Biogeosciences Discuss.,
https://doi.org/10.5194/bg-2017-142-AC1, 2017

Interactive comment on "Hydrology drives chemical synchronicity in subarctic tundra ponds" *by* Matthew Q. Morison et al.

Matthew Q. Morison et al.

mmorison@uwaterloo.ca

Received and published: 21 June 2017

General author responses: We thank the referee for their close attention to the manuscript and to several large-picture comments to improve the impact of the paper and clarify the objectives, as well as ensuring correct figure referencing, effective language and better phrasing choices. We believe that this manuscript is significantly strengthened by the suggested revisions. Here we outline our plans for revisions and address the specific concerns of the referee in each section. We mark referee comments with an (R) and author responses with an (A).

(R): This paper summarizes a study evaluating aquatic chemistry dynamics in the Hudson Bay Lowlands in northern Canada. The objectives were to determine if temporal

or spatial variability in pond chemistry is more prevalent and any variability could be used to infer processes occurring in ponds and their catchments. The paper is certainly within the scope of Biogeosciences. The authors' point is well taken that many synoptic scale studies of aquatic chemistry use very few samples, yet make broad statements about the processes at play to produce these signals. In that respect, the dataset presented for this region is quite good. However, the paper could be improved to substantively deliver on its objectives, specifically the one on relating processes to patterns. The title could be "Hydrology drives chemical synchronicity in subarctic tundra ponds sometimes".

(A): We have changed the title to reflect the fact that indeed, hydrology does not dictate the synchronous behaviour of each chemical species in this study. The new proposed title for this study is "Capturing temporal and spatial variability in the chemistry of shallow permafrost ponds". This is an important distinction and the original title may have been an overstatement on our behalf. We more specifically address the comment regarding delivering on our stated objectives later in this response.

(R): Two major issues with the paper that should be addressed. The first is that while the data suggests there are some constituents in some ponds that are clearly influenced by hydrological processes (e.g., evaporation), there are no data presented on pond hydrological fluxes or states besides pond stage. There is a diversity of responses that are interpreted through the lens of this drawdown, and the authors make some, what I think are unsubstantiated classifications of their data. For instance, what defines "consistent" in the relationship between pond stage and concentration? Another interpretation of the data in Table 5 could be that each pond has hydrologically driven chemical species, but these species may not be hydrologically driven in all ponds; "hydrologically driven if necessary, but not necessarily hydrologically driven" so to speak. There needs to be data provided on basin area, pond:catchment ratio, etc., because these may allude to runoff fluxes into and through the ponds, that may help explain these differences. This would help address a feeling the reader gets that the authors use the literature to much to help interpret their results. The paper does show how hydrology does and does not drive chemistry in these ponds, but it needs more hydrological data, and this could elevate the paper.

(A): We agree that providing catchment characteristics would better allude to some of the processes which we speculate on in the paper. Thus we have now included some additional hydrometric data in the paper which we had collected in the field but initially had not included in this paper (runoff measured into each pond over the course of the study period as well as catchment area) although to further reduce speculation we present this data as a depth of water over the pond surface as opposed to the catchment surface. We do this as a depth over the pond surface as we recognize that the variable contributing area concept applies here due to the very flat topography (regional gradient of < 1 m/km, Dyke and Sladen, 2010) and the confining role of ground frost in prohibiting or redirecting subsurface flow at different periods over the course of the season (Wright et al., 2009) and not all of the catchment may be contributing during a given event (and hence why we give runoff over the pond surface, which is also more relevant to the dilution effect). Additionally, we have clarified in a supplement to Table 5, what drove the classification schema to determine if a species was hydrologically driven, as well as noting specific instances in which a species was hydrologically driven in some ponds but not all (as the referee notes, "hydrologically driven if necessary, but not necessarily hydrologically driven")

(R): The second issue is related, and it relates to the difference between "synchronicity" and temporal coherence". First, synchronicity is not a word, but that is an argument for another day. Because the hydrological process discussed in the paper is really just a drawdown process, it is likely correlated with time, so are some of the terms really hydrologically driven, or are they just exhibiting temporal coherence? This is why discussing other hydrological processes is necessary. Also, I agree with the authors that there are landscape scale factors at play, but this relationship between time and hydrology needs to be better thought through and expressed in the paper. Doing

so, and gleaning why some species seem to be hydrologically driven, in some ponds sometimes, but not all, could bring it all together quite nicely. This could also allow the authors to better deliver on objective #3.

(A): This paper does not present data reflecting specific biogeochemical process, and certainly more research is needed to understand individual components of the cycling of this elements in these aquatic ecosystems. To reflect this we have modified our discussion to be wary of overstating the degree to which we understand exactly which processes are driving elemental concentrations. However we do believe that our results indicate a temporal coherence which appears to be very strongly tied to variations in pond water level, which we interpret as a result of close relationship with conservation of chemical mass associated with conical bathymetry. We will modify the discussion to reflect on, as the referee states “relationship between time and hydrology” to reflect on the seasonal variation in biogeochemical characteristics (such as primary productivity) with are closely tied to hydrological variation. We believe we have reasonable confidence to associate the temporal coherence in chemical concentrations with hydrological variations given the relative degree of homogeneity in hydrological forcing to these ponds (given their proximity to each other to receive similar precipitation inputs and exposure to similar atmospheric conditions driving evapotranspiration).

(R): Some minor issues include a lot of misreferenced tables and figures. The authors use "between" when they should use "among". Also, while great data for context, I’m not sure the higher frequency data adds that much to the manuscript. I’ve attached a marked up pdf version of the manuscript.

(A): We appreciate the close attention to detail by the referee and outline the comprehensive comments made in the supplement to the referee comment, and our responses below. In addition, we have carefully reviewed each figure and table reference to ensure each table and figure is correctly referenced.

(R): P.1 Line 19: “In contrast, the dissolved inorganic nitrogen species were not directly related to pond hydrologic conditions and were instead likely mediated by biological processes within ponds" Is this then different than what is suggested by the title?

(A): As noted earlier in this response, we altered the title to reflect the fact that hydrology only regulates the synchrony of some, but not all, chemical species.

(R): P.2 Line 21: "The hydrology of ponds is closely tied to chemical concentrations" - Or is it the other way around?

(A): Correct, it is the other way around. This sentence has been inverted to reflect this.

(R): P.4 Line 21: "artefacts" spelling

(A): We had spelled initially with the British/Canadian spelling, now changed here to "artifacts".

(R): P.4 Line 25: "The perimeter and area of each pond were surveyed with a Trimble Juno SB GPS unit, with a differentially corrected horizontal accuracy of $\pm$5m". This is terribly large. Is this the correct value?

(A): This is the error of the accuracy as listed by the differential correction software. This was a handheld GPS unit and these values are typical for these units: http://www.trimble.com/mappingGIS/junoS.aspx. We believe the precision is likely much better than the accuracy (C. Storie, personal communication), but we do not have a measure of that. The perimeter and area of the ponds as determined by GPS were checked against manual pond polygon tracing over satellite imagery (Google Earth) and were both within 5% of the values calculated with GPS measurements.

(R): P.5 Line 4: "Dissolved organic nitrogen (DON) concentrations were determined as the difference between DKN and NH4". First use of this acronym.

(A): We have included a definition of DKN as Dissolved Kjeldahl Nitrogen in the methods section previous to this, and now consistently refer to solely to DON in the remainder of the document.

(R): P.5 Line 22: "To determine the relationship between pond volume and concentrations of different chemical species, a power function ðİŚę = ðİŻ¡1[ðİŚě]ðİŻ¡2 was fit". Maybe present this as an equation. Make it more visible, because it is an important part of your interpretation. Right now, it is buried in the text. It is also unclear of the form; what is x and what is y, because the form of this equation in this text is backwards to that in the caption for Table 5.

(A): The previous form was backwards (with x and y in the opposite positions based on their definitions) and we have corrected this. We have now presented this as its own equation, while replacing y with "stage" to clarify the relationship between the concentration and hydrology.

(R): P.5 Line 22: "(the ratio of each concentration to the mean concentration [ðİŚě])" isn't spatial concentrations normalized by xt?

(A): This was a typo in our text, we have corrected it to read x subscript t.

(R): P.6 Line 5: "To determine if spatial variability exceeded spatial variability," temporal variability?

(A): This was a typo in our text, we have corrected it to read "spatial variability exceeded temporal variability".

(R): P.6 Line 9: "concentrations between ponds", maybe this should be "among"

(A): We have changed this language here (and elsewhere, where appropriate) to "among".

(R): P.6 Line 10: "tended to be strongly positively correlated which each other ($p < 0.01$)". Except for DON, maybe say so explicitly.

(A): We have included an explicit list of those chemical species which tended to be significantly correlated between ponds (DON, chloride, sodium, magnesium) and were not (sulphate, calcium, ammonium, nitrate).

(R): P.6 Line 17: “from 260 to”. DOY.

(A): This was a typo in our text, we have corrected it to “DOY 260”.

(R): P.6 Line 26: “As was observed for water chemistry, there was also a seasonal pattern in pond hydrologic storage. In general, ponds were full following snowmelt, with water levels generally declining throughout the season and eventually rising again in late summer (Figure 4).” Since you talk about "full", maybe put the outlet stage for each on Figure 4. You'll have to do it in such a way that it won't be too crowded. Maybe a panel for each pond; maybe a notch on the y-axis instead of a horizontal line across the whole graph.

(A): We appreciate the helpful comment to improve Figure 4 and have included notches on the y-axis to indicate bankfull storage following snowmelt in the ponds.

(R): P.6 Line 26 “all ponds were responsive to two major rain events on DOY 166 and DOY 185 (Figure 4).” Would it be hard to add rainfall to Figure 4? (A): We have added rainfall (as well as runoff amounts, as discussed previously in these author responses) to Figure 4.

(R): P. 6 Line 28 “Left pond and Strange pond experienced prolonged summer drawdown while this drawdown was less pronounced in Larch and Sandwich ponds, which have larger surface inlets and outlets, suggesting greater hydrologic connectivity to peatlands (Figure 1).” How would the morphology of the inlets and outlets relate to higher connectivity? There may be a quantum leap in logic here. Why not just examine catchment size? Also, what does "greater" connectivity mean? Does it mean a higher volume of water flows into it? Or a larger transfer of water from the peatlands to the pond? Basin area may be a better index than outlet/inlet morphology.

(A): As discussed earlier in this response, we have now included some of this data, in particular, runoff volumes and catchment areas for each pond.

(R): P. 7 Line 2 “between variation in stage variations” Delete.

(A): This was a typo in our text, we have deleted the repeated word.

(R): P. 7 Line 3 “pond geometry (depth, shoreline development, area, or perimeter).” Where are the data to show this? (A): We have presented this data in a table and added a reference to this table for this sentence.

(R): P. 7 Line 8 In each case, species with a consistent pond-specific value of$\beta 2$ (the slope of the power curve) with low root mean square error (S) were categorized as hydrologically driven” Could you explain why you chose to use pond specific terms? If it were really hydrologically driven would it not be common across all ponds, because you have normalized for time; (divide by xs)? It seems that the data point to instances where some terms of hydrologically driven in some ponds but not others. Some are consistent (Mg), some are not (K). A more rigorous explanation is needed about what was considered "consistent", because for instance, why was sulphate not considered hydrologically driven in Strange pond?

(A): As mentioned earlier in this response, we have clarified in a supplement to Table 5 what drove the classification schema to determine if a species was hydrologically driven, as well as noting specific instances in which a species was hydrologically driven in some ponds but not all (as the referee notes, "hydrologically driven if necessary, but not necessarily hydrologically driven").

(R): P. 7 Line 13 “differences in $\beta 2$ values between ponds for hydrologically driven species” again, "among"

(A): We have changed this language here (and elsewhere, where appropriate) to “among”.

(R): P. 7 Line 13 “hydrologically driven species are driven by the differences in bathymetry” "influenced"? You use "drive" three times in this sentence.

(A): We have replaced driven” with “influenced”. Thank you for the suggestion to improve the writing.

(R): P. 7 Line 14 “bathymetry driving the stage-volume relationship.” But you just said at the end of the previous paragraph that bathymetry (depth-aera) didn’t influence stage. So why would B2 vary?

(A): To clarify, the specific shape of the pond bottom (typically a rough single-deepest-point-basin cone) differs slightly between ponds and thus dictates the value of B2 based on the slope from the deepest point of the pond to the edges, although generally being extremely gradual with similarly very low slopes of <0.1% in the terrestrial landscape (Dyke and Sladen, 2010). We chose the power function to capture this and allowed the exponent in the function to vary. Theoretically, for a height-volume relationship (and under the assumption of some ions being conservative, we extend this to height-concentration relationship) the value of this coefficient should be between 0, for a perfectly cylindrical pond basin with a flat bottom, to highly negative, for a very steep cylindrical pond basin. We will clarify this in-text in the methods section.

(R): P. 7 Line 15 “3.4 Principal component analysis” There is no reference to Figure 6 in this section. Also there is some inconsistency between what is defined as "hydrologically driven" in Table 5 and the caption to Figure 6. The latter separates nitrogen species from the rest, but the former does not.”

(A): We have added a reference to Figure 6 in this section, and added additional clarification to the captions of Figure 6 and Table 5 regarding specific instances in which a species was hydrologically driven in some ponds but not all ("hydrologically driven if necessary, but not necessarily hydrologically driven").

(R): P. 7 Line 21 “Two other non-hydrologically driven ions have positive scores along PC1 with slightly positive (DON) and positive (Ca2+). . .” This is hydrologically driven in Table 5.

(A): This was a typo in our text, and was meant to be a reference to sulfate which did not show a clear relationship with stage in any pond. The sentence has been corrected to “Two other non-hydrologically driven ions have positive scores along PC1 with slightly

negative (SO42-) and positive (Ca2+). . .”

(R): P. 7 Line 31 “same magnitude over the course of several days as they did over the period of the entire snow free season (DON, K+, Ca2+, NO3-);” You seem to substitute DON and DKN sometimes.

(A): We have now defined DKN as Dissolved Kjeldahl Nitrogen and [DON] = [DKN] – [NH4] in the methods section previous to this, and now consistently refer to only DON in the remainder of the document.

(R): P. 8 Line 7 “This suggests that landscapescale factors such as climate and ecotone may be driving pond nutrient cycling and hydrological processes” nitrogen did not follow this behaviour (Figure 3).

(A): We have modified this sentence to reflect that primarily major ions follow this behavior but not nitrogen species.

(R): P. 8 Line 14 “The concepts of temporal/spatial coherence and synchronicity have been employed in temperate lake systems” Even though growing in popularity, I do not think this is a word. Synchrony is.

(A): This is duly noted, and we have removed mention of the word synchronicity and replaced with synchrony following the referee’s suggestion.

(R): P. 8 Line 18 “Magnuson et al. (1990) and Baines et al. (2000) reported Ca2+ to be temporally coherent among groups of large lakes in Wisconsin, USA, consistent with our findings” OK. What is the difference between temporal coherence and synchronicity?

(A): In this document we did not explicitly define these terms separately, but instead had used them synonymously. We have removed reference to the word synchronicity and replaced it with synchrony. We will make the interchangeable use of these terms to be explicit, as both have been employed previously to define the behaviour of chemical concentrations in pond or lakes behaving similarly through time (e.g. Magnuson et al., 1990; Baines et al., 2000).

(R): P. 8 Line 24 “In our study, chemical species which were classified as hydrologically driven (Table 5) were not necessarily the same species which showed that temporal variance exceeded spatial variance (Figure 5).” Figure 3?

(A): This was a typo in our text, we have changed the reference to read Figure 3.

(R): P. 8 Line 26 “Conversely, Ca2+ and SO4 2- display significantly greater temporal variability then spatial variability, but were not classified as hydrologically driven constituents.” You may be combining things here. Since your hydrologically driven is really just a drawdown process, it is likely correlated with time, so should Ca and sulphate be "hydrologically driven"? More thought needs to go into how these species are classified. Furthermore, this discussion about processes is speculation without some measurements that can inform understanding about process.

(A): Indeed we feel that there are other processes at play, including both reactive (biogeochemical) and also transport-driven (different amounts of runoff). We do not have measurements of these reactive process(es) to support any claims of the magnitude and rate of which processes are operating to which extent. However, the data do at least suggest some sort of homogeneity in process between these ponds which are spatially clustered (and thus subject to similar landscape-level controls such as precipitation, runoff, and general catchment characteristics). We will ensure the language of the discussion reflects the degree of uncertainty we have regarding the magnitude and rates of specific biogeochemical processes, given that we do not have any direct measurements.

(R): P. 8 Line 31 “Strange and Left ponds showed the greatest variation in pond stage (Table 2; Figure 3),” Table 3 does not show this, and it is Figure 4 that shows stage

(A): This was a typo in our text, we have changed the reference to the correct Figure and Table.

(R): P. 9 Line 2 “suggesting that variation in pond stage alone does not necessarily dictate which ions are most chemodynamic within a pond” Would adding data about stream order, basin size, flow, help?

(A): We have added catchment area data to the paper. Regarding stream order and flow, there are few persistent overland flowpaths. Due to very high hydraulic conductivity in upper parts of peat profile (Quinton et al., 2008) most of the flow is shallow subsurface flow in the upper part of the peat profile (Holden and Burt, 2003) as opposed to stream networks appearing in these small closed-basin systems.

(R): P. 9 Lines 11-12 similar concentration trajectories at the seasonal (Figure 2) and event (Figure 6) scales. Figure 3? Figure 7? I think I know what might have happened in this section with the Figure numbering.

(A): This was a typo in our text, we have changed the reference to the correct Figures (3 and 7).

(R): P. 9 Line 15 “Differences may be explained by the inclusion of additional limnological measurements into the PCA” What differences are we talking about?

(A): This was a typo in our text, and meant to be a reference to difference between our work and a study by White et al (2014) who did a study of the chemical properties of some of these same ponds in 2014 at three points of the course of the year and found difference alignment of PC axis for some of the same chemical species.

(R): P. 9 Line 33 “On the North shore of Alaska, Koch et al. (2014) showed that the chemical dynamics were less pronounced in ponds that maintained lower temperatures, limiting evaporation and biological uptake; larger ponds with dilute inflows were subject to greater evaporation as a fraction of pond volume and greater nutrient depletion over the course of the year, linking the combined effects of hydrology both directly and indirectly impacting nutrient concentrations.” It would improve this paper if data on such processes were collected and discussed.

(A): We do appreciate the need for coupling our understanding of the hydrological processes operating in northern regions with any temporal or spatial assessment of their chemical variability. In a previous study in the same catchments as this work, we completed an assessment of how different flow paths (driven by the seasonal evolution of the frost table) access different layers of the peat profile, which directly impact hydrochemical export (Morison et al., 2017). In order to strengthen this paper we have added runoff data, however, we do not have the same sampling frequency of measurements of inflow chemistry, which we presented in the aforementioned study. Future work could attempt to address both spatial and temporal variability in pond chemistry as both a function of physical hydrology (dilution and evapoconcentration) and also hydrochemistry (changing inflow concentrations as a result of differing catchment characteristics, for example).

(R): P. 10 Line 7 "In Frisbee pond, the rainfall and runoff volumes represent a much greater fraction of the total pond water at the conclusion of the event (nearly one-half)," This is another reason it would be good to have outlet stage in Figure 4

(A): We have added notches to Figure 4 indicating the pond storage at the conclusion of snowmelt (as a proxy of fullness) for reference, as suggested.

(R): P. 10 Line 8 "where event water represents a smaller proportion of the total post-event water (closer to one-quarter, Figure 5)." Figures 4 and 7

(A): This was a typo in our text, we have changed the reference to the correct Figures 4 and 7.

(R): P. 11 Line 2 "Existing studies have frequently employed a great number of spatial samples without great temporal resolution" This section has plenty of good ideas, but it does not quite relate to the objectives outlined at the end of the introduction. It may be a better approach to finish the discussion with sections on each of these objectives; not just some.

(A): We have restructured this section to more directly address each objective, paragraph by paragraph.

(R): P. 11 Line 23 "This study reported on the degree of hydrologic control on nutrient and major ion chemistry of a set six of shallow permafrost ponds in the Hudson Bay Lowlands." of six.

(A): This was a typo in our text, we have added the word "of"

(R): P. 12 Line 1 "and following precipitation events may be on equal order as the variation over the course of months" While a fair point, I'm not sure the higher frequency data adds much to the discussion with the format of the manuscript as it is now.

(A): We believe, given the projected increase in frequency and magnitude of large precipitation events over the ice-free season (Sauchyn and Kulshreshtha, 2008; Kaufman et al., 2009, Macrae et al., 2014), it is important to include this to deliver on our objective of discussion both of temporal variability and also sampling designs. We have included more motivation with references to this literature for this need for understanding chemical responses to large summer storm events in the introduction section.

(R): P. 12 Line 9 Objective 3 is not addressed at the end of the paper.

(A): We have added runoff data to the paper and speculated on biogeochemical processes which are likely to be occurring (using references to the literature from this region and similar subarctic landscapes) to guide our interpretation of the temporal trajectories of chemical concentrations of these ponds, and included a paragraph-by-paragraph breakdown of our conclusions as relating to each research objective in this season.

References:

Baines, S. B., Webster, K. E., Kratz, T. K., Carpenter, S. R., and Magnuson, J. J.: Synchronous Behavior of Temperature, Calcium, and Chlorophyll in Lakes of Northern Wisconsin, Ecology, 81(3), 815-815, 2000.

Dyke, L. D., and Sladen, W. E.: Permafrost and peatland evolution in the northern Hudson Bay Lowland, Manitoba. Arctic, 429-441, 2010.

Holden, J., and Burt, T. P.: Runoff production in blanket peat covered catchments. Water Res. Res., 39(7), 2003.

Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., and Lakes, A.: Recent warming reverses long-term Arctic cooling. Science, 325, 1236-1239, 2009.

Macrae, M. L., Brown, L. C., Duguay, C. R., Parrott, J. A., and Petrone, R. M.: Observed and projected climate change in the Churchill region of the Hudson Bay Lowlands and implications for pond sustainability. Arct. Antarct. Alp. Res., 46(1), 272-285, 2014.

Magnuson, J. J., Benson, B. J., and Kratz, T. K.: Temporal coherence in the limnology of a suite of lakes in Wisconsin, U.S.A. Freshwater. Biol., 23, 145-159, 1990.

Quinton, W. L., Hayashi, M., and Carey, S. K.: Peat hydraulic conductivity in cold regions and its relation to pore size and geometry. Hydrol. Proces., 22(15), 2829-2837, 2008.

Sauchyn, D., and Kulshreshtha S.: Prairies. In From Impacts to Adaptation: Canada in a Changing Climate 2007. Government of Canada: Ottawa, 2008.

Wright, N., Hayashi, M., and Quinton, W. L.: Spatial and temporal variations in active layer thawing and their implication on runoff generation in peatâĂŘcovered permafrost terrain. Water Res. Res., 45(5), 2009.

Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2017-142, 2017.