concentration Versus Water Discharge During Single Hydrologic Events in Rivers. *Journal of Hydrology*. 111: 89-106.