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Monitoring stream sediment loads in response to agriculture in Prince Edward Island, Canada

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Abstract Increased agricultural land use leads to accelerated erosion and deposition of fine sediment in surface water. Monitoring of suspended sediment yields has proven challenging due to the spatial and temporal variability of sediment loading. Reliable sediment yield calculations depend on accurate monitoring of these highly episodic sediment loading events. This study aims to quantify precipitation-induced loading of suspended sediments on Prince Edward Island, Canada. Turbidity is considered to be a reasonably accurate proxy for suspended sediment data. In this study, turbidity was used to monitor suspended sediment concentration (SSC) and was measured for 2 years (December 2012–2014) in three subwatersheds with varying degrees of agricultural land use ranging from 10 to 69 %. Comparison of three turbidity meter calibration methods, two using suspended streambed sediment and one using automated sampling during rainfall events, revealed that the use of SSC samples constructed from streambed sediment was not an accurate replacement for water column sampling during rainfall events for calibration. Different particle size distributions in the three rivers produced significant impacts on the calibration methods demonstrating the need for river-specific calibration. Rainfall-induced sediment loading was significantly greater in the most agriculturally impacted site only when the load per rainfall event was corrected for runoff volume (total flow minus baseflow), flow increase intensity (the slope between the start of a runoff event and the peak of the hydrograph), and season. Monitoring turbidity, in combination with sediment modeling, may offer the best option for management purposes.

Keywords Sediment · Turbidity · Agriculture · Particle size · Streamflow

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Introduction

Fine-grained sediment, resulting from erosion, has long been recognized as a major pollutant of surface waters (Walling and Fang 2003; Montgomery 2007). Sediment is often considered to be a global pollutant due to its rapid mobilization wherever soil or natural vegetation are disturbed (Davies-Colley et al. 2014). While soil erosion is a natural process, it has been greatly accelerated by anthropogenic activities such as agriculture, forestry, mining, and urban development (Waters 1995). Agriculture is identified as an important contributor to global soil erosion. Erosion rates from

conventionally plowed fields average one to two orders of magnitude higher than those from areas of native vegetation (Montgomery 2007). In light of a growing global population, increased agricultural demand will exacerbate erosion and surface water quality deterioration.

Practical and accurate monitoring methods for suspended sediment are crucial to setting environmental management targets for erosion-prone activities. Traditional methods for suspended sediment monitoring include periodic manual water sampling that can be labor-intensive, expensive, and unreliable due to the spatial and temporal variability of the suspended sediment concentration (SSC) in the water column. In some rivers, it has been estimated that approximately 70–90 % of the suspended sediment flux occurs during infrequent high flow events (WMO 2003). For this reason, inadequate sampling and analysis of SSC can lead to considerable error in suspended sediment load estimation.

Turbidity, known as the relative assessment of water clarity based on the amount of suspended particles in the water (Davies-Colley and Smith 2001), has often been used to estimate SSC. Using turbidity has gained attention as being a more acceptable substitute than the use of SSC discharge rating curves because of its intrinsic relation to suspended sediment (e.g., Gippel 1995; Teixeira and Caliari 2005; Ruzycki et al. 2014). Discharge has previously been found to be a poor estimator of suspended solids due to the hysteresis effect, where different SSC exists at the same discharge level on the rising and falling limb of the hydrograph (e.g., Walling 1977). Notably, turbidity has its limitations, and its reliability depends on proper in situ calibration (Gippel 1995; Lewis 1996; Minella et al. 2008), as turbidity values vary significantly with changes in particle size distribution, even at similar SSC levels (Pavanelli and Bigi 2005).

On Prince Edward Island (PEI), a province on the eastern coast of Canada, sedimentation is a cause for concern because of the structural characteristics of the soil and the dominance of salmonids in stream fish communities. PEI has relatively consistent geology of predominately sandstone with lesser amounts of siltstone, claystone, and conglomerate, covered by a thin layer of glacial till (van der Poll 1983). The sandy-loam soil structure and low permeability, due to excess silt and fine sand, lead to weak aggregation and increased erodability (PEI Department of Agriculture and Forestry 2003). These soil characteristics, together with abundant rainfalls and frequent seasonal freeze-thaw cycles, give PEI soils an inherently high erosion potential (PEI Department of Agriculture and Forestry 2003). The impact of greatest concern is the filling of interstitial spaces in the stream gravel that provides critical spawning habitat for brook trout (*Salvelinus frontinalis*) and the at-risk Atlantic salmon (*Salmo salar*; Curry and MacNeill 2004). Atlantic Salmon is now only present in a fraction of its former spawning range on PEI (Cairns and MacFarlane 2015).

The intensity of agriculture and current farming practices add to the potential for erosion. Approximately 2400 km^2 (representing approximately 42 % of the area of the province) has been cleared for agriculture (PEI Department of Agriculture and Forestry 2015). Potato production has dominated the agricultural sector, with 36,017 and 36,503 ha being planted in 2013 and 2014, respectively, accounting for approximately 25 % of potato production in Canada (Statistics Canada 2015). As potato farming practices require the soil be left bare for extended periods of time (fall plowing is still and accepted practice) and farming on high slope land (greater than 9 % slope) has not been entirely discontinued despite efforts to discourage it, the effects of soil erosion become apparent in PEI streams and rivers (Cairns 2002).

The objectives of this study were to quantify rainfall event loadings of sediment in PEI and to develop a cost-effective methodology for monitoring and provide baseline data for future sediment loading models. It is well established that erosion rates rise in response to increased agricultural land use. On this basis, it was expected that the intercept of the relationship between the runoff intensity and volume and total sediment load would be higher where increased agricultural land use exists and that this susceptibility (load corrected for rain event volume and intensity) could be used as a watershed-specific monitoring parameter. In this study, turbidity and discharge were measured for 2 years (December 2012–2014) in three subwatersheds with varying degrees of agriculture. Calibrated turbidity measurements were used along with discharge to estimate rainfall event sediment fluxes, and these were compared between watersheds.

Materials and methods

Study sites

Subwatersheds of three rivers on PEI with varying degrees of agricultural land use were selected for the study.

Land use statistics were computed with ARCGIS (v. 10.2) software using Corporate Land Use Inventory 2010 maps obtained from the PEI Department of Environment, Energy & Forestry (2010). Annual precipitation data (1981–2010) were gathered from nearby Environment Canada meteorological weather stations (Wheatley River ID 8300497; Souris and Cross rivers ID 8300416) (Table 1). Wheatley River (Table 1), located in the central portion of the island, was the most agriculturally intensive site with 69 % agriculture in the subwatershed (Fig. 1). Souris and Cross rivers (Table 1), both located in the eastern portion of the island, were the intermediate and least impacted sites with approximately 30 and 10 % agriculture in the subwatersheds, respectively (Fig. 1). The 1973 surficial geology map, also obtained from the PEI Department of Environment, Energy & Forestry (2002), was used to indicate differences in glacial deposit surface materials for the central and eastern regions of the island (Table 1). These surficial geology statistics were also computed with ArcGIS software (v. 10.2).

Turbidity and SSC calibration

Turbidity (NTU) was monitored in each river between December 2012 and December 2014 using Eureka Manta2 Water Quality Recorders mounted with a self-wiping turbidity sensor (ISO 7027). The unit was attached to the top of a concrete block, approximately 20 cm from bottom, and placed at a right angle to streamflow in the middle of the stream. Over the course of 2 years, turbidity readings were taken at 30-min intervals. Each sensor was calibrated with an 8122 AMCO Clear Turbidity Standard (1000 NTU) and was recalibrated approximately every 4 months.

In order to relate NTUs to SSC, three calibration methods were examined: two using sediment collected in the stream (Pavey et al. 2007) and one method involving capturing suspended sediment during rain events. Calibration curves using stream sediment were constructed by creating manual mixtures of suspended sediment covering the range of turbidity typical to each river. Streambed sediment samples passed through 2 mm and 63 μm sieves were taken from each river to create the mixtures, and separate rating curves were produced for both grain size classes. For rain event calibration, the SSC was determined by deploying an automated sampler (Teledyne ISCO 6712 Portable Sampler) before the start of the event. This calibration period extended from October to November 2014 and included two events for the Wheatley and three events for the Cross and Souris rivers. Samples were taken near the

Table 1 Summary of the subwatershed parameters for selected sites

Parameters	Sites		
	Wheatley River	Souris River	Cross River
Monitoring station coordinates	46° 21′ 50.4″ N, 63° 17′ 17.1″ W	46° 23′ 27.5″ N, 62° 18′ 26.1″ W	46° 27′ 38.5″ N, 62° 16′ 04.2″ W
Subwatershed area (ha)	2125	1452	3832
Mean slope (%)	7.5	5.9	6.0
Average annual precipitation (mm)	1257	1272	1272
Land use types (%)			
Agricultural	68.7	30.1	10.1
Forested	20.4	60.4	83.2
Other	10.9	9.5	6.8
Dominant surficial geology (%)			
Sand phase till	–	43	71
Clay-sand phase till	50	24	17
Clay, clay-silt phase till	32	–	–
Other	18	33	12

Land use and surficial data were extracted with Arc GIS v.10.2 from maps obtained from the PEI Department of Environment, Energy & Forestry
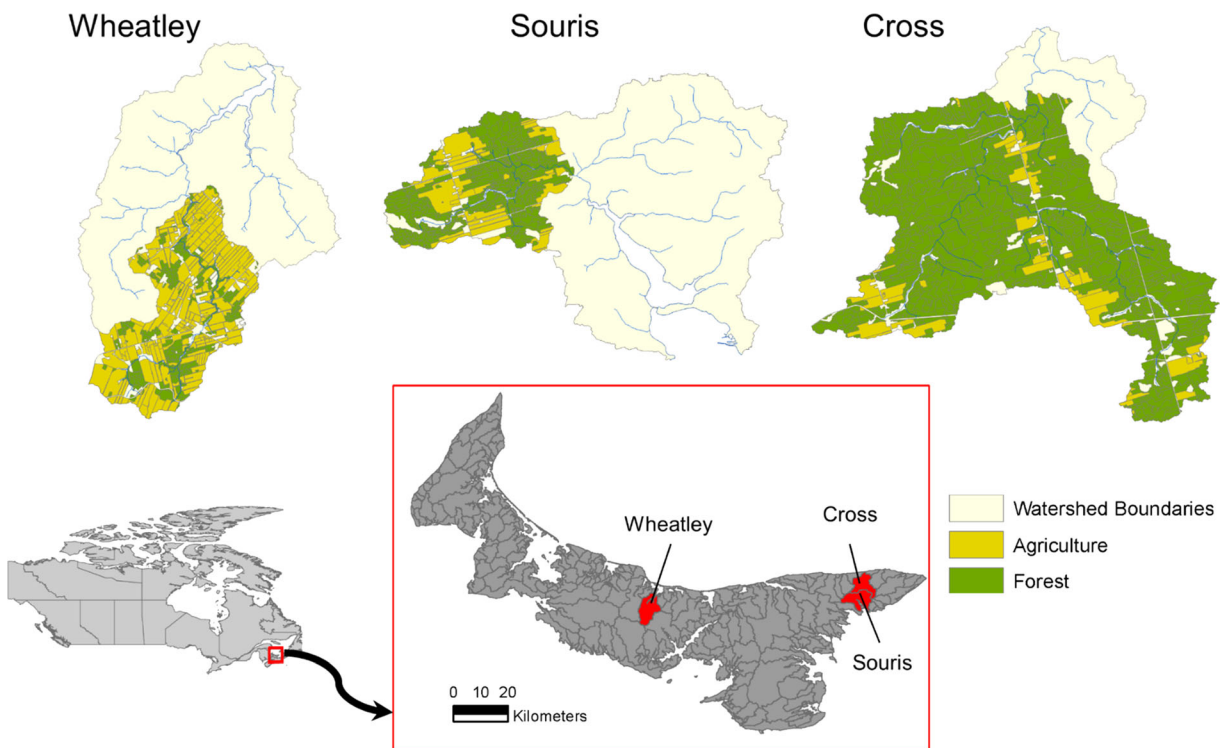
Fig. 1 Land use maps for the Wheatley, Souris, and Cross river watersheds in Prince Edward Island, Canada. Land use is only shown for the watershed area upstream from the monitoring station. Original maps were obtained from the PEI Department of Environment, Energy & Forestry (2010)

turbidity probe at hourly intervals, and SSC was determined. In total, 51, 61, and 60 suspended sediment samples were collected from the Wheatley, Souris, and Cross rivers, respectively. SSC of the 800 mL samples were determined gravimetrically, following filtration (VWR filters GF/C grade) and drying (60 °C for 24 h). For all calibration methods, SSC values were paired to their corresponding turbidity readings that were synchronized to occur at the same time.

Particle size analysis

Rainfall event subsamples (400 mL) for particle size analysis were taken from selected surface water samples by quickly pouring off subsamples after vigorous agitation to ensure a homogeneous mixture. Subsamples were spun for 1 h at $3000 \times g$ with a Beckman Alegra X12 centrifuge to allow the sediment to settle out of suspension, and the top layer of water was carefully siphoned out. The particle size distribution of the concentrated samples (10–15 mL) was determined by laser diffraction (Horiba LA-950 with AquaFlow Pump System).

Hydrograph determination

Water level, or stage, was monitored in each river at 30-min increments throughout the study with an Onset HOBO Water Level Logger installed in a stilling well comprised of a 10.2 cm i.d. ABS plastic pipe well with a 5.1 cm i.d. ABS intake pipe. A long trench was dug in the stream bank next to the turbidity logger such that the intake pipe remained submerged during low flow conditions. Two pressure loggers were installed in each well: one submerged for water pressure and one in the air to measure barometric pressure. The cap of the stilling well was drilled with holes for ventilation. Stream discharge was measured manually with a Marsh-McBirney velocity meter biweekly to construct a stage-discharge rating curve. At very high flows, during which the rivers were not wadeable, water flow was recorded from nearby bridges with a torpedo-shaped lead weight attached to the meter. Continuous discharge was computed for each river from a stage-flow relationship fitted with a power function (Wheatley $R^2 = 0.95$, Souris $R^2 = 0.96$, Cross $R^2 = 0.99$). Small gaps in water-level data were resolved using flow data from

neighboring established Environment Canada water-level gauging stations within 15 km (Wheatley with ID 01CD005, Souris and Cross with ID 01CC010). The data were interpolated by establishing a linear regression relationship between discharge time series from our study watersheds and their respective gauged neighboring watersheds (Wheatley $R^2 = 0.89$, Souris $R^2 = 0.89$, Cross $R^2 = 0.91$).

Hydrograph separation and runoff volume delineation

As local rain gauges were not always located in the watershed and may not accurately reflect the volume of precipitation in the subwatersheds above the measurement stations, the runoff was estimated by subtracting baseflow from total flow at each station. Separation of surface runoff from baseflow, or hydrograph separation, was accomplished with a recursive digital filter (Lyne and Hollick 1973). Once baseflow was separated, the baseflow index (BFI) was computed as the ratio of baseflow to total streamflow (baseflow and surface runoff). Previous work done on the Wilmot River, PEI measured an annual BFI of 66 % for that watershed (Jiang and Somers 2009). A script was created using Matlab (v. 8.5) which utilized the recursive digital filter proposed by Lyne and Hollick (1979). In order to reproduce a BFI of 66 % in the Wilmot River, three passes through the digital filter with a filter parameter of 0.925 were necessary. This filter parameter and number of passes were then applied to daily average flow from the three river datasets in this study in order to obtain a new target BFI for each river in the 2-year period. Half-hourly data were subsequently analyzed adjusting the filter parameter to 0.9975 to obtain the same BFI as determined using the daily average flow. The separated surface runoff was used to calculate runoff event parameters runoff volume and runoff intensity for each rain event for subsequent analysis. Runoff intensity is defined here as the rate of change in runoff discharge from the beginning to the peak of the rain event (the change in flow divided by the time).

A combination of Environment Canada rainfall data (Wheatley ID 830P001, Souris ID 8300562, Cross ID 8300418) and total streamflow was used to detect individual rainfall events for the purpose of delineating the water runoff from flows. The beginning of each rain event was set to the start of rainfall (>1 mm) according to the precipitation record from the nearest Environment Canada rain station, and the end of the event was set to when total streamflow returned to within 10 % of pre-rain levels. For a few larger events that did not return to within 10 % of pre-storm levels prior to the next event, the end of the event was set to when total streamflow returned to within 30 % of pre-rain levels. Out of the 158 runoff events that were extracted over the snow-free periods (May–November) during the 2-year period, only five events were delineated with the 30 % threshold. During more complex events where multiple rainfalls prevented the recession of streamflow to pre-rain levels (31 events), the end of the event was set to the point of inflection where the falling limb of the hydrograph began to rise again following another rainfall event.

Statistical analyses

A preliminary assessment of the three calibration methods was performed with a linear regression model for slope comparison. Slopes of the turbidity-SSC regressions (forced through the origin) were compared in a pairwise fashion using t tests. Bonferroni corrections of the critical probability value were made to account for the number of individual statistical comparisons made. While the 2 mm and 63 μm curves appeared linear, the curves generated from in situ sampling showed some modest deviation from linearity. Thus, linear regressions only served to obtain a general measure of the differences between the slopes of the methods in order to examine whether the 2 mm and 63 μm methods might be a substitute for in situ calibration. As the in situ calibration method was chosen for analysis of all subsequent data, a power function was subsequently used for the analysis of the SSC-turbidity curves to incorporate the non-linearity observed. Differences in particle size distribution were examined with ANOVA, followed by a post hoc Tukey's test. Prior to proceeding with the ANOVA, Levene's and Brown Forsythe tests were used to determine homogeneity of variance of data, while normality was assessed visually using normal probability plots. Data that did not conform to the appropriate parametric assumptions based on these tests were log transformed prior to statistical analysis. A preliminary examination of the nature of relationships among runoff event characteristics, sediment, and discharge was explored through a principle component analysis of the pooled dataset from all rivers. Variable loadings were examined in order to identify which variables were the most related to sediment loading. Multiple stepwise

regressions were used to identify the best subset of SSC predictor variables that maximize the explained variance (adjusted r^2). All statistics were performed in STATISTICA v. 8.0 using an experiment-wise alpha of 0.05.

Results

Suspended sediment calibration methods

It was observed that some of the in situ calibrations had minor deviations from linearity, while the 2 mm and 63 μm calibration were highly linear. The in situ calibrations were sufficiently linear so as to provide a gross comparison between the methods. The Wheatley River in situ calibration was observed to be highly linear (adjusted r^2 = 0.96), while those of Souris and Cross rivers (adjusted r^2 = 0.77 and 0.67, respectively) appeared to deviate from linearity slightly based on patterns of residuals. When the three calibration methods were compared within each river, significant differences existed between the three separate SSC-turbidity calibration methods at all three sites with the exception of the rain event and 63 μm calibrations at Cross River (Table 2). The slope of the 2 mm manual mixture of suspended sediment was between 7-fold and 30-fold higher than the slopes of the 63 μm runoff event calibration methods (Table 2). Thus, the use of the 2 mm sieve method would have resulted in a substantial overestimate of SSC as compared to the other two calibration methods. The slopes of the 63 μm manual calibration were more comparable to those of the rain event calibration in the Cross and Souris rivers. However, the 63 μm calibration would have overestimated SSC by

more than 4-fold in the Wheatley River. When the same method of calibration was compared between rivers, there were significant differences in the slope of the SSC-turbidity relationships for each of the three calibration methods with the exception of the 63 μm calibration between Souris and Cross and the runoff event calibration between Souris and Cross Rivers. As the manual mixtures of suspended sediment were generally a poor proxy for the rain event calibrations, rain event calibration was deemed to be the most accurate technique for suspended sediment estimation despite the higher variability in the calibration curves (Table 2). However, as mentioned, unlike the 2 mm and 63 μm methods, there was non-linearity apparent in the rain event method (as slope seemed to increase with greater intensity events). This non-linearity tended to cause an overestimate of SSC at very low turbidity values; thus, a power equation was used for all subsequent calculations of SSC.

Particle size analysis of the rain event suspended sediment samples indicated significant differences between the three rivers that would have accounted for the many of the differences in the SSC-turbidity calibrations (Table 2). Suspended sediment in the Wheatley River was dominated by silt and an appreciable amount of clay, which is significantly finer than the suspended sediment in both the Souris and the Cross rivers (Table 2). The smaller particle size at Wheatley River would explain why the 63 μm SSC-turbidity calibration method was an inadequate substitute for the rain event calibration, as turbidity values will differ according to grain size, for the same amount of suspended sediments. Although suspended sediment in the Cross River had a slightly coarser texture than the Souris River, the difference between the two was not significant (Table 2).

Table 2 Suspended sediment concentration linear calibration slopes (r^2 in parentheses) and particle size distribution (PSD) percentiles (SEM, n) of rain suspended sediment

River	Linear SSC calibration equation slopes			PSD percentiles		
	63 μm sieve	2 mm sieve	Rain event	D50	D10	D90
Wheatley	1.34[a] (0.99)	10.3[b] (0.995)	0.30[c] (0.920)	8.8[a] (2.2, 7)	1.1[a] (0.8, 7)	35.7[a] (8.8, 7)
Souris	1.11[a] (0.99)	14.3[b] (0.955)	2.07[c] (0.687)	27.4[b] (0.9, 5)	8.9[b] (0.7, 5)	117[b] (3.7, 5)
Cross	1.34[a] (0.99)	21.2[b] (0.83)	1.69[a] (0.51)	32.8[b] (3.8, 8)	11.2[b] (0.5, 8)	145.2[b] (20.2, 8)

Comparisons of calibration slopes were done within rivers, and comparisons of particle size percentiles were done between rivers. Different superscript letters for calibration methods indicate significant differences between rows (e.g., for Wheatley River, 63 μm slope was compared to 2 mm and rain event slope from that river only). Different superscript letters for PSD variables within columns indicate significant differences between rivers for particle size parameters (e.g., for D50, comparison is between Wheatley, Souris, and Cross rivers)

Hydrograph and sediment loads

The hydrograph for the 2-year study period along with the associated calculated baseflow is presented in Fig. 2. The mean annual BFI was determined to be 47.8, 48.4, and 59.7 for the Wheatley, Souris, and Cross subwatersheds, respectively. Mean annual flow for 2013 and 2014 was the highest in the Cross River and increased in all three rivers between years (Fig. 2). There was a notable difference in flows between 2013 and 2014 due to the all-time record high snowfall in the winter of 2013–2014 (Fig. 2, Table 3). Cross and Souris rivers were most similar in flow patterns due to the watersheds being adjacent to each other. The continuous time series of suspended sediment data are presented in Fig. 3. Levels of SSC during times of no precipitation during spring, summer, and fall were typically under 10 mg/L for all three rivers. However, SSC varied by several orders of magnitude between rivers during sediment flux events. Note that, while the SSC in the Cross River seldom exceeded 100 mg/L over the course of the 2 years, this level of suspended sediment is more commonly seen in the Wheatley and the Souris rivers. Sediment influx events over 1000 mg/L were more common in the Wheatley and Souris rivers, reaching as high as 50 g/L during an extreme event in the Souris River.

Data gaps exist in the SSC time series for 2013 and 2014, due to equipment malfunctions. While the 2014 monitoring was more complete due to less gaps (Fig. 2), the sediment loads were calculated for both the 2013 to 2014 years (December to December) and the snow-free period within those years (May to December) (Table 3). Due to the variations in watershed size, sediment loads were scaled to represent the area being drained upstream from the monitoring sites (Table 3). The data show that total annual and snow-free period sediment loads are the lowest in the Cross River and highest in the Souris River.

Fig. 2 Time series of the streamflow (m³/s) in the Wheatley (**a**), Souris (**b**), and Cross (**c**) rivers during December 2012–2014
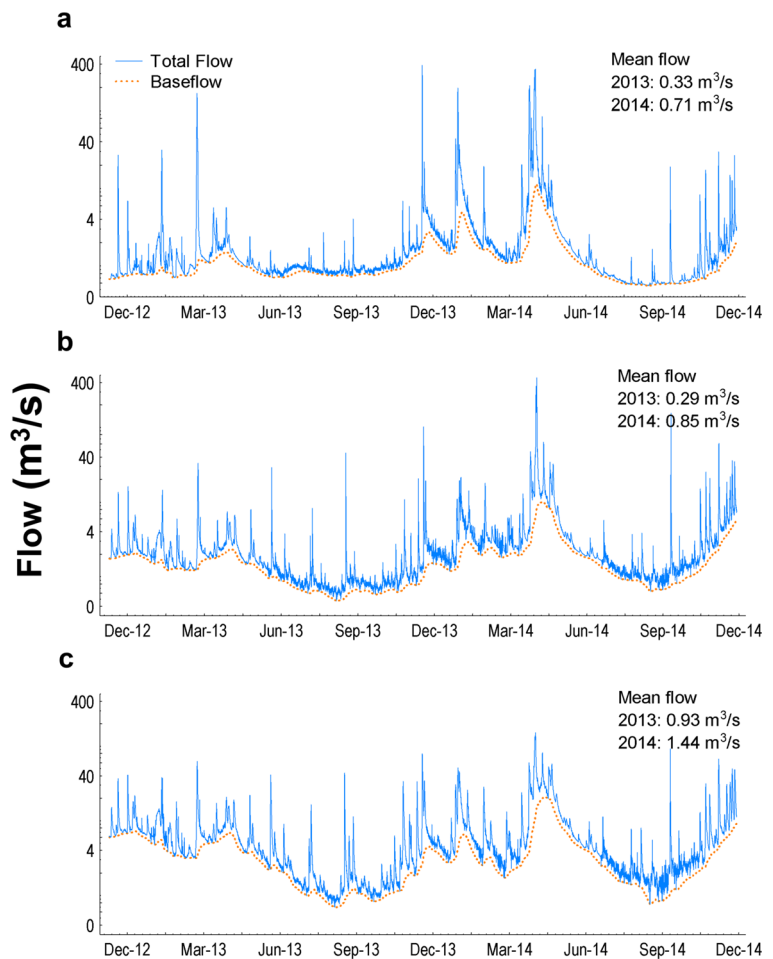
Table 3 Total streamflow volume and sediment load scaled per subwatershed area annually (December to December) and during the snow-free period (May–December) for the 2 years monitored

	Wheatley River		Souris River		Cross River	
Total volume (mL/ha)	2013	2014	2013	2014	2013	2014
Annual	4.72	10.2	6.52	17.6	8.02	11.5
Snow-free	2.51	2.58	2.46	6.93	3.61	5.51
Total sediment load (t/ha/year)						
Annual	0.352	0.458	1.506	1.778	0.082	0.290
Snow-free	0.325	0.055	0.246	0.460	0.045	0.048
Rain event sediment (%)	93.4	88.4	98.4	96.6	94.0	81.0

During the snow-free period, Wheatley and Cross rivers had similar sediment loadings in 2014, but Wheatley was significantly higher in 2013 indicating significant between-year variability at the Wheatley site. The total streamflow volume normalized for the subwatershed area for the snow-free period was found to be the highest in Cross in 2013 and highest in the Souris in 2014, with Wheatley generally having the lowest volume yield per hectare. However, considerable inter-annual variability can be observed with 2013 being the driest year. Estimation of the proportion of sediment measured during rain events shows a range of 81–98 %.

Fig. 3 Time series of the suspended sediment concentration (SSC) (mg/L) for the Wheatley (**a**), Souris (**b**), and Cross (**c**) rivers during December 2012–2014
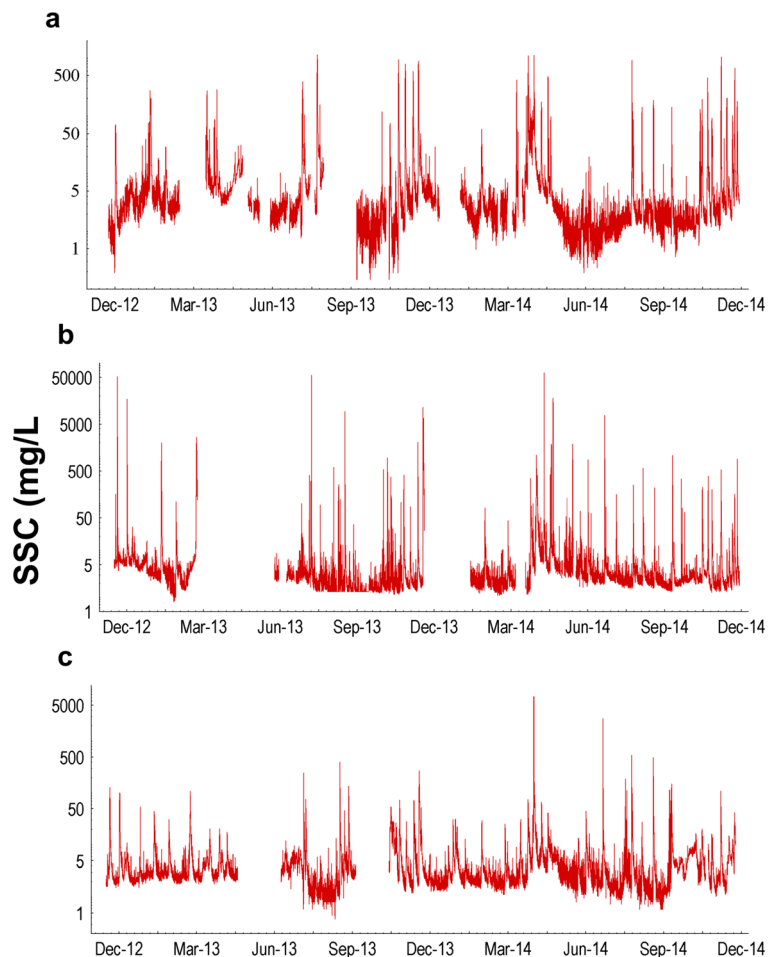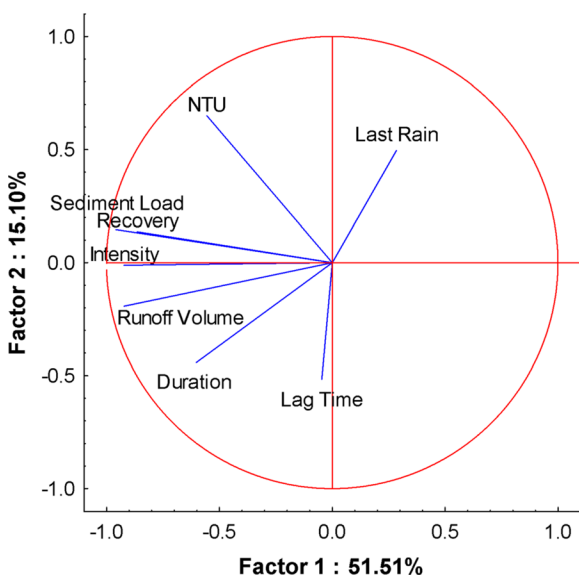
Runoff event analysis

Sediment load accumulated for each rainfall event and runoff volume (cumulative rainfall-induced surface run-off above baseflow) was calculated for a number of events during the snow-free season at each river as a method to facilitate comparison of sediment monitoring data between rivers. Preliminary exploration of relationships between the runoff event variables were explored through a PCA using a pooled dataset from all rivers in order to identify which runoff event variables were most related to sediment loading (Fig. 4). Approximately 53 % of the variability in the runoff event variables was attributed to the first principal component and 14.1 % to the second principal component. The PCA indicated that the lag time and days since the last rain <5 mm are poor predictors of sediment loading as their eigenvectors were orthogonal to sediment loading. The eigenvectors for sediment loading, runoff intensity, and runoff volume were the most similar in the first two components, and these were the variables selected for subsequent analysis.

In order to further facilitate the comparison of monitoring data, both cumulative sediment and mean turbidity during runoff events were evaluated using a stepwise regression model using the best subset approach. The variables log runoff event volume, log runoff event intensity, season, and river were included as variables based on the preliminary PCA analysis. For cumulative

Fig. 4 Principal component analysis (PCA) of the rain event variables at the three study rivers

sediment mass, the most predictive model included all four variables (adjusted $r^2 = 0.845$). In Fig. 5a, the regression line for the Cross River is translated lower than the Souris and Wheatley rivers, indicating the latter two rivers have higher susceptibility for erosion where runoff event volume is considered as the explanatory variable. Where storm intensity is considered alone as the explanatory variable, Wheatley was again most susceptible to sediment loading as compared to the other two subwatersheds (Fig. 5b).

Season and river were also significant categorical factors in the regression model. The analysis revealed that the watersheds studied were more susceptible to erosion during the summer months than in the spring and the fall months. The model also showed that there was a significant difference in the least square means of sediment load between the three rivers (Fig. 6). More specifically, runoff event sediment loading was significantly lower in the Cross River and significantly higher in the Wheatley River when runoff intensity, runoff volume, and season were accounted for. Loadings to the Souris River were intermediate and were significantly higher than the Cross but significantly lower than the Wheatley. Thus, when sediment load is scaled for runoff event intensity, runoff event cumulative volume, and season, the watershed sediment load follows the pattern of agricultural intensity in those watersheds.

In order to examine whether sites could be differentiated using turbidity alone as a variable, mean turbidity per rain event was used as a dependent variable. Stepwise regression for raw turbidity data showed a much lower explanatory power for the model (adjusted $r^2 = 0.501$). The best subset for turbidity included runoff event intensity, season, and river, but not runoff event volume. Relationships between mean turbidity and both runoff volume (surface runoff) and runoff intensity are more variable than relationships using sediment load as the dependent variable (Fig. 7). However, significant differences in the least square mean turbidity were also found between all sites.

Discussion

Turbidity was a monitoring tool used in the estimation of SSC and sediment load in three PEI subwatersheds. Due to differences in particle size in particular, in situ sampling of rain events provided the most accurate estimates of SSC. Evaluation of sediment loads during
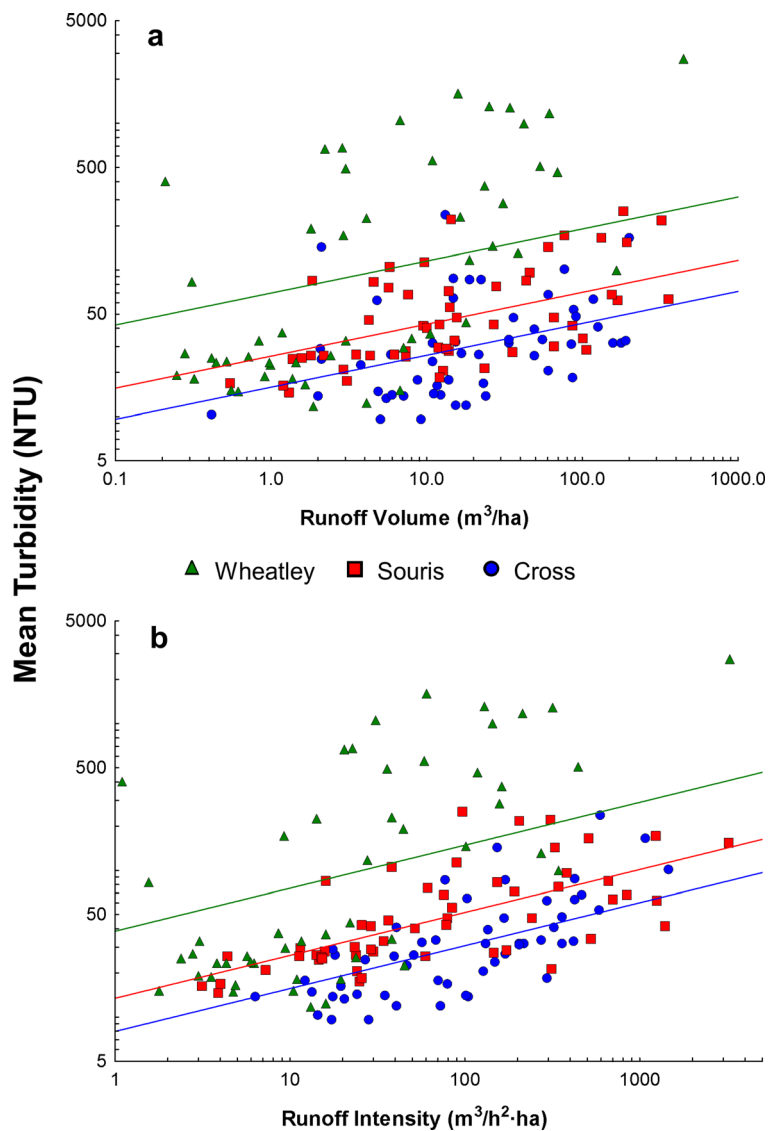
Fig. 5 Relationship between sediment load and **a** runoff volume and **b** runoff intensity
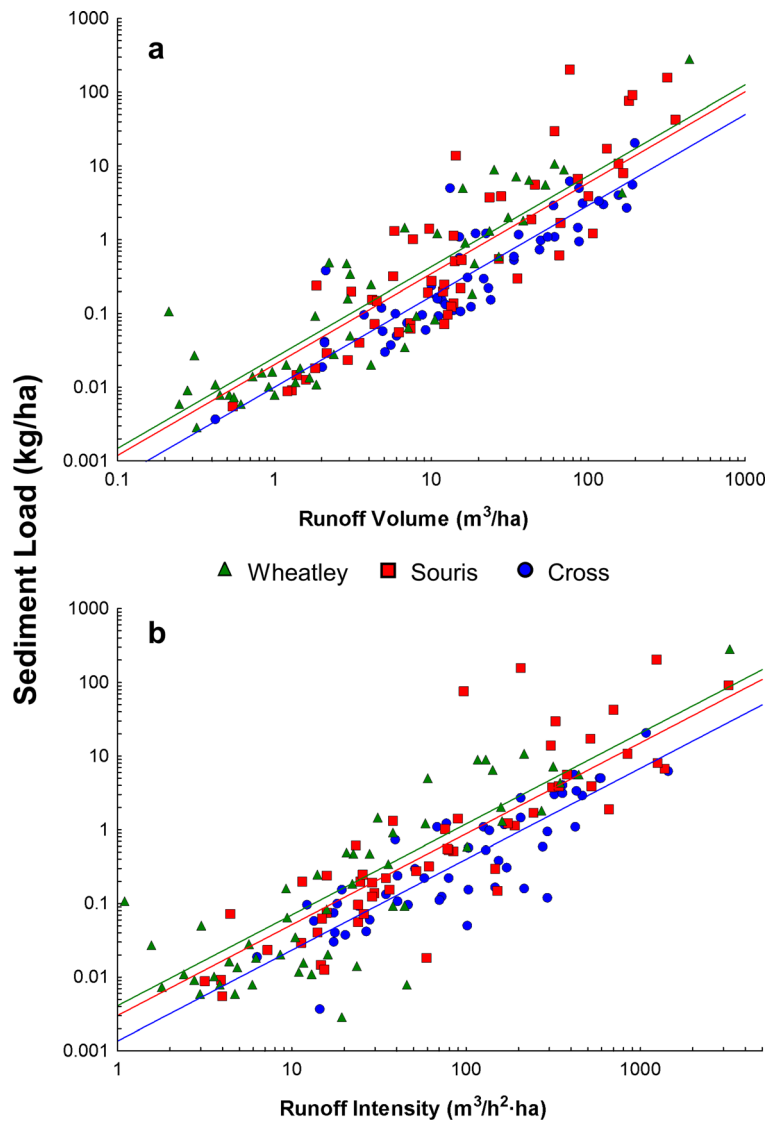
Fig. 6 Least square means (±standard error) of sediment loads for the Wheatley (*n* = 51), Souris (*n* = 54), and Cross rivers (*n* = 53). The least square means presented are adjusted for a total event runoff volume of 10.6 m³/ha with an intensity of 52.9 m³/h² ha. Means with different letters are significantly different
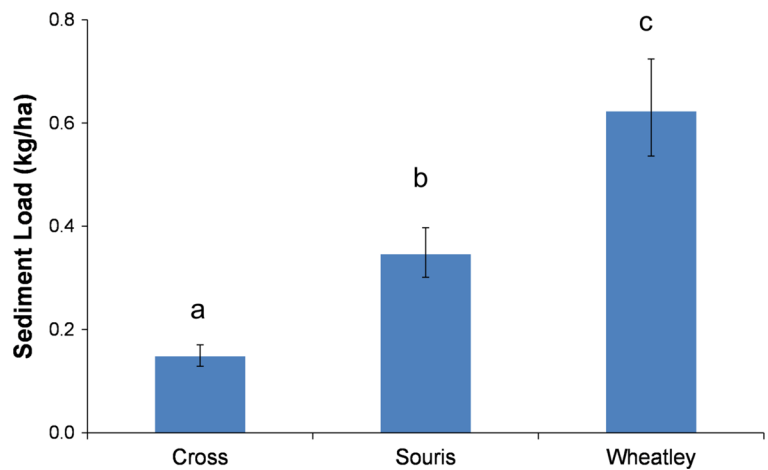
Fig. 7 Relationship between mean turbidity and runoff volume (**a**) and runoff intensity (**b**)

rain events demonstrated that the most agriculturally intensive watershed had the greatest susceptibility to erosion. A strong relationship existed between total rain event sediment load and runoff volume. However, the intensity of a storm and the season also proved to be a significant explanatory factors influencing sediment load. Accounting for these variables increased the ability of the statistical model to determine differences in erosion vulnerability between watersheds.

Although SSC-turbidity calibrations using manual mixtures of known sediment concentrations are more logistically practical than in situ suspended sediment sampling, the former method can lead to appreciable error in load estimations. Gippel (1995) found that

changes in particle size caused 4-fold variations in turbidity for the same SSC. This property has important implications for sediment yields, as even small changes in the particle size distribution can have large impacts on sediment load (Landers and Sturm 2013). The difference in the slope of calibration methods used in this study was driven by variation in the particle size distribution. Generally, sediment that is suspended during a rain event is finer than the bed sediment even when a 63 μm cutoff is used. Martilla and Kløve (2012) also created SSC-turbidity calibration curves using known concentrations of freshly deposited bed sediment. They also found that this method overestimated sediment loads due to a larger particle size distribution of bed

sediment. The inclusion particle size can help improve sediment modeling and may even provide further information into the seasonality of sediment loading. Teixeira and Caliari (2005) compared the errors associated with several regression models for SSC-turbidity calibrations. They found that including parameters such as median grain size (D50) and water color reduced the model error from 28 to 23.3 %.

The range of mass loadings of sediment observed for the watersheds studied are comparable to those from small watersheds in the literature. An agriculturally intensive watershed in New Zealand of the same approximate area as those studied herein was found to yield 0.97 t/ha/year (Hughes et al. 2012). While we found almost double that in the Souris River (1.5–1.8 t/ha/year), the PEI watersheds are likely more susceptible to erosion because of row crop agriculture, rather than the pastoral and plantation forest land in the New Zealand watersheds. The observation that slope and rainfall were both higher in the New Zealand watershed further emphasizes the increased susceptibility of the watersheds studied here. Results from a number of studies in New Zealand are summarized by Hughes et al. (2012), and the highest recorded sediment yield for a pastoral headwater system was 2.1 t/ha/year (Quinn and Stroud 2002), only marginally higher that what we observed for the Souris River. However, it is also difficult to compare watershed that have considerable annual snow cover such as those on PEI, with those that do not such as in New Zealand. Three largely snowmelt-driven forested catchments in the Lake Tahoe basin, USA, were calculated to have sediment yields of 0.04–0.34 t/ha/year (Grismer 2013). However, these are steeper than those studied on PEI and not groundwater-driven as in the current study. In a study of grassland and arable cropland watershed in Ireland, sediment yields ranged from 0.02 to 0.41 t/ha/year (Sherriff et al. 2015). However, comparison is often difficult as even within geographically similar areas with comparable land use as was studied on PEI, comparison of sediment yields can be confounded. For example, in the present study, despite a higher proportion of agricultural land use in the Wheatley River watershed, the Souris River yielded the highest uncorrected cumulative sediment loading not only due to much smaller particle size in the Wheatley River but also due to the observation that both the Souris and Cross rivers tend to have larger runoff volumes and intensity per hectare in the years studied. Only when adjusted for runoff volume and intensity did Wheatley River show the highest susceptibility to sediment load from erosion. Additional monitoring is needed to make a long-term conclusion as sediment yields as precipitation patterns can be highly variable from year to year as was illustrated here and in similar studies (e.g., Sherriff et al. 2015).

Runoff event total volume, intensity, and season all contributed to the variability in sediment loads. Beyond the obvious point that higher runoff volumes would correlate with either the intensity or the duration of a runoff event, higher runoff volumes can entrain distal sources of sediment when the supply near the channel is exhausted (Seeger et al. 2004). While often correlated, greater runoff intensities may act through a different mechanism than runoff volume and are often linked to increased sediment loading in streams (Cox et al. 2006) as the higher energy of intense rain results in greater soil loss and therefore greater stream sediment loadings. Under these types of conditions, the infiltration capacity of the soil is exceeded and erosive runoff transports sediment directly into the channel (Cox et al. 2006). However, the effect of runoff intensity (or rainfall intensity) has been found to vary with other factors such as soil type and antecedent soil moisture (Defersha and Melesse 2012).

The seasonality of sediment loading was also found to be a significant factor in this study. Contrary to what is often reported in the literature (e.g., Steegen et al. 2000), this study found a significantly higher sediment loading in the summer than spring or fall. Generally, lower SSC is expected in the summer because of the increased density of vegetative cover acting as a filter and protecting the soil from the erosive force of the rainfall (Steegen et al. 2000). Kwadd (1991) reported higher soil erosion in the summer than the winter from cultivated plots in the Netherlands related to increased high-intensity rainfall events in the summer. Rain intensity cannot explain this observation on PEI as it is generally lower in summer. The areas studied on PEI are subject to intensive row crop agriculture, with a very high proportion of potato crops. With a very late growing season at this latitude, soil is freshly turned near the beginning of summer and there is very little plant coverage through the early summer months potentially explaining the higher capacity for erosion.

While sediment mass load is clearly most relevant to what is eroding from land, as a monitoring parameter, turbidity may have important biological implications. As light penetration is a key biological factor affecting the streams, ponds, and estuaries within these river systems, turbidity may in fact be a more biologically relevant monitoring endpoint than sediment mass load. Furthermore, the smaller the particle size, the longer sediment is likely to remain in suspension in ponds and estuaries, further amplifying the biological impacts of sedimentation. It has been previously pointed out that some of the severe biological effects of sediment do not correlate well with sediment mass loading (Davies-Colley et al. 2014).

This study, like others (e.g., Gippel 1995; Jones et al. 2011; Lewis 1996), demonstrated the successful use of turbidity as a proxy for SSC. With proper calibrations to the respective river, turbidity provides a continuous record of sediment loading that is logistically difficult to achieve with grab water sampling techniques. However, we do note that time-composited, flow-proportional autosampling can achieve relatively accurate estimation of loads, though it was not evaluated here and would be at least as, if not more costly than turbidity monitoring. It was noted that turbidity monitoring is not without its limitations and considerable equipment maintenance and data quality treatment is required. Furthermore, the sampling volume is very small and may not be representative of the whole water column. Sediment concentration in a stream would not be expected to be consistent within a stream as flow is not laminar. Flow velocity is generally greater as distance gets further from banks or bottom that may lead to greater energy and ability to suspend coarse sediment. However, the streams in this study were relatively small, from 1 to 2-m width and generally less than 0.5-m depth, so within stream variability in SSC is expected to be negligible and turbidity methods relatively representative of the overall stream channel turbidity. Acoustic Doppler current profilers (ADCP) (Liu et al. 2009) may offer an alternative as acoustic-based monitoring is not as affected by fouling, ADCPs thus require less maintenance, can offer simultaneous turbidity and water velocity measurement, and sample a much larger volume of the water column. This ability to sample a greater volume of water gives ADCPs a considerable advantage over turbidity, particularly in larger rivers where SSC may not be homogeneous. However, ADCPs require sufficient depth to function, generally greater that 0.5 m, making it challenging to use ADCPs in small streams. With either technique, calibration is a challenge; in situ calibration using rain events is likely to be the most accurate method of calibration. Further research on evaluation of ADCPs as an alternative to turbidity measurement is required.

The findings herein reaffirm the multitude of reports of greater stream sediment loading where increased agricultural land use exists. Lamba et al. (2015) used a fingerprinting technique to determine the relative contribution of fine sediment in streams from various sources, notably cropland, pasture, woodland, and stream banks. The authors found that both agriculture (cropland and pasture) and stream banks were the primary sources of fine sediment in the stream. Furthermore, the relative contribution from agriculture increased as the proportion of agricultural land increased. Another study in Ireland identified the proportion of arable land as one of the key factors influencing sediment fluxes (Sherriff et al. 2015). It is impossible to determine the precise source distribution of all sediment in the present study, and while a high concentration of unsealed roads or other activities do certainly contribute, agriculture is the main difference between the watershed studies and would be expected to be the greatest contributor.

As we observed in the present study, monitoring of sediment regimes requires intensive effort to collect data and to evaluate data in a way that permits meaningful comparisons. Sediment regimes are often neglected in river management plans as they are highly complex processes with large temporal and spatial variability. The need for a better understanding of these processes however is undeniable as they can have major environmental and biological impacts. Sediment monitoring, in combination with sediment modeling, may offer the best option for management purposes, and future research will develop validated stream sediment loading models for the region.

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