Editor:

All points raised by the references have been adequately addressed in the replies. Please revise the manuscript as proposed before resubmission.

We appreciate the thorough reviews, as well as the opportunity to revise the manuscript based on these reviews. A summary of our revisions are provided below:

1- We have added more details (and equations) on the particle tracking method to section 2.3.3 (e.g., P6L19-39 and Eq.1). We have added more details on how the surface water velocity maps were approximated. We have also added more details on model input and time-step and model calibration and evaluation. Both reviewers requested adding these details.

2- We originally modeled overland flow and connectivity map in 2009 with the minimum net water flux since 2000. So that a representative range in connectivity is presented, overland flow for both the wettest year (2013) and the driest year (2009) since 2000 was presented. The corresponding new results were added to Figures 4, 5, 6 and 8 as well as to the main text. This was suggested by both reviewers.

3- We have calculated the contribution of subsurface-surface flow from each wetland to the North Saskatchewan River, and plotted these flows against the wetland distance to the river (Figure 8). This figure explores if distance is a good proxy for wetland hydrological contribution to the river. We have added corresponding text to the method, results and discussion sections. For example we have added the subsection 3.3.4 to the results. This was suggested by the first reviewer.

4- We have removed Figure 4 in the original manuscript as the first reviewer suggested.

5- We have added the long-term observations of another groundwater well at a measurement station located west of the watershed to further assess the validity of steady-state assumptions. In the revised manuscript, two measurement stations, one located 15 km east of the watershed boundary and the other located 65 west of the watershed boundary, show very small transient variations over a period of almost 40 years, supporting the steady state assumption. In particular, these observations show that the coefficient of variation in the groundwater table was almost zero for both groundwater well measurements, strongly supporting the validity of the steady-state assumption. Note that in the revised manuscript we state that the distance between Vegreville station to the watershed boundary is 15 km (rather than the distance between Vegreville station and the center of the watershed which was 60 km).

First reviewer:

This paper covers a very timely topic and would be a nice addition to HESS. The concept of hydrological connectivity is still in its infancy, but its relevance to the wetland management is obvious, even as hydrologists are still learning how to apply the concept. The authors are to be commended on their efforts to advance the thinking on this subject. The study summarized in this paper applies a series of process based models to quantify surface and subsurface hydrologic connectivity among wetlands and a major river, in order to address several goals. These include assessing the performance of the models, comparing the relative importance of surface and subsurface connections, determining if proximity can be used as a substitute for connectivity, and if their findings could be extrapolated beyond the study watershed. The authors meet all these goals but only to different degrees, and I have provided some suggestions that might elevate the study and manuscript. There are some major comments, and numerous minor ones.

We appreciate the thorough review of the first reviewer as well as his/her feedback on the novelty and necessity of the current paper. This positive feedback encourages us to continue working on this poorly understood subject in the future.

MAJOR COMMENTS

1) Could the authors perhaps present data from the surface overland flow model for a dry year? I understand why they selected 2013, but it would be good to know that the model could represent a condition that is drier, and what those repercussions are for connectivity. One downside of the research as presented is, it does not necessarily present the spectrum of connectivity that could occur in the Beaverhill watershed.

We concur with this great suggestion. In the revised manuscript, we have modeled overland flow and connectivity lines for both 2009, the driest year with the minimum net water flux since 2000, as well as 2013, the wettest year since 2000. The corresponding new results were added to figures 4, 5, 6 and 8 as well as to the main text.

In addition, at the Beaverhill watershed, the connection time to North Saskatchewan River cannot be continuous and show any spectrum of connectivity, as there is a considerable difference between the time-scale of subsurface and surface connections. The surface connection time-scale is on the order of 10^2 days but the subsurface connection is on the order of 10^5 days. In the comments below we answered this question in more detail. In addition, we have added a few sentences to the text to further clarify this on P9L32-37.

2) A more critical assessment of the simulated surface flow hydrograph is needed. The high regression coefficient is likely because of the low flow period, and the spring peak, which is relatively well simulated. The true test of a modeled surface stream hydrograph in the Prairie Pothole Region is how well it represents the summer recession, any summer events, and timing of the cessation of streamflow. The model does not do this particularly well. The manuscript would be improved if the authors explain their theories as to why the model simulated an event that did not happen, and missed one that did. Could it be that the model missed some important re-connection? If so, why? This will help inform how the model is behaving and provide some great insight.

We appreciate this concern. We agree with the reviewer that the surface flow routing model did not perfectly predict the observed surface flow at the measurement station. We have added the following paragraph to the text (P8L25-31) to explain the reason of this inconsistency and its impact on our conclusions.

"We did not expect that the surface flow model would exactly simulate the hydrograph in 1983, as we used evapotranspiration data from 2015 for 1983 (as explained in section 2.3.2). This simplification could have affected the simulated hydrograph shape leading to an earlier second peak (Figure 4a). We think this simplification would have had minimal effect on the simulated connectivity lines, as at the end of simulation period, the cumulative simulated flow (2.4 10^7 m^3) at the measurement station was only 7% less than the cumulative observed flow (2.6 10^7 m^3). Indeed, for the particle tracking scheme used to characterize the surface connectivity map, it did not make a substantial difference if the particle was at its highest velocity (e.g., June 20 vs. June 24 of 1983)."

3) I would argue that the authors misinterpret the content of Figure 9. There is good fit for short distances, but not long. Could the authors please provide more information on how the shortest distances were calculated? Are these Euclidian (i.e., "as the crow flies") estimates? Or are they along the topographic flow path? Did they come from the digital elevation model? If this is the case, this might explain the departure from the linear function in Figure 9. If I interpret the results correctly, this highlights the problem with the variety of connectivity metrics, measures and indices that are currently used in hydrology. To really address their goal of determining if proximity is a substitute for connectivity, it would be great if the authors could output the contribution of flow from each wetland to the North Saskatchewan River, and plot these flows against distance. This would truly show if distance is (or is not) a proxy for connectivity. The authors do not use a metric that demonstrates the magnitude of connectivity, only its presence or absence. They need one for magnitude to answer their question if proximity can be used as a substitute for connectivity.

We appreciate this concern and great suggestion. In the revised manuscript, we have calculated the contribution of subsurface-surface flow from each wetland to the North Saskatchewan River, and plotted these flows against the wetland distance to the river (Figure 8). We have added corresponding text to the Method, Results and Discussion sections. For example we have added the subsection 3.3.4 to the results.

MINOR COMMENTS

Some relevant work the authors should consider working into the manuscript are listed below.

Shook, K., J.W. Pomeroy, C. Spence and L. Boychuk, 2013. Storage dynamics simulations in prairie wetlands hydrology models: evaluation and parameterization, Hydrological Processes 27: 1875 – 1889.

Brannen, R. C. Spence and A. Ireson, 2015. Influence of shallow groundwater-surface water interactions on the hydrological connectivity and water budget of a wetland complex, Hydrological Processes 29: 3862-3877.

Hayashi, M., G. van der Kamp and D. Rosenberry, 2016. Hydrology of prairie wetlands: understanding the integrated surface-water and groundwater processes, Wetlands doi: 10.1007/s13157-016-0797-9

We thank the reviewer for suggesting these references. These are very relevant studies and we have referred to them in the revised manuscript (e.g., P12L3-6).

Page 1 Line 22: Could read: " ... protection, as these are small features typically vulnerable to drainage or manipulation…" As for the rest of the sentence, please provide information on why being numerous equates to a need for protection.

We thank the reviewer for bringing this to our attention. We have made the suggested revision. Note that we have removed the rest of the sentence. P1L22.

Page 1 Line 25: Maybe reference Brannen et al. here too.

We have added the reference. See P1L25-26.

Page 1 Line 26: I know that fill-and-spill has become common vernacular, but perhaps the authors could say ". . .. . . via mechanisms analogous to fill-and-spill runoff generation (Rains et al., 2006)."

We concur with this suggestion. We have made the suggested revision P1L26-27.

Page 1 Line 29: Be very careful when using the term "function" because it has very specific meanings depending on the context. For instance, the hydrological function of a specific wetland using the hydrogeomorphic assessment method, which can be required for development works, follows methodologies necessary for the specific purpose of discerning a loss or gain in wetland function relative to a reference standard. This approach was designed to detect and measure variation in function due to human impacts, not natural variation. In contrast, Black (1997) proposed that landscape units have hydrologic functions such as collecting, storing and discharging. Could I suggest the authors explicitly define what they mean by "function"? Or, use the word to "role".

We appreciate this concern. We have a rich literature to support the use of the word "function" – which refers to the hydrologic functions such as "collecting, storing, and discharging" water. We have both defined it and referred to a key reference that describes what we mean in the revised manuscript. P1L27-29.

Page 2 Line 6: Perhaps instead of committing to a statement that an inability to quantify connectivity would lead to preferential protection to certain types of wetlands, maybe say "... may lead to incorrect or inappropriate management decisions regarding wetland removal, protection or reclamation."

We concur with this suggestion. We have made the suggested revision. P2L6-7.

Page 3 Line 11: remove italics here and throughout this section.

We concur with this suggestion. We have made the suggested revision. e.g., P3L13.

Page 3 Line 12: Maybe provide a URL for the climate data.

We concur with this suggestion. We have added the following link to the text (http://climate.weather.gc.ca/) P3L15.

Page 3 Line 15: Maybe rephrase to: . . ..although snowmelt can be an important to runoff in the spring."

We concur with this suggestion. We have made the suggested revision. P3L17-18

Page 3 Line 34: Do the authors mean the probability of depression existence or presence?

We do indeed mean “probability of depression”. For more details on the technique for mapping wetlands, see reference citations below:

Lindsay JB, Creed IF, Beall FD. 2004. Drainage basin morphometrics for depressional landscapes. Water Resources Research 40: W09307.

Lindsay JB, Creed IF. 2005. Removal of artefact depressions from digital elevation models: towards a minimum impact approach. Hydrological Processes 19: 3113-3126.

Lindsay JB, Creed IF. 2006. Distinguishing actual and artefact depressions in digital elevation data: Approaches and Issues. Computational Geosciences 32: 1192-1204.

Page 3 Line 37: What are “integrated wetland features”?

The wetland mapping technique sometimes detects wetland fragments that then need to be integrated into a wetland object. We have revised the text to improve clarity. P4L1-2.

Page 4 Line 1: In recent years in the Prairie Pothole Region what would normally be considered GIWs had ponds that have been above their surface outlet elevations. Perhaps a sentence or two would be a good idea on how often a GIW needs to be not spilling in order to be considered a GIW.

We thank the reviewer for this comment. We think the frequency of filling and spilling does not influence the definition of a GIW, which is defined as a wetland surrounded by uplands, without channels but with defined bed and bank. We refer the reviewer to (Mushet et al., 2015) for more details on the definition of the GIWs. We hope this answer would be helpful.

Page 5 Line 33: Please explain why there is such a short calibration period. The gauge was open until 1986.

We did not have access to evapotranspiration data before 2000. April to August 1983 was selected as we were able to link its evapotranspiration to the one calculated during the same period in 2015 (as the monthly average humidity, maximum air temperature and minimum air temperature were similar between April 1 to August 1 1983 and April 1 to August 1 2015). Please refer to the response to major comment 2 above for more details. In addition, mesh-based physically-based hydrological models are computationally expensive compared to conceptual hydrological models (e.g., SWAT or HBV). A longer simulation period would have required more computational resources without adding more information to our paper.

Page 6 Line 7: Just my preference, but more detail in the paper on the methods would be helpful for the reader, particularly the water particle tracking approach and how surface water velocities were approximated.

We thank the reviewer for bringing this to our attention. We have added more details (and equations) on the particle tracking method to section 2.3.3 (e.g., P6L19-39 and Eq.1). In addition we have added more details (P6L19-25) on how surface water velocity maps were approximated as:

"Once the surface flow routing model was developed, the discretized surface water velocities in x and y directions at each grid point and each time step were extracted. Continuous maps of surface water velocity in x and y directions throughout the watershed were then approximated by interpolating the discretized surface water velocities. A Fourier-based interpolation scheme with 10,000 Fourier series terms was used to complete the interpolation process and generate the continuous maps of surface velocity in x ($V_S^x(x, y, t)$) and y ($V_S^y(x, y, t)$) directions for the entire watershed; the overall correlation coefficient between estimated velocities using the interpolation method and original modeled velocities at each grid point and time step was r^2=89% ($p < 0.001$)."

Page 6 Line 22: Could I suggest the Hayashi paper I note above be worked into the context here? Hayashi and his co-authors present a new conceptual model of subsurface flow in the Prairie Pothole Region that is a major departure from the model of Toth that is the basis for the assumption that geographic proximity is an indicator of connectivity.

The Hayashi paper and Brannen paper (suggested before) are relevant references for our paper. We have incorporated them in the Introduction (e.g., P1L25-26) and Discussion (e.g., P12L5-9) in the revised manuscript, but not here, as the purpose of this sentence is to explain how we compared surface and subsurface connectivity.

Page 6 Line 29: Maybe rephrase to: "... will be linear but not following y=x."

We have removed this sentence based on the reviewer's suggestion to implement a different approach to assess the effect of distance.

Page 6 Line 31: Please rearrange this sentence.

We have removed this sentence based on the reviewer's suggestion to implement a different approach to assess the effect of distance.

Results: The description of the results reads a bit terse. Sometimes the content seems little more than a figure caption. Could I suggest the authors provide more description on the results, particularly where the model does not work well.

We thank the reviewer for this very useful comment. We have added a few sentences to explain the results in more detail; P8L25-31 and P9L17-27, P9L32-37 and sub-section 3.3.4

Figure 9: It is unclear where the North Dakota data are from. Could the authors provide this detail in the Method section.

We have added the reference as (P7L23-24):

“We obtained wetland polygons in North Dakota from the National Wetlands Inventory (https://www.fws.gov/wetlands/ and stream polylines from the National Hydrography Dataset: http://nhd.usgs.gov/*).”*

Page 9 Line 15: Maybe discuss within the context of the results of Shook et al.

Good suggestion. We have included the conclusion of Shook et al here. P10L33.

Page 9 Line 36: Figure 6 does not illustrate what is discussed here.

We thank the reviewer for this concern. We think the comparison of Figures 5a and 5b (Figure 6 in the original manuscript) shows that the number of subsurface connectivity lines is significantly larger than the number of surface connectivity line (red lines).

Figure 10: The authors need a more explicit explanation of how they decided which services were associated with each portion of this curve.

We agree with the reviewer that the association of cumulative probability of travel time with functions requires explanation. The association of functions with portions of the curve reflects the collective expert judgment of an international team of researchers as recently published in the Proceedings of the National Academy of Sciences of the United States of America (Cohen et al., 2016). We have revised the text and provided relevant citations. P11L25-37.

Conclusions: Just a comment, but even though most of the hydrology community knows that wetlands are not hydrologically isolated, I completely agree that it is good to make this point.

Thank you for noting this.

Table 1: Is the p value for magnesium correct? It seems small, especially in light of the content of Table 2.

We confirm that the p-value is correct. Note that the p-value of the Wilcoxon rank sum test explores if the data in x and y are samples from continuous distributions with equal medians, against the alternative that they are not.

Figure 2: The last word in the caption “time”, could be “period”.

Good suggestion. We have made the suggested revision.

Figure 3: Great figure.

Thank you for your encouraging comment. This figure clearly shows that the new grid-free groundwater-surface water interaction method that is presented in this paper can effectively and efficiently address naturally complex systems.

Figure 4: It is hard to see the wetlands in this. If this figure was created by clipping Figure 3 by a wetland layer, my suggestion is that you delete Figure 4 because it does not add too much information

We concur with the reviewer. We have removed this Figure as it does not add too much information.

Figure 10: Why is there a gap? (Now figure 6c)

The connection time to North Saskatchewan River cannot be continuous as there is a considerable difference between the time-scale of subsurface and surface connections. The surface connection time-scale is on the order of 10^2 days but the subsurface connection is on the order of 10^5 days. This gap has also been appeared in Figure 6a (left panel). The continuous continuum of travel time typically stems from systems with a wide range of flow processes including fast overland flow, slow groundwater flow and fast subsurface stormflow. The latter is typically caused by high frequency of macropores often seen in humid forested landscapes (as shown in Ameli et al., 2015); we do not think such fast subsurface flow can occur in Prairie Pothole Region. So this gap can be attributed to lack of fast subsurface storm flow in our catchment. We have added a few sentences to further clarify this. P9L32-37.

Second Reviewer:

Authors characterized surface water and subsurface connectivity of wetlands using a physically based surface-subsurface model. Groundwater level measurements, water chemistry and stable water isotopes are used to illustrate the model performance at recharge and discharge locations. While this is an interesting study, the study can benefit by providing more quantitative measures of model performance compared to observations, justification of the modelling approach compared to the existing coupled surface water-subsurface models and sensitivity analysis.

1) Authors should provide a more quantitative measure of model performance. For example in Figure 3, authors qualitatively compare simulated recharge/discharge areas with interpolated groundwater observations. Similarly, water quality data are used to indicate differences between recharge and discharge zones using the Wilcoxon rank sum test. In Figure 5, the model predicts the second peak much earlier than the observations. The paper can greatly benefit by providing further details about the model's performance as well as discussions about discrepancy observed between simulated and observed outputs.

We thank the reviewer for these concerns.

First, for Figure 3: We had quantitatively assessed the efficiency of the subsurface model and reported the R^2 value in the text. We added the following sentence to the Figure 3 caption to clarify this in the revised manuscript:

"The correlation coefficient between simulated groundwater fluxes at the land surface and the distance of potentiometric surface above and below land surface is 75% ($p < 0.001$)"

Second, for Figure 4 (Figure 5 in the original manuscript): We agree that Figure 4 needs further explanation about the earlier prediction of the second peak. In the revised manuscript we have provided the following explanation (P8L25-31):

“We did not expect that the surface flow model would exactly simulate the hydrograph in 1983, as we used evapotranspiration data from 2015 for 1983 (as explained in section 2.3.2). This simplification could have affected the simulated hydrograph shape leading to an earlier second peak (Figure 4a). We think this simplification would have had minimal effect on the simulated connectivity lines, as at the end of simulation period, the cumulative simulated flow (2.4 10^7 m^3) at the measurement station was only 7% less than the cumulative observed flow (2.6 10^7 m^3). Indeed, for the particle tracking scheme used to characterize the surface connectivity map, it did not make a substantial difference if the particle was at its highest velocity (e.g., June 20 vs. June 24 of 1983).”

2) Authors have used a grid-free subsurface flow model to simulate groundwater flow and then used the 2D transient surface water flow of HydroGeosphere. It is not clear why authors did not use HydroGeosphere in the first place as it provides an integrated system to simulate surface water-groundwater interactions. I understand that the grid-free approach is computationally more efficient but authors should justify their approach. Indeed it would be really interesting to see how HydroGeosphere simulations compare with the modelling approach that authors developed. How much loss in accuracy is obtained by assuming steady state groundwater condition in the grid free approach compared to transient simulations?

We appreciate this suggestion.

First, it should be noted that developing map of connectivity of wetlands in this 4,000 ha watershed with more than 100,000 wetlands is challenging using integrated physically-based subsurface-surface models. Indeed, these models have not been designed with connectivity in mind. We refer the reviewer to a comprehensive review paper by (Golden et al., 2014)) that clearly explained the difficulties of the integrated physically-based subsurface-surface flow models in simulating the watershed-scale hydrologic connectivity of wetlands. We know that these models, including HydroGeoSphere, can accurately represent flow and transport at local to regional scales, but these models cannot explicitly characterize connectivity. In a recent application of HydroGeoSphere for 3D direct characterization of connectivity in a much smaller wetland-dominated watershed than ours (i.e., Liu et al 2016), the authors characterize 2D connectivity in a single cross-section. The caption of the connectivity-related Figure is as follows: “*Cross-sectional profiles (extracted at X = 350 m) showing the distribution of hydrologic heads (*left*) and saturation (*right*) for the case represented in Fig. 6. The flow lines were generated based on the heads shown in the cross sections and may not be exactly as the flow lines in the 3D domain*.” Note that in our paper we have generated more than 100,000 3D connectivity lines but only showed a small proportion of them, those that were consistent with our objective of showing wetland connectivity to the river, because of visualization constraints. In addition, 3D characterization of subsurface connectivity among 100,000 wetlands and North Saskatchewan River was necessary in our work to answer the questions raised in our paper.

Second, our paper was not intended to compare the efficiency of different models in simulating the hydrologic connections. Instead we wanted to quantify the hydrologic connection of geographically isolated wetlands for the first time and also compare the surface and subsurface hydrologic connections. We used empirical evidence from groundwater table variations for 30 years to justify why a steady-state model was valid for the groundwater-surface water interaction flow simulation in our study. We confirmed our groundwater-surface water interaction model was able to appropriately repeat the observed groundwater discharge-recharge zones (Figure 3) with a R^2 of 75%. So the model we used is an appropriate tool to explore the question we intended to answer in this paper. In the following comments we further justify why the restrictions of the semi-coupled method does not effect the conclusions we made in this paper.

In the revised manuscript, we have explained the assumptions used by our model as suggested by the reviewer; e.g., P11L2-4.

For example, we further clarified that steady-state assumption is a valid assumption in our watershed by adding more long-term observations of groundwater depth collected at measurement stations in the vicinity of the watershed. In general, if an integrated transient model exists that could solve our problem, empirical observations in the watershed suggest that it would not add much more information compared to our model. The steady-state assumption is an appropriate assumption due to the low hydraulic conductivity in the PPR (consistent with our calibrated values). We have added the following sentences to the methods section (P4L23-29) for more clarification:

"The assumption of steady-state subsurface flow is strongly supported by empirical groundwater table observations collected from the closest piezometer at the Vegreville Environment Center station (located 15 km east of the Beaverhill watershed boundary), where the water table varied with a coefficient of variation of < 0.9% in 2009 (a year when observations were used to develop the steady-state groundwater-surface water interaction model), and a coefficient of variation of 4% over 32 years (August 1985-July 2016) (Figure 2a). In another piezometer at the Barrhead Environment Center station located 65 km west of the Beaverhill watershed boundary, water table varied even less with a coefficient of variation of ~0% during 2009, and a coefficient of variation of 0.01% over 40 years (1977-2016) (Figure 2b)."

3) How does the "semi-coupling" approach of surface-subsurface processes in the model impact capturing wetland connectivity and travel time distributions? Moreover, would it be more suitable to use the term one-way coupling instead of semi-coupling as the feedback from the subsurface is not included in this approach?

We thank the reviewer for this thoughtful comment and suggestion. We agree with the reviewer that the approach we considered can be referred to as one-way coupled. We acknowledge this in the revised manuscript, including in the Methods, Results and Discussion sections (e.g., see P4L12-13, P11L2-4, P12L33).

We also agree that the one-way coupled approach (with no feedback from subsurface flow exfiltration on surface flow routing) can impact the map of surface connectivity and travel time in close vicinity of North Saskatchewan River (almost 500 m buffer) wherein subsurface water can exfiltrate and enhance surface connectivity. We acknowledge this in the Methods and Results sections and justify why it has minimum impact on our results. We have added the following sentences to the result section (P9L19-27):

"The modeling approach we used was a one-way coupling of subsurface and surface flow processes that could not consider thoroughly the subsurface flow exfiltration feedbacks on surface flow routing. This simplification had negligible effects on wetland connectivity within the moraine, as the moraine mostly consists of recharge zones with minimum subsurface exfiltration (Figure 3). This simplification could have affected the map of surface connectivity of wetlands located in close vicinity of the North Saskatchewan

River (within a 1000 m buffer) wherein subsurface water can exfiltrate and enhance surface connectivity. However, the rate of subsurface exfiltration in these riparian areas was on average 1 x 10^{-4} m/d (Figure 3a), which is considerably smaller than the average of net atmospheric inputs (precipitation-evapotranspiration) from April 1 to August 1 2013 that was equal to 7 x 10^{-3} m/d and from April 1 to August 1 2009 that was equal to 4 x 10^{-3} m/d. Therefore, the one-way coupling simplification had minimum effects on surface flow routing along the riparian wetlands located in the riparian areas."

4) It will be interesting to investigate how changes in climatic condition impact wetland connectivity and travel time distributions.

We appreciate this comment. In the revised manuscript, we modeled overland flow and surface connectivity lines in both 2009 (driest year since 2000) and 2013 (wettest year since 2000). The new results were added to Figures 4, 5, 6 and 8 as well as to the main text. Climate conditions clearly have significant effects on timing and length of connections.

5) It will be useful if authors provide further details about the model input and time step.

We thank the reviewer for this suggestion. We have now clearly reported the time steps and model inputs in section 2.3.2. As an example we have added the following:

"The 2D surface of the watershed was discretized into 22,383 grid points (43,836 triangular elements). The parameters regarding time-discretization were: maximum time step = 8640 sec; initial time step = 1800 sec; maximum time step multiplier = 1.5; and minimum time step multiplier = 0.5. A critical depth boundary condition was assigned to the grid points representing the location of the Beaverhill Creek monitoring station (Figure 1) where stream flow observations were available. A no-flow boundary condition was assigned to the watershed boundaries."

6) Authors need to provide further details about the calibration approach and identify the performance of the model for calibration and evaluation periods.

We thank the reviewer for bringing this to our attention. We have now clearly processes for calibration processes and assessing model performance. Please see P5L28-30, Section 3.1; and Section 3.2.

Short Comments by HydroGeoSphere Developer Group:

HGS-D General Comments:

It would be more appropriate and robust to use HGS as a fully coupled model than to represent groundwater with a steady state analytical solution. There is a large and growing body of literature demonstrating the application of fully integrated numerical models at the basin scale. The authors linking of a transient surface flow model to a steady-state groundwater model makes little sense. Moreover, how is the linking actually performed? Is a fluid balance maintained? Is there any justification for using a simple 2-layer model for the subsurface, especially when there doesn't seem to be any hydrostratigraphic data? In fact, the scarcity of data is a major problem to have any faith in the model.

A recent publication by Liu et al. (2106) demonstrates the application of a transient fully-integrated surface and subsurface flow model (HGS) to investigate wetland connectivity including key components of the transient water balance (precipitation, evapotranspiration, and snowmelt). This simulation domain is very similar in scale to that mentioned by the authors in their response to Reviewer 2's comments where they state that HGS was unable to solve this type of problem. HGS is regularly applied to very complicated surface and subsurface problems at a variety of scales. Considering that the authors only used 22,383 nodes in their 2D mesh for this study, it is likely that with training and support it would have been possible to apply a much higher resolution fully integrated HGS model to this domain as models on the order of 1 million nodes are now routine (e.g., Hwang et al., 2015).

Our response:

We thank the HydroGeoSphere Developer Group (hereafter, HGS-DG) for their comments that were received after the online discussion period closed.

The HGS-DG suggest that we could have used HydroGeoSphere instead of the model we have developed and applied. They suggest Liu et al. (2106) as evidence that HydroGeoSphere can be used to investigate 3D connectivity in wetland dominated landscapes. The Liu et al. (2016) paper explores 3D connectivity. However, the authors' present only 13 2D connectivity lines in one 2D cross section (see Figure 8 in Liu et al. 2016); the authors go on to explain that these 2D connectivity lines may not emulate realistic 3D connectivity lines (e.g., In the caption of Figure 8: "*The [2D] flow lines were generated based on the heads shown in the cross sections and may not be exactly as the flow lines in the 3D domain.*"), which is understandable as topography in wetland-dominated landscapes is complex and most connectivity lines have strong 3D behaviour as we have shown in our paper. Furthermore, the size of our watershed is 5 times larger than the size of the watershed used in Liu et al., (2016). We are certain that HGS-DG knows that watershed size influences the computational challenge of characterizing connectivity lines; increased watershed size increases the length of connectivity lines and thus increases the computational time required to calculate each connectivity line.

We, together with many others (e.g., see review by Golden et al. (2014)), believe that the previous lack of a robust model with the ability to efficiently and effectively characterize all of the 3D connectivity lines in wetland-dominated watersheds has led to poor understanding of the 3D connectivity among wetlands (particularly geographically isolated wetlands) to downstream waters. The HydroGeoSphere model as presented in the Liu et al. (2016) paper provides no evidence that it **efficiently** and **effectively** characterizes all of the 3D connectivity lines in large, wetland-dominated watersheds. We maintain that our model can efficiently and effectively generate 3D connectivity lines (e.g., more than 100,000 3D connectivity lines were modelled in our paper) in a large 4,000 ha watershed by respecting the geometric properties of small-scale features.

The HGS-DG criticize our use of a two-layer modelling system. We are surprised by this criticism, given that Liu et al. (2106) use a much simpler one-layer homogenous system in a complex wetland-dominated landscape ("*The aquifer was assumed to be homogenous*" page 290 of Liu et al. (2106)). Our two-layer model repeated the observed groundwater discharge and recharge areas in an exceptional manner, as the first reviewer acknowledged. Furthermore, the stratigraphy and hydraulic conductivities we used are clearly explained and justified in the Methods and Results sections of our paper, and the calibrated parameters were shown to be correlated well with observed data.

The steady-state assumption used for groundwater-surface water interaction model is a reasonable assumption in the watershed we studied. In the revised version we have further clarified the validity of this assumption in our sites by using more observations. The almost 40-year observed groundwater table showed small variability, with a coefficient of variation of less than 4% in the wells located 15 km east of the watershed and less than 0.002% in the wells located 65 km west of the watershed. Given the relative similarities in climate, geology, topography and soils within the prairie pothole region (see our original manuscript section 3.4), we believe that these observations collected at close vicinity (from east to west) of our watershed can reasonably be extended to our watershed. The low hydraulic conductivity of our prairie pothole landscape implies that there is a low possibility of fast transient flow typically seen in forested landscapes due the existence of the macropore flow. (We acknowledge that the HydroGeoSphere model would be the best option to simulate such complex fast flow in forested landscapes as was used in (Ameli et al., 2015)). Therefore, steady-state flow for watershed-scale groundwater-surface water interaction is a robust assumption for the prairie pothole landscape that was the focus of our paper. In addition, due to observed low hydraulic conductivity in Canadian PPR, groundwater flow has been typically ignored in watershed-scale modeling and only overland flow has been simulated via the mechanism of fill and spill. We are not aware of any physically based model used to characterize the 3D watershed-scale groundwater connectivity lines and fluxes in the Canadian PPR. Our model presents a significant step forward to characterize 3D watershed-scale groundwater connectivity lines and fluxes in the Canadian PPR. More importantly, it characterizes for the first time the connectivity of geographically isolated wetlands, and the connectivity-related conclusions made in our work can be extended to other parts of PPR (as was shown in the paper) making an important contribution to the implementation of policies to protect surface waters, such as the US Clean Water Rule. Given the validity of the steady-state assumption on our prairie pothole landscape, one questions if the pursuit of a transient model is worthwhile (assuming that a transient model could ever solve the connectivity-related questions raised in our work), given the considerable computational cost that would be involved particularly for model calibration.

The Beaverhill watershed used in our study is one of the most (if not the most) studied watersheds in the Canadian PPR. Therefore, this watershed was one of the best landscapes to explore our important questions on the connectivity of geographically isolated wetlands. We had (1) hydrometric observations in 1,413 artesian groundwater wells installed in the bedrock and screened 30 to 80 m below the land surface, (2) chemistry and isotopic measurements in 208 lakes, wetlands and ponds, (3) groundwater chemistry measurements in 121 shallow (< 10 m deep) groundwater wells and (4) almost 40 years groundwater table observations at two monitoring wells located in the close vicinity of the watershed. We are certain that we have used available data carefully to reasonably calibrate our groundwater-surface water interaction model. Our certainty is validated by comments made by the first reviewer (see their comment on Figure 3 of our paper) as well as leading hydrologists in the prairie pothole region in both Canada (e.g., personal communications with Dr. Jeffrey McDonnell and Dr. Less Henry, University of Saskatchewan) and the US (e.g., personal communications with Dr. Heather Golden, US-EPA).

HGS-DG Specific Comments:

P1 L14-17 – See Liu et al., (2016) for a similar study using a fully integrated surface water and groundwater model P2 L21-24 – Golden et al., (2014) primarily focused on finite-difference models such as MODFLOW which are unable to achieve local mesh refinement without incurring a high node count. Unstructured finite element methods with 3D triangular prism or tetrahedral meshes are able to achieve local mesh refinement to resolve local features with many fewer nodes than would be required for an equivalent finite difference mesh. P2 L27 – See Liu et al., (2016) P4 L18-19 – It is unclear how such a relation is established P4L20 – Can a steady-state water table, in fact steady-state subsurface flow, be supported? Are winter processes such as soil freeze/thaw and snowmelt important in this basin? There is no discussion of this, and would appear to be neglected entirely. P4L22 – One observation location situated 60 km outside of the simulated watershed does not support the use of a steady-state groundwater assumption. P4L25 – While it may be true that there is a connection between groundwater and wetland water levels, using observations from 500 km outside the watershed is extremely weak support for this assumption. Are these systems similar enough to justify this assumption? P4 L28 – 2 layers is not enough capture the details of the hydrostratigraphy P5 L22 – The HGS reference suggests that a rather old version of HGS was used. Many feature and numerical performance enhancements, including parallelization, have been made to the code since 2008. The author should contact the developers to upgrade to a current version of the code (Aquanty, 2016). P5 L25 – The coarse mesh discretization (22,383 nodes) is highly inappropriate for the stated objective of representing 130,157 wetlands. P5 L34 – How is the connection between the HGS model and the 3D analytical model achieved? This is crucial. How can transient surface flow and steady-state saturated zone models be linked. This seems incompatible. No details are provided. Is the linking mass conservative? How is the unsaturated zone dealt with for infiltration (or exfiltration)? It seems to be neglected. Section 2 – Parameterization of the groundwater model needs to be described in more detail. P7 L3 – Do the calibrated saturated hydraulic conductivity values make sense compared to the type of geologic material or available data? P7 L29 - What units is the Manning coefficient being reported in? P7 L30 – Rill storage seems very small when considering the element sizes in the model. Is a value of 1 mm physically realistic? P9 L18 - How is it possible to mix a steady-state model with a transient model? This is incompatible and it is unlikely that mass balance will be preserved. P11 L8 – The authors should provide a definition of "semi-coupled". Table 4 – Units Figure 3 – What is the rationale for blank portions in Figure 3a) Figure 5 – What is the purpose of showing the simulated hydrograph if not to compare it to observed data. Overall, the paper is technically weak and rejection is recommended.

Our response:

In their specific comments, HGS-DG asks questions to which answers to a majority of them are providing in the original manuscript and in the preceding section. Our model is based on a rich dataset that justifies our characterization of the stratigraphy, hydraulic conductivity and ultimately the steady-state assumption, and it provides an advantage over more complex models, such as HydroGeoSphere, for efficiently and effectively characterizing all required 3D subsurface connectivity lines.

In response to some of the more specific comments:

We have used “one way coupled” instead of “semi-coupled” in the revised manuscript, and justified the use of one way coupled method in our work using the original reviewers very useful suggestions. We have shown that this treatment has a minimum impact on the water balance and our simulation of 3D connectivity of geographically isolated wetlands as the majority of the watershed is a recharge zone with minimum exfiltration potential. Connection between wetland and groundwater is a reasonable hypothesis as HGS-DG state. Such connections have been observed in a wide range of studies in the Canadian PPR (van der Kamp and Hayashi, 2009) and we also confirmed this with available observations. The “rill coefficient” and “mesh discretization” are highly interrelated. Therefore, if we had used a different mesh discretization, we would have obtained a different rill coefficient as an outcome of the calibration processes (we have clearly explained this in the section 2.3.2). Nonetheless, our calibrated overland flow model corresponds with observed data with a high accuracy. We also think the calibrated value of rill is reasonable; a uniform rill coefficient was considered for the whole 4,000 ha domain, thus we expected to obtain such small rill coefficient. Above all the developed overland flow model accurately repeated the available observations.

We found HGS-DG’s editorial comments on Table 4 and the units of the Manning coefficient useful and considered them in our revised manuscript (P8L20). Blank portions in Figure 3a are also explained in the caption of Figure 3. Groundwater model parameterization is also explained in Appendix A. Based on the original reviewers’ suggestions we have further explained it in the revised manuscript (Section 2.3.1; Section 3.1; Appendix A).

There is no doubt that HydroGeoSphere is the most powerful available physically based hydrological model with the ability to solve very complex problems (as shown in Ameli et al. (2015)). However, we are certain that our analytical groundwater-surface water interaction model is an important advance to meeting the challenge of characterization of 3D connectivity lines of geographically isolated wetlands that we addressed in our study. The semi-analytical model used in our work was developed with the connectivity challenge in mind and the model’s assumptions were reasonably justified by available observations. This model has also recently been used successfully by different research groups to answer questions on biogeochemical connectivity (e.g., Ameli et al., 2017; Ameli et al., 2016).

Finally, in neither the original or revised manuscript do we discuss whether other models (such as HydroGeoSphere) solve the wetland-connectivity problem raised in our paper. We developed both surface and subsurface models using available observations with an exceptional accuracy, and answered some important questions on the connectivity of geographically isolated wetlands using carefully developed models. A model comparison was beyond the scope of our work. However, recent papers (Golden et al., 2014;Golden et al., 2017) define a series of requirements that physically-based models must have to be able to directly characterize the watershed-scale connectivity of wetlands in wetland-dominated landscapes. For example, Golden et al. (2014) analysed a wide range of finite element methods in their assessment of connectivity (Sec 2.3 pages 199-201). To see these requirements and an assessment of existing models that meet these requirements, we refer the readers to these papers.

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Quantifying hydrologic connectivity of wetlands to surface water systems

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Abstract. Hydrologic connectivity of wetlands is poorly characterized and understood. Our inability to quantify this connectivity compromises our understanding of the potential impacts of wetland loss on watershed structure, function and water supplies. We develop a computationally efficient physically-based subsurface-surface hydrological model to characterize both the subsurface and surface hydrologic connectivity of "geographically isolated" wetlands and explore the time and length variations in these connections to a river within the Prairie Pothole Region of North America. Despite a high density of geographically isolated wetlands (i.e., wetlands without surface inlets or outlets), modeled connections show that these wetlands are not hydrologically isolated. Subsurface connectivity differs significantly from surface connectivity in terms of timing and length of connections. Slow subsurface connections between wetlands and the downstream river originate from wetlands throughout the watershed, whereas fast surface connections were limited to large events and originate from wetlands located near the river. This modeling approach provides first ever insight on the nature of geographically isolated wetland subsurface and surface hydrological connections to rivers, and provides valuable information to support watershed-scale decision making for water resource management.

Keywords: wetland, geographically isolated wetlands, hydrologic connectivity, surface water, groundwater, Prairie Pothole Region

1 Introduction

Enhanced protection of wetlands is urgently needed (Dixon et al., 2016). Geographically isolated wetlands (GIWs) (Tiner, 2003) are in particular need of protection, as these are small features are vulnerable to filling or drainage (Cohen et al., 2016). Geographical isolation does not imply hydrologic, biogeochemical or biological isolation (Mushet et al., 2015; Leibowitz, 2015; Marton et al., 2015; Rains et al., 2015). Rather, GIW hydrologic connections vary in time and space, and these connections can occur through persistent but slow velocity groundwater pathways (McLaughlin and Cohen, 2013; Brannen et al., 2015; Hayashi et al., 2016) or transient but fast surface water pathways via mechanisms analogous to fill-and-spill runoff generation (Rains et al., 2006;Shaw et al., 2012;Leibowitz and Vining, 2003). Wetland ecosystem functions (e.g., collecting, storing, filtering or discharging water, sediments and solutes) arise from the cumulative effects of these diverse hydrologic connections (Cohen et al., 2016). For example, a lack of persistent surface connection from wetlands to rivers leads to the restriction of material and organism exchanges in landscapes; this restriction provides a wide range of GIW functions for surface water resources (US-EPA, 2015), including enhanced flood regulation and surface water quality (Golden et al., 2014; Leibowitz, 2003). Subsurface connections of wetlands, on the other hand, also affect surface water resources (Cook and Hauer, 2007; Euliss et al., 2004). For example, groundwater connections between GIWs and rivers can regulate the groundwater table, stabilize base flows and change base flow chemistry (McLaughlin et al., 2014). Characterization of both surface and subsurface connections are crucial for the provision of important aquatic ecosystem services (Winter and LaBaugh, 2003).

The quantification of wetland connectivity (i.e., subsurface and surface connections among wetlands and between wetlands and rivers) remains a significant scientific challenge (US-EPA, 2015; Cohen et al., 2016; Golden et al., 2017). Our inability to quantify wetland connections compromises our understanding of (1) the role of the continuum in the timing and length of wetland connections on landscape functions; (2) the effects of environmental stressors (e.g., climate and land use or land cover change) on this continuum of wetland connections; and (3) the effects of human alterations of wetland connections on downstream waters. More importantly, our inability to quantify wetland connectivity may lead to inappropriate management decisions regarding wetland protection *vs.* removal (Van Meter and Basu, 2015). Indeed, decisions to protect or drain GIWs are often made based on their proximity to a major drainage network (Cohen et al., 2016). The quantification of wetland connectivity is required to enable prioritization of wetland protection and restoration, where the optimum location of drainage or restoration of wetlands and the hydrologic, biogeochemical and biological functions of each individual drained or restored wetland can be evaluated (Golden et al., 2017).

Effective quantification of wetland connectivity requires a modeling tool that can explicitly take into account various types (surface and subsurface) and lengths of wetland connectivity under different climate and land use or land cover scenarios. Process-based modeling tools (e.g., SWAT) are useful for assessing *aggregated* impacts of wetland connectivity on watershed-scale targets (e.g., watershed-scale phosphorus load or peak flow reduction) (Shrestha et al., 2012). However, these modeling tools cannot explicitly consider individual wetlands and characterize their links to other wetlands and rivers, particularly in wetland dominated systems (Golden et al., 2014); these considerations are necessary if one intends to prioritize protection and restoration of individual wetlands (Golden et al., 2017). In contrast, numerical physically-based groundwater-surface water flow and transport modeling tools have the ability to sufficiently incorporate subsurface and surface wetland connections (Golden et al., 2014). These models, however, are typically grid-based (i.e., discrete) and require high level modeling expertise and high computational power, particularly for the simulation of watershed-scale subsurface connections. This is particularly true when these models are confronted with a range of wetland sizes; although a small sub-watershed system can be discretized so that a single wetland falls within a single grid cell, incorporation of wetlands with a variety of sizes in larger wetland-dominated watersheds is challenging and prone to discretization artifacts (Golden et al., 2014). Furthermore, watershed-scale tracking of water that flows from a wetland to other local or regional surface waters within such grid-based modeling systems can be challenging and inefficient, particularly when the size of grid spacing increases to reduce computational cost (c.f., Salamon et al. (2006)).

There is currently no physically-based model that adequately captures watershed-scale wetland connectivity. Recently, Ameli and Craig (2014) developed a grid-free physically-based integrated flow and transport scheme for simulation of 3D groundwater-surface water interactions. This 3D grid-free model is scale-independent, implying that it has the potential to efficiently simulate “watershed-scale” (or even larger scale) groundwater-surface water interaction and subsurface connections among individual wetlands and between each wetland and regional surface waters without domain discretization artifacts. Here, we use this model to map watershed-scale *subsurface* connections, and then link this model with a physically-based transient surface flow routing simulator to map watershed-scale *surface* connections.

Specifically, for a large watershed dominated with GIWs within the prairie pothole region (PPR) of North America, we: (1) Assess the performance of the 3D groundwater-surface water interaction model at regional scales against ground-based (hydrometric, tracer, isotopic) measurements; (2) Compare the distribution of time and length characteristics of simulated wetland subsurface vs. surface connections; (3) Explore if the shortest distance of a wetland to other surface water bodies is an appropriate indicator of wetland connectivity; and (4) Explore if our findings can be extended to the other parts of PPR. Our wetland connectivity modeling approach fills a fundamental gap toward advancing the science and management of wetland hydrologic, biogeochemical and biological connectivity in landscapes.

2 Material and methods

2.1 Experimental watershed

The Beaverhill watershed comprises 4,405 km^2 and is situated on the north-western edge of the Prairie Pothole Region (PPR) (Figure 1). The watershed is centered on the Cooking Lake moraine and drains into the North Saskatchewan River near Edmonton, Alberta, Canada. The watershed is dominated by natural forest within the moraine and agriculture (predominately grassland and pastureland) outside the moraine, with a considerable amount of urban and industrial development near the North Saskatchewan River and the city of Edmonton (Serran and Creed, 2015). The Cooking Lake moraine was recently recognized as a biosphere reserve by UNESCO and contains Beaverhill Lake located in the eastern portion of the watershed, which is recognized as a wetland of international importance by the RAMSAR convention on wetlands.

The climate, geology and topography have collectively created a hydrological system dominated by numerous lakes and wetlands as well as only a few intermittent or slow-moving streams. The climate is continental with cold winters and warm summers. Based on the 40-year (1974-2014) climatic data collected at the Edmonton International Airport, the average January temperature is -13.5 °C and the average July temperatures is 15.9 °C (http://climate.weather.gc.ca/). Average annual precipitation is 483 mm, of which almost 70% falls as rain between May and September, a period when the potential evapotranspiration is as large as 450 mm. This means that there is generally little surface runoff, although spring snowmelt can be an important contributor of local runoff to a wetland.

The geology is dominated by glacial deposits resulting from the Pleistocene continental glaciers. Three till sequences with variable thickness were left as a result of the last glaciation. The higher permeability shallow till often extends from the land surface down to below the average position of the water table. For example, within the St. Denis National Wildlife Area located 500 km east of the Beaverhill watershed, van der Kamp and Hayashi (2009) reported a thickness of 4-5 m with an approximate range of saturated hydraulic conductivity between 2×10^{-2} to 2 m/d, and a saturated hydraulic conductivity of less than 2×10^{-3} m/d below this layer. While the transmission rate of water from the shallow to deeper geological deposits is slow, the moraine still serves as an important source of groundwater recharge in the area, with the annual groundwater recharge rate within the Beaverhill moraine estimated to vary spatially from 5×10^{-5} m/d to 1.9×10^{-4} m/d (Barker et al., 2011; Sass et al., 2014). The surficial bedrock geology is predominantly characterized by the Horseshoe Canyon Formation that is composed of fine to medium grained sediments, inter-fingered within muddy, transgressive sediments (Barker et al., 2011). The lithology of the surficial bedrock suggests that Ca and Mg are dominant weathering-derived products at the Beaverhill watershed.

The topographic relief ranges from a high of 812 m a.s.l. in the moraine to a low of 586 m a.s.l. along the North Saskatchewan River, and reflects glacial depositional processes comprising knob, kettle and hummocky formations in the moraine surrounded by flat to rolling areas in lower elevations.

2.2 Mapping wetlands

A total of 130,157 wetlands were delineated based on the assumption that there is a strong association between terrain depressions and wetland occurrence. A Light Detection and Ranging (LiDAR) DEM captured in 2009 with a horizontal resolution of 3 m and an estimated vertical accuracy of 15 cm was used to map the probability of depression using the approach offered by Lindsay and Creed (2005). The depression probability map was then segmented into image objects using the multiresolution segmentation algorithm (Baatz and Schäpe, 2000). Average depression probability values were used to classify objects as wetland or non-wetland, and adjacent classified wetland objects were dissolved into a single wetland (Serran and Creed, 2015). Note that this method delineated both potential wetlands without surface outlets (i.e., GIWs) and with surface outlets; given the sparsity of permanent streams in the watershed most of the delineated wetlands can be considered *a priori* as GIWs. This is consistent with the observation of GIW predominance in the PPR (Cohen et al., 2016).

2.3 Modelling wetland connectivity

A 3D steady-state groundwater-surface water interaction model was used to simulate watershed-scale subsurface flow and velocity fields as well as to calibrate infiltration rate (Sect. 2.3.1). The mathematical formulation, solution parameters and boundary conditions used in the model as well as the incorporation of the map of wetlands within the model algorithm are explained in Appendix A. The calibrated infiltration rate was combined with meteorological data in a 2D transient overland flow model to simulate surface flow routing (via a fill and spill mechanism) and to simulate watershed-scale surface water level and velocity fields (Sect. 2.3.2). This one-way coupled subsurface-surface model does not consider thoroughly the potential feedbacks from subsurface flow on surface flow routing. Finally, continuous watershed-scale maps of subsurface and surface velocity were generated and coupled with the wetland map to track water movement and to determine if water issued from an individual wetland reached a discharge surface water body (e.g., North Saskatchewan River) via subsurface or surface pathways (Sect. 2.3.3). Note that to characterize the map of connectivity to North Saskatchewan River, we assumed a 500 m buffer around the original line segment of the River which was obtained from a standard hydrography dataset.

2.3.1 Groundwater-Surface water interaction model

The 3D groundwater-surface water interaction model used a free boundary condition to determine the location of the water table. This condition was iteratively imposed using a recharge-water table depth relation scheme (Ameli and Craig 2014) that creates a spatially variable recharge rate and enables delineation of discharge areas where the water table reaches the land surface. This scheme assumed a steady-state subsurface flow and a hydraulic connection between groundwater and wetland water levels. The assumption of steady-state subsurface flow is strongly supported by empirical groundwater table observations collected from the closest piezometer at the Vegreville Environment Center station (located 15 km east of the Beaverhill watershed boundary), where the water table varied with a coefficient of variation of < 0.9% in 2009 (a year when observations were used to develop the steady-state groundwater-surface water interaction model), and a coefficient of variation of 4% over 32 years (August 1985-July 2016) (Figure 2a). In another piezometer at the Barrhead Environment Center station located 65 km west of the Beaverhill watershed boundary, water table varied even less with a coefficient of variation of ~0% during 2009, and a coefficient of variation of 0.01% over 40 years (1977-2016) (Figure 2b). The assumption of hydraulic connection between groundwater and wetland water levels is supported by previously reported empirical observations at the St. Denis National Wildlife Area, 500 km east of the Beaverhill watershed, that showed a maximum difference of less than 10 cm between the groundwater level at a piezometer located 7 m from the wetland edge and the wetland water level (van der Kamp and Hayashi, 2009).

The model was calibrated using saturated hydraulic conductivities of the two-layer unconfined aquifer and actual infiltration rate (see Appendix A for more details). The model performance was assessed for its ability to map groundwater discharge vs. recharge areas and subsurface connections using multiple lines of corroborating hydrometric, chemical and isotopic evidence. First, we compared the simulated groundwater discharge and recharge areas to one derived from hydrometric measurements. We used measurements of hydraulic heads in 1,413 artesian groundwater wells installed in the bedrock and screened 30 to 80 m below the land surface (http://aep.alberta.ca/water/reports-data/alberta-water-well-information-database/) and used a kriging approach to map the potentiometric surface throughout the entire watershed for summer 2009 (see Figure 1 for the location of the artesian wells). Groundwater discharge and recharge areas are inferred as areas wherein potentiometric surface is above and below land surface, respectively (Barker et al. (2011).

Second, we determined if the simulated groundwater discharge and recharge areas had different chemical signatures. It is known that the concentration of weathering-derived products (such as Ca and Mg), chemical measures affected by weathering processes (such as alkalinity and electric conductivity, EC) and total dissolved solids (TDS) can be enhanced along the subsurface flow pathways as transit time, and therefore contact time with rock, increases (e.g., Burns et al., 2003;Maher and Druhan, 2014;Godsey et al., 2009;Cook and Hauer, 2007;Ameli et al., 2017). This implies that the concentration of Ca, Mg, alkalinity, EC and TDS in groundwater wells and surface water bodies (e.g., wetlands, lakes) located within discharge areas will be higher than recharge areas (Cook and Hauer, 2007;Euliss et al., 2004;Barker et al., 2011). We mapped Ca, Mg, alkalinity, EC and TDS measurements of 121 shallow (< 10 m deep) groundwater wells located throughout the watershed provided by Alberta Water Well Information Database (Figure 1), and for 208 surface waters including lakes and wetlands located throughout the watershed (Figure 1) in summer 2009. For the latter, water samples were collected at a depth of 1 meter using an integrated sampling tube at the center of small, shallow wetlands and 100 meters from the shores of large, deep lakes. A non-parametric Wilcoxon rank sum test was used to see if Ca, Mg, alkalinity, EC and TDS concentrations or values were significantly different (higher) at groundwater wells and wetlands located in discharge areas compare to recharge areas based on comparing the *p* values of the statistical tests to the significance level of 0.10. At any *p* values larger (smaller) than 0.10 we accept that the concentrations at discharge and recharge areas are (are not) from distributions with equal medians.

Third, we determined if the simulated discharge and recharge surface water bodies had different isotopic signatures. It is known that ^{18}O and ^{2}H signatures vary between discharge and recharge areas; indeed, discharge waters that have more old water will have different isotopic signatures than recharge waters that have new water only, either from direct precipitation or indirect precipitation via overland flow (McGuire and McDonnell, 2006;Kirchner, 2016;McDonnell and Beven, 2014). This implies that the average isotopic concentration (ratio ‰) in discharge wetlands shows greater deviation from the average watershed concentration of surface waters than the deviation of recharge wetlands. We mapped isotopic ^{18}O and ^{2}H signatures in samples collected for the same 208 surface waters for which the chemical tracers were sampled (Figure 1) in summer 2009, and used Wilcoxon rank sum test to assess the potential differences in isotopic signatures between discharge and recharge wetlands.

The first line of corroborating evidence (hydrometric) was used to calibrate the groundwater-surface water interaction model, and the second and third lines of corroborating evidence (chemical and isotopic) were used to evaluate the performance of the model.

2.3.2 Surface "Fill and Spill" overland flow model

The 2D transient fill and spill surface flow routing approach within the numerical physically-based HydroGeoSphere model (Therrien et al., 2008) was used to simulate watershed-scale surface water level and overland flow routing and ultimately to determine the surface connectivity of wetlands using a transient water particle tracking scheme. The 2D surface of the watershed was discretized into 22,383 grid points (43,836 triangular elements). The parameters regarding time-discretization were: maximum time step = 8640 sec; initial time step = 1800 sec; maximum time step multiplier = 1.5; and minimum time step multiplier = 0.5. A critical depth boundary condition was assigned to the grid points representing the location of the Beaverhill Creek monitoring station (Figure 1) where stream flow observations were available. A no-flow boundary condition was assigned to the watershed boundaries.

The 2D overland flow model was calibrated using the Manning roughness coefficients (Manning et al., 1890) in *x* and *y* directions (n_x and n_y) as well as rill depth. The former is an empirically derived coefficient, which is dependent on surface roughness and surface cover, and the latter represents the depth that must be filled at each point before any lateral surface flow can occur. Frei and Fleckenstein (2014) suggested that the implementation of an acceptable uniform value for rill depth within the HydroGeoSphere overland flow simulator leads to an accurate prediction of watershed-scale surface flow routing. The calibration was made to match observed and simulated stream flow at the Beaverhill Creek monitoring station (Figure 1) during a period when stream flow measurements were available (April 1 to August 1 1983). The inputs to the model included daily precipitation, evapotranspiration (after Morton 1978, Morton 1983) and snow water equivalent (after Sturm et al. 2010) from data collected at the Vegreville Environment Center meteorological station (15 km east of the Beaverhill watershed boundary) as well as the steady-state infiltration rate obtained using the 3D groundwater-surface water interaction model. We did not have access to evapotranspiration data before 2000 (including the calibration period, April 1 to August 1, 1983). Instead, we used the calculated evapotranspiration time history of 2015 for the same period (April 1 to August 1, 2015), because the monthly average humidity, maximum air temperature and minimum air temperature were similar between April 1 to August 1, 1983 and April 1 to August 1, 2015.

The calibrated 2D overland flow model was then used to simulate surface flow routing from April 1 to August 1, 2009 as well as from April 1 to August 1, 2013 using meteorological data for these periods as inputs to the model. The chosen time periods include the smallest and the largest cumulative net water (precipitation-minus evapotranspiration) depth observed at the Vegreville station since 2000, reflecting the minimum and maximum probability of occurrence of surface flow and therefore surface connections among wetlands since 2000. Once the surface flow routing model was developed, the discretized surface water velocities in x and y directions at each grid point and each time step were extracted. Continuous maps of surface water velocity in x and y directions throughout the watershed were then approximated by interpolating the discretized surface water velocities. A Fourier-based interpolation scheme with 10,000 Fourier series terms was used to complete the interpolation process and generate the continuous maps of surface velocity in x ($V_s^x(\mathrm{x,y,t})$) and y ($V_s^y(\mathrm{x,y,t})$) directions for the entire watershed; the overall correlation coefficient between estimated velocities using the interpolation method and original modeled velocities at each grid point and time step was r^2=89% ($p < 0.001$).

2.3.3 Subsurface and surface wetland connections

The continuous maps of subsurface steady-state ($V_m^x(x,y,z)$, $V_m^y(x,y,z)$, $V_m^z(x,y,z)$, Eq. A.4) and transient surface velocity ($V_s^x(x,y,t)$, ($V_s^y(x,y,t)$) were used to track water particles and generate a connectivity map using water particle tracking approach as follows.

In the subsurface domain:
$$\begin{aligned} x_p(t) &= x_p(t-\Delta t) + V_m^x(x_p(t-\Delta t), y_p(t-\Delta t), z_p(t-\Delta t)) * \Delta t \\ y_p(t) &= y_p(t-\Delta t) + V_m^y(x_p(t-\Delta t), y_p(t-\Delta t), z_p(t-\Delta t)) * \Delta t \\ z_p(t) &= z_p(t-\Delta t) + V_m^z(x_p(t-\Delta t), y_p(t-\Delta t), z_p(t-\Delta t)) * \Delta t \end{aligned} \tag{1a}$$

In the surface domain:
$$\begin{aligned} x_p(t) &= x_p(t-\Delta t) + V_s^x(x_p(t-\Delta t), y_p(t-\Delta t), t-\Delta t) * \Delta t \\ y_p(t) &= y_p(t-\Delta t) + V_s^y(x_p(t-\Delta t), y_p(t-\Delta t), t-\Delta t) * \Delta t \end{aligned} \tag{1b}$$

where $x_p(t)$, $y_p(t)$ and $z_p(t)$ are the position of the particle p at time t, and $x_p(t-\Delta t)$, $y_p(t-\Delta t)$ and $z_p(t-\Delta t)$ are the position of the particle p at time $t-\Delta t$. In the particle tracking algorithm, a small value of time step ($\Delta t = 0.1$ day) was assumed to ensure precise calculation of particle location and movement. A similar particle tracking method was recently used in

Ameli et al. (2016b) and Ameli et al. (2016a). Water particle release points in the tracking approach were placed uniformly with 500 m spacing along the land surface. This placement meant that there was a possibility that not all wetland connections were captured (i.e., water particle release points and small wetlands in between the 500 m placement would have been missed); nonetheless, it allowed for a consistent comparison of the general trend in subsurface and surface connections of wetlands. The generated connections were used to estimate subsurface and surface transit times (τ) and flowpath lengths (l) that were then fitted with a Gamma distribution (which provided the best fit, data not shown) to generate the transit time distribution (TTD) and flowpath length distribution (FLD):

$$\mathrm{TTD}(\tau) = \frac{a\left(\frac{\tau}{\tau_0}\right)^{a-1}}{\tau_0\Gamma(a)}e^{-a\left(\frac{\tau}{\tau_0}\right)} \quad \& \qquad \mathrm{FLD}(l) = \frac{a\left(\frac{l}{l_0}\right)^{a-1}}{l_0\Gamma(a)}e^{-a\left(\frac{l}{l_0}\right)} \tag{2}$$

where τ_0 and l_0 are the mean transit time and length of connection, $\Gamma(a)$ is the Gamma function and a is the Gamma shape parameter. The simulated subsurface connections were tested by correlating the simulated mean transit time (MTT) of water particles discharged into wetlands and the concentration of chemical tracers (Ca, Mg, EC and TDS) in wetlands and determining if wetlands with longer transit times had higher concentrations or values of Ca, Mg, alkalinity, EC and TDS. The time (and length) characteristics of the simulated subsurface and surface connections of wetlands were then compared.

We calculated the relationship between subsurface (and surface) flow contribution of each individual wetland to the North Saskatchewan River and the distance of the wetland from the river to determine whether proximity of wetlands to the North Saskatchewan River is a proxy for their hydrologic connection to the river.

The generalizability of our findings to the entire PPR was assessed by comparing climate, geology and topography of the Beaverhill watershed to the other parts of the prairie potholes regions of North America. We compared monthly-averaged climatic measures (including precipitation, evapotranspiration, snow water equivalent and temperature) of the Beaverhill watershed to the entire Prairie Pothole Region. We compared the average porosity and permeability of the Beaverhill watershed to the average of these measures in the entire Prairie Pothole region. We also compared the distribution of observed shortest distances among nearest wetland neighbour and distances between wetlands and stream network at the Beaverhill watershed to a prairie pothole landscape in North Dakota. We obtained wetland polygons in North Dakota from the National Wetlands Inventory (https://www.fws.gov/wetlands/ and stream polylines from the National Hydrography Dataset: http://nhd.usgs.gov/). To do the latter comparison, we used Quantile-Quantile plot which is a graphical non-parametric method for comparing probability distributions of two unpaired samples by plotting their quantiles against each other. If the two distributions being compared are statistically similar, the theoretical line of the Quantile-Quantile plot will be $y = x$ and the quantile pairs will approximately lie on this line. If the distributions are not statistically similar, the theoretical line of the Quantile-Quantile plot will be a linear line, but not following $y = x$.

3. Results

3.1 Groundwater-Surface water interaction model

The calibrated values of the saturated hydraulic conductivities are 10^{-1} m/d and 10^{-3} m/d for the top and bottom layers respectively. The calibrated value for infiltration rate (which here is equal to maximum groundwater recharge rate) is 1×10^{-4} m/d.

The simulated groundwater discharge/recharge map is consistent with the map of groundwater discharge/recharge inferred from measured hydraulic head (potentiometric surface) in piezometric wells (Figure 3). Figure 3a shows the spatial distribution of groundwater discharge (negative) and recharge (positive) fluxes along the land surface obtained using the groundwater-surface water interaction model. Figure 3b shows the distance of potentiometric surface from the land surface, with negative values (above land surface) representing discharge areas and positive values (below land surface) representing recharge areas, with the larger negative (or positive) values equal to larger discharge (or recharge) potential. The correlation coefficient between simulated groundwater fluxes at the land surface and the distance of potentiometric surface above and below land surface is 75% ($p < 0.001$). Figure 3 also shows the predominance of recharge area within the moraine and discharge area outside of the moraine.

The performance of the model was also assessed using chemical and isotopic tracer data. The concentrations or values of chemical tracers (Ca, Mg, EC and TDS) of water in shallow groundwater wells are different between the simulated discharge and recharge areas ($p < 0.10$) (Table 1). The average concentrations of chemical tracers are higher in the simulated discharge areas than the simulated recharge areas. In addition, the concentrations or values of all chemical tracers (except Mg) in simulated discharge wetlands are statistically different from simulated recharge wetlands ($p < 0.10$) (Table 2). The average concentrations of all chemical tracers are higher in the simulated discharge wetlands than the simulated recharge wetlands. Higher concentrations of weathering products reflect the existence of longer pathlines with larger transit times within simulated discharge areas.

The average concentration of isotopic tracers (^{18}O and ^{2}H) in simulated discharge and recharge wetlands are significantly different ($p < 0.001$) (Table 2). Also for ^{18}O (^{2}H), the average isotopic concentration in simulated discharge areas deviates 3‰ (8‰), whereas the average isotopic concentration in simulated recharge areas deviates only 0.9‰ (3‰) compared to the watershed average isotopic concentrations. This reflects a mixture of old and new waters in simulated discharge wetlands, but mostly new waters in simulated recharge wetlands, which is consistent with our expectations.

3.2 Surface "Fill and Spill" overland flow model

The manually calibrated values of the uniformly-distributed Manning roughness coefficient is 0.05 $\frac{sec}{m^{1/3}}$(equal in both *x* and *y* directions) and the rill storage height is 0.001 m. Figure 4a shows that the simulated vs. observed stream flow at the Beaverhill creek near the mouth measurement station for the major summer rainfall period from April 1 to August 1 1983 are significantly correlated ($r^2 = 0.87$, $p < 0.001$). Two statistical tests, including Wilcoxon Rank Sum (equality of median) and Levene (equality of variance), also suggest that the median and variance of both simulated and observed hydrographs are similar (*p* values are 0.44 and 0.95, respectively. We did not expect that the surface flow model would exactly simulate the hydrograph in 1983, as we used evapotranspiration data from 2015 for 1983 (as explained in section 2.3.2). This simplification could have affected the simulated hydrograph shape leading to an earlier second peak (Figure 4a). We think this simplification would have had minimal effect on the simulated connectivity lines, as at the end of simulation period, the cumulative simulated flow ($2.4\ 10^{7}$ m^{3}) at the measurement station was only 7% less than the cumulative observed flow ($2.6\ 10^{7}$ m^{3}). Indeed, for the particle tracking scheme used to characterize the surface connectivity map, it did not make a substantial difference if the particle was at its highest velocity (e.g., June 20 vs. June 24 of 1983). Figure 4 also suggests a small contribution of base flow (almost zero from early spring to end of June) to observed stream flow; this justifies the calibration of the overland flow model with the observed stream flow at the Beaverhill Creek stream flow monitoring station.

3.3 Wetland connectivity

3.3.1 Subsurface connections

The subsurface connectivity map (Figure 5a) indicates that recharge wetlands of a wide range of distances from the North Saskatchewan River can be connected to the river (red lines). These wetlands range from those located in the moraine, where the length of connectivity to the river is up to 30 km, as well as those located in the vicinity of the river, where the length of connectivity to the river is less than 5 km. The total steady-state groundwater contribution of these recharge wetlands to the North Saskatchewan River is 0.775 x 10^6 m^3 per month. Furthermore, water particles released from the recharge wetlands located in the moraine traverse from hundreds of meters (as small as 100 m) and reach discharge wetlands located in the moraine, or tens of kilometers (up to 36 km) and reach Beaverhill lake as well as discharge wetlands located outside of the moraine (blue lines). There is also possibility for subsurface connections between recharge wetlands located at the east of the watershed to Beaverhill Lake (data not shown).

3.3.2 Surface connections

The North Saskatchewan River receives a majority of its wetland-originated surface waters from wetlands located in the riparian area of the river. For the period from April 1 to August 2013, when the largest net surface water fluxes since 2000 occurred, the length of the surface connections ranged from 50 m to 8 km (Figure 6b), with the total surface water flow contribution from these wetlands being 1.43 x 10^6 m^3 per month. For the period from April 1 to August 1 2009, when the smallest net surface water fluxes since 2000 occurred, the length of the surface connections ranged from 50 m to 3 km (Figure 6c), with the total surface water flow contribution from these wetlands being 0.81 x 10^6 m^3 per month. Within the moraine, surface connections among wetlands are primarily between neighboring wetlands. For the period from April 1 to August 2013, the length of connection ranged from 25 m to 7 km (Figure 6b); only one water particle released from wetlands in the moraine reached outside the moraine during this period. For the period from April 1 to August 2009, the length of connection ranged from 25 m to 3 km (Figure 6c); no water particle released from wetlands in the moraine reached outside the moraine during this period. The modeling approach we used was a one-way coupling of subsurface and surface flow processes that could not consider thoroughly the subsurface flow exfiltration feedbacks on surface flow routing. This simplification had negligible effects on wetland connectivity within the moraine, as the moraine mostly consists of recharge zones with minimum subsurface exfiltration (Figure 3). This simplification could have affected the map of surface connectivity of wetlands located in close vicinity of the North Saskatchewan River (within a 1000 m buffer) wherein subsurface water can exfiltrate and enhance surface connectivity. However, the rate of subsurface exfiltration in these riparian areas was on average 1 x 10^{-4} m/d (Figure 3a), which is considerably smaller than the average of net atmospheric inputs (precipitation-evapotranspiration) from April 1 to August 1 2013 that was equal to 7 x 10^{-3} m/d and from April 1 to August 1 2009 that was equal to 4 x 10^{-3} m/d. Therefore, the one-way coupling simplification had minimum effects on surface flow routing along the riparian wetlands located in the riparian areas.

3.3.3 Timing and length of subsurface and surface connections

Subsurface connections between wetlands and the North Saskatchewan River (Figure 6a) and from wetlands located in moraine to other wetlands in the watershed (Figure 6b) showed a significantly slower and longer time scale compared to surface connections. The average time of the subsurface connections between wetlands and North Saskatchewan River was orders of magnitude longer than the average time of the surface connections. This difference between surface and subsurface transit times led to discontinuity in the continuum of transit times to the river as shown in Figs. 6a and 6b (left panel). This discontinuity may have been attributed to the lack of fast subsurface flow in our landscape. Fast subsurface flow has been widely observed in humid forested landscapes with a high frequency of macropores (and thus large hydraulic conductivities in the shallow portions of the soil). Available observations in the Canadian Prairie Pothole region do not support such high frequency of macropores and large shallow hydraulic conductivity. Similarly, the average length of subsurface connections of wetlands to the North

Saskatchewan River was longer than the average length of surface connections. Furthermore, among wetlands, the average of both time and length of subsurface connections were longer compared to surface connections.

Figure 7 shows the relation between simulated subsurface mean transit time of each discharge wetland and observed concentration and values of Ca, Mg, EC and TDS of the discharge wetland. We expected that the concentration of weathering-derived products and TDS and the value of EC within discharge wetlands would be positively correlated to the subsurface mean transit time of water particles discharged into the wetland. Figure 7 shows a strong positive correlation between simulated mean transit time and the concentration or value of the different constituents within the discharge wetlands.

3.3.4 Relation between wetland flow contribution to the river and wetland-river distance

To determine whether proximity of wetlands to the North Saskatchewan River is a proxy for their hydrologic connection to the river, we calculated subsurface and surface flow contributions of each wetland to the North Saskatchewan River for a period of four months. The flow contribution-distance relationship of connected wetlands to the river (Figure 8) suggests that subsurface flow contribution of wetlands to the river is in general insensitive to their distance to the river, with a negligible correlation coefficient (ρ = -0.001%) between subsurface flow contribution and distance. However, proximal wetlands contribute more surface flow to the river than distal wetlands, with a more pronounced correlation coefficient (ρ = -15%) from April 1 to August 2009, when the smallest net surface water fluxes since 2000 occurred, compared to April 1 to August 2013 (ρ = -6%), when the largest net surface water fluxes since 2000 occurred.

3.4 Extendibility to the entire PPR

Figure 9 shows that the distributions of observed shortest distance of wetlands to their nearest wetland neighbor and shortest distance of wetlands to nearest major stream are statistically similar between Beaverhill watershed and a large portion of prairie potholes in North America (the theoretical lines between distributions in Quantile-Quantile plot is $x = y$). Table 3 compares average monthly climatic measures in the Beaverhill watershed to the entire PPR. There is no significant difference in the median and variance of temperature between Beaverhill watershed and the entire PPR at significance levels of 0.05 and 0.10, respectively. There is no significant difference in the median and variance of precipitation minus evapotranspiration between the Beaverhill watershed and the entire PPR ($p > 0.10$). While there is a difference in the median snow water equivalent between Beaverhill watershed and the entire PPR ($p < 0.10$), there is no significant difference in the variance of SWE ($p = 0.92$). The geology of the Beaverhill watershed is also consistent with the geology of the entire PPR (Table 4). These similarities may suggest that the behavior of subsurface and surface connections of wetlands within the Beaverhill watershed can be extended to the other parts of the PPR.

4 Discussion

Hydrologic connectivity of wetlands determines in part their hydrologic, biogeochemical and biological functions. Hydrologic connectivity, however, is poorly understood and modeled (Cohen et al., 2016). While existing models may be able to emulate aggregate influence of wetland connectivity on the quantity and quality of downstream waters (e.g., Shook et al., 2013), very few of these models have been designed with connectivity in mind, and thus are not able to determine the local and regional interactions between wetlands and other hydrologic features in wetland-dominated landscapes.

Here, we couple a steady-state groundwater-surface water interaction model with a transient surface flow routing model to assess wetland connectivity in a large wetland-dominated watershed within the Prairie Pothole Region. The modeling approach uses a one-way coupling of subsurface and surface flow processes, and therefore ignores the potential subsurface exfiltration feedback on surface flow routing. Nonetheless, the modeling approach enables answers to long-standing questions on watershed-scale surface and subsurface connections of wetlands that far outweigh its limitations.

Model performance

The calibrated parameters of the groundwater-surface water interaction model including saturated hydraulic conductivities of the subsurface and recharge rate were consistent with observations within or close to the Beaverhill watershed. The groundwater-surface water interaction model predicts reasonably groundwater discharge/recharge areas along the land surface compared to groundwater discharge/recharge areas inferred from hydraulic head measurements, chemical tracers and isotopic signatures. The "fill and spill" overland flow model predicted observed stream flow close to the Beaverhill watershed outlet with acceptable accuracy.

Timing and length of connection

The coupled model was used to map wetland connectivity and quantify the continuum of time and length variations of this connectivity. Our results reveal that wetlands in the Beaverhill watershed, with a high density of geographically isolated wetlands (GIWs), are not hydrologically isolated. Furthermore, the subsurface and surface connections show diverse number, timing and length. The number of wetlands connected to the major drainage network (here the North Saskatchewan River) from subsurface pathways was significantly larger than the number of wetlands connected from surface pathways, even in response to large precipitation events (Figure 5). Fast surface connections originated from the wetlands located near the river (with a maximum distance of 8 km) whereas slow subsurface connections originated from a wide range of close and distant wetlands with a maximum distance of 30 km from the river. Indeed, model simulations reveal that regional surface waters integrate the entire continuum of time and length variations of connectivity, not just rapid or surface-connected flowpaths located at the top of this continuum.

Watershed hydrologic, biogeochemical and biological functions in wetland-dominated landscapes such as the Beaverhill watershed are influenced by the transit times, velocities (rates) and mode (pathways) of hydrologic connection (Bracken and Croke, 2007; Cohen et al., 2016). Wetlands that connect rapidly (but not persistently) to the river via surface fill-and-spill mechanism constrain peak flow volumes, delay peak timing, and retain sediments (Craft and Casey, 2000). However, wetlands that connect to the river only via slower subsurface flowpaths regulate water table depth (Lane et al., 2015), maintain base flow and recession rate of river hydrographs (McLaughlin et al., 2014; Golden et al., 2015), and retain and transform pollutants (Marton et al., 2015). Furthermore, long transit times and lengths of subsurface connections impact biogeochemical processes in the vicinity of the river and enhance the concentration of solutes discharged into the river, by facilitating completion of kinetically-limited reactions and enhance retention, sorption and transformation of nutrients (Min et al., 2010), metals (Mays and Edwards, 2001) and likely pesticides (Ameli, 2016), all of which influence aquatic ecosystem structure and function (e.g., Euliss et al., 2004; Cook and Hauer, 2007). Figure 6c depicts the simulated cumulative probability of transit time distribution of North Saskatchewan River (ensemble of surface and subsurface wetland-originated contributions), and summarizes the potential ecosystem services of each portion of this continuum.

Distance not a proxy for connectivity

Our results show that all wetlands located within a distance of 30 km can affect the quantity and quality of water in the North Saskatchewan River. Contrary to Hayashi et al. (2016) who hypothesized that wetlands in PPR can only be connected to closely adjacent water bodies and subsurface flow through the deeper portions is insignificant, our findings using novel 3D watershed-scale subsurface-surface connectivity model corroborates the simple pond water budget calculations of Brannen et al. (2015) who showed that wetlands in PPR can be connected to stream network through subsurface flow. Quantification of the contribution of wetlands to the river suggests that slow subsurface flow contribution to the river flow is substantial (0.775×10^6 m^3 per month) and comparable to the surface flow contribution(0.81×10^6 m^3 per month during the driest year and 1.43×10^6 m^3 per month during the wettest year since 2000). In addition, although the surface flow contribution from wetlands to the river is correlated with the wetlands distance to the river, subsurface flow contribution from wetlands to the river had a weak relationship with the distance between wetlands and the river (Figure 8), and a broad range of proximal and distal wetlands can be connected to the river (Figure 6a) and influence the river quality and quantity. This implies that decisions to protect GIWs based only on distance of the wetland to a river (e.g., 2015 U.S. Clean Water Rule (Federal Register 80: 37054-37127)), may lead to the loss of distal wetlands with important watershed functions. These findings can be extended to the entire PPR, since the climate, geology and topography can be considered similar throughout the PPR.

Guidelines for wetland protection, removal and restoration

Human alteration has changed the natural continuum and timing of hydrologic connectivity (Min et al., 2010;Pringle, 2003). Given that the aforementioned ecosystem services accrue from a continuum of transit times, the cumulative impact of such alteration can be significant (Johnston, 1991; Zedler, 2003). Current wetland management strategies in the PPR are likely to lead to loss of wetlands (particularly GIWs) located far from regional surface waters (Van Meter and Basu, 2015; Serran and Creed, 2015). Removing these wetlands can increase surface pathways towards rivers with potential consequences of flooding and eutrophication during large events. For example, the loss of GIWs in watersheds including the Beaverhill watershed has been implicated as one cause of the increase in phosphorus loading to Lake Winnipeg, located 1,300 km east of the Beaverhill watershed, leading to eutrophication events and the 2013 listing of Lake Winnipeg as the most threatened lake in the world (Ulrich et al., 2016).

Our modeling approach can explicitly assess and evaluate the hydrologic connectivity of individual wetlands, providing scientists and conservation authorities with information to understand and manage the potential response of the entire watershed to direct and indirect changes such as wetland drainage or restoration. Furthermore, coupling robust hydrologic connectivity models with biogeochemical and biological data can (1) improve our understanding of landscape hydrologic connectivity and its impact on the structure and function of wetlands, and (2) aid in the assessment of feedbacks between hydrology, biogeochemistry and biology.

5 Conclusion

A one-way coupled subsurface-surface model was developed to assess the continuum of time and distance variations of hydrologic connectivity of wetlands in a large watershed with a high density of geographically-isolated wetlands in the Prairie Pothole Region. The model showed that wetlands are not hydrologically isolated, and that the surface and subsurface hydrologic connections vary significantly in terms of their timing and length. Contributions of slow, subsurface connections from both proximal and distal wetlands to the river are substantial and comparable to the contributions of fast, surface connections.

Prioritization of protection of wetlands that relies on shortest distance of wetland to the river or surface connections alone can lead to unintended consequences in terms of loss of attending wetland ecosystem functions, services and their benefits to society. The subsurface-surface model is computationally efficient, enabling upscaling to the entire Prairie Pothole Region (and elsewhere) to assess wetland connectivity that was heretofore difficult to quantify, and providing guidance on the development of watershed management and conservation plans (e.g., wetlands drainage/restoration) under different climate and land management scenarios.

Data and code availability

The data used in this paper are available upon request from the corresponding author.

Appendix A: Mathematical formulation of Groundwater-Surface water interaction model

At each layer ($m = 1 \ldots M$) of an unconfined aquifer, the exact 3D series solution to the saturated steady flow governing equation, with no-flow conditions along the sides of the computational domain, was obtained in terms of discharge potential function ($\phi_m = K_m h_s$) as (Ameli and Craig, 2014):

$$\phi_m(x,y,z) = \sum_{j=0}^{J-1}\sum_{n=0}^{N-1} cos\,\omega_j x\, cos\,\omega_n y\,[A_{jn}^m cosh(\gamma_{jn}z) + B_{jn}^m sinh(\gamma_{jn}z)] \qquad \text{(A.1)}$$

where $\omega_j = \frac{j\pi}{L_x}$; $\omega_n = \frac{n\pi}{L_y}$; $\gamma_{jn} = \pi\sqrt{\frac{j^2}{{L_x}^2}+\frac{n^2}{{L_y}^2}}$ for $j = 0 \ldots . J-1$ & $n = 0 \ldots . N-1$

In eq. (A.1), $h_s(x,y,z)$ is the total hydraulic head, and K_m (LT^{-1}) is the *m*th layer saturated hydraulic conductivity. In addition, *j* and *n* represent the coefficient index, whereas *J* and *N* refer to number of series in the *x* and *y* directions, respectively. A total of 144 series terms (*N*=12 and *J*=12) were used. The series coefficients associated with the mth layer and *j*th and *n*th series term are A_{jn}^m and B_{jn}^m. The rectangular computational domain with no-flow side boundaries has a length of L_x = 84.5 km and L_y = 95.4 km in *x* and *y* directions, respectively, which embeds the watershed boundary as shown in Fig. 1. No-flow side boundaries were placed on average 20 km away from the watershed original border; this treatment minimized the impact of side boundaries on flow behaviour and subsurface connections. A continuous map of hydraulic head was then obtained as:

$$h_s(x,y,z) = \frac{\phi_m(x,y,z)}{K_m} \qquad \text{(A.2)}$$

To complete the solution, the unknown series solution coefficients of each layer (A_{jn}^m, B_{jn}^m) were calculated by imposing infiltration rate along the topographic surface, the no-flow condition along the bottom boundary, and the continuity of flux and head conditions along the layer interface of the multi-layer unconfined aquifer. A simple numerical least square scheme was used to impose these boundary and continuity conditions. In general, this continuous solution (Eq. (A.1)) exactly satisfies the mass balance and Darcy equations in the entire watershed, except along the boundaries where mass balance and Darcy equations are prone to numerical least square error. Ameli and Craig (2014) showed that this error can be negligible when sufficient number of control points was used within numerical least square algorithm. To ensure minimum numerical least square error along the boundary and layer interfaces, 806130 control points (uniformly-spaced at each 100 m) were placed along two boundary interfaces and the layer interface of the computational domain.

The continuous maps of Darcy fluxes at the *m*th layer and at each *x*, *y* and *z* directions can be computed by the following equation:

$$q_m^x\,(x,y,z) = \frac{d\phi_m\,(x,y,z)}{dx} \qquad \text{(A.3a)}$$

$$q_m^y\,(x, \mathrm{y}, z) = \frac{d\phi_m\,(x,y,z)}{dy} \tag{A.3b}$$

$$q_m^z\,(x, \mathrm{y}, z) = \frac{d\phi_m\,(x,y,z)}{dz} \tag{A.3c}$$

Equation (A.3) can also be used to determine groundwater discharge fluxes at discharge areas (seepage faces) along the land surface as well as groundwater recharge fluxes where the water table is below the land surface. A subsurface map of pore water velocities (V), which is required to perform subsurface water particle tracking, was obtained as:

$$V_m^x\,(x, \mathrm{y}, z) = \frac{1}{\theta_s} q_m^x\,(x, \mathrm{y}, z) \tag{A.4a}$$

$$V_m^y\,(x, \mathrm{y}, z) = \frac{1}{\theta_s} q_m^y\,(x, \mathrm{y}, z) \tag{A.4b}$$

$$V_m^z\,(x, \mathrm{y}, z) = \frac{1}{\theta_s} q_m^z\,(x, \mathrm{y}, z) \tag{A.4c}$$

where θ_s is subsurface porosity. Inputs to the model included: (1) the location and water level of wetlands; and (2) material properties of the subsurface. For (1), the delineated wetlands explained in Sect. 2.2 were used, and we assumed that the water level was equal to the average elevation of each wetland boundary. This water level was used as a constant head boundary condition at each wetland. For (2), a two-layer unconfined aquifer with a 5 m thick shallow layer was used to characterize the subsurface (as suggested in van der Kamp and Hayashi, 2009). The bottom boundary of the computational domain was assumed to be at Z = 0 with a no-flow condition. A porosity (θ_s) value of 0.14 equal to the average measured porosity at the Beaverhill watershed (Gleeson et al., 2014) was also used.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This research was funded by a NSERC Discovery Grant and an Alberta Land Institute Grant to I~~.~~F~~.~~C. The authors gratefully acknowledge Alberta Agriculture and Forestry, Alberta Environment and Parks, Alberta Geological Survey and Environment and Climate Change Canada for providing some of the data and measurements used in this paper. The authors would also like to thank Dr. Jeffrey McDonnell, Dr. Allan Rodhe, Dr. Kevin Bishop and Dr. Thomas Grabs for providing insightful comments which improved the quality of the manuscript.

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Table 1: Average concentration of chemical tracers in hydrologically-simulated groundwater discharge and recharge areas, as well as p-values of non-parametric Wilcoxon rank sum test (equality of median) used to assess the differences in shallow groundwater chemistry between simulated groundwater discharge and recharge areas. p-values less than 0.10 depicts a statistically significant deference between chemistry of simulated groundwater discharge and recharge areas.

	Ca(mg/l)	Mg(mg/l)	TDS(mg/l)	EC(μS/cm)
Discharge	123	46	1189	1631
Recharge	102	43	995	1443
p-value	0.09	0.02	0.09	0.05

Table 2: Average concentration of chemical and isotopic tracers in hydrologically-simulated discharge and recharge wetlands, as well as p-values of non-parametric Wilcoxon rank sum test (equality of median) used to assess the differences in wetland chemistry and isotopic signatures between simulated discharge and recharge wetlands. The reported values in the parenthesis for ^{18}O (and ^{2}H) are the relative difference between average isotopic concentrations (ratio) in simulated discharge or recharge wetlands from average watershed concentration.

	Ca(mg/l)	Mg(mg/l)	TDS(mg/l)	EC(μS/cm)	ALK(mEq/l)	^{18}O (‰)	^{2}H (‰)
Discharge	65	42	1144	1502	241	-8.90 (3)	-105.37 (8)
Recharge	59	34	721	923	195	-6.28 (0.9)	-91.55 (3)
p-value	0.08	0.14	0.07	0.06	0.07	<0.001	<0.001

Table 3: p-values of Wilcoxon rank sum and Levene tests that were used to assess the similarities in median and variance, respectively, between monthly-averaged climatic measures in the Beaverhill watershed and the entire Prairie Pothole Region. These statistical analyses were conducted based on 31 years (from 1981 to 2011) precipitation minus actual evapotranspiration (P-ET), snow water equivalent (SWE) and air temperature data. p-values greater than 0.10 indicate a similarity between climatic measures at a significance level of 0.10.

	Wilcoxon rank sum	Levene
P-ET	0.38	0.44
SWE	0.02	0.92
Temperature	0.08	0.19

Table 4: Comparison of the average values of geological features between Beaverhill watershed and the entire PPR. K (m^2) refers to permeability.

	PPR	Beaverhill
Mean Porosity (%)	0.15	0.14
Mean Permeability No Permafrost (log(k))	-14.94	-15.13
Mean Permeability Permafrost (log(k))	-14.94	-15.13
Mean Permeability Standard Deviation (m^2)	1.79	1.82
Bedrock Geology - Sedimentary Rocks (% Area)	96.90%	97.67%

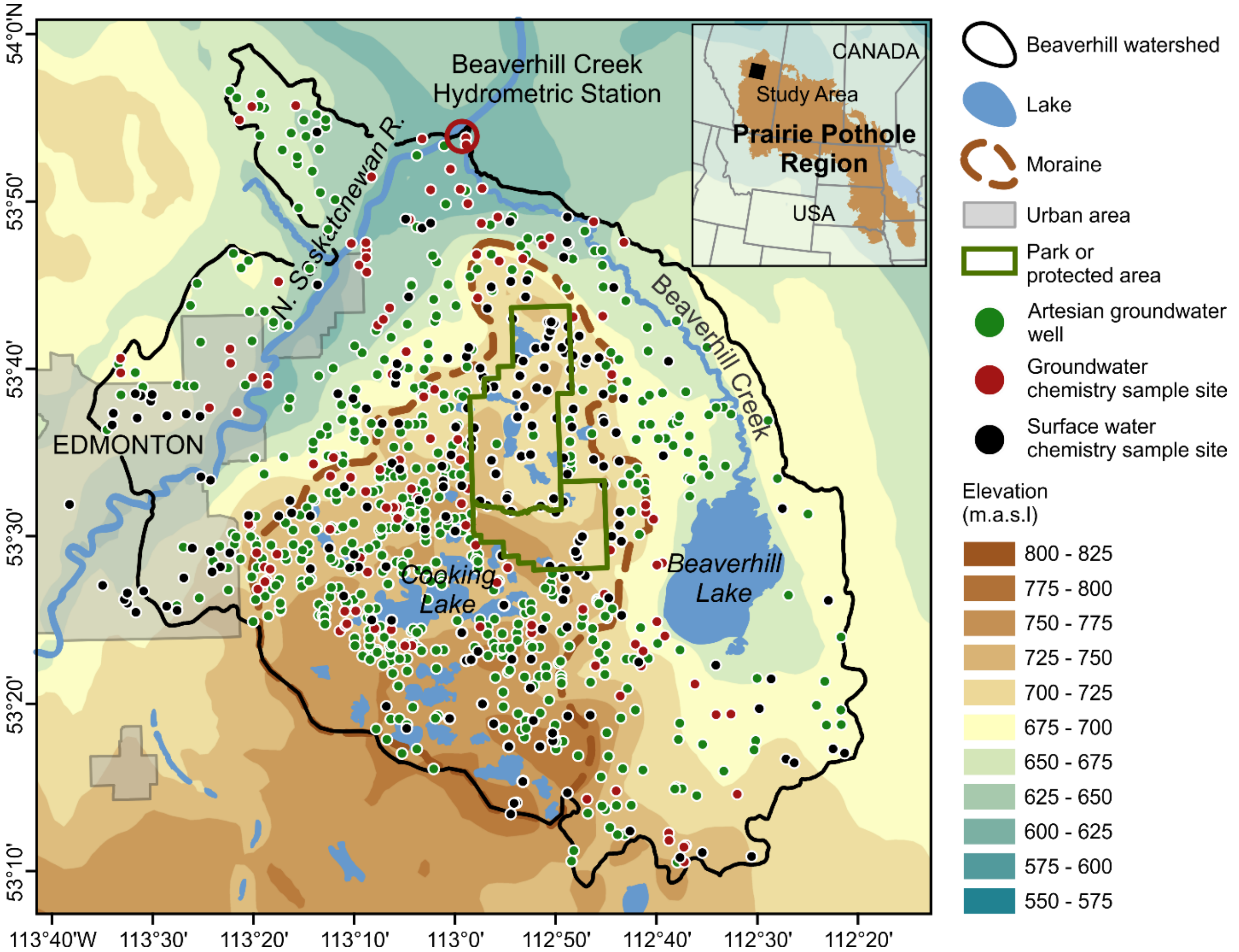

Figure 1: Beaverhill watershed, Alberta, Canada. The location of 1,413 artesian groundwater wells installed in the bedrock and screened 30 to 80 m below the land surface are shown (green dots). Black dots depict the location of 208 lakes, wetlands and ponds wherein chemistry and isotopic measurements were taken. Red dots depict the location of 121 shallow (< 10 m deep) groundwater wells wherein groundwater chemistry measurements were taken. The red ring shows the location of Beaverhill Creek monitoring station. The inset shows the map of the Prairie Pothole region of North America.

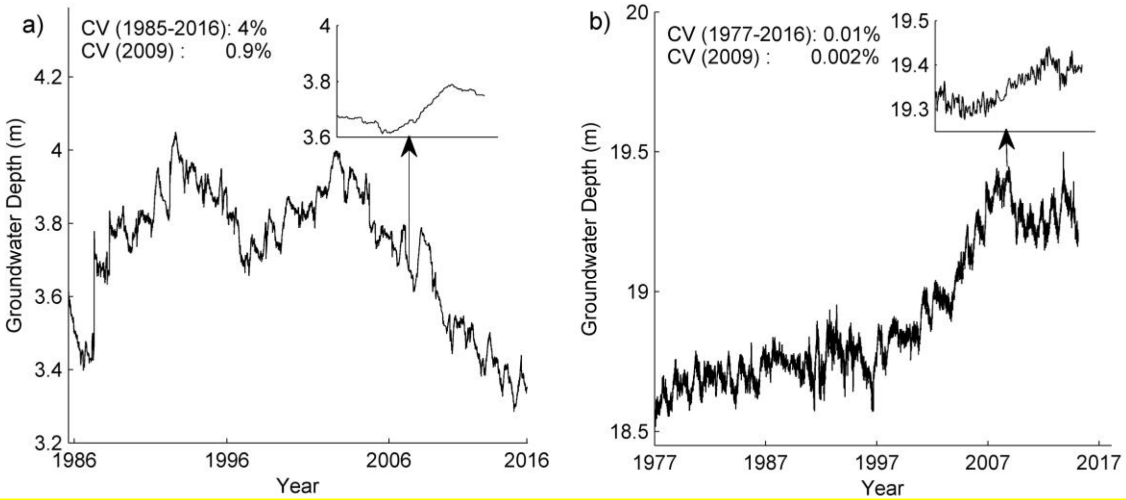

Figure 2: Observed time series of groundwater depth at two measurement stations located east and west of the Beaverhill watershed. a) Groundwater depth from August 1985 to July 2016 at the Vegreville measurement station located 15 km east of the Beaverhill watershed boundary. b) Groundwater depth from October 1977 to October 2016 at the Barrhead measurement station located 65 km east of the Beaverhill watershed boundary. The insets show the time series of groundwater depth in 2009, when the observations used here to develop the steady-state groundwater-surface water interaction model were available. CV refers to the coefficient of variation of groundwater depth data during the given period.

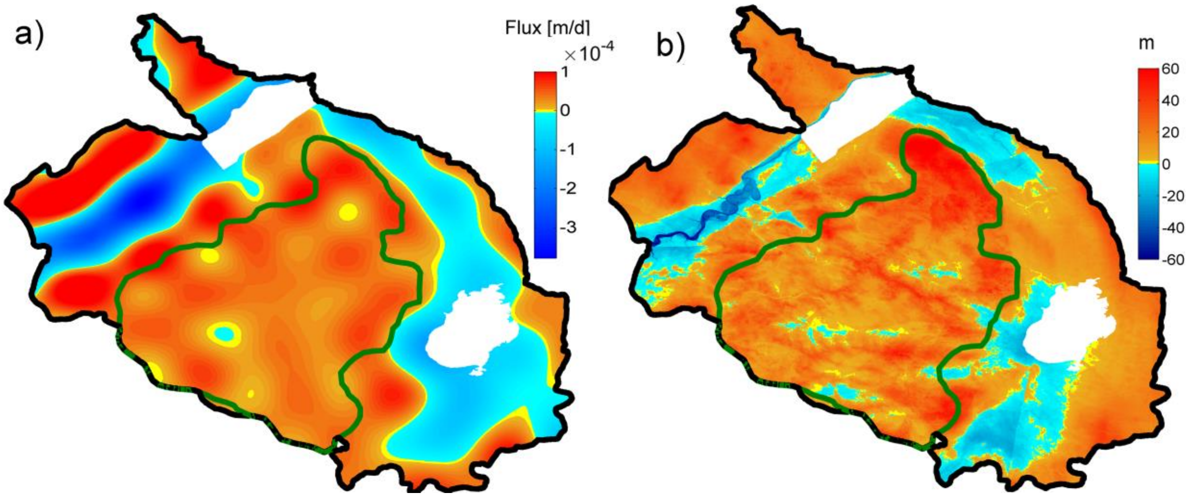

Figure 3: Comparison between simulated and inferred groundwater discharge/recharge areas. (a) Simulated groundwater discharge (blue surfaces with negative groundwater fluxes) and recharge (red surfaces with positive groundwater fluxes) areas. (b) Inferred groundwater discharge (blue surfaces) and recharge (red surfaces) areas from the potentiometric surface generated using measurements from 1,413 artesian wells. Areas where the presences of the Artesian wells were sparse (i.e., at the Beaverhill lake and in the vicinity of North Saskatchewan River, see Figure 1) were extracted. The correlation coefficient between simulated groundwater fluxes at the land surface and the distance of potentiometric surface above and below land surface is 75% ($p < 0.001$).

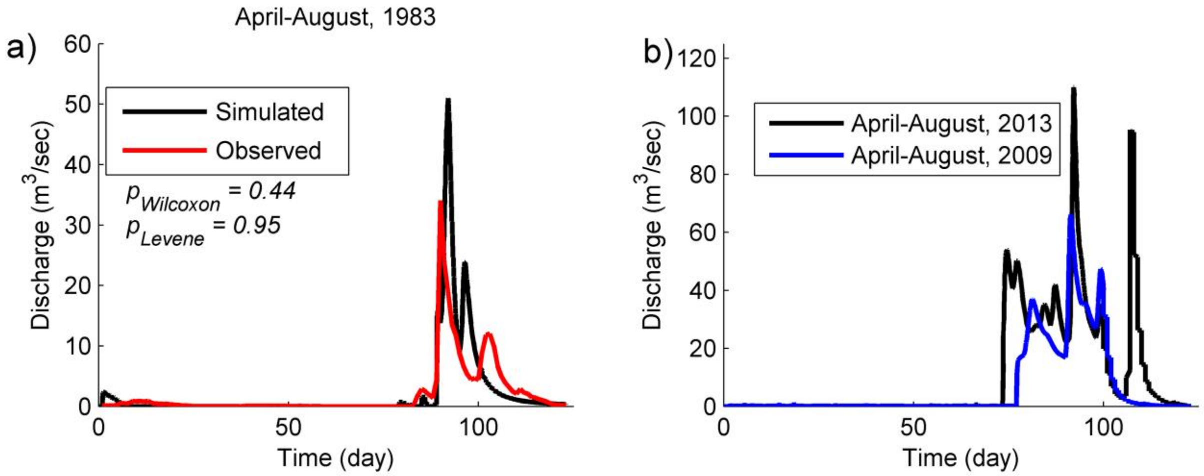

Figure 4: Simulated and observed stream flow at the Beaverhill Creek monitoring station. a) Performance of the developed overland flow model in the simulation of stream flow against observed stream flow from April 1 to August 1, 1983, when stream flow observations were available. The correlation coefficient between observed and simulated hydrographs was 87%(p < 0.001). $P_{wilcoxon}$ and P_{Levene} refer to the P values of Wilcoxon and Levene tests used to assess the similarity in median and variance between two hydrographs. b) Simulated hydrograph from April 1 to August 1, 2013 when the largest net surface water fluxes since 2000 occurred, and from April 1 to August 1, 2009 when the smallest net surface water fluxes since 2000 occurred.

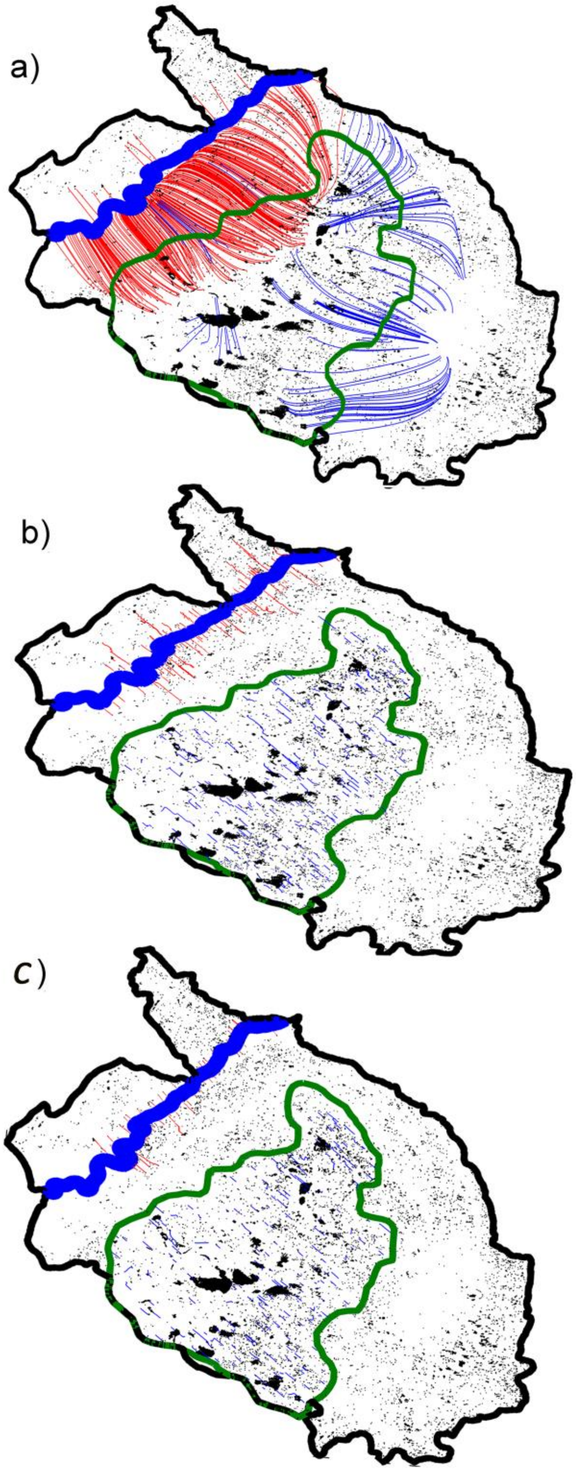

Figure 5: Hydrologic connectivity among wetlands (blue lines) and between wetlands and North Saskatchewan River (red lines). a) Map of subsurface connections, only particles released from recharge wetlands located in the moraine and reached the Beaverhill lake and discharge wetlands (blue lines), and particles discharged into North Saskatchewan River from recharge wetlands (red lines) are shown. b) Map of surface connections for the period from April 1 to August 2013, when the largest net surface water fluxes since 2000 occurred. c) Map of surface connections for the period from April 1 to August 2009, when the smallest net surface water fluxes since 2000 occurred. Only surface connections between wetlands and North Saskatchewan River (red lines), and connections among wetlands within the Moraine (blue lines) are shown.

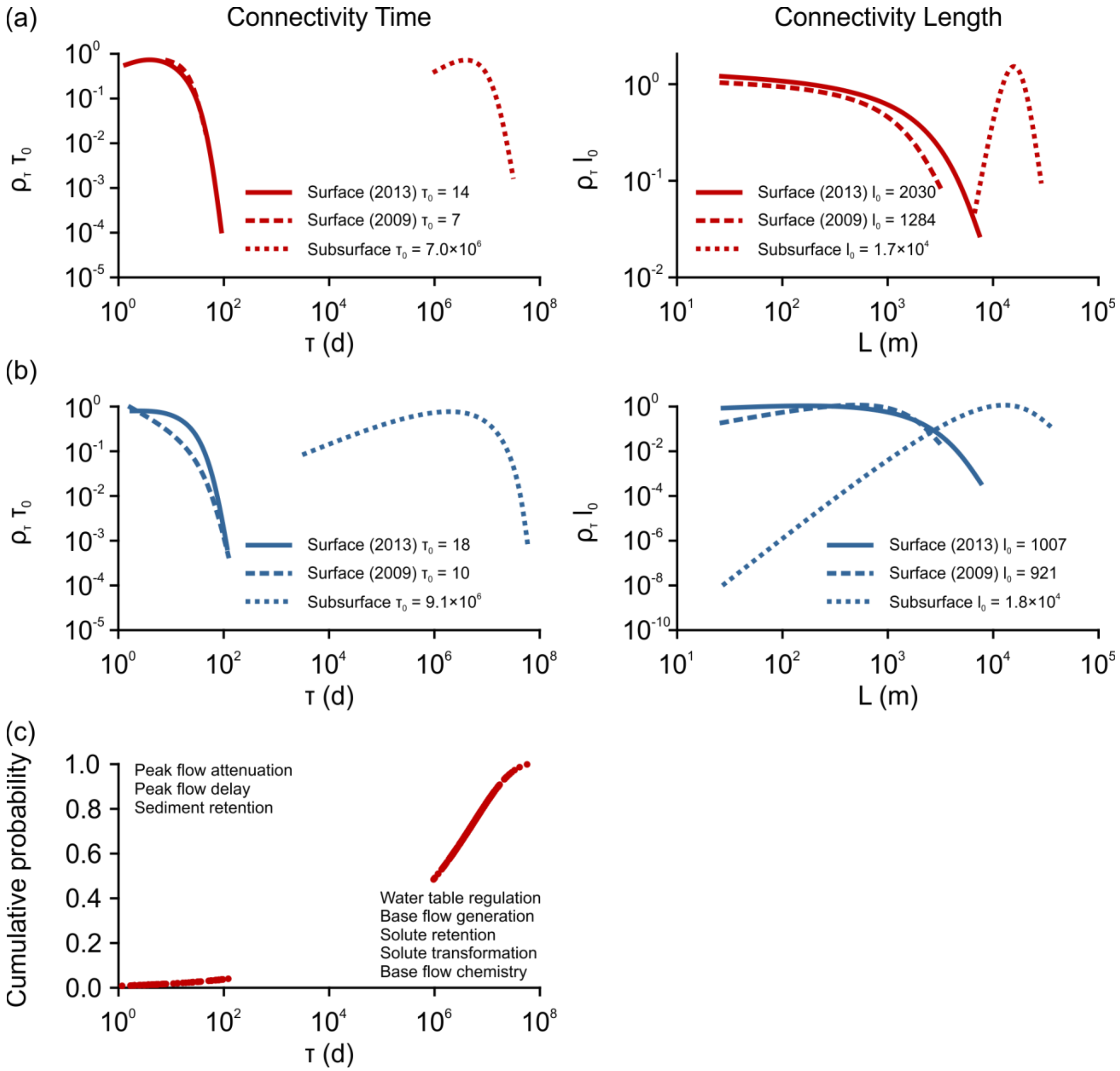

Figure 6: Fitted probability density function of subsurface or surface (both 2009 and 2013) connection transit times (left panel) and lengths (right panel) a) between wetlands and North Saskatchewan River, and b) from wetlands located in the moraine and other wetlands throughout the watershed. l₀ [m] and τ₀ [d] refer to the average length and transit time, respectively. c) Cumulative probability of transit time distribution of water particles discharged from wetlands into North Saskatchewan River. The potential ecosystem services of each portion were also shown.

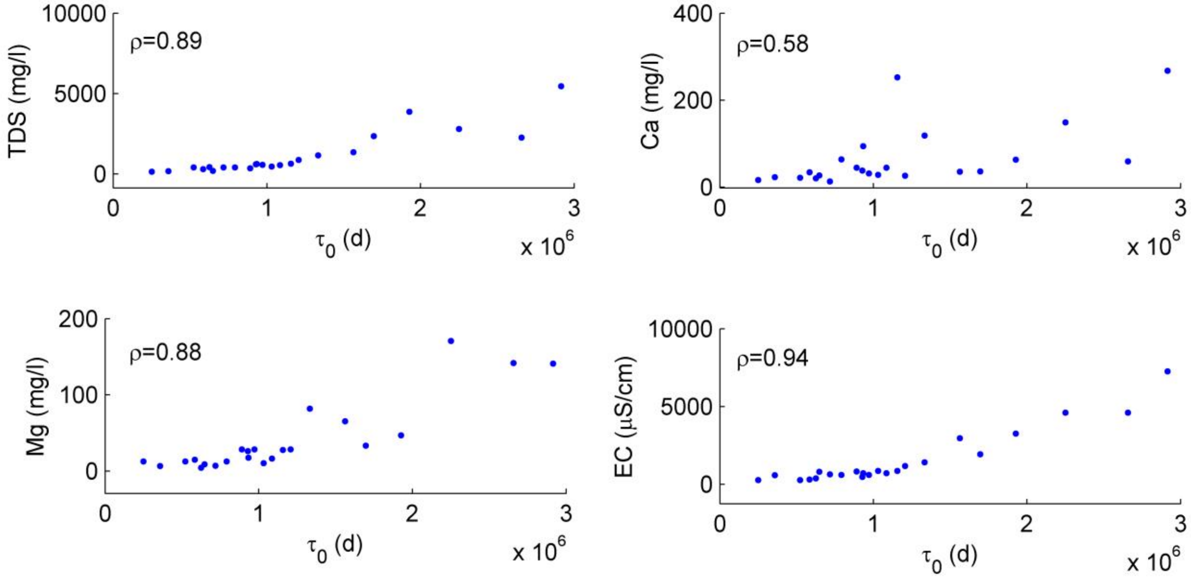

Figure 7: Relation between simulated subsurface mean transit time (τ_0) of each discharge wetland and the concentration of various chemical constituents in the wetland. Here, the pathlines discharged into each wetland and their associated transit times were calculated by back tracking from 100 uniformly-distributed particle release points located at each discharge wetland. ρ refers to the correlation coefficient between τ_0 chemical concentrations.

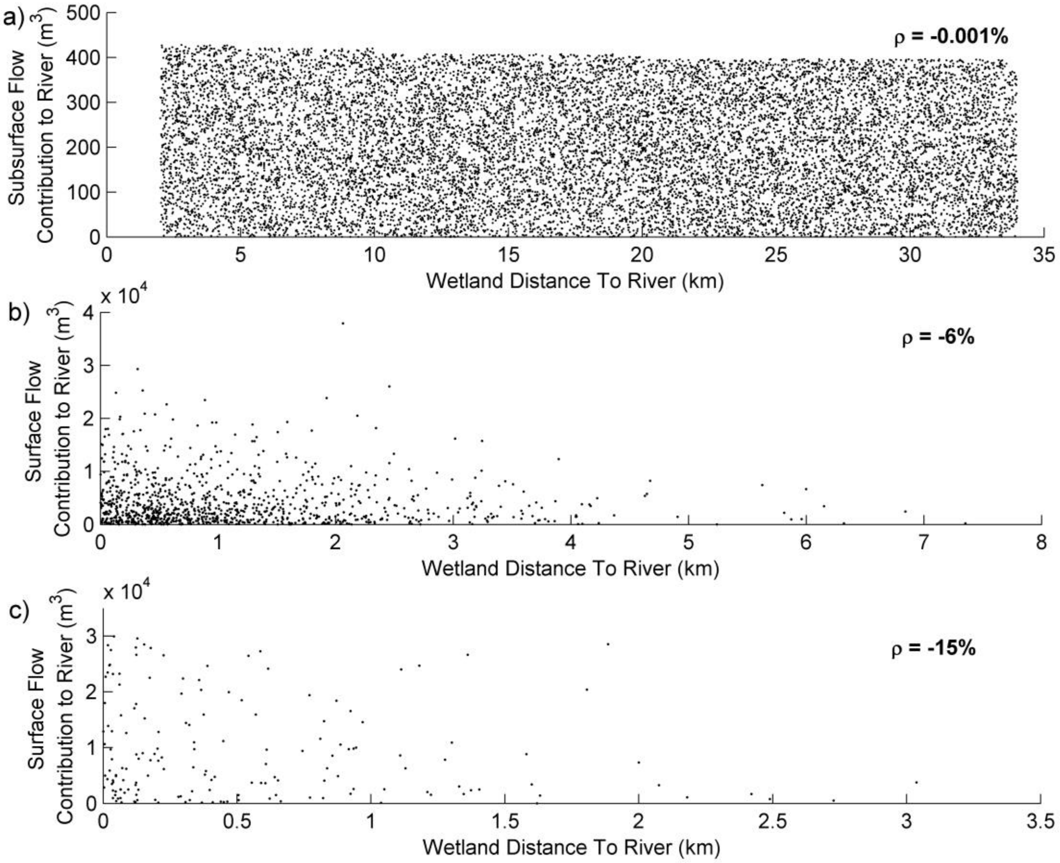

Figure 8 The relationship between flow contribution of each wetland to the North Saskatchewan River and the distance of the wetland to the North Saskatchewan River. a) Subsurface flow contribution-distance relationship. Flow contribution was calculated for four months for each wetland using the steady-state model. b) Surface (April 1 to August 2013) flow contribution-distance relationship. Flow contribution was calculated for four months (April 1 to August 2013) using the transient model. c) Surface (April 1 to August 2009) flow contribution-distance relationship. Flow contribution was calculated for four months (April 1 to August 2009) using the transient model.

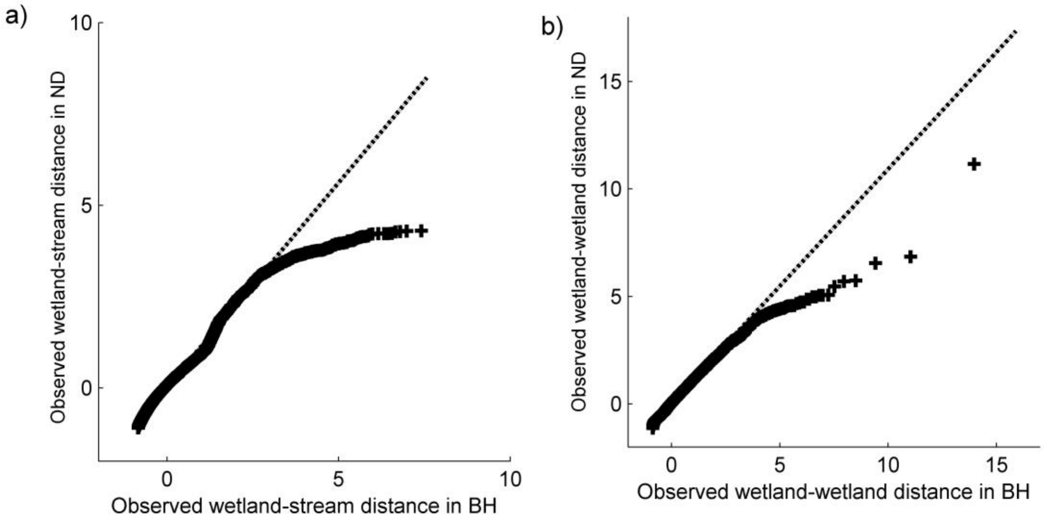

Figure 9: Quantile-Quantile (Q-Q) plot comparing the distributions of observed shortest distances between surface water bodies in Beaverhill watershed (BH) and prairie potholes in North Dakota (ND). (a) Standardized wetland-stream distance (observed shortest distances of wetland to nearest major stream) in the Beaverhill watershed (BH) vs. standardized wetland-stream distance in prairie potholes in North Dakota (ND). (b) Standardized wetland-wetland distance (observed shortest distances of wetlands to their nearest wetland neighbor) in the Beaverhill watershed (BH) vs. standardized observed wetland-wetland distance in prairie potholes in North Dakota (ND).