USE OF MONITORING DATA TO EVALUATE WATERSHED MANAGEMENT PRACTICES IN A MIXED-LAND USE WATERSHED IN NORTHERN IDAHO

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Abstract: The accuracy of sediment load estimates is critical to the detection of watershed effects including changes in watershed management practices, road building and maintenance, and stream restoration. We combined fixed-time interval monitoring at multiple locations with continuous monitoring at one location to determine the effectiveness of conservation practices at multiple locations. In 2000, we established a monitoring program in the Paradise Creek watershed near Moscow, Idaho including 15-minute average stage height and turbidity at a continuous station and bi-weekly monitoring of discharge (Q) and total suspended sediment (TSS) at eight locations. Event-based sampling of total suspended sediment concentrations and discharge was conducted at the continuous station. We applied standard linear regression to Q and turbidity data at the continuous station and Q and TSS at bi-weekly monitoring points for 2001, 2002, and 2005. Using regression equations, we established 15-minute time series at the bi-weekly monitoring points. Flow and TSS correlated well when bi-weekly monitoring points were close to the continuous station. Because bi-weekly data collection occurred during low flow conditions, the relationships between the continuous station and each bi-weekly monitoring point exhibited large errors at high flow events. When calculating sediment loads as the product of Q and TSS, the errors associated with regression alone became substantial. Despite these errors, we applied a trend analysis that shows effects of conservation practices during different years following implementation. Ongoing research attempts to reduce the regression errors include increased frequency of data collection at bi-weekly monitoring points to capture peak flow events, use of particle size distribution in TSS-turbidity relationships, and establishing a continuous flow record at monitoring points using a hydrologic model.

INTRODUCTION

Increasing emphasis on non-point sources (NPS) of pollution such as agriculture and forestry has initiated a growing need for procedures to estimate the effects of all sources of pollution within a watershed (MacDonald, 2005). These effects include changes in watershed management practices, road building and maintenance, stream restoration, and construction development sites. The routing and possible downstream accumulation of sediment from those management activities is of particular concern because it affects aquatic resources by clogging spawning beds, shortening the life of reservoirs, and degrading drinking water. Most studies relate these effects to adverse impact of land use activities. The effects of typical forest and agricultural land activities are increased runoff and sediment transport, higher peak streamflows, increased channel scouring and streambank undercutting (Queen et al., 1995).

Paradise Creek (IDHW-DEQ, 1997) requires a 75% reduction in NPS sediment loading to meet the TMDL. The impact of agricultural land use and other activities can be changed using conservation practices such as conservation tillage, buffer strips or gully plugs. To evaluate the effectiveness of conservation practices and understand the impact of other pollution sources, a monitoring program needs to include multiple sampling locations in the watershed (Mostaghimi et al., 1997). While continuous monitoring is known to provide the most accurate sediment load estimates, a typical monitoring design may use a fixed-time interval (e.g., bi-weekly) for economical reasons. Spatially distributed monitoring using continuous sampling is expensive. In this paper, we present a methodology, which combines fixed time interval monitoring at multiple locations and continuous monitoring at one location. We use this methodology to determine the effectiveness of conservation practices in the watershed at multiple locations.

METHODOLOGY

Watershed description: Paradise Creek watershed (PCW) is located in the Palouse River hydrologic basin in northern Idaho. The headwaters of the creek are located on Moscow Mountain in the Palouse Range. The watershed in total is 50,684 ha. The upper portion of the watershed is steeply sloped, with the majority of the drainage basin consisting of moderately steep rolling hills. Elevations range from 1330m to 770m. The Palouse hills are very susceptible to erosion due to their topography, soil texture, climate and land use practices. Agriculture occupies 66% of the watershed. Nearly 40% of annual precipitation falls during November through January. Most soils are deep, moderately to well-drained silt loam soils formed in loess (Brooks et al., 2002). In 2000 a monitoring program in PCW was established. This program includes continuous stream monitoring in a nested watershed system at three locations (number 20, 30 and 40 in Figure 1). Spatial monitoring on a bi-weekly basis "before" (2001 water year) and "after" (2002 and 2005 water years) implementation of conservation practices occurred at twelve locations. A set of conservation practices was implemented during 2001 including conversion to direct seeding (15% of area converted), gully plugs (25), buffer strips, rock chutes and stream restoration.

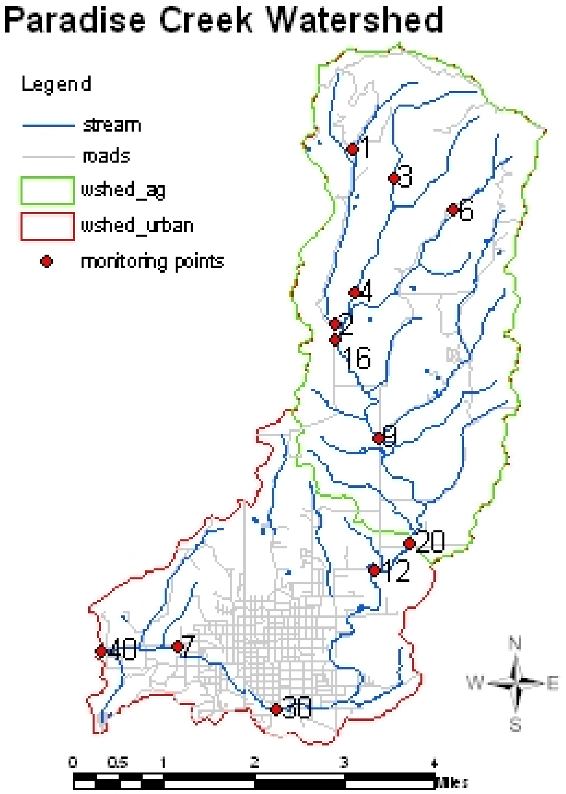

Figure 1 Map of Paradise Creek watershed showing monitoring points.

Available data: Continuous data since October, 2000 include: 15-minute average values of stream stage height, turbidity, electrical-conductivity and water temperature, event-based sampling of total suspended sediment (TSS) concentrations, and periodic discharge measurements. Data from the continuous station at location 20 (Figure 1), below agricultural land will be used in this paper. This station will be referred to as "continuous." The same set of parameters was measured manually on a bi-weekly basis at eight monitoring points within the agricultural part of the watershed (green bordered area in Figure 1) during water years 2001-2002 and 2005. Table 1 shows total precipitation, total flow volume, and maximum daily flow for the continuous station. In 2001 and 2005 total precipitation was much less than the average for the area (ca. 610mm) resulting in low flows (Figure 2) and low sediment loads (Table 1).

Table 1 Summary of hydrologic information for the continuous station for monitoring years 2001, 2002, and 2005.

Water year	Total precip. (mm)	Total flow volume (10^6 m^3)	Max daily flow (m^3/s)	Sediment loads (tons/year)
2001	422	0.51	0.60	42
2002	694	5.13	3.10	1143
2005	467	0.39	0.57	27

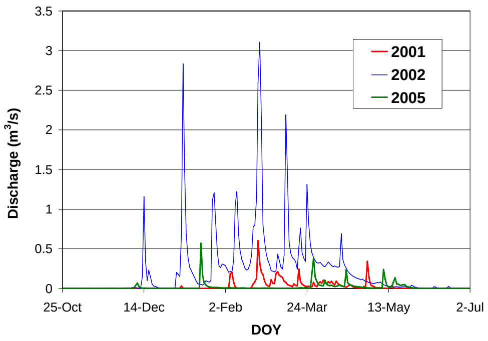

Figure 2 Daily flows at automated recording the continuous station in years 2001, 2002, and 2005.

Data analysis: Raw stage height (H) and turbidity ($NTU_{continuous}$) at the continuous station were checked for quality before analysis. Extremely high $NTU_{continuous}$ observed before regular probe cleaning were set to post-cleaning values. Continuous (15-min average) discharges ($Q_{continuous}$) were determined from H-Q rating curves. Flow lag times were evaluated between the continuous station and each of eight bi-weekly monitoring points, but were negligible. Time series were constructed consisting of data pairs of $Q_{continuous}$ and $NTU_{continuous}$, respectively, and Q_i and TSS_i, respectively, where i is a bi-weekly monitoring point, in each of the years 2001, 2002 and 2005 using standard linear regression. The coefficient of determination and 95% confidence intervals were calculated for each regression equation.

A 15-minute time series of Q_i and TSS_i was constructed separately for each bi-weekly monitoring point in each year using the general linear relationships (Equation 1 and 2):

$$Q_i = \mathrm{a}Q_{continuous} + \mathrm{b} + \mathrm{e_i} \qquad (1)$$

$$TSS_i = \mathrm{a}NTU_{continuous} + \mathrm{b} + \mathrm{e_i} \qquad (2)$$

where Q_i and TSS_i are the responses at time i, a and b are slope and intercept terms, respectively, and e_i is an error term assumed $N(0, \sigma^2)$. Annual sediment loads for every monitoring point were subsequently calculated by multiplying the predicted 15-minute Q_i and TSS_i values and summing the result over the water year. The error in these load calculations was determined using the standard formula for the variance of the product of two random variables for each 15-minute data and summed over the specified time (Mood et al., 1974) assuming statistical independence and normality of the data.

An exploratory data analysis was performed to check data quality and to see if the data were in the proper form for further statistical analysis. Log-transformations were applied to normalize the data. Autocorrelation was eliminated by aggregating data into daily time steps (Grabow et al., 1998). Discharge was selected as explanatory variable for a selected single downstream station approach. Comparisons of all 15-minute TSS_i data series were carried out using reduced model dummy variable regression following Grabow et al. (1999). The single watershed approach was used ("before/after") for each monitoring point so the comparisons allowed detection of discrete water quality changes due to land treatment changes (Grabow et al., 1998) as well as the magnitude of this change.

RESULTS AND DISCUSSION

Regression analysis: The linear relationships for Q_i and TSS_i at each monitoring point and year are summarized in Table 2 showing the estimates for slope (a) and intercept (b), the coefficient of determination (R^2), and number of observations (n). In general, R^2 for the linear regressions between $Q_{continuous}$ and Q_i for 2002 (0.44-0.94) are better than for 2001 and 2005 (0.18-0.88). In 2002, a greater range of flows (see max Q in Table 2) was observed at the monitoring points than in 2001 and 2005. The R^2 for points further upstream from the continuous station are lower than for points closer to the continuous station, reflecting the differences in hydrologic behavior of subwatersheds and subsequent flow regimes in the upper watershed relative to the lower watershed.

Table 2 Estimated regression parameters, maximum discharge, and maximum total suspended solids for bi-weekly monitoring points in years 2001, 2002, and 2005.

Monitoring site		Regression: $Q_i = a*(Q_{continuous})+b$						Regression: $TSS_i = a*(NTU_{continuous})+b$				
		slope (a)	intercept (b)	R^2	n	max Q (m^3/s)		slope (a)	intercept (b)	R^2	n	max TSS (mg/l)
2001												
PC-16		0.38	0.012	0.79	8	0.127		0.72	-4.24	0.55	9	150
PC-12		0.52	0.015	0.82	12	0.396		0.54	10.84	0.78	12	120
PC-9		0.07	0.003	0.88	9	0.048		0.15	9.60	0.29	9	40
PC-6*		0.03	0.004	0.36	11	0.017		-0.03	11.81	0.06	5	20
PC-4		0.11	0.001	0.71	11	0.105		1.79	-18.46	0.44	10	300
PC-3*		0.05	0.001	0.81	10	0.014		-0.06	19.37	0.42	4	20
PC-2		0.05	0.005	0.78	11	0.057		1.01	22.86	0.38	9	200
PC-1*		0.04	0.001	0.72	10	0.014		0.00	15.51	0.00	12	20
2002												
PC-16		0.76	0.011	0.94	11	0.765		0.09	8.78	0.24	10	25
PC-12		1.80	-0.031	0.92	16	1.982		0.32	4.59	0.70	11	35
PC-9		0.23	-0.009	0.93	16	0.227		0.05	8.45	0.09	11	15
PC-6*		0.08	0.004	0.47	13	0.057		-0.01	11.46	0.01	7	15
PC-4		0.23	0.011	0.86	11	0.255		0.07	6.67	0.19	11	20
PC-3*		0.08	0.002	0.44	12	0.042		1.38	-58.89	0.65	5	100
PC-2		0.25	-0.015	0.88	12	0.255		0.23	8.11	0.22	11	40
PC-1		0.08	0.005	0.58	16	0.085		0.09	6.29	0.76	8	30
2005												
PC-16		0.44	0.003	0.72	11	0.028		0.11	7.13	0.45	12	20
PC-12		0.80	0.001	0.82	13	0.048		0.80	-1.85	0.89	11	50
PC-9		0.12	0.003	0.18	11	0.011		0.85	1.13	0.74	8	60
PC-6*		0.07	0.002	0.27	13	0.008		-0.15	6.46	0.17	11	6
PC-4		0.10	0.004	0.28	13	0.011		0.22	12.06	0.08	12	40
PC-3*		0.07	0.000	0.62	4	0.006		-0.13	14.13	0.55	4	10
PC-2*		0.04	0.002	0.55	10	0.008		-0.01	12.74	0.00	8	15
PC-1*		0.12	0.002	0.62	13	0.011		-0.04	6.86	0.14	12	10

The R^2 for the $NTU_{continuous}$-Tes_{sa} relationships (0.0 to 0.89) are lower than for the $Q_{continuous}$-Q_i relationships. In addition to differences in flow regimes, which affected TSS and turbidity, at different locations in the watershed, differences in sediment characteristics also appeared to affect the $NTU_{continuous}$-TSS_i relationships. According to Gippel (1989), the NTU-TSS relationship is usually site specific. Just below forest land (points PC-1, PC-3 and PC-6 in Figure 1) and at point PC-2, $NTU_{continuous}$ is not or negative correlated to TSS_i. In further analysis, therefore, the $NTU_{continuous}$-TSS_i relationships for these points (marked with * in Table 2) were not used. Given the relatively even TSS_i concentrations at these points, the average observed TSS_i were used instead.

An evaluation of the errors in the 15-minute Q_i and TSS_i time series shows, as expected, that if the R^2 is lower, the corresponding 95% confidence interval on the predicted lines is greater. As an example, Figure 3 shows the $Q_{continuous}$-Q_i and $NTU_{continuous}$-TSS_i relationships with 95% confidence intervals for point PC-9 in 2002. Results from point PC-9 are shown in this paper, because a substantial number of gully plugs were installed in the subwatershed in 2001 (Dansart, 2002). For the $Q_{continuous}$-Q_i data ($R^2 = 0.93$), the confidence interval is relatively small over the range of measurements (Figure 3a), while for the $NTU_{continuous}$-TSS_i data ($R^2 = 0.29$), the confidence interval widens as the points become more scattered (Figure 3b). When applying the regression equations to obtain 15-minute time series at individual monitoring points, observed $Q_{continuous}$ and $NTU_{continuous}$ outside the range of observed Q_i and TSS_i have large errors and, thus, are less reliable. A drawback of bi-weekly monitoring designs is the tendency to collect data primarily during low flow conditions, as was experienced also in this study in all three years (Figure 4).

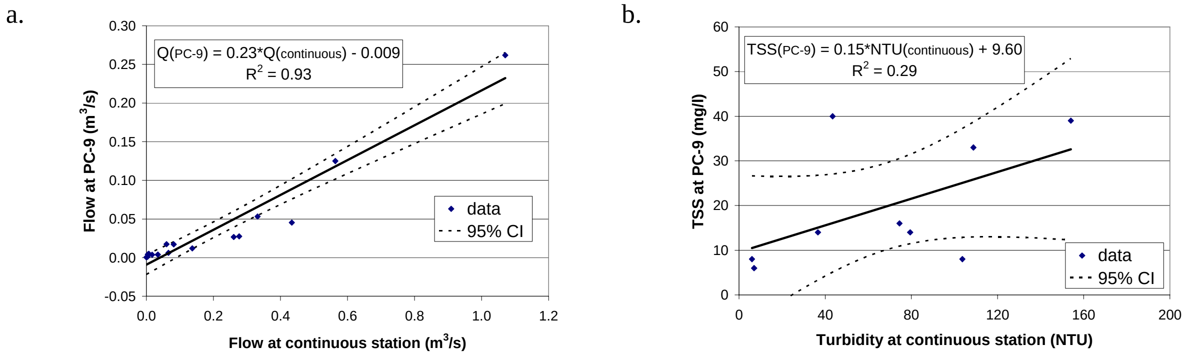

Figure 3 Regression lines with 95% confidence intervals for PC-9 (a. Q_i vs. $Q_{continuous}$, b. TSS_i vs. $NTU_{continuous}$).

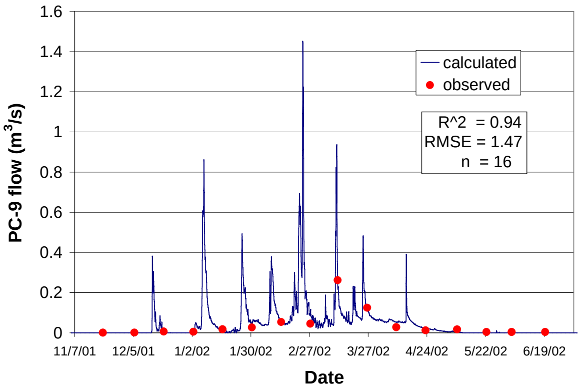

Figure 4 Comparison of calculated and observed discharges for point PC-9 in 2002 year.

Sediment loads: Sediment loads, cumulative errors, and sediment yields for all monitoring points are summarized in Table 3. The sediment loads for point PC-12 were expected to be similar to sediment loads at the continuous station given they are in close proximity (Figure 1). Indeed, the results approximately match the sediment loads at the continuous station for dry years (Table 1). However, for 2002 the sediment load was greatly underestimated (695 vs. 1143 tons/year at the continuous station). The most probable reason is the lack of high Q_i values at PC-12 in 2002 causing large errors at high $Q_{continuous}$ values. Thus, the method of data generation based on bi-weekly sampling for these data underestimated the annual sediment loads.

Cumulative errors for sediment load in Table 2 were substantial for several points. These large errors resulted when Q_i and TSS_i were extrapolated in regions with large errors of prediction. Figure 5 shows magnitudes of error up to 3000% (in kg/15-minute time step) as a function of 15-minute instantaneous discharges at point PC-9 in 2002. To decrease the cumulative errors and, in turn, increase the accuracy of the calculated loads, the measurement frequency should increase. Most importantly, more measurements must be taken at high flows.

Sediment yields for all subwatersheds above bi-weekly monitoring points are included in Table 3 and displayed in Figure 6. Dramatic increases in sediment yield in 2002 were followed by the strong decreases in 2005 at all monitoring points showing the influence of climate variability (see Table 1) between years. Overall, based on these data, no definitive conclusions can be drawn about true reductions in sediment concentrations and the evaluation of conservation practices. If we consider the average sediment yield estimates, however, the subwatershed above PC-9, appears to have a sediment yield similar to the subwatersheds in the upper watershed (e.g., PC-1, PC-3 and PC-6), where agricultural impacts were much less.

Table 3 Sediment load characteristics for all monitoring points in years 2001, 2002, and 2005.

Monitoring point	Area (ha)	Sediment loads (tons/year)			Cumulative error +/- (tons/year)			Sediment yield (kg/ha/year)		
		2001	2002	2005	2001	2002	2005	2001	2002	2005
PC-16	214.2	25.6	121.2	4.4	579	1919	54	119.7	565.9	20.3
PC-12	1047.4	35.3	694.5	31.8	710	5584	225	33.7	663.0	30.3
PC-9	409.9	2.5	22.3	6.9	66	530	168	6.1	54.5	16.8
PC-6	189.3	1.2	6.0	0.3	32	135	5	6.6	31.9	1.6
PC-4	307.9	14.8	31.0	3.0	588	555	86	47.9	100.8	9.8
PC-3	160.0	0.7	4.7	0.3	22	461	15	4.5	29.4	2.0
PC-2	353.9	11.6	71.1	0.7	299	1446	12	32.9	201.0	1.9
PC-1	172.6	0.9	12.1	0.4	38	149	6	5.0	69.9	2.6

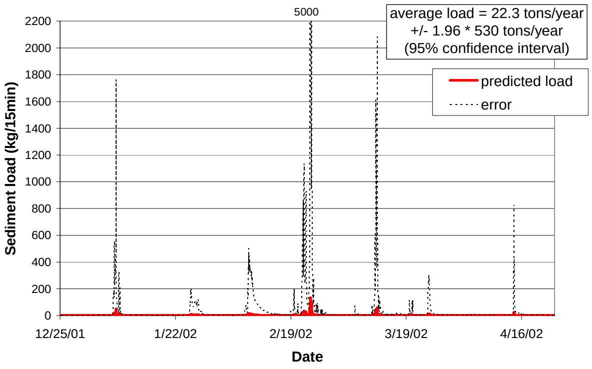

Figure 5 Calculated 15-minute sediment load estimates with possible errors at point PC-9 for 2002 water year.

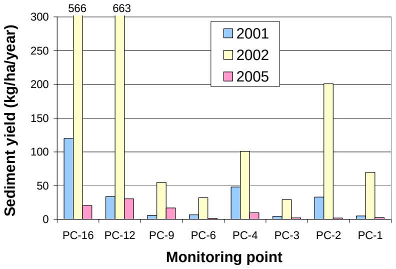

Figure 6 Sediment yields at all monitoring points for monitoring years 2001, 2002, and 2005.

Comparison of trends: A reduced model dummy variable regression analysis was performed on the 15-minute Q_i and TSS_i data series for each monitoring point. Data were aggregated into daily flows excluding periods of time when the creek was dry. Comparisons were made for 2005 vs. 2001, 2002 vs. 2001 and 2005 vs. 2002. Analyses were not applied to points marked with a * in Table 2 since TSS_i were relatively constant throughout the year at these locations. Table 4 lists the average change in TSS concentration, parameters B2 and B3 (difference in intercepts and difference in slopes between regression lines, respectively) and their statistical significance reflected by p-values. In general, a significant percent reduction in sediment concentrations (from 64 to 97%) was observed in 2002 vs. 2001 for all points (bold values in Table 4, negative sign indicates the reduction). In 2005, TSS_i increased to levels higher than in 2001, except at PC-4.

Table 4 Comparison of regression parameters B2 and B3 and average change in TSS concentrations for all monitoring points in monitored years.

	PC-16	PC-12	PC-9	PC-4
2005 vs. 2001				
B2	0.50	0.03	0.57	-0.68
B3	-0.78	0.09	0.40	-0.16
p-value B2	0.0000	0.4661	0.0000	0.0000
p-value B3	0.0000	0.3163	0.0003	0.1449
Average change in TSS (%)	19	12	60	**-76**
2002 vs. 2001				
B2	0.31	-0.49	-0.46	-1.42
B3	-0.88	-0.24	-0.38	-0.39
p-value B2	0.0024	0.0000	0.0000	0.0000
p-value B3	0.0000	0.0277	0.0000	0.0000
Average change in TSS (%)	**-65**	**-80**	**-64**	**-97**
2005 vs. 2002				
B2	0.19	0.52	1.04	0.74
B3	0.11	0.33	0.78	0.23
p-value B2	0.0000	0.0000	0.0000	0.0000
p-value B3	0.0714	0.0002	0.0000	0.0037
Average change in TSS (%)	46	85	91	84

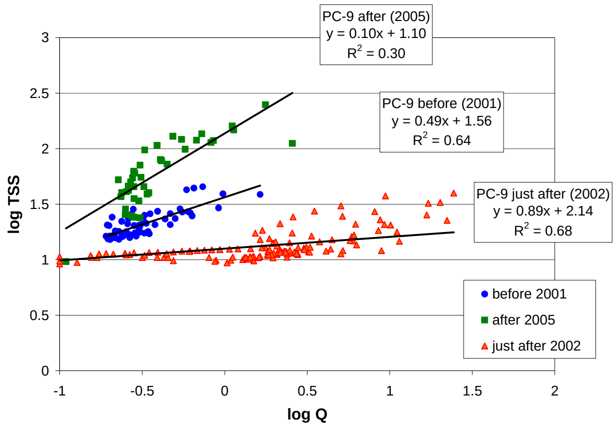

Figure 7 Log-log plot of total suspended sediment (TSS) versus discharge (Q) and best-fit lines for point PC-9.

Results of analyses for TSS_i at point PC-9 are shown in Figure 7. For 2002 (red triangles) vs. 2001 (blue dots) the p-value for the B2 parameter (Table 4) indicates that a statistically significant difference in TSS intercepts between year 2002 and 2001 exists at the 99% confidence level. The B2 value of -0.46 represents the magnitude of the difference while the negative sign indicates a reduction. The negative value of B3 indicates greater reductions occurred at higher TSS_i (also at the 99% confidence level; p-value for B3). The overall 64 percent average reduction in TSS_i exists for PC-9 in 2002 vs. 2001.

Despite the increased sediment yields and loads for all monitoring points in 2002 a significant reduction in TSS_i concentrations was observed. It may indicate that the conservation practices were the most effective in 2002 throughout the watershed, just after installation. The increase in TSS_i in 2005 may be explained by increased human impact observed in the watershed such as dredging the stream channels or road and ditch maintenance which masked the effectiveness of applied conservation practices.

CONCLUSION

A new methodology for the spatial evaluation of conservation practices was presented. The method is based on the generation of spatial time series data from discrete sampling and continuous data recorded at an automated stream station using linear regression. Bi-weekly sampling data collected primarily during low to medium flows used in this paper were not satisfactory for accurate assessment of sediment loads. The extrapolations for high flows produced large errors. To decrease the cumulative errors and, in turn, increase the accuracy of the calculated loads, the measurement frequency should increase. Most importantly, more measurements must be taken at high flows. Comparison of trends revealed that conservation practices were most effective just after their implementation. The increase in sediment concentrations recorded recently is most likely due to increased anthropogenic impact that masked the effectiveness of applied conservation practices.

As a next step to improve the regressions, and thus the sediment load estimates, we will be following three strategies. (i) We will collect discharge and sediment data more frequently at the bi-weekly monitoring points, especially during higher flows, to improve the regressions. During the 2006 water year, we will add a storm chasing procedure to the existing bi-weekly monitoring program as recommended by Robertson and Roerish (1999). (ii) We will improve the TSS-NTU relationships by incorporating changes in particle size distribution during rising and falling limbs of the hydrograph. (iii) We will use flows simulated with a GIS-based hydrologic modeling at the bi-weekly monitoring points to augment the discharge time series.

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REFERENCES

Brooks, E.S., and Boll, J. (2002). “Evaluation of a distributed hydrology model to support restoration efforts in small watersheds with limited data: from research scale to management scale,” UNESCO technical reports, presented at the 2002 ERB/Friend 5 conference, Demanovska dolina, Slovakia, 6 p.

Dansart, W. (2002). “Paradise Creek Water and Sediment Control Structure Efficiency,” Idaho Soil Conservation Commission, Moscow, Draft Report, August 1. 7 p.

Gippel, C.J. (1989). “The Use of Turbidity Instruments to Measure Stream Water Suspended Sediment Concentrations,” Monograph Series No. 4. Department of Geography and Oceanography, University College, The University of New South Wales and Australian Defense Force Academy, 204 p.

Grabow, G.L., Spooner, J., Lombardo, L.A, and Line, D.E. (1998). “Detecting water quality changes before and after BMP implementation: Use of a spreadsheet for statistical analysis,” NWQEP Notes, No. 92.

Grabow, G.L., Lombardo, L.A., Line, D.E., and Spooner, J. (1999). “Detecting water quality improvement as BMP effectiveness changes over time: use of SAS for trend analysis,” NWQEP Notes, No. 95.

IDHW-DEQ. (1997). Paradise Creek TMDL.

MacDonald, L.H. (2005). “Predicting and Managing Cumulative Watershed Effects,” College of Natural Resources, University of Minnesota. http://www.cnr.umn.edu/FR/courses/fr5153/MacDonald.pdf, accessed on May 27, 2005.

Mood, A.M., Graybill, F.A., and Boes., D.C. (1974). Introduction to the Theory of Statistics. Third Edition. McGraw-Hill Book Company, pp 175-181.

Mostaghimi, S., Park, S.W., Cooke, R.A., Wang, S.Y. (1997). “Assessment of management alternatives on a small agricultural watershed,” Water Resources, 31(8), pp 1867-1878.

Queen, L.P., Brooks, K.N., Wold, W.L. (1995). “Assessing cumulative effects in the Nemadji River Basin, Minnesota,” Proceedings of the 1995 Watershed Management Symposium, August 14-16, San Antonio, TX, USA, ASCE, pp 239-249.

Robertson, D.M., and Roerish, E.D. (1999). “Influence of various water quality sampling strategies on load estimates for small streams,” Water Resources Research, 35(12), pp 3747-3759.