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Modelling extreme suspended sediment concentrations in North America: frequency analysis and correlations with watershed characteristics

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Abstract Suspended sediment concentration (SSC) is an important abiotic variable for river habitats. Inspired by the statistical methods developed for flood frequency analysis, the probabilistic approach adopted in this paper is used to quantify extreme SSC events. Probability distributions were fitted to 149 series of annual maxima of SSC in Canada and the USA in order to estimate quantiles of SSC for different return periods. The most adequate probability distributions for modelling extreme events of SSC were selected based on the Bayesian information criteria. Seasonal patterns of occurrence of extreme concentrations were also analysed. Then, in order to investigate the links between magnitude of extreme SSC and drainage basin characteristics, correlations between annual maximum SSC, discharge, and a large range of physiographic variables were calculated, and the most significant ones were highlighted.

Key words extremes; frequency analysis; physiographic influences; suspended sediment concentrations

INTRODUCTION

Extreme suspended sediment concentrations (SSC) are a threat to aquatic life and the sediments possibly carry high amounts of pollutants. Exceeding relatively high thresholds of SSC is known to be harmful to certain species of fish and aquatic organisms and increases the cost of drinking water treatment processes (Waters, 1995). Relatively few rivers in the world are monitored daily for SSC and this lack of information makes it difficult to predict and quantify extreme events. The number of stations in existing daily SSC monitoring networks has been decreasing over time in the USA (Osterkamp & Parker, 1991) and Canada (Day, 1991). High concentrations may also be difficult to measure due to limitations of some measurement protocols (Gray & Glysson, 2002). The objective of this work is to estimate the magnitude and probability of exceedence of extreme events of SSC. This can be done using frequency analysis. Inspired by the statistical methods developed for flood frequency analysis, a probabilistic approach is used to quantify extreme events of SSC (Tramblay *et al.*, 2006). Then, as a preliminary step to evaluating the feasibility of estimating extreme SSC in watersheds with no records, the hypothesis that the magnitude of extreme SSC could be correlated with physiographic features of the watersheds was verified. The hypothesis has to take into account the fact that suspended sediments come from the hillslopes of the watersheds as well as from the river channel, and the relative importance of these two sources can vary considerably from one river to another (Russel *et al.*, 2001). Several studies have already established correlations between watershed characteristics and sediment yield (Ludwig & Probst, 1998; Restropo *et al.*, 2006), or mean SSC values (Robertson & Saad, 2003; Dodds & While, 2004). The present study provides additional information by focusing on the relationship between the magnitude of extreme SSC events and land use, as well as climatic and geomorphologic characteristics of the drainage basins.

METHODOLOGY AND DATA SET

Local frequency analysis

The main objective of frequency analysis is to infer the probability of exceedence of extreme SSC from observed values. This probability can be calculated by fitting to the observed data a statistical distribution that represents the relationship between the magnitude of the event and the exceedence probability. The theory and its application are described in details in many textbooks (e.g. Rao & Hamed, 2001). The parameters of the probability distribution are estimated from the sample. By using the fitted probability distribution, it is possible to predict the probability of exceedence for a specified magnitude (i.e. quantile) or the magnitude associated with a specific exceed ence probability. Time series used for frequency analysis must comply with the hypothesis of homogeneity, stationarity and randomness. To verify these hypotheses, three non-parametric tests were used: the Wilcoxon test for homogeneity, the Wald-Wolfowitz test for randomness and the Kendall test for stationarity. The Grubbs-Beck test was also used to detect potential outliers. Once these requirements were completed, 16 statistical distributions that are commonly used in hydrology were fitted to the data series, using the most adequate parameter estimation method for each distribution. The Bayesian information criterion (BIC), based on the log-likelihood function, was used to select the best distribution for each series:

$$\mathrm{BIC} = -2\log(L) + 2k\log(N) \tag{1}$$

where L is the likelihood function, k is the number of parameters and N is the sample size. The best distribution fit is the one associated with the smallest BIC. The three lowest scores were considered, in order to minimize the number of distributions selected. The χ^2 test was also used to verify the adequacy of fitting.

North American data sets

Data from 149 gauging stations in North America (Fig. 1) constituted the basis of the project. The selection criteria for these stations were record length, number of missing data, hypotheses tests and watershed size. All stations have 10 years or more of data with drainage areas of between 20 and 200 000 km^2.

Data series were screened to make sure they included no more than 60 missing days per year, except for the northern stations with no records during winter months. All these stations passed the Wilcoxon, Wald-Wolfowitz and Kendall tests at the 1%

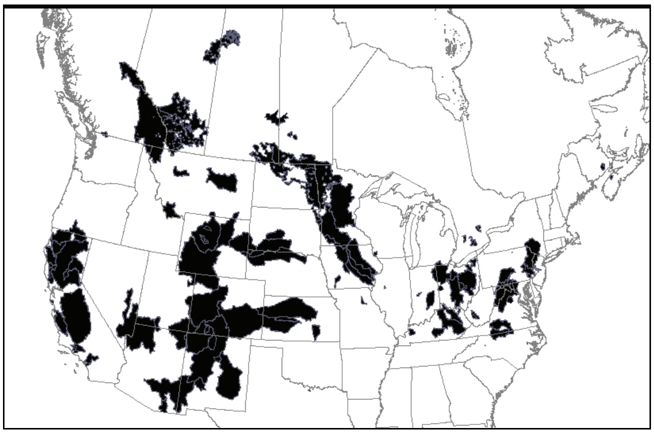

Fig. 1 Location of the 149 watersheds.

significance level. In Canada, the data were retrieved from the Environment Canada HYDAT Database (41 stations). In the USA, the data (108 stations) were provided by the US Geological Survey Sediment Database. These stations cover a wide range of climates and landscapes. Average record length is 17.5 years. Annual maximum values of SSC were extracted from all daily time series and screened for outliers. A GIS database was created to retrieve land cover, topography, soils and climate characteristics of the river basins. Boundaries of watersheds were found in Hydrologic Units of the USA (USGS) and using the National Scale Framework database of National Resources Canada. Climate data were collected from USHCN (NOAA), Environment Canada stations and interpolated by ordinary kriging. For the USA, a digital elevation model and land cover was provided by the USGS, soil data was extracted from the STATSGO database of USDA. For Canada, a digital elevation model and land cover came from the Department of Natural Resources, soil data from the Canadian Soils Information System, augmented by data provided by L. van Vliet, D. Brewin and W. Eilers of Agriculture and Agri-Food Canada. Parameters were spatially averaged within the boundaries of each watershed. Several parameters were extracted as shown in Table 1. Elevation data is available at 1:250 000 scale, and soil characteristics at 1:1 000 000 scale. Due to different classification systems and resolutions for the Canadian (1 km) and American (30 m) land cover data, several classes have been aggregated if they were similar in the two classifications.

RESULTS AND DISCUSSION

Seasonality of annual maximum of SSC

The SSC series used complied with hypotheses of homogeneity, randomness and stationarity as a prerequisite for frequency analysis. In Canada and the USA, the annual SSC maxima usually occur in spring and summer. For most stations in the Canadian Prairies, the annual maximum generally occurs in the summer. For rivers located in California, annual maxima are recorded during the winter season. Some stations exhibit a bimodal behaviour, with an annual maximum occurring in spring and

Table 1 Correlations of log-SSC mean and quantiles with physiographic parameters.

Watershed characteristics	Significant correlations at the 5% level					
Land use	C20	C10	C5	C2	CMO	CMA
Total forest (%)	–0.15	–0.16	–0.17	–0.18	–0.26	–0.17
Grassland	0.43	0.43	0.42	0.39	0.44	0.41
Total barren land (%)	0.14	0.13	0.11			
Urban/built-up (%)						
Water and lakes (%)						
Topography						
Size drainage area (km^2)	0.12	0.13	0.15	0.16	0.27	0.15
mean elevation (m)	0.31	0.29	0.27	0.24	0.27	0.27
Mean slope (%)	0.14	0.12				
Max elevation difference	0.30	0.29	0.27	0.24	0.26	0.27
Soils						
K Factor from USLE		0.11	0.13	0.15	0.11	0.13
S oil drainage class (1–7)	–0.28	–0.27	–0.25	–0.22	–0.18	–0.25
Available water capacity (mm)				0.13	0.12	
Depth to bedrock (cm)	–0.13	–0.12				
Coarse fragments (>2mm content, %)						
Bulk density (g/cm^3)	0.32	0.32	0.32	0.32	0.33	0.33
Volume cc sand (%)						
Volume of silt (%)						
Volume of clay (%)	0.18	0.20	0.21	0.21	0.25	0.20
Volume of organic materials (%)	–0.25	–0.26	–0.27	–0.28	–0..24	–0.27
Climate – hydrology						
Precipitation peakedness (%)	0.31	0.30	0.29	0.24	0.28	0.28
Mean annual precipitation	–0.38	–0.37	–0.36	–0.33	–0.40	–0.36
Mean annual temperature (°C)	0.13	0.14	0.15	0.16	0.11	0.15
Mean annual discharge (m^3)						
Mean annual maximum discharge (m^3)						

also in autumn from year to year. The Wilcoxon test was used on a seasonal basis to confirm that all annual SSC maxima for a given station come from the same population. The hypothesis of a homogenous population was found to be acceptable for all stations at both the 5% and 1% significance levels.

Selected distributions

The most adequate probability distributions for modelling extreme SSC events were selected based on the lowest score of the Bayesian information criterion. The most commonly used two-parameter distributions were lognormal, exponential, Gamma and Weibull. These distributions were selected for 80% of the data series (Fig. 2).

The remaining 20% of annual maximum SSC series were best fitted using six other distributions including the GEV, log-Pearson type III, Generalized Pareto and lognormal (three parameters) as well as two-parameter distributions such as the Normal or Leaks. There is also no apparent link between selected distributions and drainage area or length of time series. Geographically, SSC series from neighbouring

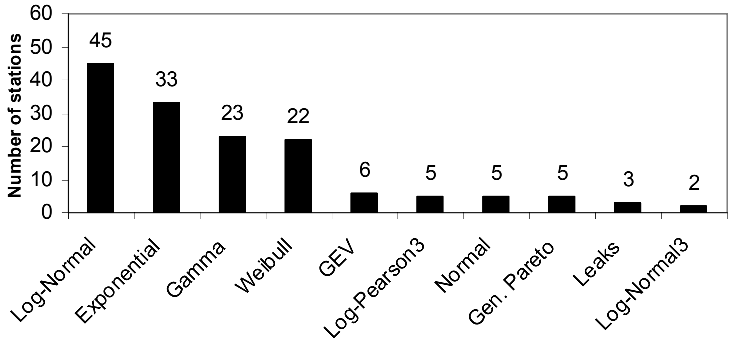

Fig. 2 Distributions selected by BIC criterion.

river basins or even sometimes two stations within the same basin could be fitted with a different statistical distribution. Using probability distributions to model the series of annual SSC maxima, it becomes possible to extract additional information on extremes. One application could be to estimate the quantiles of SSC for different return periods, from 2 years up to 50 years. It also becomes possible to associate return periods with certain values of SSC, for example lethal thresholds or stressful values for specific fish species. These thresholds can be established from several published studies (e.g. Wood & Armitage, 1997) or textbooks (Waters, 1995).

Figure 3 shows a map of quantiles corresponding to a T = 5-year return period. This figure shows spatial variability in SSC quantiles. It can be seen that most of the rivers located on the Atlantic coast, from the Maritimes region of Canada to the north-eastern states of the USA are characterized by SSC < 500 mg/L for a five-year return period. The highest SSC quantiles are found in the Midwest, the Rocky Mountains and

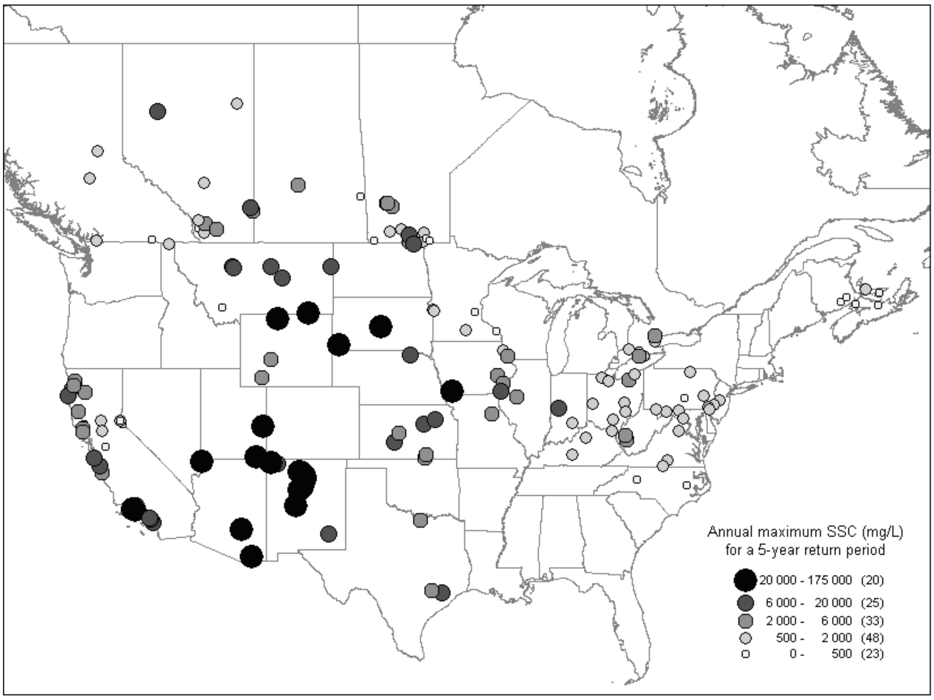

Fig. 3 Quantiles of SSC concentrations for a 5-year return period.

the Canadian and American Prairies. These results are consistent with those found by Meade & Parker (1984) or Dodds & Whiles (2004) using mean concentrations. It has to be taken into consideration that the right tail of the distribution is the one with the largest confidence interval, meaning that extrapolating for high return periods is less accurate (Klemes, 2000). Since SSC annual maximum series are significantly shorter than what is usually available for flood frequency analysis, there is a greater uncertainty concerning the distribution fit. Return periods that exceed twice the length of the available sample should be interpreted with caution.

Correlation with discharge

Since estimation of SSC is often done with rating curves that establish the relation between concentration and discharge, we analysed the correlation between annual SSC extremes and corresponding flow. For 65% of stations, the annual maximum SSC and annual maximum discharge occur during the same month. The correlations between each annual SSC maximum and discharges within a 5-day lag or lead were examined. The Kendall τ correlation coefficient based on rank, which is less sensitive to outliers, was preferred to the Pearson coefficient. There are significant correlations between annual maximum SSC and flow for 80 stations (53%) at the significance level of 5%. Correlation is greater when flow peak occurs after the annual SSC maximum. Median τ values are above 0.5 for correlation with discharge after the annual peak of SSC and less than 0.5 for correlation before. The average period between the SSC event and a peak of discharge (lag or lead) is 0.7 days. Most of the stations exhibit a clockwise hysteretic effect with high SSC preceding a high discharge event, and there are no particular geographic patterns for the stations that have a lead or a lag. Larger basins have a longer delay between peak SSC and the corresponding flow. These results are similar to those found by Dodds & While (2004) with mean SSC.

Correlations with watersheds characteristics

The Kendall τ rank correlation coefficient was computed between several physiographic features of the watersheds and SSC quantiles of return periods 20, 10, 5 and 2 years (C20, C10, C5, C2), as well as mean SSC (CMO) and mean annual maximum SSC (CMA). The results of the significant correlations at the 5% level are shown in Table 1. It can be seen that, in most cases, mean and extreme SSC variables are correlated with the same catchments attributes. SSC extremes are correlated with most land cover variables; there is a negative correlation with forest cover, and a positive correlation with grassland and barren land. "Cropland" and "wetland" are described by different categories in the USA and Canada land cover classifications at different scales (30 m for USA, 1 km for Canada). Comparing and interpreting such heterogeneous data at this scale is complex, as shown in several studies aiming to establish a link between land use and sediment yield (Walling, 1999). This difficulty is exacerbated in areas with changing agricultural practices. Higgitt & Lu (1999) showed the difficulties in assessing land use impact on sediment delivery at large catchments scales as well as the lack of synchronism between land use and SSC records. Therefore, we did not create a land cover class aggregating these different agricultural land use categories. In the USA, mean and extreme SSC show a positive correlation with orchards, vineyards, fallow and small grains, a negative correlation with pasture, hay (mean $\tau = 0.3$) and row crops (mean $\tau = 0.2$). There is also a negative correlation with wetlands (mean $\tau = 0.2$). The negative correlation with pasture, hay and row crops (corn, soybeans, cotton) and extreme SSC may show the effects of land conservation practices to reduce soil loss in high productivity areas (Walling, 1999). In Canada, among the six categories describing agricultural land use, there is a positive correlation with medium and low density cropland (mean $\tau = 0.2$), mainly located in the Prairies region, and no significant correlation with wetland cover.

SSC extremes are also correlated with mean elevation, maximum elevation difference and drainage area. The largest basins with high elevation are likely to have higher mean and extreme SSC values. Among soil characteristics, SSC are correlated with the soil erodibility factor (K) of the Universal Soil Loss Equation, and with quality of soil drainage, bulk density, clay and organic material volume in the top layers. Soil drainage is a categorical variable with seven classes of soils, each identifying soils with similar runoff potential under similar storm and cover conditions. Watersheds that include soils with a high erodibility factor (K factor) and are well drained and with a dense top layer can produce large amounts of fine sediment and therefore induce high SSC values. The amount of organic material in the top layers appears to be a limiting factor for extreme SSC. Strong correlations exist between SSC and annual precipitation and an index of precipitation peakedness (mean annual precipitation divided by the maximum monthly precipitation). Areas where there is less precipitation, but which occurs in rare events during the year, have the greatest mean and extreme SSC. Mean annual values for discharge and maximum discharge are not significantly correlated with SSC. These results of correlation analysis with mean SSC are similar to those found in previous studies. In their study on 622 American rivers, Dodds & While (2004) found positive correlations between mean SSC and cropland ($\tau = 0.16$) and drainage area ($\tau = 0.29$), as well as a negative correlation with forest cover ($\tau = -0.37$). Robertson & Saad (2003) studied 234 rivers in the Upper Midwest. They also found a negative correlation with forest and wetland cover, and a positive correlation with cropland, K factor and clay content of the soil.

CONCLUSIONS

This paper describes a local frequency approach as a preliminary study before developing a regionalization approach to estimate extreme SSC in ungauged catchments. The probabilistic approach provides a method to estimate annual SSC maxima at different return periods with the most adequate probability distributions. Discharge alone is not sufficient to estimate extreme SSC, therefore correlations between SSC and several physiographic features of the watersheds were investigated. Several land cover, soil and climatic characteristics have been identified as factors that could possibly be used to model extreme SSC in ungauged catchments.

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