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Reconstructing past hydrology of eastern Canadian boreal catchments using clastic varved sediments and hydro-climatic modelling: 160 years of fluvial inflows

By Antoine Gagnon-Poiré, Pierre Brigode, Pierre Francus, David Fortin, Patrick Lajeunesse, Hugues Dorion and Annie-Pier Trottier.

Point-by-point reply to the three referee comments

The review made by the three referees is gratefully acknowledged. The manuscript has been modified in response to the comments and suggestions. In the following document, the referee comments are listed in italic blue, the specific responses to referee comments previously given by the authors during the public discussion are in italic black, and the modifications of the manuscript made by the authors are in black. The line numbers mentioned in section “authors' modification”, refer to the line numbers in the Marked-up manuscript. The marked-up manuscript version is presented at the end of this document.

REFEREE #1

This paper presents a short varve chronology from Labrador along with various hydroclimatic interpretations. The identification of varves in this particular region is important due to the limited availability/identification of palaeoenvironmental proxies in the Boreal region of eastern Canada. This work proposes to help fill that gap. The authors suggest a potential for a longer-term record to emerge from this lake – this would greatly benefit hydro-climate reconstructions in this region. The palaeohydrologic interpretation of the varve record is robust, supported by independent dating and multiple statistical approaches.

Overall, the sedimentary analyses and interpretations are sound. Most of my comments below focus on the reporting of the statistical analyses. The figures are well drawn. There is a heavy reliance on acronyms which take some time to get familiar with. In many places, a comma is used instead of a period for quantities (eg, Fig 9 vs Table 1) – from a Canadian perspective it doesn't matter which is used but pick one convention for consistency. Four research objectives are identified in the introduction, and the paper discusses each of these sufficiently.

I would recommend publication of this manuscript with the below comments/suggestions/questions addressed.

Reply:

We thank reviewer #1 for his positive comments on our manuscript. The use of acronyms reduced to facilitate the reading of the manuscript. Also, a descriptive table grouping the main acronyms used in this study could be a good way to help readers familiarised with acronyms and make the reading more fluid. The used of the period for quantities uniformized.

Authors' modification:

The acronyms used for the 3 seasonal sub-layers (ESL, DL and AWL) are no longer used in the text. Same for PSI (particle-size indices) and IRD (ice-rafted debris). The acronyms defining varve's physical parameters (TVT, DLT and $P99D_0$) are still present in the text considering they are widely seen in literature on varved sediment.

Specific comments:

Line 111-113: how are "winters" and "summers" defined? Later in the paragraph the snowmelt season is defined as AMJ, but there is no similar definition of the seasons. Assume JFM and JAS?

Reply:

Winter (DJFM) and summer (JJA) will be defined in the revised version.

Authors' modification:

Winter (DJFM) and summer (JJA) are defined, line 134.

Line 189: "counts were executed repeatedly". How were the counts made? Multiple counters? Multiple counts per counter? There is a mention of counting difficulty (line 382). If multiple counts were made, how consistent were those counts? Given the clear images and laminae it would seem to be fairly clear-cut, but I'd like to see some mention of the accuracy/precision of the counting process to fortify that.

Reply:

Due to the great quality of the varved sequences, two counts were made by one counter (AGP). As mentioned in the text, counting difficulties occur within varve years 1952-1953, 1935-1934, 1918-1919. The error percentage between the 2 counts will be mentioned in the text to further demonstrate the accuracy/precision of the counting process.

Authors' modification:

The counting error percentage is now mentioned, line 521.

Line 244-245: Only 1 of the 5 instrumental records goes back to 1966 (incomplete data 1966-68?). Is this good enough to extend the composite instrumental record back to 1969? "Strong positive correlations" are stated but not shown – could these be added to Table 2? Also, the extension crosses pre- and post-diversion boundary – is it still reasonable extend the record back past 1971?

Reply:

There is an error in the Tab. 2, the Eagle series goes from 1969 to 2016, not 1966 to 2016. This will be corrected. Dinis et al., 2019, produced an observed river index of summer regional discharge in Labrador for the 1969-2009 period. They normalised and average hydrometric data from the Eagle River; 1969–2009, Alexis River; 1978–2009 and Little Mecatina River; 1979–2009. As this paper has been accepted and published in the international journal Climate Dynamics, we think it is reasonable to use the same methodology to produce our Labrador region mean annual discharge series.

Dinis, L., Bégin, C., Savard, M. M., Marion, J., Brigode, P., and Alvarez, C.: Tree-ring stable isotopes for regional discharge reconstruction in eastern Labrador and teleconnection with the Arctic Oscillation, Clim. Dynam., 53, 3625-3640, https://doi.org/10.1007/s00382-019-04731-2, 2019.

The significant positive correlations between the four streamflow series (Tab. 2) with Naskaupi River discharge mentioned in the section '' 3.4 Hydro-climatic variables used'' (line 242) are rather shown in the result section ''4.5 Relation *between varve series and instrumental record'' (line 455) because we believe that these are results. A note in section 3.4 will be added to guide readers (i.e. see section 4.5 for details on correlations).*

We think that it is useful to extend the regional mean annual discharge series back past diversion boundary with the Eagle River hydrometric data because this produce a longer calibration period using a large watershed of the Labrador region which is devoid of anthropogenic modifications. This also allows to calibrate the few varves pre-diversion with discharge data. We think this are valid justifications to extend the regional record beyond 1971, otherwise we still could use the Eagle data from 1978-2016 (or 1973-2016) to standardize with other regional basins.

Authors' modification:

Discussion on the regional hydrological signal in Labrador and the similarities between the Naskaupi River hydro-climatic variables with other Labrador hydrometric stations is now presented in section 4.5, line 638.

The period covered by the Eagle hydrometric station instrumental data (1969 to 2011) has been corrected in Tab. 2.

Line 252: linear regression models. "simple linear regression" is used to model the relationship between varve thickness and hydrometric variables. Adjusted R2 is listed as an evaluative statistic. Adjusted R2 should be reserved for multiple regression, since it adjusts the coefficient based on the number of independent variables. With only one independent variable, the unadjusted R2 is appropriate (listed as Multiple R-squared in R). Similar with Figs 8 & 9.

Reply:

The unadjusted R^2 will be used instead of the adjusted R2 as the linear regression model implied only one independent variable.

Authors' modification:

Adj R^2 was changed for R^2 in the text and figures.

Line 371-374: This triggered a flag for me – why did the 1971 changes result in a thick and coarse unit? It is explained later on (section 5.2) but left me wanting more explanation here in the results section.

Reply:

We agree that it would be useful to include in the revised version of the manuscript a short explanation why did the 1971 changes result in a thick and coarse in this section of the text.

Authors' modification:

We clarified the short text on the suggested link between the distinct 1972 marker layer with the occurrence of the Naskaupi River diversion, which supports the reliability of the constructed chronologies (line 507). We also refer the readers to section 5.2 for more details.

Line 411-: a lot of p-values shown here using a 0.05 threshold (and Table 1). This defeats the purpose of using p-values which are intended to show the actual probability of attaining the particular statistic. Really this is just the same as accept or reject at 95% confidence, which is far too arbitrary. Can these threshold values be replaced with actual p-values to make the analysis more objective? To make matters worse, the threshold value changes to 0.01 in Fig 6. Reporting actual p-values will help with consistency. In line 435-438 there are several r values with no p-value attached. They are "significant" correlations, but no indication of how significant. I would suggest actual p-values to 3 decimal places would suffice.

Reply:

We agree with that comment. P-values shown in the manuscript using threshold values (0.05 and 0.01) will be replaced with actual p-values to make the analysis more consistent and objective.

Authors' modification:

P-values for the main correlations are now shown in Fig. 8, 9, 10 of the manuscript and in Tab. S4 and S5 of the Supplements.

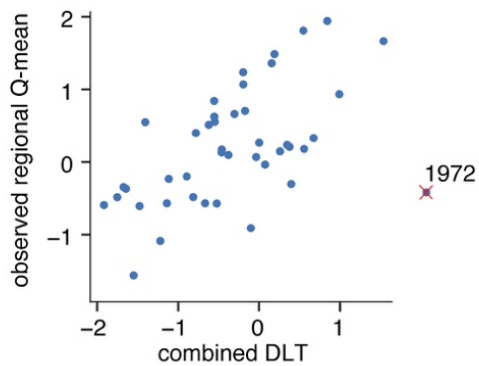
Line 474: "1972 is considered as an outlier". Is this a subjective consideration or is it supported by the statistical analyses? For example, does the leverage for 1972 appear high when evaluating the regression analyses?

Reply:

The fact that the varve of the year 1972 is considered as an outlier is supported by the statistical analyses. When evaluating the regression analyzes, 1972 is far high from the cloud. Indeed, this lamination is interpreted as not being caused by natural hydrological conditions but rather by anthropogenic modification of the watershed. The thickness and the grain size from this varve don't match the annual hydrological instrumental data. Adding 1972 would have the effect of changing the position of the least squares line and inducing an error in the linear regression between variables.

Authors' additional reply:

Here is the scatter plot presented in Fig. 9 including the 1972 detrital layer thickness measurement. The 1972 detrital layer thickness, which is far from the cloud, is considered as an outlier and was not included in all reconstructions.



Technical corrections: remove/add what is in [ ]

Line 32: take[s]

Reply:

OK

Authors' modification:

Done, line 32.

Line 69: method[s]

Reply:

OK

Authors' modification:

Done, line 73.

Line 79: switch "into" and "the" around

Reply:

OK

Authors' modification:

Done, line 95.

Line 135: [a]eolian [this is very picky]

Reply:

OK

Authors' modification:

Done, line 160.

Line 157: [an] undisturbed or undisturbed area[s]

Reply:

OK

Authors' modification:

Done, line 184.

Line 211: Using [a] custom

Reply:

OK

Authors' modification:

Done, line 278.

Line 227: replace indice with index

Reply:

OK

Authors' modification:

Indice was replaced by ''The 99th percentile'', line 294.

Line 244: allows [an extension to the] instrumental

Reply:

OK

Authors' modification:

Done, line 317.

Line 249 Table 2: km2 - add superscript

Reply:

OK

Authors' modification:

Done, line 322.

Line 255: Model[s]

Reply:

OK

Authors' modification:

Done, line 337.

Line 275: station[s]

Reply:

OK

Authors' modification:

This text was removed, line 357.

Line 279: "thanks to the. . ." – this is rather informal compared to the rest of the writing. Change to "using the Oudin et al. . ."? Same on line 304.

Reply:

OK

Authors' modification:

Done, line 362.

Line 378-379: structures allowed [to build] a robust age-model reproducible among cores [to be constructed].

Reply:

OK

Authors' modification:

Done, line 514.

Line 379: why is the 1 – 5 km distance "significant"? Significant with respect to what? Suggest removing the word.

Reply:

OK

Authors' modification:

Done, line 515.

Line 392: ([F]ig. 6a)

Reply:

OK

Authors' modification:

Done, line 538.

Line 401/415: “slight” – what does this mean? Can this decrease in TVT/DLT be supported statistically?

Reply:

We will support this decrease statistically in the revised manuscript.

Authors' modification:

Statistical support is now available in the Supplements Fig. S1, S2, S3 and Tab. S1, S2, S3.

Line 444: [since]

Reply:

OK

Authors' modification:

This text was removed, line 694.

Line 490: 1887-1991 – should this be 1887-1891?

Reply:

Yes, this will be changed.

Authors' modification:

Done, line 740.

Line 491-493: this sentence is incomplete. Perhaps solved by removing the “While” at the beginning.

Reply:

OK

Authors' modification:

This sentence has been removed from this section, line 741.

Line 500: varve[s]

Reply:

OK

Authors' modification:

This text has been modified, line 793.

Line 514: replace on with for

Reply:

OK

Authors' modification:

Done, line 819.

Line 538/589: important. What does this mean? It seems to be used as a synonym for significant, but it doesn't fit well. The sentences work without the adjective.

Reply:

OK

Authors' modification:

"important" was removed, line 834.

Line 552: Beaver[s]

Reply:

OK

Authors' modification:

Done, line 849.

Line 583: "floods of [the years] 1972 CE [has (have)] remobilized"

Reply:

OK

Authors' modification:

Done, line 919.

Line 588: bank[s]

Reply:

OK

Authors' modification:

Done, line 917.

Line 589: [r]iver

Reply:

OK

Authors' modification:

Done, line 918.

Line 595: replace for with to

Reply:

OK

Authors' modification:

Done, line 955.

Line 625: good – another of those pesky vaguely meaningful words. What does it mean in this case – what is a good correlation? Can 'significant' be used here instead? Line 634: global. Do these cores contain a global hydro-climatic signal? Or is it regional (see line 92)?

Reply:

That will be clarified.

Authors' modification:

"Significant" was used instead of "good", line 999.

Line 685: recorded in [the] Grand Lake. . .

Reply:

OK

Authors' modification:

Done, line 1126.

Line 699: discharge[s]

Reply:

OK

Authors' modification:

Done, line 1141.

Line 746: record[s]

Reply:

OK

Authors' modification:

‘’record’’ has been replaced by ‘’sequence’’, line 1229.

REFEREE #2

General comments:

The manuscript by Gagnon-Poire and co-authors entitled 'Reconstructing past hydrology of eastern Canadian boreal catchments using clastic varved sediments and hydro-climatic modeling: 160 years of fluvial inflows' presents river discharge reconstructions from three short cores containing clastic varves reaching 160 years back in time. For the discharge reconstruction mainly two proxies have been applied (grain size and layer thickness). These data demonstrate the large potential for discharge reconstructions using annually laminated sediments.

Reply:

We thank reviewer #2 for his positive comments on our manuscript.

However, a few week points in the interpretation need to be better clarified. In general, it is difficult to follow the large number of different statistical correlations between cores, proxies, proxy reconstruction and model results. A more concise approach with a focus on main correlations would make the manuscript easier to read. Furthermore, instead of levelling out the different signals in the three cores by a pooling approach, the causes for these differences should be better examined and documented. The implications of the difference between cores for selecting the most suitable core location for palaeoydrological reconstruction should be elaborated.

Reply:

We have indeed tried to reconstruct streamflow using single core data and all possible core combinations. However, statistical analysis of these reconstructions shows poorer results (un-significant p values, negative average reduction of error (RE) and negative average coefficient of efficiency (CE) (values > 0 are needed to validate the twofold cross-validation technique). The pooled data from the 3 cores (mean DLT series and mean $P99D_0$) are the combinations showing the best statistical results (calibration and validation).

We used pooled data from 3 cores in order to better capture the regional hydroclimatatic data, and also to somehow remove the noise that is inherent from the analysis of the tiny part of a single core in a very large lake. We do not believe that selecting a single "most suitable core" for paleohydrological reconstruction is the right strategy because a single core will be more sensitive to local disturbances and is probably less representative of the entire hydrogram.

One of the main goals of the paper is making the demonstration that Grand Lake sediments record a regional hydroclimate signal, not only to reconstruct the Naskaupi river hydrogram. We will clarify this in the revised version of the manuscript. Nevertheless, we agree it would be useful to include in the revised *version of the manuscript a better explanation of the causes of the differences between the cores.*

Authors' modification:

Text was added in section 5.1. line 853, and 5.3, line 1009, to better justify the use of the combined series from the 3 sites for reconstructions, which in our opinion, allows to better capture the hydrological signal from a larger region.

Section 4.6 has been modified to better support the choice of the proposed reconstructions. For the sake of transparency, all the other reconstrcutions, i.e. Naskaupi River Q-mean and Q-max reconstructed from the DLT and $P99D_0$ series using single-core data, the combined series, and other core combinations are now presented in the Supplements Fig. S4 and S5. Results of the model calibration for all Naskaupi River Q-mean, Q-max and Labrador region Q-mean reconstructions are also presented in the Supplements Tab S6, S7, S8, S9, S10, S11. We decided to include these informations in Supplements in order to keep the manuscript as simple as possible, as suggested by the reviewer.

The "mean DLT and $P99D_0$ series" used to define the pooled data from the 3 sites in the previous version of the manuscript are now named "combined DLT and $P99D_0$ series". Data from the three sites have been normalized and averaged to produce combined series.

The cores have been taken from different parts of the delta surface and even the most distal core location is still 70 m above the deep basin. Sediment reworking processes on the delta should have an influence on the deposition and layer thickness as well as grain size. For example, a thinning of discharge layers from the proximal to the distal delta location (NAS-1 to NAS-2) should be expected, which, however, is not seen in the layer thickness plots shown in figure 6. A more detailed discussion of sedimentological processes on the delta surface should be added for clarification.

Reply:

Thank you for this suggestion, we will add a discussion about the sedimentological processes on the delta surface, although core NAS-2 is no longer on the delta itself. We will locate the NAS-1 coring site on the 3.5 kHz subbottom profile of the Naskaupi River delta on the Fig. 1C to help visualize the Naskaupi deltaic context and feed the discussion on sedimentological processes. Yet, there is a thinning of the detrital/discharge layers between NAS-1 and NAS-2, although quite small indeed. The mean DTL thickness of both cores will be added. It is clearly visible on Figure 4. In the context of this very large lake, the distance between the 2 cores is quite small, so we are not surprised to see such a small difference, especially considering that the laminations are still formed at *the very end of the end (+/- 45 km away) and can be correlated with laminations from the proximal zone. The grain size is also finer in NAS-2 compared to NAS-1. The median grains size of both cores will be added.*

Authors' modification:

Similarities of sedimentological processes between sites is now discussed in section 5.1, line 853. Specifications on the coring site's location was added in section 3.1, line 185. The location of the NAS-1 site is shown on the 3.5 kHz subbottom profile of the Naskaupi River delta on the Fig. 1c. Note that the vertical exaggeration is 12x. This helps to visualize that the NAS-1 site is located in a relatively flat area where reworking processes are not conducive. The mean of the thickness and particle size measurements are presented in the Supplement's Tab. S1, S2, S3, showing that their absolute values are in the same range, indicating that they are likely produced by similar sedimentary processes.

The 'anthropogenic impact' after dyke construction (in 1971 or 1972?) has been stressed several times (e.g. lines 444/445). However, it is not clear how exactly dyke construction impacted on the sedimentation. Was the main effect generated by the earth movements during dyke construction (if at all, how long did his effect last?) or by the reduction of the catchment? If dyke construction resulted in 'increased availability of sediments in the river system' as suggested (lines 588-589), why is that only seen in NAS-1 core? Why should there be more sediments in the system although the catchment size decreased? The different behavior of the cores NAS-1 and NAS-2 after 1972need to be better elaborated. The argumentation that NAS-2 behaves like BEA-1 (lines598 and following) is not convincing because the BEA-1 location is not affected by the Naskaupi River inflow, whereas NAS-1 and NAS-2 are located in the same direction towards the river inflow. Furthermore, in contrast to DLT, grain-size data do not show major difference between both cores after 1972. How is that explained?

Reply:

We are quite surprised by these comments. Section 5.2 answers most of these questions: for instance, the reviewer question, "Why should there be more sediments in the system although the catchment size decreased?", was answered in lines 585-589: "The reduction of nearly half of the area of the Naskaupi River watershed reduced the water inflows and changed the base level of the downstream river system. The rapid base level fall must have triggered modifications of the fluvial dynamics such as channel incision, banks destabilization and upstream knickpoint migration, likely increasing the availability of sediments in the River system.". Maybe the arguments were not enough clearly outlined, and we will make sure to improve the clarity of that section. What is certain is that the varve structure in both NAS-1 and NAS-2 *cores changed after 1972, and we will emphasize that feature in the revised version of this section 5.2.*

Authors' modification:

Section 5.2 has been modified to better explain the effect of the dyke system on the Naskaupi River sediment inputs.

Due to the core differences, post 1972 DLT data of NAS-1 were excluded from statistical analyses? Instead of excluding the data, correlation of NAS-1 and NAS-2 core data post 1972 with hydrological data should be compared. It would be interesting to see how the sedimentological differences affected the correlations with hydrological data.

Reply:

As mentioned earlier, we tried to reconstruct streamflow using single core data and all possible core combinations. Maybe could we outline this in the supplementary data in order to keep the manuscript as simple as possible, focusing on the main arguments as suggested by the reviewer.

Authors' modification:

The combined DLT series without the 1972-2016 period presents a slightly better fit with the instrumental data (Supplement Tab. S6, S7). However, there are small differences between reconstructions using the combined DLT and $P99D_0$ series and the combined series without the NAS-1 1978-2016 period (Supplement Fig. S4, S5).

The proxy data from different cores have been pooled to obtain a better statistical correlation with hydrological variables (lines 630-631). However, pooling masks the different sensitivity of the different core locations in recording natural hydrologicial variability. Moreover, it is not clear if the pooling includes all data from all cores or if some parts of the data are excluded. In line 614 it was pointed out that the post 1972 period has been excluded from one of the cores (NAS-1). If this part of the record is also not included in the pooling approach you put apple and pears in the basket and I wonder about the meaning of improved statistical correlation. Since the BEA-1 and NAS-1 (lines 599-604) are considered to record the 'natural hydro-climatic signal' one should expect a better representation of palaeohydrogical changes in one of these cores rather than in pooled data from all cores.

Reply:

Well, our text in lines 599-604 explains that BEA-1 and NAS-2 (not NAS-1) are considered to record the 'natural hydro-climatic signal', i.e. without the influence of the dyke. So maybe there is some sort of misunderstanding here.

Authors' modification:

As mentioned above, section 4.6 has been modified to better justify the proposed reconstructions in the manuscript. Text was added in the section 5.3 (line 1009) to better justify the use of the combined series from the 3 sites for reconstructions.

The authors report variability on different time scales, i.e. long-term trends in mean annual discharge (line 687) and decadal-scale variability (e.g. lines 56-57) but they do not explicitly relate these. The appearance of variability at different time scales is an interesting finding that should be more emphasized and elaborated in the paper.

Reply:

Yes indeed, this is an interesting finding, but this theme will be exploited in an upcoming paper from the same site with a longer and even more interesting record. Unless the editor wants us to expand on this, we would like to hold that information for the time being.

Authors' modification:

This theme will be discussed in detail in an upcoming article from the same site. The observation of variability on different time scales is no longer reported in the manuscript. The following text discussing this aspect has been removed from the manuscript: "Reconstructed Q-max series reveals more significant interannual and decadal-scale variability, however long-term trend is observed in both reconstructed Q-mean and Q-max series. Ongoing work on Grand Lake varved sequence suggests that variability in river discharge may occur at different timescales in the Labrador region".

The statement about dyke effects on sediment transport and its 'implications for palaeohydrological reconstruction' (lines 703-705) and that dyking effects are 'clearly visible in the sedimentary record' (lines 743-744) are too much simplified. It has been shown that one coring sites has been affected by dyke construction but the two others not or only to a minor degree. This differentiation between core locations is an important point and knowledge about these differences and their causes is essential to select the most suitable coring locations for palaeohydrological reconstruction. In this respect, and here I repeat my previous comment, I do not consider the pooling as suitable approach even if it may improve statistical correlation. Often unspecific terminology is used like, for example, 'thick and coarse', 'thicker' (examples in specific comments). This should be changed into quantified information.

Reply:

We agree to improve the text related to the explanation of the dyking effects, and augment our discussion about the differences in sedimentary processes occurring in the coring sites. We will make our terminology more specific, and change it in quantified information.

Authors' modification:

As mentioned above, section 5.2 has been modified to better explain the effect of the dyke system on the Naskaupi River sediment inputs. Similarities of sedimentological processes between sites are now discussed in section 5.1, line 853.

The unspecific terminology was changed into quantitative data. Additional visual support and statistical information on TVT, DLT and $P99D_0$ series from each different core are now provided in the Supplement.

Specific comments:

A number of 'distinctive marker layers' (labelled A-P, Figure 4, lines 381, 382) have been defined but it is not explained how distinctive these layers are and what makes them distinctive. In figure 4 they do not appear distinctly different neither in the core image nor in the XRF data.

Reply:

An explanation will be added.

Authors' modification:

Chronology of each core was confirmed by cross-correlation between thick laminations selected as distinctive marker layers along the different sediment sequences (section 3.2, line 239).

In the chapter 'Regional setting' some information about vegetation cover should be added since that may influence catchment erosion and clastic sediment transport into the lake.

Reply:

We will specify what is the vegetation of the High Boreal Forest ecoregion.

Authors' modification:

Specifications on vegetation cover was added in section 2, line 131 and 137.

In chapter 4.7 it is not clear which sediment proxies have been compared with the rain fall-runoff modeling approach. Are these proxy data from individual cores (which?) or from pooled data? If it is pooled data, how did you account for differences in TVT between cores?

Reply:

We will specify that it is from pooled data, and we will provide the comparison for each core in a supplement in order to keep the MS simple.

Authors' modification:

We specified that it is the combined DLT and $P99D_0$ that have been compared with the rain-fall runoff modeling approach (section 4.7, Fig. 10 caption).

Line 162: It should be specified which efforts were made to retrieve undisturbed sediment surfaces. Taking short cores from such deep lakes without disturbance is a common problem to the community and it would be helpful to know how the authors tried to improve the coring in this respect.

Reply:

This will be specified.

Authors' modification:

Our technique to retrieve undisturbed sediment surfaces is now explained in section 3.1, line 191.

Lines 185-186: Sampling intervals for Cs-dating are unclear. Was it attempted to sample individual varves or only sublayers? Sample intervals vary between 2 and 0.5 cm but according to figure 6 layer thickness was > 4cm? Please clarify.

Reply:

This section is confusing and will be clarified.

Authors' modification:

Description of the sampling intervals for Cs-dating has been clarified (section 3.2, line 230).

Line 226: Specify 'coarse debris' and quantify grain sizes

Reply:

This will be done.

Authors' modification:

Grain size of the coarse debris observed in the early spring layer (µm to mm scale) is mentioned in section 4.1, line 424.

Line 227: Explain the PSI. Is this a mean grain size for each lamination? What is 'lamination' in this respect? A varve or a sublayer (which?)?

Reply:

This will be done.

Authors' modification:

The Acronym PSI (particle-size indices) is no longer used in the text and have been replaced by the 99th percentile ($P99D_0$) of the particle size distribution. The $P99D_0$ was obtained for each detrital layer (section 3.3, line 295).

Line 325: What is 'occasionally'? Provide the number or percentage of DL with sharp lower boundary.

Reply:

This information will be added.

Authors' modification:

"Occasionally" has been removed. The detrital layer always has a sharps lower boundary (section 4.1, line 428).

Line 327: Explain 'non-annual' for these layers. All three described sub-layers (ESL, DL, AWL) are seasonal, i.e. non-annual. Also quantify 'thin coarser'. What is the thickness (range or mean) and grain size of these layers? Finally, quantify 'some cases',i.e. how many of these layers did you count?

Reply:

This will be explained.

Authors' modification:

The term "Non-annual" is no longer used. The varve structure can be divided in 3 seasonal layers. So, now we say: the upper part of the detrital layer consists of a finer detrital grain matrix containing thin visually coarser intercalated sub-layers in ~75% of the laminations (line 429). However, we did not calculate the particle size of these particular sub-layers individually.

Lines 328-329: Provide information why Ca and Sr are relatively higher in DLs, i.e. which minerals in the DLs include these elements?

Reply:

Allochthonous lithoclastic materials that composed the DLs are rich in Ca and Sr. These elements come mainly from eroded sediments of the Grenville geological province (i.e. plagioclase, granodiorite?) deposited in the Grand Lake's watershed during glacio-marine/lacustrine phase and remobilized by spring floods. We did not perform EDS analysis.

Authors' modification:

We now say to be more specific that: "The allochthonous lithoclastic materials which compose the detrital layers are associated with higher density values (Fig.

4) and an increase in the relative intensity of elements Sr and Ca (Zolitschka et al., 2015)" (section 4.1, line 430).

Line 344: 'thick and coarse' is unspecific. Provide information about thickness and grain size of this prominent layer. Are there distinct differences also in the elemental composition of this layer?

Reply:

This section will be clarified.

Authors' modification:

Thickness and grain size of the 1972 marker layer were provided in section 4.1, line 467.

Lines 349/350/351: the ESL of pre-1972 CE is 'thicker'. Provide quatified information instead of this unspecific information. It should be easy to calculate mean contribution of the ESL (in %) to the total varve thickness for the pre- and post-1972 intervals

Reply:

This will be done.

Authors' modification:

The mean contribution of the early spring layer and autumn and winter layer to the total varve thickness for the pre- and post-1972 intervals are provided in section 4.1, line 475.

Lines 350, 352: 'post-1971' or 'post-1972'?

Reply:

This will be clarified.

Authors' modification:

Post-1972, i.e. after the Naskaupi River diversion effect (line 470 and 473).

Lines 372/373: When exactly was the anthropogenic change in the catchment? Was it in the year before the 1972 marker layer or in 1972? If it was in the year before, why was there a 1 years delay in the sediment response?

Reply:

On 28 April 1971, by closing a system of dykes, the headwaters of Naskaupi River watershed were diverted into the Churchill River hydropower development. The base level fall must have triggered modifications of the fluvial dynamics such as channel incision, bank destabilization and upstream knickpoint migration *during the rest of the year. We interpret that it was only during the following spring flood (1972) that the destabilized sediments (during the previous year) were the most remobilized and deposited on the Naskaupi delta. This section will be clarified.*

Authors' modification:

The exact date of the dyke construction (April 1971) is now mentioned in section 5.2, line 914. The text has been reworked to better explain when the anthropogenic change occurred in the catchment and the 1-year delay in the sediment response.

Figure 6. Add the position of marker layers A-P in the figure.

Reply:

This will be done.

Authors' modification:

The position of marker layers A to M were added in the Fig. 6.

Lines 414 and following: How is the P99D0 value influenced by the ratio DL/TVT?

Reply:

There is a significant positive correlation (R2 = 0.38 p-values = 0.01) between DL/TVT and $P99D_0$. A lamination with a high LDL / TVT ratio is more likely to have high grain size values. However, this correlation shows that DLT and $P99D_0$ remain independent variables and can both reveal different information (i.e. Q-mean and Q-max).

Authors' modification:

Additional discussion on the relation between TVT, DLT and $P99D_0$ was added in section 4.3, line 599.

Line 550: How often is 'seldom'? In how many layers erosion traces have been observed.

Reply:

This will be clarified.

Authors' modification:

The wording of the original sentence was clumsy. We meant that clasts of eroded material could be found in the early spring layers at 3 sites we sampled, but not that the early spring layers were impacted by erosion at these 3 sites. We modified the text accordingly (section 5.1, line 846 and 853).

Line 550/551: What kind of traces of erosion are these. Provide a description. I would expect differences between the proximal and distal cores. Please clarify.

Reply:

This will be clarified.

Authors' modification:

This is now explained in section 5.1, line 846 and 853.

Line 580: I disagree that river sediment input was 'quantitatively and spatially constant' before 1971. There is distinct variability at different time scales in the data, e.g.between 1920 and 1960s.

Reply:

Reviewer is right, this statement is confusing, we will be more specific.

Authors' modification:

This sentence was removed from the text (line 913).

Line 602-604: It is assumed that 'natural hydro-climatic signal' drives the sedimentation in BEA-1 (and NAS-2) without saying what this 'natural hydro-climatic signal' is. This statement should be easy to be proven or disproven by correlation with instrumental hydrological data.

Reply:

This will be done.

Authors' modification:

Indeed, the observed Naskaupi River Q-mean series also shows a decrease on the 1978-2011 period (section 5.2, line 963).

Line 634: You will get at best a regional hydro-climatic signal but certainly no global.

Reply:

Yes, reviewer is right, that will be changed.

Authors' modification:

"global" was replaced by "from a larger region", line 1018.

Line 642: Quantify 'slight variability'

Reply:

The variability will be quantified.

Authors' modification:

"slight variability" was removed. This part of the text was reworked (section 5.3, line 1059).

Line 648: How do you explain 'high thickness values' (need to be quantified!) of ESL sand AWLs during the 1920s?

Reply:

This will be quantified. Hypotheses will be provided.

Authors' modification:

This text was removed to keep the manuscript as simple as possible (section 5.3, line 1059), focusing on the main arguments, as suggested by the reviewer.

Lines 675-677: There is a detailed discussion on thresholds and flood amplitude re-construction in Kaempf et al., 2014 (J. Quat. Sci.) that you may consider including in this part of the discussion.

Reply:

We are going to consider including this information.

Authors' modification:

We included this reference in the text (line 1115).

Technical corrections:

Lines 328-329: 'abundance of elements'. This is wrong because XRF scanner data are relative variations of element intensities but not quantified amounts

Reply:

OK

Authors' modification:

"abundance of elements" was removed. We now said to be more specific that: "Elements were normalized by the total count (cps) for each spectrum" (line 209).

Line 547: instead of ‘underlying’ it should be ‘overlying’

Reply:

OK

Authors' modification:

Done line 843.

Line 571 (figure caption): see comment above, XRF data does not give ‘abundances’. This are relative changes of element intensities

Reply:

OK

Authors' modification:

“abundance” was changed for “relative intensities” in Fig 4. 5 and 11 captions.

REFEREE #3

General comments:

This study by Antoine Gagnon-Poiré and colleagues entitled "Reconstructing past hydrology of eastern Canadian boreal catchments using clastic varved sediments and hydro-climatic modeling: 160 years of fluvial inflows" presents an interesting counterpart to rainfall-runoff modeling approaches that aim at expanding instrumental streamflow datasets for multi-decadal analysis of hydrological variability. Indeed, this study based on varved sediment sequences aims at producing long river discharge records (>100 years) to support, help refine or contradict paleo-hydrological records offered by the modeling approaches.

The strength of this study is clearly provided by the very high-quality analysis of the varve record and the robustness of the sediment chronology. Varve boundaries are clearly defined through high-quality startigraphical analysis combined with CT images and state-of-the-art microscopy-based grain size analysis. Varve counts are consistent between the cores of different locations, and they are supported by independent 137Cs dating. The varve record thus offers an annual view into past changes without chronological constraints, which is a major advantage for developing a proxy-climate or proxy-hydrology models.

Varve stratigrahical analysis further allowed to select the best varve parameter (i.e., meaningful season) to compare with hydrological data. The proxy-hydrology correlations have been significantly improved by selecting the thickness of the detrital layer (DLT) instead of total varve thickness (TVT), thus reducing potential noise; spring discharge being the main driver for sediment erosion and transport in the nival catchment of Naskaupi River. In this context, Figure 11 is very stunning, and shows how a varve record can best be exploited to look at micro-meteorology and lower-than-seasonalresolution river hydrodynamics; this is novel.

However, although the quality of the sedimentary investigation is very robust, general important comments relate to the methods to produce the paleo-hydrological record and its regional signal. I hope that these major comments will be well received and accepted, and that they will be of good use to improve the present manuscript.

> *Reply:*
> *We thank reviewer #3 for his positive comments on our manuscript.*

Normalizing total varve thickness (TVT) is interesting when several sediment cores are collected at the same location => thus to reduce local error in the proxy-hydro/climate relationship. However, merging TVT from a proximal (more sensitive, thus with larger amplitude) and distal record (buffering large changes in river discharge, recording annual change in hydrodynamics and only sensitive to the most intense discharge events) is neither properly justified in the text, nor fully appropriate. It gives the impression that the different records were merged in the way that the correlation with *hydrometric data would be maximize, at the cost of process understanding. A great example is losing the downward trend in TVT from NAS-2 by merging its record with NAS-1, which has no trend. The same applies to (and I would say particularly applies to) P99D0. Mean values are strongly driven by NAS-1, the proximal coring site. As such, it is not surprising to find the best correlation for Qmax to NAS-1 (proximal) and for Qmean to NAS-2 (distal). Overall, there is no mechanistic logical explanation in merging TVT, DLT or P99D0 from the three cores to help maximize the correlation. This is particularly the case integrating BEA core, for which it is argued (L604) that "it is quite unlikely that the sedimentary input from the Naskaupi River contributed to sediment accumulation at the mouth of the Beaver River" (i.e., BEA core). L443: There is no clear explanation on why the post-anthropogenic watershed modification would support the discarding of NAS-1 in the TVT, DLT and P99D0 normalization of the cores. It further supports the impression that the best records were merged in the way that the correlation with hydrometric data would be maximize, at the cost of process understanding. L461: Table 3 is named Table 1. . ..it took me some time to realize that Table 3 was not missing, while being important and largely cited.*

Reply:

Thank you for that comment. Considering the very large size of the lake, the coring sites are quite close to each other, especially NAS-1 and NAS-2 (~1km). It is more than probable that the sediment deposition phenomena at the different sites are similar. We normalized and pooled data from 3 cores in order to somehow reduce the local sensibility recorded and better capture the regional hydroclimatic signal.

We will better explain our choice to merge the DLT or $P99D_0$ of the three cores in the revised version of the manuscript. We will show in supplement material of the revised version streamflow reconstructions using single core data and all other core combinations. This will help discuss process understanding, anthropogenic watershed modification and the result of adding and discarding some cores or core section.

We consider that the Naskaupi and the Beaver rivers have a very similar annual hydrological dynamic due to their close proximity. (L604) Evidence leads us to believe that it is quite unlikely that the sedimentary input from the Naskaupi River contributed to sediment accumulation at the mouth of the Beaver River. The BEA core does not record the Naskaupi River input but rather the hydrological conditions of the Beaver River which are quite similar. With the meteorological dataset used in our study (e.i. temperature and precipitation), it appears that the two catchments have very similar climatological characteristics. Integrating BEA core in the pooled data allows to capture the hydrological signal from a larger region (Nakaupi + Beaver watersheds).

The mistake concerning the Table 3 will be corrected, sorry for that.

Authors' modification:

As mentioned in the referee #2 response, similarities of sedimentological processes between sites is now discussed in section 5.1, line 853.

Text was added in section 5.1. line 853 and 5.3, line 1009, to better justify the use of the combined series from the 3 sites for reconstructions.

Naskaupi River Q-mean and Q-max reconstructed from the DLT and $P99D_0$ series using single-core data, the combined series, and other core combinations are now presented in the Supplements Fig. S4 and S5. Results of the model calibration for all Naskaupi River Q-mean, Q-max and Labrador region Q-mean reconstructions are also presented in the Supplements Tab S6, S7, S8, S9, S10, S11.

The "mean DLT and $P99D_0$ series" used to define the pooled data from the 3 sites in the previous version of the manuscript are now named "combined DLT and $P99D_0$ series". Data from the three sites have been normalized and averaged to produce combined series.

An explanation on why we suggest discarding of NAS-1 1978-2011 period in the combined DLT series for Q-mean reconstructions is provided in section 4.6, line 703.

Table 3 is now correctly named.

#General comment on the comparison between sedimentary data and hydrological

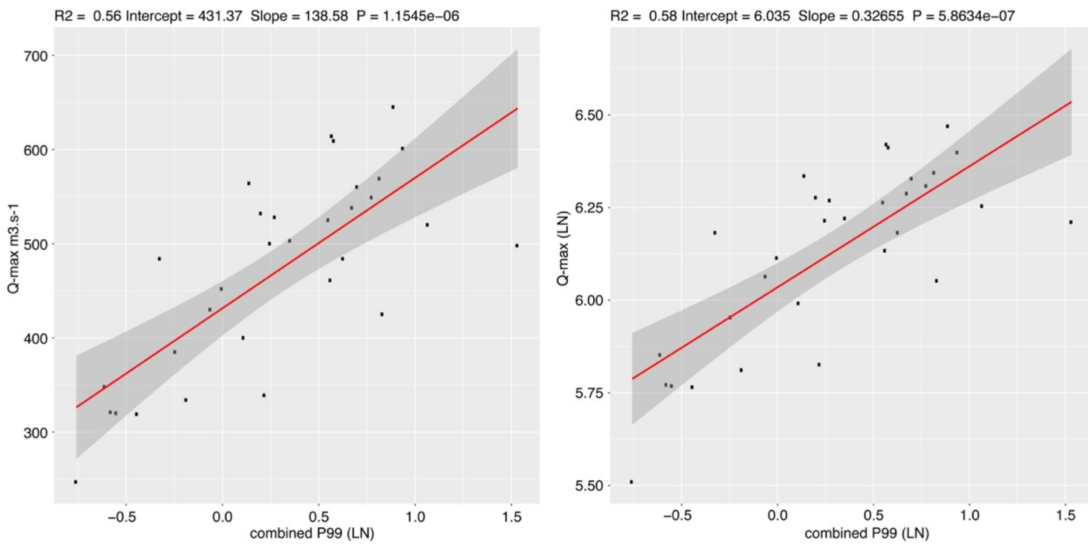
Variables Q vs SSC are always presented as a log-log linear regressions. The same should applied to DLT vs Q, likely to P99D0 vs Q. From the scatterplot presented in Fig 8, it is likely that the general proxy-hydrometric relation follows a DLT=f(log(Q)), or a log(DLT)=f(log(Q) relation rather than a linear relation. See Warrick (2015) and references therein, or Thurston et al. (2020). This should be tested as it has major implications on statistical yields in the sediment-hydrological relations.

Warrick, J. A. (2015). Trend analyses with river sediment rating curves. Hydrological Processes, 29, 936–949. https://doi.org/10.1002/hyp.10198
Thurston et al. (2020). Modelling suspended sediment discharge in a glaciated Arctic catchment–Lake Peters, Northeast Brooks Range, Alaska. https://doi.org/10.1002/hyp.13846

Reply:
Thank you for that comment and literatures. This will be tested.

Authors' additional reply:

Variables DLT and $P99D_0$ vs Q were tested with a log-log linear regression. It improved very slightly the statistical results but had no major impacts (right scatterplot). Therefore, we are still proposing our reconstructions in cubic meters per second.

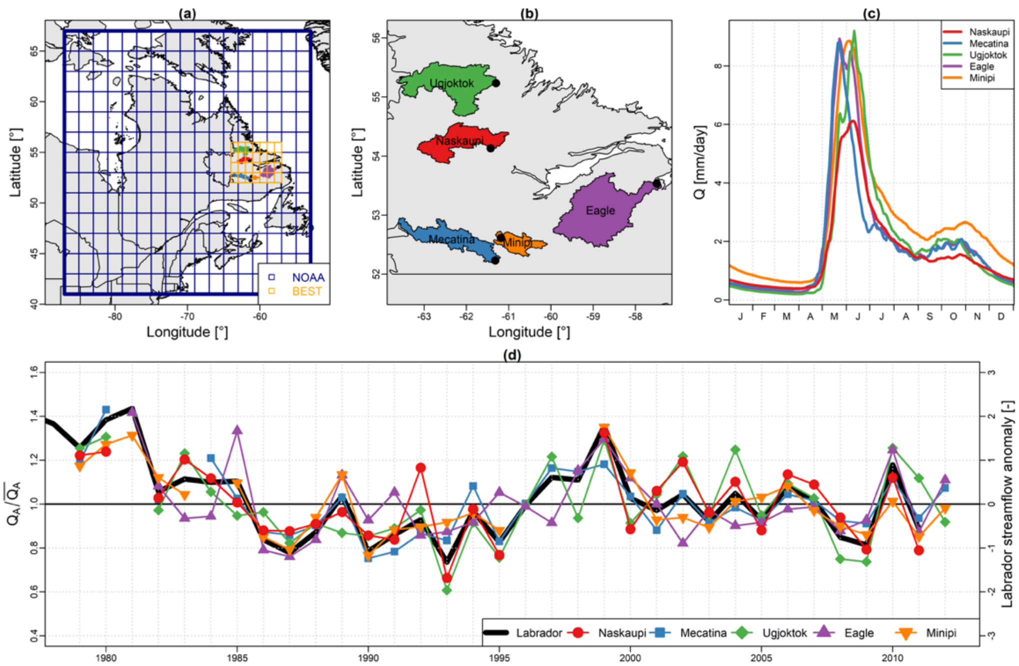


#General comment on the regionalization of the signal

The merging of the different watersheds of the region is interesting, but I don't think that the quantitative analysis is relevant. This is exemplified by the low correlation of r=0.49 (even though significant) between the Naskaupi River and the Eagle station. This means that the discharge data from the Naskaupi River can only explain 24% of the variance in Eagle discharge data, independently from the sediment context. Removing Eagle from this merging exercise will not solve this issue. Each watershed is sensitive in its own way not only to specific climatic (evidence is missing that the climate in the Naskaupi region is representative of a broader region, not only through correlation between hydrometric station data) but also to geomorphic conditions that are not integrated into the daily climatic series of the CemaNeigeGR4J model (such as slope, erosion susceptibility, potential geological difference, orientation. . .), and that can differ significantly within the 500x500km grid used in this manuscript. A more detailed analysis of the different watershed, their runoff response (timing, strength, duration, sensitivity to snowmelt vs rainfall) would merit further investigation. L241: "These four streamflow series (Tab. 2) show strong positive correlations with Naskaupi River discharge", one expects to see these strong positive correlations. Figure 3 presenting the location of the different catchment for regionalization of the findings would have benefited an additional panel with daily streamflow time series for each catchment as in Figure 2, for instance.

Reply:

This is an excellent suggestion. Additional panels on Fig. 3 (streamflow regime for each catchment as in Figure 2 and series of annual streamflow anomalies from all hydrometric stations used in this study) will help discuss the similarity between different watersheds and justify the used of our regional instrumental series.



The daily climatic series used to build our Labrador region mean annual discharge series does not come from the rainfall-runoff model (CemaNeigeGR4J) but rather from instrumental data from hydrometric stations. We will make sure to improve the clarity of that section.

Authors' modification:

Additional panels were added in Fig. 3. Discussion on the similarity between the hydrology of the different watersheds in Labrador was added in section 4.5, line 638.

#General comments on the calibration-in-time model

A proxy-hydrology calibration model is built for the period 1978-2011, and reconstructed back to 1876. Post 1972 (River deviation) shows that the system has changed hydrologically with discharge reduced by a factor 2. This should also be true sedimen-tologically, and a few points are in line with this (contre-)hypothesis: clear change in the preservation of DLT in NAS-2, change in the mean P99D0 record of NAS-1, change in mean and variance of DLT and TVT of BEA-1, and most significant change for TVT and

DLT post 1972 in NAS-2. These observations thus contradict the sentence L580 "River sediment input seems to have been quantitatively and spatially constant." The principle of stationarity being not respected hydrologically, it is doubtful that the calibration model post anthropogenic modification remains valid for the preceding period. Deeper discussion are required on this topic, e.g., by proposing evidence that the sediment record (through TVT, DLT, or best P99D0) is not significantly affected by this change and can be used to infer river hydrodynamics prior 1972.

Reply:

There is no instrumental data available for the Naskaupi basin before 1972. Thus, it is not possible to calibrate the model for the 1856-1971 period. We will further discuss the limitation and weakness of our calibration model in the revised version of the paper.

Our text in lines L580 explains that "River sediment input seems to have been quantitatively and spatially constant." Here we are talking about the 1856-1971 period (Fig. 6). This sentence does not apply for the period after the Naskaupi River diversion. This section will be clarified.

The diversion of the Naskaupi River caused certain changes in the sediment dynamics but did not modify it drastically. Despite the observed post-diversion changes in varve's parameters, the varves still respond directly to the river discharge. The part of the watershed that has been diverted is a section composed mainly of lakes which are not very hydrologically reactive.

The BEA core records inputs from the Beaver River, an adjacent watershed devoid of anthropogenic modifications. By integrating the BEA core into the pooled data, it helps to improve the natural hydrological signal in our mean series used for reconstruction.

Authors' modification:

The limitation of our calibration model is now mentioned in section 5.2, line 973.

Despite the observed post-diversion changes in varves' physical parameters in cores NAS-1 and NAS-2, the varves still responded directly to variations in river discharge. The upper part of TVT and DLT series in core NAS-1 (1972-2016) show the most perceptible differences after 1972. This is the reason why this section was discarded from the combined DLT series used to reconstruct Q-mean to remove the likely anthropogenic impact on sedimentation during this period. There is also an increase of $P99D_0$ values in core NAS-1 after 1972, but this increase remains very moderate (see Supplement Fig. S3, and Tab. S3). We think that $P99D_0$ is not significantly affected by the Naskaupi River diversion and can be used to infer Q-max prior to 1972.

The sentence: “River sediment input seems to have been quantitatively and spatially constant.” was removed from the text (line 913).

The integration of BEA-1 in the combined series is discussed in section 5.3, line 1009. In our opinion, this allows to capture the hydrological signal from a larger region (Nakaupi + Beaver watersheds).

L604: “it is quite unlikely that the sedimentary input from the Naskaupi River contributed to sediment accumulation at the mouth of the Beaver River” is in contradiction with L440 : “data from core BEA-1 (1856-440 2016), NAS-1 (1856-2016) and NAS-2 (1968-2016) have been normalized and averaged to produce mean TVT, DLT and P99D0 series” to be compared to the Naskaupi River hydrometric station. This questions the selection of BEA-1 in the merging approach of the sedimentary data.

Reply:

Data from the Naskaupi River hydrometric station are considered to be also valid for the Beaver River due to the proximity of those watersheds. There are no instrumental data available for the Beaver River. Even if the core BEA does not directly record the inputs of the Naskaupi, it records the very similar inputs of the Beaver. This section will be clarified.

Authors' modification:

As mentioned above, the integration of BEA-1 in the combined series is discussed in section 5.3, line 1009.

Moreover, the justification that Naskaupi River discharge does not affect BEA-1 location is made by the fact that (L598-608) “the absence of any traces of the 1972 CE marker bed at the Beaver River mouth (BEA-1) supports this hypothesis.” This argument is not admissible, especially with regards to the previous discussion (L583) that the “flood(s) of the years 1972 CE has (have) remobilized newly available sediments and deposited a thick and coarse-grained turbidite on the lake floor”. It is indeed likely, with regards to the sedimentary facies of cores NAS, that the 1972 flood transported coarse material that plunged in the river proximal and extended as hyperpicnal flow following the lake Bathymetry (NAS-1 to NAS-2), thus not affecting BEA core location. However, discussion about flood hydrodynamics and annual river discharge in terms of sediment transport should be decoupled in the discussion.

Reply:

OK, this section will be clarified.

Authors' modification:

This section was modified, line 918.

The argument that a decline in varve thickness is also observed post 1972 in BEA, thus related to a natural hydro-climatic signal can be true, but seems superimposed to the effect of the Naskaupi River diversion, especially for cores NAS. While discreet peaks of sediment proxy (TVT, DLT, P99D0) for the different sediment cores are consistent (occurring at the same date), the variance, mean, and trend in these data are not comparable enough to allow the merging. Also, the three records from the three cores respond totally differently to the pos-1972 hydrological changes: lower mean for BEA-1, higher mean and increase variance for NAS-1, lower mean + decreased variance + decreasing trend for NAS-2. Suggestion: change point analysis (mean, variance and trend) can be performed on each times series, both from the hydrological and sedimentary variables. This would give statistical support to visual information.

Reply:

We will add statistical supports to discuss the different response to post-1972 hydrological changes between cores.

Authors' modification:

The Supplement now provides additional visual support and statistical information on varve's parameters series. Quantitative data on the sedimentological response of cores NAS-1 and NAS-2 to post-1972 Naskaupi River hydrological changes are also available. These supplements show that total varve thickness (TVT), detrital layer thickness (DLT) and the particle size ($P99D_0$) series from different sites (BEA-1, NAS-1 and NAS-2) share similarities in their short- and longer-term variability, that help justified the combination of sedimentological data from different sites (combined series).

Finally, I am really surprised to see a 5-year running mean for the reconstruction of hydrological data. As the varve chronology is more than robust, through its coherence between the different locations and perfect correspondence with 137Cs, it is a pity that annual time series are not reconstructed. This choice of smoothing the data needs to be justified. Running mean in lake sediment studies are generally used to account for the error in the varve chronology, with statistical justification for significant improvement of the proxy-climate correlations (cf. Von Gunten et al., 2012). + Figure 10 compares the rainfall-runoff model and sedimentary data at annual resolution, with no lag (L624). This gives again the impression that correlation values are maximized at all cost.

von Gunten, L., Grosjean, M., Kamenik, C. et al. Calibrating biogeochemical and physical climate proxies from non-varved lake sediments with meteorological data: methods and case studies. J Paleolimnol 47, 583–600 (2012). https://doi.org/10.1007/s10933-012-9582-9

<u>Reply:</u>
The running mean was used to help the reader to visualize the low frequency hydrological variability, but it was not used to make the correlation. The annual time series (Q-mean and Q-max) are indeed reconstructed. We will consider removing the running mean from Fig. 8, 9.

<u>Authors' modification:</u>

Considering the reply above, the 5- years running mean is still presented for the reconstructed annual Q-mean and Q-max time series in Fig. 8, 9.

The sentence: ''Cross correlations between varve parameter series (1856-2016) with instrumental data (1969-2011) and rainfall-runoff modeling reconstructions (1880-2011) show no lag, which demonstrates the accuracy of the time series used in this study'' (line 999) was removed from the text to focus on the main discussion.

#General comment on the rainfall-runoff modeling approach

A key point of this review is the comparison between sedimentary data and modeling. The rainfall-runoff modeling for each catchment is merge to a single ANATEM time series (Fig. 10) and compared to the sediment properties of the varves. This ANATEM time series is based on the pre-determination of single catchment area, then extended for the whole studied period. However, the Naskaupi river watershed pre- and post-1972 is different (smaller after the 1972 river deviation) and should be adapted in the modeling; producing two time series (i) 1880-1971, (ii) 1973-2011. This likely explains that stronger correlations found between e.g., DLT and ANATEM for the period 1972-2011 (r=0.54) compared to the preceding period (r=0.31).

<u>Reply:</u>
There is some sort of misunderstanding here. The rainfall-runoff modeling was not performed on each catchment and merge to a single ANATEM time series. The rainfall-runoff modeling was solely performed with the Naskaupi River hydrometric station area (Fig. 10). This will be clarified in the revised version.

As mentioned above, there is no instrumental data available for the Naskaupi basin before 1972. So, it is not possible to calibrate the modelling for the 1856-1971 period…

<u>Authors' modification:</u>

It is now specified that the rainfall-runoff modelling was performed for the Naskaupi River hydrometric station area (section 3.6).

#Specific comments

L68: to reconstruct daily. . .

Reply:

OK

Authors' modification:

Done, line 72.

L73: "Long hydro-climatic series based on natural proxies in the study region are rare and limited to tree-ring". What have all these studies produced? What conclusions ? Is the aim of the present study to comfort previous finding, to increase spatial coverage? This does not say why clastic lake sediment are better than tree rings or pollen data (which is suggested here) Aren't tree-ring records not enough? Are they all from the Labrador region? Are the hydroclimate records consistent with each others? Answering these question would help re-shaping the sentences in explaining what makes clastic varves so specific and powerful.

Reply:

This is an excellent suggestion. This will be done in the revised version.

Authors' modification:

The introduction has been improved according to this suggestion, line 79 to 93.

L76: "clastic" are not defined prior to this mention

Reply:

Clastic will be defined.

Authors' modification:

"Clastic" was defined (line 89).

L79: Remover 'The' between area and into

Reply:

OK

Authors' modification:

Done, line 95.

L81: Amann et la., should be et al.,

Reply:

OK

Authors' modification:

Done, line 97.

L231 : remove 'used' form the title

Reply:

OK

Authors' modification:

Done, line 305.

L245: Suggested change; 'This allows to extend instrumental data series for the period 1969 to 2011, and fill in data for the missing years.'

Reply:

OK

Authors' modification:

Done, line 317.

L252: title could be simply, e.g., varve properties and hydrological variables

Reply:

OK

Authors' modification:

This title was simplified (line 334).

L456: "data show significant ($p < 0.01$) strong positive correlation." Remove 'strong', especially referring to $r = 0.49$ in brackets, this is not a strong correlation, especially in such hydrological context.

Reply:

OK

Authors' modification:

Done, line 643.

L478: " The significant correlation between reconstructed Q-mean and Q-max values and observed discharge data validates the predictive capacity of the model." I don't see how the fact that Qmean and Qmax correlates validates the proxy-Q model.

Reply:

This sentence will be changed.

Authors' modification:

This sentence was removed when modifying section 4.6.

L496: "demonstrates that the Grand Lake varved sequence is robust and contains a regional signal." You mean the hydrological reconstruction is robust? I would not say that R2 = 0.41 is robust. Remove 'robust' and keep 'contains a regional signal.
Q-mean and Q-max are sometimes written with a capital M (e.g., Q-Mean), sometimes not (Q-mean). Please stay consistent.

Reply:

This will be done.

Authors' modification:

Done, line 746.

L595: it should read 'indicate that the capacity of spring discharge to transport fine sediment and its ability to float ice to Grand Lake decreases due to the decrease in water supply.'

Reply:

OK

Authors' modification:

Done, line 955.

L650: please consider changing 'robust' for 'best proxy'

Reply:

This will be done.

Authors' modification:

Done, line 1059.

L697: extracted from

Reply:

OK

Authors' modification:

Done, line 1139.

L706: change “could help to better our reconstructions” to ‘could help better refine these reconstructions”

Reply:

OK

Authors' modification:

Done, line 1175.

Reconstructing past hydrology of eastern Canadian boreal catchments using clastic varved sediments and hydro-climatic modelling: 160 years of fluvial inflows

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Abstract

Analysis of short sediment cores collected in Grand Lake, Labrador, revealed that this lake is an excellent candidate for the preservation of laminated sediments record. The great depth of Grand Lake, the availability of fine sediments along its tributaries, and its important seasonal river inflow have favoured the formation of a 160 years-long clastic varved sequence. Each varve represents one hydrological year. Varve formation is mainly related to spring discharge conditions with minor contributions from summer and autumn rainfall events. The statistically significant relation between varve parameters and the Naskaupi River discharge observations provided the opportunity to develop local hydrological reconstructions beyond the instrumental period. The combined detrital layer thickness and the particle size (99th percentile) series extracted from each varve yield the strongest correlations with instrumental data (r = 0.68 and 0.75) and have been used to reconstruct Naskaupi River mean and maximum annual discharges, respectively, over the 1856-2016 period. The reconstructed Q-mean series suggest that high Q-mean years occurred during the 1920-1960 period and a slight decrease in Q-mean takes place during the second half of the 20th century. Independent reconstructions based on rainfall-runoff modelling of the watershed from historical reanalysis of global geopotential height fields display a significant correlation with the reconstructed Naskaupi River discharge based on varve physical parameters. The Grand Lake varved sequence contains a regional hydroclimatic signal, as suggested by the statistically significant relation between the combined detrital layer thickness series and the observed Labrador region Q-mean series extracted from five watersheds of different sizes.

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1. Introduction

Climate changes caused by rising concentrations of greenhouse gases can alter hydro-climatic conditions on inter- and intra-regional scales (Linderholm et al., 2018; Ljungqvist et al., 2016; Stocker et al., 2013). Hydropower, which is considered as a key renewable energy source to mitigate global warming, has strong sensitivity to changes in hydrological regime especially in vulnerable northern regions (Cherry et al., 2017). Therefore, a clear understanding of the regional impacts that recent climate change combined with natural climate variability can have on river discharge and hydroelectric production is needed.

However, the lack of instrumental records and the uncertainty related to hydroclimate variability projections (Collins et al., 2013) are obstacles to sustainable management of these water resources.

The Labrador region in eastern Canada is a critical area for hydropower generation, hosting the Churchill River hydroelectric project, one of the largest hydropower systems in the world. Average annual streamflow has been varying in eastern Canada during the last fifty years, with higher river discharges from 1970 to 1979 and 1990 to 2007, and lower discharges from 1980 to 1989 (Mortsch et al., 2015; Déry et al., 2009; Jandhyala et al., 2009; Sveinsson et al., 2008; Zhang et al. 2001). These changes in streamflow represent a significant economic challenge for the long-term management of hydropower generation. The few decades of available instrumental observations (<60 years) and their low spatial coverage are not sufficient to allow a robust analysis of multi-decadal hydrological variability.

The study of multi-decadal hydrological variability requires long instrumental records (>100 years), but such long-time series are non-existent for the Labrador region. Recently, rainfall-runoff modelling approaches have been used to expand instrumental streamflow datasets, using long-term climatic reanalysis as inputs. Rainfall-runoff modelling was used by Brigode et al. (2016) to reconstruct daily streamflow series over the 1881–2011 period in northern Québec. Nevertheless, this type of method suffers from the limited observations in order to evaluate and validate the reconstructed hydro-climatic temporal series. The deficiency of observations led to the exploration of various natural archives for reconstructing past hydro-climatic conditions. Long hydro-climatic series based on natural proxies in eastern Canada are rare, limited to a tree ring (Boucher et al., 2017; Begin et al., 2015; Naulier et al., 2015; Nicault et al., 2014; Boucher et al., 2011; Begin et al., 2007; D'Arrigo et al., 2003) and pollen datasets (Viau et al., 2009) and mainly focused on temperature reconstructions. Reconstructing river hydrological series using dendrological analysis is complex in the boreal region due to the indirect relation between tree-ring indicators and streamflow. One study has reconstructed streamflow variations over the last two centuries in Labrador based on tree-ring isotopes series (Dinis et al., 2019). Still, the

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spatial coverage of palaeohydrological records from independent proxies must be increased in this region. In this perspective, annually laminated sediments composed of minerogenic particles (clastic varves) formed when seasonal runoff carrying suspended sediment enters a lake (Sturm, 1979) have the potential to produce long paleohydrological series. The direct relationship between clastic varves and hydrological conditions makes this type of varve a specific and powerful proxy for streamflow reconstructions. Clastic varves can provide, in favourable settings, annually to seasonally resolved information about downstream sediment transport from catchment area into lake basin depending on regional hydro-climatic conditions (Lamoureux, 2000; Lamoureux et al., 2006; Tomkins et al., 2010; Cuven et al., 2011; Kaufman et al., 2011; Schillereff et al., 2014; Amann et al., 2015; Heideman et al., 2015; Zolitschka et al., 2015; Saarni et al., 2016; Czymzik et al., 2018).

Preliminary analysis of short sediment cores collected in Grand Lake, central Labrador, revealed that this lake is an excellent candidate for the preservation of recent fluvial clastic laminated sediment record (Zolitschka et al., 2015). The objectives of this paper are to: (1) Confirm the annual character of the laminations record; (2) Establish the relation between the physical parameters of laminations and local hydro-climatic conditions to examine the potential proxy for hydrological reconstructions; (3) Reconstruct the hydrology of the last 160 years and compare its similarities and differences with Brigode et al. (2016) rainfall-runoff modelling over the 1880-2011 period; and (4) Determine if there is a Labrador regional streamflow signal recorded in Grand Lake laminated sediments.

2. Regional setting

Grand Lake is a 245-m-deep (Trottier et al., 2020) elongated (60-km-long) fjord-lake located in a valley connected to the Lake Melville graben in central Labrador (53°41'25.58"N, 60°32'6.53"O, ~15 m above sea level) (Fig. 1). The region is part of the Grenville structural province and is dominated by Precambrian granite, gneiss and acidic intrusive rocks. Grand Lake watershed deglaciation began after ~8.2 cal ka BP (Trottier et al., 2020). During deglaciation, marine limit reached an elevation of 120-150 m above modern sea level and invaded further upstream in the modern fluvial valleys that are connected to the lake (Fizthugh, 1973). This former glaciomarine/marine sedimentary fjord

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basin has been glacio-isostatically uplifted and isolated by a morainic sill to become a deep fjord-lake (Trottier et al., 2020). The regional geomorphology is characterized by glacially sculpted bedrock exposures, glacial deposits consisting of till plateaus of various elevations, glacial lineations, drumlins, kames, eskers and raised beaches (Fulton 1992). Podzolic soils dominate, with inclusions of brunisols and wetlands.

Grand Lake is located in the High Boreal Forest ecoregion, one of the most temperate climates in Labrador, hosting mixed forests dominated by productive, closed stands of Abies balsamea, Picea mariana, Betula papyrifera, and Populus tremuloides (Riley et al., 2013). This region is influenced by temperate continental (westerly and southwesterly winds) and maritime (Labrador Current) conditions with cool humid summers (JJA) (~8.5 °C) and cold winters (DJFM) (~-13 °C). The Grand Lake watershed extends upstream over the low subarctic Nipishish-Goose ecoregion, a broad bedrock plateau (<700 m.a.s.l.) located on the west flank of the Lake Melville lowlands. Lichen-rich Picea woodlands with open canopies predominate. With cooler summers and longer cold winters, this area is slightly influenced by the Labrador Sea. Mean annual precipitation in the study region ranges from 800 mm to 1 000 mm, with 400 cm to 500 cm of snowfall. The regional hydrological regime typically exhibits winter low flow and spring freshet, followed by summer flow recession (Fig. 2). Snowmelt in Grand Lake region takes place from April to June (AMJ).

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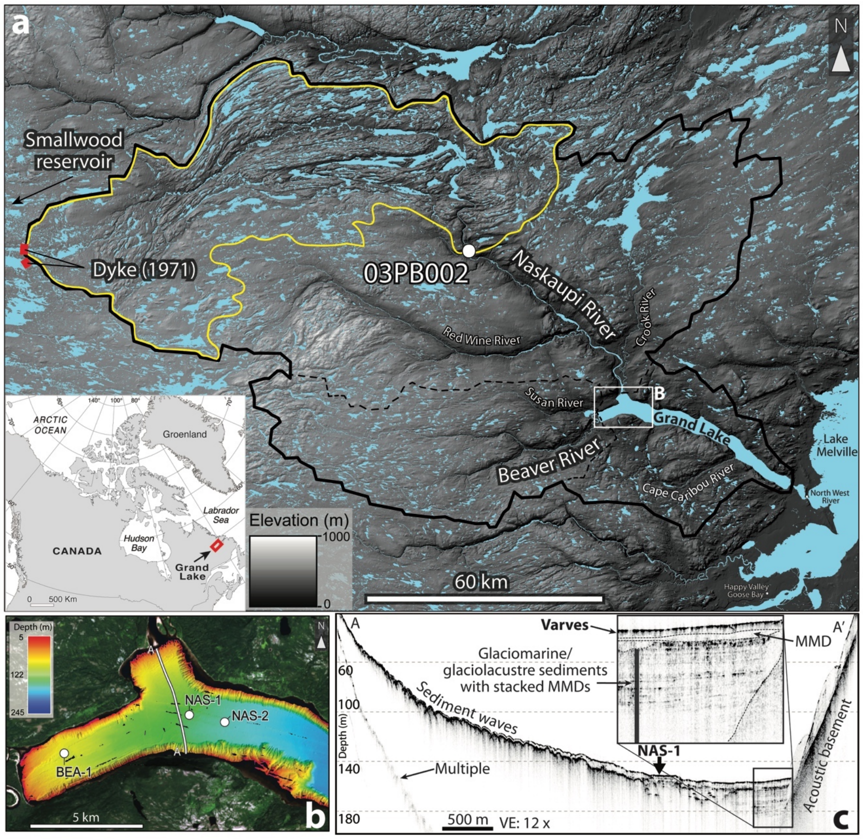

Figure 1. (A) Location of Grand Lake watershed (black line) and its principal tributaries. The Naskaupi River hydrometric station (03PB002: white dot) covering an area of 4480 km² (yellow line). Location of the dykes constructed in 1971 to divert water from the Naskaupi River to the Smallwood reservoir hydroelectric system are also shown by the red bars. (B) High-resolution swath bathymetry (1-m resolution) of Grand Lake (Trottier et al., 2020) coupled with a Landsat image (USGS) and core site locations. The white line indicates the location of a typical 3.5 kHz subbottom profile (C) of the Naskaupi River delta (A-A') showing the approximate location of core NAS-1.

The main tributary of Grand Lake is the Naskaupi River located at the lake head (Fig. 1a). The downstream part of the Naskaupi River is fed by the Red Wine and the Crook rivers. The Beaver River is the secondary tributary of Grand Lake. Naskaupi and Beaver rivers structural valleys that connect to the Grand Lake Basin have a well-developed fluvial plain and a generally sinuous course that remobilize former deltaic systems and terraces composed of glaciomarine, marine, fluvio-glacial, lacustrine and modern fluvial deposits.

Upstream river terraces show mass movement scarps and are affected by gully and aeolian activity. Grand Lake flows into a small tidal lake (Little Lake) and subsequently towards Lake Melville. On 28 April 1971, by closing a system of dykes, the headwaters of Naskaupi River watershed (Lake Michikamau) were diverted into the Churchill River hydropower development (Fig. 1a). This diversion has reduced the drainage area of the Naskaupi River from 23 310 km^2 to 12 691 km^2 (Anderson, 1985).

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Hydroacoustic data were collected in Grand Lake in 2016 (Trottier et al., 2020). The swath bathymetric imagery and 3.5 kHz subbottom profile show that the prodelta slopes present well-defined sediment waves at the Naskaupi River mouth (Trottier et al., 2020; Fig. 1b). The upper acoustic unit is composed of a high amplitude acoustic surface changing into low amplitude acoustic parallel reflections (Fig. 1c), a type of acoustic facies which can be associated with successive sedimentary layers of contrasting particle sizes (Gilbert and Desloges, 2012).

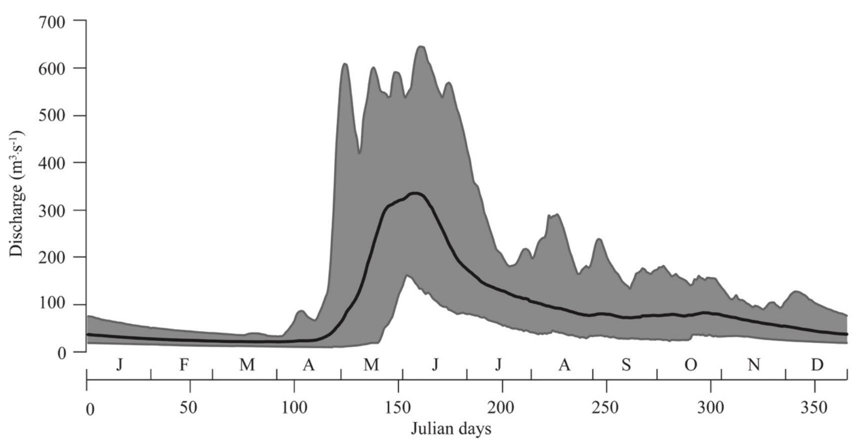

Figure 2. Observed mean daily discharges of the Naskaupi River (hydrometric station 03PB002) for the 1978-2012 period (black line). The gray zone represents the minimum and maximum observed discharges.

3. Methods

3.1 Sediment coring and processing

Four short sediment cores (BEA-1, NAS-1A, NAS-1B and NAS-2) were collected using a UWITEC percussion corer in March 2017 deployed from the lake ice cover. These cores were collected in undisturbed areas according to the swath bathymetry and subbottom profiling data (Trottier et al., 2020). Core BEA-1 was collected in the axis of the Beaver River at a depth of 93 m. Core NAS-1 and NAS-2 were collected in the axis of the Naskaupi River at a depth of 146 and 176 m, respectively (Fig. 1b). Site BEA-1 and NAS-1 are located at the distal frontal slope of the Beaver and Naskaupi river deltas (fig. 1c); site NAS-2 is located away from the Naskaupi River delta, at the beginning of the deep lake basin. Duplicate cores of different lengths have been retrieved at each site to maximize undisturbed sediment recovery. Following the extraction of each core, wet floral foam was gently inserted through the top of the filled coring tube and slowly pushed towards the sediment surface to seal and preserve the sediment-water interface. A plastic cap was then installed on top of the foam to secure its position in contact with the intact sediment surface and avoid disturbance during transport of the cores. The cores were scanned using a Siemens SOMATOM Definition AS+ 128 medical CT-Scanner at the multidisciplinary laboratory of CT-scan for non-medical use of the Institut National de la Recherche Scientifique - Eau Terre Environnement (INRS-ETE). The CT-scan images allowed the identification of sedimentary structures (i.e., laminated facies, perturbation and hiatus). Expressed as CT-numbers or Hounsfield units (HU), X-Ray attenuation is a function of density and the effective atomic number, and hence sensitive to contrasts in mineralogy, grain size and sediment porosity (St-Onge et al., 2007). CT-numbers were extracted at a resolution of 0.06 cm using the ImageJ software 2.0.0 (imagej.net). The cores were then opened, described and photographed with a high-resolution line-scan camera mounted on an ITRAX core scanner (RGB colour images; 50 µm-pixel size) at INRS-ETE. Geochemical non-destructive X-Ray Fluorescence (XRF) analysis was performed on the core half (30 kV and 30 mA). XRF elements profiles were used to visualize the structures and boundaries of the laminations and estimate particle size variability in sediment cores (Kylander et al., 2011; Cuven et al., 2010; Croudace et al., 2006). Elements were

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normalized by the total of count (cps) for each spectrum. Continuous XRF measurements were also carried out on overlapping impregnated sediment blocks in order to superpose element relative intensity profiles on thin-sections.

3.2 Chronology and thickness measurement

Surface sediments from cores BEA-1 and NAS-1A were dated with ^{137}Cs method (Appleby and Oldfield 1978) using a high-resolution germanium diode gamma detector and multichannel analyzer gamma counter. ^{137}Cs activity was used to identify sediment deposited during 1963-1964 peak of nuclear tests and validate the annual character of the layers. A sampling interval of 2 cm was used to approximately identify the depth at which the ^{137}Cs peaks were located. Subsequently, a sampling interval of ± 0.5 cm was used to sample each lamination for the period 1961-1965 to determine the exact ^{137}Cs peak location (1963-1964). In order to establish a chronology for each core, detailed laminations counts were executed on CT-scan images and high-resolution photographs using ImageJ 2.0.0 and Adobe Illustrator CC softwares (Francus et al., 2002). As all of the core surface has been well preserved, the first complete lamination below the sediment surface was considered to represent the topmost year (i.e., 2016 CE). Chronology on each core was confirmed by cross-correlation between thick laminations selected as distinctive marker layers along the different sediment sequences (A to M; Fig. 4).

Thin-sections of sediments were sampled from cores BEA-1 (1856-2016), NAS-1A (1953-2016), NAS-1B (1856-1952) and NAS-2 (1968-2016) (see Fig. 4 for thin-section location) following Francus and Asikainen (2001) and Lamoureux (1994). Digital images of the thin-sections were obtained using a transparency flatbed scanner at 2400 dpi resolution (1 pixel = 10.6 µm) in plain light and were used to characterize lamination substructure. Lamination counts and thickness measurements using a thin-section image analysis software developed at INRS-ETE (Francus and Nobert 2007) were performed to duplicate and validate previous chronologies established on CT-Scan images and high-resolution photographs. Two counts were made from thin-section by the same observer (AGP). Total Varve Thickness (TVT) and Detrital Layer Thickness (DLT) of each year of sedimentation were measured from images of thin-sections. Lamination counts made on CT-scan images, high-

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Supprimé: . the 3 coring sites Continuous TVT measurements allowed the establishment of high-resolution age-depth models for the three sites resolution photographs and thin-sections are identical while TVT measurements show negligible difference ($R^2 = 0.96$; $p < 0.05$). The thickness measurements made from CT-scan images and high-resolution photographs have been used to prolong the TVT series of core NAS-2 from 1968 back to 1856. Continuous TVT measurements allowed the establishment of high-resolution age-depth models for each site.

3.3 Image and particle size analysis

Using custom-made Image Analysis software (Francus and Nobert, 2007), regions of interest (ROIs) were selected on the thin-section images. The software then automatically yielded SEM images of the ROIs using a Zeiss Evo 50 scanning electron microscope (SEM) in backscattered electron (BSE) mode. Eight-bit greyscale BSE images with a resolution of 1024 x 768 pixels were obtained with an accelerating voltage of 20 kV, a tilt angle of 6.1 and an 8.5 mm working distance with a pixel size of 1 µm. BSE images were processed to obtain black and white images where clastic grains (>3.5 µm) and clay matrix appeared black and white respectively (Francus, 1998).

Each sedimentary particle (an average of 2 225 particles per image) was measured according to the methodology used by Lapointe et al. (2012), Francus et al. (2002) and Francus and Karabanov (2000) in order to calculate particle size distribution on each ROI image. Due to the thickness of the laminations, results from several ROI images were merged to obtain measurements for each year of sedimentation, with an average of 4 images per lamination. Only clastic facies related to spring and summer discharges were used for particle size analysis in order to exclude ice-rafted debris (µm to mm scale) observed in the early spring layers (see Fig. 5 for details). The 99th percentile ($P99D_0$) of the particle size distribution for each detrital layer was obtained from thin-sections (Francus, 1998) for the last 160 years (1856-2016) for core BEA-1 and NAS-1, and for the last 47 years (1968-2016) for core NAS-2, from 795, 717 and 132 BSE images respectively (Fig. 4).

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3.4 Hydro-climatic variables

Hydrological variables (Tab.1) were calculated from the time series of daily discharges recorded by the Naskaupi River hydrometric station over the 1978-2011 period (missing data from the years 1996, 1997 and 1998).

Table 1. Hydro-climatic variables used in this paper

Hydrological variable	Unit	Description
Q-max	m^3/s	Annual maximum of daily discharges
Q-mean	m^3/s	Mean annual discharge
Q-max-Jd	Julian days	Julian day at which the discharge reaches its maximum annual value
Rise-Time	Days	Number of days between the minimum winter flow and the maximum spring flow
Nb-Days-SupQ80	Days	Number of days with discharge greater than the 80th daily percentile
Q-nival	mm	Nival runoff (April, May, June, July)
Snow-Win	mm	Winter snowfall (September to May)
Ptot-Annual	mm	Winter Snowfall + Summer rainfall
Ptot-Summ	mm	Summer rainfall (March to October)
Temp-Spring	°C	Average spring temperature (April, May, June)

The Naskaupi River hydrological variables have been compared with four other hydrometric station data available around the study region (Fig. 3a, Tab. 2), which are devoid of anthropogenic perturbations. Q-mean series from the five stations have been normalized for the common 1979–2011 period and averaged, to produce a Labrador region mean annual discharge series. This allows to extend instrumental data series for the period 1969 to 2011, and fill in data for the missing years. The Labrador hydrometric station data used in this study come from a Government of Canada website (https://wateroffice.ec.gc.ca 05/2018).

Table 2. Description of hydrometric stations used in this study

Hydrometric station	ID	Area (km^2)	Location (N,W)	Recording period
Ugjoktok River	03NF001	7570	55° 14' 02", 61° 18' 06"	1979-2011
Naskaupi River	03PB002	4480	54° 07' 54", 61° 25' 36"	1978-2011
Minipi River	03OE003	2330	52° 36' 45", 61° 11' 07"	1979-2011
Little Mecatina River	02XA003	4540	52° 13' 47", 61° 19' 01"	1979-2011
Eagle River	03QC001	10 900	53° 32' 03", 57° 29' 37"	1969-2011

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3.5 Varve physical parameters and hydrological variables

A simple linear regression model was used to fit the DLT and P99D$_0$ series with local (1978-2011) and regional (1969–2011) instrumental series and reconstructed hydrological variables (Q-mean, Q-max) back to 1856. Model calibration was performed using a twofold cross-validation technique over the instrumental period. Root mean squared errors (RMSE) and coefficient of determination (R^2) were calculated for calibration periods, while average reduction of error (RE) and average coefficient of efficiency (CE) were calculated to evaluate reconstruction skills (Briffa et al. 1988, Cook et al., 1999). The RE and CE of the verification periods must be > 0 to validate the model skills. Statistical analysis was realized using the treeclim package (Zang and Biondi, 2015) in the R-project environment (R Core Team, 2019, http://www.r-project.org/).

3.6 Hydro-climatic reconstruction based on rainfall-runoff modelling

The applied reconstruction method is based on rainfall-runoff modelling. Firstly, it aims at producing, for the Naskaupi River hydrometric station catchment (Fig. 1a), daily climatic time series using a historical reanalysis of global geopotential height fields extracted over the studied region for a given time period (here 1880-2011). Secondly, the produced climatic series are used as inputs to a rainfall–runoff model previously calibrated on the studied catchment in order to obtain daily streamflow time series. The reconstruction method is fully described in Brigode et al. (2016) and was recently applied over southeastern Canada catchments in Dinis et al. (2019). It is summarized in the following paragraphs.

The available observed hydro-climatic series for the Naskaupi River hydrometric station catchment have been aggregated at the catchment scale. Climatic series (daily air temperature and precipitation) have been extracted from the CANOPEX dataset (Arsenault et al., 2016), built using Environment Canada weather stations and Thiessen polygons to calculate climatic series at the catchment scale. Daily air temperature series have been used for calculating daily potential evapotranspiration at the catchment scale, using the Oudin et al. (2005) formula designed for rainfall-runoff modelling.

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These daily series have been used for calibrating the GR4J rainfall-runoff model (Perrin et al., 2003) and its snow accumulation and melting module, CemaNeige (Valéry et al., 2014a), using the airGR package (Coron et al., 2017). This combination of GR4J and CemaNeige (hereafter denoted CemaNeigeGR4J) has been recently applied over eastern Canada catchments and showed good modelling performances (e.g., Seiller et al., 2012; Valéry et al., 2014b, Brigode et al., 2016). CemaNeigeGR4J has been calibrated on the recorded period of the Naskaupi River hydrometric station catchment using the Kling and Gupta efficiency criterion (Gupta et al., 2009) as objective function.

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Then, the observed climatic series have been resampled over the 1880-2011 period, based on both season and similarity of geopotential height fields (Kuentz et al., 2015). The resampling is performed by calculating Teweles and Wobus (1954) distances between four geopotential height fields: (i) 1000 hPa at 0 h, (ii) 1000 hPa at 24 h, (iii) 500 hPa at 0 h, and (iv) 500 hPa at 24 h. The NOAA 20th Century Reanalysis ensemble (Compo et al., 2011, hereafter denoted 20CR) has been used as a source of geopotential height fields (Fig. 3b).

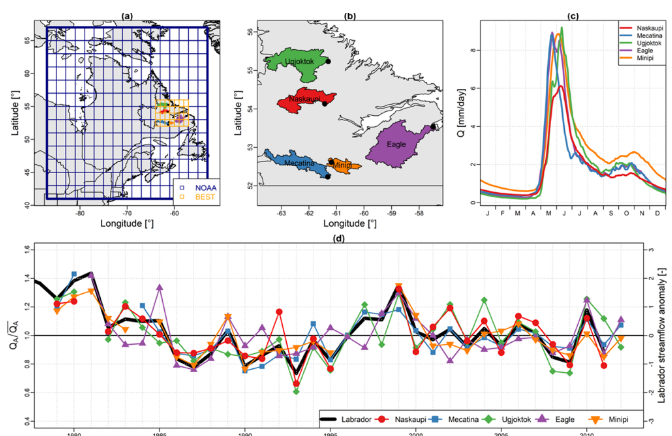

Figure 3. (a) Dataset used for the hydro-climatic reconstruction based on rainfall-runoff modelling: the extension of the 20CR grid used is shown in blue, while the BEST grid used is highlighted in orange. (b) Spatial distribution of hydrometric stations used in this study (black dots) and their catchment area. (c) Observed mean daily discharges of each hydrometric station for the 1978-2012 period. (d) Labrador streamflow anomaly and the Labrador region mean annual discharge series (thick black line).

As in Brigode et al. (2016), the resampled series of air temperature have been corrected at the catchment scale using a regression model calibrated with the Berkeley Earth Surface Temperature analysis (Rohde et al., 2013, hereafter denoted BEST). BEST is a gridded air temperature product starting in 1880 at the daily timestep (Fig. 3b).

Finally, the daily climatic series are used as inputs to the CemaNeigeGR4J model in order to obtain daily streamflow time series on the same 1880-2011 period. Thus, the outputs of the hydro-climatic reconstruction are an ensemble of daily meteorological series (air temperature, potential evapotranspiration and precipitation) and an ensemble of daily streamflow series.

4. Results

4.1 Lamination characterization

Sediment retrieved at the head of Grand Lake (Fig. 4), consist of dark grayish to dark yellowish brown (Munsell colour: 10YR-4/2 to 10YR-4/4) laminated minerogenic material, interpreted as clastic lamination of fluvial origin. Lamination structure can be divided in 3 seasonal layers (Fig. 5) based on their stratigraphic position and microfacies. Annual sedimentation starts with a layer composed of silt and clay sediment matrix which sometimes contains ice-rafted debris (µm to mm scale) interpreted as an early spring layer. The major lamination component is a spring and summer/autumn detrital layer. Its thick basal part is mostly poorly sorted, graded and composed of coarse minerogenic grains comprising fine sand and silts (< 150 µm) with some redeposited cohesive sediment clasts eroded from the underlying early spring layer. This detrital layer has a sharp lower boundary. The upper part of the detrital layer consists of a finer detrital grain matrix containing thin visually coarser intercalated sub-layers in ~75% of the laminations. The allochthonous lithoclastic materials which compose the detrital layers are associated with higher density values (Fig. 4) and an increase in the relative intensity of elements Sr and Ca (Zolitschka et al., 2015). Few organic debris and charcoal fragments are observed throughout the detrital layers. The third topmost lamination layer is formed by a fine to medium silty layer with abundant clay rich in Fe and interpreted as an autumn and winter layer, also known as a clay cap (Zolitschka et al., 2015). The Fe peak values in autumn and

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winter layers, are hence used to determine the upper lamination boundary (Fig. 4) (Zolitschka et al., 2015) as previously performed in other varved sequences (Cuven et al., 2010; Saarni et al., 2016).

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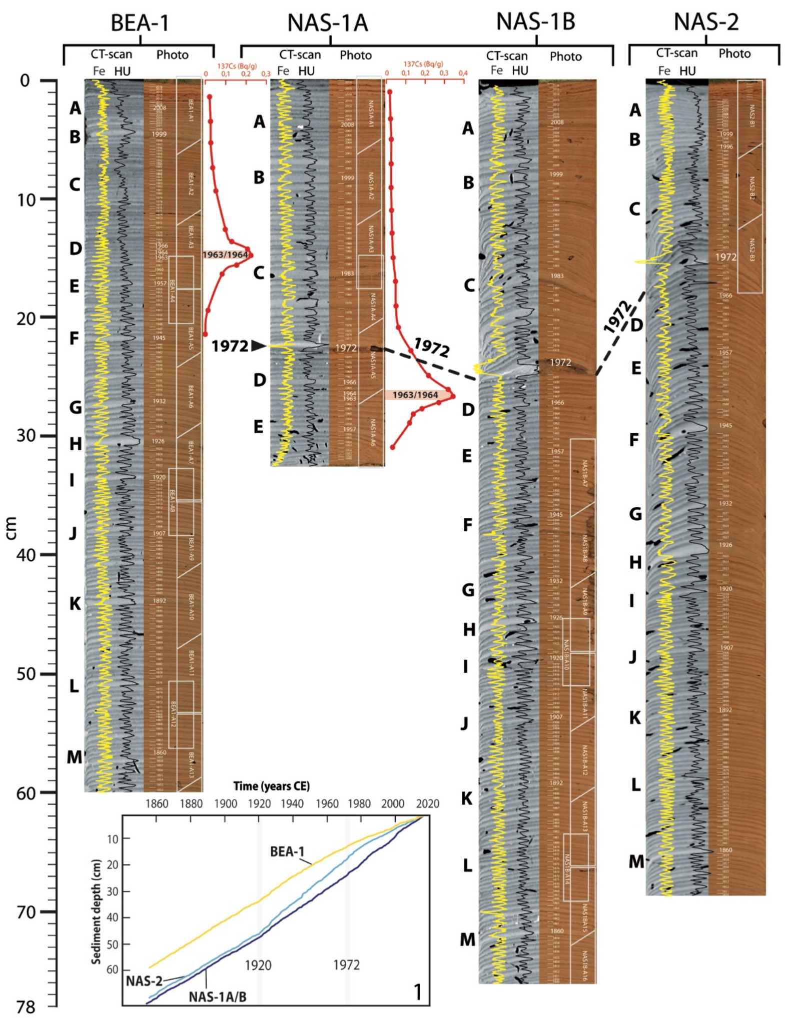

Figure 4. Varve counts made on (left) CT-scan and (right) high resolution images from core BEA-1, NAS-1A/B and NAS-2. Distinctive marker layers are identified by letters A to M. The 1972 marker layer is outlined by the thick dark gray line. Fe relative intensity and density (HU) profile represented by the yellow and black line respectively, show rhythmic laminations. The activity profile of ^{137}Cs in core BEA-1, NAS-1A is shown by the red line. Approximate thin-section locations are outlined by white boxes. The age-depth model of the 3 cores is also presented (Box. 1). See Fig. 1b for core locations.

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The lamination deposited in 1972 from sites in the axis of the Naskaupi River (NAS-1; Fig. 5b and NAS-2; Fig. 4), present a thick (8.2 mm) and coarse (67.8 µm) detrital layer composed of very fine sandy and very coarse silt (Fig. 5b) representing the highest particle size measured in all sequences. Furthermore, there is a difference in lamination physical parameters and microfacies deposited before and after the 1972 marker bed, especially in core NAS-1, the proximal site from the Naskaupi River mouth. Laminations deposited prior 1972 have a well-developed substructure relatively constant among each annual lamination (Fig. 5b). The early spring layer of the pre-1972 laminations is thicker and more clearly visible. Conversely, the detrital layer of laminations post-1972 is thicker, while the early spring layer is more difficult to discern and contributes less to the TVT (Fig. 5a). The mean contribution of the early spring layer and autumn and winter layer to the total lamination thickness is 35% for the pre- and 52% for the post-1972 intervals. The early spring layer in lamination post-1971 from sites NAS-1 and NAS-2 no longer contains isolated coarse debris. The changes in lamination facies are less noticeable in core NAS-2, which was sampled further away from the Naskaupi River mouth. The 1972 marker bed and related facies changes are not found at the Beaver River mouth site BEA-1.

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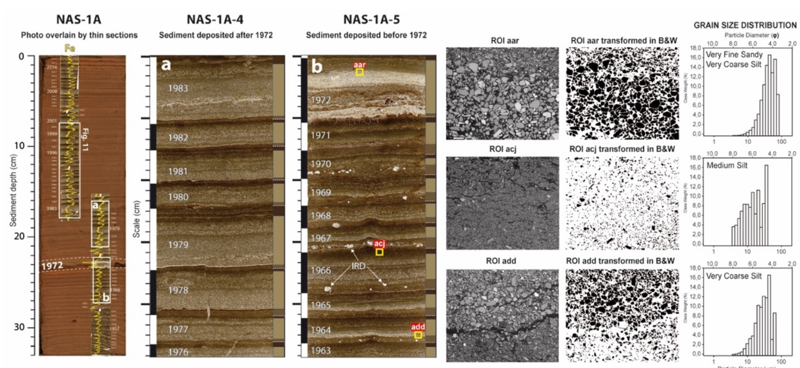

Figure 5. (Left) Photo of core NAS-1A overlain by thin-section image and Fe relative intensity profile (yellow lines). The 1972 marker layer is outlined by the white dashed lines. Thin-section images showing sedimentary structure of varves deposited (B) before and (A) after the 1972 marker bed. Varve boundaries are represented by the vertical black and white bars. Varve layers are delimited by the medium brown (early spring layer), pale brown (detrital layer) and dark brown (autumn and winter layer) bars. Typical Ice-Rafted Debris (IRD) are shown by the white arrows on the b panel. (Right) BSE images of three ROIs transformed in B&W and their associated particle size distribution (aar: the 1972 marker layer; acj: a typical autumn and winter layer; add: the base of a typical detrital layer) (see yellow squares on the b panel for ROIs location).

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4.2 Varve chronology

The laminated sequences chronologies are consistent with the Cesium-137 main peaks corresponding to the highest atmospheric nuclear testing period (1963-1964 CE) (Appleby, 2001). Peaks are found at 14-14.5 cm (BEA-1) and 26.5-27 cm (NAS-1A) depth (Fig. 4) and perfectly match the lamination counts in both cores, confirming the varve assumption. The presence of the distinct 1972 marker layer at this chronostratigraphic position in the varve sequence which coincides with the occurrence of the Naskaupi River diversion that took place in April 1971 (see section 5.2 for details) supports the reliability of the constructed chronologies.

Independent varve chronologies were established from sediment cores BEA-1, NAS-1 and NAS-2 (Fig. 4). A total of 160 varves were counted at each site, covering the 1856-2016 period. The thickness and the good quality of the well-preserved varve structures allowed a robust age-model reproducible among cores to be constructed. Despite the distance between the coring sites (1 to 5 km) and the two different sediment sources (Naskaupi and Beaver River) (Fig. 1b), there is no varve count difference between the selected thick marker layers (A to M; Fig. 4) among cores. The few counting difficulties occur within varve years 1952-1953, 1935-1934, 1918-1919, as it contains ambiguous coarse non-annual intercalated sub-layers with intermediate clay cap that can be interpreted as one year of sedimentation. Both varve counts performed on thin-sections show a low overall counting error (±1.8%) which demonstrated the precision and accuracy of the varve sequences chronology. The age-depth models (Fig. 4, Box. 1) show changes in sediment accumulation rates (thickness) among cores in 1920 and 1972.

4.3 Thickness and particle size measurements

The TVTs from core BEA-1, NAS-1 and NAS-2 vary between 0.9 and 12.9 mm, with an average thickness of 4.09 mm (Fig. 6a, b, c, Supplements Fig. S1 and Tab. S1). The DLTs vary between 0.3 and 8.3 mm, with an average thickness of 1.9 mm (Fig. 6a, b, c, Supplements Fig. S2 and Tab. S2). There are significant strong positive correlations between TVT and DLT for each core (r = 0.79 to 0.91; $p < 0.01$). A step in the TVT is observable in the early 1920s at the three sites (Fig. 6a, b, c), especially in core NAS-2,

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which recorded their highest values (12.9 mm) during the 1920-1972 period (Fig. 6c). Since the 1920s, there is a statistically significant decreasing trend in TVTs and DLTs in core BEA-1 (Fig. 6a). Thickness data from the three sites have been normalized and averaged to produce combined TVT and DLT series (Fig. 6d, e). From 1920 to 1972, combined TVT and DLT series show a statistically significant downward trend, despite an increase in years associated with high thickness values. Overall, TVT and DLT vary similarly in time between sites during the 1856-1971 period (Fig. 6d, e). However, after 1972, TVT and DLT series are more diverging. From 1972 to 2016, there is a statistically significant decreasing trend in TVT and DLT in cores NAS-2 (Fig. 6c), and the amplitude of their variability tends to diminish. For core NAS-1 (Fig. 6b), post-1971 period is associated with higher thickness values. Core NAS-1 has recorded a slight TVT and DLT decrease for the 1972-2016 period, but unlike the other cores, the variability tends to increase. The TVT and DLT are overall finer in the distal core NAS-2 compared to the more proximal core NAS-1 (Fig. 4, Box. 1, Supplements Tab. S1, S2).

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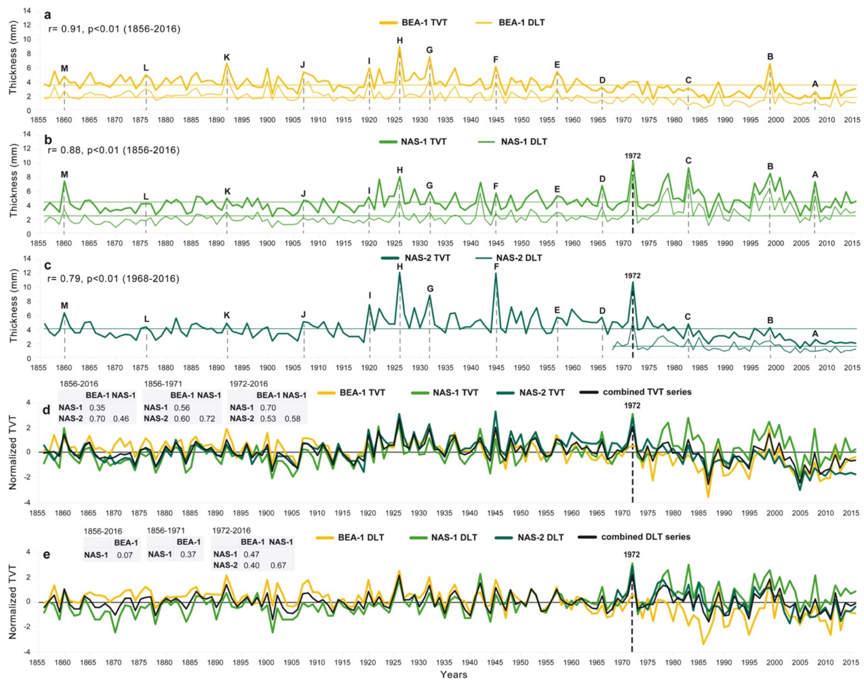

Figure 6. Total Varve Thickness (TVT; thick line) and Detrital Layer Thickness (DLT; thin line) time series of core (a) BEA-1, (b) NAS-1 and (c) NAS-2. Normalized (d) TVT and (e) DLT series and the combined series (mean of the normalized data from the 3 sites). Pearson correlation coefficients between TVT and DLT for the 1856-2016, 1856-1971 and 1973-2016 periods are shown. The selected marker layers are identified by letters A to M and the 1972 marker layer is outlined by the thick black dashed line.

The $P99D_0$ of cores BEA-1, NAS-1 and NAS-2 vary between 20 and 67.8 µm, with an average value of 34.3 µm (Fig. 7, Supplements Fig. S3 and Tab. S3). The grain size is finer in core NAS-2 compared to core NAS-1. Particle size data from the three sites have been normalized and averaged to produce combined $P99D_0$ series (Fig. 7c). The combined $P99D_0$ series show a slight coarsening trend towards the end of the 19th century. From 1900 to 1971, $P99D_0$ values are generally below average. The 1972 marker layer of core NAS-1 presented the maximum $P99D_0$ values (Fig. 7b). After 1972, there is an increase of $P99D_0$ values in core NAS-1, where a step is observable. Pre-1971 varves in core NAS-1 have a mean $P99D_0$ of 32,47 µm compared to 42,91 µm for the 1972-2016 period.

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There is weak to moderate positive correlation between TVT and $P99D_0$ from a same core (BEA-1: $r = 0.41$ $p < 0.01$; NAS-1: $r = 0.52$ $p < 0.01$; NAS-2: $r = 0.27$, $p < 0.05$). The correlation between DLT with $P99D_0$ is stronger (BEA-1: $r = 0.49$ $p < 0.01$; NAS-1: $r = 0.65$ $p < 0.01$; NAS-2: $r = 0.49$, $p < 0.01$). Thick varves are more likely to have high grain size values. However, these correlations show that TVT, DLT and $P99D_0$ remain independent variables and can both reveal different hydrological information.

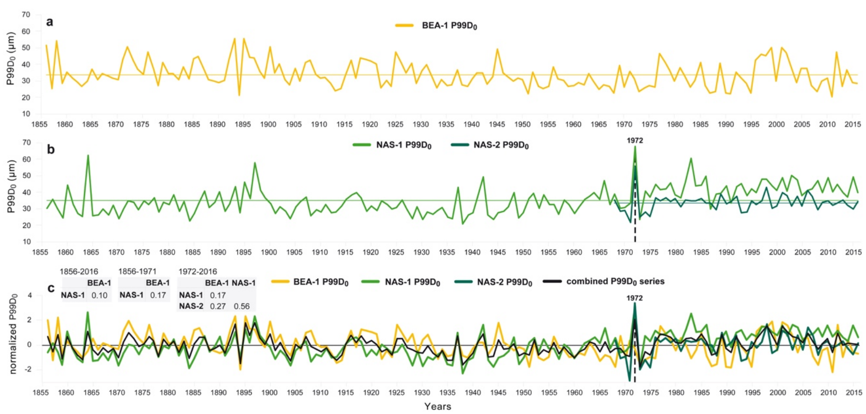

Figure 7. $P99D_0$ time series of cores (a) BEA-1, (b) NAS-1 (1856-2016) and NAS-2 (1968-2016). (c) Normalized $P99D_0$ series and the combined series (mean of the normalized data from the 3 sites). The 1972 marker layer is outlined by the black dashed line. Pearson correlation coefficients between $P99D_0$ series for the 1856-2016 and 1968-2016 periods are shown.

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4.5 Relation between varve series and instrumental record

4.5.1 Naskaupi River

To examine how the physical parameters of the varves are related to local hydroclimate and to demonstrate their potential for hydrological reconstruction, sediment parameters (TVT, DLT and $P99D_0$) of each core were systematically compared to hydrological variables (Tab. 1). TVT, DLT and $P99D_0$ series from the three coring sites show significant positive correlations with the Q-mean and Q-max extracted from the Naskaupi River hydrometric station (03PB002) data on the 1978-2011 period (n=31) (Tab. 3). The TVT and DLT of cores BEA-1 and NAS-2 show stronger correlation with Q-mean, while TVT and DLT of cores NAS-1 have a better relation with Q-max. There is a significant negative correlation between $P99D_0$ of core NAS-1 and Q-max-Jd ($r = -0.38$) and Rise-Time ($r = - 0.47$). Sediment parameters also present significant positive correlations with Q-

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Nival (r = 0.32 to 0.61), Snow-Win (r = 0.47 to 0.61) and Nb-days-SupQ80 (> 125 $m^3 \cdot s^{-1}$) (r = 0.44 to 0.62). Moreover, the maximum particle size series of core NAS-1 show significant (p = 0.02) positive correlations with the average spring temperature (r = 0.40; not shown in Tab. 3). Combined DLT and $P99D_0$ series (Fig. 6d, e; 7c) yields the strongest correlations in our dataset (r = 0.68 and 0.75; Tab. 3) and have been used to reconstruct Naskaupi River Q-mean and Q-max respectively (Fig. 8).

4.5.2 Labrador region

To determine if there is a regional hydrological signal in Labrador and whether the Grand Lake varved sedimentary sequence has recorded this signal, the Naskaupi River hydro-climatic variables were compared with other Labrador hydrometric stations (Tab. 2). Despite specific local geomorphological and climatic conditions, strong similarities exist between observed mean daily discharges (Fig. 3c) and annual streamflow (Fig. 3d) recorded by hydrometric stations in Labrador for the 1978-2011 period. The shape of the five annual regimes shows similar characteristics (i.e. flood-timing, strength, duration, snowmelt and rainfall response). The instrumental Naskaupi River mean annual discharge series data show significant ($p < 0.01$, Supplements Tab. S5) positive correlations with other hydrometric stations (Ugjoktok: r = 0.84; Minipi: r = 0.70; Little Mecatina: r = 0.73; Eagle: r = 0.49). Hydrological conditions in the Naskaupi river region is thus representative of a broader region of Labrador. Therefore, the combined DLT series (without the NAS-1 1978-2016 period) has been used to reconstruct the Labrador region mean annual discharge series (Fig. 9).

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Table 3. Matrix of correlation coefficients (Pearson r) of the hydro-climatic variables defined in Tab. 1 with Total Varve Thickness (TVT), Detrital Layer Thickness (DLT) and particle size ($P99D_0$) on the instrumental period (1978-2011; n=31) for each core. Correlations between the hydro-climatic variables and the combined TVT, DLT and $P99D_0$ series (normalized and averaged varve parameters of cores BEA, NAS-1 and NAS-2) are also present. Correlations in boldface are significant at $p < 0.05$ (Supplements Tab. S4). Correlations marked by an asterisk were used for the final Q-mean and Q-max reconstructions.

Hydroclimatic variables of station 03PB002

Sediment parameters

Core BEA-1	Q-mean	Q-max	Q-max-Jd	Rise-Time	Nb-days-supQ80	Q-nival	Snow-Win
TVT	**0.53**	**0.46**	-0.19	-0.06	**0.54**	**0.41**	**0.47**
DLT	**0.54**	**0.38**	-0.01	0.22	**0.44**	**0.32**	0.29
$P99D_0$	**0.56**	**0.56**	-0.05	0.17	0.34	**0.40**	0.24

Core NAS-1	Q-mean	Q-max	Q-max-Jd	Rise-Time	Nb-days-supQ80	Q-nival	Snow-Win
TVT	**0.52**	**0.64**	-0.31	-0.26	**0.55**	**0.56**	**0.55**
DLT	**0.53**	**0.67**	-0.31	-0.27	**0.53**	**0.54**	**0.50**
$P99D_0$	0.19	**0.60**	**-0.38**	**-0.47**	0.26	**0.40**	0.30

Core NAS-2	Q-mean	Q-max	Q-max-Jd	Rise-Time	Nb-days-supQ80	Q-nival	Snow-Win
TVT	**0.49**	**0.45**	0.04	-0.24	**0.56**	**0.47**	**0.61**
DLT	**0.62**	**0.57**	0.07	-0.13	**0.59**	**0.61**	**0.60**
$P99D_0$	0,39	**0.43**	0.19	0.26	0.31	**0.40**	0.11

combined series	Q-mean	Q-max	Q-max-Jd	Rise-Time	Nb-days-supQ80	Q-nival	Snow-Win
TVT	**0.56**	**0.58**	-0.19	-0.20	**0.60**	**0.53**	**0.59**
DLT	**0.68***	**0.65**	-0.11	-0.07	**0.62**	**0.58**	**0.54**
$P99D_0$	**0.59**	**0.75***	-0.09	0.05	**0.43**	**0.56**	0.23

4.6 Hydrological reconstructions using varve parameters

4.6.1 Naskaupi River Q-mean and Q-max

The Naskaupi River mean and maximum annual discharges (Q-mean and Q-max) were reconstructed using DLT and $P99D_0$ series for the 1856–2016 period. The reconstructions were performed using single-core data, combined DLT and $P99D_0$ series and other combinations of core data, in order to propose the most relevant reconstructions (Supplements Fig. S4, S5). The observations and the reconstructed Q-mean and Q-max extracted from the different series over the 1978-2011 period are consistent. Despite differences, all reconstructions tested using different sources of sedimentological data generally share common interannual and longer-term variability.

Excluding the 1972-2016 measurements from NAS-1 from the combined series for reconstructions was also tested to remove the likely anthropogenic impact on sedimentation during this period. The combined DLT series without the 1972-2016 period presents a

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The reconstructed Naskaupi River Q-mean from combined DLT series varies between 73 and 126 $m^3 \cdot s^{-1}$, with an average of 96 $m^3 \cdot s^{-1}$ (Fig. 8a), and remains relatively stable from 1856 to 1920, mainly near average. Several years with high Q-mean occurred during the 1920-1960 period. A statistically significant downward trend of the Q-mean is observed over the last 90 years. Recently, high Q-mean periods are observed from 1976 to 1985 and 1996 to 2002 and lower Q-mean periods from 1986 to 1995 and 2003 to 2016. The reconstructed Naskaupi Q-max from combined $P99D_0$ series varies between 192 and 681 $m^3 \cdot s^{-1}$, with an average of 426 $m^3 \cdot s^{-1}$ (Fig. 8b). There is a slight upward trend in Q-max at the end of the 19th century. The 1900-1971 period is characterized by a Q-max generally below average. Three periods of high Q-max are observed from 1887 to 1900, 1976 to 1986 and 1995 to 2008 (Fig. 8b).

4.6.2 Labrador region Q-mean

The consistency between combined DLT series and the observed Labrador region Q-mean series (Fig. 9), based on the discharge variability of five watersheds of different size and location, demonstrates that the Grand Lake varved sequence contains a regional signal. The best reconstruction of Labrador region mean annual discharges is the one performed using the combined DLT series without the NAS-1 1972-2016 period. This reconstruction demonstrates the best predictive capacity (RE and CE must be > 0 to validate the model

Supprimé: Due to the suggested anthropogenic origin, the varve of the year 1972 is considered as an outlier and thus was not included for reconstruction.The cross-validation method demonstrates the quality of the reconstructions. The R^2 of the two calibrated periods are significant ($p < 0.0001$) and the RE and CE of the verification periods are > 0 which validates the model skills (Fig. 8, 9). The significant correlation between Q-mean/Q-max reconstructed values and observed discharge data on the 1978-2011 period validates the predictive capacity of the model. ¶

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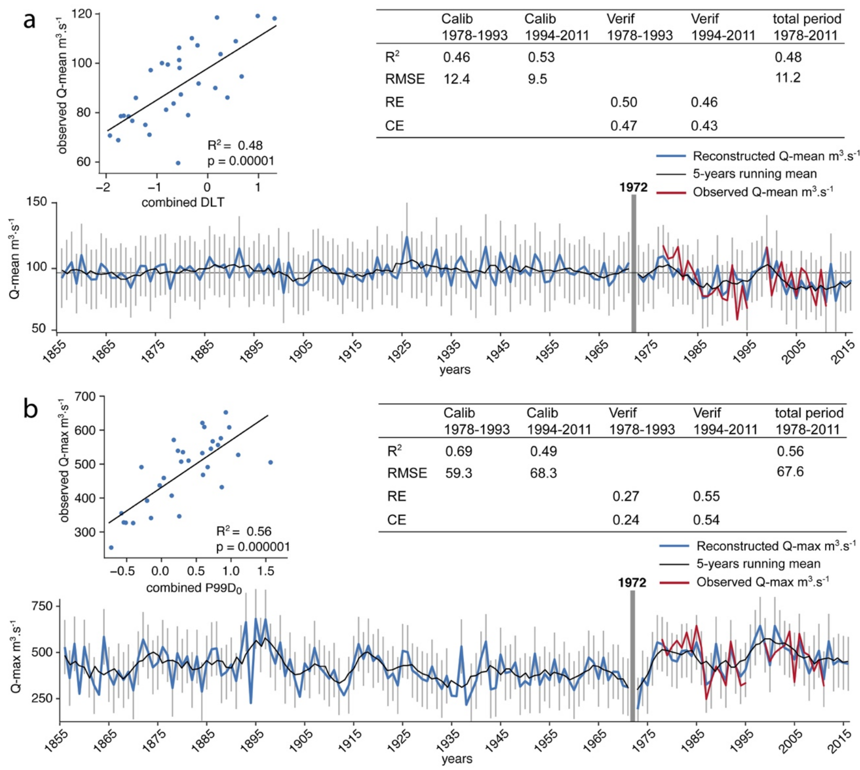
skills, Supplements Tab. S10, S11). The regional Q-mean reconstruction for the 1856–2016 period is presented in Fig. 9.



	Calib 1978-1993	Calib 1994-2011	Verif 1978-1993	Verif 1994-2011	total period 1978-2011
R^2	0.46	0.53			0.48
RMSE	12.4	9.5			11.2
RE			0.50	0.46	
CE			0.47	0.43	

	Calib 1978-1993	Calib 1994-2011	Verif 1978-1993	Verif 1994-2011	total period 1978-2011
R^2	0.69	0.49			0.56
RMSE	59.3	68.3			67.6
RE			0.27	0.55	
CE			0.24	0.54	

Figure 8. Naskaupi River (a) Q-mean and (b) Q-max reconstructed from combined DLT (Without the NAS-1 1978-2016 period) and $P99D_0$ series respectively, for the 1856–2016 period (blue line), with 5-year moving average (black line). Error bars represent the 95% confidence interval. Observed Q-mean and Q-max are also shown for the 1978-2011 period (red line).

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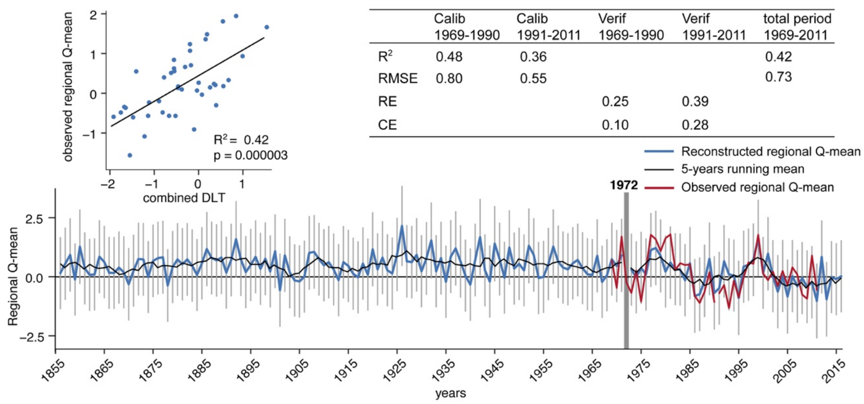

Figure 9. Labrador region Q-mean reconstructed from combined DLT series (without the NAS-1 1972-2016 period) for the 1856–2016 period (blue line), with 5-year moving average (black line). Error bars represent the 95% confidence interval. Observed Labrador region Q-mean series is also shown for the 1969-2011 period (red line).

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4.7 Hydrological reconstruction using the rainfall-runoff modelling approach and comparison with the varved-based reconstruction

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Naskaupi River Q-mean and Q-max (Fig. 8) were also reconstructed using the ANATEM rainfall-runoff modelling (Fig. 10). The independent modelling approach results show similarities with reconstructions based on varved series. The ANATEM reconstructions are statistically and positively correlated with the yearly time series obtained from combined DLT and P99D$_0$ series during the 1880-2011 period (Q-mean: r = 0.41; Q-max: r = 0.22; n = 131; p < 0.01). The reconstructed Q-mean and Q-max annual variabilities show similarities, especially during the 1973–2011 period (Q-mean: r = 0.58; Q-max: r = 0.34; n = 43 p < 0.05).

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Q-mean reconstructions with both varve parameters and modelling are better correlated than the Q-max reconstructions. This may be due to the higher uncertainty related to the Q-max reconstruction with the modelling approach. Indeed, high flow modelling requires good reconstruction performances on several hydro-climatic processes (i.e., snow accumulation during the winter, timing of the snowmelt, spring precipitation). Moreover, the uncertainty of the hydrological reconstruction is less important on recent periods (>1950), due to the better quality of the geopotential height field reanalysis over recent decades, as more stations series are available and thus used in the reanalysis. The decrease

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in the uncertainty related to reanalysis over time might explain the better correlation between the two approaches for the recent period.

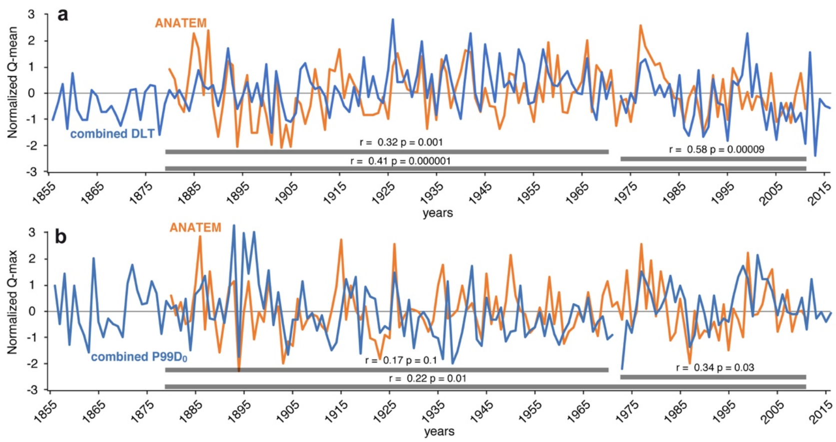

Figure 10. Comparison between the Naskaupi River (a) Q-mean and (b) Q-max reconstruction using combined Detrital Layer Thickness (DLT) (without the NAS-1 1972-2016 period) and P99D$_0$ series respectively (blue line) and the rainfall-runoff modelling (orange line) for raw yearly data.

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5. Discussion

5.1 Grand Lake varve formation

Lakes containing well-defined and continuous varved sequences that allow the establishment of an internal chronology are rare in boreal regions. However, the great depth of Grand Lake, the availability of fine sediments in its watershed due to the glacial and postglacial history of the region (Trottier et al., 2020), as well as its important seasonal river inflow have favoured the formation and preservation of exquisite and thick varves. The seasonal streamflow regime plays a significant role in the annual cycle of sedimentation in Grand Lake and is responsible for the formation of the three distinct varve layers. Due to the thickness and the clarity of the varve structures, it is possible to infer the deposition mechanism for each layer and the season in which they were deposited.

The early spring layers are interpreted to be deposited during the river and lake ice break-up and disintegration period, when erosion and resuspension of fine-grained sediments are initiated but still low. Available Landsat-8 images of Grand Lake covering the 1983-2018 period (courtesy of the U.S. Geological Survey) shows that Grand Lake ice cover starts to melt at the Naskaupi and Beaver River mouths. This ice melting pattern creates open bays where drifting floating ice melts, thus depositing ice-rafted debris (Lamoureux 1999, 2004) as observed in the early spring layer facies. The overlying detrital layers are interpreted as flood-induced turbidites deposited at the lake bottom during the open-water season. High energy sediment-laden river flows produce hyperpycnal flows allowing silt and sand-size sediments to reach the cored sites (Cockburn and Lamoureux, 2008). The sharp contact boundary between the early spring layer and the detrital layer at the top part of the early spring layer supports the hypothesis that the detrital layers originate from underflows (Mangili et al., 2005). The sediment waves on the Naskaupi and Beaver river delta slopes (Trottier et al., 2020) (Fig. 1b, c) also indicate significant downstream sediment transport by supercritical density flows (Normandeau et al., 2016). The thick and grading upward basal part of the detrital layers are deposited during the high spring discharge period generated by snowmelt runoffs. The lack of erosion marks between the early spring layer and the detrital layer and the incorporation of rare cohesive sediment clasts within the detrital layer suggests that erosion of the underlying early spring layers occurs in more

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proximal and energetic settings. Three observations justify the combination of varve measurements from the 3 coring sites : 1) the sedimentary processes inferred from the observation of thin-sections, the high resolution bathymetric and the sub-bottom surveys are similar; (2) the similarity of the varve facies and properties for each single year at the 3 different sites suggest a sedimentary pattern devoid of disturbances due to local factors; (3) Grains-size differences are too subtle to infer different sedimentary processes and environments. The upper part of varve structure in core NAS-1 show the most perceptible different after 1972 (see discussion below). In spring, river discharge reaches its annual peaks and sediment transport capacities that are then no longer reached during the rest of the summer and autumn (Fig. 2, 3c, 11). However, the presence of thin coarser intercalated sub-layers in the upper part of the detrital layer indicates that some rainfall events, as observed in Fig. 11 (i.e., 1983, 1987, 1992, 1999) also contribute to deposition of sediments in this layer. The overlying autumn and winter layer resulted from the settling and flocculation of fine particles in non-turbulent condition from fall through the onset of lake ice, forming a typical clay cap.

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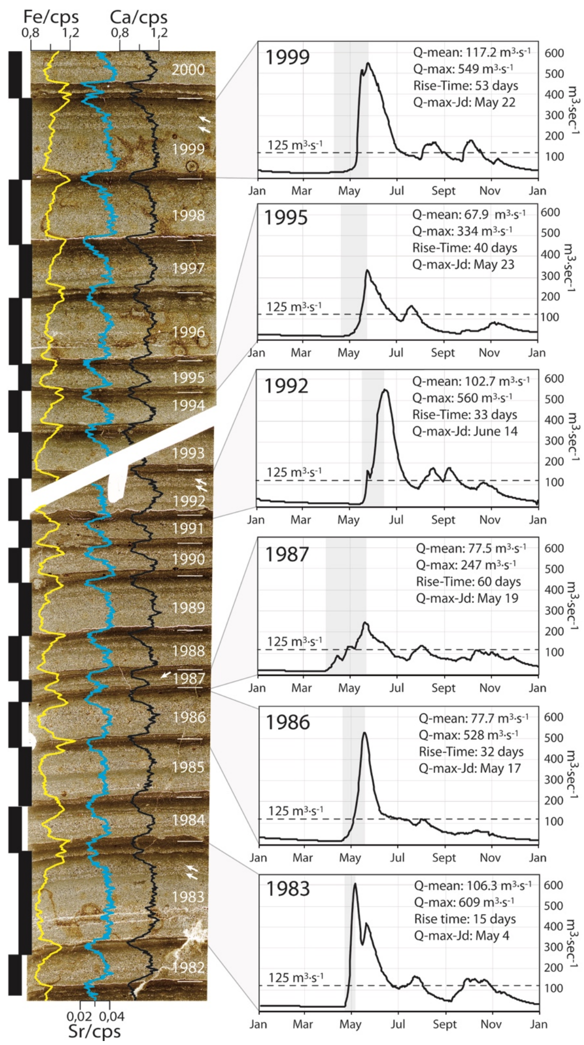

Figure 11. Qualitative comparison between NAS-1A varves from thin-sections (delimited by the black bars) with the hydrographs of the Naskaupi River. Observed annual Q-mean and Q-max as well as the timing and rise time of the peak spring discharge are shown. Black dotted lines represent the discharge threshold of ~125 m^3·sec^{-1}. (1999, 1992, 1986, 1983) Strong spring floods associated with thick coarse varves. (1995, 1987) Low spring floods associated with thin varves. (1999, 1992, 1987, 1983) Coarser intercalated sub-layers in the upper part of the detrital layer, linked with summer and autumn high-discharge events. (1986) Strong spring flood with a low summer and autumn flow associated to a varve without substructure. Thin-sections are overlain by iron (Fe: yellow line), strontium (Sr: blue line), and calcium (Ca: black line) relative intensities. See Fig. 5 for thin-sections locations.

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5.2 Anthropogenic influences on recent sedimentation

Anthropogenic environmental impacts on watersheds can be preserved in varved lake sediments (Zolitschka et al., 2015; Saarni et al., 2016; Czymzik et al., 2018). Changes observed in physical parameters of the varves deposited pre- and post-1971 at the NAS sites suggest that the effect of the dyke system on the Naskaupi River sediment inputs is perceptible in the Grand Lake varved sequence. The well-developed layers of varves deposited prior to 1972 from sites NAS-1 (Fig. 6b) and NAS-2, and the similarity between TVT and DLT values and variations among all sites over the 1856-1971 period (Fig. 6d) indicate that before the Naskaupi River diversion, seasonal sedimentation cycles appeared to have reached a relative state of equilibrium. The reduction of nearly half of the area of the Naskaupi River watershed due to its diversion in April 1971, reduced the water inflows and changed the base level of the downstream river system. The rapid base level fall must have triggered modifications of the fluvial dynamics from late-spring to winter 1971 (i.e., channel incision, bank destabilization, and upstream knickpoint migration), likely increasing the availability of sediments in the river system. The Naskaupi River spring/summer/autumn flood(s) of 1972 have then remobilized and transported a large amount of newly available floodplain sediments. This major sediment discharge plunged in Grand Lake and extended as hyperpycnal flow in the axis of the Naskapi River depositing a thick and coarse-grained turbidite following the lake bathymetry. This 1972 marker bed suggests that the Naskaupi River diversion had an impact on sedimentation at sites NAS-1 and NAS-2.

The increase in thickness and particle size values of varves deposited post-1971 in core NAS-1 (Fig. 5a, 6d/e, 7b, 11) suggest that the diversion has affected sedimentation at this site over time. During the 1972-2016 period, the river floodplain morphology must have been in a re-equilibration phase favourable to erosion, sediment transport, and deposition of coarser varves on the Naskaupi River delta slope. Since the river diversion, sedimentation at NAS-1 site appears to have become more sensitive to maximum discharges variations in spring than mean annual discharges. The sensitivity of the more proximal NAS-1 site to Naskaupi River extreme discharges variability may partly explain why better results are obtained without the 1972-2016 period to reconstruct Q-mean and

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by keeping this period to the Q-max reconstruction. The negative correlation between $P99D_0$ of the core NAS-1 and the timing and rise time of spring discharge (Table 3) also demonstrate reactivity to spring entrainment energy conditions at this site. The distal NAS-2 site shows that post-1971, sedimentation seems to have slightly lost sensitivity to river discharge, and that sediment input continued to decline at the beginning of the deep lake basin. The thin early spring layers free of ice-rafted debris in varve post-1971 of core NAS-1 (Fig. 5a, 11) and NAS-2 indicate that the capacity of early spring discharge to transport fine sediments and its ability to float ice to Grand Lake decreases along with the decrease in water supplies.

It is tempting to link the decrease of varve thickness in core NAS-2 over the 1972- 2016 period with the discharge reduction due to the river diversion. However, similarities with core BEA-1, a site devoid of anthropogenic perturbations (unaffected by the Naskaupi River diversion) which also shows a decline in varve thickness, suggest that this decrease can potentially be due to natural hydro-climatic conditions. The observed Naskaupi River Q-mean series also show a decrease on the 1978-2011 period. Indeed, because of the distant location of site BEA-1 from the Nakaupi River mouth, the diversion is most likely not responsible for the decrease of varve thickness in this sector. Moreover, it is quite unlikely that the sedimentary input from the Naskaupi River contributed to sediment accumulation at the mouth of the Beaver River. The absence of any traces of the 1972 marker bed at the Beaver River mouth (BEA-1) supports this hypothesis. Furthermore, the thickness decrease observed in BEA-1 began after ~1920 (Fig. 6a), which is before the 1971 diversion.

Anthropogenic modification of the Naskaupi River watershed makes it challenging to discuss natural hydroclimate-related variations before and after 1971. Some caution should be applied when comparing pre- to post 1972 reconstructions, given the changes in watershed conditions that happened after the construction of the system of dykes. There is no instrumental data available for the Naskaupi River watershed before 1971 to confirm that the calibration model post-diversion (1978-2011) is similarly robust for the preceding period. The river diversion affected the Naskaupi River sedimentation dynamics but did not modify it drastically. Despite the observed post-diversion changes in varves' physical

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parameters in cores NAS-1 and NAS-2, which are however moderate, the varves still responded directly to variations in river discharge. In addition, the part of the watershed that has been diverted is an area composed mainly of lakes, which are not very hydrologically reactive.

5.3 The hydro-climatic signal in the varve record

The significant correlations between continuous varve thickness and particle size measurements with instrumental hydrological variables (Tab. 3) show that Grand Lake varved sediments are reliable proxies to reconstruct past hydrologic conditions through time at the annual to seasonal scale. The thick and/or coarse-grained varves correspond well to years of high river discharges, whereas thin and/or fine-grained varves are related with years of low discharge. Moreover, figure 11 clearly demonstrates how Grand Lake varve record can be exploited to examine the interaction between meteorological conditions and rivers discharge at an inter-seasonal scale, which is a temporal resolution rarely obtained with natural proxies.

Data from the 3 sites were combined in order to better capture the regional hydroclimatic signal and to somehow attenuate the noise that is inherent from the analysis of a single core in a very large lake. A single core will be more sensitive to local specificities and is probably less representative of the entire hydrogram. The Beaver and the Naskaupi Rivers have adjacent catchments that share the same climatological and geological characteristics, while the Beaver River's catchment is devoid of anthropogenic modifications. The combination of varve parameters from different coring sites with distinct sediment sources (Fig. 1b) improved the correlations with local and regional hydrological variables (Tab. 3) and thereby the reconstructions (Fig. 8, 9). By integrating the core BEA into the combined data, it allows to capture the hydrological signal from a larger region (Nakaupi + Beaver watersheds) and it helps to capture the natural hydrological signal in our combined series used for reconstructions.

As demonstrated by previous studies on varved sediments, the use of both varve thickness and particle size analysis allows for a more specific investigation of the range of

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hydroclimate conditions recorded within varves (Francus et al., 2002; Cockburn and Lamoureux, 2008; Lapointe et al., 2012). For Grand Lake, the combined DLT is found to be the best proxy to reconstruct all hydrological events occurring throughout the year (Q-mean). DLT series are better at predicting Q-mean because the early spring layers and autumn and winter layers thickness are more variable and are included in the TVT measurements. This variability can be linked to specific climatic and geomorphological parameters such as the duration of ice cover on Grand Lake and the Naskaupi River ice breakup processes which induce noise in the hydrologic signal contained in TVT series. The combined P99D_0 yields the strongest correlation in our dataset (Tab. 3) and is the best proxy to reconstruct maximum annual discharges (Q-max). This result is logical because the peak discharge is controlling the competence of the river and consequently the size of the particles that can be transported. Moreover, this indicator is not sensitive to sediment compaction, which may affect other proxies based on thickness.

The significant positive correlations between varve physical parameters and Snow-Win, Q-nival (Tab. 3) and even Temp-Spring demonstrate that Grand Lake varve predominantly reflects spring discharge conditions (e.g., Ojala and Alenius 2005; Lamoureux et al., 2006; Saarni et al., 2016; Czymzik et al., 2018), which is the major component of the regional streamflow regimes classified as nival (snowmelt-dominated) (Bonsal et al., 2019). In boreal regions, the intensity and length of spring floods are controlled by the snow accumulation during winter and by the temperature of the melting period (Hardy et al., 1996; Snowball et al., 1999; Cockburn and Lamoureux, 2008; Ojala et al., 2013; Saarni et al., 2017). The negative correlation between P99D_0 of the NAS-1 and the timing and rise time of spring discharge suggests that early spring flows that increase rapidly are conducive conditions for high entrainment energy and the deposition of coarser laminations on the distal part of the delta slope (Fig. 11; site NAS-1). The erosion of detrital materials in early spring increases when the snowmelt runoffs occur on soils that are not yet stabilized and protected by vegetation (Ojala and Alenius 2005, Czymzik et al., 2018).

Intercalated sub-layers in the upper part of the detrital layer are interpreted to be produced by summer or fall rainfall events (Fig. 11). Yet, the significant positive correlations

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between varve thickness and Nb-days-SupQ80 suggests that a daily discharge of ~125 $m^3 \cdot s^{-1}$ represents an approximate threshold above which the deposition of coarse sediments in Grand Lake (detrital layers) is more likely to occur (Fig. 11) (e.g., Czymzik et al., 2010, Kämpf et la., 2014). According to the instrumental data (Fig. 2, 11), such a discharge can be generated during the summer/autumn period, confirming that rainfall events can indeed be triggering the deposition of thin intercalated sub-layers observed in the upper part of the detrital layers (Fig. 11). However, there is non-significant low correlations between varves thickness and Ptot-Annual/Ptot-Sum (not shown) suggesting that rainfalls contributions to TVT remain small. These rainfall events have no contribution to $P99D_0$ because the coarsest particles are found at the base of the detrital layers.

The comparison between the Naskaupi River hydro-climatic variables and other Labrador hydrometric stations (Fig. 3) show that a coherent regional hydrological pattern exists in the Labrador region. The performed regional Q-mean reconstitution and validation (Fig. 9) indicated that the Labrador region hydrologic signal is recorded in the Grand Lake varve sequence. The local and regional Q-mean reconstructed from the combined DLT series (without the NAS-1 1972-2016 period) suggest a statistically significant decreasing trend in mean annual discharge during the last 90 years. Naskaupi River Q-mean and Q-max reconstructions based on both varve series and rainfall-runoff modelling revealed high value periods from 1975 to 1985 and 1995 to 2005, and low values from 1986 to 1994 and 2006 to 2016 (Fig. 10). These results agree with the downward trend of the annual streamflow observed in eastern Canada during the 20th century in other studies and also with the reported higher river discharges from 1970 to 1979 and 1990 to 2007, and lower discharges from 1980 to 1989 (Zhang et al. 2001; Sveinsson et al., 2008; Jandhyala et al., 2009; Déry et al., 2009; Mortsch et al., 2015; Dinis et al., 2019).

In addition to providing a new high-quality varved record in eastern Canada, this research highlights the complementarity between palaeohydrological reconstructions extracted from clastic varved sediments and rainfall-runoff modelling. Both methods independently offer a similar, yet robust, centennial perspective on river discharge variability in an important region for the economic and sustainable development of water resources in

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Canada. Reconstructed long-term mean and maximum annual river discharges series provide valuable quantitative information particularly for water supply management for hydropower generation and the estimation of flood and drought hazards. The varved sediment of Grand Lake also allows documenting the effect of dyke systems on the downstream sediment transport dynamic into a watershed and its implication for palaeohydrological reconstruction. Further investigation of the impacts of the Naskaupi watershed reduction on sediment transport could help better refine these reconstructions. Future work in Grand Lake should be directed towards the high-resolution analysis of long sediment cores in order to produce longer reconstructions. The Grand Lake deeper varved sequence potentially recorded the hydro-climatic variability that occurred during the Late Holocene in region sensitive to the North Atlantic climate, allowing interesting prospects into large-scale atmospheric and oceanic modes of variability.

6. Conclusions

The great depth of Grand Lake, the availability of fine sediments along its tributaries, and its important seasonal river inflow have favoured the formation and preservation of fluvial clastic laminated sediments. By using a new varved record in eastern Canada and a rainfall-runoff modelling approach, this paper provides a better understanding of the recording of hydro-climatic conditions in large and deep boreal lakes and allows extending the hydrological series beyond the instrumental period as well as the spatial coverage of the rare annual palaeohydrological proxies in North America. The key results of this study are:

- The annual character of the 160 years-long lamination sequence has been confirmed. Each varve, composed of an early spring layer, a summer/autumn detrital layer and an autumn and winter layer, represents one hydrological year.
- Grand Lake varve formation is mainly related to the largest hydrological event of the year, the spring discharge, with minor contributions from summer and autumn rainfall events.
- Two hydrological parameters, the Naskaupi river Q-mean and Q-max annual discharges, are robustly reconstructed from two independent varves physical parameters, i.e., the detrital layer thickness (DLT) and grain size ($P99D_0$) respectively, over the 1856-2016 period. The reconstructed Q-mean series suggest that high Q-mean

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years occurred during the 1920-1960 period and a decrease in Q-mean takes place during the second half of the 20th century.

- The same two hydrological parameters (Q-mean and Q-max), were also reconstructed using the ANATEM rainfall-runoff modelling. ANATEM discharges series show similarities with reconstructions based on the varved series, which support the reliability of the two independent reconstruction approaches.
- The statistically significant relation between combined DLT series and the observed Labrador region Q-mean series, extracted from five watersheds of different size and location, demonstrates that Grand Lake varved sequence can also be used as a proxy of regional river discharges conditions.
- The effects of Naskaupi River dyking in 1971 are clearly visible in the sedimentary record and affected sedimentary patterns afterwards. While this event makes the hydroclimatic reconstruction trickier, it remains that the outstanding quality of this varved sequence provides one of the best hydroclimatic reconstruction from a sedimentary record, with Pearson correlation coefficients up to r = 0.75.

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Data availability

The data set used in this study will be available on the PANGAEA database.

Author contributions

This study is part of AGP's thesis under the supervision of PF and PL. AT and PL provided geophysical data (Fig. 1b, c) and useful information on the morpho-stratigraphical framework of Grand Lake. AGP and DF conducted the coring fieldtrip. AGP and PB collected instrumental data. PB calculated hydro-climatic variables from instrumental data (Fig. 3) and performed the rainfall-runoff modelling. HD and AGP adapted the code used to establish the relationship between the varve parameters and the instrumental data and for the regression model. AGP performed most of the data analysis, wrote the manuscript and created the figures with contributions from PF and PB. All authors provided valuable feedback and contributed to the improvement of the manuscript.

Competing interests

The author Pierre Francus is a member of the editorial board of the journal.

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