Response to Referee #2

General comments:

The authors report on a bromide tracer experiment that took place in a single highcentered polygon and a single low-centered polygon in northern Alaska at the Barrow NGEE-Arctic site. The tracer was applied in 2015 and then measured through several sampling ports installed at different locations and depths across the polygon, including in adjacent troughs. The field conditions at the site are difficult and the thaw season is short; hence, the amount of data is sparse, as is the potential to conduct similar experiments across a larger number of polygons. The authors used a 1-D analytical solution to the convective-dispersion equation to estimate subsurface flow parameters, including vertical and lateral hydraulic conductivity (it appears that retardation factor was assumed based on a literature value). The comments below identify a number of areas that need further consideration. For example, the analytical solution assumes a point application, but the tracer in this case was applied to a large area; how should we interpret the boundary conditions used to determine lateral transport parameters? Also, the authors did not include any soil temperature in the manuscript, which would help identify freeze up and thaw, and the potential existence of ice lenses that would almost certainly impact the uniformity of vertical soil water flow. Without these data, the authors relied on conjecture to explain non-uniform transport behavior through the upper thawed soil. It is recommended that the authors include the time-series data on ice table depth, thus potentially helping here. Other comments are found below.
Specific comments – comments called out by x/y, where x is page and y is line number

We appreciate the time and careful consideration the reviewer has given to this manuscript. Comments regarding the analytical solution were particularly helpful in strengthening the position of our research. All aspects of the general comments are addressed in the specific comments below.

Specific comments:

3/8 – authors should clarify here that only one high-centered polygon and one lowcentered polygon were analyzed. As written, it appears that multiple polygons of both types were studied.
Text has been modified:

*"*The purpose of this paper is to examine how differently a low- and high-centered polygon behave hydrologically…*"*

4/15 – what was the total area into which bromide tracer was applied?
Additional text added to include area of tracer application for each polygon:

"Blue circle indicates area of tracer application and encompasses the polygon center: 167.4 m^2 for the low-center polygon and 41.6 m^2 for the high-center polygon"

5/8 – swap Figs. 4a and 4b to follow the order of call outs. Also, the description of the field setup using the silicon sheets doesn't appear on the subfigures. Suggest showing more detail in the schematic, so that the reader can note the silicon sheet, and that "surface" equals ground surface in current Fig. 4b.

Agree – this is a good suggestion. We have updated the figure and figure call outs according to feedback.

5/26 – does the HCP have rims, as indicated in the sentence?
Usual descriptions include centers, rims, troughs – we are trying to stick to established convention.

6/18 – given that ponded water apparently existed in the LCP during tracer application, any information on soil water content to confirm that the thawed soil was fully wetted?
Stating that the water was ponded during this time was an error – we have removed this language.

6/30 – any soil temperature here or elsewhere at BEO that might be applicable here? Also, it would be helpful for the authors to add a table (here or SI) that lists the frost table depth with time, especially given the importance to lateral transport and heterogeneity of the frost table depth.

Yes, temperature has been collected in proximity to these polygons, but the data does not necessarily reflect frost table position. However data from these other studies do show seasonal trends:
https://ngee-arctic.ornl.gov/data/pages/NGA167.html
https://ngee-arctic.ornl.gov/data/pages/NGA118.html
As for frost table data, we will place frost table depth with time in supplemental information.

Figure 5 – suggest adding calendar date to either the x-axis or the caption, so that the reader can understand year-to-year variability of onset of thaw
Caption text changed to include dates:

"Precipitation events, from July 3, 2015 to September 30, 2016, used in the calculation of characteristics of well response."

8/10 – van Genuchten and Alves (1982) solution assumes 1D transport, or in the context of this experiment, a point application of tracer. How does the broad area of application square with this assumption? Was it only used to estimate velocities during that segment of the flowpath, and then a second calculation for estimating horizontal flow? How is lateral distance determined for those sampling clusters outside of the application area? Also note that the van Genuchten and Alves reference on 24/33 is incomplete.

The reviewer is correct, the analytical solution by van Genuchten and Alves (1982) is for an infinite one-dimensional system, not for a broad area. In this manuscript, the analytical solution is used to describe the fate and transport of the tracer in a typical flow path with the boundary conditions imposed at the surface of the experimental domain. This conceptualization is a parsimonious approach to explore the first-order factors controlling fate and transport and time scales within this complex system. A more detailed modeling approach is out of the scope of this work, but it will be a future contribution. Finally, the lateral distances are estimated as the distance from the sampling cluster to the edge of the polygon center (tracer application area), a simplification used to estimate the order-of-magnitude of the solute arrival times and hydraulic conductivities. Essentially, a point to point solution is appropriate in this case.

We have added the following language to the paper to emphasize this point and the assumptions of the analysis - Page 8, line 6:

"To this end, velocities were estimated by assuming that the transport of the tracer within the polygons can be approximated as a one-dimensional advective-dispersive problem with adsorption effects – a reasonable assumption given the lack of information and uncertainty in the spatial distribution of hydraulic parameters. This is a parsimonious approach to explore the first-order factors controlling fate and transport and time scales within this complex system."

We have also modified text on Page 9, line 2:
"…x [cm] is the lateral distance from the sampling nests to the edge of the tracer application area."

Also note that the van Genuchten and Alves reference on 24/33 is incomplete
This is a good catch. We have updated the reference.

9/5 – check table 2. As presented, neither background concentrations nor tracer injection data are included
The reviewer is correct. We have removed the reference to Table 2 – this is a vestige from an earlier version of the paper. Background concentrations and tracer injection data are presented in the following sentence (page 9, line 5).

9/9 – the retardation factor for Korom's experiment were for sediment with a pH of between 5.1 and 5.7. According to Goldberg and Kabengi (2010, doi:10.2136/vzj2010.0028), retardation of bromide is very pH dependent. In some cases, bromide transport in soil with can lead to retardation factors significantly less than one (see for example Hills et al., 1991, WRR, paper 91WR015). How do the soil conditions at the Barrow site compare with those from Korom? Are the data robust enough to estimate R either through parameter estimation or other means? Given how R scales the tracer velocity, so more thought on this issue is warranted.
We thank the reviewer for pointing this out. The soil conditions at the Barrow site are comparable to those from Korom . We have included the following for clarification:

"With an average pH of 5.6 in the study area (Newman et al.), the retardation factor was approximated as R=1.56 (Korom, 2000) – a reasonable value given the pH in Korom's experiment was between 5.1 and 5.7."

9/23 – any particular reason why sampling and analyses occurred for only two years, when it became clear that tracer recovery would be so low?
Yes, funding was limited. The extensive sampling array and analytical costs became prohibitive. Also, this paper is based on my Master's thesis and my Master's degree program came to an end.

9/25 – here and elsewhere, it is suggested that the authors refer to tracer application in the polygon interior, rather than application in the polygon center. Indeed, most of the interior of the polygon received tracer, rather than a point application.
It is a well-established convention to refer to this microtopographic feature of the ice-wedge polygon as the polygon center. We wish to adhere to this convention in order to avoid confusion.

10/8 – if I understand the narrative correctly, the polygon was represented as an idealized vertical cylinder, and the flux was estimated through the bottom of the cylinder based on measurements from the rhizon nests, is that correct? Was the flux then used as initial conditions for the lateral flow the nests outside of the cylinder?
To clarify, the polygons were represented as idealized cylinders and lateral flux was estimated through the sides of the cylinder, not the bottom. This flux estimate was based on measurements from the most distal rhizon nests (troughs). In other words, the most distal rhizon nests would be located at the sides of the cylinder (edge of the polygon) rather than outside of the cylinder, so flux was not used as an initial condition for flow to the very same rhizon nests. We have modified the text for clarification:

Page 10, line 10:
"Second, flux was calculated <u>through the side of the cylinder</u>…."

11 (general) – the authors seem to bounce from LCP and HCP results, first referring to water levels, then to delta H values for both. It would be easier to discuss LCP first, then HCP second
Agree – We have rearranged this section as the reviewer suggests.

Figure 8 – Fig. 8a shows location of GPR measurements and results, but not frost table slope, and Fig. 8b shows frost table slope but not GPR measurements. Could both results be shown for both polygons?
Both Figure 8a and 8b show GPR measurements. As explained in section 2.5, the spatial density of the GPR data at the high-center polygon was sufficient enough to produce an elevation map of the frost table, which is what Figure 8b depicts (see legend). As for Figure 8a, the spatial

density of the GPR survey was not sufficient to produce an elevation map of the frost table. Therefore, a frost table slope could not be determined.

Text modified in figure caption to clarify – page 12, line 14:

"Note that transect lines indicate frost table elevation at the low-centerd polygon (a) while topo lines indicate frost table elevation at the high-centered polygon (b)."

14/2 – replace "Surface" with "Trough"
This sentence is referring to surface water in the troughs and it is important to distinguish this from subsurface water collected in the troughs. We have modified this sentence for clarity:

"Surface water samples collected from troughs during 2016 did not show a clear trend of increasing tracer concentration (Fig 10a)."

14/5 – similar to the comment above, any soil temperature data that could help interpret these results in successive years? The reduced concentration from the end of 2015 to the beginning of 2016 is puzzling and potentially indicates transport even though water appeared frozen.
We appreciate the suggestion. As stated above, we will place frost table depth with time in supplemental information. As discussed in section 4.2 of the paper, there does appear to be a reduced concentration from the end of 2015 to the beginning of 2016 and we have provided some possible reasons why this occurred.

15/22 – are the authors stating that tracer recovery of 4.80% is actually a high estimate?
Yes, we are stating that we consider 4.80% to be a high estimate for the lower bounding value. Because of spatial variability and different tracer arrival times and concentrations, the mass balance is presented as a range with 4.80% at the low end of this range.

15/25 – when authors refer to polygon 'center,' is this really the polygon 'interior?'
We thank the reviewer for this comment. We have modified the text for clarification:

"Even though these estimates have large uncertainties, it appears that most of the tracer remains within the interior of both polygon centers."

16/21 – authors are using either preferential flowpaths or heterogeneity of subsurface media as possible reasons for non-uniform vertical flow, or bypass flow around shallow samplers. A third explanation here is that the soil has undergone partial melting or partial freezing, reducing liquid water-filled transport pathways, and facilitating transport through specific pathways. This might also explain why tracers are changing concentration so drastically between thaw seasons.
We have added this to our discussion of ice lenses and CT scans of frozen cores:

"These patterns may also be indicative of partial melting or partial freezing of the soil profile as a driver of heterogeneous flow."

Figure 12 – though the figures are interesting, there's not enough explanation behind them to know whether the conditions represented by these images are the same as those observed at the traced polygons. It is suggested that the authors either more closely tie the images from Romanovsky to the site being reported on here, or consider removing the figures altogether.

These cores were collected within same general study area (BEO) in similar polygons. We obviously could not core before our experiment because it would have confounded the tracer test.