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Temporal variations of suspended sediment transport in Oneida Creek watershed, central New York

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SUMMARY

Using event-based suspended sediment data collected from 2008 to 2010 in a medium-size agricultural watershed in Central New York, we first examined the statistical properties of suspended sediment concentration, C and the associated water discharge, Q. Next, we identified two different transport processes in two discharge ranges separated by a different threshold Q_t for each season. Different exponents of sediment rating curves (SRCs) in each season revealed that sediment was transported near capacity during lower discharges but well below capacity during higher discharges. The persistence of these two trends in all seasons suggested that suspended sediment transport was generally supply limited. Sediment loads predicted by a single seasonal SRC are similar to those predicted by the two separate SRCs for above and below Q_t, which suggests that the two transport processes are not significantly different and seasonal sediment transport may be described by a single SRC. The better fit of SRC for the combined 3-year data compared to those for individual years indicates that seasonal changes of suspended sediment transport are limited and the transport dynamics that emerge at shorter time scales (i.e., event and season) are effectively averaged out. We then calculated sediment yields for 3 years using a process-based SRC method: annual hydrograph was divided into storm and base flows using values of Q_t for all seasons and only storm flows were used to calculate sediment yields based on the developed SRCs. Comparing sediment yields of 3 years calculated using three seasonal SRCs to those using the combined 3-year SRC indicated that the discrepancies between the two were less than 5%, suggesting that sediment yield may be accurately estimated using the single combined-year SRC. Finally, we discussed the appropriate sampling strategy in the region and demonstrated geomorphological nature of sediment transport based on the calculated effective discharges and cumulative sediment loads.

1. Introduction

As a major component in hydrological, geomorphological, and ecological functioning of rivers, suspended sediment has been identified as the leading direct cause of river impairments (USEPA, 2000). Yet, it has been widely recognized that suspended sediment transport varies both spatially and temporally at the watershed scale (e.g., Ali and De Boer, 2007; de Vente and Poesen, 2005; Nadal-Romero et al., 2008; Walling and Kane, 1982; Wilkinson et al., 2009). Although suspended sediment load may be estimated using a variety of physically-based watershed models (e.g., de Vente et al., 2006; Gao, 2008; Kliment et al., 2008), the modeling results require validation using the measured sediment data. Therefore, estimating suspended loads at different temporal scales continues to be crucial for various river and watershed management (Kuhnle and Simon, 2000). Two approaches have been commonly used to calculate suspended load, though others, such as the artificial-neural-networks model (Cobaner et al., 2009; Jain, 2001; Partal and Cigizoglu, 2008), were also adopted. The first is the so-called interpolation procedure (Walling and Webb, 1981), which requires regular sediment sampling over relatively long time periods. The load is determined as a product of mean sediment concentration and water discharge over some time period such as 1 h, 1 day, or 1 month. Based on different assumptions, Walling and Webb (1981) provided six different equations for load calculation to account for different temporal variations of the data. These methods have been used in both long-term suspended load determination and nutrient loads estimation (Bowes et al., 2005; Cordova and Gonzalez, 1997; Hollingera et al., 2001; Li et al., 2003; Pepin et al., 2010; Quilbe et al., 2006; Walling et al., 1992). Their main limitation is the requirement of substantial data sampled at a regular time interval, which are only available in rivers that have long-term monitoring stations.

The second approach is the regression analysis (or extrapolation procedure) (Walling and Webb, 1981), the most popular of which is the sediment rating curve method (Alexandrov et al., 2010; Kazama et al., 2005; Mano et al., 2009; Quilbe et al., 2006 and other

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references in Gao (2008)). A sediment rating curve (SRC) is an empirical relationship between suspended sediment concentration, C (mg/l) and the associated water discharge Q (m^3/s), in the form of a power function:

$$C = aQ^b \tag{1}$$

where a is a dimensional coefficient and b is a dimensionless exponent. Using the established SRC and the available continuous discharge data (usually mean daily discharges), sediment load for a given time period (usually 1 year or longer) may be calculated by summing the estimated daily loads (e.g., Crowder et al., 2007; Quilbe et al., 2006; Walling and Webb, 1988) or by the magnitude-frequency method (e.g., Biedenharn and Thorne, 1994; Cordova and Gonzalez, 1997; McCuen, 2004; Mckee and Hossain, 2002; Stow and Chang, 1987). However, the complex dynamics of suspended sediment transport often lead to poor fitting of Eq. (1) to measured sediment data. In addition to various correction methods described in Gao (2008), the SRC method has also been modified by (i) creating SRCs for rising and falling limbs of events, respectively or for different seasons (e.g., Asselman, 2000; Old et al., 2005; Picouet et al., 2001; Rovira and Batalla, 2006; Sadeghi et al., 2008b), (ii) establishing an event-based load rating curve first and converting it into an equation for total load (e.g., Moliere et al., 2004), (iii) using polynomial or more complex functions (e.g., Cordova and Gonzalez, 1997; Horowitz, 2003; Rustomji and Wilkinson, 2008; Wang and Linker, 2008), (iv) including an additional term (e.g., the first difference of discharge with time or a more complex form) to account for variations in sediment supply (e.g., Morehead et al., 2003), and (v) using a physically based model that includes discharge, time (seasonal or monthly), and stream coefficients to improve predicting accuracy (e.g., Toprak et al., 2009).

The diversity of the correction methods suggests that sediment dynamics are spatially variable and different SRC methods should be used in different regions. In Central New York, suspended sediment transport has been studied based on lake sediment deposition (Bookman et al., 2010), which merely revealed historical effect of sediment transport. At the watershed scale, dynamics of suspended sediment transport is still poorly understood. Many watersheds in this region have no sediment monitoring programs. Consequently, no continuous sediment data are available to estimate sediment loads. Calculating suspended loads depends on the selection of both a sampling strategy and a load estimation method. In this study, we collected sediment data from a medium-size agricultural watershed using an event-based sampling strategy. After investigating the seasonal patterns of suspended sediment transport based on statistical properties and established SRCs, we developed a process-based SRC load estimation method. We close with the discussion of the developed SRC method and the calculated effective discharge and cumulative sediment loads.

2. Study area

Our study area was in Oneida Creek watershed, located in the southeastern side of Oneida Lake in central New York (Fig. 1). The study area, which will be referred to as the studied watershed hereafter, contains the middle and upper parts of Oneida Creek watershed and covers 311 km^2. The topography of the area is characterized by generally high and variable elevations in the uplands, especially near the divide with the highest elevation of 574 m, and the low elevations downstream with the lowest elevation of 123 m at the outlet. The stream network of the studied watershed has branches with stream orders ranging from 1 to 4. The main stream, Oneida Creek, is a 4th-order stream and the main tributary, Sconondoa Creek, is a 3rd-order stream. Oneida Creek has a bed-rock reach with a waterfall upstream indicating that sediment supplied into this reach is efficiently transported downstream without deposition. The lower section of the Oneida Creek features a stream bed of gravels of various sizes mixed with sand, silt, and clay. Most transported sediment is from hillslopes and is of finer sizes mainly moving in suspension. Bed load may only be entrained during very high flows; the same is true for localized bank erosion.

The studied watershed has a humid continental climate with distinguishable seasonal changes and the mean annual precipitation of more than 1270 mm. Stream flow variations and the associated sediment transport are caused by snowmelt and/or rainfall in winter and spring, and rainfall of varying intensities in summer and fall. The studied watershed is categorized as an agricultural watershed because it consists of 50% of dairy farms and crop lands. The remaining areas are covered by forest (23%), grass (13%), and wetland (7%) with urban areas comprising about 7%. The agricultural lands yield considerably more suspended sediment than other lands. Consequently, in contrast to other forest-dominated watersheds draining to Oneida Lake, the studied watershed supplies about 22.3% of the total sediment load, though the Oneida Creek only contributes 7% of the total water inflow to the Oneida Lake (Makarewicz and Lewis, 2003). Both the Oneida and Sconondoa Creeks have been listed as priority water bodies for treatment (CNYRPDB, 2004). Understanding the temporal variations of suspended sediment transport and estimating sediment loads are therefore essential for future watershed management plans.

3. Methods

3.1. Field and laboratory sampling and measurement

At the outlet of the studied watershed (Fig. 1), an ISCO automatic pumping sampler that contains a pressure transducer, a pumping tube, 24 sample bottles, and a distributer arm controlled by a microcomputer, was installed on the left bank of the stream. The pressure transducer was secured near the channel bed to measure flow stages at that location. The pumping tube was fixed about 0.2 m above the pressure transducer to collect suspended sediment samples. The sampler was triggered by a pre-set threshold value of the flow stage, H_t. Since we focused on sampling storm flows, values of H_t varied from event to event. We determined H_t values based on weather forecast of the coming event and personal experience with past events. Sampling intervals were similarly determined based on the expected magnitudes of the forecasted events. In general, time interval between samples varied from 1 to 4 h. The collected samples were subsequently brought back to the Physical Geography Laboratory at Syracuse University and their sediment concentrations were measured using the standard gravimetric method. Water discharges at the sampling cross section were calculated using the continuous discharges recorded at the nearby USGS gauging station (Fig. 1). This calculation was based on the correlation between the flow stages measured by our sampler and the associated readings at the USGS gauging station. This allowed us to obtain the continuous and historical discharge data at the sampling site.

Since the automatic sampler collects sediment concentration at a point, whether it is representative of the mean concentration of the entire cross section requires verification (Hicks and Gomez, 2003). During two relatively low flows of different events, we collected depth-integrated samples using a USGS DH-48 suspended sampler at three different locations along the cross section of the sampling site and compared them with the simultaneous grab sample collected by the automatic sampler at the sampling site. For the first set of collected samples, sediment concentrations were so low that no differences among samples were observed. For the second one, the three depth-integrated samples had suspended

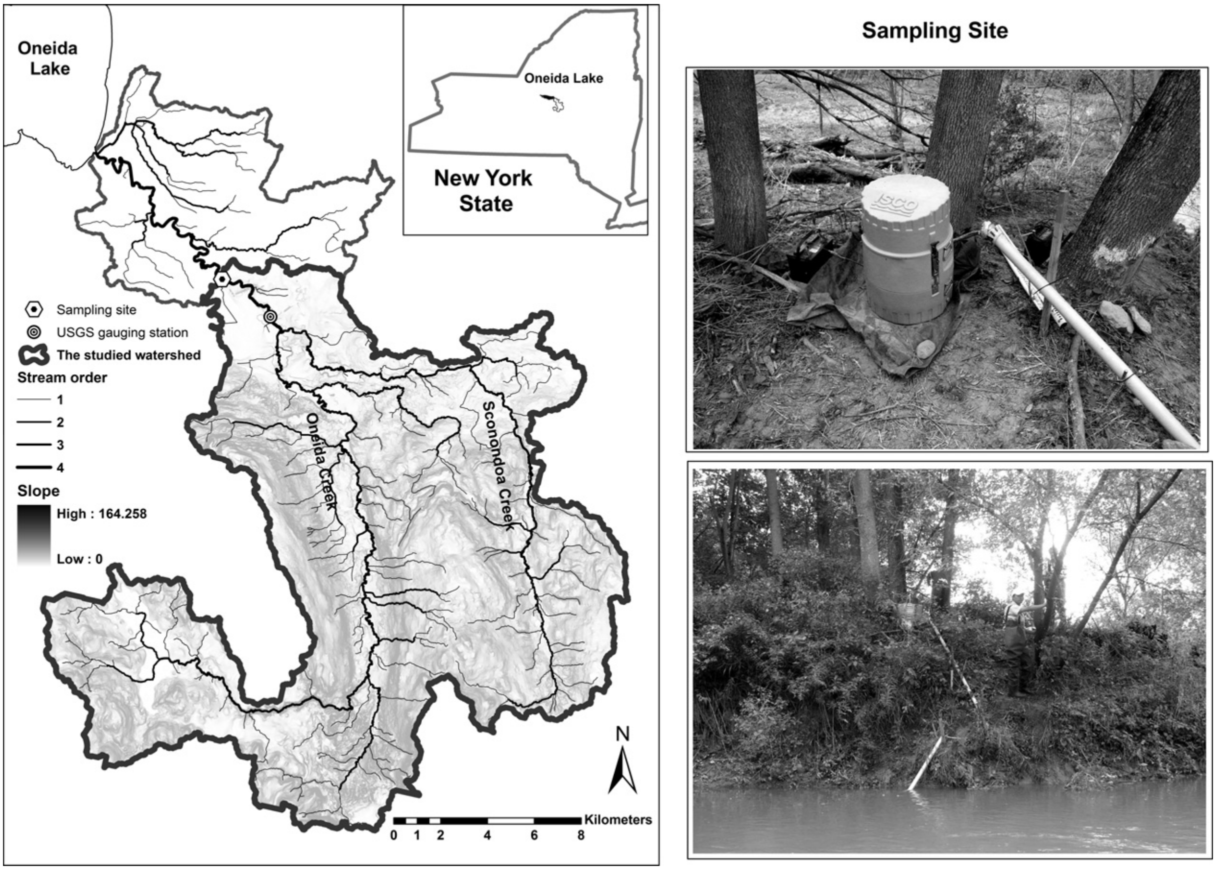

Fig. 1. The location of the sampling site and the setup of the sampler in the studied watershed.

sediment concentration (C) around 78 mg/l, whereas the value of C at the sampling site measured 91 mg/l. The about 14% of error is within the range of errors was found in a highly erodible watershed of southern Pyrenees (Lopez-Tarazon et al., 2009). This error is also much less than concentration variations as discharges increase during the rising limb or decrease during the falling limb. Thus, this difference is acceptable and samples collected at the sampling site may be roughly representative of the mean cross section C. During higher flows, the stream was not wadable. However, we did particle size analysis for a few samples collected from higher flows and found that suspended sediment was predominantly comprised of silt and clay with the largest grain size less than 2 mm composed. This suggests that suspended sediment during higher flows may be well mixed as well. We think in such relatively well mixed high flows, the difference between C at the sampling site and the mean cross-section C should not be significantly different. So, we concluded that samples collected at the sampling site may be generally regarded as the cross-section averaged samples.

Channel cross section at the sampling site was surveyed several times during the study period to obtain an average cross section profile. Bed material sizes were also sampled using the Wolman Pebble Count method (Wolman, 1954). These data were later input into the Reference Reach Spreadsheet v4.2 to calculate the bankfull discharge (Mecklenburg, 2006).

3.2. Data analysis

Calculated water discharge (Q) and suspended sediment concentration (C) data from 2008 to 2010 were used to examine processes of suspended sediment transport at different temporal scales from four different perspectives. First, statistical properties of both Q and C were described based on three seasons: spring, summer, and fall. Winter in the studied watershed is normally snowy with negligible sediment transport. However, occasional temperature spikes can cause significant sediment transport. Data collected during these events were grouped into fall if they were collected in December or into spring otherwise.

Second, different late trends of data in the plot of C versus Q were identified in each season combined from 3 years of data. A sediment rating curve (SRC) in the form of Eq. (1) was developed for each trend found within each season. We then examined possible transport processes by comparing SRCs of different trends in each season and distinguished the threshold discharge, Q_t that separates these trends. Third, we developed various sediment rating curves for each season, each year, and the combined 3 years. Comparison of these SRCs allowed us to reveal the general trend of sediment transport at different temporal scales (e.g., seasonal, annual, and the combined 3 years).

Fourth, we developed a new procedure of calculating seasonal sediment loads and annual sediment yields. In the studied watershed, sediment transport is predominantly driven by either rainfall or snowmelt events. Thus, it is the storm flow that is mainly responsible for the transport of suspended sediment. This physical process enables us to calculate seasonal and annual sediment loads only using storm flows. However, separating storm flow from base flow confronts two problems. First, rainfall events may occur consecutively. During these events, base flow is overlapped by the following storm flow and hence is difficult (if not impossible) to recognize. Second, hydrological events with different intensities may create base flow of different magnitudes, which means base flow changes from event to event. Therefore, we introduced a single seasonal criterion to separate base flow from storm flow for each season in terms of Q_t identified in previous analysis. Based on the selected storm flows, we calculated sediment yields for the 3 years using both seasonal SRCs and the combined-year SRC and compared the results from the two types of SRCs.

4. Results and analysis

4.1. Statistical properties of Q and C

The total of 275 samples was collected between 2008 and 2010, 89 of which were from spring, 133 from summer, and 53 from fall (Table 1). Fall had the highest mean discharge (24.93 m^3/s), which we attributed to relatively more intensive rainfalls, but spring had the highest maximum discharge (97.71 m^3/s), which can be explained by the mixture of rainfall and snowmelt. Summer, on the other hand, had the lowest maximum and minimum discharges (60.12 and 1.21 m^3/s, respectively). Among the three seasons, summer had the most variable discharges (CV = 1.10), while discharges in spring and fall had similar degree of variations (CV = 0.89 and 0.90, respectively). Statistically, discharges in summer are relatively low and those in spring and fall are relatively high and comparable.

Suspended sediment concentration (C) did not follow the seasonal patterns of discharges. Spring had both highest mean and maximum C (684.3 and 4797.0 mg/l, respectively). Although mean C in fall was higher than that in summer, the maximum C in summer was higher than that in fall (Table 1). This was consistent with higher summer C variation than that in fall (CV = 1.65 and 1.07, respectively). Generally, spring transported more sediment than the other two seasons, whereas, sediment transport in summer had highest variability (Table 1). The high spring sediment concentrations were partly contributed from sediment stored both on hillslopes and in streams during winter snowmelt events and flushed by early spring floods. The greater sediment variations in summer were caused by high variations of summer rainfall events, which agreed with the high variation of summer discharges described above. The general pattern also coincides with the seasonal changes of land cover: relatively larger areas of exposed bare soils and less vegetation cover in spring, and wider coverage of thicker vegetation in fall. This coincidence suggests that suspended sediment transport is not only related to stream discharges, but also affected by seasonal changes in land use and land cover, which control sediment supply from upland hillslopes to stream network. Values of C in all seasons are generally higher than those in an agricultural watershed of similar size and percentage of farm lands in Indonesia (Verbist et al., 2010), but much lower than those in a Mediterranean watershed that has drier climate and highly erodible badlands (Lopez-Tarazon et al., 2009).

4.2. Seasonal transport processes

We have demonstrated that suspended sediment transport during a hydrological (rainfall or snowmelt) event often follow a hysteresis loop, simple or complex, in the studied watershed (Gao and Josefson, 2012). This indicated that the transport of suspended sediment is dynamic and changes from event to event. At the seasonal scale, however, variable processes of sediment transport are affected by all events within the season and hence may be different from those during individual events.

In fall, our data clearly showed two different trends that are separated by a threshold value of water discharge ($Q_t \approx 5.8$ m^3/s) (Fig. 2a). Each trend can be fairly well described by a power equation (higher R^2 values). The exponent (i.e., the b value in Table 2) for the trend in $Q < Q_t$ was greater than that for the trend in $Q > Q_t$. Because the data in the two discharge ranges were collected from multiple events and covered both the rising and falling limbs, the difference between the two exponents cannot be due to the difference of transport processes between the two limbs as illustrated by Park (1992). The most plausible explanation is that the different b values reflect the different river erodibilities in the two discharge zones as the exponent represents the erosive power of a river (Asselman, 2000; Ganju et al., 2008; Gao, 2008; Morgan, 2005). However, the greater b value in $Q < Q_t$ suggests that lower discharges or less intensive rainfall events are more powerful in eroding hillslope surface and stream bed and banks within the same season. This is obviously at odds with the physical law of erosion.

By comparing event sediment loads supplied from hillslopes and observed at the outlet of the studied watershed using data collected both from upland sub-watersheds and at the outlet in fall, 2007, Gao and Puckett (2011) revealed that the difference of the exponent b is caused by the different transport processes in the two discharge ranges. The higher exponent for the trend with $Q < Q_t$ indicates that suspended sediment concentration (C) increased faster in this range than that in the range of $Q > Q_t$ for the same increase of water discharge. This faster increase of C is not the result that greater amount of sediment was transported from upland hillslopes or channel bed and bank experienced more intensive erosion because discharges and hence hydraulics (i.e., shear stress) in this range are relatively low. The reason is that relatively low discharges for $Q < Q_t$ had relatively smaller transport capacities. Within the fall season, land use and land cover conditions are similar. Thus, smaller discharges, which must be induced by less intensive rainfall events, should bring less total sediment load from hillslopes than bigger discharges produced by more intensive rainfalls. On the other hand, the smaller transport capacities of lower discharges limited the maximum amount of sediment that can be transported by a given Q for $Q < Q_t$. Consequently, the relatively smaller sediment supply for $Q < Q_t$ is sufficient enough to generate faster increase of C as Q increases in this range. For $Q > Q_t$, the higher sediment supply is

Table 1
Statistical summary of the instantaneous samples in three seasons.

Variables	Statistics	Spring	Summer	Fall	Total
	N	89	133	53	275
Q (m^3/s)	Mean	18.22	9.09	24.93	15.10
	Stdev.	16.26	9.96	22.38	16.35
	Max.	97.71	60.12	86.94	97.71
	Min.	2.59	1.21	2.69	1.21
	CV	0.89	1.10	0.90	1.08
C (mg/l)	Mean	684.3	400.6	513.0	514.1
	Stdev.	909.2	662.9	548.1	741.5
	Max.	4797.0	4167.1	2531.1	4797.0
	Min.	13.0	6.8	7.8	6.8
	CV	1.33	1.65	1.07	1.44

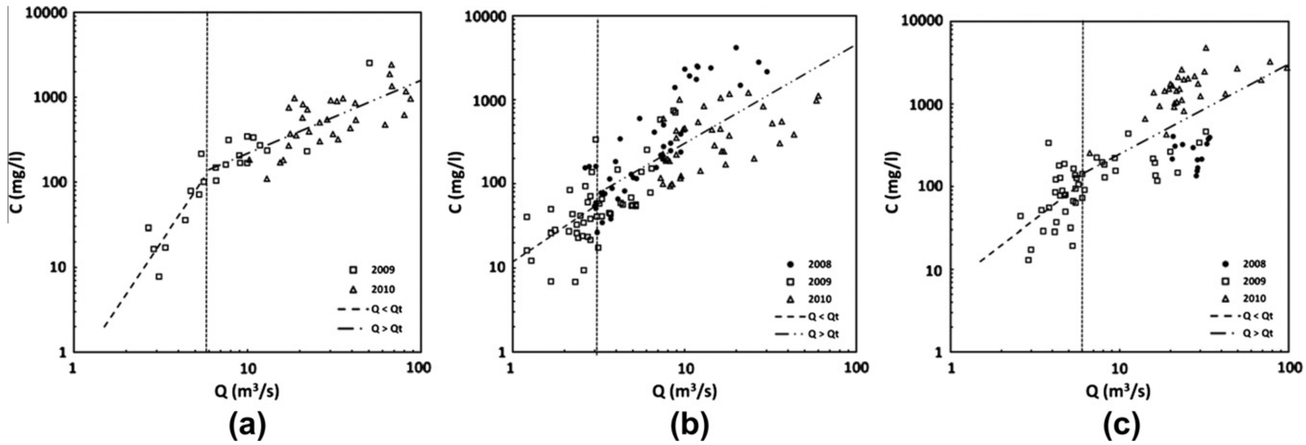

Fig. 2. The two different sediment rating curves (SRCs) separated by a discharge threshold value in each season. Values of coefficients and exponents of the SRCs are in Table 2. (a) Fall, (b) Summer, and (c) Spring.

Table 2
Statistical results for small and big events of three seasons.

	Spring		Summer		Fall	
	$Q < Q_t$	$Q > Q_t$	$Q < Q_t$	$Q > Q_t$	$Q < Q_t$	$Q > Q_t$
a	6.63	20.09	11.86	19.89	0.58	29.84
b	1.57	1.09	1.37	1.18	3.05	0.86
R^2	0.17	0.33	0.16	0.46	0.68	0.61
p	0.0136	<0.0001	0.0067	<0.0001	0.0039	<0.0001

Table 3
Statistical results for the three seasons, three years, and all years.

	Spring	Summer	Fall	2008	2009	2010	All years
a	11.19	14.03	11.53	42.99	12.07	38.36	15.69
b	1.27	1.32	1.15	0.84	1.18	0.90	1.16
R^2	0.63	0.63	0.76	0.31	0.57	0.40	0.64
p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

not sufficient to satisfy the increased transport capacity, leading to the comparably smaller C increase per unit increase of discharge. Therefore, fall season is controlled by supply limited sediment transport for big events and less limited or near capacity sediment transport for small events. The exponent b reflects the degree at which sediment is supplied from uplands to streams in a supply-limited system.

The two SRCs in Fig. 2a, which were based on sediment data in fall seasons from 2008 to 2010, were similar to those in Gao and Puckett (2011) for sediment data in fall, 2007. Furthermore, values of Q_t in the two different data sets were also similar. These similarities reveal that the two different transport processes and the transport-limited nature are generally true in fall season of the studied watershed.

In summer, data showed greater scatter causing relatively low R^2 values (Fig. 2b). Nonetheless, the two SRCs are statistically significant because of very low p-values (Table 2). This indicates the existence of two statistically significant correlations between Q and C divided by an identifiable threshold value, $Q_t \approx 3$ m^3/s. Although the two trends were relatively weak, particularly in the region of $Q < Q_t$, the exponent of the trend in the lower discharge region was still higher than that in the higher discharge region. In spring, data also showed certain degree of scatter, but had two obvious trends with statistical significance separated by $Q_t \approx 6$ m^3/s (Fig. 2c). The exponent of the trend for $Q < Q_t$ was again greater than that for $Q > Q_t$.

Despite the relatively high scatter and different values of threshold discharges, Q_t for different seasons, data in summer and spring displayed similar patterns to those in fall. This suggests that the different transport processes in the two ranges of Q prevalent in fall took effect in summer and spring. Overall, though suspended sediment transport in all seasons varied with events, it displayed a general pattern at the seasonal scale: suspended sediment is transported closer to capacity during low flows, whereas it is well below the transport capacity during high flows. This general pattern reflects a fundamental nature of sediment transport in the studied watershed: suspended sediment transport is supply limited. The degree of sediment supply depends on seasonal variations of land use and land cover.

4.3. Seasonal and annual sediment rating curves

We adopted the sediment rating curve (SRC) approach to estimate seasonal and annual sediment loads. The existence of two different trends shown in Fig. 2 suggests that sediment loads in each season should be calculated separately. However, in both spring and summer, the suspended sediment concentrations (C) for $Q < Q_t$ had very low R^2 values (Table 2) suggesting they failed to accurately characterize variable concentrations in this range. We then developed SRCs for the three entire seasons. In each season, the developed SRC had generally high R^2 values (Table 3) and showed good agreement with the data (Fig. 3). Furthermore, their R^2 values are higher than those of each trend in all three seasons. The improved SRCs indicate that suspended sediment transport in each season may be statistically characterized by a single equation over the full range of discharges. This reveals that though sediment transport during low and high flows is controlled by different processes, the difference is not statistically significant. This finding is contrary to the significant seasonal variations of a Mediterranean agricultural catchment with the area of 1.03 km^2 in Spain (Estrany et al., 2009), probably because of the different watershed areas and climatic conditions.

Using all data collected in each year, we developed SRCs for 2008, 2009, and 2010 (Table 3). The agreement between the SRCs and the data was generally poor with the best fit in 2009 (Fig. 4a–c). Different values of coefficients and exponents in these 3 years (Table 3) signify that at the annual scale, sediment transport varies from year to year. The general higher R^2 values of seasonal SRCs than those of annual ones denotes that variation of sediment transport is controlled by seasonal changes rather than

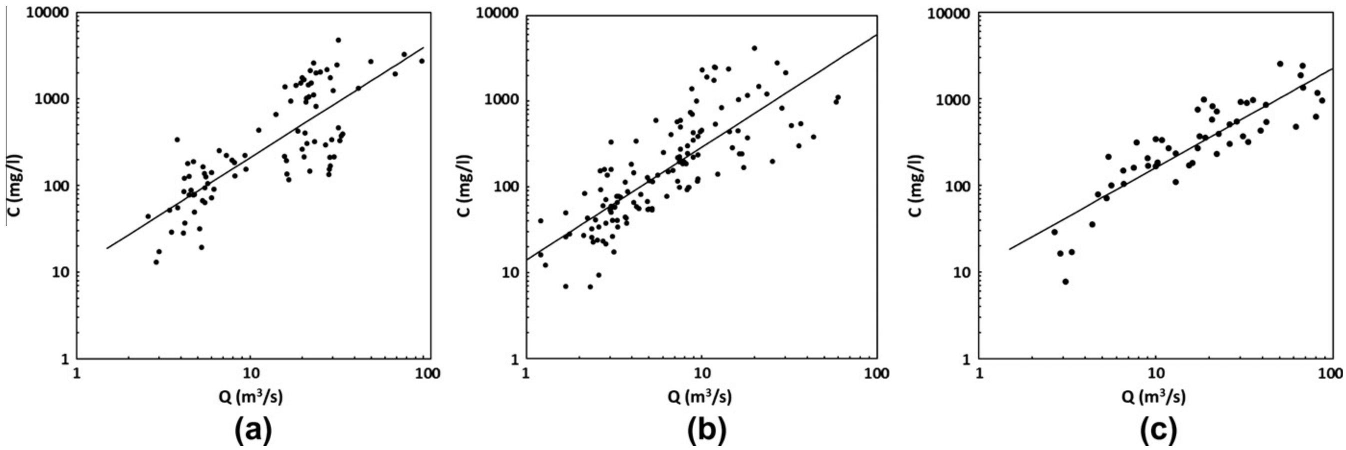

Fig. 3. The sediment rating curves (SRCs) for the three seasons. Values of coefficients and exponents of the SRCs are in Table 3. (a) Spring, (b) Summer, and (c) Fall.

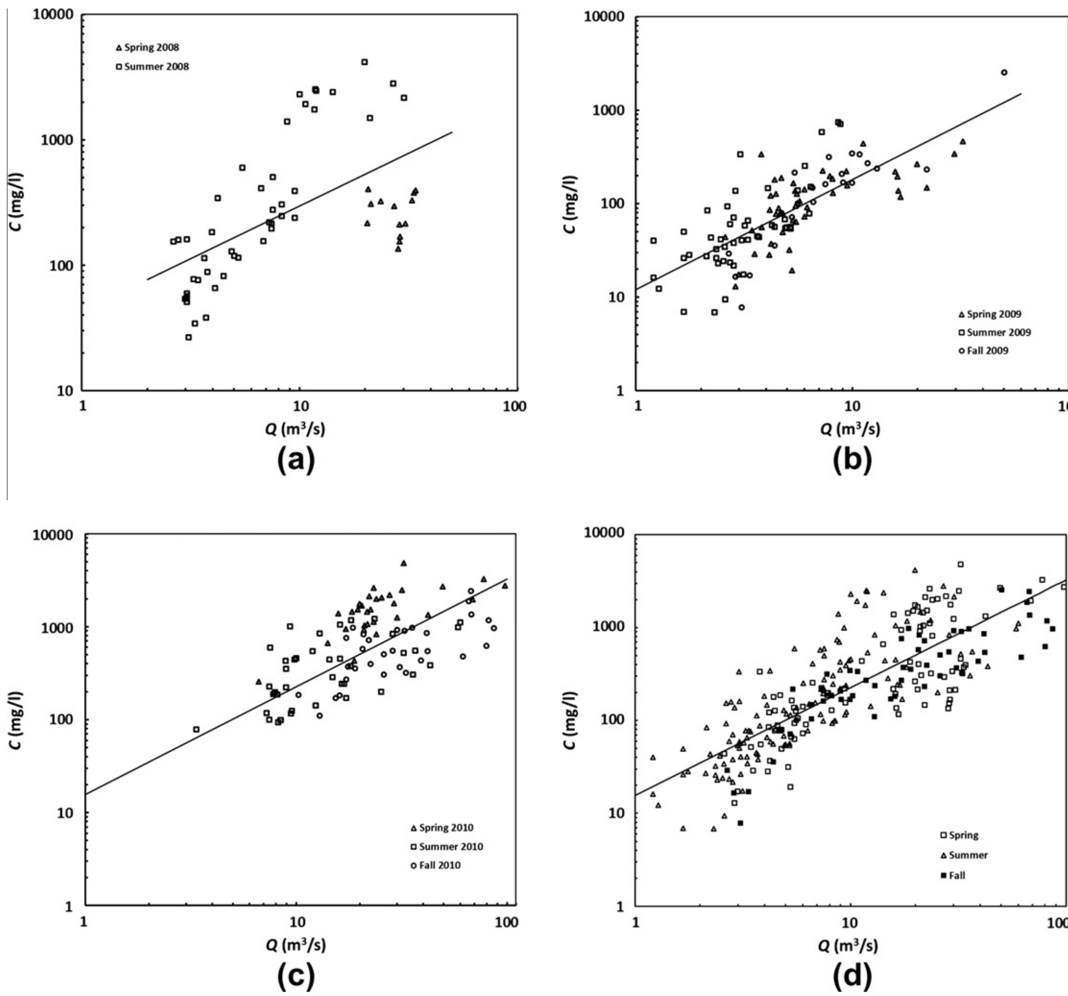

Fig. 4. The sediment rating curves (SRCs) for each year and all three years. Values of coefficients and exponents of the SRCs are in Table 3. (a) 2008, (b) 2009, (c) 2010, and (d) all three years.

by annual variations. The SRC developed using the data from all years and seasons showed an improved R^2 (Table 3) and fit the data well (Fig. 4d). This suggests that though seasonal variations of sediment transport may be significant (Fig. 4a–c), they, after lumped over several years, become less significant. The phenomenon of improved SRC over the longer time period does not exist in small watersheds ($A < 10\ \mathrm{km}^2$) (Lefrancois et al., 2007; McKergow et al., 2003; Sadeghi et al., 2008a), which may imply that certain threshold area is needed to smooth the higher sediment variability at smaller spatial scales.

4.4. Estimation of sediment yields

We previously demonstrated that sediment transport in each season may be divided into two different trends using a threshold discharge Q_t of different magnitudes for different seasons (Fig. 2). Applying these values to annual hydrographs of 2008–2010 splits each into two parts: (i) small events whose peak discharges were less than Q_t or lower sections of big events whose peak discharges are greater than Q_t, and (ii) the higher sections or all of the big events. (Fig. 5a–c). Discharges associated in the first part (i.e., $Q < Q_t$) is treated as 'base flow' and those from the second part (i.e., $Q > Q_t$) are regarded as 'storm flow'. We adjusted some Q_t values to better reflect the variable patterns of seasonal hydrographs in different years. For instance, Q_t was set as 2.5 m^3/s for summer of 2008 and 2.8 m^3/s for summer of the other 2 years. The main purpose of separating storm flows from base flows is to avoid the overestimation of seasonal and annual sediment yields as base flows do not significantly contribute to sediment transport. However, use of the threshold values ruled out some storm flows in small events of the first part (e.g., those in summer of 2008–2010) that actually transport sediment (Fig. 5). Fortunately, Fig. 2 assures that the missed sediment concentrations were not big enough to cause underestimation of the total loads. Because these separation criteria are based on processes of seasonal sediment transport, they are more reliable than separating each individual hydrograph.

Comparison of specific sediment yields (SSYs) calculated using two different methods for the 3 years showed that SSY predicted by the second method (i.e., M_a in Table 4) is 5% greater than predicted by the first one (i.e., M_s in Table 4) for 2008, 1.3% smaller for 2009, and 4.5% greater for 2010 (Table 4). Given the general high variability of sediment yield (Gao, 2008), these minor differences between the two methods suggests that the second method can predict sediment yields as well as the first one, though the first one seems to be more accurate (because it captures seasonal variations by using separate SRCs). Specific sediment yield demonstrated obvious differences among years. From 2008 to 2009, SSY decreased 43.7%, while from 2009 to 2010, it increased 56.7%. The variation is consistent with the annual climatic change – that is, relatively wet years in 2008 and 2010, and a relatively dry year in 2009. On average, SSY in 3 years was 251.4 t/km^2, which is 20% lower than the highest SSY in 2008 and 28% higher than the lowest SY in 2009. This value is lower than not only those (414–800 t/km^2/year) in Mediterranean catchments with the area around 1 km^2 (Lopez-Tarazon et al., 2009), but also those (350–410 t/km^2/year) of watersheds with similar sizes (de Vente et al., 2006; Francke et al., 2008). This suggests that the studied watershed is generally less erodible, which is consistent with its supply-limited nature. Because discharge data can be easily calculated using the data from the nearby USGS gauge station, future sediment yield may be reasonably well predicted using these discharge data and the combined-year SRC developed in this study.

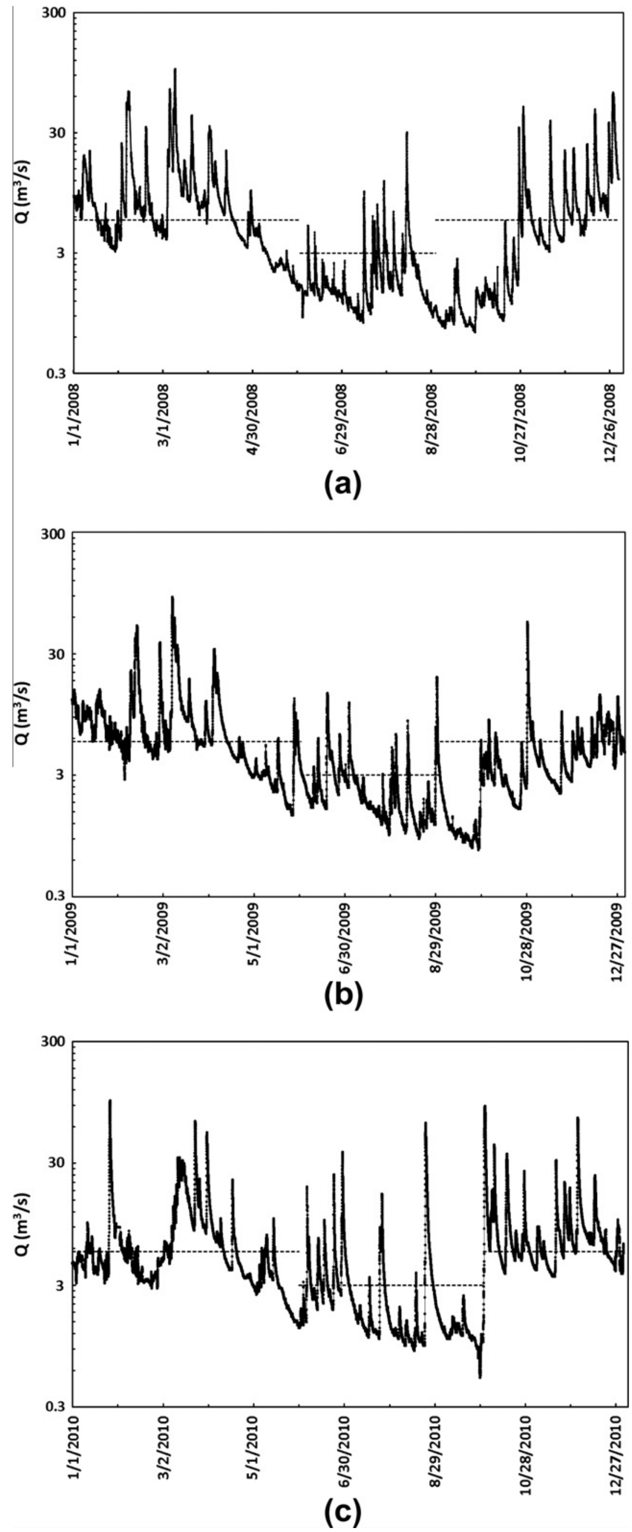

Fig. 5. Separation of storm flows from base flows using the seasonal threshold discharge values. (a) 2008, (b) 2009, and (c) 2010.

5. Discussion

5.1. Sediment sampling and sediment yield estimation

Suspended sediment transport in rivers is profoundly affected by sediment supply, which varies spatially and temporally at the watershed scale and often leads to the hysteresis effect. Thus, an ideal sampling strategy is to capture variations of sediment transport by continuously monitoring turbidity (e.g., Gao et al., 2008; Olive and Rieger, 1988; Sun et al., 2001). Unfortunately, turbidity is significantly affected by sediment size distribution and other uncertainties (Navratil et al., 2010; Pavanelli and Bigi, 2005), which makes it difficult to establish a reliable turbidity-C curve for estimating continuous C in rivers transporting sediment of variable sizes. Therefore, we often have to collect discrete suspended sediment samples and use the sediment rating curve approach to estimate sediment yield. However, use of this approach suffers a couple of theoretical biases inherent in statistically fitting sediment data by means of nonlinear or log-linear regressions

Table 4
Specific sediment yields estimated using two different methods.

	M_s[a] (t/km^2)	M_a[b] (t/km^2)	*Diff.* (%)
2008	302.7	319.3	5
2009	182.1	179.6	−1.3
2010	269.5	281.5	4.5

[a] M_s refers to the load calculation method based on seasonal SRCs.
[b] M_a refers to the load calculation method based on the combined-year SRC.

(Asselman, 2000; Crawford, 1991; Walling et al., 1992). The common correction methods are limited by their assumptions, such as the residuals of sediment data should be log-normally distributed or the data should be stationary (Asselman, 2000; Cohn et al., 1992; Ferguson, 1986). These assumptions are often not satisfied by the measured data, giving rise to inaccurate load estimation (Achite and Ouillon, 2007; Crowder et al., 2007).

In our approach, we, based on the transport processes (Fig. 2), eliminated low discharges that transport low or do not transport suspended sediment loads. From the statistical perspective, this approach avoids the extrapolation of the SRC to the domain where no data were used in developing the SRC. From the sediment transport perspective, it assumes that seasonal and annual sediment loads are predominantly contributed by storm flows. This assumption can be confirmed by estimating seasonal and annual sediment loads using two methods: the first uses the SRCs for $Q > Q_t$ (Table 2) and the second uses the seasonal SRCs (Table 3). The first method is only based on storm flows, whereas the second involves the influence of base flows. Our calculations showed that in seven out of nine seasons of the 3 years, the difference between sediment loads calculated using the two methods was less than 10% (Table 5). Although the highest discrepancy reached 16% in fall of 2009 (Table 5), grouping the sediment loads based on years indicated that the differences between sediment yields calculated using the two methods for 2008–2010 were 6%, 2%, and 6%, respectively. It follows that sampling high flows is sufficient to capture the major sediment variations during an event and to generate SRCs that can lead to reasonably accurate sediment yields in the studied watershed.

The sufficiency of the high-flow data alone to predict sediment yields further suggests that though continuous data (e.g., hourly, weekly or daily data) provide detailed information of sediment variations, some of the information actually introduces noise that leads to SRCs with low R^2 values. These SRCs provide poor estimations of short-term (daily or weekly) loads, but may accurately predict sediment yields because the noises are effectively averaged out at the longer time scale (Crowder et al., 2007; Horowitz, 2003). The lumping effect over longer time periods is also supported by a significantly improved SRC when instantaneous SSCs are replaced by event sediment yield (Hicks, 1994). Thus, collecting more sediment data may not necessarily lead to better load estimation.

Because our data do not follow the log-normal distribution, we did not use the previously described correction methods. Instead, we performed both nonlinear and log-linear regressions for each sediment rating curve. Comparison of the results showed that SRCs based on log-linear regression generally had significantly higher R^2 than those based on nonlinear regression. Consequently, we adopted the values of coefficients and exponents from log-linear regression for all SRCs. Our process-based load estimation approach promotes a cost-effective sampling scheme that only samples high flows during several representative hydrological events (i.e., rainfalls with significantly different intensities) of a season. In many small or medium watersheds where long-term sediment sampling is not available, data required by this approach may be obtained using an automatic pumping sampler with less time and labor investment. It should be noted that the proposed sampling strategy and load calculation approach is mainly appropriate for medium-size watersheds where sediment transport is dominated by supply-limited processes.

5.2. Effective discharge and cumulative sediment load

Effective discharge (Q_{eff}) has been identified as a channel-forming discharge in rivers and used to characterize ecological processes in streams (Doyle et al., 2005a,b; Emmett and Wolman, 2001; Pickup and Warner, 1976). A widely accepted definition of Q_{eff} is the discharge that performs the most work in terms of sediment transport (Wolman and Miller, 1960). Determination of Q_{eff} for a given river reach generally involves three steps. First, a sediment rating curve is established using the measured sediment data. Second, a magnitude-frequency curve for water discharge is created. Third, the effective discharge curve is calculated as the product of the previous two and the effective discharge is identified as the modal discharge of this curve. Although it has been determined based on dissolved load or bed load rating curves (Andrews, 1980; Barry et al., 2008; Schmidt and Morche, 2006; Torizzo and Pitlick, 2004), Q_{eff} is also commonly calculated using suspended load rating curves (Crowder and Knapp, 2005; Knighton, 1998; Nash, 1994).

The combined 3-year SRC for suspended sediment concentrations and the available 3-year discharge data sampled at the 15-min interval allowed us to determine Q_{eff} in the Oneida Creek. Fig. 6a indicated that Q_{eff} is about 65 m^3/s. Flood frequency analysis using the annual maximum discharges from 1990 to 2010 revealed that the value of Q_{eff} is equivalent to the discharge with the recurrence interval of 1.2, $Q_{1.2}$, which is consistent with the results from many other rivers and confirms the assertion that stream channels are shaped by relatively moderate flows rather than catastrophic events (Knighton, 1998; Simon et al., 2004). Furthermore, based on our measured channel cross section profile and bed-material size distribution, we calculated the bankfull discharge (Q_{bf}) of the sampling cross section using the Reference Reach Spreadsheet v4.2 developed for channel survey management (Mecklenburg, 2006). The resulting bankfull discharge $Q_{bf} \approx 150$ m^3/s, has the recurrence interval of 5.2. This difference between Q_{eff} and Q_{bf} is consistent with the findings from other rivers (Lenzi et al., 2006; Schmidt and Morche, 2006; Torizzo and Pitlick, 2004; Whiting et al., 1999) and has been mainly ascribed to the uncertainties in determining Q_{bf} or the physical

Table 5
Seasonal load calculation using two different methods.

	Spring			Summer			Fall		
	M_{s1}[a] (*t*)	M_{s2}[b] (*t*)	*Diff.* (%)	M_{s1} (*t*)	M_{s2} (*t*)	*Diff.* (%)	M_{s1} (*t*)	M_{s2} (*t*)	*Diff.* (%)
2008	68,212	63,180	**7**	1555	1575	**−1**	24,386	23,788	**2**
2009	50,671	48,929	**3**	1354	1464	**8**	4594	5325	**16**
2010	44,722	42,460	**5**	13,465	11,958	**11**	25,614	24,681	**4**

[a] M_{s1} (*t*) refers to sediment load calculated using the seasonal SRC.
[b] M_{s1} (*t*) refers to sediment load calculated using the seasonal SRC for $Q > Q_t$.

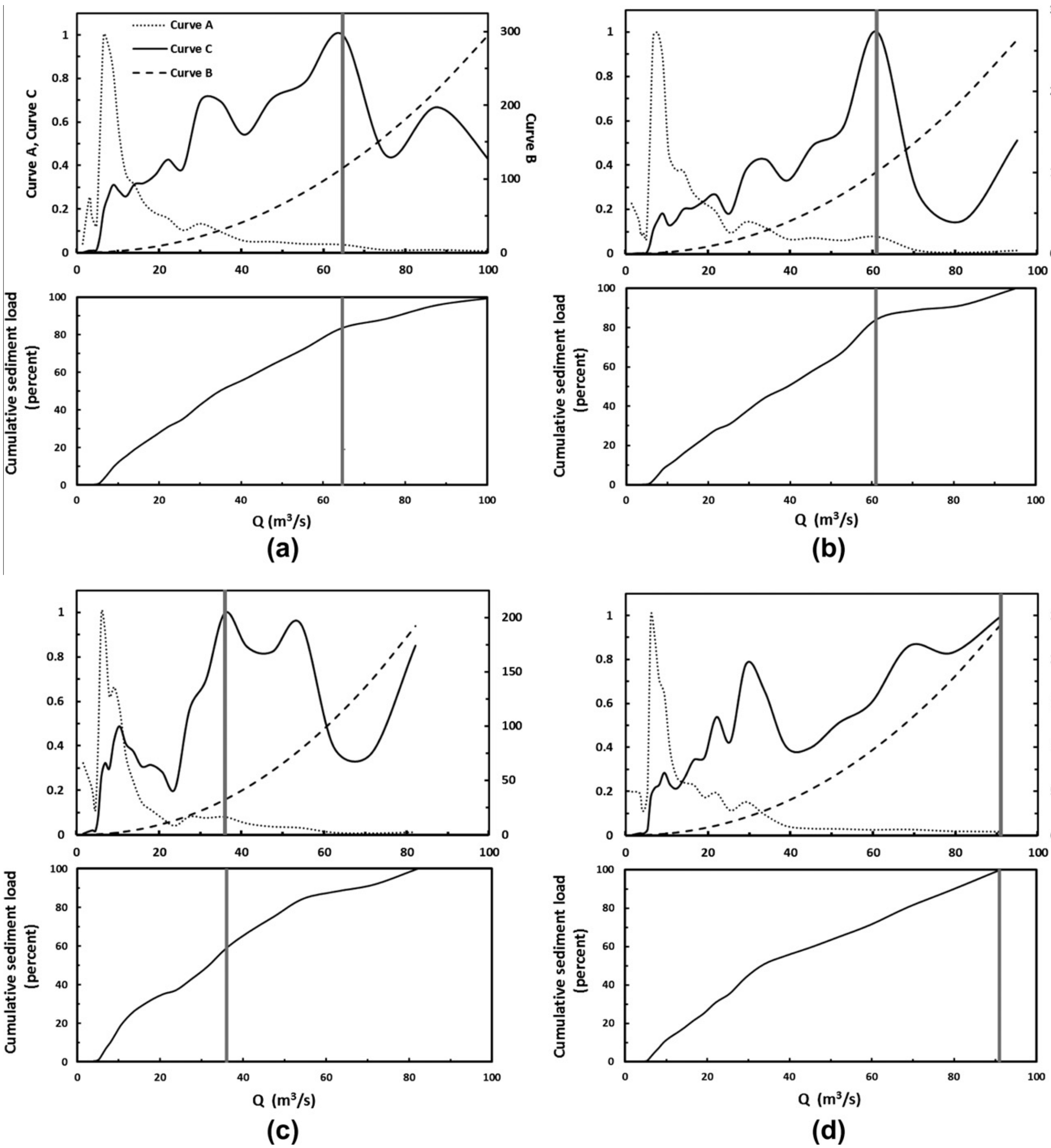

Fig. 6. Effective discharges and cumulative sediment loads. (a) all 3 years, (b) 2008, (c) 2009, and (d) 2010.

distinction between channel form parameters and Q_{bf} (Knighton, 1998).

The curve of cumulative sediment load versus discharge (Fig. 6a) illustrated two different zones separated by Q_{eff}. About 80% of total suspended sediment load was transported by discharges of the first zone (i.e., $Q < Q_{eff}$), while discharges in the second zone only transported less than 10% of it. The lower transport efficiency of the discharges in the second zone (i.e., $Q > Q_{eff}$) may be attributed to two reasons. First, these discharges occurred in only 1% of the time in the studied period. Second and more important, the studied watershed is a supply limited system. Higher discharges can only bring limited sediment from upland hillslopes due to relatively good ground vegetation cover. In streams, riparian vegetation strengthens the bank so well that only local, restricted bank erosion occurs during very high flows. The fact that the majority of higher discharges in the second zone are still below Q_{bf} suggests that they are not competent enough to scour the channel bed that consists of a large proportion of gravels (the size less than 65% of bed materials D_{s35} = 8.1 mm).

Although the concept of effective discharge is based on long-term averaged effect of sediment transport, it is informative to extend this concept to annual hydrograph and sediment transport. Our calculation of annual effective discharges revealed (Fig. 6b–d) that Q_{eff} is 61 m^3/s in 2008, 36 m^3/s in 2009, and 91 m^3/s in 2010, indicating significant variations of Q_{eff} from year to year. In 2008, Q_{eff} was similar to the overall Q_{eff} and more than

80% of suspended sediment load was transported by discharges no more than Q_{eff} (Fig. 6b). In 2009, however, the Q_{eff} had the recurrence interval of less than 1 year, which was determined based on the peak over threshold (POT) (or partial) flood frequency analysis (Kidson and Richards, 2005; McCuen, 2004) where the threshold flood discharge was set as 5.7 m^3/s, similar to Q_t in spring and fall. In contrast to 2008, less than 50% of suspended sediment load was transported by discharges up to the Q_{eff} in this year (Fig. 6c), while discharges greater than Q_{eff} contributed to more than 50% of total sediment load. In 2010, the Q_{eff} had the recurrence interval of approximately 1.5 years. Bigger discharges ($Q > Q_{eff}$) contributed to more than 30% of sediment yield. These variations suggest that even within a relatively stable stream, discharges that transport most annual sediment load can vary significantly.

6. Conclusions

We collected suspended sediment data from an agricultural watershed in Central New York for 3 years (2008–2010). Both water discharge and suspended sediment concentration (C) data showed clear seasonal patterns. Spring had the highest discharges due to rainfall on snowmelt events, while fall had the highest mean discharge because of relatively more intensive rainfall. Discharges in summer were relatively low but with greatest variation. Values of C were generally high in spring and varied with the highest degree in summer. These patterns indicated that seasonal sediment transport was controlled more by seasonably variable land use and land cover than by water discharge.

The processes of suspended sediment transport had similar patterns in all seasons. During lower flows caused by less intensive rainfall of a season, sediment transport was close to the lower transport capacity. During higher flows of the same season, the limited sediment supply due to relatively good surface vegetation cover provided less sediment than can be transported due to the increase of water discharges. These different processes could be reasonably quantified by two different sediment rating curves (SRCs) for the two ranges of discharges separated by a threshold discharge Q_t, though values of Q_t were different in different seasons. The different exponents of the SRCs reflect different degrees of sediment supply of the studied watershed.

Our analysis using both seasonal and annual data revealed that (i) in each season, sediment transport may be reasonably well characterized by a single SRC, and (ii) sediment transport in all 3 years may be described by a single SRC. The single seasonal SRC suggests that the two types of transport processes for lower and higher flows in each season were not significantly different and can be quantified by a single empirical equation. The good performance of the single combined 3-year SRC implies that the differences among seasonal patterns were constrained and sediment transport in general can be characterized by a single SRC. Thus, variations of sediment transport at a short time scale can be effectively averaged out at a longer time scale.

Instead of using the interpolation methods to calculate sediment yields, we developed a process-based SRC method that involves two steps. First, annual hydrograph was divided into storm and base flows using the identified seasonal Q_t values. Second, the combined 3-year SRC was used to calculate C and the associated sediment transport rate Q_s (kg/s) for each storm flow record. The sum of all Q_s produced the total sediment load of a given time period. Sediment yield calculated by this method was compared with that estimated using the three seasonal SRCs, which are presumably more accurate. Similar results of sediment yield estimation using the two methods suggest that the combined 3-year SRC is sufficient to characterize the processes of sediment transport in the studied watershed. A scheme of sampling a few big-flow events in each season may be deployed in similar watersheds that are dominated by supply-limited transport processes. Further effective discharge analysis and cumulative sediment load calculation indicated that sediment in the studied watershed was transported by more frequent, but moderate discharges. These hydrological and sediment transport properties provide a useful benchmark for watershed management in other watersheds of Central New York and regions that have similar climates and land-cover conditions.

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