HYDROLOGICAL PROCESSES
Hydrol. Process. (2012)

(wileyonlinelibrary.com) DOI: 10.1002/hyp.8462

Estimating suspended sediment concentrations in areas with limited hydrological data using a mixed-effects model

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Abstract:

Sediment rating curves are commonly used to estimate the suspended sediment load in rivers and streams under the assumption of a constant relation between discharge (Q) and suspended sediment concentrations (SSC) over time. However, temporal variation in the sediment supply of a watershed results in shifts in this relation by increasing variability and by introducing nonlinearities in the form of hysteresis or a path-dependent relation. In this study, we used a mixed-effects linear model to estimate an average SSC–Q relation for different periods of time within the hydrologic cycle while accounting for seasonality and hysteresis. We tested the performance of the mixed-effects model against the standard rating curve, represented by a generalized least squares regression, by comparing observed and predicted sediment loads for a test case on the Chilliwack River, British Columbia, Canada. In our analyses, the mixed-effects model reflected more accurate patterns of interpolated SSC from Q data than the rating curve, especially for the low-flow summer months when the SSC–Q relation is less clear. Akaike information criterion scores were lower for the mixed-effects model than for the standard model, and the mixed-effects model explained nearly twice as much variance as the standard model (52% vs 27%). The improved performance was achieved by accounting for variability in the SSC–Q relation within each month and across years for the same month using fixed and random effects, respectively, a characteristic disregarded in the sediment rating curve. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS linear mixed-effects model; discharge-suspended sediment concentrations; hysteresis effects; sediment dynamics; hydrology

Received 3 August 2011; Accepted 15 December 2011

INTRODUCTION

Suspended sediment dynamics are important components of many physical, chemical and biological processes in rivers and streams. Although there are positive factors associated with sediment transport and deposition for aquatic organisms, many studies have linked increased suspended sediments over background levels (e.g. fine sand, silt and clay) with negative consequences for aquatic biota (Kerr, 1995). Most attempts to conserve and protect aquatic ecosystems from the deleterious effects of suspended sediments have focused their attention on the need to develop sediment control strategies for stream restoration and watershed management (e.g. Reiter *et al.*, 2009). With respect to river ecology, it is important to characterize the movement of fine sediment within the fluvial system and to identify the natural and human forces that drive this movement. For example, forest-harvesting activities can lead to an increase in sediment supply and hence change the sediment texture of the streambed (Nistor, 1996; Nistor and Church, 2005). In particular, the accelerated production and mobilization of fine material can increase its proportion in the channel and affect the quality of habitat for fish and other aquatic species. Suspended sediments also reduce drinking water quality, which might pose health problems and increase the cost of water supply to urban communities (Salant and Hassan, 2008).

Several studies of suspended sediment dynamics have shown that the bulk of the sediment is transported by single-flood events, usually of short duration and high magnitude, and that the relation between the suspended sediment concentration (SSC) and the water discharge (Q) is highly variable (e.g., Walling and Webb, 1987; Salant *et al.*, 2008). This variability is usually displayed by greater interevent and intraevent differences, more noticeable for small and medium size streams than for large lowland rivers (Lenzi and Marchi, 2000). Different patterns of hysteresis in the SSC–Q relation are related to the types and locations of active sediment sources (Lenzi and Marchi, 2000). In British Columbia, Canada, and the Pacific North West of USA, three main sources of fine sediment can be observed in forested streams: (i) episodic release due to mass movement events that reach the stream channels, (ii) bank erosion during and between floods and (iii) release of sediment stored behind log jams. Very little sediment is contributed from erosion of the landscape surface by overland flow and from within the bed (Nistor, 1996). Although fine sediments have been the focus of many studies, the current knowledge of sediment sources transfer and storage is inadequate to address the wide set of environmental effects caused by suspended sediments in forested landscapes.

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A large portion of research in hydrology has investigated the relations between discharge and fine sediments, an area of research that continues expanding because predictions of fine sediment transport rate via hydraulically based functional relations are often more than two times different than rates calculated from direct sampling in the field. This discrepancy has been explained by the major role that fine sediment supply plays on sediment dynamics in rivers and streams. Predicting suspended sediment by using channel hydraulics places an upper limit on how much fine material can be carried, although there is rarely enough sediment to meet a river's capacity. Sediment rating curves are the most common method used to estimate the suspended sediment load in streams (e.g. Walling, 1974; Walling, 1977; Church and Gilbert, 1975). However, the performance of sediment rating curves is often low because suspended sediment transport is a function of sediment supply and discharge. Any variation in the sediment supply of a watershed results in shifts in the relation between discharge and suspended sediments, thus introducing variability (frequently in the form of hysteresis), which is not often captured by the rating curve.

The presence of a hysteresis effect leads to a nonunique relation between SSC and Q. There are several ways to deal with the problem of hysteresis effects such as by the development of separate rating curves for rising and falling limbs of the hydrograph (e.g. Walling, 1974; Walling and Webb, 1987) or the inclusion of a sediment supply parameter in the model (cf. Asselman, 1999). Researchers have developed various modifications that include grouping the suspended sediment data according to seasonal or hydrological patterns, developing watershed specific correction factors or using nonlinear regression models (Bunte and MacDonald, 1999; Horowitz, 2003). Some approaches have attempted to improve the relationship between SSC and Q by incorporating turbidity as an additional variable (Chanson *et al.*, 2008; Rasmussen *et al.*, 2009) or by modelling time and seasonality as a covariate (Runkel *et al.*, 2004). These attempts to deal with sediment hysteresis present challenges because they often do not address the problem of the sediment supply and thus the changing relation between SSC and Q. Furthermore, poor data quality and lack of continuous measurements inhibit progress toward development of reliable suspended sediment models for better management of stream ecosystems. This fact demonstrates the need for suspended sediment transport models that explicitly include hysteresis effects in a way that hydrologists can make use of the often limited hydrological data. Nevertheless, rating curves remain the primary practical method for estimating suspended loads in streams.

An alternative way to approach sediment hysteresis effects is to model the relation between SSC and Q using a mixed-effects linear model. A mixed-effects model incorporates a mixture of fixed and random effects. Fixed effects are associated with the average or typical dynamic (e.g. SSC–Q relation) that may differ among groups within a population, where the modeller decides on the grouping depending on the research needs (Pinheiro and Bates, 2000). For example, a hydrologist can determine the grouping in relation to sections of a hydrological cycle that share similar characteristics to estimate the typical SSC–Q relation for that section of the cycle. Random effects are associated with the variability of the dynamic among groups (Pinheiro and Bates, 2000). In this case, random effects are associated with the variability in the SSC–Q relation between years on the same month (e.g. January 1970, January 1971, January 1972, etc.), which may be related to hysteresis patterns, climatic influences and changes in the sediment sources. The mixed-effects model approach allows us to directly account for seasonality and hysteresis, which may vary across years and within months, respectively, especially in watersheds with clearly defined discharge regimes.

The purpose of this study is to present a novel methodology to estimate SSC for rivers and streams with limited hydrological data using a mixed-effects model. To test whether or not the mixed-effects model performs better than the rating curve, we compared the estimates of SSC using Q as the predictor variable resulting from applying the mixed-effects model with the estimates of a rating curve, represented by a generalized least squares (GLS) regression.

METHODS

Errors in the SSC–Q relation

It is important to understand that the estimation of sediment loads from temporal records of SSC and Q, regardless of the approach used, is subject to errors that arise from field and laboratory methods and data processing. Suspended sediment rating curves have the form of power function:

$$\mathrm{SSC} = aQ^b \tag{1}$$

where SSC is the suspended sediment concentration, Q is the water discharge and a and b are regression coefficients. Errors in the relation expressed in Equation (1) and errors associated with sampling have been a matter of study by several authors. Topping *et al.* (2006) examined the error related to depth-integrated suspended sediment sampling and found errors of 10% in suspended silt-clay concentration (the grain material addressed in our case study), 22% in suspended sand concentration and 12% in the median grain size. Smith *et al.* (2003a,2003b) examined the sampling errors associated with seasonality and storm regime finding errors on the order of 5% to 10%. Errors in the suspended sediment estimates are related to different aspects of the methods of data collection, quality and frequency of sediment sampling and laboratory processing of samples (Webb *et al.*, 1997; Phillips *et al.*, 1999; Smith *et al.*, 2003a,2003b). Mweempwa (1993) analyzed the sampling techniques used by the Water Survey of Canada and concluded that it presents reliable estimates contained within ±10% accuracy for the Chilliwack River (see Case

Study section). Specific hydrometric stations can also provide an idea of the quality of data they produce. For example, the SEM annual load for Chilliwack River station at Vedder Crossing (station number 08MH001, discussed in the Case Study section) ranged between 16.2% and 43.0% from 1965 to 1976 (Environment Canada, 1992). Other sources of errors may arise from the data format itself. For example, data can also be irregularly spaced, leaving ‘blanks’ that can bias parameter estimation in the model. Additional errors and biases in the estimation may result from the data not conforming to the assumptions underlying the model being applied. These will be discussed in greater detail in the following sections.

Mixed-effects model formulation

Before fitting a mixed-effects model, it is advisable to perform an exploratory data analysis to help choose the grouping in the data set (e.g. seasons, months and weeks within the hydrologic cycle) and decide on the potential structure of random effects (e.g. which coefficients in Equation (1) should vary among groups).

In the case study, there are two levels of variation in the data: groups (same month in different years) and observations nested within groups (individual measurement of SSC and Q in each month measured in mg l^{-1} and $\mathrm{m}^3\ \mathrm{s}^{-1}$, respectively). In this particular study, we used 12 mixed-effects models, one for each month across all years in the data set. The reason for formulating 12 mixed-effects models was to account for seasonal variability from month to month while acknowledging within-month variability from year to year. In each model corresponding to a month (e.g. mixed-effects model for June), observations between years (for that month) are independent, but observations within year (in that month) are correlated (Pinheiro and Bates, 2000). In this manner, we estimated an average set of coefficients for Equation (1) for each month (the fixed effects) but allow these to vary across years for that month (the random effects). The variability in the coefficients across years for the same month (i.e. June 1969 versus June 1970) may be due to hysteresis patterns, changes in the sediment sources and climatic factors (Figure 1). The software used to fit the mixed-effects models was the *lme* library in R, version 2.10.2 (Pinheiro *et al.*, 2010).

Although there are several ways to formulate a linear mixed-effects model, we used different equations for the two levels of nested data (Singer, 1996; Snijders and Bosker, 1999; Lai and Helser, 2004; Zuur *et al.*, 2009). The first level describes the variability in SSC as a function of Q within each month, and the second level describes the variability in the SSC–Q relation among years in the same month (e.g. variability among the Januaries of the data set). The first level is represented by

$$y_{ij} = \beta_{0j} + \beta_{1j}x_{ij} + \varepsilon_{ij}, \quad \varepsilon_{ij} \sim N(0, \sigma^2) \qquad (2)$$

where $y_{ij} = \log_e(\mathrm{SSC}_{ij} + 1)$, $x_{ij} = \log_e\ (Q_{ij} + 1)$ for an observation i in year j, and β_{0j} and β_{1j} are the intercept and slope relating to a and b in Equation (1), respectively. The +1 is used to avoid conflicts in the logarithmic transformation when zeros were present in the data. The data transformation is necessary and commonly used when

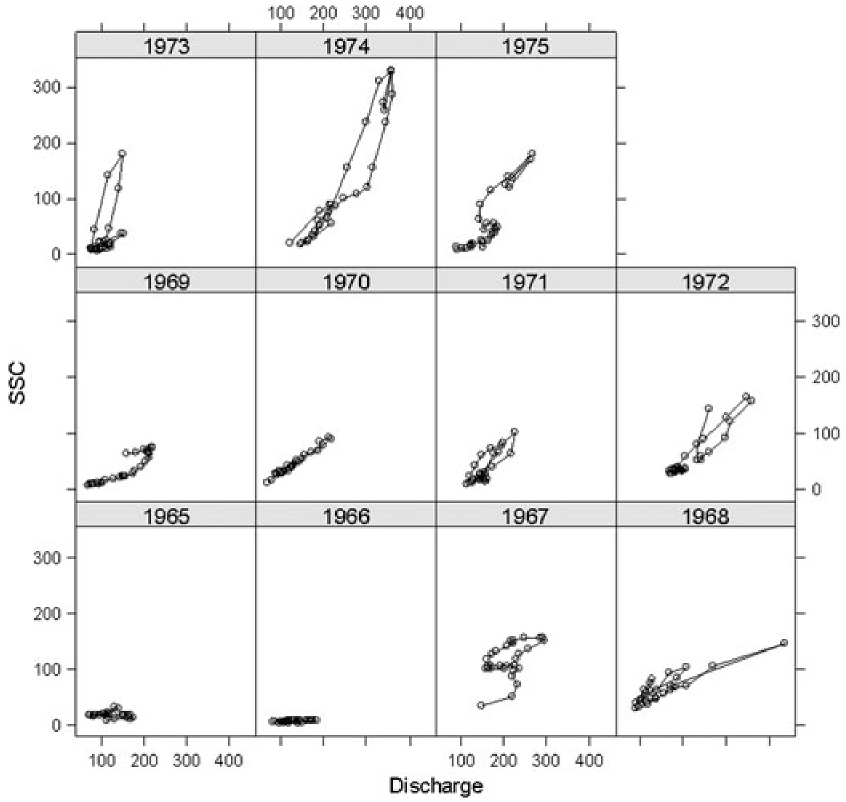

Figure 1. Different hysteresis patterns for the month of June across all years in the data set (1965–1975)

addressing SSC–Q to ensure normality of the residuals. The random error ε_{ij} represents the within-month variance, and it is assumed to be independent and identically normally distributed with mean equal to zero and common variance σ^2. The second level is represented by

$$\beta_{0j} = \beta_0 + b_{0j}, \quad \beta_{1j} = \beta_1 + b_{1j}$$
$$b_j = \begin{bmatrix} b_{0j} \\ b_{1j} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \xi \right) \quad \xi = \begin{bmatrix} \sigma_0^2 & \sigma_{01} \\ \sigma_{01} & \sigma_1^2 \end{bmatrix} \quad (3)$$

where the intercept and slope β_{0j} and β_{1j} are assumed to be multivariate normally distributed with mean (β_0 and β_1) and variance–covariance matrix ξ representing the between-year variance and covariance for the vector of random effects b_j, which describes the variation of the SSC–Q relation in each month among years. Substitution of Equation 3 into Equation 2 leads to the final linear mixed-effects model:

$$y_{ij} = \beta_0 + b_{0j} + \beta_1 x_{ij} + b_{1j} x_{ij} + \varepsilon_{ij}, \quad \varepsilon_{ij} \sim N(0, \sigma^2) \quad (4)$$

The fixed-effects coefficients β_0 and β_1 in Equation 4 are frequently called the population averages (Lai and Helser, 2004; Zuur *et al.*, 2009). These coefficients are the ones that can be potentially used to extrapolate SSC using Q as a predictor for the periods when only Q is available. The residual error ε_{ij} (difference between fitted and observed $\log_e$-transformed values) and the SD of random effects, b_{0j} and b_{1j}, could be further explored to apply a stochastic extrapolation.

The parameters of the variance–covariance matrix ξ in the mixed-effects model can be estimated using either maximum likelihood (ML) or restricted ML (REML) (Harville, 1977; Lai and Kimura, 2002). We used REML as the parameter estimation method because biases can be present with ML that result from lost degrees of freedom (Corbeil and Searle, 1976). To compare the results from the mixed-effects model, we also estimated 12 GLS regressions fitted by REML representing monthly sediment-rating curves and then compared the performance of the rating curves and the linear mixed-effects models at representing the trends in the data.

Addressing model assumptions

There are several fundamental assumptions for the application of linear mixed-effects models. When evaluating temporal SSC–Q relations for a single stream, river or watershed, the experimental units are groups within which the observations of SSC and Q are made, which are specific to each situation. Thus, the researcher needs to define the grouping structure depending on the patterns present in the data (e.g. type of hydrological cycle) and considering factors such as data resolution and research needs.

After fitting the model, it is essential to evaluate the residuals and conduct diagnostics for homogeneity (via residuals versus fitted plots), normality (via quantile–quantile plots) and independence. Crawley (2007) emphasized the normality and independence in observations between groups and within groups and that the covariance matrix needs to be independent of the group. However, in time series, temporal correlation in the residuals is expected, thus violating the assumption of independence (Crawley 2007). For this reason, it is necessary to evaluate the correlation structures within groups containing data (e.g. a week of continuous SSC observations). Although autocorrelation does not bias the model coefficient estimates, it tends to underestimate their SE when the autocorrelations are present at low positive lags (as shown in the autocorrelation function plot in Figure 2). Mixed-effects models assume a hierarchical structure in the data, and even if all the groups of the population are sampled (as in this case), it is still necessary to consider the covariance structure of the entire population (Aitkin and Longford, 1986; Lai and Helser, 2004).

When using the mixed-effects model population averages (mean intercept and mean slope) as the only coefficients taken for extrapolation, the effects of autocorrelation can be disregarded. However, if one wishes to assess the uncertainty associated with the predictions, one must propagate the SE of the coefficients into the prediction errors. In such cases, the SE of the coefficients must be calculated properly and may require the addition of an autocorrelation term in the mixed model. The *lme* package allows for the inclusion of autocorrelation terms as well as other terms to correct for heterogeneous variance.

Testing mixed-effects models

To test whether a rating curve (GLS) or a more sophisticated technique such as a mixed-effects model

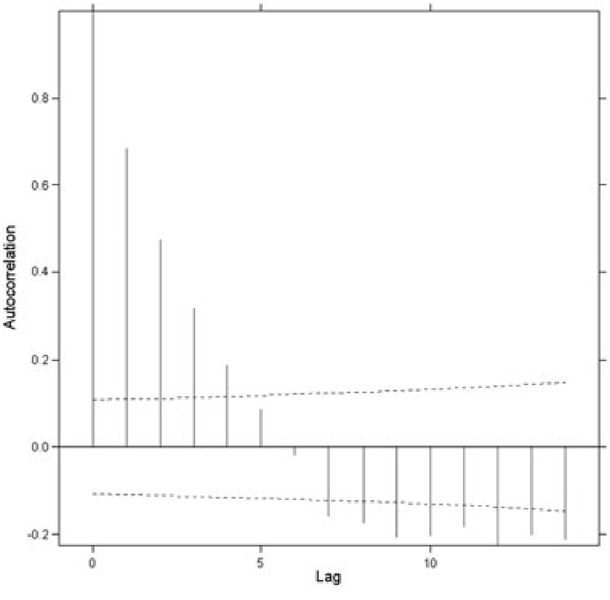

Figure 2. Autocorrelation plot representing the temporal correlations among all observations for the month of December across years. In this example, there is highly significant autocorrelation at lags 1 to 3 and marginally significant autocorrelation at lag 4. Although autocorrelation does not bias the model coefficient estimates, the SE of the coefficients tend to be underestimated at low positive lags

should be used to represent the SSC–Q relation, several tests and measures of goodness of fit can be performed. For example, the likelihood ratio test can be used to compare the fit of nested models. In this case, the test will return a small P value if the mixed-effects model is a good choice (Crawley, 2007). An alternative way to decide on what model to use is to compare the model scores of the Akaike information criterion (AIC), which we have included in this analysis, or the Bayesian Information Criterion (BIC). Each of these criteria examine the trade-offs between model complexity and improved goodness of fit for nonnested models (Burnham and Anderson, 1998) with lower values indicating greater parsimony.

CASE STUDY

The model was designed and tested using SSC and Q data from the Chilliwack River. The main reasons for choosing this watershed included the following: (i) the availability of 10.5 years of daily averages of SSC and Q, (ii) the wide range of sediment sources within the basin, (iii) the temporal variability in the system with very active floods in the fall/winter and spring and (iv) habitat concerns related to the increased sedimentation due to human industrial activities.

The Chilliwack River is a tributary of the Fraser River, and it is located in the Skagit Range of the Cascade Mountains, British Columbia, Canada (Figure 3). The watershed covers approximately 1230 km^2, and it is composed primarily of rocks of the Chilliwack Terrane, consisting of marine sedimentary, volcanic and metamorphic rocks. Portions of the watershed are underlain by Tertiary plutonic rocks of the Chilliwack Batholith (Monger 1970, 1989). Surficial materials common within the Chilliwack Valley include basal and alblation till and colluvial deposits as well as glaciofluvial and glaciolacustrine terraces. Maximum relief is approximately 2300 m, and there are extensive ridge systems above the tree line as well as some remnant pocket glaciers. The main biogeoclimatic zones within the Chilliwack Valley are Coastal Western Hemlock and Mountain Hemlock. Snow accumulations of up to 5 m occur from 1500 m of elevation and yearly rainfall averages 2500 mm in the valley bottom (Brayshaw, 1997).

McLean (1980) identified three major sources of sediment supply into the river: (i) mass movement such as landslides and debris flow, (ii) bank erosion and (iii) tributary creeks. Although mass movements are not frequently occurring events, they do occur in certain areas and can be an important source of sediment supply into the river. Because of the seasonal weather pattern, the Chilliwack River experiences two runoff peaks: the first occurring in the fall and winter associated with significant rainfall events and the second occurring in the spring due to snowmelt (Martin and Church, 1995). Although significant flow events occur in the spring, the fall and winter floods present the highest flows, which are responsible for the mobilization of most sediment (Church *et al.*, 1989).

Analysis of the data demonstrated that suspended sediment transport of silt and clay is highly episodic with most transport occurring during large events reflecting the hydrological regime of the river with well-defined seasonal patterns (Figure 4). Four periods of monthly flow regime have been identified in the watershed: (i) spring snowmelt, (ii) summer low flow, (ii) autumn rise due to rainstorms and (iv) winter low due to decrease in precipitation (McLean, 1980). During the 1960 to 2008 period, there were several significant high flow events along the Chilliwack River. The estimated 5-year peak flow events for the winter and spring were 430 and 300

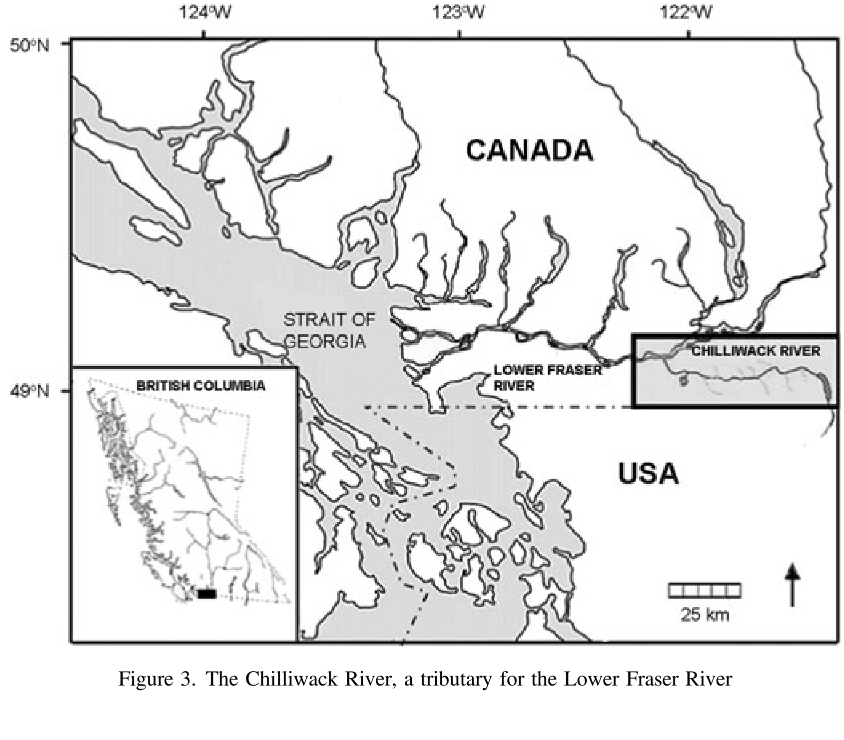

Figure 3. The Chilliwack River, a tributary for the Lower Fraser River

$m^3 s^{-1}$, respectively. The largest winter rainfall event had an estimated discharge of 776 $m^3 s^{-1}$, whereas the largest snowmelt event was 280 $m^3 s^{-1}$ (Martin and Church, 1995). Despite the high flows of the winter, the highest monthly mean SSC was obtained for the snowmelt events in the spring (Figure 5). This outcome reflects the relative importance of the flood duration on the daily and monthly SSC. In the basin, the snowmelt events are of much longer duration than the rainfall counterpart. Of particular interest is the December 1975, which experienced the highest sediment yield in record (see Church *et al.*, 1989). Despite the large magnitude of sedimentation events on this month, the sediment concentration remained within the range of results obtained for the rest of the records, perhaps because of the high magnitude but short duration of the flood.

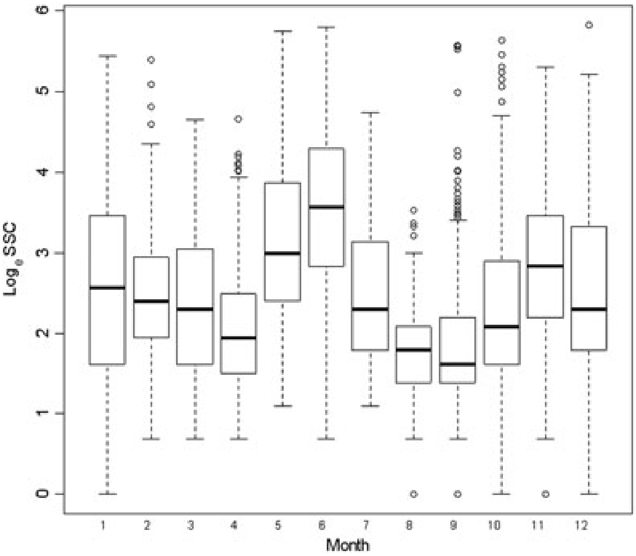

Figure 4. Monthly distributions of $\log_e$ SSC for all years in the data set showing a cyclical pattern. The highest values of SSC occur during spring to early summer and winter months. In addition, considerable less within-month variability is observed for the late summer and fall months exhibiting marked heterogeneity

Data

The Water Survey of Canada provided daily averages of SSC (mg l^{-1}) from 1965 to 1975 (Figure 5) and Q (l s^{-1}) from 1965 to 2006, taken at the Vedder River crossing, station number 08MH001 (WSC, 2008). No recent continuous data on SSC were available. Daily averages are unlikely to capture within-event variability; however, that will not likely affect our analysis here because most major events in the river last for several days (Church *et al.*, 1989), especially in the case of the spring snowmelt. Working with daily averages provides a good opportunity to observe hysteresis patterns and the seasonal variability of the suspended sediment. For defining the groups for the

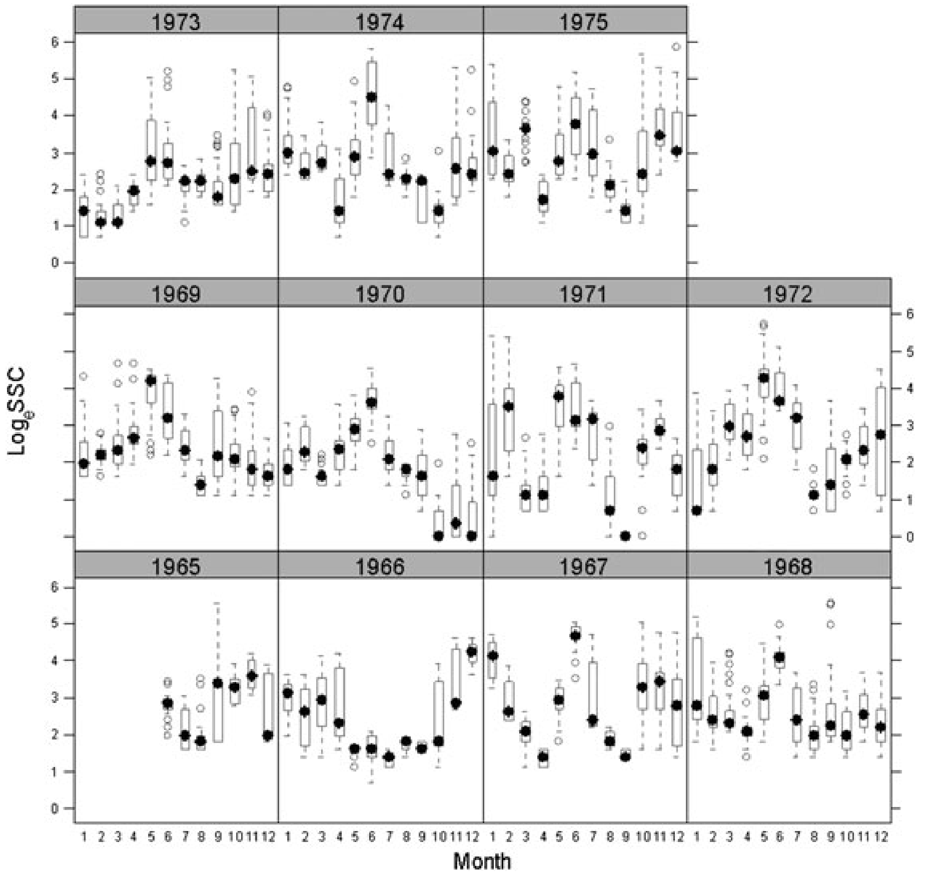

Figure 5. Monthly distributions of $\log_e$ SSC in each year of the data set. Q and SSC present fairly defined cyclical seasonal patterns with the highest values of SSC during spring and early summer. Seasonal patterns depend upon winter snow accumulations, which affect the spring and summer discharge and vary from year to year

DOI: 10.1002/hyp

mixed-effect model, we were interested in the within month and interyear variability rather than the variability among single events. Our long-term interest lies in assessing the effects of sedimentation on aquatic organisms, and daily averages provide a practical time frame (cf. Newcombe and Jensen, 1996).

Information on suspended sediment texture in the watershed is limited. On the basis of incomplete data, the grain size analysis shows that most of the suspended sediment falls within the silt and clay texture (Scott *et al.*, 1993; EBA, 2001). The Chilliwack River channel is steep, and its flow mean velocity is relatively high and very turbulent (2.0 m s^{-1} measured at station 08MH001 at Vedder Crossing) (Mweempwa, 1993). Therefore, most of the suspended load is likely to be washed out of the river system and little might settle within the channel. The magnitude and the duration of a flood are important factors in determining the amount of sediment mobilized. Inspection of the flood hydrographs showed that several large events occurred during the study period.

Interyear variability is an important feature in the system because it depends on larger climatic influences such as the pacific decadal oscillation or El Niño (Lofgren *et al.*, 2010). Because of the large number of years with data, it is not feasible to present all results from the interyear variability. Instead, we presented selected results that typify the trends observed. This interyear variability affects both the intercept and slope of the SSC–*Q* relation.

RESULTS

Mixed-effects model coefficients

The coefficients produced by the linear mixed-effects model are shown in Table I. The log-intercept (β_0) and log-slope (β_1) for each month varied considerably, as expected given the seasonal patterns observed in the data. The SDs of random log-intercepts (b_0) and random log-slopes (b_1) indicate the interannual variability in the distribution of each month's intercept and slope with respect to the estimated parameter values β_0 and β_1 and reflects the interannual variability in the SSC and *Q* patterns. To assess for violations to homogeneity, we plotted the standardized residuals for all models. The standardized residuals concentrate around zero showing homogeneity, and no aggregation patterns in the plot quadrants were observed (e.g. Figure 6).

Goodness of fit and comparison to standard rating curve

We compared the goodness of fit for both the mixed-effects model and the rating curve generated with GLS regressions using the AIC. When applying AIC to evaluate the rating curve (GLS) and the mixed-effects model for each month, the AIC for the mixed-effects model presented lower scores (better goodness of fit) for all months (Table II). When plotting the observed data from 1965 to 1975 against the fitted values for the same period (Figure 7), the plot corresponding to the mixed-effects model shows less total spread around the 1:1 line, with less spread indicating better fit. The mixed-effects models explain approximately 53% of the variability in

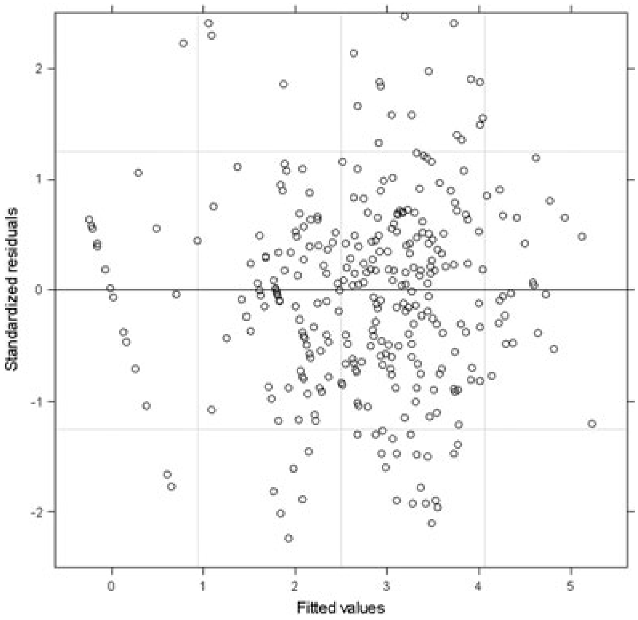

Figure 6. Plot of standardized residuals against fitted values for the mixed-effects model representing the month of December

Table I. Mixed-effects model results for the Chilliwack River watershed

Month	Log-intercept β_0	SE β_0	Log-slope β_1	SE β_1	SD of random log-intercepts b_0	SD of random log-slopes b_1
January	−3.70	0.80	1.60	0.19	2.39	0.57
February	−5.61	1.40	2.14	0.42	4.25	1.29
March	−2.96	0.79	1.41	0.18	2.25	0.51
April	−6.22	1.54	2.09	0.35	4.64	1.04
May	−3.40	0.96	1.37	0.22	2.90	0.67
June	−5.68	1.55	1.81	0.31	4.97	1.01
July	−7.06	1.71	2.03	0.36	5.54	1.18
August	−0.25	1.07	0.49	0.27	3.41	0.85
September	−3.67	0.97	1.59	0.33	2.84	0.99
October	−3.24	0.63	1.48	0.14	1.91	0.41
November	−4.66	0.66	1.85	0.14	2.00	0.41
December	−4.25	0.79	1.67	0.15	2.51	0.48

The table shows the log-coefficients from the mixed-effects model with their respective SD.

DOI: 10.1002/hyp

Table II. Comparison of AIC scores for the mixed-effects model and the rating curve (GLS) for all the months in the data set

Month	Linear mixed-effects model	Rating curve (GLS)
January	392	766
February	216	502
March	300	760
April	326	587
May	375	669
June	326	740
July	289	705
August	215	581
September	480	906
October	532	767
November	355	696
December	392	684

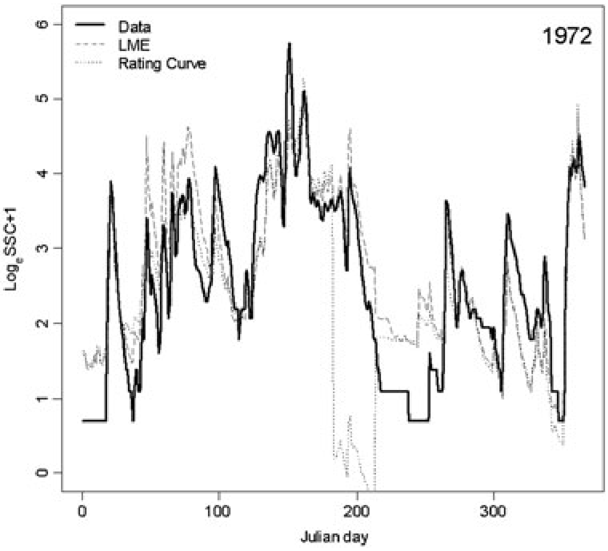

Figure 8. Comparison between the original time series of 1972, interpolated values using the mixed-effects model coefficients (LME) and the monthly rating curve estimates. The year was randomly selected within the data set. Notice the much better performance of the mixed-effects model to represent SSC, particularly during the month of August compared with the performance of the rating curve. For this year during the early spring, the rating curve seems to do a slightly better job at capturing the trend in the data, although the mixed-effects model managed to represent the SSC pattern correctly

the SSC–Q relation (pseudo-$R^2 = 0.528$). The pseudo-R^2 represents the proportion of variability in the observed versus predicted data accounted for by the 1:1 line. The standard rating curve only captured around 28% of the variance and had difficulty fitting the low-flow summer months as evidenced by the cluster of points well below the 1:1 line.

To compare the predictive ability of the mixed-effects model and the standard rating curve generated by GLS, we also examined the fitted time series and fitted SSC–Q lines generated by each model. A year randomly taken from the fitted time series generated by the mixed-effects model and the rating curve is illustrated in Figure 8. Overall, both models seemed to capture the general seasonal variability. However, the mixed-effects model does much better at representing the seasonal trend in the summer low-flow period, the month of August in particular. When comparing the fitted average curve generated by the mixed-effects model, the fitted year-specific monthly curves, and the standard rating curve generated by GLS, the mixed-effects model presents less bias in representing the SSC–Q relation in the summer months because it is less affected by years with extreme SSC–Q values (Figure 9).

Extrapolating SSC using discharge as predictor

The main potential application of the method presented here is the extrapolation of SSC using Q as a predictor. In such case, using the population averages (fixed-effect intercept and slope) for each month will be used to produce a time series of SSC into the future. For example, the fixed-effect coefficients extracted from the mixed-effects model

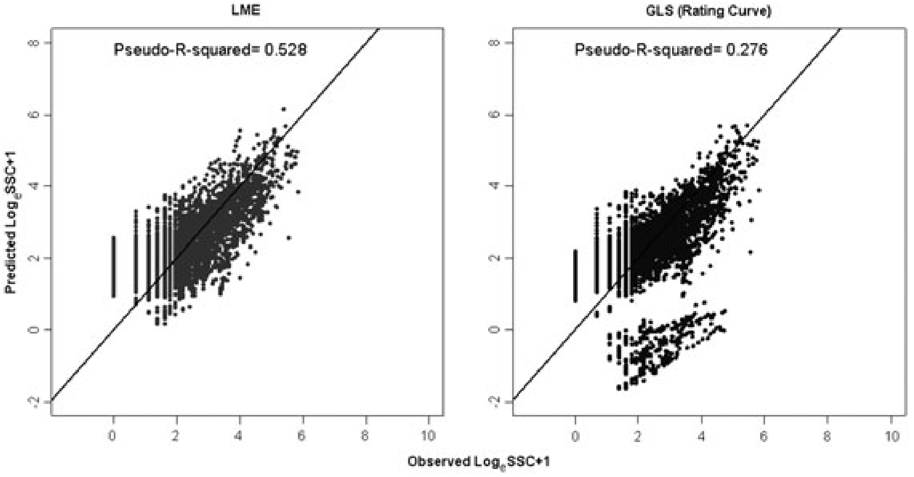

Figure 7. Observed versus predicted $\log_e$ SSC values for 1965 to 1976. The mixed-effects model captures better the trend in the observed values (pseudo-$R^2 = 0.528$) compared with the estimates of the rating curve (pseudo-$R^2 = 0.276$). The low-flow summer months with odd Q–SSC relations produced many negative estimates of SSC when using the rating curve, which makes results difficult to interpret. The predictive power of both the mixed-effects model and the rating curve increases at higher values of Q and SSC

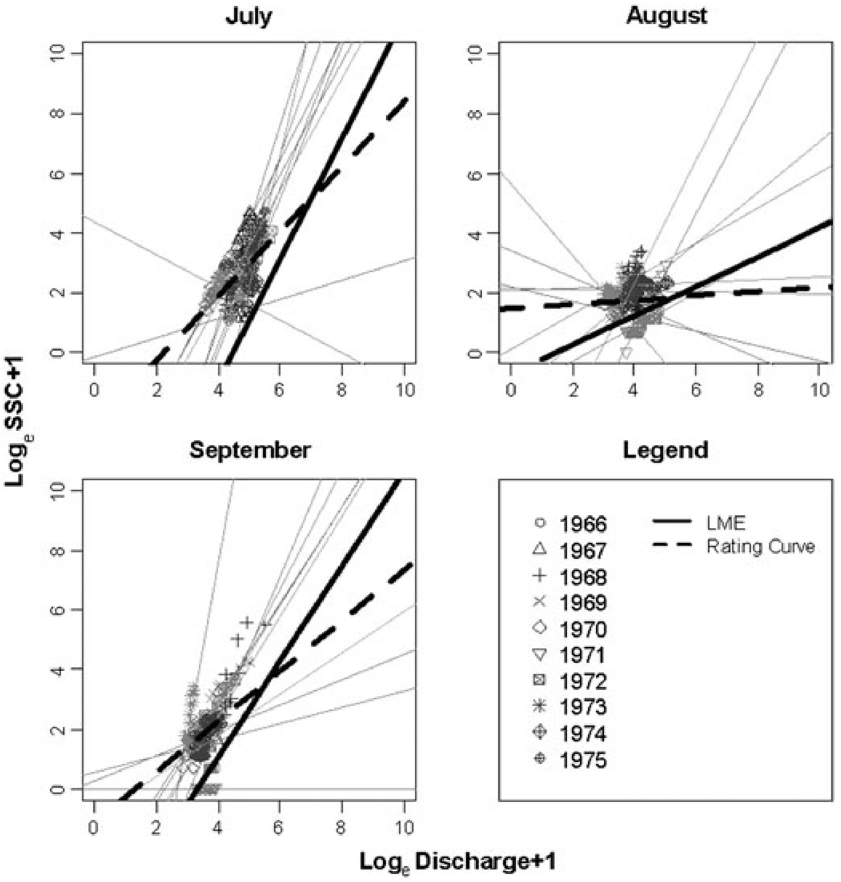

Figure 9. Log_e (SSC) versus $\text{Log}_e(Q)$ for late summer months across all years in the data set. These months are characterized by low flows with episodic high levels of SSC. The change in the dynamics of the Q–SSC relation tends to bias the estimates of the rating curve (dashed line) obtaining nonsignificant relations (e.g. August). The mixed-effects model (LME, solid line) performs much better at capturing the trends in the data even in the presence of years with odd Q–SSC relations. The thin gray solid lines represent the monthly linear fits

applied to a month (e.g. January) across all years with complete SSC and Q data could be used to extrapolate SSC in the Januaries where only Q data are present. Although we could have split the original data set into calibration and validation sets and test the model with the validation data set, this would have meant less data in the calibration set and therefore lesser power over all. However, when using the results from a linear mixed-effects model, we would expect to see better estimates of SSC using Q as a predictor given its better goodness of fit.

DISCUSSION

We presented a novel methodology to estimate the coefficients (intercept and slope) of the linear relation between SSC and Q that directly takes into account both seasonality and hysteresis, both of which may vary across years. The fixed and random effects in the mixed-effects model address this variability explicitly. The fixed effects represent the typical SSC–Q relation for a given month, and the random effects reflect the variability in that relation across years due such factors as the availability of the sediment sources and the climate regime.

The results from using the coefficients from both the mixed-effects model and the rating curve suggest that the mixed-effects model reflects more accurate patterns of SSC derived from Q data, especially for the low-flow summer months when the SSC–Q relation is less clear. The SSC–Q relation tends to be strong in the winter months, although it can vary for the rest of the year, particularly during the spring and the late summer months. The mixed-effects model's better performance was achieved by including the mixture of fixed and random effects to account for intramonth and interyear variability in the SSC–Q relation, a characteristic disregarded in traditional extrapolation techniques such as the sediment rating curve. Disregarding this variability resulted in nonrepresentative values for the coefficients of the rating curve for months with highly varying or anomalous relations between SSC and Q. However, the predictive power of both the mixed-effects model and the rating curve increases at higher values of SSC and Q as observed for the spring and winter months.

We assumed that the SSC dynamics in the river in the period represented by the data are still valid for the present and future, although changes in the sediment sources over time might have altered these dynamics. Although we explicitly consider uncertainty, it is important to understand that errors or bias in the results may arise from using older data sets, and the best outcome is achieved by using up-to-date information. When direct SSC data are lacking, it is important to obtain accurate estimates of suspended sediments derived from discharge records. In this respect, better estimates of

SSC can minimize the need for intense monitoring and help managers and scientists determine the impact of suspended sediments on aquatic species. For example, in coastal British Columbia, the aquatic species contained in many coastal watersheds are susceptible to elevated SSC levels.

CONCLUSION

This study shows that mixed-effects models can help predict more accurate values of SSC than the standard rating curves. These models do so by directly modeling the intramonth and interyear variability in the SSC–Q relation. In the case study, the predictive power of both the mixed-effects model and the rating curve increased at higher values of SSC and Q, as their relation becomes stronger. For the low-flow summer months, the mixed-effects model proved to be a more valuable alternative than the sediment-rating curve, an important feature when estimating SSC in areas with limited hydrological data. This advantage can equip managers and scientist with better knowledge of suspended sediment and therefore aid addressing its effects on important physical, chemical and biological processes in rivers and streams.

ACKNOWLEDGEMENTS

The authors thank Ashley Page, Duncan Knowler, Erland MacIsaac, Athena Ogden, Carrie Holt and Ken Lertzman for their ideas or contributions to the manuscript and the valuable input of two anonymous reviewers. The Forest Investment Account–Forest Science Program from the Ministry of Forests and Range of British Columbia (FIA-FSP) Project Y092250 (Year 2) and the Natural Sciences and Engineering Research Council of Canada (NSERC) provided the funding for this project.

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