Reconstructing the Natural Streamflow of a Regulated River: A Case Study of La Grande Rivière, Québec, Canada

Marco A. Hernández-Henríquez, Theo J. Mlynowski, and Stephen J. Déry

Abstract: The regulation of rivers by dams, diversions, and reservoirs leads to perturbed streamflow time series, making it difficult for hydrological studies to assess natural trends and variability in runoff. This case study applies a variation of Hirsch's maintenance of variance extension (MOVE) method to reconstruct La Grande Rivière's 1979-2004 natural streamflow. The 1960-2004 hydrometric data for the Eastmain River and Grande Rivière de la Baleine are summed and compared with the 1960-1978 pre-regulated runoff time series of La Grande Rivière. Statistical analyses reveal a reasonable Nash-Sutcliffe efficiency (NSE) index ($E_f = 0.58$) and near 1:1 ratio between the standardized anomalies of the two river combination and La Grande Rivière's 1960-1978 natural flow records. The accuracy of the proposed method is confirmed by the low error rates and a reasonably high NSE index ($E_f = 0.64$) exhibited between La Grande Rivière's 1960-1978 observed and reconstructed monthly streamflow time series. Moreover, the reconstructed flows exhibit variability and a natural flow pattern that is indicative of nival rivers, whereas the 1984-2004 regulated flow rates from Hydro-Québec show minimal streamflow variability and a flattened annual hydrograph. Trend analyses (1960-2004) in total annual runoff reveal opposite trends from the Eastmain and Grande Rivière de la Baleine that offset each other to yield no trend when these two rivers are used to reconstruct La Grande Rivière's streamflows. The methodology applied in this study is a reliable way to complete the hydrometric record of La Grande Rivière, making it more feasible for future studies to investigate the natural variations and possible effects of climatic forcings on the hydrological cycle of the regulated river.

Résumé:
La réglementation des rivières par des barrages, détournements, et réservoirs donnent des séries hydrométriques perturbées, ce qui rend difficile l'étude des tendances et de la variabilité naturelle dans ces systèmes. Cette étude de cas applique une méthode développée par Hirsch qui conserve la variabilité dans un système afin de reconstruire les débits naturels de La Grande Rivière pour la période 1979-2004. Des données hydrométriques de 1960 à 2004 pour les bassins versants contiguës de la Rivière Eastmain et Grande Rivière de la Baleine sont ajoutées et comparées à celles de 1960 à 1978 pour La Grande Rivière, avant la construction des infrastructures hydroélectriques. Des analyses statistiques révèlent un haut coefficient d'efficacité Nash-Sutcliffe (ENS; $E_f = 0.58$) et un rapport près de 1:1 entre les débits

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normalisés des deux rivières combinées et ceux de La Grande Rivière pour la période 1960-1978. La précision de la méthode est vérifiée par le faible taux d'erreurs et un niveau élevé de l'indice ENS ($E_f = 0.64$) entre les débits mensuels observés et reconstruits de La Grande Rivière. De plus, les débits reconstruits pour La Grande Rivière révèlent une variabilité et un régime naturel indicatif d'un système nival, alors que les débits anthropiques d'Hydro-Québec de 1984 à 2004 ont peu de variabilité entre chaque mois et un hydrographe annuel aplati. Une analyse des tendances (1960-2004) des débits totaux annuels révèle une hausse (baisse) pour la Rivière Eastmain (Grande Rivière de la Baleine) qui entraîne aucune tendance pour les débits naturels de La Grande Rivière. La méthode appliquée dans cette étude est donc fiable pour reconstruire les débits naturels de La Grande Rivière, permettant à d'autres études d'investiguer la variabilité naturelle et les effets des changements climatiques sur le cycle de l'eau dans un bassin versant réglementé.

Introduction

La Grande Rivière is one of the largest rivers (by volume) in eastern Canada. From its headwaters in north central Québec, it drains a total area of 97,600 km^2 as it travels westward to James Bay (Natural Resources Canada, 2009). La Grande Rivière contributes ~16% of the total annual gauged streamflow input to Hudson Bay (Déry *et al.*, submitted). The hydroelectric potential of this river was developed during the late 1970s and early 1980s by Hydro-Québec, giving rise to the James Bay Hydroelectric Complex. During this period the natural flow regime of the river was anthropogenically influenced as several dams, diversions, and reservoirs were commissioned. Consequently, the natural flow records of La Grande Rivière are only available from 1960 to 1978, making it difficult for hydrological studies (Déry and Wood, 2005; Déry *et al.*, 2005) to assess long-term trends and variability in runoff. It is therefore imperative to complete La Grande Rivière's runoff record by reconstructing its natural streamflow.

The streamflow time series of anthropogenically influenced rivers (referred hereafter as regulated) are typically reconstructed using hydrological models that incorporate both physical (e.g., topography) and climatic (e.g., rainfall) characteristics of the catchment area (Beven, 2001). Multivariate time series analysis has also been successfully used to reconstruct the natural flow of a regulated river system (Wen, 2009). This method utilizes pre-regulated streamflow records and climate data to build multiple regression models that represent the natural flow of the river. All of these reconstruction methods involve the use of various parameters and are limited by the uncertainty of the parameter values being used within the models. In contrast, many streamflow reconstruction methods have been developed based on simple regression between concurrent flows from a site with a short historic record and a nearby long-term station. Matalas and Jacobs (1964) determined that linear least squares regression underestimates the variance of the reconstructed values. Hirsch (1982) addressed this problem by proposing the maintenance of variance extension, MOVE (types 1 and 2), techniques which preserve the streamflow variability by using standardized monthly flows. The MOVE techniques depend on the long- and short-record stations sharing similar flow characteristics, such as distribution shape, serial correlation or seasonality (Hirsch 1982).

In this case study, a variation of Hirsch's MOVE (type 1) technique to reconstruct La Grande Rivière's 1979-2004 'natural streamflow' (i.e., free of anthropogenic disturbances, such as dams, diversions, and reservoirs) was adopted. Although the applied method is not novel, this is the first known study that attempts to reconstruct La Grande Rivière's natural streamflow by using pre-regulated hydrometric data (1960-1978) and flow records from two adjacent rivers (1960-2004). By using two surrounding basins, some of the latitudinal effects on climate and land-surface characteristics that influence river runoff can be captured. The accuracy of the reconstruction methodology was evaluated and the reconstructed flows for interannual variability and trends was analyzed. Furthermore, the anthropogenic influence (dams, diversions, and reservoirs) on the runoff of La Grande Rivière was investigated and compared with the reconstructed flow rates.

Data and Methods

Study Site

The James Bay Hydroelectric Project is located in the taiga region of northwestern Québec (Maxwell *et al.*, 1997). This region extends from 48°N to 55°N and covers an area of 350,000 km^2 (Sénecal and Égré, 1999). Nearby climate data (1971-2000) collected from the La Grande Rivière Airport (53.38°N, 77.42°W; Climate ID: 7093715) indicate that the region is subject to a relatively cold mean annual air temperature of -3.1°C and receives an average 684.0 mm of precipitation (i.e., 437.6 mm of rainfall and 246.4 mm of snowfall) each year (Environment Canada, 2009). Some of the main rivers found in this region include the La Grande, Eastmain, Grande Rivière de la Baleine, Caniapiscau, and Rupert (Figure 1). The hydroelectric complex encompasses the drainage basin of La Grande Rivière along with the flows diverted from the Caniapiscau, Opinaca, and Eastmain Rivers (Messier *et al.*, 1986). La Grande Rivière is about 800 km in length and drops 376 m in elevation as it travels toward its outlet at James Bay (Hamley, 1983). In November 1978, the natural flows of La Grande Rivière began to be modified as reservoirs were filled along the length of the river (Messier *et al.*, 1986). The Eastmain River, which is located 150 km south of La Grande Rivière, flows a distance of 700 km westward into James Bay and drops a total of 760 m in elevation (Société d'énergie de la Baie James, 1988). In July 1980, the flows from the Eastmain and Opinaca Rivers were diverted northward to La Grande Rivière, resulting in a 90% flow reduction downstream from the diversion on the Eastmain (Messier *et al.*, 1986). Grande Rivière de la Baleine is located 130 km north of La Grande Rivière and drops 400 m in elevation during its 724 km journey from Lac Bienville to its outlet at Hudson Bay (Natural Resources Canada, 2009). In January 1984, the easternmost part of the Grande Rivière de la Baleine basin experienced an increase in volume as 48% of the flows from the Caniapiscau River were diverted west to La Grande Rivière (Société d'énergie de la Baie James, 1988).

Data

Observed hydrometric data for the Eastmain River and Grande Rivière de la Baleine are used to reconstruct the flows of La Grande Rivière for the period 1979 to 2004. The temporal coverage of this study is limited to 45 years owing to a lack of operational river gauges collecting adequate data prior to 1960 and after 2004. Daily runoff rates for each of the rivers are extracted from Environment Canada's online Hydrometric Database (HYDAT) (Water Survey of Canada, 2009). HYDAT datasets from 1960 to 2001 exist for the Eastmain River and Grande Rivière de la Baleine, whereas for La Grande Rivière, data are only available from 1960 to 1978. Additional (2001-2004) daily hydrometric measurements for the Eastmain and Grande Rivière de la Baleine are obtained from the Ministère de l'Environnement du Québec (Ministère de l'Environnement du Québec, 2009). If a river is affected by an anthropogenic disturbance (dams, diversions, and/or reservoirs), only observed hydrometric data from gauges located upstream of the disturbance are used. Therefore, 1980-2004 streamflow data for the Eastmain River are obtained from a flow gauge located upstream of the diversion that was commissioned in 1980. In addition, observed regulated monthly runoff rates (1980-2004) measured at the La Grande-1 (LG1) power generating station are obtained from Hydro-Québec (Note: only data from 1984 to 2004 are used because notable flow regulation of La Grande Rivière commenced in 1984).

Measurements from river gauge stations covering a total area of 1.8×10^5 km^2 form the basis of the streamflow time series for each river. The locations of the flow gauges with respect to dams, diversions, and reservoirs are illustrated in Figure 1. Geographical characteristics and temporal evolution of data availability for each gauge can be found in Table 1, and the annual statistics for the rivers of interest are presented in Table 2.

Methods

Gaps in the streamflow time series are in-filled following Déry *et al.* (2005). Gauges furthest downstream were first used to maximize the drainage area. When there are data missing from these downstream gauges, streamflow measurements from

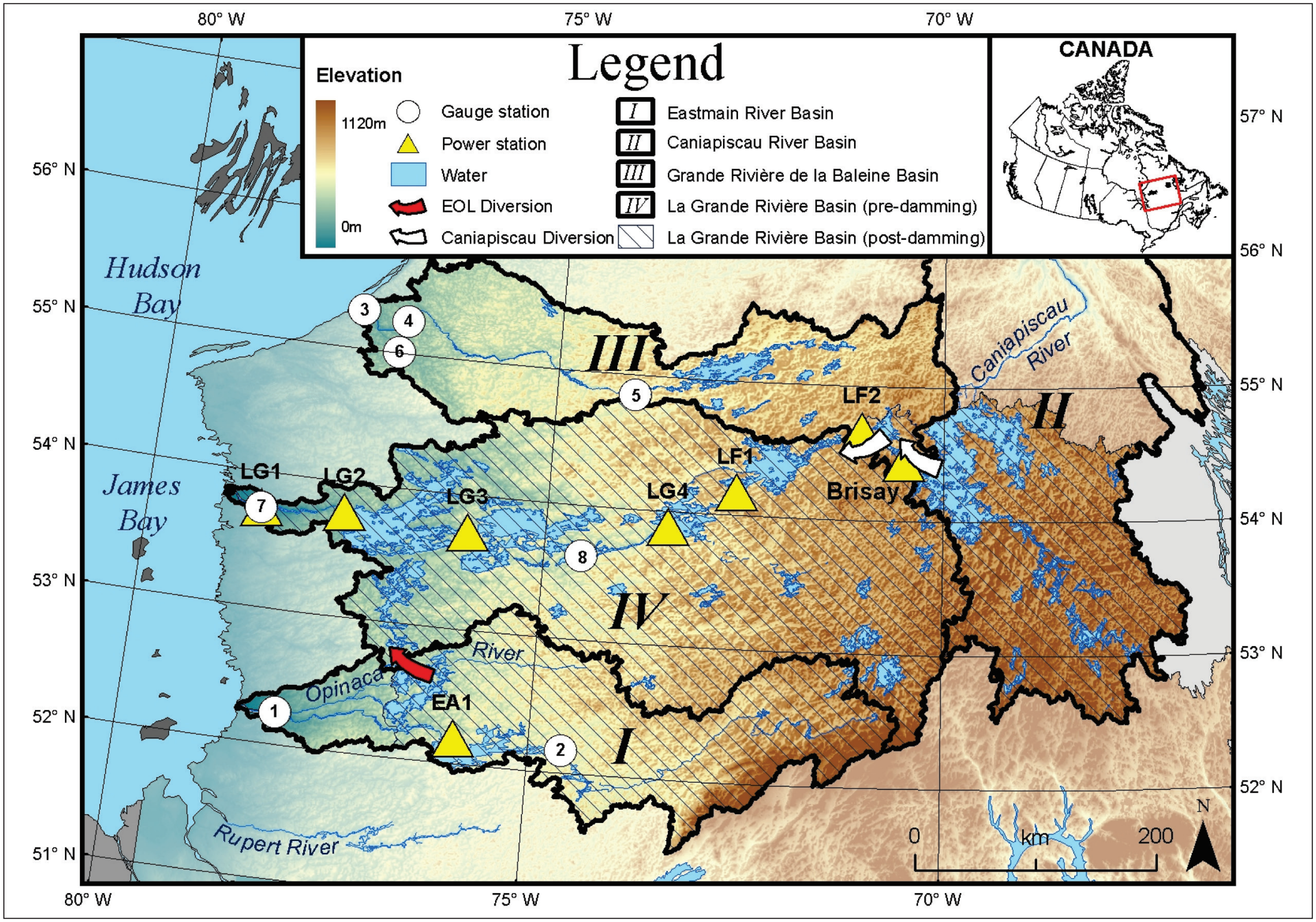

Figure 1. Map of northwestern Québec showing the location of the hydrometric gauges (refer to Table 1) along the Eastmain River, Grande Rivière de la Baleine, and La Grande Rivière. Some of the main power generating stations and diversions (e.g., Eastmain-Opinaca-La Grande (EOL) Diversion commissioned in 1980) are also shown.

Table 1. The gauge identification numbers and coordinates, total area gauged, period of data availability, and fraction of available data used for the Eastmain River, Grande Rivière de la Baleine, and La Grande Rivière. An * indicates the gauges used by the Ministère de l'Environnement du Québec to collect the daily hydrometric measurements (2001-2004) for the Eastmain River and Grande Rivière de la Baleine.

River	Num.	I.D.	Lat. (°N)	Lon. (°W)	Gauged area (km^2)	Data period	Fraction used (%)
Eastmain River	1	03CC001[a]	52.24	78.07	44,300	1960-1980	45.7
	2	03CB004*	52.17	74.59	21,400	1979-2004	53.4
Grande Rivière de la Baleine	3	03ED002[a]	55.29	77.59	43,200	1960-1970	20.0
	4	03ED001*	55.24	76.98	36,300	1961-2004	73.3
	5	03EA001	54.84	73.98	21,000	1962-1993	4.7
	6	03EC001	55.01	77.06	4,660	1960-1993	0.5
La Grande Rivière	7	03DF001[a]	53.72	78.57	96,600	1960-1978	98.7
	8	03DC002	53.62	74.52	37,000	1960-1978	1.3

[a] Data for these gauges are available from 1958 to 1960 but are not used in this study.

Table 2. The annual mean, minimum, maximum, standard deviation, and coefficient of variation (CV) in runoff rates for the Eastmain River (1960-2004), Grande Rivière de la Baleine (1960-2004), and La Grande Rivière (1960-1978). Flow gauges nearest to the mouth with the largest contributing gauged area are chosen to represent each river.

River	I.D.	Runoff Mean ($mm\ yr^{-1}$)	Min. ($mm\ yr^{-1}$)	Max. ($mm\ yr^{-1}$)	St. Dev. ($mm\ yr^{-1}$)	CV
Eastmain River	03CC001	687.0	462.8	887.0	98.4	0.14
Grande Rivière de la Baleine	03ED002	458.1	298.7	607.2	63.8	0.14
La Grande Rivière	03DF001	559.7	411.4	697.6	83.7	0.15

the nearest upstream station are used and adjusted to account for the missing contributing area of the gauge downstream. For instance, flow rates recorded by the gauge upstream of the diversion on the Eastmain River are used to in-fill and complete the streamflow time series for the downstream gauge from 1980 to 2004.

The MOVE (type 1) technique presented in Hirsch (1982) was then followed and applied to reconstruct the 1979-2004 naturalized streamflow of La Grande Rivière. Instead of using streams (Hirsch, 1982), only large adjacent rivers running parallel (east to west) and in close proximity to La Grande Rivière are considered for this study. These rivers share similar geographical characteristics (i.e., vegetation, permafrost cover, topography) and have complete hydrometric datasets extending over the period of interest. The 1960-1978 monthly runoff time series of two neighbouring rivers are summed to create a new time series, $r_{(A+B)}$, that is compared to La Grande Rivière's runoff data for that period (Note: the runoff of two nearby rivers is summed because their catchment areas are nearly identical, see Table 1). This is given by the following formula:

$$r_{(A+B)} = r_{\mathrm{A}} + r_{\mathrm{B}} \tag{1}$$

where r_A and r_B are the monthly runoff of rivers A and B, respectively.

Correlations are then performed on the 1960-1978 monthly runoff time series of each river combination with those of La Grande Rivière. The Nash-Sutcliffe efficiency (NSE) index (E_f) is computed for all comparisons between the observed and reconstructed flows following the methodology by McCuen *et al.* (2006) (equation 1 in McCuen *et al.,* 2006). The sum of the Eastmain River (EA) and Grande Rivière de la Baleine (GR) streamflow time series, $r_{(EA+GR)}$, is selected for the reconstruction because of their reasonable NSE index ($E_f = 0.58$) with La Grande Rivière's (LA) time series and near 1:1 ratio revealed from the linear trend analysis (Figure 4). The reconstruction method involves computing the mean monthly runoff ($\bar{r}$) and standard deviation (σ_r) values for La Grande Rivière (1960-1978) and Eastmain+Grande Rivière de la Baleine (1960-2004).

Unlike Hirsch's MOVE (type 1) technique, which only standardizes the monthly flows for the period with overlapping data (Hirsch, 1982), the standardized monthly runoff anomalies of the Eastmain+Grande Rivière de la Baleine time series, $\text{S.A.}_{(EA+GR)_i}$, for the entire 45-year period (1960-2004) is computed using the following formula:

$$\text{S.A.}_{(EA+GR)_i} = \frac{r_{(EA+GR)_i} - \bar{r}_{(EA+GR)}}{\sigma_{r_{(EA+GR)}}} \qquad (2)$$

where $r_{(EA+GR)_i}$ is the monthly runoff at year *i*, and where the overall 45-year mean and standard deviation in monthly runoff are denoted by $\bar{r}_{(EA+GR)}$ and $\sigma_{r_{(EA+GR)}}$, respectively.

La Grande Rivière's 1960-2004 monthly streamflow time series (r_{LA}) is then reconstructed by:

$$r_{(LA)_i} = \left(\text{S.A.}_{(EA+GR)_i} \times \sigma_{r_{LA}}\right) + \bar{r}_{LA} \qquad (3)$$

where $\text{S.A.}_{(EA+GR)_i}$ is the Eastmain+Grande Rivière de la Baleine standardized monthly runoff anomaly for year *i*, and where $\sigma_{r_{LA}}$ and $\bar{r}_{LA}$ are La Grande Rivière's mean monthly standard deviation and runoff values, respectively, for the period 1960-1978.

The accuracy of the reconstruction methodology is assessed by performing correlation and error analyses (mean absolute error and root-mean-square error) between the 1960-1978 observed and reconstructed flows of La Grande Rivière. In addition, the anthropogenic influence that dams, diversions, and reservoirs have on the runoff of La Grande Rivière was examined by comparing the 1984-2004 mean monthly runoff values from the reconstruction with those obtained from Hydro-Québec. Using the mean monthly runoff and standard deviation values, the variability in the streamflow time series was assessed by computing the coefficient of variation in runoff. The methodology presented in Déry *et al.* (2005) for the investigation of trends in runoff was followed in this assessement. In brief, trends in total annual river runoff (1960-2004) were calculated using the Mann-Kendall test (Mann, 1945; Kendall, 1975), and Kendall-Theil Robust Lines (KTRLs) (Theil, 1950) were used to determine the sign and magnitude of these trends. Trends were considered to be statistically significant when $p < 0.05$ and were characterized as "detectable" when their signal-to-noise ratios (SNRs) are greater than unity.

Results

The 1960-1978 annual cycles of mean monthly runoff for the Eastmain, Grande Rivière de la Baleine, and La Grande Rivière are shown in Figure 2. It is evident that each nival river exhibits a natural flow pattern throughout the year and experiences peak flows in the spring or early summer and secondary peak flows in the fall. For the Eastmain, a spring runoff peak of 107.7 mm month^{-1} occurs in May, while Grande Rivière de la Baleine and La Grande Rivière experience peak flows in June that amount to 76.2 mm month^{-1} and 93.2 mm month^{-1}, respectively. The Eastmain contributes on average 16.9% and 16.4% of its total annual runoff in May and June, respectively, whereas Grande Rivière de la Baleine and La Grande Rivière contribute an average of 15.9% and 16.6%, respectively, of their total annual runoff in June. During the month of July, Grande Rivière de la Baleine and La Grande Rivière contribute 13.3% and 12.4%, respectively, of their total annual flows, whereas the Eastmain only contributes 9.6%. All the rivers experience a secondary peak flow during the month of October in which they all contribute close to 11.5% of their total annual runoff. The coefficient of variation in monthly runoff ranges from 13.5% to 54.9% for the Eastmain, 13.7%

to 47.7% for Grande Rivière de la Baleine, and 16.6% to 33.6% for La Grande Rivière. Each river exhibits its largest coefficient of variation in runoff during the months of April (Eastmain and Grande Rivière de la Baleine) or May (La Grande Rivière).

Figure 3 shows the monthly mean percentage of annual runoff and coefficient of variation for La Grande Rivière and Eastmain+Grande Rivière de la Baleine over 1960 to 1978. The hydrographs have similar annual runoff cycles, contributing similar amounts of runoff on a monthly basis. There is good agreement between the mean monthly flows as 96% of the variance is explained. The main difference in monthly runoff contribution arises in May, with La Grande Rivière and Eastmain+Grande Rivière de la Baleine contributing an average of 11.3% and 14.2%, respectively, of the total annual runoff. Both hydrographs show the largest runoff contribution during June and the least runoff contribution throughout the winter months. The Eastmain+Grande Rivière de la Baleine dataset exhibits a 43.5% coefficient of variation in April, causing both datasets to not correspond well (r^2 = 0.07); however, exclusion of this month from the analysis results in a high degree of correspondence (r^2 = 0.72).

Figure 4 provides a comparison between the monthly runoff rates for La Grande Rivière and the sum of the monthly runoff rates for Eastmain+Grande Rivière de la Baleine from 1960 to 1978. There is a reasonable NSE index (E_f = 0.58) between the two datasets. This suggests that the sum of the Eastmain and Grande Rivière de la Baleine time series are sufficiently accurate to be used in the reconstruction of La Grande Rivière's 1979-2004 time series.

Table 3 presents a comparison between the annual observed and reconstructed river runoff of La Grande Rivière for the period 1960-1978. The error analysis demonstrates that the reconstructed flows for La Grande Rivière match well with the observed rates, confirming the accuracy of the reconstruction methodology. Similar trends exhibited by the observed and reconstructed annual streamflow time series also support the reconstruction method as 64% of the variance is explained (Figure 5a). The observed mean annual runoff rate for La Grande Rivière is 559.7 mm yr^{-1}, with a standard deviation of 89.7 mm yr^{-1} and a coefficient of variation of 15.0%, whereas the reconstructed mean annual runoff rate is 546.0 mm yr^{-1}, with a standard deviation of 80.9 mm yr^{-1} and a coefficient of variation of 14.8%. Interannual variability exists in the annual runoff rates of La Grande Rivière, with the observed and reconstructed time series having similar ranges in runoff of 286.2 mm yr^{-1} (1961 min. = 411.4 mm yr^{-1}; 1965 max. = 697.6 mm yr^{-1}) and 260.9 km^3 yr^{-1} (1962 min. = 402.3 mm yr^{-1}; 1966 max. = 663.2 mm yr^{-1}), respectively. It is also apparent that there is a one-year lagged response in the observed annual time series between 1968 and 1971. Furthermore, Figure 5b demonstrates how the applied method captures seasonality effects and interannual variability in La Grande Rivière's reconstructed flows over a period of 48 months.

Figure 6 compares La Grande Rivière's reconstructed flows with those obtained from Hydro-Québec for the period 1984-2004. The reconstructed mean monthly flows exhibit strong annual runoff periodicity and a high NSE index (E_f = 0.99) when compared to the reference hydrograph of the observed record (1960-1978). Both hydrographs show the spring freshet occurring in May and peak runoff contributions taking place in June. The coefficient of variation in mean monthly flows ranges from 14.0% to 31.1% (Reconstructed) and from 16.6% to 33.6% (Observed). In contrast, the Hydro-Québec hydrograph shows fairly constant monthly contributions throughout the year, ranging from 6.4% to 11.1%. La Grande Rivière's regulated flows are highest during the winter and early spring, and lowest in the summer and early fall. Hydro-Québec's dataset exhibits a relatively constant coefficient of variation in monthly runoff as values range from 15.1% to 25.1%.

Trends in the total annual runoff rates for La Grande Rivière (Reconstructed), Eastmain River, and Grande Rivière de la Baleine are presented in Figure 7 for the period 1960-2004. Each river exhibits

Table 3. Error analysis for La Grande Rivière's reconstructed (LA REC) mean annual runoff values compared to observations (OBS) for the period 1960-1978. The NSE index (E_f), mean absolute error (MAE), and the root-mean-square error (RMSE) are given.

Dataset	Mean (mm yr^{-1})	E_f	MAE (mm yr^{-1})	RMSE (mm yr^{-1})
OBS	559.7	—	—	—
LA REC	545.6	0.64	37.9	48.7

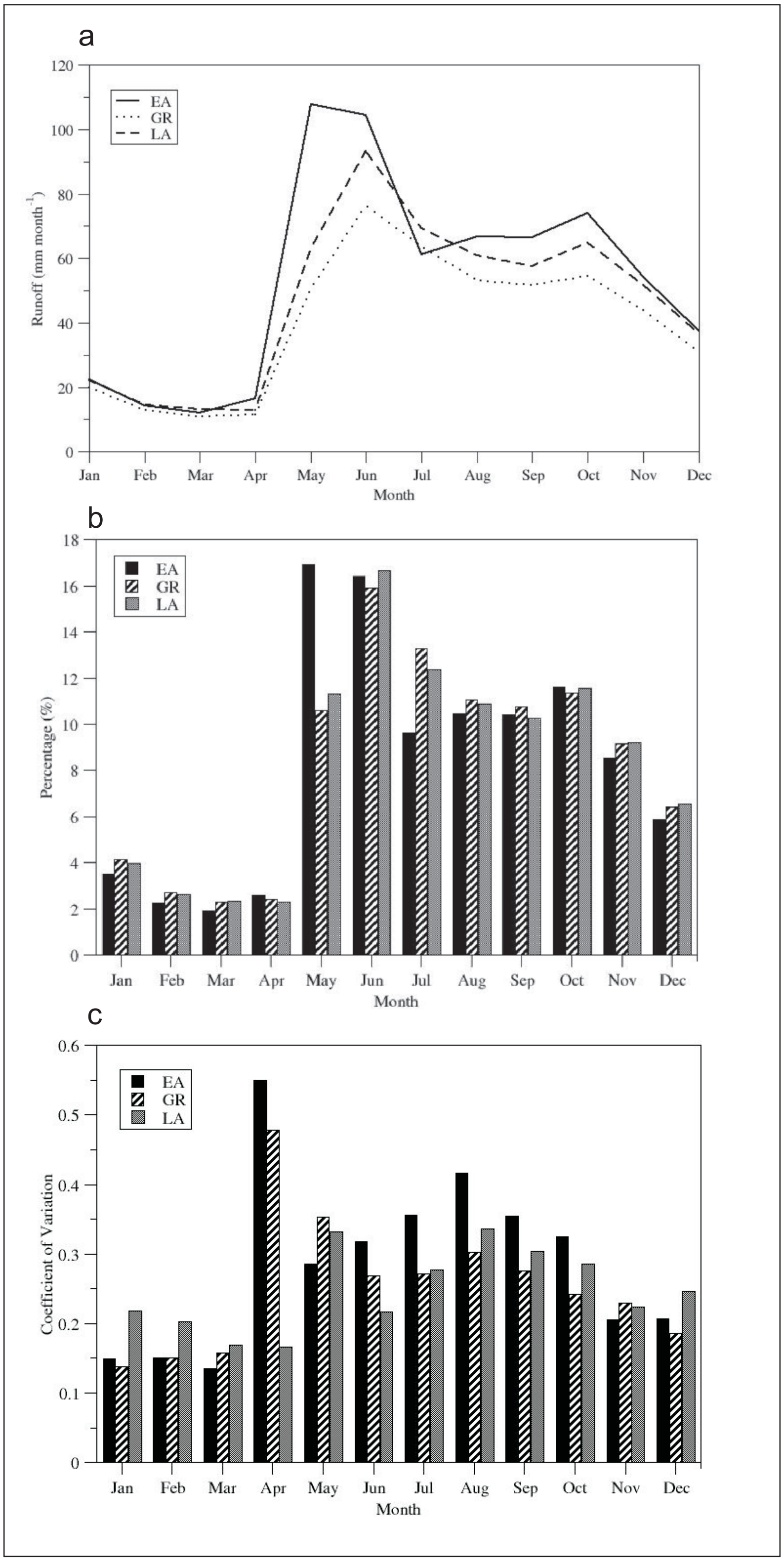

Figure 2. (a) Annual cycle of mean monthly runoff, (b) monthly mean percentage of the total annual flow, and (c) coefficient of variation for the Eastmain River (EA), Grande Rivière de la Baleine (GR), and La Grande Rivière (LA) for the period 1960-1978.

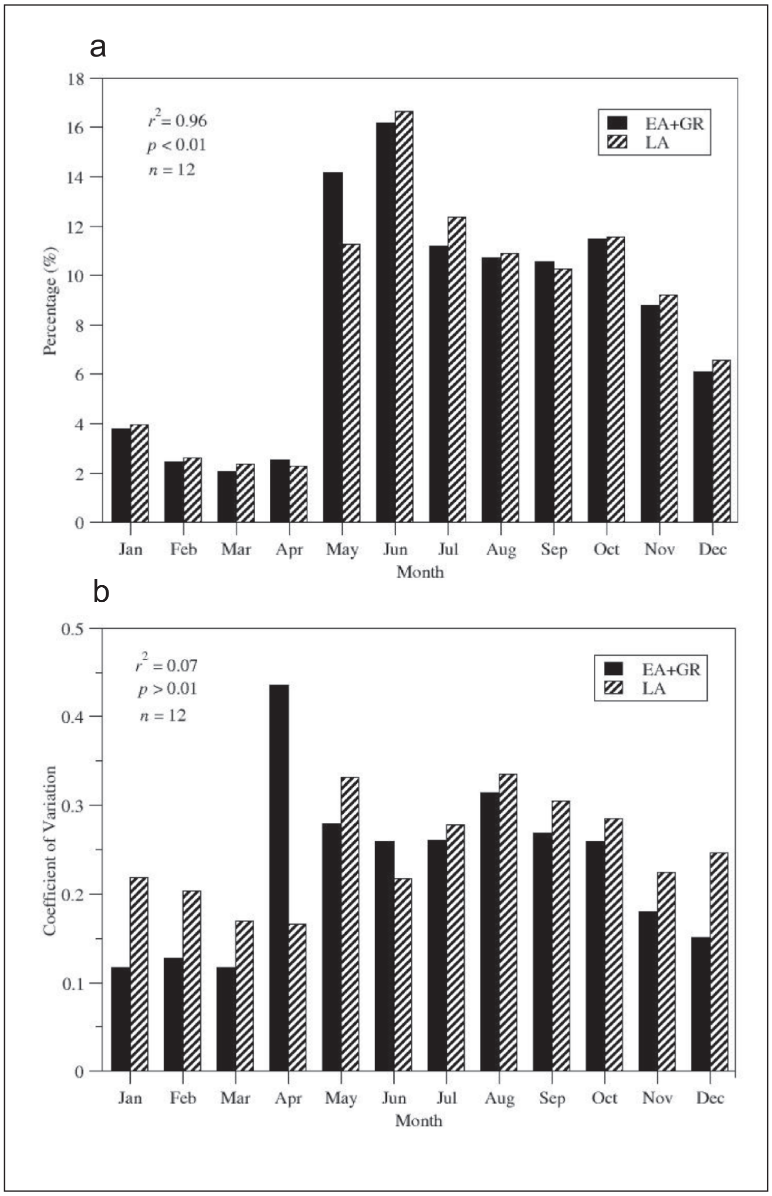

Figure 3. (a) Monthly mean percentage of the total annual flow, and (b) coefficient of variation for La Grande Rivière (LA) and Eastmain+Grande Rivière de la Baleine (EA+GR) for the period 1960-1978.

interannual variability in its annual runoff rates. The Eastmain River has a range of 424.2 mm yr^{-1}, with an annual minimum of 462.8 mm yr^{-1} in 1963 and maximum of 887.0 mm yr^{-1} in 1999, whereas Grande Rivière de la Baleine has a relatively smaller range of 308.5 mm yr^{-1}, with a minimum of 298.7 mm yr^{-1} in 1998 and a maximum of 607.2 mm yr^{-1} in 1965. La Grande Rivière (Reconstructed) has a range of 559.7 mm yr^{-1}, with a minimum of 402.3 mm yr^{-1} in 1962 and maximum of 711.6 mm yr^{-1} in 1999. The KTRLs reveal a significant increase of 16.6% (2.53 mm yr^{-1} yr^{-1}, p = 0.022, SNR = 1.16) in the annual runoff of the Eastmain River, and a significant reduction of 17.5% (−1.78 mm yr^{-1} yr^{-1}, p = 0.017, SNR = −1.25) for Grande Rivière de la Baleine over the 45-year period. There is a 1.0% (0.13 mm yr^{-1} yr^{-1}) increase in the annual streamflows of La Grande Rivière (Reconstructed) as trends of opposite signs exhibited by the Eastmain River and Grande Rivière de la Baleine offset each other to yield no trend.

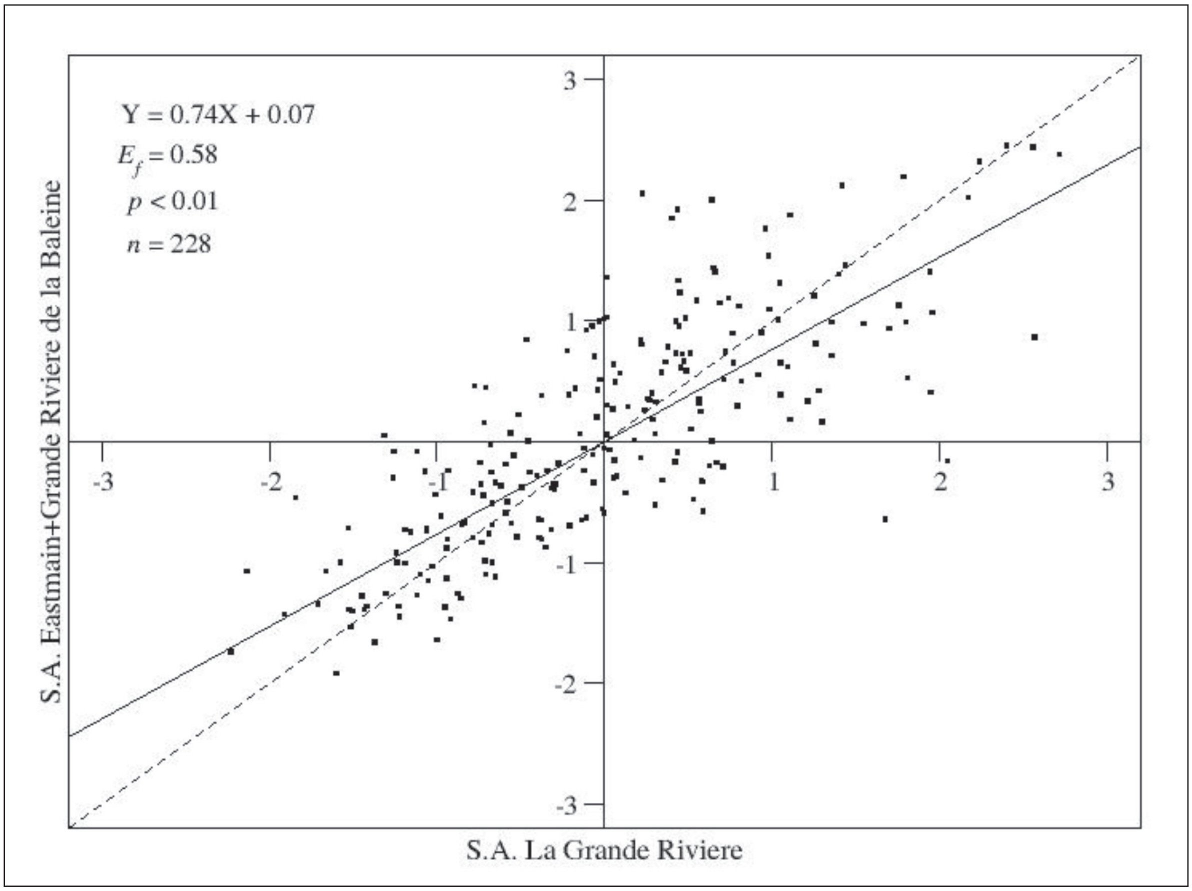

Figure 4. Comparison of the standardized anomalies (S.A.) in mean monthly runoff for La Grande Rivière and Eastmain+Grande Rivière de la Baleine for the period 1960-1978. The black line is the linear regression and the dashed line is the 1:1 line.

Discussion

La Grande Rivière's natural streamflow (1979-2004) was reconstructed using hydrometric data from the Eastmain River and Grande Rivière de la Baleine. The combination of the 1960-1978 standardized anomalies of these two rivers exhibited a high NSE index (E_f = 0.58) with the observational values from La Grande Rivière, making them suitable candidates for the reconstruction. This method was applied by choosing adjacent rivers located in a fairly homogeneous region with flows running parallel to La Grande Rivière. The similar climate, landforms, soils, vegetation, and hydrologic processes found within this region minimized the level of uncertainty in the proposed method. This is supported by the low error rates that were obtained from the error analyses. In addition, La Grande Rivière's reconstructed flows match well with the 1960-1978 observed runoff values obtained from HYDAT as well as a 1981-2000 dataset of naturalized flow rates constructed by Ouranos (René Roy at Hydro-Québec, personal communication, 2010). The seasonality effects and interannual variability were successfully captured by the applied method.

Other reconstruction methods (e.g., hydrological models) incorporate various parameters that have the potential to negatively affect the accuracy of the intended method (Wagener *et al*., 2001). For instance, rainfall-runoff models are dependent on high quality precipitation, air temperature, and runoff data collected from various regional weather and river gauge stations (Beven, 2001). Thus, poorly monitored areas increase the likelihood of errors arising in the reconstruction methodology, leading to less certainty in the streamflow values being reconstructed in the process. In addition, if precipitation and air

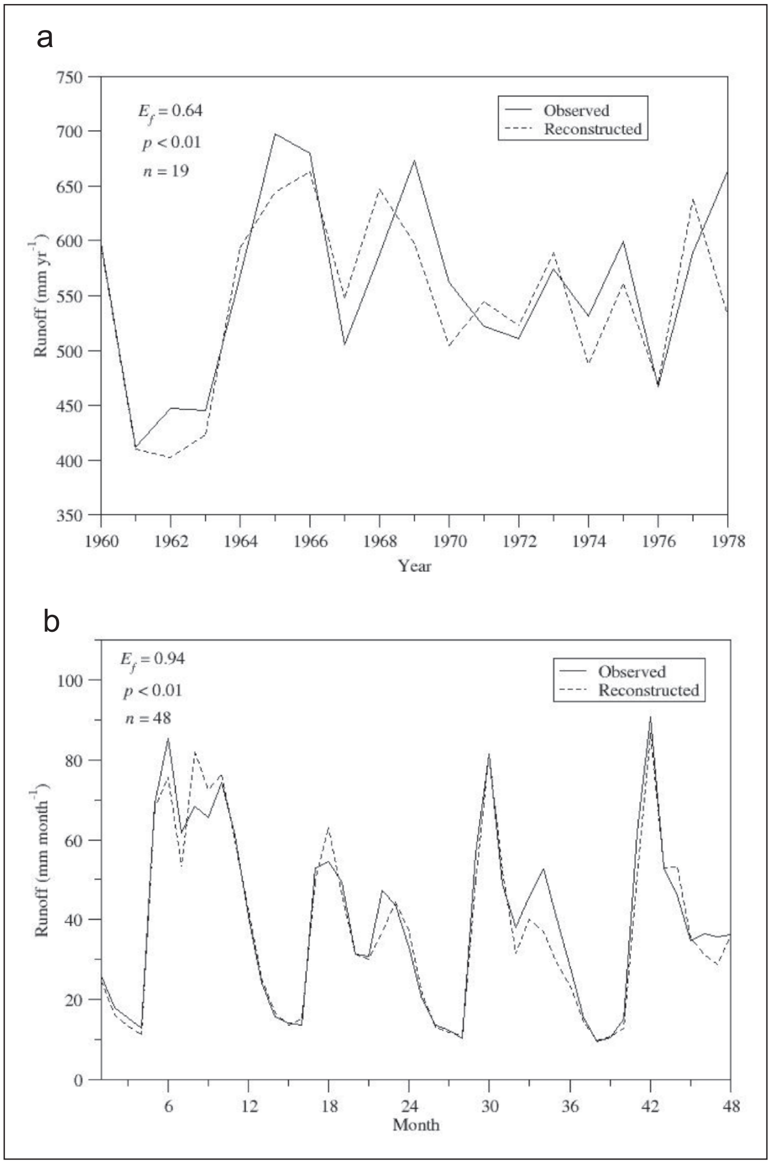

Figure 5. La Grande Rivière's observed and reconstructed (a) mean annual runoff time series for the period 1960-1978, and (b) monthly streamflow for the period 1960-1963.

temperature data are missing, then these hydrological modelling techniques may not be used, whereas the reconstruction method demonstrated here only requires that natural streamflow data be available. In La Grande Rivière's case, it was possible to take advantage of the close proximity of all three rivers, allowing for the natural streamflow to be reconstructed without various parameters being included, which would have undoubtedly increased the degree of uncertainty.

The proposed method is limited by the climatic gradient that exists between the selected rivers. The latitudinal position of each river is largely responsible for its varying climatology, thus rivers that are located further north will experience a later spring freshet than those located further south (Prinsenberg, 1980; Déry *et al.*, 2005). The climatic gradient was minimized by selecting adjacent rivers that are in close proximity to one another, running parallel to La Grande Rivière. The air temperature, precipitation, and snow fields in this region have a tendency to follow a north-south gradient (Société d'énergie de la Baie James, 1988; Brown, 2010). The reconstruction method combined

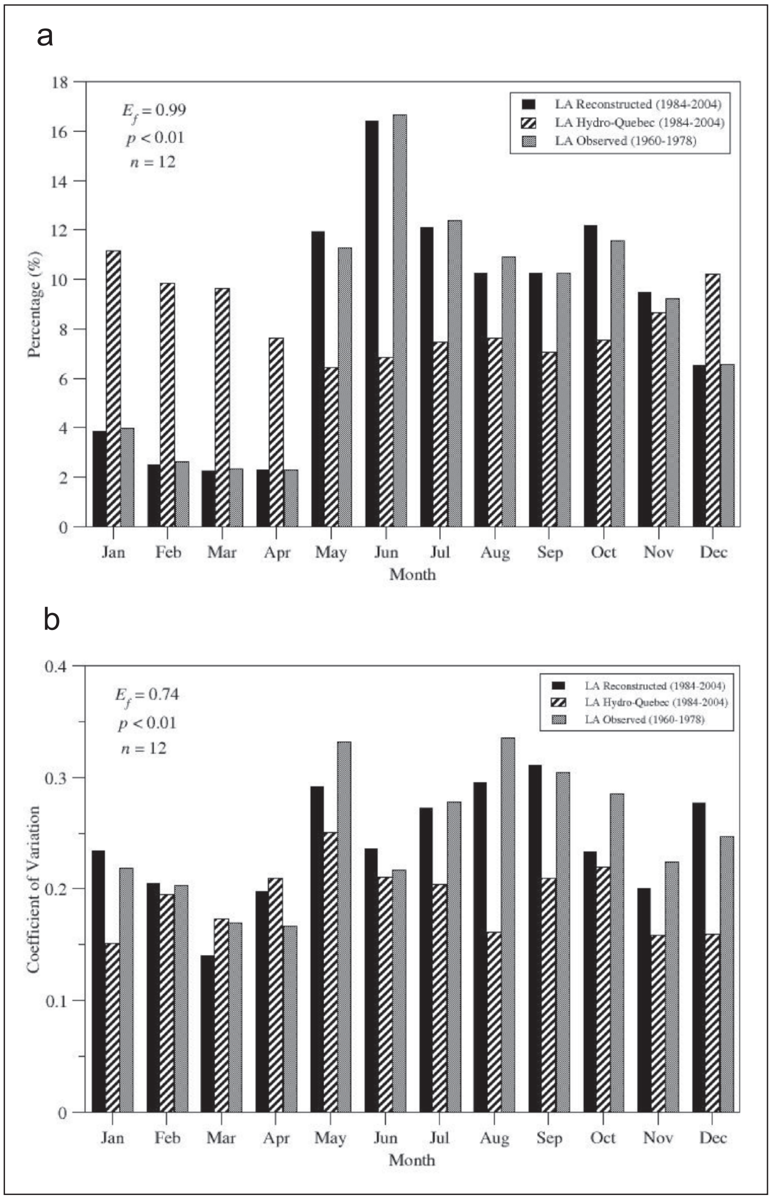

Figure 6. (a) Monthly mean percentage of the total annual flow and (b) coefficient of variation for La Grande Rivière's (LA) reconstructed flows and the regulated runoff from Hydro-Québec for the period 1984-2004. The pre-dam (1960-1978) observed mean monthly runoff data for La Grande Rivière are shown (Note: Hydro-Québec time series is not used in NSE analysis).

the climatic gradients of the Eastmain River and Grande Rivière de la Baleine, which are located south and north, respectively, of La Grande Rivière. This river combination achieved a balance that corresponds well with the expected climatic gradient of La Grande Rivière. The combined time series of these two rivers exhibited a large amount of interannual variability for the month of April. Since the Eastmain is located further south (see Figure 1), the spring freshet always occurs either in late April or early May, leading to a higher degree of variability in both of these months.

The trend analyses for the annual runoff revealed trends of opposite signs for the Eastmain River and Grande Rivière de la Baleine 45-year time series. La Grande Rivière's reconstructed time series exhibited no trend in its annual runoff rate. It is therefore apparent

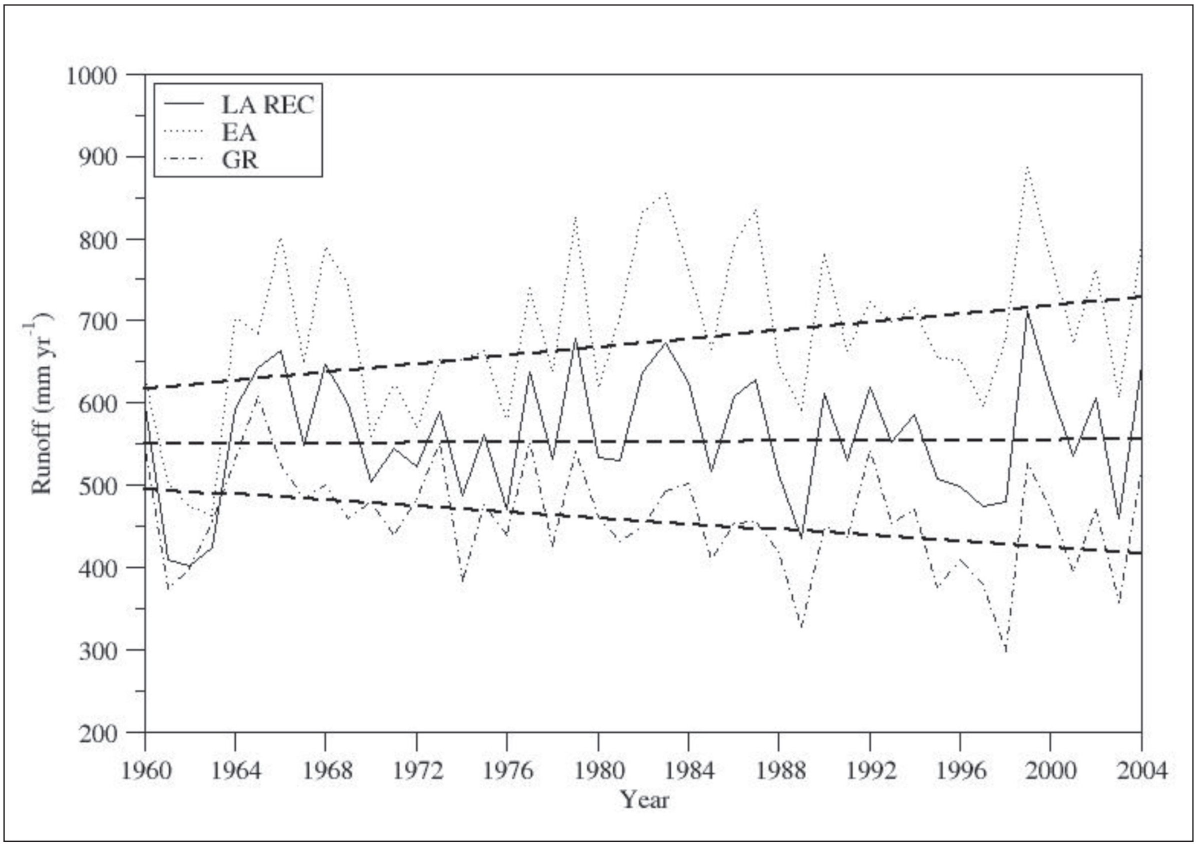

Figure 7. Temporal evolution of the annual runoff of La Grande Rivière (Reconstructed) (LA REC), Eastmain River (EA), and Grande Rivière de la Baleine (GR), 1960-2004. The KTRLs are denoted by thick dashed lines.

that the opposing trends from the Eastmain River and Grande Rivière de la Baleine offset each other to yield no trend when these two rivers are used to reconstruct La Grande Rivière's streamflow. The increasing trend exhibited by the Eastmain River appears to have more of an influence than La Grande Rivière de la Baleine's decreasing trend. Déry *et al.* (2005) provide evidence for the occurrence of these trends and suggest that large-scale atmospheric anomalies, such as the Arctic Oscillation, may be governing the amount of freshwater runoff in these rivers (Déry and Wood, 2004). Moreover, findings show that the North Atlantic Oscillation influences the precipitation responses in this region, such that the Eastmain River experienced an increase in precipitation over 1950-1998 (Zhang *et al.*, 2000) and La Grande Rivière de la Baleine a decrease over 1950-1990 (Stone *et al.*, 2000).

Long-term streamflow records are an integral component of hydrological studies investigating the temporal evolution of freshwater runoff in a river system. Rivers that are regulated do not have complete 'natural' time series, making it difficult to assess seasonal trends and interannual variability. Previous studies have investigated the physical and biological effects of flow regulation in the La Grande Rivière basin. Some of their findings show that the increase in winter runoff and accumulation of freshwater in the region have caused the under-ice plume around James Bay to extend over a larger area (Messier *et al.*, 1989; LeBlond *et al.*, 1996), resulting in the freshening of near-shore surface waters (Ingram and Larouche, 1987) and the disruption of surface currents (Messier *et al.*, 1986). Thus, based on the ongoing research being conducted in this area, it is imperative that future oceanographic studies employ La Grande Rivière's reconstructed flows when assessing the magnitude of human impact and investigating the natural variations in the hydrological cycle of the basin. This is particularly of concern given that Hydro-Québec has recently diverted a portion of the nearby Rupert River (catchment area of ~43,400 km^2) northward into La Grande Rivière, further altering the natural water cycle of northern Québec.

Conclusion

This case study applies a method for reconstructing the 1979-2004 natural streamflow of La Grande Rivière. Hydrometric data for the Eastmain River and Grande Rivière de la Baleine were summed to reconstruct the naturalized streamflow time series of La Grande Rivière. The low error rates and high NSE index between La Grande Rivière's observed and reconstructed flows confirm the accuracy of the applied method. Thus, hydrological studies focusing on La Grande Rivière will now have access to a relatively long and plausible naturalized streamflow time series that possesses statistical characteristics similar to those of the observed record, making it feasible to investigate the effects of water resources development and management practices. Other regulated rivers as well as those not having complete hydrometric records may also benefit from this simple approach, which must be carried out with caution, as all three rivers need to be located in the same climatic zone, consisting of similar landforms, soils, vegetation, and hydrologic processes. In addition, the recent decline in monitoring of river discharge to northern regions of Canada (Mlynowski *et al.*, submitted) emphasizes the need to apply extension methods, such as the one employed in this study, for reconstructing the natural streamflow of rivers. In doing so, future studies will be better able to give an indication of natural trends and variability in river discharge and identify how climatic forcings affect the hydrologic response of a region.

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References

Beven, K. J. 2001. *Rainfall–runoff modelling: The primer*. Chichester, UK: John Wiley and Sons, Inc., 372 pp.

Brown, R. D. 2010. Analysis of snow cover variability and change in Québec, 1948-2005. *Hydrological Processes*, Published online in Wiley InterScience, doi: 10.1002/hyp.7565.

Déry, S. J. and E. F. Wood. 2004. Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. *Geophysical Research Letters* 31, L18205, doi:10.1029/2004GL020729.

Déry, S. J. and E. F. Wood. 2005. Decreasing river discharge in northern Canada. *Geophysical Research Letters* 32, L10401, doi:10.1029/2005GL022845.

Déry, S. J., M. Stieglitz, E. C. McKenna, and E. F. Wood. 2005. Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964–2000. *Journal of Climate* 18: 2540–2557.

Déry, S. J., T. J. Mlynowski, M. A. Hernández-Henríquez, and F. Straneo. Submitted. Variability and trends in streamflow input to Hudson Bay. Submitted to *Journal of Marine Systems*.

Environment Canada. 2009. *Canada climate data.* http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html (accessed July 2009).

Hamley, W. 1983. Hydroelectrical developments in the James Bay region, Québec. *Geographical Review* 73(1): 110-112.

Hirsch, R. M. 1982. A comparison of four streamflow record extension techniques. *Water Resources Research* 18(4): 1081-1088.

Ingram, R. G. and P. Larouche. 1987. Changes in the under-ice characteristics of La Grande Rivière plume due to discharge variations. *Atmosphere-Ocean* 25(3): 242-250.

Kendall, M. G. 1975. *Rank correlation methods*. New York: Oxford University Press, 202 pp.

LeBlond, P. H., J. R. Lazier, and A. J. Weaver. 1996. Can regulation of freshwater runoff in Hudson Bay affect the climate of the North Atlantic? *Arctic* 49(4): 348-355.

Mann, H. B. 1945. Non-parametric test against trend. *Econometrika* 13: 245-259.

Matalas, N. C. and B. Jacobs. 1964. A correlation procedure for augmenting hydrologic data. *U.S. Geological Survey Professional Paper*, 434-E, 1-17. Washington, DC: U.S. Geological Survey

Maxwell, J., J. Lee, F. Briscoe, A. Stewart, and T. Suzuki. 1997. Locked on course: Hydro-Québec's commitment to mega-projects. *Environmental Impact Assessment Review* 17: 19-38.

McCuen, R. H., Z. Knight, and A. G. Cutter. 2006. Evaluation of the Nash-Sutcliffe efficiency index. *Journal of Hydrologic Engineering* 11(6): 597-602, doi: 10.1061/(ASCE)1084-0699(2006)11:6(597).

Messier, D., R. G. Ingram, and D. Roy. 1986. Physical and biological modifications in response to La Grande hydroelectric complex. In *Canadian Inland Seas*, Ed. I. P. Martini, 403-424, Elsevier Oceanography Series. Amsterdam: Elsevier.

Messier, D., S. Lepage, and S. De Margerie. 1989. Influence du couvert de glace sur l'étendue du panache de la Grande Rivière (baie James). *Arctic* 42: 278-284.

Ministère de l'Environnement du Québec. 2009. *Suivi hydrologique de différentes stations hydrométriques*. http://www.cehq.gouv.qc.ca/suivihydro/default.asp (accessed June 2009).

Mlynowski, T. J., M. A. Hernández-Henríquez, and S. J. Déry. Submitted. Hydrometric monitoring across the Canadian Pan-Arctic region, 1950-2008. Submitted to *Hydrology Research.*

Natural Resources Canada. 2009. *The atlas of Canada*. http://atlas.nrcan.gc.ca/ (accessed July 2009).

Prinsenberg, S. J. 1980. Man-made changes in freshwater input rates of Hudson and James Bays. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 1101–1110.

Sénecal, P. and D. Égré. 1999. Human impacts of the La Grande hydroelectric complex on Cree communities in Québec. *Impact Assessment and Project Appraisal* 17(4): 319-329.

Société d'énergie de la Baie James. 1988. *The La Grande Rivière hydroelectric complex: Phase one development*. Montréal: Société d'énergie de la Baie James, 467 pp.

Stone, D. A., A. J. Weaver, and F. W. Zwiers. 2000. Trends in Canadian precipitation intensity. *Atmosphere-Ocean* 38(2): 321-347.

Theil, H. 1950. A rank-invariant method of linear and polynomial regression analysis. *Indagationes Mathematicae* 12: 85-91.

Wagener, T., D. P. Boyle, M. J. Lees, H. S. Wheater, H. V. Gupta, and S. Sorooshian. 2001. A framework for the development and application of hydrological models. *Hydrology and Earth System Sciences* 5(1): 13-26.

Water Survey of Canada. 2009. *HYDAT database.* http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1 (accessed June 2009).

Wen, L. 2009. Reconstruction natural flow in a regulated system, the Murrumbidgee River, Australia, using time series analysis. *Journal of Hydrology* 364: 216-226, doi:10.1016/j.jhydrol.2008.10.023.

Zhang, X., L. A. Vincent, W. D. Hogg, and A. Niitsoo. 2000. Temperature and precipitation trends in Canada during the 20th Century. *Atmosphere-Ocean* 38(3): 359-429.