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Reply on RC4

Paul H. Whitfield et al.

Author comment on "The spatial extent of hydrological and landscape changes across the mountains and prairies of Canada in the Mackenzie and Nelson River basins based on data from a warm-season time window" by Paul H. Whitfield et al., Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2020-613-AC4>, 2021

Reply to HESS-613 R4

Whitfield et al detail a study that examined trends in streamflow and satellite indices for a large area in central Canada. Many government operated hydrometric stations in this region are only active during warm or open-water season. Because of this, many previous studies looking at long-term flow trends have not used these stations and instead focused on stations operated year round. The authors overcome this issue by using an approach called dynamic time warping to account for differences in timing of streamflow across latitude and elevation. They apply these methods to 395 stations and classified 12 streamflow regime types. They also looked at seasonal trends in streamflow using k-means clustering. They complemented the flow analysis with an analysis of trends in three satellite indices (NDVI, NDWI and NDSI). They suggest that trends in streamflow are organized spatially and influenced by location and ecozone, but not streamflow regime type. They document regional trends and speculate on the underlying hydrologic changes that may be driving those regional trends.

The study is interesting and the methods applied seem useful. My biggest issue with the manuscript is that it is long and feels like it lacks focus at times (I would echo many of the comments of RC3). During my readings of the manuscript, I often felt that content was repeated numerous times (e.g., the conclusions simply repeat some of the discussion), I wasn't sure what the key points of the study were (e.g., was the application of relatively novel methods or was it the hydrologic insight - in the case of the hydrologic insights, I wasn't always sure what I was supposed to take away from the results), and there were often statements made that seemed to have major implications for understanding the study, but were not expanding upon.

[Authors response] We acknowledge that the paper is long, but not that it lacks focus. We sought to be thorough in our descriptions, to ensure the work is reproducible, and to provide the reader with the necessary information to elucidate our results.

It is challenging when a reviewer says that the paper is too long yet asks for additional details and information as below. We have tried to balance these requests in our responses.

To build on this last point, the following are some statements that I wished were developed more:

[Authors response] The reviewer has highlighted a number of statements that we have revisited and revised accordingly.

- "Clearly historical budgetary and management decisions in the Canadian hydrometric program affect any current analysis of hydrological trends and change." (L217-18) How does it affect analysis? How does it affect this study in particular? What are the implications?

[Authors response] The data that were available for this study were not specifically collected to support any specific analysis. What is presented in this paper in an approach that looks at spatial patterns in streamflow regimes, streamflow trend patterns, and trends in satellite indices based on available data. The paragraph in question starts with:

"The stations in this study were operated for differing periods of time and with differing operating schedules."

"Clearly historical budgetary and management decisions in the Canadian hydrometric program affect any current analysis of hydrological trends and change."

Changed to:

The complexity of the dataset results from historical budgetary and management decisions in the Canadian hydrometric program. Assessing hydrological regimes and trends in this dataset requires approaches that are different from "standard" methods.

- "The dataset contains nested basins." (L156) Okay - what should the reader make of this? My first thought is that these stations will exhibit correlation and may be considered

a form of pseudo-replication... how does this impact the analysis?

[Authors response] It is important to inform the reader that some stations are nested within this study. The reviewer is correct that this would result in correlation between stations which would be considered a lack of independence. That would be an issue for many statistical tests, but has no negative effect on the analysis which looks at the spatial pattern of groups with similar hydrologic regimes or trend patterns. The nesting results in a signal that propagates downstream along some rivers as we acknowledge at lines 491 and 745. That nested sites are clustered together is logical support of their similarity.

Text has been added to state this explicitly at line 156.

"The dataset contains nested basins and may have some correlation; the analysis performed does not require sites to be statistically independent."

- "Determining the magnitudes of trends in annual runoff or other annual attributes using this methodology is not appropriate." (L714-715). Why and what is the implication here?

[Authors response] This originated as a response to a previous reviewer. This is a simple statement that when one compares trends in records from different time periods or with different coverage in a common period of years one should not compare magnitudes.

No change was necessary.

- "While these GRACE trend regions are consistent with the results presented here, the mechanisms that Rodell et al. (2018) suggest are not." (L823-824). This seems to come out of nowhere. What are the mechanisms presented by Rodell et al? How do they compare with the speculations made in this study? I think this is partially attempted in the following paragraphs, but the comparison between this study and Rodell is not clear.

[Authors response] Thank you for this comment. We have rewritten the lines:

"... These four regions correspond to areas with changes in water storage (Rodell et al. 2018); precipitation increases in northern Canada, a progression from a dry to a wet period in the eastern Prairies/Great Plains, a region of surface water drying in the eastern Boreal, and of no change along the Rocky Mountains. While these GRACE trend regions are consistent with the results presented here, the mechanisms that Rodell et al. (2018) suggest are not.

And replaced them with:

"... These four regions correspond to areas with changes in water storage reported in Rodell et al. (2018). These four GRACE trend regions are consistent with the results presented here. Rodell et al. (2018) suggested the regions result from the following mechanisms: [1] precipitation increases in northern Canada; [2] a progression from a dry to a wet period in the eastern Prairies/Great Plains; [3] a region of surface water drying in the eastern Boreal; and, [4] a region of no change along the Rocky Mountains. Based on the results presented here, mechanisms different from those suggested by Rodell et al. (2018) should be considered.

- "It is important to note that climate signals, particularly for the Pacific Decadal Oscillation [PDO] and Arctic Oscillation [AO] were not considered here. Oscillation in the climate system can be manifest as tests on short time periods." (L970) This seems like a big deal and was an immediate concern that popped into my mind as I was reading the manuscript the first time. Given that the stations sample different years, how does one consider the potential influence of periodic climate signals that may be in different modes for available station records?

[Authors response] It is indeed an important caution. This study reported changes and trends in a large spatial domain where warming is taking place [lines 53-84] but the focus was on detecting change and not attribution. In the paragraph at line 970 we discuss why some of the observed changes could be driven by PSO and AO and suggest a method which could resample the available data to be able to examine relationships to climate indices.

- "Interpreting the results from any fixed period may not be representative of historical variability (Hannaford et al. 2013)." (L1026-1027) Can the implications and importance of this statement for this study be expanded upon?

[Authors response] This originated as a response to a previous reviewer who was of the opinion that any trend study needed to have a common period of years. Our study did not have a fixed period but used all available data.

We removed this from the conclusion and moved it to the discussion. ~line 705.

I have a few specific comments listed below, but another part of the analysis that seems to warrant some consideration is how does size of the basin impact the trends in the satellite indices? I would guess that larger basins may aggregate different temporal patterns across the space thereby smoothing out potential trend signals. Are identified (or lack of) trends related to basin area?

[Authors response] This is an interesting question and one that should be considered in future research but is really beyond the scope of the present work. As the text indicates, we chose a simple straightforward approach that meets the needs of this study with nearly 400 basins. For each basin three time series (mean, maximum, minimum) from composite imagery for NCVI, NDWI, and NDSI and then determined trends using Mann-Kendall. This was necessary to treat these in a comparable basis in this context. As is mentioned in the text, more complex analysis such as bfast would be suitable for assessing change, but that analysis results in a large collection of statistical models that make comparing and contrasting this large number of basin impractical.

Specific comments

Abstract: Agree with another reviewer that this is too long. The first paragraph could be substantially reduced and incorporated into the second paragraph. There's perhaps too much detail provided here. Distill this down to the key points of the study.

[Authors response] We agree that the abstract is long in an attempt to summarize the key aspects of a complex study of a large and variable hydrological dataset.

We have made some edits to shorten the abstract by some 30%.

L35-38: Not clear what this sentence is trying to say.

[Authors response]

"Streamflow regime types, the trend patterns, and satellite indices trends each showed spatially coherent patterns reflecting the influence of sources in the Canadian Rockies and other range in the west and poorly defined drainage basins due to post-glacial topography in the east and north. "

As part of the rewritten abstract, now:

"Regime types, trend patterns, and satellite indices trends each showed spatially coherent patterns separating the Canadian Rockies and other mountain ranges in the west from the poorly defined drainage basins in the east and north. "

L70-71: 'hydrological' is repeated twice.

[Authors response] Second occurrence deleted.

L74-77: Run-on sentence.

[Authors response] The whole region is subject to strong seasonality, continental climate, near absence of winter rainfall, seasonally frozen soils and from the mid-boreal forest northwards and at high elevations the sub-surface below an annually thawed active layer are permanently frozen (permafrost).

Changed to:

The whole region is subject to strong seasonality, continental climate, near absence of winter rainfall, and seasonally frozen soils. From the mid-boreal forest northwards, and at high elevations, the surface is an annually thawed active layer below which materials are permanently frozen (permafrost).

L78: Change one of the 'dominate'

[Authors response] Changed to:

Tens of millions of lakes and wetlands cover the northern and eastern part of this region where the Canadian Shield dominates topography and hydrography.

L87-89: Seems like these two sentences repeat the same point.

[Authors response] The hydrographs of all rivers in this domain reflect contributions from snowmelt, the magnitude of which differ in both space and time. There are important regional differences in how snowmelt contributes to the seasonal pattern of hydrographs.

We agree, changed to:

The hydrographs of all rivers in this domain reflect contributions from snowmelt, the magnitude of which differ in both space and time.

L92: The rationale for ecozones comes on a little abruptly. So 'ecozones were chosen as an appropriate level for comparisons', but the reader doesn't really know what we will be comparing yet.

[Authors response] Ecozones were chosen as an appropriate level for comparisons (Marshall et al. 1999; Eamer et al. 2014; Ireson et al. 2015) rather than physical attributes such as climate, permafrost, or geology, since ecozones represent regions where the ecology and physical environment operate as a system.

Was changed to:

Ecozones (Marshall et al. 1999; Eamer et al. 2014; Ireson et al. 2015) were chosen as an appropriate level for comparisons of hydrologic patterns and trends rather than physical attributes such as climate, permafrost, or geology, since ecozones represent regions where the ecology and physical environment operate as a system.

L85-112: Some of this feels more like a description of the methods and data used. Consider revising this to focus the introduction on setting the context of the study and what research gaps are addressed, and use the methods section to focus on details about the data used.

[Authors response] This important background information for the reader. An alternative would be to move it to a separate section but we did not feel that would improve the paper.

Hydrological processes differ widely in this domain, which spans 11 of Canada's 15 terrestrial ecozones, and includes many small basins where streamflow is only temporary (Buttle et al. 2012). The hydrographs of all rivers in this domain reflect contributions from snowmelt, the magnitude of which differ in both space and time. Other flow contributions, from glaciers and rainfall, all vary spatially across the domain with glacier contributions focussed in high mountain headwaters and rainfall contributions increasing at lower elevations and latitudes. Ecozones (Marshall et al. 1999; Eamer et al. 2014; Ireson et al. 2015) were chosen as an appropriate level for comparisons rather than physical attributes such as climate, permafrost, or geology, since ecozones represent regions where the ecology and physical environment operate as a system. It is important to note that many river basins in this study originate in one ecozone and cross through other ecozones whilst maintaining the characteristics of their source.

Streamflow data in this domain is taken from stations that were operated either year-round or seasonally (MacCulloch & Whitfield 2012); seasonal stations generally provide records from April through the end of October, because there is either no streamflow in the winter, or because the channels become completely frozen. This approach contrasts with many studies that use only stations having continuous records and a common period of years (e.g. Whitfield & Cannon 2000); one novel aspect of this study is that it demonstrates a method which incorporates records from both continuous and seasonal stations. Trend assessment is conducted on an annual common time window for both continuous and temporary streams.

Landscape changes may cause or result from hydrological changes. Satellite imagery and derived spectral indices were used to assess the changes in the landscapes of basins in relation to their hydrological response. Normalized Difference Indices of vegetation, water, and snow (NDVI, NDWI and NDSI) were constructed using optical imagery from the Thematic Mapper (TM) sensor (USGS 1984) on board the Landsat 5 satellite for individual basins (e.g. Hall et al. 1995; Su 2000; Hansen et al. 2013; Pekel et al. 2016). Although the temporal coverage of the indices differs from that of the hydrometric data, the trends in these indices over many basins provide another perspective of change over the study domain.

L110-112: The difference in temporal coverage of the streamflow and vegetation/water/snow indices feels like a big deal that is somewhat glossed over here. In addition, I'm not sure what 'trends in these indices over many basins provide another perspective of change over the study domain' means. Could this be clarified?

[Authors response] Although the temporal coverage of the indices differs from that of the hydrometric data, the trends in these indices over many basins provide another perspective of change over the study domain.

We were not intending to 'gloss over' but to emphasize that those satellite data have coverage for another time period. Changed to:

The temporal coverage of the indices differs from that of the hydrometric data used in this study. Trends in these indices over many basins from the satellite imagery that is available provides a complementary perspective on hydrological change over the study domain.

L115: Do you need both 'separately' and 'individually' here?

L115: What is 'hydrological structure'?

[Authors response] "The objective of this study was to examine the hydrological structure and changes in seasonal streamflow patterns by combining data from perennial and temporary streams, which had previously only been treated separately and individually, to diagnose hydrological structure and change in western Canada's cold interior."

Changed to:

"The objective of this study was to examine the hydrological structure and changes in seasonal streamflow patterns by combining data from perennial and temporary streams to diagnose hydrological process differences and change across western Canada's cold interior."

L120: What 'mechanisms' were considered in this study? It seems like some basic indices were related to streamflow patterns. Why should this be considered as 'mechanisms'?

[Authors response] "[2] how are climate related trends and mechanisms distributed?, and "

Changed to:

"[2] how are climate related trends distributed?, and "

L142: What is meant by 'annual time window' here?

[Authors response]

The alternative approach used here includes data from a large number of seasonal and continuously observed sites, which are considered using only an annual time window described below.

Not sure why this is an issue as the common time window is described in the next paragraph.

Changed to

The alternative approach used here includes data from a large number of seasonal and continuously observed sites, which are compared using only the data available from April to the end of October.

L150-151: Why is the link to CCRN process-based studies important?

[Authors response] "and including these stations provides a link to CCRN process-based studies (DeBeer et al. 2016)."

This text is to inform the reader that our study of many stations, provide a spatial and temporal study of change which complements these process intensive study locations.

"and including these stations provides a link between the spatial patterns reported in this study and intensive process-based CCRN studies (DeBeer et al. 2015; in press)."

L164-166: Check grammar.

[Authors response]

"Satellite imagery and derived spectral indices are valuable for assessing effects of environmental changes the hydrological responses of the gauged basins as these methods allow determination of changes in vegetation, water bodies and snowcover for large areas (e.g. Hall et al. 1995; Hansen et al. 2013; Pekel et al. 2016; Su 2000)."

Changed to:

"Satellite imagery and derived spectral indices are valuable for assessing effects of environmental changes and the hydrological responses of the gauged basins; these methods allow determination of changes in vegetation, water bodies and snowcover for large areas (e.g. Hall et al. 1995; Hansen et al. 2013; Pekel et al. 2016; Su 2000)."

L180: What 'related packages'?

[Authors response] "Maps were plotted using maps and related packages. "

Deleted.

L310-314: How much of an issue was this? I can imagine certain regions across the study region are more prone to cloud cover than others. Did this bias the analysis in any way?

[Authors response]

"Theoretically this would allow for spatially-complete mosaics given the 16-day revisit time of the satellite. "

This is described in the sentences that follow in the text. We actually determined the actual coverage fraction of images a typical example of which is shown in Figure S14. We used the annual maximum, minimum, and mean of these composited over basin areas. Visual inspection suggests that these time series of indices demonstrate a common seasonal patterns despite the missing observations.

Section 3.4: There are a number of speculations made about hydrologic processes underlying the detected trends in streamflow and satellite indices (e.g., increased greenness results in increased ET, increased NDWI is due to increases in PPT). There are a number of limitations to these indices and making some of these links to actual hydrologic fluxes and storages may be confounded by other influences. It seems like some of these speculations could be checked by looking at available meteorological data, such as precipitation trends for some of these NDWI trends, for example.

[Authors response] We felt it important to make the suggestions and others might want

to explore those in specific areas within our study. But, this suggestion would be outside the scope of our study.

L730-733: This feels like a major issue - that the key hydrologic runoff event for some of these catchments is not always accounted for using the time window considered in this study.

[Authors response]

"and c) the snow melt period often occurs before the beginning of the annual common time window."

This really is a simple statement of fact. Since we are not looking at annual runoff but changes in runoff across five day periods the data are being compared on a consistent and logical manner.

L745-748: I'm left wondering what the deal is with these flow regime types that contain only one or two stations. Why did these stations stand out? What makes them unique? It seems a lot could be learned about the hydrology and/or the methods used in this paper by looking at these specific classes more closely.

[Authors response]

Three clusters (Streamflow Regime Types 6, 7, & 8) each contained a single member and one (Type 10) had only two members. These Streamflow Regime Types are very different from those containing large numbers of members and any clustering of hydrographs in this way must balance common characteristics against uniqueness.

This is a classic issue with hierarchical clustering as it often separates individual of small groups of cases preferentially when dealing with time series. Our decision was to acknowledge these more 'unique' cases, but to focus on the groups with larger memberships.

L758-759: Could you elaborate on why these results are different from those reported by these other two studies?

[Authors response]

"Basins in mountainous areas generally lack consistent patterns of trends, but some exceptions do occur. This is counter to many studies that have shown late summer streamflow declines (Jost et al. 2012; Fleming & Dahlke 2014)."

Changed to:

Basins in mountainous areas generally lack consistent patterns of trends (Trend Pattern 5), but some exceptions do occur. Many studies in British Columbia have shown late summer streamflow declines (Leith & Whitfield 1998; Jost et al. 2012; Fleming & Dahlke 2014). This may be the result of hydrologic resilience (Harder et al. 2015) in mountain basins east of the continental divide.

L990: In what way are the available data 'messy'?

[Authors response]

The available data are messy, and there was an uneven distribution of stations by ecozones.

Changed to:

The structure of the available data is complicated, the dataset contains streamflow records from entire years and/or only the warm season, and for a variety of periods of years, and the sites are not evenly distributed across ecozones.

L991-994: Run-on sentence.

[Authors response]

Determining the magnitudes of annual trends was not appropriate with the approach used because of the inconsistency of years of data between sites, but by including the data from seasonal stations and an annual common time window rather than only entire years, the results provide an interesting spatial story of trend direction.

Changed to:

Determining the magnitudes of annual trends was not appropriate with the approach used because of the inconsistency of years of data between sites. But, including the data from

seasonal and continuous stations and focussing an annual common time window rather than only entire years, the results provide an interesting spatial story of trend direction.

L1002-1019: The first half of this paragraph is a little strange to read. Stating that this study is important because it connects to existing research programs doesn't seem like a strong rationale. Emphasizing the points in the second half of this paragraph would make for a stronger point.

[Authors response]

The paragraph was split into two and the first portion rewritten.

The motivation for this study came from the NSERC Changing Cold Regions Network study of 2013-2018 (DeBeer et al. 2015; in press) of Western Canada's rapidly changing cold interior. That study sought to integrate existing and new sources of data with improved predictive and observational tools to understand, diagnose, and predict interactions amongst the cryospheric, ecological, hydrological, and climatic components of this study area. The results presented here are already informing several science research agendas in Canada and internationally. The results also contribute to the Global Water Futures programme of 2016-2023 (www.globalwaterfutures.ca), which has an overarching goal to deliver risk management solutions to manage water futures in Canada in a time of unprecedented change.

The first step to managing future water changes is to understand those of the recent past and that are currently underway and this study makes a strong contribution to that process. In particular, this study represents a step forward in addressing the complexity of hydrological change; there are many studies of individual basins where, when results are considered individually, tend to be more anecdotal than systematic. It is indeed simpler and easier when there are only a few cases to consider with common variables and record length, as in many studies, but with large numbers of basins the tools for dealing with significant changes are more limited. Sensitivity studies that assess the limits of partial year analysis of hydrological structure and change are required and seem a logical next step.

Table 2: What is the point of including this table? Could be moved to the SI.

[Authors response]

This table was added in response to an earlier reviewer's suggestion as they wanted to be able to know actual dates corresponding to period numbers. Moving it to Supplementary material would make it necessary for the reader to have the SI in hand.

Figure 1: The map projection used doesn't look typical for showing this region. The northern region is stretched considerably.

[Authors response]

This is standard Mercator projection that is commonly used in North America. It indeed stretches the north.

Figure 6: The dashed lines are obscured in some of the plots (e.g., regime type 1 and 5). The axes labels could be more descriptive. Colouring the individual lines doesn't make much sense to me since we have no way to connect these back to stationID.

[Authors response]

This is an issue with the originating software that uses "ggplot" where the centroid is plotted first and over-plotted with the individual lines that are coloured based on internal code in that function. We have changed the description to be more precise:

"Each of the twelve plots contains a line for each gauged basin in that Type and the heavy dashed line, where visible, is the centroid of all members; the colour of the lines is based upon stationID."

Many of the figures are not colour-blind friendly. I would suggest using a more colour-blind friendly colour palette.

[Authors response] Using colour requires many considerations. Where we had control, we have used contrasting and consistent colours and line types. Two important constraints we faced were [1] using the ecozone colours conforming to those commonly used in ecosystem/ecoregion mapping, and [2] using package default graphs in dtwclust that are produced using "ggplot".

Figure

- 1 *Map with red symbols and brown basin outlines on Mercator projection.*
- 2 *Default colours from CSHShydRology function with red down and blue up arrows*
- 3 *Default colours from CSHShydRology function with red down and blue up arrows*
- 4 *Solid lines in gray and heavy dashed lines in blue*
- 5 *Red dashed line and solid blue lines*
- 6 *Plot from dtw that relies on "ggplot". Line colours assigned based on case order. Heavy dashed lines [centroids] plotted first.*
- 7 *Cluster colours based on the ggplot output in Figure 6. Base ecosystem colours conform to those used by originating agency.*
- 8 *Line colours defaults within dtwclust which uses ggplot.*
- 9 *Default colours and line weights from CSHShydRology with vertical heavy blue dashed lines added.*

- 10 *Red and blue pixels match colours for decreases and increases. Consistent use of six cluster colours. Base ecosystem colours conform to those used by originating agency. Added dashed lines differ in dash length and colour.*
- 11 *Colours conform to those used for six change patterns. These were chosen to reflect the types of clusters. Four increasing patterns are shown with distinct shades of blue [3] and darkgreen; one decreasing pattern is shown in red, and the cluster without patterns in a neutral gray. These six are used consistently throughout.*
- 12 *Consistent use of six cluster colours. Base ecosystem colours conform to those used by originating agency.*
- 13 *Red down triangles and cyan up triangles used to indicate trends. Base ecosystem colours conform to those used by originating agency.*