CORRELATING STREAMFLOW, TURBIDITY, AND SUSPENDED-SEDIMENT CONCENTRATION IN MINNESOTA'S WILD RICE RIVER

Christopher A. Ellison, cellison@usgs.gov; Richard L. Kiesling, kiesling@usgs.gov; James D. Fallon, jfallon@usgs.gov, all are Hydrologists, U.S. Geological Survey, Mounds View, Minnesota

Abstract The ability to understand the relations between suspended-sediment concentration (SSC) and measurements of water transparency is critical for assessing the effectiveness of programs that address nonpoint source pollution. The Wild Rice River, a tributary of the Red River of the North in northwestern Minnesota, has been listed since 2006 on the U.S. Environmental Protection Agency's 303(d) impaired stream list for turbidity and the associated threat to aquatic-life uses. The U.S. Geological Survey (USGS), in cooperation with the Wild Rice Watershed District (WRWD) and their consultant, Houston Engineering, collected water-quality data for seven constituents at five monitoring sites in the Wild Rice River Basin from February 2007 to June 2009. Study objectives were to define the relation between turbidity and SSC for use in developing criteria for total maximum-daily loads and to improve estimation techniques for SSC and suspended-sediment loads (SSL). Accurate estimates of SSC and SSL are important to the WRWD for developing systems that temporarily retain flood flows until flooding has receded. Flood damage in the basin is estimated to be $3.6 million annually.

Traditional statistical techniques were used to assess spatial and seasonal variations and to evaluate relations among streamflow, SSC, turbidity measured in nephelometric turbidity units (NTU), and transparency tube readings. Pearson's correlation test was used for normalized data, and Kendall's tau correlation test was used for censored data. Pearson's correlation test indicated strong positive relations between NTU and SSC (r = 0.96) and between streamflow and NTU (r = 0.71). Kendall's tau test indicated a strong negative relation between transparency tube readings and NTU (*tau* = -0.82). Linear regression analysis demonstrated that turbidity (r^2 = 0.93) was superior to streamflow (r^2 = 0.51) and transparency (r^2 = 0.84) as a predictor of SSC. Regression equations that used turbidity to calculate SSC at each site were similar, suggesting that a single regression equation may be used to calculate SSC for the entire basin. These data indicate that using turbidity as a surrogate for sediment will improve time-series calculations of SSC and SSL. Additionally, sediment-transport curves will provide insight on long-term sediment transport and improve understanding of how SSC relates to total maximum-daily loads and turbidity along the Wild Rice River.

INTRODUCTION

The Wild Rice River Basin encompasses an area of 4,144 square kilometers (1,600 square miles) in northwestern Minnesota and is a primary tributary to the Red River of the North (Fig. 1). The basin includes the drainage basin of the Wild Rice River and its tributary, the South Branch Wild Rice River. The main stem is 257 kilometers (160 miles) long and flows in a westerly direction from Mud Lake in Clearwater County past the towns of Twin Valley, Ada, and Hendrum where it joins the Red River of the North. The river has a long history of water-related problems including flooding, erosion, sediment deposition and degradation of riverine and terrestrial habitat. Numerous studies and projects have been implemented over the years with the intent of reducing flood damages, which are estimated to be $3.6 million annually. The Wild Rice Watershed District (WRWD), located in Ada, oversees projects related to stream bank restoration, flood and erosion control, wetland restoration, and best-management practices under authority of the Minnesota Watershed District Act of 1955 (WRWD, 2009).
In 2006 the Minnesota Pollution Control Agency (MPCA) listed the lower reach of the Wild Rice River as impaired for excess turbidity. The impaired reach is located from the river's confluence with the South Branch of the Wild Rice River to the confluence with the Red River and is about 48 kilometers (30 miles) in length.

Turbidity is listed as the third leading cause of impairments in Minnesota waters, affecting 7,667 kilometers (4,764 miles) of rivers and streams (USEPA, 2009). Turbidity, an expression of the clarity of water, is impacted by the presence of suspended and dissolved material such as clay, silt, organic matter, and plankton (Anderson, 2005). The turbidity standard for aquatic life is currently set at 25 nephelometric turbidity units (NTU). Suspended sediments, generally originating from eroding soil and bedrock, (Satterland and Adams, 1992) are transported downstream as part of the cycle of erosion. Although some areas have naturally higher erosion rates and sediment yields due to geologic, climate, soil, and vegetation types, the erosion process can be accelerated by anthropogenic disturbances

resulting from agricultural operations, logging, recreation, and urbanization.

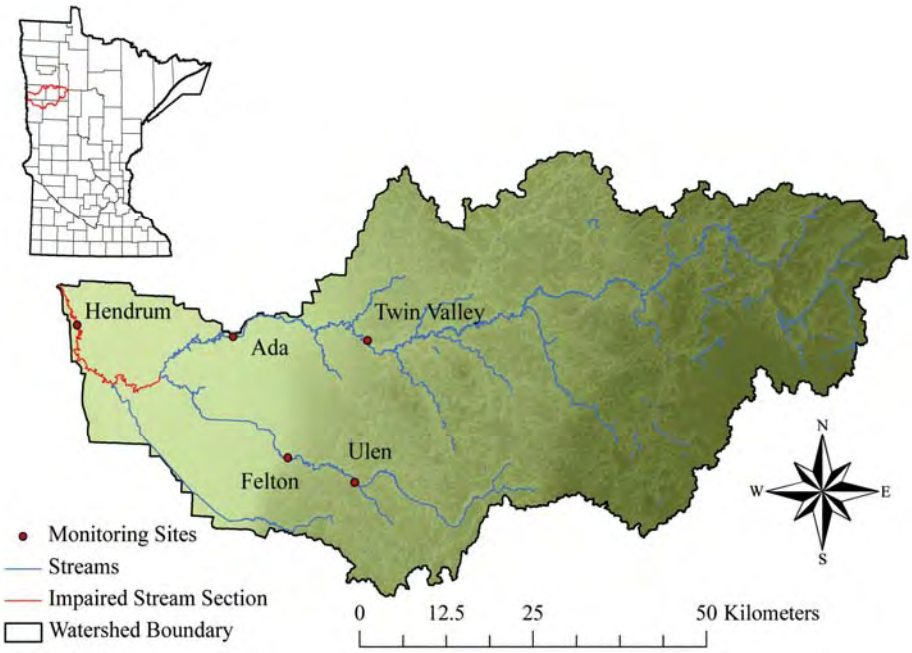

Figure 1 Location of the Wild Rice River Basin, impaired stream reach, and monitoring sites in Minnesota.

Elevated concentrations of suspended sediment can adversely affect water supply, recreation, aquatic life, and flood control (Angino and O'Brien, 1968). Understanding the relations between suspended-sediment concentration (SSC) and water transparency levels in addition to measuring changes in suspended-sediment loads (SSL) are important factors in assessing the effectiveness of programs for abating nonpoint source pollution (Crawford, 1991).

METHODS

Data Collection Site specific data were collected from five sites in the Wild Rice River Basin from February 14, 2007 to June 11, 2009. Monitoring site names, U.S. Geological Survey (USGS) site identification numbers, locations, and drainage areas are presented in table 1. Site positions and identification numbers are available from the National Water Information System (NWIS) at http://waterdata.usgs.gov/mn/nwis/si. The drainage area for each site was obtained from the USGS Interactive Watershed Web site available at http://gisdmnspl.cr.usgs.gov/watershed/index.htm.

Table 1 Selected information for monitoring sites in the Wild Rice River Basin.

Site name	Site identification number	Longitude (decimal degrees)	Latitude (decimal degrees)	Drainage Area (square miles)
Wild Rice River at Twin Valley	05062500	-96.2444	47.2667	934
Wild Rice River near Ada	05063000	-96.5000	47.2639	1,100
South Branch Wild Rice River at Ulen	05063380	-96.2578	47.0861	147
South Branch Wild Rice River at Co. Rd. 27 near Felton	05063398	-96.3858	47.1133	190
Wild Rice River at Hendrum	05064000	-96.7972	47.2681	1,560

Water quality parameters collected for this study included streamflow, turbidity nephelometric turbidity units (NTU), suspended-sediment concentration (SSC), transparency (Ttube), specific conductivity (SpC), percentage of suspended sediment sieve diameter (SSSD) less than 0.062 millimeter, and water temperature. Samples were collected at six-week intervals with up to two additional samples obtained during amplified streamflow events. Monitoring sites were chosen near highway bridges. Sampling locations at Twin Valley, Felton, and Hendrum were located near permanent USGS streamflow gaging stations. For sampling sites at Ulen and Ada, a USGS gaging station was not available and gage heights were measured using wire-weight gages referenced to known benchmarks. For these two sites, gage heights were used to estimate streamflow using an established rating table.

USGS protocols for collecting and analyzing streamflow were followed according to Rantz and others (1982). For flows too deep to wade, streamflow was collected using an Acoustic Doppler Current Profiler (ADCP) (Teledyne RD Instruments, San Diego, CA), otherwise a Flowtracker (Son Tek/YSI, San Diego, CA; Yellow Springs, OH) was used.

Turbidity was measured using an aliquot from a weighted bottle sampler lowered into the water near the stream centroid. The sample was read using a HACH 2100P (Hach Company, Loveland, CO) and an HF scientific DRT-15CE (HF scientific, Fort Meyers, FL) portable desktop turbidimeters. Instantaneous readings from the two turbidimeters were averaged for the statistical analysis.

Suspended sediment was collected using the Equal Width Increment (EWI) method following Edwards and Glysson (1999), with all suspended-sediment concentrations analyzed according to standard USGS protocols (Guy, 1969). All samples were sent to the USGS sediment lab in Iowa City, Iowa for analysis.

Transparency was measured using a 60 cm length transparency tube. Water samples for transparency readings were obtained using a weighted-bottle sampler. Numerous samples exceeded the 60 cm limitation of the transparency tube and were recorded as right-censored values. For readings that did not exceed the 60 cm limit, a mean of the observed distances to the Ttube's secchi disk and the secchi disk center-screw was used as the Ttube reading.

Samples were analyzed for sand/fine partitioning using 0.062 mm as the reference size to delineate between sand-sized and fine material particle sizes. This coarse/fine separation facilitates the physical characterization of suspended material among streamflow and monitoring sites. It also helps identify unusual samples during data analysis.

Statistical Analysis Statistical analyses were conducted using S-Plus statistical software (TIBCO Software Inc., Palo Alto, Calif.) to develop relations between suspended-sediment concentrations and measures of water transparency, and to assess spatial and seasonal variability. Variables included streamflow, stream temperature, SSC, NTU, and transparency. Statistical techniques included Pearson and Kendall's tau correlations, summary statistics, and simple linear regression (Helsel and Hirsch, 1992). The data were checked for statistical assumptions of normality and homogeneity of variances. All variables violated statistical assumptions of normality and equal variances and were transformed using the log base 10 function.

RESULTS AND DISCUSSION

Summary Statistics Summary statistics were computed using raw values from each variable for the individual sites. Values of the maximum, minimum, mean, and standard deviation were calculated using S-Plus software. The descriptive statistics for each site are presented in table 2. The largest streamflow of 8,560 cubic feet per second (cfs) occurred on March 30, 2009 at Hendrum during record flooding in the Red River Basin. It is notable that the highest streamflow value did not yield the highest SSC or NTU value. For example, streamflow of 8,560 cfs at Hendrum had an associated SSC of 64 milligrams per liter (mg/L) and a turbidity value of 52 NTU. In comparison, a much lower streamflow of 2,280 cfs on April 2, 2007 at Hendrum had an associated SSC of 474 mg/L and a turbidity value of 347 NTU. During this same period, upstream at Ada on April 2, 2007, streamflow of 1,720 cfs had an associated SSC of 1,140 mg/L and a turbidity of 685 NTU. Large spatial and temporal variations in the SSC-streamflow relation indicated that factors other than streamflow magnitude have a substantial effect on the concentration of suspended sediment in the Wild Rice River. It is hypothesized that part of this variation at Hendrum may be attributable to backwater effects from the Red River of the North. During flooding of the Red.

Table 2 Summary statistics of streamflow, transparency, turbidity, suspended-sediment sieve diameter, and suspended-sediment concentration for monitoring sites of the Wild Rice River Basin from February 2007 to June 2009.

[cfs, cubic feet per second; mg/L, milligrams per liter; NTU, nephelometric turbidity unit; Ttube, transparency tube; <, less than; %, percent; mm, millimeter; cm, centimeter]

Site	Statistic	Streamflow (cfs)	Transparency (Ttube) (cm)	Turbidity (NTU)	Suspended-sediment sieve diameter (% < than 0.062mm)	Suspended-sediment concentration (mg/L)
Twin Valley	Minimum	26	3	4.5	52	3
	Mean	921.52	32.55	71.40	87.60	108.53
	Maximum	4920	66	400	98	775
	N	21	20	21	20	19
	SD	1296.24	21.22	106.10	10.68	200.22
Ada	Minimum	23	3	4.1	50	6
	Mean	1008.58	30.59	102.89	78.24	196.94
	Maximum	6050	66	685	96	1140
	N	19	17	19	17	18
	SD	1598.40	20.25	184.47	13.47	349.56
Hendrum	Minimum	27	3	12	76	15
	Mean	1302.50	21.55	72.50	91.67	102.29
	Maximum	8560	61	347	99	474
	N	22	20	22	21	21
	SD	2102.15	18.07	74.45	6.27	103.53
Ulen	Minimum	3	16	2.85	70	3
	Mean	390.03	41.45	18.29	89.88	29.33
	Maximum	3240	60	73.5	98	118
	N	12	11	12	8	9
	SD	906.65	15.00	19.01	9.88	34.38
Felton	Minimum	9	3	1.35	57	17
	Mean	732.6	29.56	65.73	79.31	138.13
	Maximum	4190	60	400	94	715
	N	10	9	10	8	8
	SD	1432	18.24	119.57	13.00	235.61

River of the North, the water surface in the lower reach of the Wild Rice River is substantially raised at the mouth extending upstream from Hendrum. Backwater has the effect of lowering stream velocity and causes deposition of sediments that would normally remain in suspension if backwater conditions were not present

Correlations Bivariate relations were developed using Pearson and Kendall's tau tests at an alpha value of 0.05 for a 95-percent confidence level. Pearson's correlation test was used to test transformed variables whereas Kendall's tau test was used to test transparency due to censored values. The inverse of transparency was used for the Kendall's tau correlation test. This is required to convert the right censored data into left censored values. Converting right censored data into left censored data has the effect of changing the sign on the resulting 'r' value, thus the sign must be reversed to reflect the correct bivariate relation. Correlation 'r', "tau", and p-values are presented in table 3 for eight variables.

For these data, turbidity (NTU) demonstrated an exceptionally strong positive relation with SSC (r = 0.96). Other strong positive relations were observed between streamflow and turbidity (r = 0.71) and with SSC (r = 0.65). Transparency demonstrated negative relations with turbidity (r = -0.82), SSC (r = -0.70), and streamflow (r = -0.48). Specific conductance also had negative relations with streamflow (r = -0.66), turbidity (r = -0.53), and SSC (r = -0.40). These data indicated that streamflow accounted for significant responses in 4 of 7 variables. As streamflow increased, SSC and turbidity increased, which likely occurred from a combination of overland transport of sediment into streams due to erosion of the landscape, scouring of streambanks, and re-suspension of sediment from channel beds. The resultant increases in SSC and turbidity caused lower Ttube readings. For SpC, increased streamflow has a dilution effect, resulting in lower specific conductance values. Few correlations were observed between seasons and each of the other variables. This is hypothesized to result from the sampling design, which emphasized sampling elevated streamflow during the monitoring period.

Table 3 Summary of bivariate correlations between selected parameters in the Wild Rice River Basin, 2007 – 2009. [cfs, cubic feet per second; NTU, nephelometric turbidity unit; Ttube, transparency tube; cm, centimeter; mg/L, milligrams per liter; %, percent material less than 0.062 millimeters in size; µS/cm, microSiemens per centimeter; <, less than; °C, degrees Celsius; 1, winter; 2, spring; 3, summer; 4, fall]

	Correlation Statistic	Stream-flow	Turbidity	Transparency	SSC	SSSD	SpC	Temp	Sea-son
Streamflow (cfs)	Pearson	1							
	p-value	0							
Turbidity (NTU)	Pearson	0.71	1						
	p-value	< 0.01	0						
Transparency (Ttube) (cm)	Kendall's tau	-0.48	-0.82	1					
	p-value	< 0.01	< 0.01	0					
Suspended-sediment concentration (mg/L)	Pearson	0.65	0.96	-0.70	1				
	p-value	< 0.01	0	< 0.01	0				
Suspended-sediment sieve diameter (%)	Pearson	0.05	0.08	-0.09	-0.02	1			
	p-value	0.66	0.51	0.26	0.85	0			
Specific conductivity (µS/cm)	Pearson	-0.66	-0.53	0.31	-0.40	0.04	1		
	p-value	< 0.01	< 0.01	< 0.01	< 0.01	0.70	0		
Temperature (°C)	Pearson	-0.07	0.03	0.02	0.02	-0.12	0.14	1	
	p-value	0.47	0.79	0.83	0.84	0.29	0.18	0	
Season (1, 2, 3, 4)	Pearson	-0.05	0.20	0.003	0.15	0.10	0.06	0.69	1
	p-value	0.61	0.04	0.97	0.16	0.38	0.53	< 0.01	0

Linear Regression Regression models were developed between SSC and streamflow, SSC and transparency, and SSC and turbidity using S-plus software at an alpha value of 0.05 for a 95-percent confidence level. Streamflow, SSC, and transparency violated statistical assumptions of normality and equal variances and were transformed using the log base 10 function. Regression model development, diagnostics, back transformations, and bias correction factors were accomplished following Helsel and Hirsch (1992) and Rasmussen and others (2009). Graphs of relations between selected variables and least-squares regression lines for each site are illustrated in figures 2 through 4. Table 4 presents regression equations along with model attributes of r^2, p-values, and model standard percentage errors for individual sites.

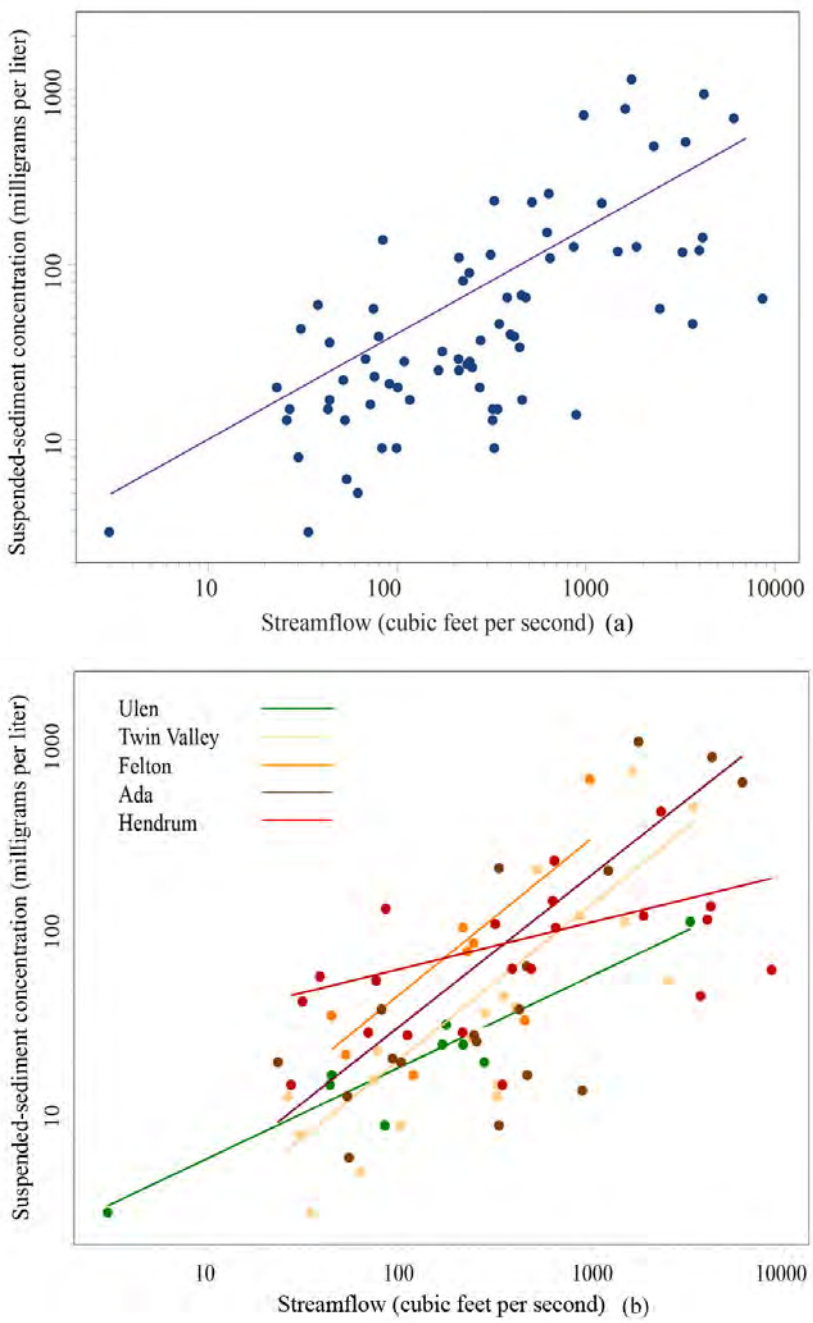

Figure 2 Relation between suspended-sediment concentration and streamflow for all sites (a) and individual sites (b) along with least-square regression lines for the Wild Rice River Basin, 2007 to 2009.

The relation between SSC and streamflow was significant and positive (r^2 = 0.51) with variation in the data approaching two orders of magnitude. Figure 2 indicates nearly parallel slopes for Twin Valley, Felton, and Ada, whereas Ulen and Hendrum had markedly lower slopes in comparison. Ulen is located higher in the basin and the lower channel slope coefficient may be due to less erosive, weather-resistant parent material (glacial moraines) as compared to down gradient sites (sands, silts, clays). Hendrum's channel slope coefficient is lower than any of the other sites (Figure 2 and Table 4). It is hypothesized that backwater effects account for the differences in slope between Hendrum and upstream sites Ada, Twin Valley, and Felton. Hendrum is located near the confluence of the Wild Rice River and the Red River in low relief, flat terrain.

The relation between SSC and transparency demonstrated a strong negative relation (r^2 = 0.84) with lower variation (≈ 1 order of magnitude) when compared to streamflow. Transparency was collected to evaluate the use of a transparency tube for estimating point measurements of SSC. Ttube readings can't be automated or collected continuously like streamflow and turbidity but would be useful for point calculations of SSC.

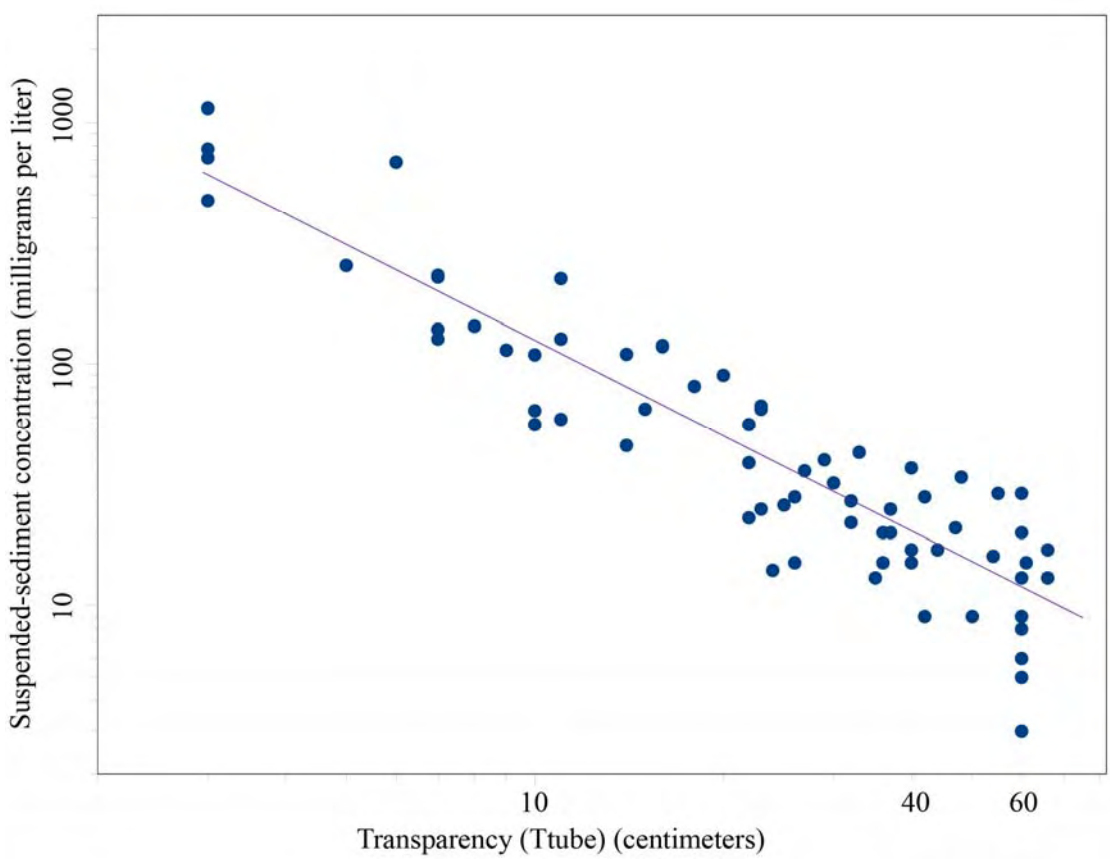

Figure 3 Relation between suspended-sediment concentration and transparency (Ttube) and least-square regression line for the Wild Rice River Basin, 2007 to 2009.

A distinct improvement in calculating SSC was observed when using turbidity as the explanatory variable. The relation between SSC and turbidity (r^2 = 0.93) indicates that turbidity is a strong surrogate for SSC in the Wild Rice River. Also, figure 4 indicates low variability in the data and small differences in slope coefficients between sites, suggesting that a single regression equation may be suitable for calculating SSC at all sites. In contrast, figure 2 provides evidence that using a single regression equation developed from streamflow would overestimate values of SSC at Hendrum and Ulen. Table 4 shows that model standard percentage errors are optimized when using turbidity as the predictor of SSC when compared to both streamflow and transparency.

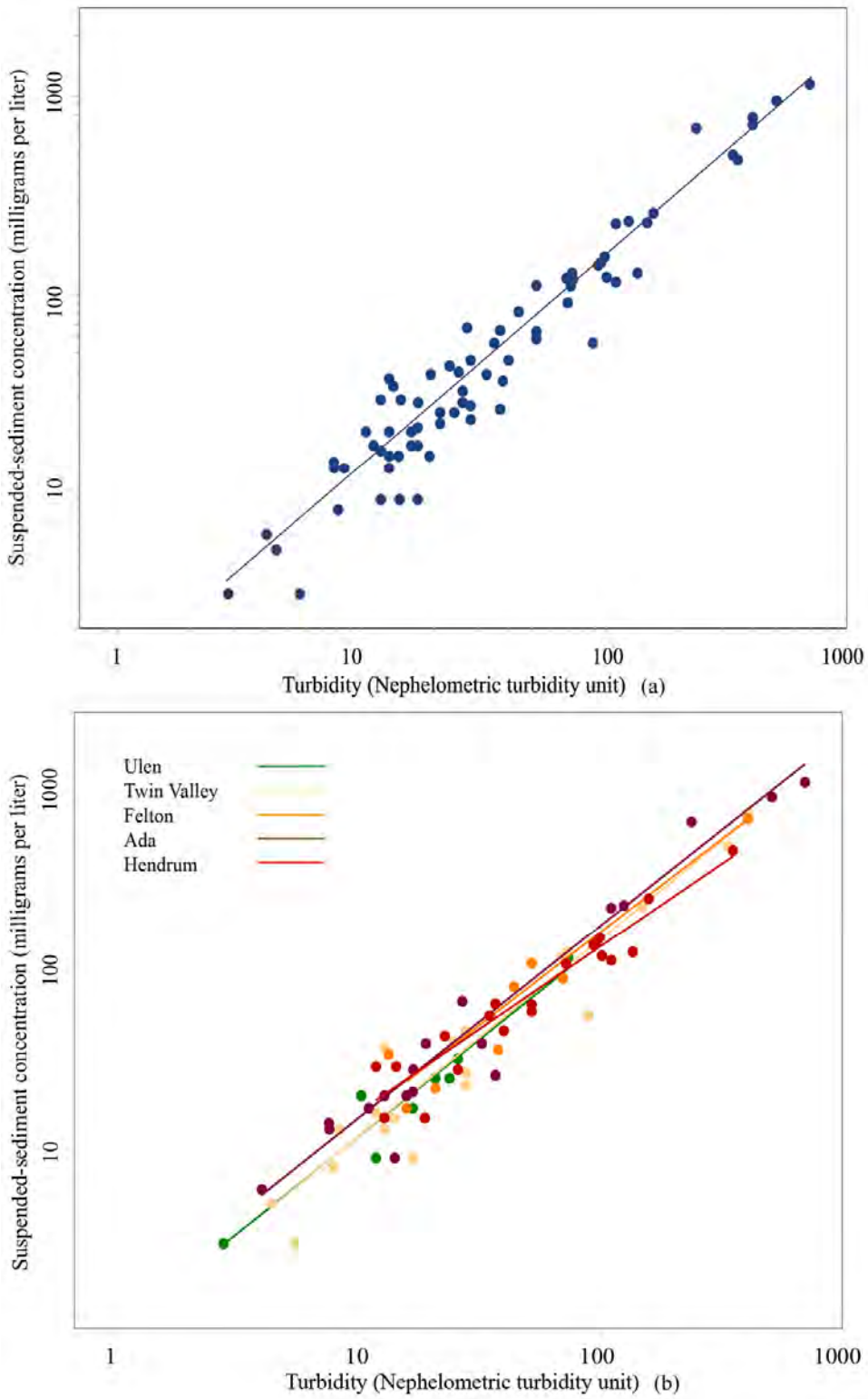

Figure 4 Relation between suspended-sediment concentration and turbidity for all sites (a) and individual sites (b) along with least-square regression lines for the Wild Rice River Basin, 2007 to 2009.

Table 4 Summary of simple linear regression equations, r^2, p-values, and lower and upper model standard percentage errors (MSPE) of suspended-sediment concentration, turbidity, and transparency models for the Wild Rice River Basin, 2007 – 2009.

Suspended-sediment concentration versus streamflow

Site	Regression equation (***SSC*** =)	n	r^2	p-value	MSPE lower	MSPE upper
All sites	$2.47\boldsymbol{streamflow}^{0.6025}$	78	0.51	< 0.01	61	156.7
Twin Valley	$0.42\boldsymbol{streamflow}^{0.8489}$	19	0.69	< 0.01	56.7	130.8
Ada	$0.69\boldsymbol{streamflow}^{0.8302}$	17	0.59	< 0.01	65.4	189.0
Hendrum	$19.90\boldsymbol{streamflow}^{0.2568}$	21	0.22	0.02	54.3	118.7
Ulen	$1.87\boldsymbol{streamflow}^{0.5004}$	9	0.88	< 0.01	28.9	40.8
Felton	$1.16\boldsymbol{streamflow}^{0.8554}$	8	0.48	0.03	57.6	135.6

Suspended-sediment concentration versus transparency (Ttube)

Site	Regression equation (***SSC*** =)	n	r^2	p-value	MSPE lower	MSPE upper
All sites	$3417.47\boldsymbol{Ttube}^{-1.3821}$	68	0.84	< 0.01	40.4	67.8

Suspended-sediment concentration versus turbidity

Site	Regression equation (***SSC*** =)	n	r^2	p-value	MSPE lower	MSPE upper
All sites	$1.09\boldsymbol{turbidity}^{1.0774}$	74	0.93	< 0.01	30.2	43.3
Twin Valley	$0.90\boldsymbol{turbidity}^{1.1127}$	19	0.92	< 0.01	35.4	54.7
Ada	$1.21\boldsymbol{turbidity}^{1.0860}$	17	0.95	< 0.01	32.0	47.0
Hendrum	$1.84\boldsymbol{turbidity}^{0.9353}$	21	0.91	< 0.01	23.9	31.3
Ulen	$1.03\boldsymbol{turbidity}^{1.0917}$	9	0.92	< 0.01	24.3	32.1
Felton	$1.28\boldsymbol{turbidity}^{1.0544}$	8	0.89	< 0.01	32.4	47.9

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