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Implications of climate change in the twenty-first century for simulated magnitude and frequency of bed-material transport in tributaries of the Saint-Lawrence River

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Abstract:

More frequent extreme flood events are likely to occur in many areas in the twenty-first century due to climate change. The impacts of these changes on sediment transport are examined at the event scale using a 1D morphodynamic model (SEDROUT4-M) for three tributaries of the Saint-Lawrence River (Québec, Canada) using daily discharge series generated with a hydrological model (HSAMI) from three global climate models (GCMs). For all tributaries, larger flood events occur in all future scenarios, leading to increases in bed-material transport rates, number of transport events and number of days in the year where sediment transport occurs. The effective and half-load discharges increase under all GCM simulations. Differences in flood timing within the tributaries, with a shift of peak annual discharge from the spring towards the winter, compared to the hydrograph of the Saint-Lawrence River, generate higher sediment transport rates because of increased water surface slope and stream power. Previous research had shown that channel erosion is expected under all GCMs' discharge scenarios. This study shows that, despite lower bed elevations, flood risk is likely to increase as a result of higher flood magnitude, even with falling base level in the Saint-Lawrence River. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS morphodynamic model; Saint-Lawrence River; flood risk; bed-material transport; effective discharge; recurrence interval

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INTRODUCTION

From a global point of view, it is expected that climate change in the twenty-first century will increase both the magnitude and the frequency of floods as a result of an increase in rare meteorological events (Middelkoop *et al.*, 2001; Reynard *et al.*, 2001; Milly *et al.*, 2002; Prudhomme *et al.*, 2002; Robson, 2002; Lane *et al.*, 2007, 2008). Predicting extremes in a changing climate remains a challenge, particularly in terms of local flooding events (Hunt, 2002; Kundzewicz *et al.*, 2005; Kay *et al.*, 2006), but irrespective of the precise nature of hydrological change consequences for the transport of sediment by rivers are inevitable. To examine the role of climate-induced changes in the frequency, duration and seasonality of floods, an analysis of future sediment fluxes at the event scale is required.

One widely used approach for understanding how the trade-off between flood magnitude and frequency affects sediment transport is to combine the flow duration curve with a transport rating curve to determine the transport magnitude–frequency curve. Wolman and Miller (1960) proposed that the effective discharge (that which transports the greatest portion of the annual sediment load) is close to the bankfull discharge (with a recurrence interval of about 2 years) or mean annual flood (Wolman and Miller, 1960; Pickup and Warner, 1976; Andrews, 1980; Carling, 1988; Nash, 1994; Emmett and Wolman, 2001; Barry *et al.*, 2008). However, the frequency of occurrence of the effective discharge is known to vary greatly (Pickup and Warner, 1976; Ashmore and Day, 1988; Nash, 1994; Torizzo and Pitlick, 2004). Furthermore, for a given mean discharge and sediment rating curve, the effective discharge has been shown theoretically to be higher when the variability in discharge is greater (Nash, 1994; Vogel *et al.*, 2003). Long-term sediment yield may be dominated by rarer catastrophic events, particularly in steep gravel-bed rivers (Kirchner *et al.*, 2001; Lenzi *et al.*, 2006), although there is yet no consensus on this issue. An alternative approach, such as the half-load discharge (the flow value above and below which half the long-term sediment load is transported), was also presented by Wolman and Miller (1960), although most of the subsequent literature has only used their effective discharge method. Vogel *et al.* (2003) revived this second approach, which they considered more meaningful to determine which discharges are responsible for carrying most of the long-term load. Despite the work of Coulthard *et al.* (2005, 2008), Kundzewicz *et al.* (2007) and Gomez *et al.* (2009), very little work has been done on the impacts of the expected increase in high-magnitude

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floods due to climate change on sediment loads in rivers, particularly with respect to bedload transport.

We have examined elsewhere the likely impacts of climate change on mean annual bed-material transport rates (fine sand and coarser) and aggradation/degradation in the lowermost parts of three tributaries of the Saint-Lawrence River (Verhaar *et al*., 2010). Predicted changes in temperature and precipitation from global climate models (GCMs) were transformed into daily discharges using a hydrological model (HSAMI). A one-dimensional (1D) morphological model (SEDROUT4-M, Hoey and Ferguson, 1994; Verhaar *et al*., 2010), using these simulated discharges, predicted an increase in sediment transport in these sand-bed rivers, and hence an increase in the sediment delivery to the Saint-Lawrence River, with the largest changes occurring during the winter and spring seasons (Verhaar *et al*., 2010; Boyer *et al*., 2010a,b). The objective of this study is to examine climate-induced changes in the magnitude–frequency–duration relation for bed-material load in these tributaries as a consequence of climate change.

STUDY AREA

The three tributaries of the Saint-Lawrence River (Batiscan, Richelieu and Saint-François Rivers) are located between Montréal and Québec City, Eastern Canada (Figure 1). They have large catchment areas ($>$10 000 km^2), low distal gradients ($<$0·0001) and predominantly sandy beds (Table I). The bankfull width-to-depth ratio of the tributaries ranges between 25 and 62. Their planforms are generally straight, except for the most upstream section of the Batiscan River, which has irregular meanders, and for a large island in the downstream section of the Saint-François River. With the exception of 18 (out of 79) sections located in the apex of meanders in the Batiscan River, cross-sectional shapes are close to rectangular. Each river is exploited for hydroelectricity or influenced by dams used for flood control, water intake or recreational activities, but the impact of these structures on the natural flow regime of the river is low for the Batiscan and Richelieu Rivers and only moderate for the Saint-François River (Boyer *et al*., 2010b).

Morphodynamic simulations by Verhaar *et al*. (2010) indicate that the Batiscan River is currently slowly aggrading, the Saint-François River is slowly degrading and the Richelieu River is close to equilibrium. As the results of Verhaar *et al*. (2010) suggest that the morphological state of a river gives rise to variable responses to climate change, the magnitude–frequency analysis in this study has been conducted for all three tributaries.

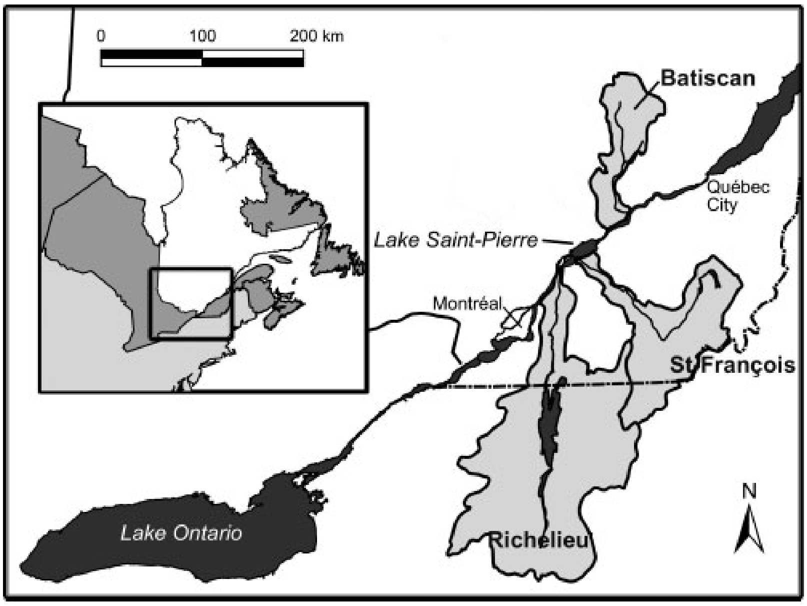

Figure 1. Location of the studied Saint-Lawrence River tributaries

Table I. Characteristics of the studied tributaries

River	Water surface bankfull width (m) mean	(min–max)	Length of studied reach (km)	Mean discharge (m^3/s)	(mean annual flood)	Energy slope of studied reach (−)	Upstream sediment size D_{50}–D_{84} (mm)	Downstream sediment size D_{50}–D_{84} (mm)
Batiscan	167	(77–277)	17	99	(613)	6×10^{-5}	0·52–1·03	0·37–0·57
Richelieu	198	(89–278)	15	346	(1045)	5×10^{-5}	0·41–0·89	0·32–0·48
Saint-François	233	(88–415)	15	208	(1421)	3×10^{-5}	8·04–17·57	0·30–0·38

Detailed profiles of bed topography were taken in 2004 and 2005 with a boat-mounted echo sounder at several cross sections (ranging from 79 to 100 per tributary, with a spacing of 80–300 m), from the tributary confluences with the Saint-Lawrence River to 15–17 km upstream. Bed composition was obtained from samples also collected from a boat using a grab bucket. A detailed description of the field data collection, river characteristics and validation of the morphodynamic model can be found in Verhaar *et al.* (2008, 2010).

METHODOLOGY

Climate scenarios

Three GCMs (CSIRO-Mk2, ECHAM4 and HadCM3) and two greenhouse gas (GHG) emission scenarios (A2 and B2, Nakicenovic *et al.*, 2000; Raupach *et al.*, 2007) were used by the Ouranos research centre, a consortium on regional climatology and adaptation to climate change (www.ouranos.ca), to produce discharge scenarios for the three tributaries (Chaumont and Chartier, 2005; Boyer *et al.*, 2010b). The resolution in latitude and longitude for CSIRO-Mk2, ECHAM4 and HadCM3 is respectively $3{\cdot}2^\circ \times 5{\cdot}6^\circ$, $2{\cdot}8^\circ \times 2{\cdot}8^\circ$ and $2{\cdot}25^\circ \times 3{\cdot}75^\circ$ (Chaumont and Chartier, 2005). Current GHG emissions exceed both the A2 and B2 scenarios, but A2 is closest to the actual emissions (Raupach *et al.*, 2007), and only these results are presented here. The GCMs were selected on the basis of their differences in predictions of precipitation and temperature to represent a wide range of outputs when compared to a multi-model dataset (Meehl *et al.*, 2007). The standard perturbation (or delta) method was used to add predicted changes in precipitation, temperature and evapotranspiration to an observational database, which is used as input to a hydrological model to represent future climate (Arnell, 1998; Rosberg and Andréasson, 2006; Graham *et al.*, 2007; Rydgren *et al.*, 2007). The use of the Canadian regional climate model (CRCM, Caya and Laprise, 1999) was not considered to be optimal in this case as preliminary analyses by Ouranos showed that, in southern Québec, where the topography is relatively smooth and the climate is not influenced by maritime conditions, using delta values for regional models at a 45-km resolution added little information compared to delta values derived from GCMs at a 250-km resolution (Boyer *et al.*, 2010b).

The hydrological model HSAMI (Chaumont and Chartier, 2005; Minville *et al.*, 2008; Boyer *et al.*, 2010b), which is a lumped rain and snowfall runoff model used by Hydro-Québec (Québec national hydro-electricity company), was used by Ouranos to produce the three GCM time series of daily discharge values. The delta values (precipitation and temperature) were added to the reference period (1961–1990) for three different 30-year time periods or 'horizons' (2010–2039, 2040–2069 and 2070–2099). The model was calibrated and validated on measured discharge data over the 1961–1990 time period with high Nash coefficients of 0·85, 0·83 and 0·79 for the Batiscan, Saint-François and Richelieu Rivers respectively (Chaumont and Chartier, 2005; Boyer *et al.*, 2010b). The simulated daily discharges for the 1961–1990 period are used as a reference discharge scenario for the morphological modelling by repeatedly using the same 30-year daily discharge time series for the periods 2010–2039, 2040–2069 and 2070–2099, referred to as RefQ hereafter. Despite using the same input discharge for each future horizon in the RefQ scenario, the morphological outcomes differ as the river bed evolves over time. More details on the simulation scenarios can be found in Boyer *et al.* (2010b) and Verhaar *et al.* (2010).

Morphodynamic model

In this study, only bed-material transport in the lower reaches of the tributaries is considered. Washload supplied from the catchments is excluded as it does not contribute to river morphology and it requires a catchment-wide erosion model as it is supply limited. We have used a reach-scale morphodynamic model to take into account the throughput of sediment supplied from upstream and the within-reach gain (or loss) of sediments from the channel bed. This approach also allows the long profile and bed composition (and through them the local transport rates) to vary over time in response to any changes in base level and hydrology. In the context of climate change simulations for the twenty-first century, we decided that running long-term simulations with a daily time step over long reaches could only be achieved through a 1D model in which channel width is spatially variable but invariant over time, and flow and transport calculations are made using width-averaged properties. One consequence of this decision is that any divergence in bed-material flux is accommodated entirely by a change in bed elevation, whereas in reality there is probably some accompanying adjustment of width. However, there is no well-tested way to predict event-by-event width changes over many decades in both degrading and aggrading conditions. Like others (e.g. Gomez *et al.*, 2009), we therefore adopted the fixed-width approach. Another potential limitation of 1D models is that, because local bed-material load is a non-linear function of the local flow strength, a width-averaged calculation underestimates the total load of the river to the extent that there is spatial variance in the excess of flow strength over the threshold for motion. However, Ferguson (2003) showed by quantitative analysis that this bias is much smaller for sand-bed rivers than for gravel-bed rivers due to significantly higher excess shear stresses in the former case, and is also smaller for relatively uniform cross sections than for those of actively meandering or braided rivers. In the present case, the bias during a range of flood conditions is calculated to be typically only about 10% and never more than 20%, so that it will have little effect on the pattern of results.

Simulations were made using SEDROUT4-M, a modified version of SEDROUT (Hoey and Ferguson, 1994) that allows simulation of sand-bed rivers, variable discharge, downstream water level fluctuations and flow and sediment routing in channels with islands. A detailed description of SEDROUT4-M and a morphological validation are provided in Verhaar *et al.* (2008).

The model is forced by daily discharges and downstream water levels. From the step backwater solution of the width- and depth-averaged hydraulic continuity and momentum equations, the shear stress at each cross section is predicted using a calibrated constant roughness (Manning-n) value. The shear stress is used to predict bed-material transport rates of each of 10–13 half-phi grain size fractions. After each time step, the bed elevation and bed composition are updated using both overall and fractional conservation of sediment. This model has been fully validated and proven to be capable of simulating morphological changes over different lengths of longitudinal profiles at various temporal scales (e.g. Hoey and Ferguson, 1994; Talbot and Lapointe, 2002; Hoey *et al.*, 2003; Ferguson and Church, 2009). Initial bed topography and bed composition are based on observations (2004/2005), which take into account cross-section averaged bed composition. Because sediment supply to the study reaches is unknown, we assume a bedload supply equal to the transport capacity as an upstream boundary condition for each time step. This is a common assumption in long-term modelling and is reasonable for sand-bed rivers as they are typically transport limited (e.g. Montgomery and Buffington, 1997). This condition causes upstream sediment supply to vary with bedload transport capacity (i.e. with changes in discharge and any change in slope following aggradation or degradation in the upstream segment of each reach). Verhaar *et al.* (2010) present a sensitivity analysis to test the effect of this assumption, which shows that setting supply to slightly less or more than capacity has little impact on sediment output from the reach during the first two horizons, but more during the third horizon. However, the effect was less when there was no downstream water-level decrease, as is the case in this study.

Climate change models use fixed time horizons in the future, i.e. the 2020s (2010–2039), the 2050s (2040–2069) and the 2080s (2070–2099), so we either had to assume that the channel configuration in 2010 would be the same as we had measured in 2004/2005 or to model changes over the intervening 5 years. We chose the latter approach and simulated morphological changes from 2004–2005 to 2010 using observed discharges in the period from 2000 to 2005 and averaged water levels in the Saint-Lawrence River as measured over 1996–2005 at gauging stations close to the river mouths. No exceptional flood occurred during the 2005–2009 period, and the mean annual maximum discharges in the period 2005–2009 were similar to the 30-year values used in our simulations for the three tributaries. The different modelled trends of aggradation (Batiscan River), near-equilibrium (Richelieu River) and degradation (Saint-François River) are also consistent with field observations. The bed topographies and composition predicted by these simulations were used as initial conditions for the near-future simulations over the period 2010–2099.

Climate changes are expected to result in a decrease in the Saint-Lawrence River level due to increased evaporation in the Great Lakes following temperature increases (Croley, 2003; Chaumont and Chartier, 2005; Morin *et al.*, 2005). Verhaar *et al.* (2010) present simulations with both steady water levels and a steady decline in the base level of 0·01 m/year. Here, we focus on the current daily-averaged Saint-Lawrence water levels, although the effects of steady base level fall on the results are also discussed later.

Bed-material transport rates were simulated with the Ackers and White (1973) total load formula and the parameter settings from White and Day (1982). A fixed washload cut-off size has to be specified in the model to avoid the mass conservation issues that would arise if the cut-off was allowed to vary in space and time. By equating settling velocity (from the universal equation of Ferguson and Church (2004)) with shear velocity, we calculated that particles smaller than 0·125 mm (3φ) would be washload in most events and places and are therefore neglected in the morphodynamic model. For low and moderate flow conditions (under bankfull), SEDROUT4-M was found to simulate the water level and mean cross-sectional velocities accurately (Verhaar *et al.*, 2008). The morphological performance of the model was also verified by comparing simulated changes in bed topography over a period of 1 year with observed changes (Verhaar *et al.*, 2010). Although this period is unavoidably short, trends in erosion and sedimentation pattern were well captured showing the applicability of this model. Furthermore, the simulations are compared to a reference scenario in an effort to eliminate or reduce uncertainty of morphological modelling. That is to say, we are comparing relative changes between different simulation scenarios.

Verhaar *et al.* (2010) showed that SEDROUT4-M results for the studied tributaries are not sensitive to grain size distribution at the top of each reach. However, uncertainty in bedload transport predictions resulting from entrainment thresholds and transport equations is harder to assess. Several transport equations (Einstein, 1950; Parker, 1990; Wilcock and Crowe, 2003) were tested in Verhaar *et al.* (2008) before choosing the Ackers and White (1973) model. The simulated morphological changes were also shown to be in good agreement with measured bed elevation changes over a 1-year period in the Batiscan and Richelieu Rivers (Verhaar *et al.*, 2010). For the Saint-François River, although the simulation and measurements both indicated that the reach is undergoing degradation, the amplitude of changes in the simulations was markedly lower than that in the measurements (Verhaar *et al.*, 2010). The difference in grain size distribution between the upstream and downstream reaches of the Saint-François River is much larger than for the two other tributaries, and, although the Ackers and White (1973) formula was most appropriate for the sandy reaches, our tests reveal that it may have under-predicted sediment transport in the upstream zone. However, this did not result in an overestimation of degradation compared to field measurements. Thus, it is likely that using different sediment transport equations would alter the numbers, but would not affect the general tendency in each reach when different scenarios are compared.

Event analysis

Differences in mean annual bed-material transport strongly depend on discharge scenarios resulting from different GCMs (Verhaar *et al.*, 2010). However, to examine how more extreme events associated with climate change affect bed-material transport, in this study we compare scenarios for different tributaries at the sediment transport event scale instead of the annual scale. Unlike in gravel-bed rivers, where sediment transport drops to zero between events, sand-bed rivers are often characterized by very long tails in sediment transport curves at low discharges. To analyse data at the event scale, bed-material transport events were defined here as successive days of bed-material transport exceeding 10 m^3/day (~1 g/m/s), with a single peak of bed-material transport of over 50 m^3/ day. These values were determined after examining several sediment transport events associated with several multiple peak floods. Events were separated where the minimum transport between two peaks occurred. For each sediment transport event, the maximum discharge, duration and transported volume were calculated.

Discharges are expressed in recurrence intervals to facilitate the comparison between the different tributaries and between the climate scenarios. They were calculated with the Pearson-type III approach from the annual maximum discharge time series. For each tributary, the present-day recurrence intervals were computed from the 1932–2004 record (HYDAT, Environment Canada), whereas the future recurrence intervals were obtained from the 2010–2099 series for each GCM scenario. Note that the perturbation method used in this study, which has the advantage of being stable and robust (Graham *et al.*, 2007), replicates the inter-annual variability of climate variables of the reference period and thus cannot introduce new types of variability, which may occur under future climate (Boyer *et al.*, 2010b). The frequency/magnitude analysis and calculation of recurrence intervals for future scenarios must therefore be used with caution. However, the objective here is not to predict future discharge values corresponding to a given recurrence interval, but rather to investigate the relative contributions to sediment transport of events of different recurrence intervals.

Effective and half-load discharge

Wolman and Miller (1960) noted that, because transport rates tend to zero in the lowest flows, but flow frequency tends to zero at the highest transport rates, the product of transport rate and frequency must be greatest at some intermediate discharge, which they termed the effective discharge. Estimated values of effective discharge depend on the choice of discharge intervals (called bins hereafter) for which the daily sediment transport volumes are summed (Crowder and Knapp, 2005). The effective discharge was calculated for about 25 arithmetic bins, following Crowder and Knapp (2005). The chosen class intervals have a bin width of 30, 50 and 70 m^3/s for the Batiscan, Richelieu and Saint-François Rivers respectively, although our tests using alternative bin widths did not reveal marked differences. Nevertheless, the effective discharge metric has been criticized as it does not clearly document which discharges are responsible for carrying the bulk of the long-term load (Vogel *et al.*, 2003; Doyle and Shields, 2008). Hence, an alternative approach using the half-load discharge is also used. This is defined as the discharge value above and below which 50% of the total load is transported (Wolman and Miller, 1960; Vogel *et al.*, 2003).

RESULTS

Hydrology

Discharges corresponding to present-day recurrence intervals of 1, 2, 5, 10, 20 and 50 years for the three tributaries are presented in Table II. The mean annual maximum discharge for the RefQ scenario (1961–1990) in each tributary is close to the 2-year recurrence interval. When comparing each recurrence interval to the present-day 2-year recurrence interval, there is a tendency for high discharge events (long recurrence intervals) to become more frequent, particularly for the Richelieu River (Figure 2). For the Batiscan and Saint-François Rivers, this trend is less marked, but it is visible for the 50-year recurrence interval, with the exception of the ECHAM4 scenario (Figure 2a and c).

The change in the mean annual maximum discharge for the three GCMs does not show a consistent trend for all the tributaries and is markedly different from the change in the mean daily discharge, with a larger variation for the mean annual maximum discharge (−21 to +44%) compared to that for daily discharges (−10 to +14%) (Table III). However, in most of the cases (with two exceptions), the direction of change (either increasing or decreasing) remains the same for the two types of discharge. The changes in the mean annual

Table II. Discharge (m^3/s) associated with recurrence intervals of 1, 2, 5, 10, 20 and 50 years for the three tributaries, based on the present-day (1932–2004) records at gauging stations

Recurrence interval	1	2	5	10	20	50	Q_{MAM}
Batiscan	315	587	741	841	936	1059	465
Richelieu	538	1025	1246	1375	1488	1623	1095
Saint-François	661	1360	1755	2012	2255	2567	1277

Q_{MAM} is the mean annual maximum discharge for the reference scenario.

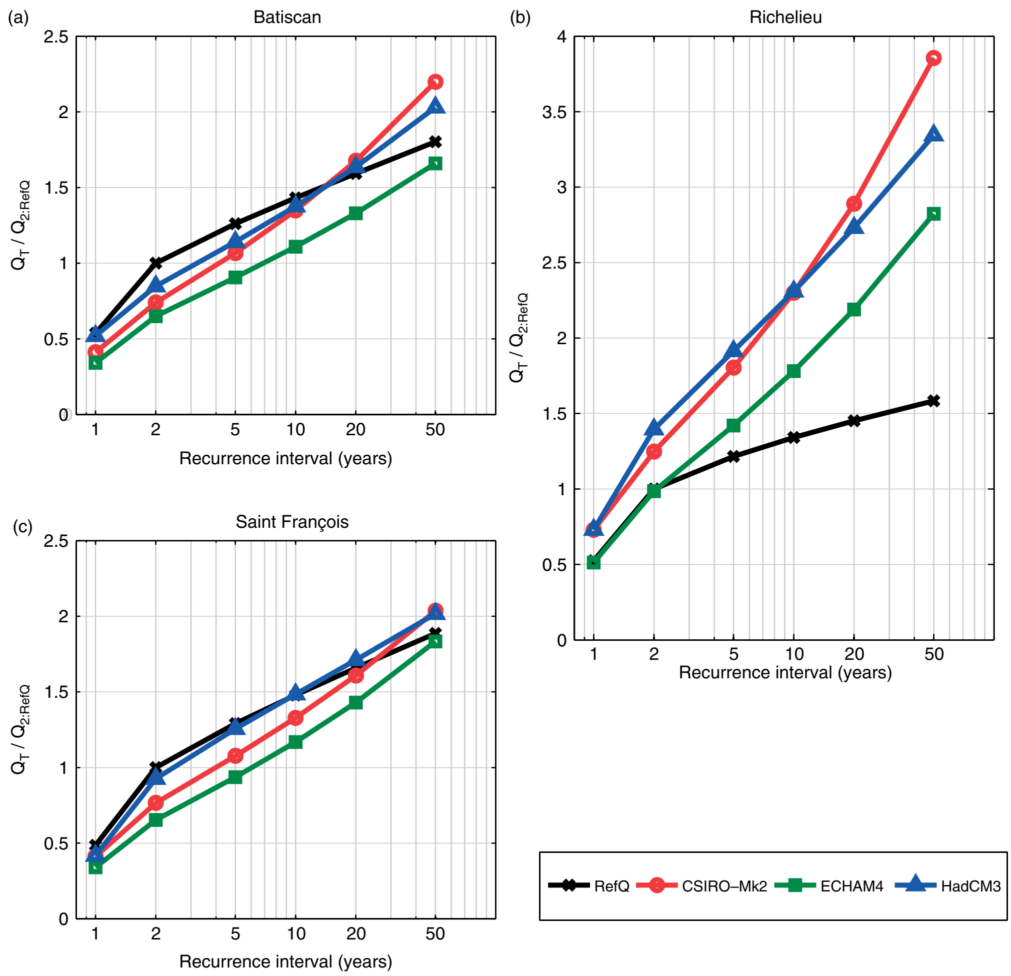

Figure 2. Dimensionless flood frequency expressed as discharge of a given recurrence interval divided by discharge of a 2-year recurrence interval in the reference scenario (RefQ), against recurrence interval for (a) the Batiscan River, (b) the Richelieu River and (c) the Saint-François River

Table III. Percentage of change in mean daily discharge (Q_{daily}) and the mean annual maximum discharge (Q_{MAM}) for the period 2010–2099 compared to the RefQ scenario for three GCMs in each tributary

	CSIRO-Mk2		ECHAM4		HadCM3		Mean	
	Q_{daily} (%)	Q_{MAM} (%)	Q_{daily} (%)	Q_{MAM} (%)	Q_{daily} (%)	Q_{MAM} (%)	Q_{daily} (%)	Q_{MAM} (%)
Batiscan	6	8	−7	−9	10	19	3	6
Richelieu	6	36	−9	5	14	44	4	28
Saint-François	4	−8	−10	−21	9	6	1	−8
Mean	5	12	−9	−8	11	23		

maximum discharge are largest for the Richelieu River where it increases in all GCM scenarios. The ECHAM4 model reduces the mean daily discharge for all tributaries, whereas the HadCM3 model results in the largest differences for both the daily and the mean annual maximum discharge (Table III). For each GCM scenario, the direction of change in the mean annual maximum discharge compared to that in RefQ varies from year to year, as illustrated in Figure 3 for the Batiscan River. The CSIRO-Mk2 and HadCM3 models generally predict higher floods than ECHAM4. For all tributaries, the timing of flood events also changes for all GCMs, with the spring flood expected to advance by 22–34 days by the last horizon (2070–2099) (Boyer *et al*., 2010b).

Sediment transport

Magnitude–frequency analysis. The impact of GCM scenarios on the effective discharge is examined in Figure 4, which shows sediment load histograms for the first and last horizon in all tributaries. All three tributaries have a bimodal distribution of bed-material transport in the RefQ scenario, which might imply that both high- and low-frequency events are important for long-term sediment transport volume. The effective discharge is around the 2-year (present-day) recurrence discharge for the Richelieu and Saint-François Rivers (Figure 4b and c) and around the 5-year (present-day) recurrence interval for the Batiscan River (Figure 4a). The transported volume varies for the three horizons, with

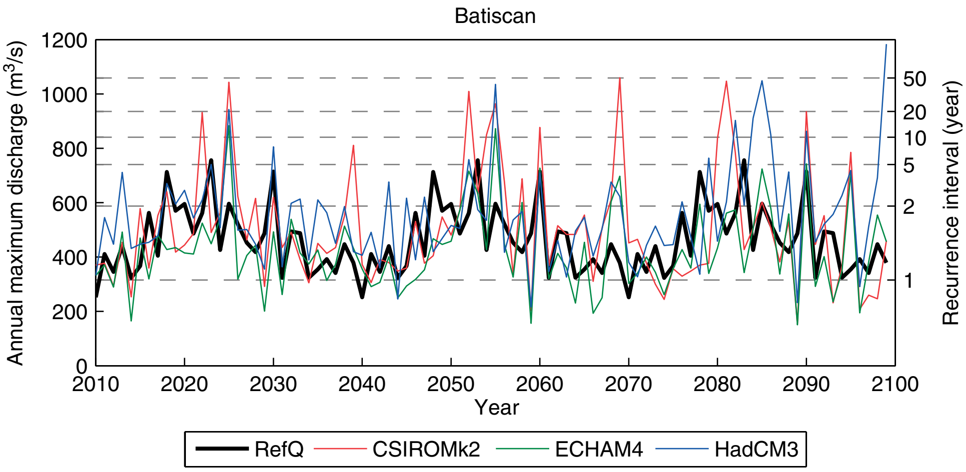

Figure 3. Annual maximum discharge of each river over the simulated period (2010–2099) for the RefQ and GCM scenarios for the Batiscan River. Dashed lines refer to the different discharges associated with recurrence interval of 1, 2, 5, 10, 20 and 50, based on the 1932–2004 records at the Batiscan gauging station

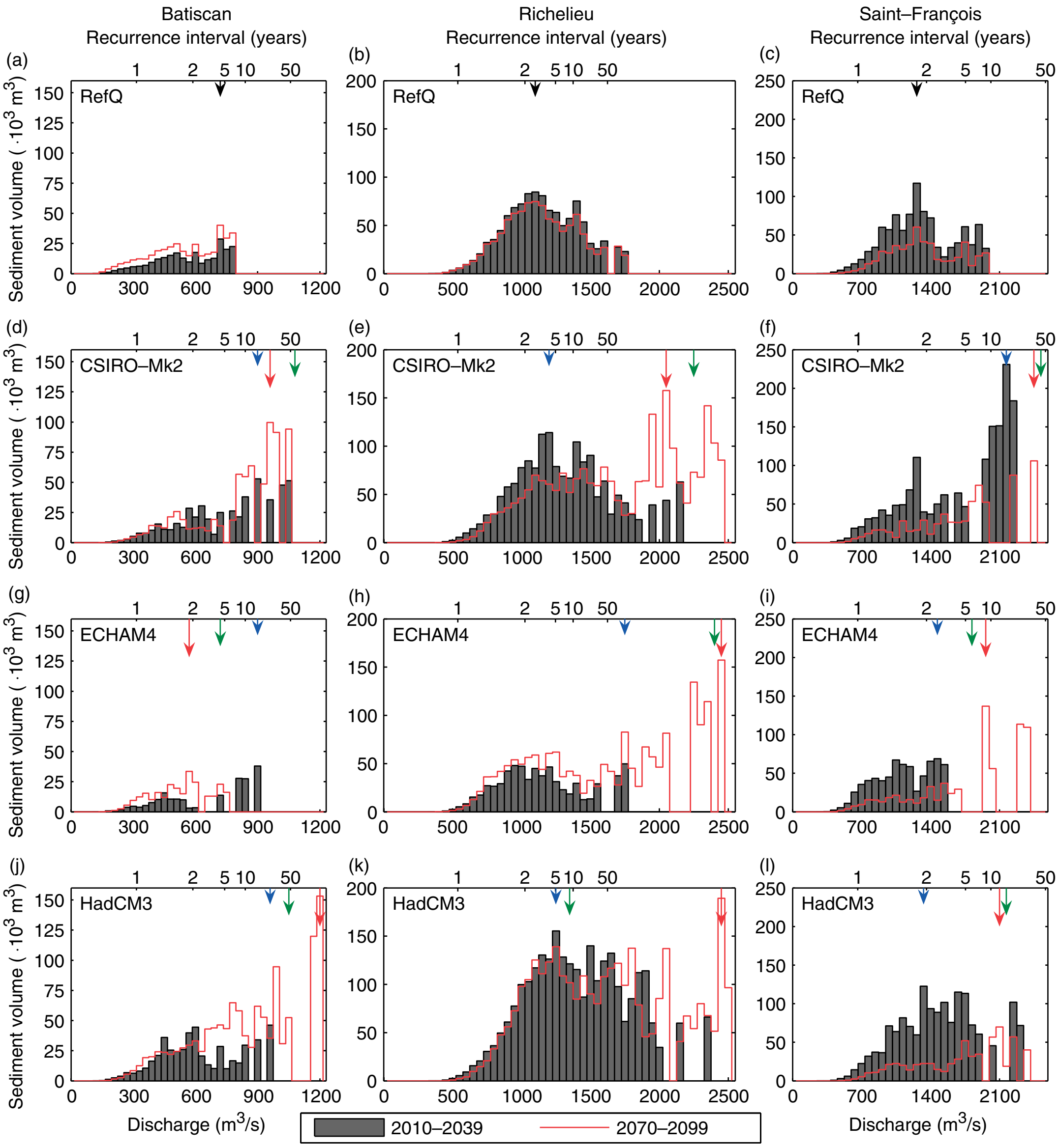

Figure 4. Histograms of bed-material sediment transport as a function of discharge at the downstream boundary for the first (2010–2039) and last (2070–2099) horizons for the Batiscan River (a,d,g,j), the Richelieu River (b,e,h,k) and the Saint-François River (c,f,i,l) for the RefQ (a,b,c), CSIRO-Mk2 (d,e,f), ECHAM4 (g,h,i) and HadCM3 (j,k,l) models. The arrows indicate the effective discharge for each horizon (black: RefQ, small blue: first horizon, medium green: second horizon and long red: third horizon). The upper *x*-axis represents the present-day recurrence intervals from the 1932–2004 records

Table IV. Half-load discharge (m^3/s) for each discharge scenario for each horizon and for the entire simulated period

	Horizon	RefQ	CSIRO-Mk2	ECHAM4	HadCM3
Batiscan	2010–2039	522	623	470	551
	2040–2069	506	750	603	567
	2070–2099	500	760	516	721
	2010–2099	**509**	**717**	**538**	**621**
Richelieu	2010–2039	1112	1233	1052	1370
	2040–2069	1102	1353	1175	1293
	2070–2099	1093	2022	1366	1711
	2010–2099	**1102**	**1516**	**1203**	**1464**
Saint-François	2010–2039	1210	1362	1076	1416
	2040–2069	1226	1516	1329	1400
	2070–2099	1251	1620	1906	1745
	2010–2099	**1225**	**1463**	**1279**	**1469**

Half-load discharge is defined as the value above and below which 50% of the total load is transported.

an increase for the Batiscan River, a slight decrease in the Richelieu River and a decrease in the Saint-François River. For the GCM scenarios, the effective discharge increases by several bin classes to discharges with present-day recurrence intervals of more than 50 years, with a clear shift towards higher discharge from the first to the last horizon (2070–2099). For all tributaries, the CSIRO-Mk2 and HadCM3 models have similar effective discharges with an increase in their value with time compared to the RefQ scenario. For the ECHAM4 model in the Batiscan River (Figure 4g), the effective discharge decreases over time and becomes smaller than the RefQ scenario in the last horizon.

Half-load discharges also increase for all the GCM scenarios over the 2010–2099 period, although less so for the ECHAM4 model (Table IV). The half-load discharge for each horizon remains fairly constant within the RefQ scenario, in a similar way to the effective discharge. For GCM scenarios, the overall trend is an increase compared to the RefQ as well as an increase towards the last horizon (Table IV). The CSIRO-Mk2 produces the largest increase (33% on average for the three rivers for the entire period), followed by HadCM3 (25%) and ECHAM4 (6%). Note that changes in half-load discharges exhibit markedly less variability than the effective discharge changes (Figure 4).

The bed-material transport rate has a higher variation than water discharge, mainly because of the non-linear character of sediment transport. The change in bed-material volume transported over the whole simulation period (2010–2099) is presented in Figure 5. In this figure, sediment volume is split in recurrence interval ranges. For example, bed-material transported during floods with a maximum discharge falling between recurrence intervals of 2–5 years were grouped together (green in Figure 5). The present-day recurrence intervals are used for the RefQ scenarios of each tributary, whereas the future recurrence intervals are used for the three GCM scenarios. The total bed-material transport increases the most for the HadCM3-scenario, with values 209%, 286% and 134% of the volume in the RefQ scenario for the Batiscan, Richelieu and Saint-François Rivers respectively. The CSIRO-Mk2 model also results in increased transport, whereas ECHAM4 simulations are usually close to, or slightly less than, the RefQ (Figure 5). In the two cases where the changes in mean daily and annual maximum discharge are opposite to each other (Richelieu River, ECHAM4, and Saint-François River, CSIRO-Mk2, Table III), the total bed-material transport remains close to the RefQ scenario.

In the RefQ scenario, discharges with a recurrence interval of 2 years or less transport about 50% of the sediments in the Batiscan and Saint-François Rivers (Figure 5). In all GCM scenarios, this proportion is reduced for the Batiscan and Saint-François Rivers, but it increases for the Richelieu River except for the ECHAM4 scenario (Figure 5). However, with the CSIRO-Mk2 and HadCM3 scenarios, the total volume of transported sediment increases, thus the proportion of transport associated with discharges having recurrence intervals of 2 years or less is smaller (17% on average for all tributaries, with a range from 7 to 35%). In the Richelieu River, discharges with recurrence intervals of 5 years or less contribute to 50% of the total volume in the RefQ scenario. This volume, as well as volumes associated with larger recurrence intervals, remains similar in all GCMs in the Richelieu River (Figure 5b). However, in the Batiscan and Saint-François Rivers, there is a marked tendency for extreme events (with long future recurrence intervals) to be responsible for a larger proportion of the volume of transported sediments under all GCM scenarios (Figure 5a and c). For example, the five largest sediment transport events in the CSIRO-Mk2 transport 36% of the total volume in the Batiscan River, and 29% of the total volume in the Saint-François River. In the RefQ scenario, the five largest events transported only 24% and 13% of the total volume in the Batiscan and Saint-François Rivers respectively.

The threshold discharge for sediment transport in the Richelieu River is estimated at 450 m^3/s. The mean daily discharge for the RefQ scenario in this river is 437 m^3/s, and is thus very close (97%) to this threshold. The Batiscan and Saint-François Rivers have estimated threshold values of approximately 150 and

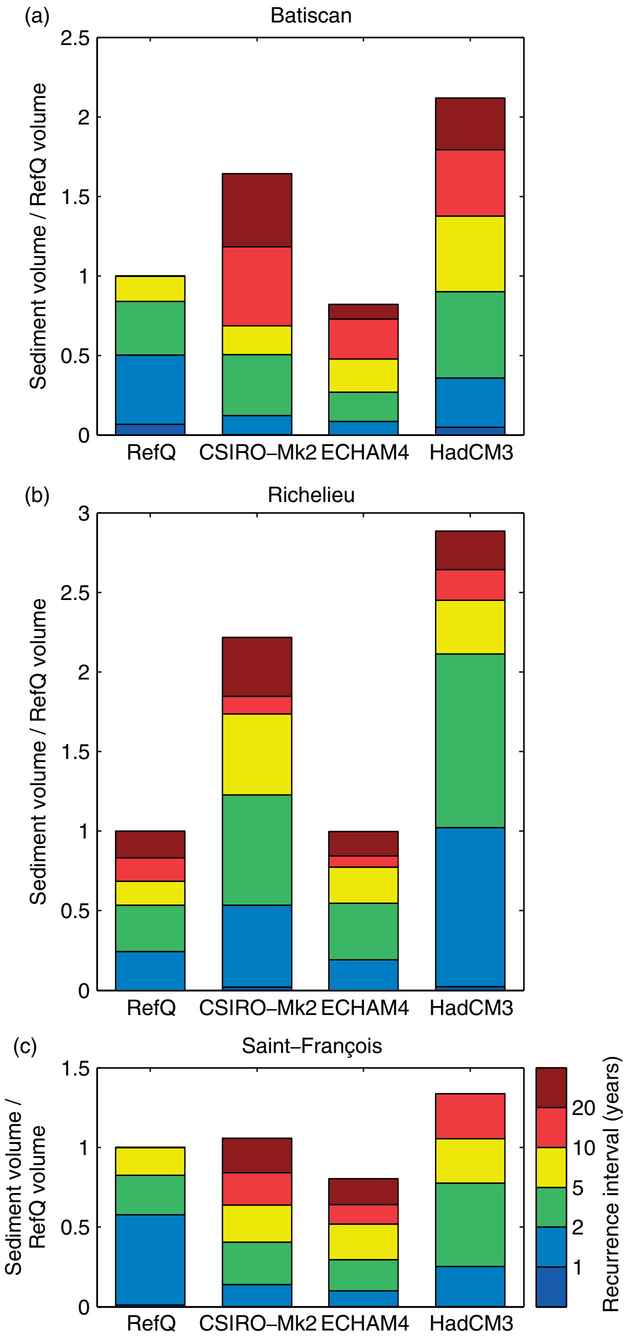

Figure 5. Sediment transport volume as a fraction of the total volume transported with the RefQ scenario for (a) the Batiscan River, (b) the Richelieu River and (c) the Saint-François River. Sediment volumes associated with events where the maximum discharge is within the same range of recurrence intervals within the scenario are grouped together. For the RefQ scenario, the present-day intervals (1932–2004) are used, whereas the future recurrence intervals (2010–2099) are used for each GCM

330 m^3/s, respectively, with mean discharges of 97 and 196 m^3/s for the RefQ scenarios, which correspond to 65% and 60% of the threshold discharge, respectively. The Richelieu River is the only tributary where in the future scenarios the mean discharge exceeds the threshold value for sediment transport, which partly explains why the increase in sediment volume is higher in this river (Figure 5b).

Event analysis. When events of specific recurrence intervals are examined more closely, the variability of sediment transport volume becomes apparent (Figure 6). In Figure 6, all flood events (i.e. from RefQ and GCM simulations) are combined together as no difference in trend was observed between them. In other words, an event with a maximum discharge of, say, 500 m^3/s in the RefQ time series for a given river should result on average in the same volume of bed-material transport as a 500 m^3/s event size in the GCM time series. Figure 6 presents relative sediment transport rates per event, defined as the volume of each individual event divided by the average volume of all events in a given river. The variability in sediment transport per event is particularly large for discharges smaller than 587, 1025 and 1360 m^3/s for the Batiscan, Richelieu and Saint-François rivers respectively (events that occur more than once every 2 years), which is likely due to the wide range of event duration for these discharges (Figure 6). Floods with a recurrence interval larger than 2 years generally transport more than the mean volume of all events and their variability is much less than that of the lower magnitude events. The larger events are also less sensitive to the duration as the volume of transport mainly depends on the maximum discharge, which greatly exceeds the threshold of sediment transport.

The effect of flood peak and duration on bed-material transport volume is further investigated in Figures 7–9 for the reference and GCM scenarios. Individual events are plotted in these diagrams as circles of area proportional to the bed-material volume. Vertical dashed lines indicate the half-load discharge over the 2010–2099 period in the RefQ scenario, which is used to separate 'small' and 'large' events. Note that, because the total sediment volume transported for a given event is plotted for the maximum discharge of the event (i.e. it is not plotting daily sediment volume related to a given daily discharge), the proportion of large events (on the right side of the vertical dashed line in Figures 7–9) is larger than 50% by definition. The median duration of sediment transport events in the RefQ scenario was used as a threshold to separate short from long events (horizontal dashed line).

As expected, there are more small-magnitude, short-duration events—falling in the lower left zone in Figures 7–9)—for all tributaries and GCMs. For the Batiscan and Saint-François Rivers (Figures 7 and 9), the relative contribution of short events (below the horizontal dashed line) increases from 30% in the RefQ scenario to 39–57% for all the GCMs, whereas for the Richelieu River (Figure 8) the relative contribution remains similar to RefQ (44%) for the CSRIO-Mk2 and HadCM3 scenarios (47%) and increases to 56% for the ECHAM4 scenario. For all GCMs and tributaries, the large events (right of the vertical dashed line) contribute more to sediment volume than the RefQ, except for the Saint-François River in the ECHAM4 scenario, where it remains similar (69%) to the RefQ value. In general, the relative contribution of large events for the CSRIO-Mk2 and HadCM3

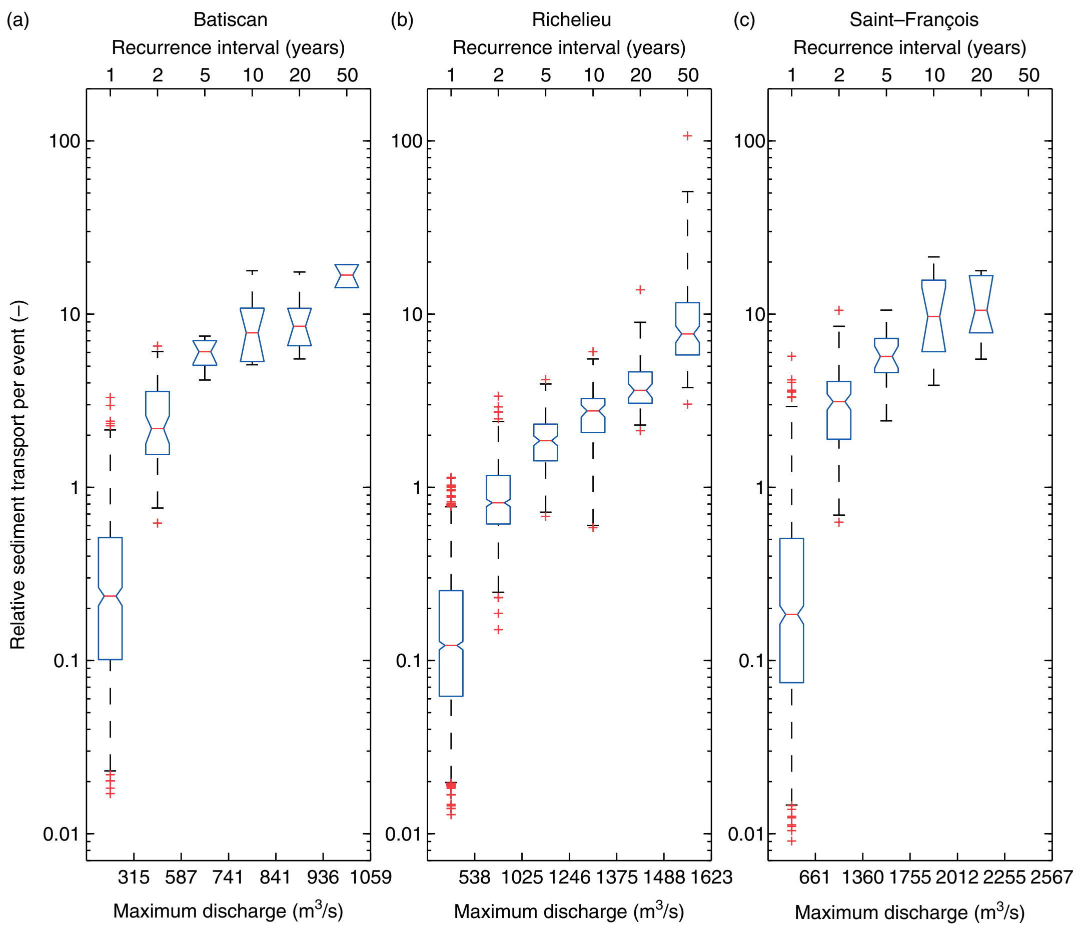

Figure 6. Boxplots of the relative sediment transport volume as a function of maximum discharge per event, grouped by present-day recurrence interval of their maximum discharge for (a) the Batiscan River, (b) the Richelieu River and (c) the Saint-François River. Whiskers (–) represent the 1% and 99% percentile and symbols (+) represent outliers. Relative sediment transport volume per event is the volume of each individual event divided by the average volume of all events in the river concerned. All simulated maximum discharges (i.e. RefQ and GCMs) are combined in this figure

scenarios (77–88%) is similar for all the tributaries, and the ECHAM4 model (68–72%) lies between the RefQ (64–69%) and the other two GCMs.

For the RefQ scenario, the sediment transport during winter is mostly associated with events with small maximum discharge in the Richelieu and Saint-François Rivers (no winter events occurred in the RefQ scenario for the Batiscan River—Figure 7). In all the tributaries and under all GCM scenarios, both the frequency and magnitude of winter events increase. The spring events remain more spread out than the winter events, with both short- and long-duration and small and large maximum discharge, although for the Richelieu River the winter and spring events become similar. The events that occur in summer and fall remain similar to the RefQ in terms of duration and maximum discharge for all the tributaries for the CSIRO-Mk2 and HadCM3 scenarios.

More sediment transport events occur in the Richelieu River than in the other tributaries. The Richelieu River has a total sediment transport duration ranging from 18 to 28% of the simulated period, whereas in the Batiscan and Saint-François Rivers the total sediment transport duration ranges from only 3 to 7%. The Richelieu River also has sediment transport events with a longer median duration (12 days compared to 10 and 6 days for the Batiscan and Saint-François Rivers respectively).

DISCUSSION

Our research shows that climate-induced changes in discharge in the twenty-first century are very likely to affect the magnitude and timing of floods—with more frequent long-duration, large events in the winter—in the three studied Saint-Lawrence River tributaries (Boyer *et al.*, 2010a). There is some variability between the three GCM scenarios, as expected because they were specifically chosen to represent a wide range of precipitation and temperature outputs (Chaumont and Chartier, 2005; Boyer *et al.*, 2010b), but simulations show the same trend for all combinations of river and GCM: floods of a given high magnitude will become more frequent. Similar findings in terms of recurrence intervals were found for fall and summer simulations of the Châteauguay River, another tributary of the Saint-Lawrence River (Roy *et al.*, 2001). However, recurrence intervals can be misleading because they are determined from the peak magnitude of flow and they do not take into account the magnitude and duration of out-of-bank flow (Lane *et al.*, 2007). In this study, the

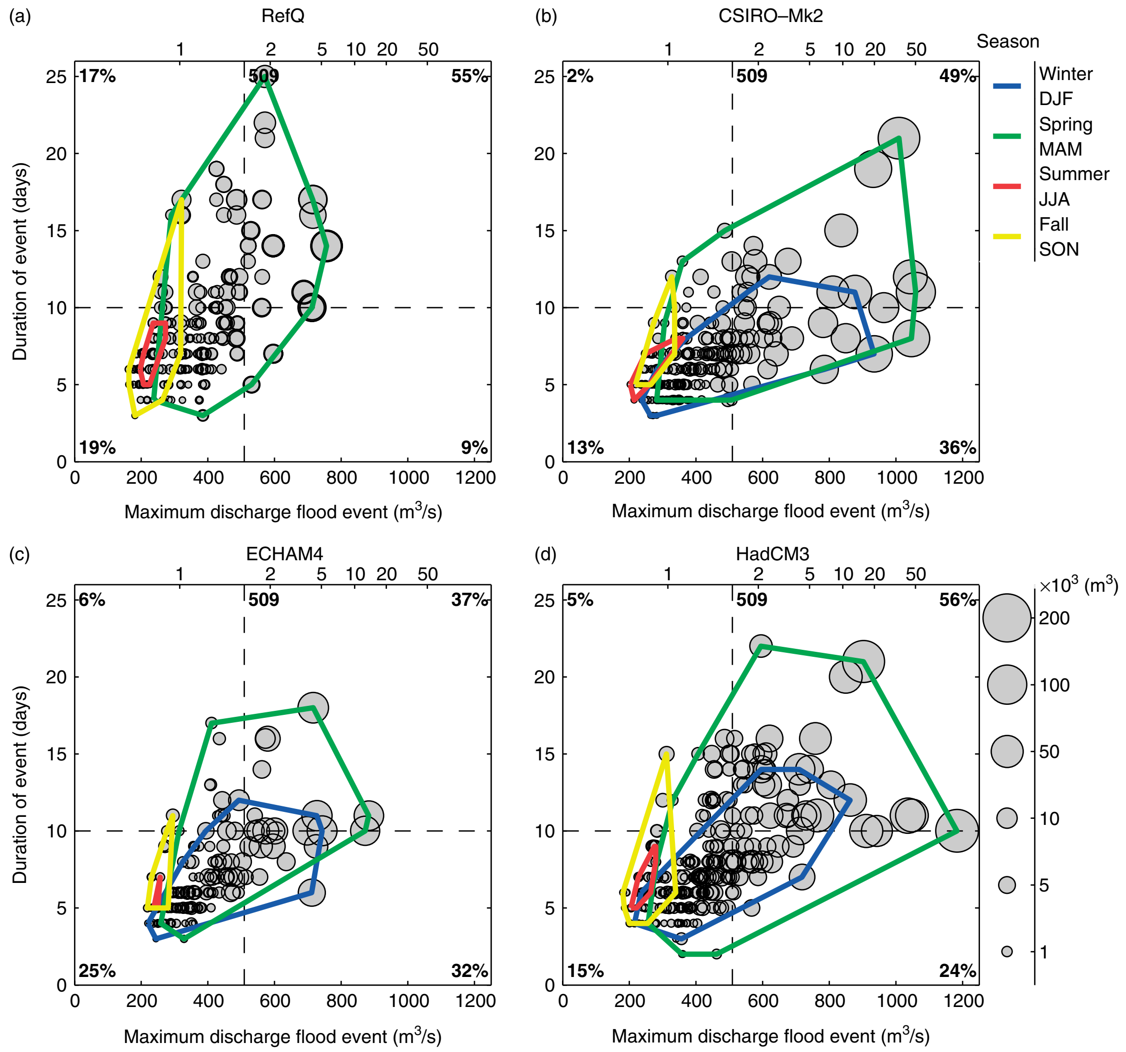

Figure 7. Duration/magnitude diagram of sediment transport event duration against maximum discharge for the Batiscan River. Circles are proportional to the volume of sediment transported during the event. The vertical dashed line indicates the half-load discharge for the RefQ scenario for the 2010–2099 period (509 m^3/s). The horizontal dashed line represents the median value of sediment transport event duration (i.e. 50% of the transport events are shorter than this value) in the RefQ scenario ($d = 10$ days). The percentage in each quadrant gives contribution to the total sediment transport of short/long and small/large events. The upper x-axis represents the present-day recurrence intervals. The continuous coloured lines indicate 'envelopes' of events occurring within each season. (a) RefQ, (b) CSIRO-Mk2, (c) ECHAM4 and (d) HadCM3

reliability of the determination of recurrence intervals is also limited by the fact that simulations for the twenty-first century are based on a 30-year reference period (1961–1990) that is repeated in each of the three horizons. Furthermore, the perturbation method is known to generate over-prediction of rare events (Lenderink *et al.*, 2007), so a precise analysis of shifts in effective discharge should not be attempted. However, the qualitative trend corresponds well to findings from other studies (e.g. Andrews, 1980; Nash, 1994; Emmett and Wolman, 2001). To add to this complexity, relationships between discharge and sediment transport are themselves complex (Reid *et al.*, 2007a,b; Coulthard *et al.*, 2008). As highlighted in Figure 6, the relationship between sediment transport and discharge is highly variable, and the same flow may have very different effects at different times and places due to factors such as hysteresis and channel bed changes (Carling and Beven, 1989; Phillips, 2002; Fuller, 2008). This complexity is clear when examining plots of sediment discharge against water discharge for the three tributaries (Figure 10). For a given discharge, the variation in sediment transport can be more than 1 order of magnitude, as is frequently observed in field measurements (e.g. Emmett and Wolman, 2001). Note that the bedload transport rating curve for the Batiscan River (Figure 10a) suggests two distinct data groups. This is likely due to the different timing of floods in the different GCM scenarios (with the double-peaked shape of the spring flood hydrograph and more frequent fall floods in the Batiscan River compared to those in the other two tributaries) as the same flood magnitude would occur at different levels in the Saint-Lawrence River.

The effective discharge is predicted to increase in all GCMs and tributaries, except for the Batiscan River in the ECHAM4 scenario (Figure 4). Grain size, flow variability and basin size are considered to be the most important factors influencing the effective discharge recurrence interval (Wolman and Miller, 1960; Andrews, 1980;

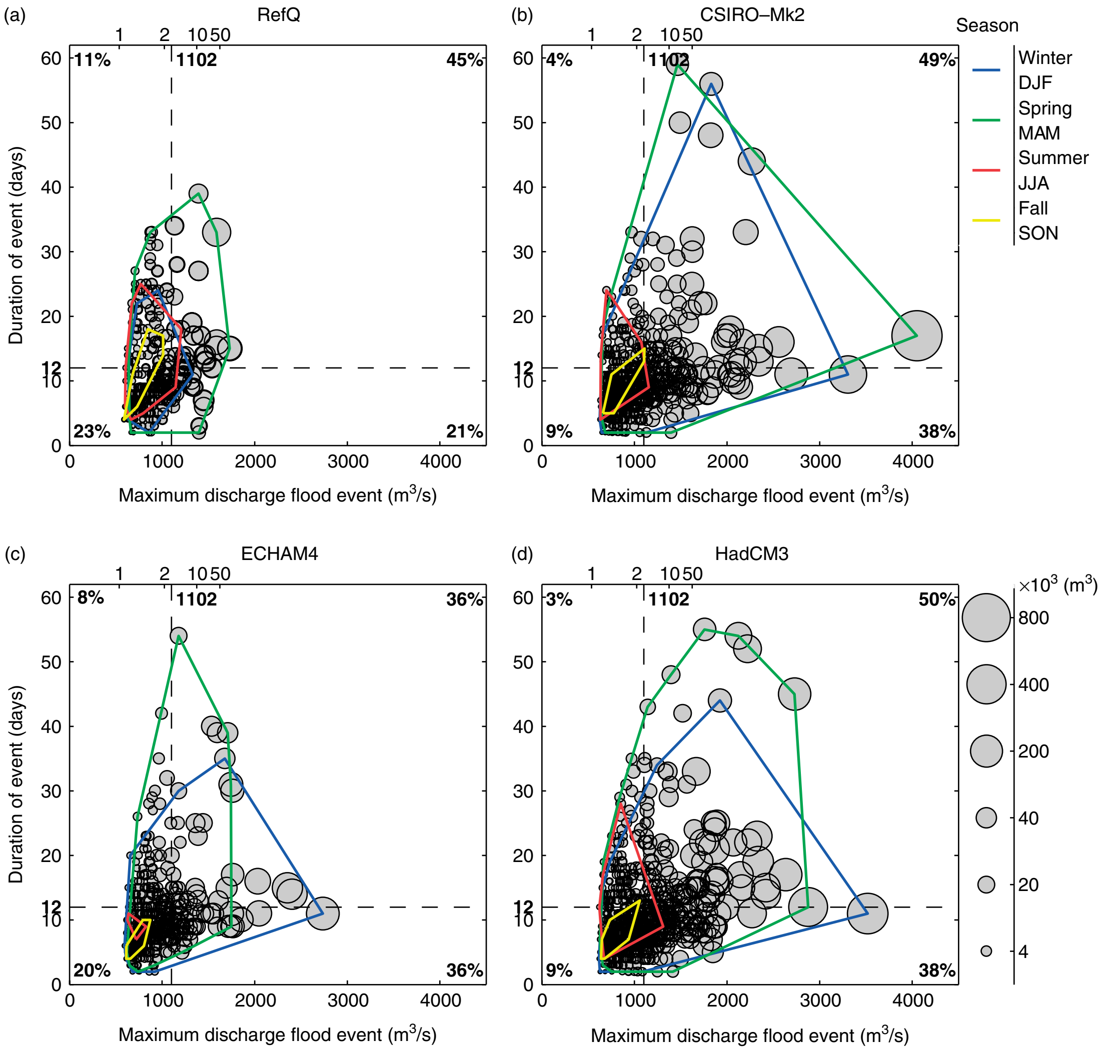

Figure 8. Duration/magnitude diagram of sediment transport event duration against maximum discharge for the Richelieu River. Circles are proportional to the volume of sediment transported during the event. The vertical dashed line indicates the half-load discharge for the RefQ scenario for the 2010–2099 period (1102 m^3/s). The horizontal dashed line represents the median value of sediment transport event duration (i.e. 50% of the transport events are shorter than this value) in the RefQ scenario ($d = 12$ days). The percentages in each quadrant give the contribution to the total sediment transport of short/long and small/large events. The upper x-axis represents the present-day recurrence intervals. The continuous coloured lines indicate 'envelopes' of events occurring within each season. (a) RefQ, (b) CSIRO-Mk2, (c) ECHAM4 and (d) HadCM3

Knighton, 1998; Doyle *et al*., 2007). In our study, the grain size remains about the same and basin size is constant so the predicted shift in effective discharge, towards low-frequency floods, is solely a result of increased flow variability. The use of effective discharge has been a topic of debate since it was first introduced by Wolman and Miller (1960), and much uncertainty remains around its calculation (Ashmore and Day, 1988; Lenzi *et al*., 2006; Doyle and Shields, 2008). For the three rivers studied here, the effective discharge in the RefQ scenario corresponds to a 2–5-year recurrence interval, which is larger than the 1–2-year value reported in Wolman and Miller (1960), but conforms to observations of Doyle *et al*. (2007) for lowland sand bed rivers. One of the consequences of climate change modifications to discharge in these rivers is a transition from a relatively simple distribution of effective discharges (Figure 4a–c) to more complex ones with multiple peaks (Figure 4d–l). This may also be the case in other rivers, particularly where there is a predicted shift in spring flood discharge. This could indicate a channel-maintaining role of near-bankfull flows with recurrence intervals of 2–5 years, with extreme rare events mainly affecting channel bank erosion (Pickup and Warner, 1976; Carling, 1988; Phillips, 2002).

Half-load discharges (Vogel *et al*., 2003) show trends similar to the effective discharge for the RefQ scenario (Table IV and Figure 4), with an overall increase in the twenty-first century. However, half-load discharge trends for the GCM scenarios are more consistent than those in the effective discharge. Because the half-load discharge is not dependent on bin size, it provides a more robust indicator of change in morphological behaviour than the effective discharge, and is also simpler to calculate. Vogel *et al*. (2003) suggested that the half-load discharge for the total load corresponds to a relatively rare event compared to the effective discharge of Wolman and Miller (1960). In contrast, for the lowland rivers

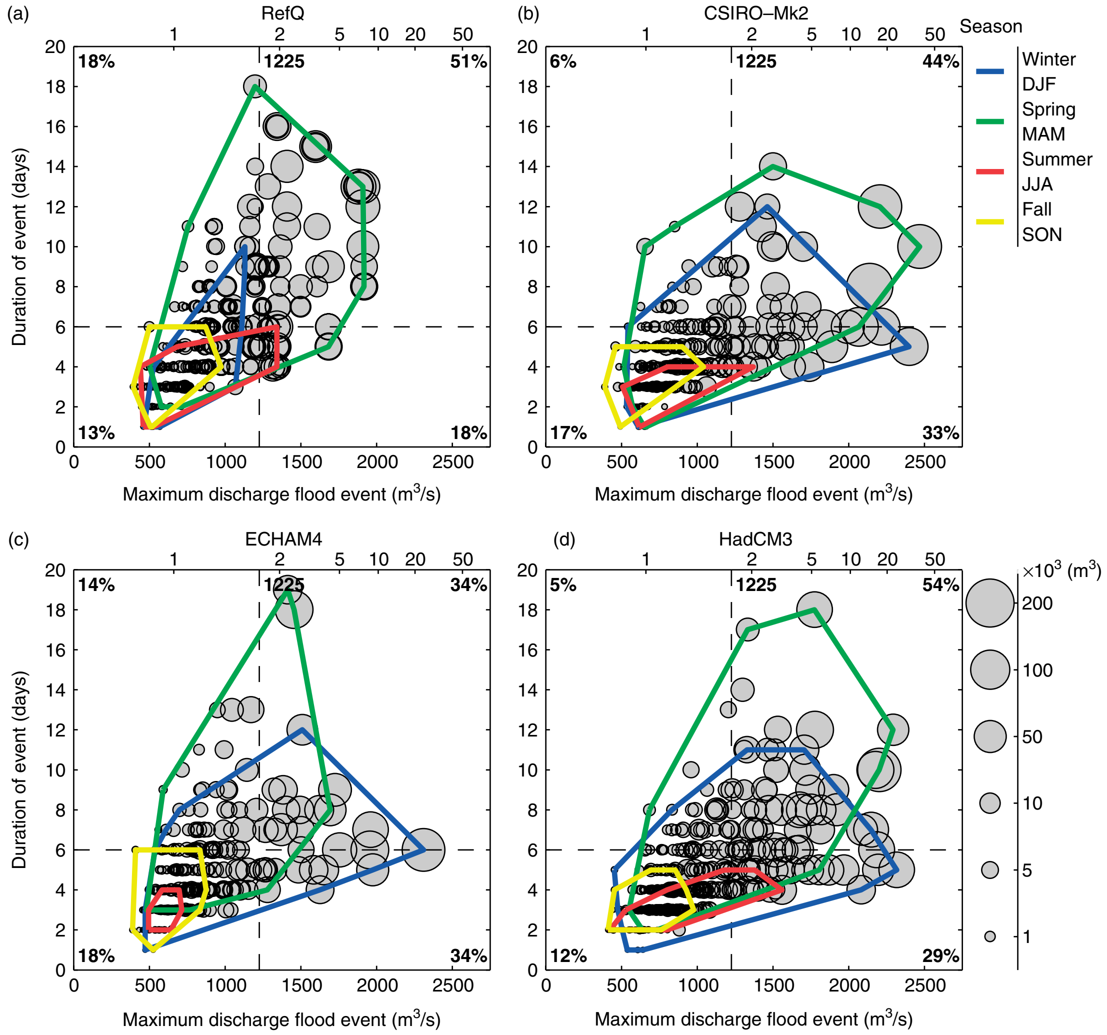

Figure 9. Duration/magnitude diagram of sediment transport event duration against maximum discharge for the Saint-François River. Circles are proportional to the volume of sediment transported during the event. The vertical dashed line indicates the half-load discharge for the RefQ scenario for the 2010–2099 period (1225 m^3/s). The horizontal dashed line represents the median value of sediment transport event duration (i.e. 50% of the transport events are shorter than this value) in the RefQ scenario ($d = 6$ days). The percentages in each quadrant give the contribution to the total sediment transport of short/long and small/large events. The upper x-axis represents the present-day recurrence intervals. The continuous coloured lines indicate 'envelopes' of events occurring within each season. (a) RefQ, (b) CSIRO-Mk2, (c) ECHAM4 and (d) HadCM3

studied here, half-load discharges for bed-material in the RefQ scenario correspond to recurrence intervals of about 2 years. The half-load discharge is lower than the effective discharge for the Batiscan and Saint-François Rivers, and approximately the same for the Richelieu River.

The increase in frequency and magnitude of winter events results in higher transport rates because, for the same discharge, the water surface slope for high-magnitude events in the tributaries is markedly higher in the winter compared to that in spring when the Saint-Lawrence River, with highly regulated water levels (Fagherazzi *et al.*, 2005), reaches its maximum level (Boyer *et al.*, 2010a). Because the slopes of the tributaries are very low (less than 0·1 m per km), the impact of base-level changes on hydraulics and bed shear stress is significant, unlike in small upstream systems with much steeper slopes. The seasonal effect is enhanced under all GCM scenarios as longer-duration, higher-magnitude winter events are predicted for all tributaries (Figures 7–9). The impact of the base-level change is further exacerbated by the predicted 20% decrease in discharge of the Saint-Lawrence River, resulting in a 0·5 to 1 m decrease in its water level during the twenty-first century (Croley, 2003). This effect has been tested using two base-level decrease scenarios in the Saint-Lawrence River (see details in Verhaar *et al.*, 2010). The same winter discharge events when the Saint-Lawrence level was between 0·5 and 1 m lower than their current values resulted in average increases in sediment transport of 40% for the Richelieu and Saint-François Rivers and 116% for the Batiscan River.

It is commonly assumed that if climate change leads to a more frequent occurrence of high-magnitude, long-duration flood events, there is an increased risk of over-bank flooding. However, peak-flow magnitude is not the only control on flood risk, as changes in channel geometry, in particular in systems undergoing long-term aggradation, also need to be considered (Lane *et al.*, 2007, 2008). Our morphodynamic simulations suggest

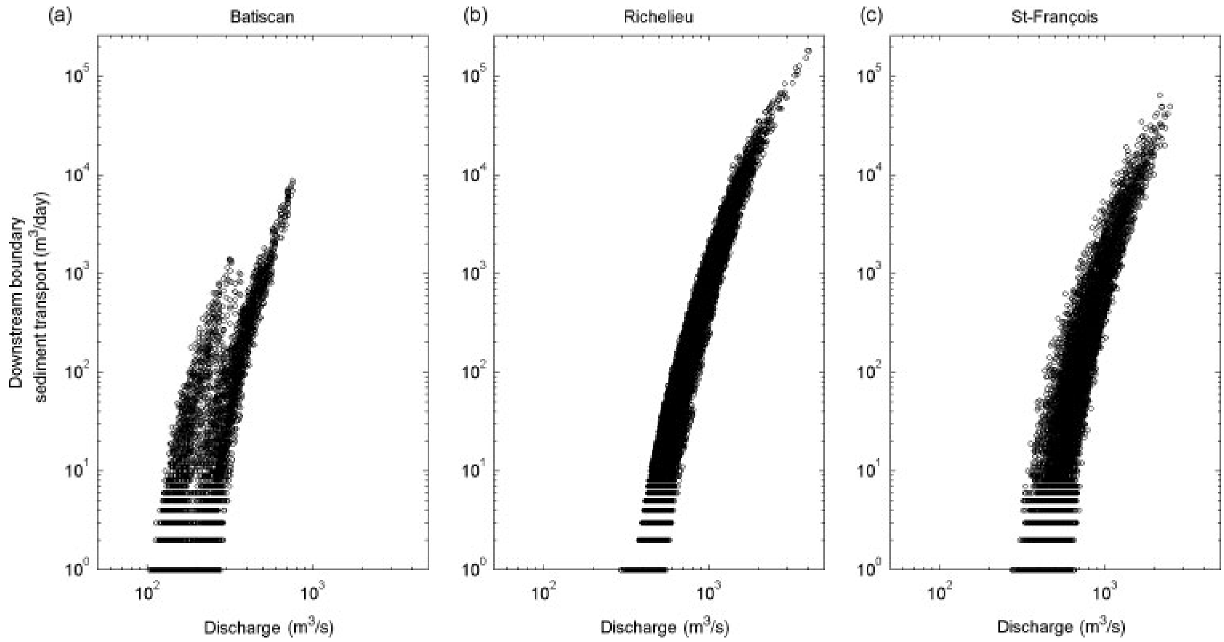

Figure 10. Scatterplot of the sediment transport rate (m^3/day) at the downstream boundary against the daily discharge (m^3/s) for (a) the Batiscan River, (b) the Richelieu River and (c) the Saint-François River. The different hydrological scenarios are combined in these plots

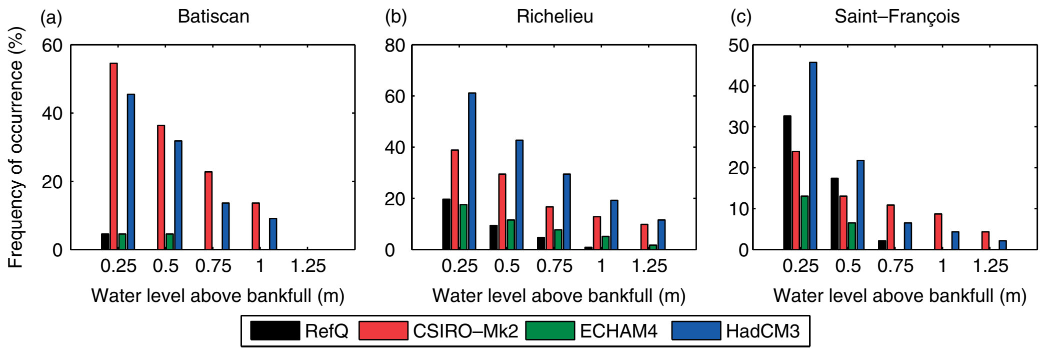

Figure 11. Frequency of the number of occurrences per year of five water surface elevations above bankfull level at the upstream boundary for (a) the Batiscan River, (b) the Richelieu River and (c) the Saint-François River. Frequency of occurrence is expressed as a percentage of the number of occurrences per year (e.g. 20% is once in 5 years). The bankfull water surface elevations (calculated on the basis of a 2-year recurrence interval) for the Batiscan, Richelieu and Saint-François rivers are 6·47, 6·59 and 7·55 m, respectively

that the Batiscan River is undergoing slight aggradation under the present hydrological regime, the Saint-François River is degrading slightly and the Richelieu River is almost in equilibrium (Verhaar *et al.*, 2010). However, under all climate-change scenarios, increased bed erosion is predicted, resulting in reduced aggradation with some erosion in the downstream reaches for the Batiscan River, a switch from equilibrium to a degradational state for the Richelieu River and increased degradation in the Saint-François River (Verhaar *et al.*, 2010). Thus, the increase in flood risk due to more frequent extreme events is in part compensated by bed incision in the three studied tributaries. Higher flood levels that occur more often are predicted for all GCMs and all three tributaries (Figure 11). This shows that, although lower bed elevation decreases flood risk, the increased frequency of rare events outweighs this effect and the likelihood of observing floods in the range of 1–1·25 m above the bankfull level increases, particularly with the CSIRO-Mk2 model. Note that this increased flood risk is also present for all simulations with a steady fall (0·01 m/year) in the downstream water levels of the Saint-Lawrence River, with the exception of the ECHAM4 model in the Saint-François River.

Because of the scarce availability of long-term series of sediment transport data to investigate the geomorphic impacts of infrequent large floods *versus* more frequent smaller events, the sediment modelling approach used in this study provides an additional method for assessing the role of different discharges within rivers (Shields *et al.*, 2003). However, ideally, a more sophisticated 2D modelling approach, which could simulate bank erosion, would be required to assess the role of extreme events on bank erosion and sediment supply. In the Batiscan and Richelieu Rivers, banks are stable, but high lateral migration rates were observed in the Saint-François River, which cannot be adequately modelled in a 1D approach.

CONCLUSION

Morphodynamic simulations for the twenty-first century based on three GCM scenarios for three tributaries of the Saint-Lawrence River indicate that climate-induced changes in discharge will markedly increase the low-frequency, high-magnitude events, which will have an important impact on both bed-material transport and flood risk. Although the mean daily discharge does not change much in GCM scenarios, there is an increase in flow variability that results in higher effective and half-load discharges under future scenarios. Very large volumes of sediment are transported by fewer, extreme flood events in most simulations compared to a reference scenario where events of recurrence interval of 5 years or less transported most of the sediment. The change in the timing of these events, with more frequent long-duration, high-magnitude floods in the winter, will also have a major impact as these events occur during low flow in the Saint-Lawrence River, leading to a greater water surface slope in the tributaries and thus higher transport capacity.

Although the three GCMs predict an increase in large magnitude events, there remains a large variability between these scenarios, with ECHAM4 (dry/warm prediction) resulting in the smallest impact in terms of sediment transport and flood risk, and HadCM3 (largest change in precipitation) having the largest impact on these variables. Future research on climate-induced morphodynamic changes in rivers should thus continue to use more than one GCM scenario, unless or until GCM refinement leads to a convergence of climate predictions. Furthermore, there is a need to develop further 2D modelling tools that could run long-term unsteady simulations of bed-material transport and incorporate the impacts of bank erosion on channel evolution.

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REFERENCES

Ackers P, White WR. 1973. Sediment transport: new approach and analysis. *Journal of Hydraulic Engineering* **99**: 2041–2060.

Andrews ED. 1980. Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology* **46**(3–4): 311–330.

Arnell NW. 1998. Climate change and water resources in Britain. *Climate Change* **39**(1): 83–110.

Ashmore PE, Day TJ. 1988. Effective discharge for suspended sediment transport in streams of the Saskatchewan River basin. *Water Resources Research* **24**(6): 864–870.

Barry JJ, Buffington JM, Goodwin P, King JG, Emmett WW. 2008. Performance of bed-load transport equations relative to geomorphic significance: predicting effective discharge and its transport rate. *Journal of Hydrologic Engineering-ASCE* **134**(5): 601–615. DOI:10.1061/(ASCE)0733–9429(2008)134 : 5(601).

Boyer C, Verhaar PM, Roy AG, Biron PM, Morin J. 2010a. Impacts of environmental changes on the hydrology and sedimentary processes at the confluences of St-Lawrence tributaries: potential effect on fluvial ecosystems. *Hydrobiologia* **647**(1): 163–183 DOI: 10.007/s10750-009-9927-1.

Boyer C, Chaumont D, Chartier I, Roy AG. 2010b. Impact of climate change on the hydrology of St-Lawrence tributaries. *Journal of Hydrology* **384**(1–2): 65–83.

Carling P. 1988. The concept of dominant discharge applied to 2 gravel-bed streams in relation to channel stability thresholds. *Earth Surface Processes and Landforms* **13**(4): 355–367.

Carling P, Beven K. 1989. Floods: hydrological, sedimentological and geomorphological implications. In *The Hydrology, Sedimentology and Geomorphological Implications of Floods: An Overview*, Beven K, Carling P (eds). Wiley: Chichester; 1–9.

Caya D, Laprise R. 1999. A semi-implicit semi-Lagrangian regional climate model: the Canadian RCM. *Monthly Weather Review* **127**(3): 341–362.

Chaumont D, Chartier I. 2005. Développement de scénarios hydrologiques à des fins de modélisation de la dynamique sédimentaire des tributaires du Saint-Laurent dans un contexte de changements climatiques. Special report, Ouranos, Montréal, Canada, 46 pp (in French).

Coulthard TJ, Lewin J, Macklin MG. 2005. Modelling differential catchment response to environmental change. *Geomorphology* **69**(1–4): 222–241. DOI:10.1016/j.geomorph.2005.01.008.

Coulthard TJ, Lewin J, Macklin MG. 2008. Non-stationarity of basin scale sediment delivery in response to climate change. In *Gravel-bed Rivers VI: From Process, Understanding to River Restoration*, Habersack H, Piégay H, Rinaldi M (eds). Elsevier: Amsterdam, The Netherlands; 315–331. DOI:10.1016/S0928-2025(07)11131-1.

Croley TEI. 2003. Great Lakes climate change hydrologic impact assessment: I.J.C. Lake Ontario-St. Lawrence River regulation study. Technical Memorandum GLERL-126, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan.

Crowder DW, Knapp HV. 2005. Effective discharge recurrence intervals of Illinois streams. *Geomorphology* **64**(3–4): 167–184. DOI:10.1016/j.geomorph.2004.06.006.

Doyle MW, Shields CA. 2008. An alternative measure of discharge effectiveness. *Earth Surface Processes and Landforms* **33**(2): 308–316.

Doyle MW, Shields D, Boyd KF, Skidmore PB, Dominick D. 2007. Channel-forming discharge selection in river restoration design. *Journal of Hydrologic Engineering-ASCE* **133**(7): 831–837. DOI:10.1061/(ASCE)0733–9429(2007)133 : 7(831).

Einstein HA. 1950. The bed-load function for sediment transport in open channel flows. *Technical Bulletin*, vol. 1026. Soil Conservation Service, US Department of Agriculture, Washington, DC.

Emmett WW, Wolman MG. 2001. Effective discharge and gravel-bed rivers. *Earth Surface Processes and Landforms* **26**(13): 1369–1380.

Fagherazzi L, Guay R, Sassi T. 2005. Climate Change analysis of the Ottawa River System. Report for the commission mixte internationale—Lake Ontario-St. Lawrence River study on discharge regulation, 72. 72 p.

Ferguson RI. 2003. The missing dimension: effects of lateral variation on 1-D calculations of fluvial bedload transport. *Geomorphology* **56**: 1–14.

Ferguson RI, Church M. 2004. A simple universal equation for grain settling velocity. *Journal of Sedimentary Research* **74**(6): 933–937.

Ferguson RI, Church M. 2009. A critical perspective on 1D modeling of river processes: gravel load and aggradation in lower Fraser River. *Water Resources Research* **45**(11): W11424, DOI:10.1029/2009WR007740.

Fuller IC. 2008. Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand. *Geomorphology* **98**(1–2): 84–95. DOI: 10.1016/j.geomorph.2007.02.026.

Gomez B, Cui Y, Kettner AJ, Peacock DH, Syvitski JPM. 2009. Simulating changes to the sediment transport regime of the Waipaoa

River, New Zealand, driven by climate change in the twenty-first century. *Global and Planetary Change* **67**(3–4): 153–166. DOI:10.1016/j.gloplacha.2009.02.002.

Graham LP, Andreasson J, Carlsson B. 2007. Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods—a case study on the Lule River basin. *Climatic Change* **81**(Suppl. 1): 293–307. DOI:10.1007/s10584-006-9215-2.

Hoey TB, Ferguson RI. 1994. Numerical-simulation of downstream fining by selective transport in gravel-bed rivers—model development and illustration. *Water Resources Research* **30**(7): 2251–2260.

Hoey TB, Bishop P, Ferguson RI. 2003. Testing numerical models in geomorphology: how can we ensure critical use of model predictions? In *Prediction in Geomorphology*, Wilcock P, Iverson R (eds). AGU Geophysical Monograph 135, : Washington, DC; 241–256.

Hunt JCR. 2002. Floods in a changing climate: a review. *Philosophical Transactions of the Royal Society A—Mathematical, Physical and Engineering Sciences* **360**(1796): 1531–1543. DOI:10.1098/rsta.2002.1016.

Kay AL, Reynard NS, Jones RG. 2006. RCM rainfall for UK flood frequency estimation. I. Method and validation. *Journal of Hydrology* **318**(1–4): 151–162. DOI:10.1016/j.jhydrol.2005.06.012.

Kirchner JW, Finkel RC, Riebe CS, Granger DE, Clayton JL, King JG, Megahan WF. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* **29**(7): 591–594.

Knighton D. 1998. *Fluvial Forms and Processes: A New Perspective*, Arnold: London.

Kundzewicz ZW, Ulbrich U, Brucher T, Graczyk D, Kruger A, Leckebusch GC, Menzel L, Pinskwar I, Radziejewski M, Szwed M. 2005. Summer floods in central Europe—climate change track? *Natural Hazards* **36**(1–2): 165–189. DOI:10.1007/s11069-004-4547-6.

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen Z, Shiklomanov IA. 2007. Freshwater resources and their management. In *Contribution of Working Group II to the Fourth Assessment Report of the Intergouvernemental Panel on Climate Change*, Parry ML, Canziani OF, Palutikof JP, van der Linden P, Hanson CE (eds). Cambridge University Press: Cambridge, UK; 173–210.

Lane SN, Tayefi V, Reid SC, Yu D, Hardy RJ. 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms* **32**(3): 429–446. DOI:10.1002/esp.1404.

Lane SN, Tayefi V, Reid SC, Yu D, Hardy RJ. 2008. Reconceptualising coarse sediment delivery problems in rivers as catchment-scale and diffuse. *Geomorphology* **98**(3–4): 227–249. DOI:10.1016/j.geomorph.2006.12.028.

Lenderink G, Buishand A, van Deursen W. 2007. Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrology and Earth System Sciences* **11**(3): 1143–1159.

Lenzi MA, Mao L, Comiti F. 2006. Effective discharge for sediment transport in a mountain river: computational approaches and geomorphic effectiveness. *Journal of Hydrology* **326**(1–4): 257–276. DOI:10.1016/j.jhydrol.2005.10.031.

Meehl GA, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JFB, Stouffer RJ, Taylor KE. 2007. The WCRP CMIP3 multimodel dataset—a new era in climate change research. *Bulletin of the American Meteorological Society* **88**(9): 1383–1394. DOI:10.1175/BAMS-88-9-1383.

Middelkoop H, Daamen K, Gellens D, Grabs W, Kwadijk JCJ, Lang H, Parmet BWAH, Schadler B, Schulla J, Wilke K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change* **49**(1–2): 105–128.

Milly P, Wetherald R, Dunne K, Delworth T. 2002. Increasing risk of great floods in a changing climate. *Nature* **415**: 514–517.

Minville M, Brissette F, Leconte R. 2008. Uncertainty of the impact of climate change on the hydrology of a nordic watershed. *Journal of Hydrology* **358**(1–2): 70–83. DOI:10.1016/j.jhydrol.2008.05.033.

Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* **109**(5): 596–611.

Morin J, Champoux O, Martin S, Turgeon K. 2005. Modélisation intégrée de la response de l'écosystème dans le fleuve Saint-Laurent: Rapport final des activités enterprises dans le cadre du plan d'étude sur la regularisation du lac Ontario et du fleuve Saint-Laurent. Rapport scientifique—RS-108, Environment Canada, SMC-Hydrologie, Sainte-Foy, Québec, Canada (in French).

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grubler A, Kram TY, Kram T, La Rovere EL, Michaelis L, Moris S, Morita T, Pepper W, Pitcher H, Price L, Raihi K, Roehrl A, Rogner HH, Sankovovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z. 2000. *IPCC Special Report on Emissions Scenarios*, Cambridge University Press: Cambridge, UK.

Nash DB. 1994. Effective sediment-transporting discharge from magnitude-frequency analysis. *Journal of Geology* **102**(1): 79–95.

Parker G. 1990. Surface based bedload transport relation for gravel rivers. *Journal of Hydraulic Research* **28**: 417–436.

Phillips JD. 2002. Geomorphic impacts of flash flooding in a forested headwater basin. *Journal of Hydrology* **269**(3–4): 236–250.

Pickup G, Warner RF. 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. *Journal of Hydrology* **29**(1–2): 51–75.

Prudhomme C, Reynard N, Crooks S. 2002. Downscaling of global climate models for flood frequency analysis: where are we now? *Hydrological Processes* **16**(6): Sp. Iss. SI): 1137–1150. DOI:10.1002/hyp.1054.

Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG, Klepper G, Field CB. 2007. Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America* **104**(24): 10288–10293. DOI:10.1073/pnas.0700609104.

Reid SC, Lane SN, Berney JM, Holden J. 2007a. The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river. *Geomorphology* **83**(1–2): 152–182. DOI:10.1016/j.geomorph.2006.06.030.

Reid SC, Lane SN, Montgomery DR, Brookes CJ. 2007b. Does hydrological connectivity improve modelling of coarse sediment delivery in upland environments? *Geomorphology* **90**(3–4): 263–282. DOI:10.1016/j.geomorph.2006.10.023.

Reynard NS, Prudhomme C, Crooks SM. 2001. The flood characteristics of large UK Rivers: potential effects of changing climate and land use. *Climatic Change* **48**(2–3): 343–359.

Robson AJ. 2002. Evidence for trends in UK flooding. *Philosophical Transactions of the Royal Society of London Series A—Mathematical, Physical and Engineering Sciences* **360**(1796): 1327–1343. DOI:10.1098/rsta.2002.1003.

Rosberg J, Andréasson J. 2006. From delta change to scaling and direct use of RCM output. *European Conference on Impacts of Climate Change on Renewable Energy Sources*. Reykjavik, Iceland, June 5–9.

Roy L, Leconte R, Brissette FP, Marche C. 2001. The impact of climate change on seasonal floods of a southern Quebec River basin. *Hydrological Processes* **15**(16): 3167–3179.

Rydgren B, Graham P, Basson M, Wisaeus D. 2007. Addressing climate change-driven increased hydrological variability in environmental assessments for hydropower projects—a scoping study. Technical report, Vattenfall Power Consultant AB, Sweden, 41 pp.

Shields FD, Copeland RR, Klingeman PC, Doyle MW, Simon A. 2003. Design for stream restoration. *Journal of Hydraulic Engineering-ASCE* **129**(8): 575–584. DOI:10.1061/(ASCE)0733–9429(2003)129 : 8(575).

Talbot T, Lapointe M. 2002. Numerical modeling of gravel bed river response to meander straightening: the coupling between the evolution of bed pavement and long profile. *Water Resources Research* **38**(6): WR000330. DOI:10.1029/2001WR000330.

Torizzo M, Pitlick J. 2004. Magnitude-frequency of bed load transport in mountain streams in Colorado. *Journal of Hydrology* **290**(1–2): 137–151. DOI:10.1016/j.hydrol.2003.12.001.

Verhaar PM, Biron PM, Ferguson RI, Hoey TB. 2008. A modified morphodynamic model for investigating the response of rivers to short-term climate change. *Geomorphology* **101**(4): 674–682. DOI:10.1016/j.geomorph.2008.03.010.

Verhaar PM, Biron PM, Ferguson RI, Hoey TB. 2010. Numerical modelling of climate change impacts on Saint-Lawrence tributaries. *Earth Surface Processes and Landforms* **35**: 1184–1198, DOI: 10.1002/esp.1953.

Vogel RM, Stedinger JR, Hooper RP. 2003. Discharge indices for water quality loads. *Water Resources Research* **39**(10): 1273, DOI:10.1029/2002WR001872.

White WR, Day TJ. 1982. Transport of graded gravel bed material. In *Gravel-bed Rivers: Fluvial Processes, Engineering and Management*, Hey RD, Bathurst JC, Thorne CR (eds). Wiley: Chichester; 181–213.

Wilcock PR, Crowe JC. 2003. Surface-based transport model for mixed-size sediment. *Journal of Hydraulic Engineering* **129**(2): 120–128. DOI:10.1061/(ASCE)0733–9429 (2003)129 : 2(120).

Wolman MG, Miller JP. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* **68**: 54–74.

