Impacts of climate variability on wetland salinization in the North American Prairies.

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Detailed below are our responses to reviewers 1, 2, and 3 as submitted in the responses letters. Where relevant the page and line numbers of the changes in the manuscript were added.

Reply to reviewer #1.

We followed reviewer #1 suggestion and we added a short section (section 3.9 at Pages 14-15) to explain our conceptual model in a concise manner. The new section describes the differences between snowy and rainy conditions as well as presenting all of the potential interactions between the ponds and their adjacent uplands and other ponds. We also added a new diagram showing the various water flow paths for rain and snow associated wet conditions (Figure 10). The new figure is attached below.

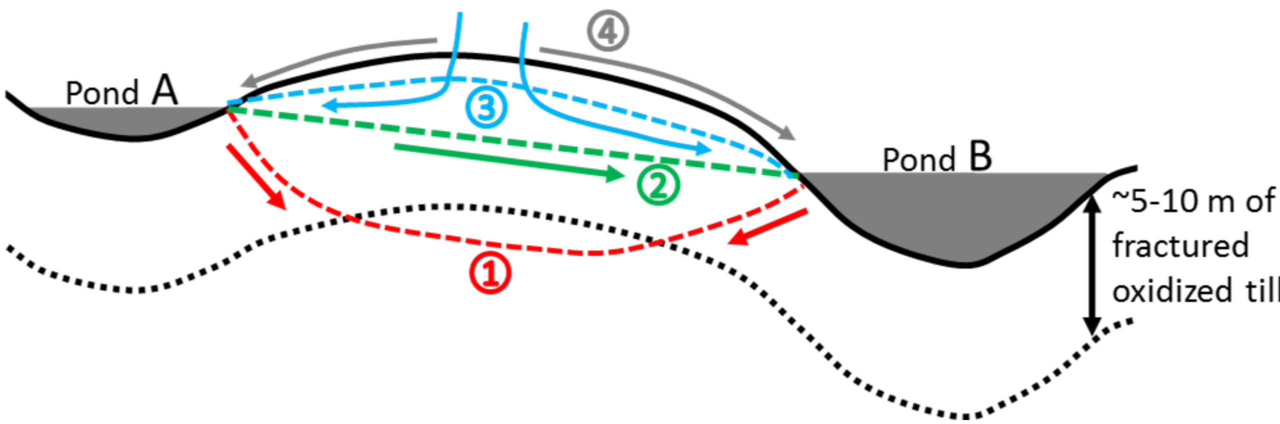


Figure 10: Conceptual water flow paths (arrows) between two adjacent ponds in the prairie pothole region. Red line and arrows (1) indicate ground water levels and flow paths, respectively, for dry conditions. Green line and arrows (2) indicate wet conditions where pond A is feeding pond B via the subsurface effective transmission zone. Blue lines and arrows (3) shows wetter conditions with a mounded water table and flow diverging from a groundwater divide between the ponds. Gray arrows (4) show typical flow paths for snow melt water over frozen soils, away from the topographic divide.

Below we provide a response to each of the reviewer's specific comments.

- Reviewer comment for Page 5, Line 116; reviewer is correct, 'water table depths' was changed to 'hydraulic heads in the piezometers'. **Now in Page 6, Line 135.**

- Reviewer comment for Page 9, Line 236; ‘The year’ was added upon comment. **Now in Page 10, Line 257.**
- Reviewer comment for Page 10, Line 271; ‘whilst’ will remain in the text.
- Reviewer comment for Page 12, Line 319; we rephrased the text based upon the reviewer suggestion to make the sentence more easy to read. The rephrased text is: “It follows that exchanges of water between the pond and soils/groundwater are far more efficient at transporting salts by advection into the pond than out. For example, for pond 109, in order to remove the salts added to the pond for every volume unit of inflow (i.e. exfiltration of groundwater), 3 – 5 times more volume units of outflow (i.e. infiltration of pond water) would be required.” **Now in Page 13, Lines 343-347.**
- Reviewer comment for Page 12, Lines 319-321; the sentence was rephrased to be read more easily as we emphasized that the units we are refereeing to are volume units. The rephrased sentence is: “For example, for pond 109, in order to remove the salts added to the pond for every volume unit of inflow (i.e. exfiltration of groundwater), 3 – 5 times more volume units of outflow (i.e. infiltration of pond water) would be required.” **Now in Page 13, Lines 345-347.**
- Reviewer comment for Page 13, Line 345; reviewer is correct. In the M&M section we even named these pipes mini observation wells. The word ‘piezometers’ was replaced by ‘mini observation wells’ throughout the text.
- Reviewer comment for Page 13, Line 353; ‘reduced’ was replaced by ‘declined’ as suggested by the reviewer. **Now in Page 14, Line 379.**
- Reviewer comment for Page 24, Line 521 (figure caption 5); reviewer is correct and the meanings of WC and NC were added to the caption.
- Reviewer comment for Page 28, Lines 536-538 (Figure caption 9); text improved upon reviewer suggestions.

<u>Reply to reviewer #2.</u>

We highly appreciate this review and the detailed comments and suggestions provided by the reviewer. To address the overriding issue of clarity of the manuscript (which was also raised by the other reviewers) we added another section (section 3.9) before the conclusions which summarizes our hypothesized conceptual model of the system in a clear way, with a new diagram (please see response to reviewer 1). In addition we have considered all of the reviewer's comments and revised the manuscript as described in the responses below.

Specific comments:

Page 13476, Line 14: In the rest of the manuscript, as well in the data analysis, you mention and use a period of 20 yr of observations, though one plot is shown for the period of 40 yr (Fig. 4). For the clarity of the paper, and since you mainly use the data from 1993 onwards, I would suggest that you change the sentence to "… taken over the last 20 yr", and present Fig. 4 using the same time range. That way the temporal changes of the pond depth that you are explaining in the text would be more perceptible as well.

- We understand the reviewer's point, but we prefer to leave Figure 4 as is (with 40 years of data) as it shows the observed changes in the pond depth over a longer period, which highlights how exceptional the recent period has been. However, since all of the other data is from 1993 onward (20 years) we changed the text from the abstract to indicate that the majority of the data is from the last 20 years and not 40 as written. **Now in Page 2, Line 33.**

Page 13476, Line 20: Please indicate what is your explanation why the wet conditions associated with high snowmelt do not pose a threat to salinization. The statement that it is your conceptual understanding of the system is quite vague.

- We rephrased the last paragraph of the abstract to be clearer and to present shortly the differences between rain and snow associated wet conditions. **Now in page 2, Lines 37-40.** In additions, as mentioned previously, we added another section (and figure) toward the end of the paper to summarize and present the conceptual model in a concise and clear manner. **Now in Pages 14-15 and Lines 386-413.**

Page 13478, Line 1: I would like to see few sentences explaining briefly the conceptual representation of salt dynamics from Nachshon et al. (2013). This would give insight into salt dynamics you are trying to capture with experimental data analysed in this work. Finally, I think you should come back to some of the findings in 2013 paper when explaining the results presented in this manuscript (please see comments Page 13476, Line 20 and Page 13490, Line 3).

- We added a short overview of our paper from 2013 in the introduction (**Page 4, Lines 74-80**) and we will relate our experimental findings back to this conceptual model in the conclusions (**Page 15, Line 416-417**).

Page 13478, Line 12: I think the manuscript would be easier to follow if here you would give a brief description of the analysis you will undertake, emphasising that you will be starting with the field scale analysis, followed by looking at a specific transect and finally finishing with small scale (single pond) analysis.

- We added the following text at the beginning of the M&M section: "In this work extreme rain and snow conditions will be examined with respect to their impact on salt transport, salt accumulation and wetland salinization. Salinization processes are studied at field scale by examining changes in pond salinity throughout the entire site; at the pond scale by observing a specific pond with a high temporal resolution; and along a transect connecting two neighboring ponds with high temporal and spatial resolution". **Page 4, Lines 96-100**.

Page 13479, Line 5: A table summarising available data, corresponding locations, period and frequency of acquisition would, I think, contribute greatly to following the results presented (e.g. Precipitation / 35km of St Denis site / 1993-2012 / daily?).

- This is a good idea and we added the following table at the M&M section.

Property	**Location of measurement**	**Measurement period**	**Temporal resolution**
Precipitation (rain+snow)	Saskatoon	1993-2012	continuous hourly

Rain	St. Denis	5-24/7/2012	continuous hourly
Ground water levels	St. Denis	1997-2012	continuous daily / hourly
Pond 109 depth	St. Denis	1968-2012	continuous monthly
Ponds salinity	St. Denis	2009-2012	sporadic monthly
Pond 109 salinity	St. Denis	1993-2012	continuous monthly / weekly
Pond 109 chemical composition	St. Denis	2007-2009, 2012	sporadic monthly
Mini-observation wells	St. Denis	7/2012	continuous weekly / daily
EM-38	St. Denis	24/7/2012	One time

Page 13479, Line 8: Please add location of the climate station to Fig. 1A.

- The station is in Saskatoon (Appear on the map in Figure 1A). We added this information to the text. **Page 5, Line 120**.

Page 13480, Line 4: Please add the information where you obtained the data for the pond depths presented in section 3.1.

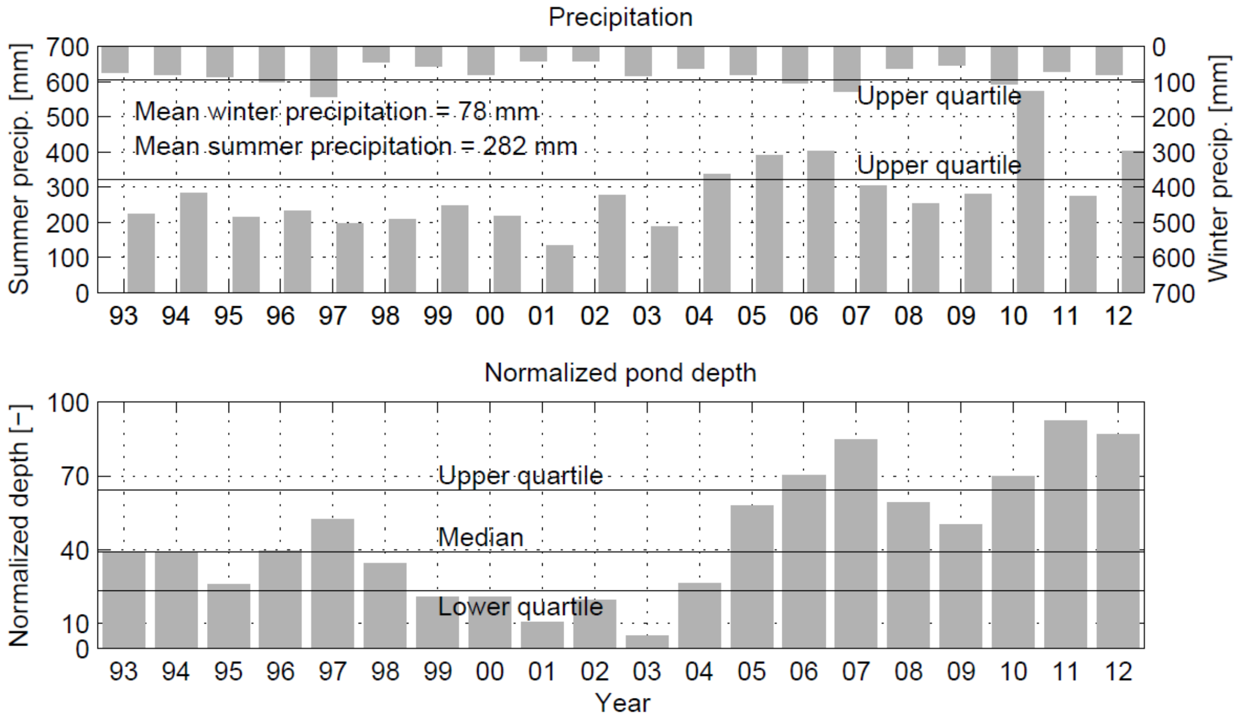
- We rephrased the text to indicate that these measurements were taken by Environment Canada. **Page 5, Line 131**.

Page 13482, Line 22: Why some of the ponds used for water level analysis are different than ones used in section 3.2 for salinity analysis? It would make sense that you use the same ponds for field scale analysis, as you are trying to correlate the water levels with pond salinity.

- The reviewer is correct, but unfortunately, we can only use the data that are available.

Page 13482, Line 26: Please explain why you have chosen the normalized water level of 70% as representative for wet conditions.

- We did not intend this threshold to be over interpreted – we do not have enough data to do rigorous statistical analysis of extremes. Originally, we simply selected the years which appeared to be significantly wetter than the rest of the data using our best judgment. However, we have modified this analysis very subtly to focus instead on the upper quartile of pond levels and precipitation data. This is still an arbitrary selection, but is a bit more transparent. The upper quartiles are indicated as thresholds in a revised Figure 2 (attached below), which is now completely consistent with Table 2 (accounting for the correction pointed out by the reviewer, see response immediately below this one).



Page 13483, Line 2: Table 1 would make even more sense if the data would be sorted from the highest (2011) to lowest (2010) water table level. This could give indication of the dominant processes that influence high water levels in the ponds – it seems that high water levels in previous year and highly saturated soil at the beginning of winter are the dominant factors that cause the increase in the pond depth. Furthermore, in Table 1 if you include year 2006 as High Winter Snowpack, then based on Fig. 2 year 2010 should be included as well.

- We prefer to leave the table sorted chronically. The point is that all four of the factors in the table can contribute to high pond levels, but they have different impacts on salinity, as is brought out later in the paper. We do not discuss groundwater/water tables, in this section of the paper, as it is difficult to have a single, meaningful measure of groundwater for the entire site. We agree on the comment regarding 2010 and this year will be marked as a snowy year as well.

Page 13483, Line 19: I am assuming that the pond classification based on salinity presented in Fig. 3 was determined based on the measurements of EC from 2009 – please clarify.

- Reviewer is correct and this point was clarified by indicating in the text that we refer to the measurements of 2009. **Page 9, Line 227.**

Page 13483, Line 22: All brackish-saline ponds become diluted, except pond 70 during 2010. Please comment on that.

- The reviewer is correct that there is a single datapoint that is not consistent with the overall pattern – in Pond 70 there is an anomalous drop in concentration in 2010. We do not know whether this is real or a measurement error. We had previously written that the pattern was "almost completely consistent" (Page 9, Line 226) and the "almost" was referring to this datapoint. We will add the following sentence (bold): "There is an almost completely consistent pattern in the response, with fresh water ponds becoming salinized over the wet period from 2010 onwards, brackish-saline ponds becoming diluted, and moderately-brackish ponds having relatively stable EC values. **The only significant anomaly to this pattern is in Pond 70 in 2010, which we cannot explain.**" **Page 9, Lines 229-230.**

Page 13483, Line 23: I am not sure what you mean by sentence: "The water flushed into ponds…. ". Please clarify.

- We meant to say that the fact that the moderately-brackish ponds didn't change their salinity under rain associated wet conditions indicates that the salinity of the water entering the ponds is similar to the moderately-brackish ponds salinity. We will improve the sentence to improve clarity. **Page 9, Lines 230-233.**

Page 13484, Line 2: The conclusion about increase in the salt mass would be clearer if the subplot showing Msalt for the selected pond vs. time would be added in Fig.3 (if Msalt can be calculated using Eq. 1 and 2 with data from section 3.1).

- This would be good, but unfortunately Msalt for all of the ponds presented in Figure 3 cannot be calculated as we don't have observations of all of the pond depths and do not know all of the pond depth-volume relationships, both of which are required to estimate Msalt. This relationship has been established for a small number of ponds, notably pond 109, which we focus on in detail.

Page 13484, Line 14: As mentioned before, I would present water depths in pond 109 from 1993, to correspond to all the other data analysis.

- As mentioned above, we prefer to leave this figure for the 40 years record to emphasize the unique conditions observed at 2010 onward.

Page 13485, Line 25: As mentioned before, please explain why you think snowmelt has a negligible effect on the salt cycle.

- As mentioned in our reply earlier, we will rephrase the manuscript, mainly by adding another section at the end to explain the conceptual model and to explain why snowmelt impact on ponds salinization is minimal. **Pages 14-15 and Lines 386-413.**

Page 13487, Line 15: I am assuming that the valid assumption could be that there is more than one inflow/outflow point to the pond, and hence though the piezometers analysed show the inflow at that locating, the overall system could be receiving water causing decrease in salinity.

- This is true and this is the point we wanted to make. Apparently it wasn't clear enough and we improved the sentence. **Pages 12-13, Lines 332-334.**

Page 13490, Line 3: In the Nachshon et al. (2013) the potential impacts of increased snowfall and precipitation are analyzed, concluding that more rainfall could cause the raise of groundwater levels beneath uplands compared to ponds, which could direct the groundwater flow from upland to pond and hence increase the pond salinity. On contrary, the increase in snowfall will increase spring snowmelt, hence increasing surface runoff and diluting the pond water. These conclusions entirely correspond to ones presented in this manuscript, and support the conceptual representation of the process given in Nachshon et al. (2013). Hence, I would suggest the authors to use the 2013 paper to support the conclusions in this manuscript, and also add additional value to their previous work.

- We highly appreciate the reviewer for raising this point and we added at the end of the manuscript regarding the conceptual model and summary of the presented concepts from the paper. **Pages 14-15 and Lines 386-413.**

Technical corrections:

All lines: The text is generally too dense in a sense that separating it into more paragraphs would make it much easier to read.

- We went over the text improved it as much as possible.

All lines: Since you use capital letters in Figure labelling, please use the same notation in the text as well (e.g. Fig. 1A instead of Fig. 1a).

- Done.

Page 13477, Line 14: Please add the full stop at the end of the sentence "…Montana and the Dakotas in USA."

- Done.

Page 13477, Line 21: I would use full stop rather than semicolon (the same applies for Line 25). If, however, the semicolon is used, then please use the small letter in Line 21 for snowmelt.

- Done.

Page 13478, Line 24: You use willow ring term twice, once with and once without (Line 26) quotation marks. Please correct.

- OK. We omitted the quotation marks.

Page 13481, Line 14: Please replace "For this period,…" with "During this period,…"

- Done.

Page 13485, Line 4: When explaining Fig. 5, please put subplot notation before the text, i.e. "Fig. 5 presents (A) estimated pond…."

- Done.

Page 13486, Line 20: Please add comma in the sentence: "…, and epsomite ($MgSO_4$ $7H_2O$), which…."

- Done.

Page 13499: In Fig. 5 please indicate what you mean by NC and WC (NC=normal conditions, WC=wet conditions?).

- Done.

Furthermore, the scale for the y-axis in subplot (B) for EC and Msalt could be decreased at least to 3000, which would make the trends in salinity change more visible.

- This is true for all years excluding 2012, where Msalt reaches 4000. We did previously try the plots with a decreased scale on the y-axis, but we prefer to leave the scale as is to show the high values reached in 2012 and to enable easy comparison on the same scale between all the years.

Page 13503: In Fig. 9 please indicate dates of data sampling.

- The dashed line in Column (A) indicates the day the measurements were taken, and this is pointed out in the figure caption.

Reply to reviewer #3 (Dr. Goldhaber).

We highly appreciate the review of Dr. Goldhaber which was positive and encouraging in respect to the paper goals, concept, and its contribution to the understanding of the North American wetlands salinization processes. On the other hand the reviewer had some major concerns regarding several issues raised in the paper and we will reply to these comments in here.

In concurrence with the two other reviewers, also Dr. Goldhaber found the paper to be not clear in respect to the conceptual model of salt transport processes for extremely wet conditions associated with rainy summers and snowy winters. Consequently, we added another section (section 3.9, **Pages 14-15 and Lines 386-413**) before the conclusions section to summarize and explain conceptually the processes that were observed in this study. The impact of salinity on the ponds ecological conditions is not in the scope of our paper, however, it was discussed by various other studies (e.g., Stewart and Kantrud, 1972; Brunet and Westbrook, 2012 and others).

The reviewer had a criticism on the fact that the transect study was done between ponds 107 and 108A, while the rest of the work focused on pond 109. He suggested that the transect study had to be done between ponds 108A and 109. This suggestion appears to be reasonable, but in fact the 108A-109 transect is very flat and short and most of the time water was flowing from 108A to 109 over the ground surface to the extent that the two ponds were almost connected. Thus observations of the subsurface conditions along the 108A-109 transect would have shown little of the processes by which salts are moved into the surface water. However, the salt content of the surface water flowing along this transect was measured from time to time and corresponded to the salinity of the water in the centre of 108A, in the range of 2000 to 3000 uS/cm as indicated in figure 8. We added arrows in **figure 8** to indicate the direction and location of overland flow during the observation period.

The most intriguing point raised by the reviewer is about the Mg/Ca ratio and the source of the dissolved salts water that are being flushed into the ponds. In the paper we showed that in 2012, after a series of wet summers the cation composition of the pond water was enriched by Mg and Na, while the molar fraction of Ca in the water was reduced. We interpreted this to indicate water flowing processes from distant parts of the uplands that are known to be rich in Mg sulfate salts. The reviewer suggested that the input of enriched Mg water into the pond is due to the Mg enrichment of the pore water (not crystallized salt) at the saline ring. It is well known from literature that due to crystallization of Calcite and Gypsum in the saline ring, close to the pond, the pore water is enriched with Mg, Na and depleted in Ca and SO4, (St. Arnaud, 1979). Consequently the reviewer suggests that flushing of the Mg enriched pore water is the reason to the increase of the Mg/Ca ratio. We believe that this option is interesting and likely valid. However, it is important to mention that in most spring times following the snow melt and soil thawing, some dissolved salts are washed from the saline ring to the pond and still the enrichment of the pond water with Mg was never observed prior to 2012. In the revised manuscript we changed **section 3.5.** that talks about the pond water chemistry to say that the Mg enrichment could be attributed also to the washing of the saline ring water as suggested by the reviewer (**Page 12, Lines 306-308**), as well as dissolution and washing of Mg-Sulfate salts from more distant parts of the uplands. We also mentioned that future studies are needed to better address this point (**Page 12, Lines 315-317**).

Last – the reviewer claimed that the salt distribution in the landscape is second in its importance compare to reaction processes of the Pyrite, Calcite, and Dolomite that can be found in the till. This is true over very long time scales (hundreds and thousands of years) and for regional changes in the water table depths. In shorter time scales that are of interest to the ecological and agricultural purposes, the salt transport, dissolution, and accumulation processes are the main story and in our paper we tried to improve our understanding of these processes. We believe that the revised conclusion section pass this point.