Our replies to referee comments (black italics) are provided below in blue.

Author response to Anonymous Referee #1:
Anonymous Referee #1 comments:

General comment

This works uses hydrochemical data to describe and infer runoff generation processes in the subcatchments of the Rocky Mountains. The topic is certainly interesting for the readership of HESS. The manuscript is generally well written. However, there are two main points that do not sound convincing to me: i) the focus on catchment resilience and disturbance, that do not appear to be logically linked to the investigations carried out and sounds out of context; ii) the presence of hydrochemical data only: despite the powerful nature of hydrochemistry as hydrological tracer, the combination of racer data and hydrometric data can help to unravel the complexity of hydrological processes at the catchment scales. Thus, the manuscript fails to describe in a robust, quantitative, and convincing way how water moves through this landscape in response to both rainfall and snowmelt. As a result, a clear contribution of this study to the body of knowledge is not evident. Please, find some specific and minor comments below.
Reply: The authors thank the referee for their comments.

i) Hydrological resilience observed in this region (e.g., Harder et al., 2015; Goodbrand and Anderson, 2016) was the motivation to undertake this research. Others have suggested that complex subsurface flow pathways and large subsurface storage are potential factors that lead to hydrologic resilience (Harder et al., 2015) but, critically, little is known about runoff generation in the eastern slopes of Alberta's Rocky Mountains. To address this evidence gap, developing a conceptualization of groundwater-surface water interactions and runoff generation processes was the first step towards understanding why this region appears to be resilient to change. Despite this, we understand the referee's concerns about the lack of linkage between resilience and the research presented in our draft manuscript. To address the concerns of the referee, the draft Introduction has been reformulated to more clearly draw attention to the poor current understanding of runoff generation in regions with both highly permeable bedrock and deep soils/glacial till in contrast to conceptually less complex and comparatively well studied systems with impermeable bedrock and shallow soils because this was ultimately our intention. We believe this more clearly establishes the impact of this work in advancing the body of knowledge on catchment scale runoff generation. All references to watershed resilience have been removed as suggested.

ii) We agree with the referee's comment regarding coupled geochemical and hydrological data to unravel hydrologic behaviour at the watershed scale. Indeed, this study is part of a larger research project that has been published in part. Our first published manuscript includes estimates of dynamic storage by water balance method, a hydrograph recession analysis to infer groundwater contributions, snowfall-runoff ratio relationships to understand the influence of pre-winter storage, and hydrograph response at the storm scale in wet and dry seasons (Spencer et al. 2019). These analyses were used to develop a conceptual model of storage and runoff generation for alpine and subalpine/montane regions in Star Creek. This was the first step in understanding runoff generation in regions with glacial till overlaying permeable sedimentary bedrock. The aim of this draft manuscript submitted to HESS is to develop further lines of evidence to address the complexity of runoff generation in this region. While Harder et al. (2015) postulated that this region has complex subsurface flow pathways, to our knowledge, no studies have characterized runoff generation in the subalpine region of Alberta's Rocky Mountains. The Introduction of the present draft manuscript has been reformulated to stress the connection with Spencer et al. (2019) and position this research in context with other regions with shallow soils and impermeable bedrock.

It was an oversight not to include any data that shows the runoff patterns in the draft manuscript. Figure 3 new has been added to link observed inputs (daily precipitation and continuous snow depth) to observed responses (specific discharge, stream water chemistry, and shallow groundwater levels). Similar figures are often presented along with hydrochemical data in other publications (e.g., Blumstock et al., 2015; Barthold et al., 2017; Ali et al., 2010; Cowie et al., 2017; Inamdar et al., 2013; Hoeg et al., 2000; Sueker et al., 2000; Correa et al., 2019). A table with precipitation event characteristics is also often presented in conjunction with the hydrographs; however, storms were not the focus of our study so other metrics such as average annual discharge, percent of streamflow that occurs from May to July, and annual peak flow have been added to further characterize the hydrological setting.

We have not included unmixing model results because of the violation of multiple EMMA assumptions. We had explored this option before and decided that the errors associated with the percent contributions outweighed the potential contributions. This is similar to Hoeg et al., (2000) who found geographic hydrograph separations did not lead to conclusive results, and Inamdar et al., (2013), who suggested that caution should be applied when calculating percent contributions where there is large variation in end members and assumptions are violated. If the critical assumptions of EMMA were not violated, we would also have examined model accuracy using virtual mixtures of the sampled water sources since model tests using such mixtures are becoming more commonplace in the international literature using source apportionment methods. However, as we state above, assumption violation precludes inclusion of such work.

Specific comments from Reviewer 1:

The abstract is a bit vague. The motivation sounds weak, there are no specific objectives, the methods are partly unclear (water sources were sampled for what kind of analysis?), and the concept of hydrological resilience is not specified. I suggest revising it entirely.
Reply: This comment is connected with this referee's general comments above. The abstract has been heavily revised to reflect the changes in the revised Introduction and Discussion and to clarify the conclusions that were made in relation to runoff generation.

- The Introduction fails to clearly stress what it is not well known about the specific topic and what is the main research gap, and the reader, at the end of the Introduction is left wondering why another study on streamflow contribution is needed. An overall objective and testable hypothesis is not reported. The two specific objectives are introduced quite abruptly, without a clear and logical connection with the paragraph above. I suggest to heavily revise the Introduction to keep these points into consideration.

Reply: This comment also reflects the referee's general comments above. The draft Introduction has been heavily revised to better clarify research gaps and the concomitant rationale for this study.

- 190-208. I suggest to consider the work by Barthold (2001) and to specify the reported approaches were preferred over this method. Moreover, briefly mention how TVR and LDA work to allow the reader better understanding the methods that were used.
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2011WR010604

Reply: The draft text has been revised to specify why the approach used here was preferred over the method outlined in Barthold et al. (2011).

"Although others have often used the selection criteria presented in Barthold et al. (2011), an inability to run the unmixing routine (stream water fell outside the bounds of the source water; see Results) hindered the use of these methods. Rather, the tracer variability ratio (TVR; explained below) and linear discriminant analysis (LDA; explained below) have been presented as effective parameters to subjectively determine if tracers are included in the analysis and if sources are well separated or grouped appropriately, respectively (Pulley et al., 2015; Pulley and Collins, 2018; and others – see comprehensive review in Collins et al., 2017)."

The explanation of how TVR and LDA work has been expanded.

"TVR was calculated using the following equation: the percent difference between source group median divided by the average coefficient of variation between group pairs, for each tracer pair and compared between each group (Pulley et al., 2015)."

"LDA optimizes separation between centroid of group clusters by partitioning the variation across each tracer and weighing that variation into two axes (reducing the dimensionality). Other statistical classification methods, such as hierarchical clustering or k-means clustering, were not appropriate because source categories were known a priori. The data were processed in R (R Core Team, 2014) using 'lda' function in the MASS package (Venables and Ripley, 2002) to reduce dimensionality and assess the separation visually and the klaR ('stepwise' function; Weihs et al., 2005) package to model the data and determine the ability to separate groups statistically. The 'stepwise' function models the data while removing individual tracers iteratively. The 'backwards' direction was used in an attempt to maintain the most tracers with the 'lda' method, and 'ability to separate' criterion."

- I suggest merging Figs. 5 and 6 (making a multi-panel figure) and sections 5.2.1 ad 5.2.2, and Fig. 7 and 8 and sections 5.2.3 and 5.2.4 in order to present the results from the two subcatchments more organically. Similarly, I recommend merging Section 5.3.1 and 5.3.2 (Star West), and 5.3.3 and 5.3.4 (Star East) to avoid too much text and results in fragmentation.
Reply: These sections and figures have been revised as suggested.

- Since there is, at least in some cases, a strong seasonal pattern in hydrochemistry, I suggest considering making a time series plot of the different water sources in the two subcatchments in order to show, for instance, when and to which extent the stream water signature gets closer to that of hillslope groundwater and riparian water. In addition, the Authors might consider adding times series of groundwater temperatures or boxplots, as this tracer is part of the story and was shown to be able to partly explain groundwater contributions to streamflow.
Reply: Time series plots of various ion concentrations for water sources and stream water have been added as suggested. However, bedrock groundwater was not included in the time series because those samples were collected in 2016 and 2017 while all other samples were collected in 2014 and 2015. These time series plots have replaced the insets in Figures 7 and 8 because they better illustrate the patterns we describe in the text. In addition, a boxplot of groundwater temperatures, stream water temperatures, and seep temperatures has been added as suggested.

- 417-418. Which evidence do the Authors have to infer the temporal dynamics of hillslope water moving to the stream? Moreover, how could the Authors describe old water mobilization without having quantified its proportion in stream water? Or this is a general statement not based on the presented dataset? Please, explain.
Reply: Temporal dynamics of hillslope water moving to the stream are inferred from the PCA plots as stream water is similar to the various source water at different times of the year as well as the time series of streamflow, shallow groundwater and snowmelt (Figure 11). Figure 11 also shows the concentration of calcium increased in the early spring in 2014 just as snowmelt starts and before there is a large response in the stream. Hillslope-stream connectivity was inferred from the shallow water table responses, similar to Jencso et al. (2009). The draft manuscript has been revised to clarify that we are using these lines of evidence to infer the temporal dynamics of hillslope water moving to the stream.

- 464-474. I feel this part is quite out-of-context and disconnected from the previous discussion. In general, I think that focusing on catchment resilience is not so straightforward and sound a bit contrived to me. The same comment applies to the Conclusions.
Reply: All references to catchment resilience have been removed as suggested.

Minor comments and technical corrections:

1. The title is long and complex. I suggest making it more compact and clearer.
Reply: The title has been revised to: “Hillslope and groundwater contributions to streamflow in a Rocky Mountain watershed underlain by glacial till and fractured sedimentary bedrock”.

11. I suggest to change as follows: "A lack of : : :but mechanisms governing: : :".
Reply: This sentence was removed during revision of the draft Abstract.

13. ": : :although much: : :": I cannot see the logical link in this sentence. Please revise.
Reply: The abstract has been revised for clarification and to reflect the changes in the Introduction and additions to the draft manuscript. This sentence has been removed.

13-14. "to interpret how forest disturbance may impact streamflow quantity". I would not focus on understanding runoff generation processes to this aim, but mostly on the ecohydrological role of forest on streamflow. Please, revise.
Reply: The focus of the manuscript has been revised. See reply to general comment and Introduction comment above. The abstract has been revised for clarification and to reflect the changes in the Introduction and additions to the draft manuscript.

22. "but was unlike the measured sources": this sentence is not clear before reading the abstract. Please, clarify.
Reply: Revised to: "Conversely, in Star East, the composition of stream water was similar to hillslope water in August but plotted outside the boundary of the measured sources in September and October. The chemical composition of groundwater seeps followed the same temporal trend as stream water, but consistently cold temperatures of the seeps suggested deep groundwater was likely the source of this late fall streamflow."

29: Perhaps put it more general, mentioning pathogens.
Reply: Revised as suggested.

35. What do the Authors refer to by "features"? Please explain.
Reply: Here, "features" was referring to "watershed features (e.g., bedrock, surficial geology, wetlands)" and has been revised for clarification.

112. ": : :a priori: : :": Was there any evidence, field observation, previous study or knowledge of the area that allowed for this assumption?
Reply: Stream water sources were hypothesized based on field observations and previous knowledge of the area. This research is part of the Southern Rockies Watershed Project, which has been conducting research in this watershed and other watersheds in the area since 2004. As such, the stream water sources were based on local knowledge from working in these mountains. This has been clarified in the text.

193. TVR: please report the definition and possibly the equation to let the reader immediately understand it.
Reply: The text has been re-arranged for clarification. The definition and equation have been stated more explicitly so the reader can immediately understand it.

229-230. This sentence is not clear to me (without reading the cited references). Please specify.
Reply: Revised to: "Greater variation within- compared to between-source groups violates assumption 3) for EMMA (source water does not change) and was considered unacceptable. As a result, rather than calculating mixing ratios or percent contribution of sources to stream water on the basis of an un-mixing routine in EMMA, trends in stream water distribution were described in relation to source water dynamics and runoff processes."

245. leu?
Reply: This was a typo and has been corrected.

269: Perhaps add "compared to bedrock groundwater".
Reply: Sentence has been revised to: "Hillslope groundwater exhibited greater chemical variation across samples (SD of 3.8 and 2.0 for PC1 and PC2, respectively) compared to bedrock groundwater (SD of 2.9 and 4.8 for PC1 and PC2, respectively), but no clear temporal pattern was observed."

Fig. 6b). Could the Authors perhaps colour-code samples for season (spring, summer, fall)?
Reply: Rather than colour-coding, time series have been added to illustrate this pattern. Insets have been removed because time series have made them redundant.

322. Which are these months?
Reply: Text has been revised to: '…months of open-water flow (Apr-Oct)…'

340. Why a source might be missing? Please, explain.
Reply: This sentence was removed when Sections 5.3.1 and 5.3.2 were combined.

393-394: Are groundwater levels available? Their temporal patterns could help understand which feeds which. Perhaps some piezometers could be installed for a follow-up study.
Reply: Groundwater levels are available in the riparian, toe slope and upper hillslope areas. The following sentence has been added: "Timing of riparian and stream water level responses may be used to help clarify these patterns in future research."

429-430. What does "increase in stream water chemistry" mean? Moreover, how would be possible to infer connectivity through hydrochemical data only? Some speculations could be done but a combination of hydrometric and tracer data would serve this purpose better.
Reply: Revised to "increase in stream water ion concentrations".

These water chemistry observations were taken in conjunction with shallow groundwater wells using similar methods as Jencso et al. (2009) to infer connectivity. Figure 11 new has been added to help visualize connectivity in conjunction with stream discharge response and changes in stream chemistry.

431. Contributions to what? Please specify.
Reply: Revised to: 'Source water contributions to the stream…'

433. It cannot be all rain water, can it? Please, revise/explain.

Reply: No, this is not all rain water. It is almost entirely snowmelt as this is a snow-dominated watershed but some summer rain storms would also contribute to runoff. Snowmelt saturates the landscape in May and causes a significant dilution effect in the stream. However, the water that is contributing to the stream is not as dilute as snowmelt water itself, suggesting that there is a mixture of snowmelt and hillslope water contributing to the stream. We state that it is most like precipitation to stress this dilution effect, but not to suggest that the water entering the stream is pure snowmelt or rain. Water chemistry of rainfall and snowmelt were essentially identical so there was no way to separate the contribution of rain and snow.

Text added: "It should be noted that although dilution was observed, stream water was less dilute than snowmelt alone. Snowmelt water interacts with the soil as it moves through the subsurface to the stream directly influencing the chemical composition of the snowmelt contributions to streams (Sueker et al., 2000)."

Possible useful readings for additional analyses and for the discussions section:
Correa, A., Breuer, L., Crespo, P., Célleri, R., Feyen, J., Birkel, C., Silva, C., Windhorst, D., 2019. Spatially distributed hydro-chemical data with tempo-rally high-resolution is needed to adequately assess the hydrological functioning of headwater catchments. Science of The Total Environment 651, 1613–1626. https://doi.org/10.1016/j.scitotenv.2018.09.189
Godsey, S.E., Hartmann, J., Kirchner, J.W., 2019. Catchment chemostasis revisited: Water quality responds differently to variations in weather and climate. Hydrological Processes 33, 3056–3069. https://doi.org/10.1002/hyp.13554
Hoeg, S., Uhlenbrook, S. and Leibundgut, C., 2000. Hydrograph separation in a mountainous catchment - combining hydrochemical and isotopic tracers. Hydrol. Process., 14: 1199-1216. doi:10.1002/(SICI)1099-1085(200005)14:7<1199::AIDHYP35>3.0.CO;2-K
Hrachowitz, M., Bohte, R., Mul, M.L., Bogaard, T.A., Savenije, H.H.G., Uhlenbrook, S., 2011. On the value of combined event runoff and tracer analysis to improve understanding of catchment functioning in a data-scarce semi-arid area. Hydrol. Earth Syst. Sci. 15, 2007–2024.
Nadal-Romero, E., Khorchani, M., Lasanta, T., García-Ruiz, J.M., 2019. Runoff and Solute Outputs under Different Land Uses: Long-Term Results from a Mediterranean Mountain Experimental Station. Water 11, 976. https://doi.org/10.3390/w11050976
Penna, D., van Meerveld, H.J., Zuecco, G., Dalla Fontana, G., Borga, M., 2016. Hydrological response of an Alpine catchment to rainfall and snowmelt events. Journal of Hydrology 537, 382–397. https://doi.org/10.1016/j.jhydrol.2016.03.040
Suecker, J.K., Ryan, J.N., Kendall, C., Jarrett, R.D., 2000. Determination of hydrologic pathways during snowmelt for alpine/subalpine basins, Rocky Mountain National Park, Colorado. Water Resour. Res. 36, 63–75. https://doi.org/10.1029/1999WR900296

Reply: Thank you for these suggestions. These references were incorporated where applicable.

Author response to Editor comment:

This reviewer is very critical about the scientific (added) value of the paper and recommends rejection in the formal reviewer report. This overall assessment is motivated by the statement that "the manuscript fails to describe in a robust, quantitative, and convincing way how water moves through this landscape in response to both rainfall and snowmelt.".

This statement is motivated by two main critics:

"i) the focus on catchment resilience and disturbance, that do not appear to be logically linked to the paper investigations carried out and sounds out of context;

ii) the presence of hydrochemical data only: despite the powerful nature of hydrochemistry as hydrological tracer, the combination of racer data and hydrometric data can help to unravel the complexity of hydrological processes at the catchment scales."

The authors' response to the second point does not contain any detailed plans at this stage. I am waiting for a third editor report but I already invite the authors to provide a more detailed planned how you plan to address the above second point before I can give a recommendation on the submission of a revised version.

Reply: We thank the editor for their comments and clarification on this issue. We have elaborated on our comments and edits to Referee #1 (above).

Author response to Anonymous Referee #2:
Anonymous Referee #2 comments:

Overview

This is an interesting research manuscript with well-defined objectives of using EMMA to understand relative variation in stream water sources in forested and alpine watersheds of the Canadian Rocky Mountains. Overall the manuscript is sound and has relatively minor grammatical errors. However, it is suggested that the introduction and discussion sections more clearly identify the secondary objectives and how the study. It is unclear if the results of this study have a primary goal of improving understanding of the variability between different groundwater sources of (e.g. bedrock groundwater vs. glacial till groundwater) in alpine and sub-alpine watersheds, or to understand/predict how future forest disturbance will impact watershed hydrology and runoff generation.
Reply: Firstly, we thank the referee for their positive comments.

This is a similar comment to the general comments by Referee #1 who suggested that any discussion of hydrologic resilience be removed. We agree that revising the draft Introduction will strengthen the context of this research and clarify that the impetus to conduct this study was to improve our understanding of runoff generation in watersheds with permeable fractured bedrock and deep glacial till (compared to systems with impermeable bedrock and shallow soils that have been more extensively studied). The primary goal was to improve understanding of variability between different groundwater sources, rather than predicting how future forest disturbance will impact watershed hydrology and runoff generation. The draft Introduction and Discussion have been revised for clarification in response to this, and the previous referee's general comments.

It is suggested that the study site description be expanded to more clearly quantify the size and extent of surface and sub-surface biological and geological features (talus slopes, alpine areas, glacial till, forested areas, riparian areas, etc.). It was hard to determine where and why the division of upper and lower sub-watersheds was chosen for this study and how that division was critical to addressing the question of the impacts of forest disturbance on hydrologic disturbance. Both upper and lower sub-watersheds had forested areas so the separation of upper and lower sub-watersheds did not appear to be a proxy for forested vs unforested/disturbed areas.

Reply: The separation between upper and lower watersheds was made in 2008 in anticipation of the Mountain Pine Beetle expanding into our research watersheds (which did not actually occur). The upper stations were positioned at the transition between 1) primarily lodgepole pine dominated forests (upper Montane ecozone) and 2) the narrower band of subalpine fir dominated stands and the treeless alpine valley above this (sub-alpine and alpine ecozones). The higher elevation sub-watersheds would have theoretically been spared from the pine beetle attack allowing for a potential comparison after beetle attack if that had actually occurred. Pine beetle did not reach our research watersheds, so they were maintained as reference watersheds. The upper sites were maintained because they represent the difference between subalpine/alpine zone and the upper montane zone.

The upper montane zone is fully forested, and slopes are slightly gentler. The subalpine/alpine zone is partly forested but also has regions of talus slopes, near vertical bedrock cliffs, and alpine grasses. The streams in the alpine flow over bedrock in some places with colluvial or alluvial material present in other areas. Rather than being a comparison of forested and unforested sub-watersheds, the research presented here capitalized on this nested gauging data to advance the conceptualization from Spencer et al. (2019), comparing subalpine/alpine to upper montane responses.

The draft Study Site description has been expanded to clarify the differences between the upper and lower sub-watersheds. Talus slopes, forests, glacial till, and alpine areas have been added to Figure 1 and the area of surficial deposits have been quantified in the text. Riparian areas have not been added because we do not have accurate measurements of riparian widths at this time.

Secondly, the discussion and conclusion sections should be expanded to more clearly indicate how the results in this study advance or improve the scientific understanding of "how forest disturbance may impact streamflow quantity". It is unclear if the study was able to confirm or reject the hypothesis stated in the abstract that "slow release of groundwater from glacial till" (line 24) generates "hydrologic resilience" in the Rocky Mountains?

Reply: Again, this is a similar issue as raised by Referee #1 who suggested that all sections relating to hydrologic resilience in the Rocky Mountains be removed. The revised section no longer discusses how forest disturbance may impact streamflow quantity. However, discussion surrounding the slow release of groundwater from glacial till remains but has been revised to reflect the removal of the aforementioned discussion.

Line 18: Suggest defining "old water" as related to time the water has spent in the watershed rather than the true age of water.
Reply: Revised to: "An initial displacement of water stored in the hillslope over winter ("reacted water" rather than "unreacted" snowmelt and rainfall) occurred at the onset of snowmelt before stream discharge responded significantly."

Line 20: In Star east in September and October the stream water was unlike the sources. What is the additional source or is it a mixed signal?
Same statement is in the conclusion but the proposed explanation of the "missing" sources is either absent or not clear in the conclusion. Clarification would be helpful.
Reply: The draft Abstract and Conclusion have been revised for clarification of this issue.

Abstract: "Conversely, in Star East, the composition of stream water was similar to hillslope water in August but plotted outside the boundary of the measured sources in September and October. The chemical composition of groundwater seeps followed the same temporal trend as stream water, but consistently cold temperatures of the seeps suggested deep groundwater was likely the source of this late fall streamflow."

Conclusion: "Star West stream water was once again similar to hillslope water or riparian water, but Star East stream water plotted outside the boundary of the measured sources. Seep water temperatures were cool and had low variability suggesting it may be deeper bedrock water contributing to the stream. Slower recession rates (and likely lower hydraulic conductivity) in the till groundwater well than in the bedrock groundwater well suggest that water recharged into the till groundwater may be slowly released to the stream. Contamination of the till groundwater well made it unclear when it was contributing to the stream but groundwater table fluctuations suggested it is likely contributing during late summer or fall."

Line 29: What is the specific reference for beetle infestation? A few Studies from the Rocky Mountains to consider reviewing, Pugh & Small, 2011. https://doi.org/10.1002/eco.239
Bearup et al., 2014. https://doi.org/10.1038/nclimate2198
Reply: Boon (2012) is the specific reference for beetle infestation. The authors incorporated Pugh & Small (2011) and Bearup et al. (2014) as suggested.

Line 53: Consider reference of Cowie et al. (2017) here as that study does use EMMA to examine potential source waters from bedrock groundwater, glacial till groundwater, talus slope water, and soil water on streamflow contributions in forested and alpine watersheds in the Rocky Mountains.
Reply: Cowie et al. (2017) was not initially included in this section of the draft Introduction because bedrock in the Colorado Rocky Mountains is mainly granodiorite, rather than permeable sedimentary bedrock and we were trying to make a distinction between bedrock types. However, Cowie et al. (2017) is relevant to the current knowledge and overall discussion in this paper and has been incorporated into the revised Introduction.

Line 77: Define area weighted precipitation. Was precipitation measured at multiple elevations? With > 1000m elevation change how much does the total precipitation change over that gradient? One suggestion is use of a hypsometric curve to distribute precipitation over elevation (see Cowie et al., 2017)

Reply: Precipitation was measured at nine precipitation gauges in Star Creek and a neighbouring watershed (North York Creek). Spencer et al. (2019) used the thiessen polygon area-weighted method to estimate average watershed precipitation rather than using one particular rain gauge to represent the entire watershed. Both area-weighted and hypsometric approaches are good approximations of average precipitation if rain gauges are distributed across a range of elevations. While our gauges were distributed between 1482 m and 1873 m., vertical headwalls and talus slopes in the alpine basins limited the placement of precipitation gauges above 1900 m and in this case hypsometric-based weighting of precipitation may overestimate precipitation at higher elevations where precipitation inputs to near-vertical surfaces is unclear. Accordingly, we choose to use the well-established thiessen polygon method to spatially weight precipitation from our gauge network to reflect elevation as a key factor driving spatial precipitation (i.e. lapse rates) in our study area.

Text has been revised to: "Average annual precipitation was 720 mm at Star Main (1482 m a.s.l.) and 990 mm at Star Alpine (1732 m a.s.l.; Spencer et al., 2019). The area-weighted average annual precipitation (2005-2018) was 950 mm using the Thiessen-polygon method and nine precipitation gauges at a range of elevations in and surrounding Star Creek; 50-60 % of the precipitation falls in the form of snow (Spencer et al., 2019)."

Line 78: Please cite the precipitation and % snow. Is this from the same study (Spencer et al., 2019) which is cited in the discussion in reference to the sub surface storage capacity of the watersheds?

Reply: Yes, this is the same data from Spencer et al. (2019), although 2015-2018 were added to the years of record. Spencer et al. (2019) has been cited and sentence has been revised to as stated above.

Line 83: "Talus slopes" Please expand this description to include more information on the relative size of this geographic feature in the upper watersheds. Previous studies of source waters to alpine watersheds in the Rocky Mountains (suggested references listed below) indicate that talus slopes and underlying features can be significant source water areas.

Is there any information or indication of permafrost, ice lenses, or rock glaciers in the alpine talus areas that could provide a unique source water?

Caine, N, 2010. Recent hydrologic change in a Colorado alpine basin: an indicator of permafrost thaw? https://doi.org/10.3189/172756411795932074

Clow, D. W., Schrott, L., Webb, R., Campbell, D. H., Torizzo, A., and Dorblaser, M.: Ground water occurence and contributions to streamflow in an alpine catchment, Colorado Front range, Ground Water, 41, 937–950, 2003.

Hood, J. L., Roy, J. W., and Hayashi, M.: Importance of groundwater in the water balance of an alpine headwater lake, Geophys. Res. Lett., 33, L13405, doi:10.1029/2006GL026611, 2006.

Roy and Hayashi, 2009. Multiple, distinct groundwater flow systems of a single moraine-talus feature in an alpine watershed. https://doi.org/10.1016/j.jhydrol.2009.04.018

Williams et al., 2006. Geochemistry and source waters of rock glacier outflow, Colorado Front Range.

https://doi.org/10.1002/ppp.535

Reply: Talus slopes (where present) terminate below the near-vertical headwalls the alpine region and in some cases at the transition between alpine-forested regions of the watershed. Streams or tributary features flowing overland from the talus slopes have not be observed. Snowmelt and rain may be temporarily stored in talus slopes as documented in other Rocky Mountain watersheds (Cowie et al., 2017; Clow et al. 2003; Hood and Hayashi et al., 2015; McClymont et al., 2010), but it is highly likely that this water would infiltrate into the subsurface prior to arriving in the stream, thereby changing the chemical concentrations of this water. Permafrost, ice lenses, or rock glaciers are not present in the alpine talus areas of this region based on the data we have from the Alberta Geologic Society, so it is unlikely that they could serve as a potential unidentified source. The draft Study Site description has been heavily revised to address these comments.

The description of geographic features has been expanded so differences between Star Creek and other Rocky Mountain watersheds (indicated above) has been clarified.

Line 86: Can the amount of glacial till deposits be estimated or quantified for the sub-watersheds? There is no indication of spatial extent beyond description on line 80. It would help the reader to understand the potential storage capacity of the till especially since till water was excluded as a potential source water due to sampling well contamination (line 181). One suggestion is moving the citation on line 444 (AGS, 2004) to section 2 study site description and elaborating on the description of the "spatially heterogenous surficial deposits…" to help describe the watershed(s) in more detail.

Reply: The description of geologic features has been expanded in the revised Study Site description. Data from the Alberta Geologic Society was used to estimate the extent of glacial till deposits and the geospatial distribution was added to Figure 1. Talus slopes were digitized from an orthoimage in ArcGIS and added to Figure 1. Unfortunately, beyond the spatial extent shown in Figure 1 and on the ground inspection of exposed till (observed clay layers vs. unsorted clay to boulder sized material), little is known about the thickness and composition of the glacial till.

The statement "heterogeneous surficial deposits and geology" is based on the fact that across the 10 km^2 watershed, there is variability in surficial deposits (e.g., slightly leached till, cirque till, colluvium), geologic formations (various geologic formations, although they are all primarily composed of shale and sandstone) and distribution of fractures and faults. As indicated above, the draft Study Site description has been heavily revised to address these comments and the comments above.

Line 95: Figure 1. It would be helpful to define tree line (separation of alpine from forested area within the sub-watershed. Important because the paper is framed as a study related to "forest disturbance" so the alpine portion of the study areas should be clearly separated from the forested areas.
Also please add the locations of the seeps that were sampled and used as potential end members in EMMA.

Reply: The extent of the forested area and seep locations have been added to Figure 1.

Line 125: Snowmelt collection methods. Perhaps expand explanation of the snowmelt sample timing in order to reduce known uncertainty of changes in snowmelt chemistry related to timing of the melt.

There is a known ionic pulse at the initiation of snowmelt (see Williams et al., 2009), which can be followed by dilute meltwater.
Reply: In general, snowmelt samples were collected at random and opportunistically when our field crew happened to be on site rather than at specific intervals. “The timing of sample collection was based on access to backcountry sites and were taken opportunistically when crews were in the area and were able to observe active snowmelt” has been added to the sampling description to clarify the sampling regime.

Time series of stream and source water have been added to the manuscript to address comments by Referee #1. These time series show the presence of a pulse in ion concentration at the onset of snowmelt in 2014 but not in 2015. Samples collected in early May in 2014 had elevated concentrations of ions compared to samples collected in early June. The pulse of higher concentrated meltwater was likely missed in 2015 due to the very early melt. The known ionic pulse in snowmelt to which Referee #2 is referring is very interesting and has been added to the discussion: “Although three snowmelt samples in 2014 showed similar ionic pulses early in the snowmelt season to those reported in the Colorado Rocky Mountains (Williams et al., 2009), the concentrations were notably less than from all other sources and thus not likely an important source of the observed early season increase in stream water concentration of some ions.”

Are there any occurrences of dust on other impurities in the snowpack in this region which could impact the snowmelt chemistry or the timing and magnitude of snowmelt? Dry deposition was mentioned for rain water collection (line 121) but not for snowmelt.
Reply: Dry deposition of dust/dirt can be a problem in the summer when the landscape is directly exposed to wind but is not an issue in the winter when the ground is frozen and snow covered. Dry deposition from major cities and industrial areas is not known to be a problem because neither are in proximity to the study site. However, organic material shed and transported by wind from forest vegetation and excreted from wild animals would be deposited onto the snowpack.

Line 171: Is the data from the Hobo sensors used in this paper? If not then this method does not support the paper and should be removed.
Reply: Data from Hobo sensors were used in Figure 13 and to determine the temperature range of bedrock and till groundwater in wells (Figure 5).

Line 274: Bedrock groundwater, “excluded as a source at the upper sites”. Please explain how the groundwater seep used in SEU (line 313, figure 8b) was classified as having consistently cool GW temperatures, but was not considered to be a “bedrock groundwater source”?
Reply: These sections have been revised for clarification.

“Bedrock groundwater samples were collected from a lower elevation in the watershed and may not be representative of higher elevation groundwater chemical composition; therefore, they were excluded from the analysis for the upper sites. Further, there were only two seeps identified in the upper watershed, but the temperature and chemical composition of these seeps were not reflective of bedrock groundwater. While this did not exclude bedrock groundwater contributions to streamflow in the upper regions of the watershed, it showed the chemical composition of the bedrock well and the two seeps may not have been representative of the bedrock groundwater chemistry in the Star West Upper sub-watershed."

"A single groundwater seep was identified in SEU. The seep was chemically similar to stream water but temperatures were consistently cool and indicative of a deep groundwater source so it was retained to aid in the explanation of stream water dynamics (Figures 8 and 9)."

Line 276: Suggest replacement of "a couple samples" with a more quantitative description.
Reply: Revised to: "…except for four snow samples and one rain sample…"

Figures 5-8: Suggest a more detailed explanation of the hysteresis present in the stream water samples. One option is to place the day of year (DOY) on each sample so readers can decipher movement within months which are plotted as one color. For example in figure 7A are the September samples temporally migrating in the mixing space or are sample points randomly distributed?
Reply: We tried adding the Julian day to the figure but there are two years of data in the figure so adding dates created too much clutter and did not contribute to the description of hysteresis. In general, sample points are randomly distributed so categorizing by month is the smallest timestep that we can show in these figures. However, the time series (Figures 7, 9, and 10) that have been added to the revised manuscript help illustrate patterns in the chemical composition of stream and source water at a finer scale.

Detailed explanation of the hysteresis patterns has also been added to the discussion: "Differences in the east and west forks were also evident in the hysteresis pattern in stream water chemistry from spring to fall. Star West sub-watersheds had a counterclockwise pattern, whereas Star East sub-watersheds had a clockwise pattern. In general, this is an artefact of the PCA analysis driven by the specific ions that defined each PC (Table 1). In Star East, the first PCs were dominated by anions and the second PCs were dominated by SO_4^{2-} (negative relationship). While the first PCs for Star West were dominated by anions, the second PCs included a mix of anions and cations and SO_4^{2-} with a positive correlation thereby producing an opposite hysteresis pattern. Although this is an artefact of the PCA analysis, it was ultimately due to slight variations in the sources contributing to the streams at different times during the flow season."

Figures 7 and 8: SEU and SEL both appear to have an unidentified source water in October as the October samples plot further away from the identified potential end-members. A more detailed interpretation of this observation is recommended for the discussion?
Reply: The discussion surrounding the unidentified source in October has been greatly expanded as suggested. See Paragraph 8 in discussion.

Line 325: Section 5.3: It is understood that you were not able to sample in the winter, however you state that sampling stopped "before fall rains" (line) in previous section and in this section the "end" of seasonal sampling is stated as "start of the next year's snow accumulation period" (line 326). Just want to be clear on the terms used to describe the end of seasonal study periods.
Reply: Groundwater seeps were sampled only three times a year due to the large amount of resources it

required compared to other sources. All other sources (other than snow) were sampled between April and October. The description for groundwater seep sampling has been revised to clarify this difference.

Added text: "This sampling campaign required more resources than for other sources, as a result sampling was completed only three times a year during hydrologically important extreme flow conditions rather than every two weeks from April to October as for other sources."

If precipitation is lumped by rain and snow how do you know which form of precipitation is influencing stream flow in which season? For example line 342, the stream is "more similar to precipitation in June and July" Is this recent precipitation from rain or assumed to be the lagged input of snowmelt from the previous winter?
What would be helpful is a hyetograph over the study period so reader has some better sense of when the annual precipitation occurs. Also is there a way to present the timing and magnitude of snowmelt? Figure 10 suggests that there are multiple snowmelt pulses in winter and spring, can this be elaborated in the description of site climate and hydrologic inputs?
Reply: Ion concentrations of rainfall and snowmelt were essentially identical so there is no way to distinguish between these two sources based on the chemistry we have (we do not have isotopes). Thus, the lagged input of snowmelt and recent rainfall inputs cannot be separated. Further, the 2-week sampling schedule did not allow for the resolution needed to really identify a rainfall pulse moving through the watershed. Figure 11 (new) has been added to better describe the relationships between when snowmelt was occurring (snow depth time series), the distribution of daily precipitation (snow vs rain), shallow water table responses, and the annual hydrograph. Stream water chemistry has also been included to show how snowmelt dilutes stream water chemistry over the melt period and the recovery (increase) in concentration later in the summer. Continuous snow depth measurements are used in lieu of snow pillow data (snow water equivalent) because SWE was not available. Thus, while we cannot describe how much water is being lost from the snowpack (change in SWE), we can describe the timing of melt.

Line 399: "increases the concentration in water" should be "increases tracer concentrations in the soil water.." if you are speaking about the inverse of water chemistry "dilution" from snowmelt.
Reply: Revised to: "…thereby increasing ion concentrations in the soil water …"

Line 429: Please clarify "increases in stream water chemistry" to specify that you are speaking about tracer concentrations or "concentration of stream water ions" (line 450). Consistent terminology will help the flow of the manuscript.
Reply: Revised to: "…an increase in stream water ion concentrations…"

Line 457: Please provide citation for this statement "Excess water associated with forest disturbance would infiltrate into the subsurface". These assumed hydrologic dynamics should be discussed in more detail because there is potential for a varying hydrologic response from forest disturbance.
For example, in a forested snowmelt dominated watershed the timing and magnitude of snowpack accumulation and ablation in relation to canopy cover/density dynamics may be variable depending on forest dynamics. Sublimation rates on canopy snow interception (see Classen and Downy, 1995), and

impacts of forest shading on radiative forcing on snowpack ablation could influence infiltration rates. I would also suggest mention of rainfall intensity relative to infiltration capacity in forested vs alpine or disturbed areas. Recommended references to review:
Molotch et al., 2009. Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. https://doi.org/10.1002/eco.48
Harpold et al., 2014. Soil Moisture response to snowmelt timing in mixed-conifer subalpine forests. https://doi.org/10.1002/hyp.10400
Musselman et al., 2012 Influence of canopy structure and direct beam solar irradiance on snowmelt rates in a mixed conifer forest. https://doi.org/10.1016/j.agrformet.2012.03.011
Reply: This statement and the rest of the discussion on hydrologic resilience has been removed as suggested by Referee #1.

Line 475: Figure 10 caption revision. Second sentence is an interpretation of the graph rather than a description and should be included in the text. Recommend clarifying text description of "more responsive" and "slower recession slopes" in reference to depth to groundwater below the surface.
Reply: The second sentence in the figure caption has been removed as suggested. The interpretation described in body of the text: "The till groundwater well showed consistently slower recession curves compared to the bedrock groundwater well" has been expanded and revised to:

"Water table depth in the till groundwater was more responsive than bedrock groundwater level in the spring, though the overall rise in water level in the bedrock was slightly greater. Despite the flashier response earlier in the year, till groundwater levels remained elevated longer than bedrock groundwater resulting in a slower recession (slower drainage) in the till groundwater well in the summer (Figure 13)."

Figure 10: In the soil/till GW, what causes the sharp response (increase in water table elevation) in November? Is this related to early season snowfall that melts or other factor such as vegetative senescence? Does the chemistry change in that water source in late fall?
Can you explain the two separate groundwater level increases in the till well that occur in February and then again in March/April? Is this related to intermittent snowpack throughout the winter (as briefly mentioned in the snowmelt sampling methods line 125)?
Reply: Figure 13 (formerly Figure 10) was added simply to characterize the water table recession and infer the hydraulic conductivity of the bedrock well compared to the glacial till well. The fine-resolution temporal responses of wells in November, February, and March/April were not investigated because these responses were for 2017 and we were focusing on 2014/2015 seasons. However, the March response corresponds to the onset of the spring melt season, particularly at the lower elevations where the till well is located. The exact timing of the spring response cannot be directly linked to the responses observed in 2014/2015 because the 2017 season likely had different timing for snowmelt and groundwater table responses. The time scale on the figure has been changed to March-October to reflect a similar time period as stream water and source water samples. March was included in the figure to show the earlier melt response in 2017.

Although the 2017 season is outside the scope of this manuscript, we did investigate the timing of the February and November till well responses in comparison to precipitation timing and air temperature during revision of this manuscript. The till groundwater table response in November 2017 was caused by brief warm air temperatures and a large rainfall event which are common in the late fall/early winter in this watershed. The mechanisms that lead to the February 2017 response are less clear. A large snowstorm occurred in 1.5 weeks prior the well response during a period of very cold temperatures (-15 to -25 °C). Following the snowstorm and in the days leading up to the well response, the air temperature increased significantly to 5 °C and the snow depth decreased. Thus, it is possible that a mid-winter melt event caused the water table response. Again, these events are outside the scope of the current manuscript but can be addressed in a future manuscript.

Line 480: Replace "old water" with a more accurate description representative of transit time or sub-surface residence time rather than speaking to the age of the water, or define old water to mean "reacted" waters that have had extended contact time with the sub-surface (see Liu et al. 2004) The same suggestion was made previously for defining the use of "old water" in the abstract.
Reply: Any reference to "old water" has been revised to "reacted" water or water that was stored in the watershed over winter rather than a specific age of the water.

Line 485: Indicates that till groundwater could be slowly released to the stream (longer recession in Figure 10). It is not clear if the intention was to suggest that this could be the unidentified source water end member in late fall in Star East, but was not was not captured or used in EMMA due to experimental design issues leading to well contamination?
Reply: The conclusion has been expanded and clarified:

"Star West stream water was once again similar to hillslope water or riparian water, but Star East stream water plotted outside the boundary of the measured sources. Seep water temperatures were cool and had low variability suggesting it may be deeper bedrock water contributing to the stream. Slower recession rates (and likely lower hydraulic conductivity) in the till groundwater well than in the bedrock groundwater well suggest that water recharged into the till groundwater may be slowly released to the stream. Contamination of the till groundwater well made it unclear when it was contributing to the stream but groundwater table fluctuations suggested it is likely contributing during late summer or fall. More research on the variability of bedrock and till groundwater chemistry is needed to clarify the difference between these sources and their contributions to streamflow throughout the year."

Line 486: Please expand the conclusion/suggestion that till groundwater (although not used as an end member for EMMA) has the potential to mute the effects of disturbance on peak flow. I assume you are referring to forest disturbance, but it is not clear of the locational relationship between till groundwater sources and forested areas within the watersheds. Is the till groundwater believed to be sourced from direct overhead recharge (in the same location as currently existing forests)? or is there another hypothesized mechanism of recharge such as mountain block recharge from higher alpine regions already void of forest cover?
Reply: Reference to resilience has been removed from the conclusions (and the rest of the manuscript)

as suggested by Referee #1. However, clarification of till groundwater responses/sources in Line 486 have been added to the manuscript as indicted above (Line 485).

Author response to Anonymous Referee #3:
Anonymous Referee #3 comments:

Summary of the paper:
In this study, multiple tracers were used to identify dominant runoff generation mechanisms over two hydrologic years in Star-east and Star-west watersheds. Principal component analysis was used to reduce the complexity that may arise by analyzing every tracer combination. The study concluded that streamflow during early melt was dominated by hillslope groundwater. As snowmelt peaked, the entire landscape became connected and all the water sources contributed to streamflow (the proportion from different sources is not computed). During the Fall season, hillslope and bedrock groundwater became the major sources of streamflow in Star West watershed (proportions not computed), however the sources were unresolved in the Star East watershed. The authors then went on to conclude the subsurface flow pathways in this region are complex and this complexity along with slow release of groundwater from glacial till ensures hydrologic resilience in this region.
This study tries to resolve the seasonal sources of streamflow which is a very interesting research topic and definitely fit for this journal. However, quantitative estimates of source proportions are missing from this study which is possible to compute given the number of tracer variables that were monitored.
Reply: We thank the referee for their review of this draft manuscript.

Major comments:
1. The abstract and introduction talks in detail about the concept of hydrologic resilience, however I do not find any attempt to quantify this statistic in the remainder of this article (except a very brief discussion on recession rates at the end). I will recommend either quantifying resilience or removing it (at least from the abstract).
Reply: All sections relating to hydrologic resilience have been removed.

2. The source apportionment which is the key focus of this study was done qualitatively because TVR was below 2. A TVR value below 2 signifies that sources are not completely differentiable. In such cases, the uncertainty in the contribution of different sources is higher, which does not mean that an EMMA is useless. I will encourage the authors to undertake a simple EMMA and report the results for the same. An easy way to do this will be using one anion and one cation (reason in #3 below) and some variant of an EMMA. On the point of violation of assumptions, instead of a conventional EMMA, a Bayesian mixing model can be used where the error distribution can be parameterized and later verified.
Reply: The mixing model portion of EMMA was not run because of the violation of key assumptions, the large variability in source water, and Star East stream water not being bound by its sources. The seasonal variation in stream water and large overall variation in source water added uncertainty to

mixing results; median or mean values of source water would not have physical meaning during a given season or month. Additionally, while not mentioned in the draft manuscript, small numbers of samples per source can also add uncertainty to mixing proportions. Small et al. (2002) suggested that greater than 20 samples per source are required to reduce this uncertainty; however, in many cases, we have far fewer than 20 samples. Due to the combination of the factors above, the error associated with the un-mixing model would be very large and results would not be particularly meaningful. We decided that a qualitative description of these data displayed in a PCA plot would still provide insight into the hydrological processes in our study region because the principal components (PC1/PC2) were created from the variability across multiple tracers.

It is important to note that it has been shown that less accurate predicted mixing proportions can arise from reducing the number of tracers used in the un-mixing model (Barthold et al., 2011). While others have historically used two tracers, close scrutiny of predicted portions using known mixtures have shown that larger number of tracers generate more accurate results (Collins et al., 2017; Sherriff et al., 2015). The importance of testing mixing model predictions using mixtures, rather than goodness-of-fit tests for the prediction of measured tracer values in mixed waters, as was conventional for many years, has been critical in revealing the dangers of using overly reductionist signatures. Thus, undertaking a simple EMMA or a Bayesian mixing model with 2 tracers as suggested would have the same problems regarding source water variation and large uncertainty in predicted proportions compounded with overall less accurate mixing proportions. As a result, we did not to pursue this approach in the revised manuscript.

3. On visual inspection of Figure 4, it seems that Cl- is markedly different from the other tracers. Most of the cations are positively correlated and offer complementary information. Is this the case? If yes, why not simply use one anion and one cation instead of doing a principal component analysis using all the tracers. The problem with PCA is that readers do not know which tracers influence PC1/PC2 and to what extent, losing physical significance. This will also ensure that an EMMA model can be setup in a very simple way (using one cation and one anion as the tracers)
Reply: Yes, most ions were positively correlated but Cl- was also positively correlated with these same ions except for a few samples that had higher concentrations. SO_4^{2-} better separated the source and stream water samples along a biplot axis and would likely be the better choice if conducting a 2-tracer mixing space/model. However, as explained above, a 2-tracer mixing model would still have large uncertainties associated with the estimated proportions since overly reductionist signatures generate less accurate proportions versus known mixtures (either virtual or actual). The methods used in this study were intended to maximize the statistical information provided by the tracer suite without overstating the inferences or conclusions that we could draw from this dataset.

Regarding which tracers influence PC1/PC2, a simple option to help clarify the physical significance of the PCA plot is to include a table with the tracers that influence PC1 and PC2 (Table 2). These types of tables are provided often along with PCA plots and has been added to the revised manuscript (Table 1).

4. Sections 5.2 and 5.3 can be combined into one section, that will make it easier to read the sections and also help avoid repetitions.

Reply: Referee #1 suggested we combine sub-sections within Sections 5.2 and 5.3 to avoid repetitions and we agree that this will help streamline the draft Results. We have revised these sections to avoid repetition but have maintained separate sections because we did not want to lose the ability to stress some key discussion points in source water dynamics. However, the draft Discussion has been heavily revised to combine Sections 6.1 and 6.2 to add better flow to the revised Discussion and reduce repetition throughout the manuscript.

Minor comments:

1. The number of sources are different in different parts of this article (eg: P1L15, P3L67, P5L112, P9L232, etc.). I will recommend using the same number of sources at different instances in the article.

Reply: These lists have been revised to be consistent across lists. However, upper and lower sites have different numbers of sources based on the outcome of the analysis.

2. How many of the 11 snowmelt samples came from North York Creek? (P5L124)

Reply: Two of the snowmelt samples came from North York Creek. Text has been revised to: "Nine snowmelt samples were collected from sub-alpine regions of Star Creek and two from North York Creek…"

3. Were EC measurements also taken? These can also be used to verify if the seep water is coming from a groundwater pool. (P11L249)

Reply: EC was taken from seeps, stream, and till and bedrock wells, but not hillslope/riparian wells or suction lysimeters. EC has been added (Figure 5) to the revised manuscript.

4. Water temperature has been discussed at different places in the article, however there are no figures of water temperature in the article. I will recommend to include at least one figure for water temperature.

Reply: A box and whisker plot has been added (Figure 5) to display the range in water temperature in till and bedrock wells, seeps, and the stream. Water temperature was not measured in hillslope/riparian wells.

5. The reported hillslope groundwater includes riparian water and soil water. How is a riparian zone part of hillslope? (P11L260)

Reply: Hillslope groundwater included riparian water when the chemical signature of riparian water was not statistically different from the chemical signature of water from hillslope wells. While the processes that occur in the riparian area certainly differ from those on the hillslope, there was not a significant difference between these sources at Star West Lower and Star East Upper so these sources were grouped together. The following text has been added for clarification:

"Although riparian water mixes with stream water and should be chemically different from hillslope water as a source, soil water, toe slope water, and upper hillslope water were grouped with riparian water for most sites because the distribution of these samples were too similar to be considered separate sources. The exception was SEL and SWU in which riparian water was considered as a separate source."

6. Section 5.3 indicates some kind of a hysteresis pattern in the PC plots of streamflow (anticlockwise direction in Star west (Figures 5, 6) and clockwise direction in Star east (Figures 7, 8)). I will encourage more discussion about the reason behind this.

Reply: The following text has been added as well as Table 1 indicating the ions that define PC1 and PC2: "Differences in the east and west forks were also evident in the hysteresis pattern in stream water chemistry from spring to fall. Star West sub-watersheds had a counterclockwise pattern, whereas Star East sub-watersheds had a clockwise pattern. In general, this is an artefact of the PCA analysis driven by the specific ions that defined each PC (Table 1). In Star East, the first PCs were dominated by anions and the second PCs were dominated by SO_4^{2-} (negative relationship). While the first PCs for Star West were dominated by anions, the second PCs included a mix of anions and cations and SO_4^{2-} with a positive correlation thereby producing an opposite hysteresis pattern. Although this is an artefact of the PCA analysis, it was ultimately due to slight variations in the sources contributing to the streams at different times during the flow season."

7. There is no work done on the water age, how have old or new water been defined? (P1L18, P18L418, L420, etc.)

Reply: No work has been conducted on water age. "Old water" was used in contrast to "newer water" (precipitation) that would be added during snowmelt. Referee #2 has suggested we clarify the definition of old water to mean "reacted waters", water that has spent time in the watershed and reacted with its surroundings. References to old water have been changed to make it clear that we are talking about water that was already in the watershed prior to snowmelt in contrast to unreacted water such as rain and snow.

List of Relevant Changes:

- Introduction and context of manuscript heavily revised
- Added box plots of water temperature and conductivity of bedrock well, groundwater seeps, and stream water
- Added time series of relevant ion concentrations
- Added hydrometric data: 1) Table with streamflow and precipitation metrics and 2) Plot with observed inputs (snow depth and daily precipitation) and outputs (stream discharge, Ca concentration, shallow groundwater table)
- Discussion was streamlined into one section to avoid repetition
- Abstract and Conclusion revised to reflect changes
- Many smaller changes made to the manuscript to address Editor and Referees' comments

H~~Seasonally varied h~~illslope and groundwater contributions to streamflow in a ~~glacial till and fractured sedimentary bedrock dominated~~ Rocky Mountain watershed underlain by glacial till and fractured sedimentary bedrock~~.~~

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Abstract. ~~-~~T~~Whereas a lack of streamflow response to significant forest disturbance (e.g., forestry, wildfire, and insect infestation) has been observed at multiple locations i~~he~~n the~~ Canadian Rocky Mountains is~~,~~ a unique region with large storage capacity and complex subsurface flow pathways due to permeable ~~-~~sedimentary bedrock overlain by glacial till~~, mechanisms governing this lack of change remain unclear~~. While ~~-S~~some inferences can be drawn from conceptualizations of runoff generation (e.g., runoff thresholds and hydrologic connectivity) in physically similar watersheds, relatively little research has been conducted in snow-dominated watersheds with multi-layered permeable substrates that are characteristic of the Canadian Rocky Mountains. ~~although much of the focus has been on rainfall-runoff dynamics. Thus, there is a need to describe runoff generation in this snow-dominated area to interpret how forest disturbance may impact streamflow quantity for downstream users.~~ Stream water and source water (~~snow,~~ rain, snowmelt, soil water, hillslope groundwater, till groundwater, and bedrock groundwater ~~and seeps~~) were sampled in four sub-watersheds (Star West Lower, Star West Upper, Star East Lower and Star East Upper) in Star Creek, SW Alberta to characterize the spatial and temporal variation in source water contributions to streamflow in upper and lower reaches of this watershed. Principal component analysis was used to determine the relative dominance and timing of source water contributions to streamflow over the 2014 and 2015 hydrologic seasons. An initial displacement of ~~old water~~water stored in the hillslope over winter ("reacted water" rather than "unreacted" snowmelt and rainfall) occurred at the onset of snowmelt~~,~~ before ~~the~~ stream discharge responded significantly. This was followed by a dilution effect as snowmelt saturated the landscape, recharged groundwater, and connected the hillslopes to the stream. Fall baseflows were dominated by either riparian water or ~~hillslope groundwater or bedrock~~hillslope groundwater in Star West. Conversely, in Star East, the composition of stream water was similar to hillslope water in August but plotted outside the boundary of the measured sources~~was unlike the measured sources~~ in September and October. The chemical composition of groundwater seeps followed the same temporal trend as stream water, but consistently cold temperatures of the seeps suggested deep groundwater was likely the source of this late fall streamflow. Temperature and chemical signatures of groundwater seeps also suggest highly complex subsurface flow pathways. The insights gained from this research help improve our understanding

of the processes by which water is stored and released from watersheds with multi-layered subsurface structures. ~~Hydrologic resilience in the Rocky Mountain eastern slopes may be, in part, due to these complex subsurface pathways in combination with the slow release of groundwater from glacial till.~~

1 Introduction

Forest disturbance from wildfire, ~~pine beetle infestation~~pathogens, or forest harvesting removes the forest canopy increasing the total precipitation that reaches the forest floor (Williams et al., 2019; Burles and Boon, 2011; Boon, 2012; Pugh and Small, 2012; Varhola et al., 2010) often altering the dominant flow pathways, increasing streamflow quantity and changing the timing of flows in forested watersheds (Stednick, 1996; Scott, 1993; Bearup et al., 2014; Winkler et al., 2017). However, large variability has been observed in streamflow responses following disturbance due to differences in disturbance type, vegetation type, precipitation regimes, and soil moisture storage (Brown et al., 2005; Stednick, 1996). Some studies in Alberta's Rocky Mountains have reported little, if any, change in streamflow following disturbance (Williams et al., 2015; Harder et al., 2015; Goodbrand and Anderson, 2016; Andres et al., 1987) but the mechanisms and ~~or~~ watershed features (e.g., bedrock, surficial geology, wetlands) potentially responsible for the lack of flow response have received little attention~~remain unclear~~. I~~Watershed resilience, when a watershed maintains a similar form and function following forest disturbance (Creed et al., 2011), has been used to explain the lack of change in streamflow following disturbance (Harder et al., 2015). W~~t has been suggested that watersheds exhibiting a lack of change in streamflow following disturbance ~~resilience~~ might be associated with a large storage capacity and complex subsurface flow pathways (Harder et al., 2015) but the higher-order controls regulating these muted responses remain unclear~~where water can be stored for months or years and be subsequently released to the stream gradually thereby buffering the flow response of watersheds from disturbance (Creed et al., 2011)~~.

Runoff generation has been extensively studied in regions with relatively impermeable bedrock overlain by shallower soils, which has led to broadly accepted conceptualizations of runoff dynamics. However, these conceptualizations may not apply to regions with more complex structural controls on runoff such as permeable bedrock, deeper soils, or where multiple subsurface systems interact. Runoff generation in Alberta's Rocky Mountains has added complexity because of the combination of both permeable sedimentary bedrock (highly fractured and faulted) and an overlying layer of deep, heterogenous glacial till (3 m deep on average, up to 10 m deep) (AGS, 2004; Waterline Resources, Inc., 2013). This is in contrast to regions such as the southern Rocky Mountains in Colorado (Sueker et al., 2000; Cowie et al., 2017) and Montana (Jencso et al., 2009; 2010; Nippgen et al., 2015) that are often dominated by less permeable metamorphic or igneous bedrock and thinner soils. While runoff generation processes may differ from these regions, some inferences can be drawn from studies in regions with either permeable bedrock or deep soils alone. Watersheds with h~~H~~igh bedrock permeability ~~is a watershed~~

~~feature that has~~have been associated with longer subsurface flow pathways and the slow release of stored water to streams during baseflow (Uchida et al., 2006; Liu et al., 2004; Pfister et al., 2017)~~, thereby potentially influencing the hydrological resilience~~. Uchida et al. (2006) reported that a watershed with greater bedrock permeability had larger aquifer storage, and the subsequent release of stored water maintained baseflow later in the year. Similarly, Liu et al. (2004) showed that the recession limb of the annual hydrograph in the Colorado front range Rocky Mountains was driven by baseflow released from fractured bedrock but Cowie et al. (2017) also stressed the importance of talus slopes as a source of streamflow in the same alpine watershed. Deep soils and till deposits with large storage capacities have also been shown to sustain baseflows during drier periods (Floriancic et al., 2018; Shanley et al., 2015). Deep sediment deposits in the Poschiavino watershed, in Switzerland, were associated with ~~larger~~ greater storage capacity and higher winter baseflows compared to watersheds with shallow sediment deposits (Floriancic et al., 2018). Similarly, deep basal till in Sleepers River watershed in Vermont was associated with large storage capacity and low permeability that promoted extended maintenance of baseflow (Shanley et al., 2015). While these studies illustrate the influence of permeable or fractured bedrock, deep soils, or till on baseflows, few studies have explored the combination of these storage zones on streamflow contributions (Burns et al., 1998; Dalke et al., 2012; Shaman et al., 2004~~pencer et al., 2019~~). Burns et al. (1998) characterized the difference in deep (bedrock) and shallow (soils and till) flow systems in the Catskill Mountains in New York, a region with both glacial till and permeable sedimentary bedrock. Baseflow was maintained by discharge from perennial springs, which originated from bedrock fractures, rather than contributions from the soil and till flow system (Burns et al., 1998). Conversely, fragipan layers contributed to differing flow systems under dry vs wet antecedent conditions in central New York state, USA (Dalke et al., 2012). Stormflow was generated from deep flow pathways below the fragipan during dry conditions and near surface flow pathways during wet conditions. Comparatively little research on runoff generation processes have been conducted in the Canadian Rocky Mountains in part due to deep snow that is present for much of the year (Oct-May). While some studies have shown the importance of groundwater contributions to streamflow in alpine watersheds in the Rocky Mountains (Hood and Hayashi, 2015; McClymont et al., 2010), the additional complexity imposed by highly heterogeneous glacial till and permeable bedrock in sub-alpine and upper montane watersheds has limited more extensive research on runoff dynamics of this region. As a first attempt to conceptualize runoff generation in Alberta's Rocky Mountains, Spencer et al. (2019) quantified storage and precipitation-runoff relationships from hydrometric data. Results indicated that runoff generation was strongly governed by the interaction of two zones of storage – soil and till storage and bedrock storage. The alpine region and sub-alpine/upper montane region were also identified as two separate hydrologic response units that differed in timing and flow pathways for runoff response. While Spencer et al. (2019) developed a conceptualization of runoff generation for this region, they concluded that ~~Similarly, precipitation-runoff relationships in Alberta's Rocky Mountains indicated that runoff generation is complicated by the interaction of two storage zones – soil and till storage and bedrock storage (Spencer et al., 2019) where~~ coupled flow and tracer approaches would be needed to reduce uncertainty in estimated flow contributions from each storage zone. ~~Others have also shown the importance of groundwater contributions to streamflow in alpine watersheds in the Rocky Mountains (Hood and~~

~~Hayashi, 2015; McClymont et al., 2010). However, due to the highly heterogeneous nature of glacial till, more research is needed to differentiate between baseflow contributions from glacial till and bedrock storage sources.~~

Chemical signatures of source water (~~e.g.,~~rain, snowmelt, soil water, hillslope groundwater, ~~glacial~~ till groundwater, and bedrock groundwater~~), soil water, and precipitation)~~ and stream water can be used to determine which sources are contributing to streamflow during different flow conditions using end-member mixing analysis (EMMA; Christophersen and Hooper, 1992). The key assumptions for EMMA are: 1) the tracers are conservative; 2) the mixing process is linear; 3) source chemistry does not change temporally or spatially over the period or area studied (Inamdar, 2011; Hooper, 2003), and; 4) all sources have been identified and have the potential to contribute to streamflow. Many studies have used EMMA to conceptualize when different geologic components are contributing to the stream (e.g., James and Roulet, 2006; Cowie et al., 2017; Ali et al., 2010). However, this approach has been most successful in smaller watersheds (1 km^2) because of more constrained variation in source water at smaller spatial scales (Hoeg et al., 2000). Large watersheds could be characterized based on smaller sub-watersheds (James and Roulet, 2006) if sub-watersheds are homogeneous. Others have concluded that where source water displays large variation or assumptions cannot be met, runoff processes should be described qualitatively (Inamdar et al., 2013; Hoeg et al., 2000; Correa et al., 2019).

To expand on recent work carried out in the same study area by Spencer et al. (2019), this study aims to advance the conceptualization of runoff generation in the Rocky Mountains in Alberta, Canada. ~~Accordingly, t~~The objectives of this study were to: 1) characterize how sources of stream water (rain, snowmelt~~precipitation~~, soil water, hillslope groundwater, till groundwater, and bedrock groundwater~~, and seeps~~) vary spatially across four sub-watersheds of a Rocky Mountain watershed and temporally from spring snowmelt to the start of the next year's snow accumulation period ~~fall low flows~~, and; 2) determine the relative contributions of source water to the stream from spring to fall for each sub-watershed. ~~Two adjacent geologically similar watersheds were compared to explore the relative variation in stream water sources across key physiographic zones (higher elevation alpine/sub-alpine vs lower elevation upper montane) that were evident within Star Creek watershed.~~ This study should help inform the current conceptualization of runoff generation in northern Rocky Mountain watersheds~~, thereby providing new understanding of the potential factors influencing watershed resilience to close a critical evidence gap~~.

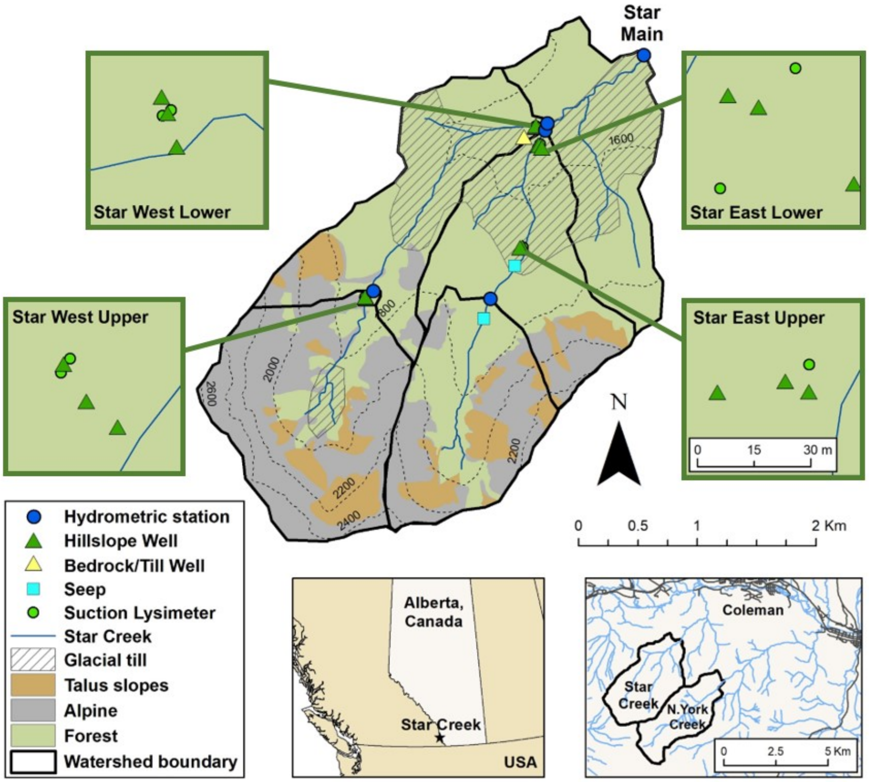
2 Study Site

Star Creek watershed (10.4 km^2; Figure 1) is located in the eastern slopes of Canada's Rocky Mountains; a region with fractured sedimentary bedrock overlain by glacial till. Average annual precipitation was 720 mm at Star Main (1482 m a.s.l.) and 990 mm at Star Alpine (1732 m a.s.l.; Spencer et al., 2019). The a~~A~~rea-weighted average annual precipitation (2005-2018) was 950 mm using the Thiessen-polygon method and nine precipitation gauges at a range of elevations in and surrounding Star Creek ~~is 950 mm;, with~~ 50-60 % ~~in~~of the precipitation falls in the form of snow (Spencer et al., 2019). ~~-~~Soils are Eutric Brunisols (Can. Soil Classification, or Eutric Cambisols in Food and Agriculture Organization system) approximately 1 m deep, on average. Star Creek is underlain by u~~U~~nsorted and uncompacted glacial till is generally less than 3 m deep~~, on average,~~

~~with some clay-rich layers distributed unevenly throughout the watershed~~with an estimated total area of 2.4 km^2 (AGS, 2004; Figure 1). Some clay-rich till layers, likely from localized glacial ice melt features, occur intermittently throughout the watershed resulting in heterogeneous and uneven distribution of glacial till throughout the watershed. Sedimentary geologic formations (Upper Paleozoic formation, Belly River-St. Mary Succession, and Alberta Group formation) are primarily composed of shale and sandstone (AGS, 2004) and are highly fractured due to folding and faulting (Waterline Resources, Inc., 2013) ~~(AGS, 2004)~~.

~~There are~~Star Creek includes two main sub-watersheds, Star East (3.9 km^2; 1537-2628 m above sea level) and Star West (4.6 km^2; 1540-2516 m above sea level). Unvegetated talus slopes (0.50 km^2 in Star East and 0.53 km^2 in Star West, digitized from orthoimages) and~~beneath~~ exposed bedrock form the upper portion of alpine zones in both sub-watersheds (Figures 1 and 2). Talus slopes terminate in the alpine and transitional forested regions of the watershed but streams or tributary features flowing from talus slopes have not been observed. There is also no evidence of permafrost, ice lenses, or rock glaciers, unlike in other Rocky Mountain regions (Cowie et al., 2017; Clow et al. 2003; Hood and Hayashi et al., 2015; McClymont et al., 2010). Star West has a larger alpine region with cirque till deposits (estimated area of 0.14 km^2 (AGS, 2004)) that includes a narrow marshy area proximal to the stream that holds water throughout the summer and drains into the main channel that is primarily bedrock in the upper reaches. The Star East alpine region is smaller and more constricted than in Star West (Figure 2) and is comprised mostly of a grassy meadow with the stream originating from springs where the water table reaches the soil surface and is incised in colluvium with large boulders. In the lower reaches, streams in both sub-watersheds are composed of a series of step-pools incised in alluvium and colluvium with some areas of exposed bedrock. ~~where the lower sub-alpine and upper Montane zones are dominated by sub-alpine fir (*Abies lasiocarpa*) and Englemann spruce (*Picea Englemannii*) above lodgepole pine (*Pinus contorta*) dominated forests in lower reaches (Dixon et al., 2014; Silins et al., 2009).~~

Two historical streamflow gauging sites exist in each sub-watershed – a lower site (Star West Lower (SWL) and Star East Lower (SEL)) near the confluence of the two sub-watersheds (1540 m above sea level) and an upper site (Star West Upper (SWU) and Star East Upper (SEU)) located at approximately 1690 m above sea level in the ~~alpine/~~sub-alpine transition zone (Figure 1).~~-~~ The sub-alpine and upper Montane zones are dominated by sub-alpine fir (*Abies lasiocarpa*) and Englemann spruce (*Picea Englemannii*) above lodgepole pine (*Pinus contorta*) dominated forests at lower elevations (Dixon et al., 2014; Silins et al., 2009). Vegetation in upper and lower watersheds (Figure 1) are distinguished by a transition between higher elevation alpine heath/shrub vegetation and sub-alpine fir dominated forests in the upper watersheds and lodgepole pine dominated forest in the lower watersheds.


Star Main
Star West Lower
Star East Lower
Star West Upper
Star East Upper
1600
1800
2000
2200
2400
2600
N
0
15
30 m
0
0.5
1
2 Km
Hydrometric station
Hillslope Well
Bedrock/Till Well
Seep
Suction Lysimeter
Star Creek
Glacial till
Talus slopes
Alpine
Forest
Watershed boundary
Alberta, Canada
Star Creek
USA
Coleman
Star Creek
N.York Creek
0
2.5
5 Km

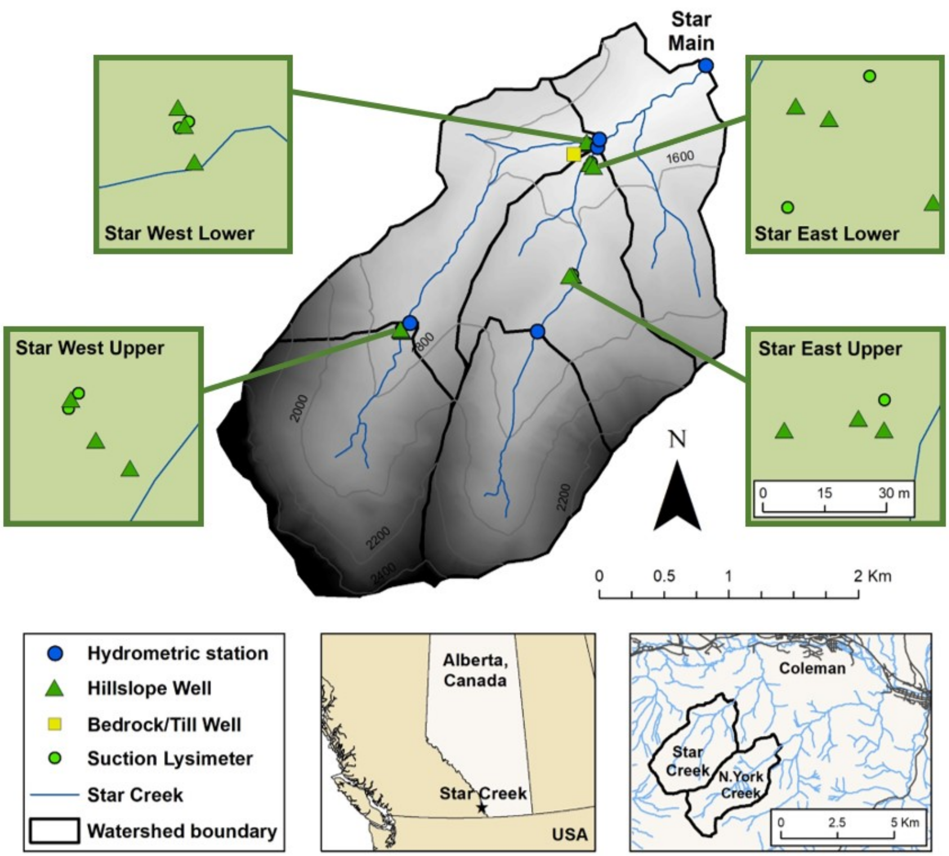


Figure 1: Star Creek watershed. Suction lysimeter and hillslope groundwater well locations are magnified in green boxes.

Figure 2: Star East (left) and Star West (right) sub-watersheds. The Star East alpine area is more constrained and smaller than the Star West alpine area. Both sub-watersheds have steep headwalls with talus slopes in the alpine zone.

3 Methods

3.1 Stream water chemistry

Stream water samples were collected from the four streamflow gauging stations (SEL, SEU, SWL, SWU; Figure 1) every two weeks from April to October, in 2014 and 2015, to capture the full range in streamflow chemistry over the hydrologically active period. One litre plastic bottles were triple rinsed prior to sample collection. Samples were analyzed for major cations and anions (Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, SO_4^{2-}) and silica (Si as SiO_2) in the Biogeochemical Analytical Service Laboratory (University of Alberta). An inductively coupled plasma-optical emission spectrometer (Thermo Scientific ICAP 6300) was used to measure Na^+, Mg^{2+}, Ca^{2+}, K^+ with analytical precision of 1.9 %, 3.0 %, 1.9 %, and 2.4 %, respectively. An ion chromatograph (Dionex DX600 and Dionex ICS 2500) was used to measure Cl^- and SO_4^{2-} with analytical precision of 2.4 % and 3.1 %. Flow injection analysis (Lachat QuikChem 8500 FIA automated ion analyzer) was used to measure Si with analytical precision of 3.4 %.

Continuous stream discharge was estimated from stage-discharge relationships developed at each gauging station. Stage was measured at a 10-minute interval using a bubbler system (H350/H355 Waterlog Series, YSI Inc./Xylem Inc., Yellow Spring, Ohio, USA) or a pressure transducer (HOBO U20, Onset Computer Corp., Bourne, MA, USA). Discharge measurements were taken with a velocimeter (SonTek/Xylem Inc., San Diego, CA, USA) 12-18 times from April to October at each site in 2014 and 2015.

3.2 Source water chemistry

Stream water sources were a priori hypothesized to ~~be~~ consist of rain, snowmelt, soil water, hillslope groundwater, ~~and~~ till groundwater, and bedrock groundwater (seeps used as a proxy for till and bedrock groundwater) ~~seeps~~ based on field observations and inferences made from research conducted in this watershed since 2004 (Silins et al., 2016). All source water samples were collected in triple rinsed (with source water) 50 ml plastic vials and analyzed with the same methods as the stream water samples to support application of end-member mixing analysis. Source water collection and sampling methods are detailed below.

3.2.1 Rainfall and snowmelt

Rain samples were collected in ~~a~~ clean buckets ~~that was~~ rinsed with deionized water. Buckets were placed in open areas throughout the watershed or in the nearby townsite (Coleman, AB; within approximately 8 km of Star Creek watershed) after a rainstorm began. Locations were chosen opportunistically depending on storm timing and site access. Samples were collected at the end of the day or once there was enough water in the bucket to sample~~,~~ to prevent changes in chemical composition due to dry deposition of dust or evaporation. Five, four, and three samples were collected throughout the summers of 2013, 2014, and 2015, respectively. The difficulty of capturing large convective storms and the large frequency of storms less than 5 mm (Williams et al., 2019) prevented the collection of more rainfall samples.

Nine~~Eleven~~ snowmelt samples were collected from sub-alpine regions of Star Creek and two from North York Creek (an adjacent watershed, Figure 1) throughout spring and early summer in 2014. Three additional samples were collected in spring 2015 but mid-winter melt of snowpacks hindered the collection of more snowmelt samples. Eavestroughs, 3 m in length, were installed perpendicular to the stream with a small overhang off the edge of the hillslope in Star Creek and North York Creek watersheds in the fall prior to snow accumulation. Samples were collected directly from snowmelt troughs and snow bridges with clearly visible melt. Snowmelt was sampled, instead of the snowpack, to better reflect the meltwater signature during the snowmelt period (Johannessen and Henriksen, 1978). The timing of sample collection was based on access to backcountry sites and were taken opportunistically when crews were in the area and were able to observe active snowmelt.

3.2.2 Soil water

Suction lysimeters were installed between 30-60 cm depth using a hand auger in two locations near the toe of the hillslope in each sub-watershed in early spring 2014 (2015 for SEU; Figure 1). Suction lysimeters consisted of a 0.5 Bar ceramic cup and 38.1 mm PVC pipe to ensure ample water was collected for chemical analyses. Water from the suction lysimeter was sampled using a hand pump every two weeks between April and October in 2014 and 2015. Suction lysimeters were pumped dry following sampling and pressure was applied. Thus, soil water was composed of water that was able to pass through the ceramic cup over the two-week period until the lysimeter was at equilibrium pressure with the surrounding soil. Shallow depths were targeted with the intention to collect the unsaturated soil water above the saturated zone in the hillslope, which was sampled separately.

3.2.3 Hillslope groundwater

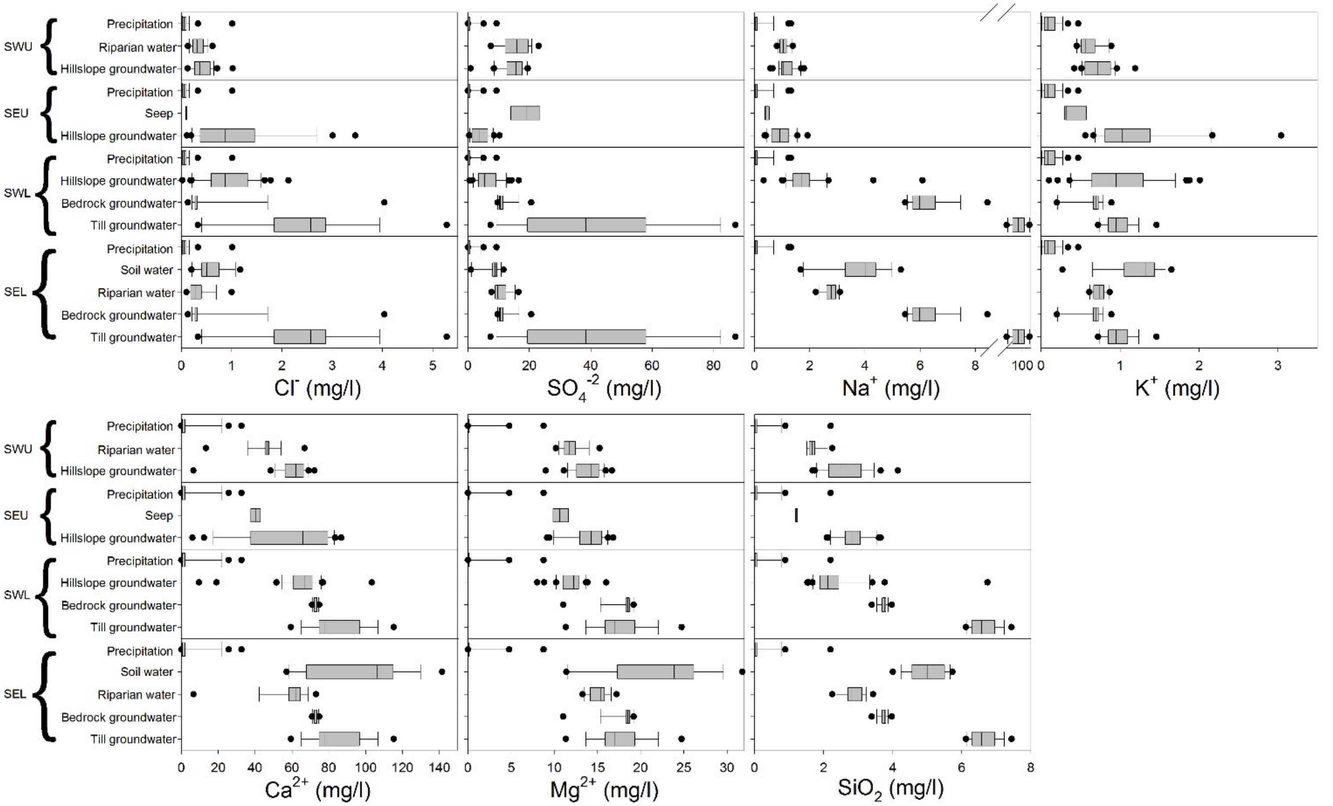
Hillslope wells were installed with a shovel or hand auger to depth of refusal or maximum auger depth (1.5 m) near the hydrometric gauging stations at SEL, SEU, SWL and SWU (Figure 1). A site was added at SEU at the end of the summer in 2014, whereas the other sites were established during summer 2013. Wells were installed in three locations at each site: riparian, toe slope, and hillslope positions to determine the full range in hillslope groundwater. Well depths ranged between 0.5 m (riparian wells) and 1.6 m. Wells were purged using a hand pump prior to sampling. Samples were collected approximately every two weeks, as available, between April and October in 2014 and 2015. Samples from the upper hillslope wells were generally only obtained during the snowmelt or high flow period; these wells were often dry during late summer. Riparian and toe slope wells contained water for all or most of the year, respectively. Water table depths were monitored with capacitance loggers (Odyssey, Dataflow Systems Ltd., New Zealand) at 10-minute intervals to identify the timing of shallow groundwater table responses to infer potential periods when hillslope-stream connectivity occurred.

3.2.4 Groundwater seeps

At the onset of this research, lack of access to backcountry sites restricted the installation of deep bedrock or till groundwater wells in upper sub-watersheds. Rather, groundwater seeps were used to characterize the possible range in groundwater signatures (both bedrock and till groundwater) within Star Creek. Seeps are defined here as areas of visible water seeping from hillslopes proximal to the stream or from small wetland areas further from the stream that form small tributaries or rivulets that flow into the stream. The east and west forks were initially surveyed from the confluence with the main stem to the stream origins in the alpine area in July 2013.~~;~~ 25 visible seeps were identified and~~.~~ s~~S~~amples were collected during three flow conditions: high flow (May/June), recession flow (mid-July), and baseflow (early September prior to fall rains), in both 2014 and 2015. This sampling campaign required more resources than for other sources, as a result sampling was completed only three times a year during hydrologically important extreme flow conditions rather than every two weeks from April to October as for other sources. Water temperature and electrical conductivity ~~was~~were ~~also~~ measured with a handheld multimeter (YSI85, YSI Inc./Xylem Inc., Yellow Spring, Ohio, USA) during sample collection to aid in differentiating between deep bedrock groundwater, till groundwater and hillslope groundwater.

3.2.5 Bedrock and till groundwater

Preliminary end-member mixing analysis showed that a water source was missing from those initially collected (above) highlighting the need to characterize deeper groundwater. Due to monetary and access limitations, a single borehole was drilled to 12 m depth (15.2 cm in diameter) in the topographic ridge between SEL and SWL (approx. 500 m upstream from gauging sites) in October 2015 (Figure 1). Two wells were installed in the borehole, one well in a water-baring formation in the bedrock at 11 m depth, and a second well in the glacial till deposits at 4.5 m depth, to characterize the differences in bedrock and till groundwater chemistry. Both wells had screens that were 1.5 m in length. Sand was used to backfill the borehole around the screened section of the bedrock groundwater well and was capped with bentonite clay. Local material removed during drilling was used to backfill the borehole up to the till layer. The same method of back filling (sand, bentonite clay, local material) was used for the till groundwater well. Bedrock and till wells were sampled every two to four weeks from April to October in 2016 and 2017. Water in the till well was purged until dry prior to sampling. Water in the bedrock well was purged for 2-5 minutes prior to sampling because the recharge rate was faster than the pump rate. Water table depth and temperature were measured continuously with pressure transducers (HOBO U20, Onset Computer Corp., Bourne, MA, USA) at 10-minute intervals.



~~Figure 3: Box plots for Star West Upper (SWU), Star East Upper (SEU), Star West Lower (SWL), and Star East Lower (SEL) showing the ranges in chemistry for potential sources.~~

High concentrations of Na^+, Cl^-, and SO_4^{2-} in till groundwater (Figure 3) and large variability between years suggested that the till groundwater well was likely contaminated by the bentonite clay used to backfill and seal between layers (Remenda and van der Kamp, 1997). Slow recharge rates (and therefore, low hydraulic conductivity) of glacial till prevented the removal of three pipe volumes when sampling and the corresponding low hydraulic conductivity resulted in little flushing of bentonite contaminants. Faster recharge rates (and therefore, higher hydraulic conductivity) of the bedrock groundwater would aid in better flushing of bentonite contaminants which would reduce the effects on bedrock groundwater chemistry (Remenda and van der Kamp, 1997). As a result, the till groundwater samples were not included in the analyses herein; however, water table depths and water temperature dynamics could still be used to understand the differences between till and bedrock groundwater responses and their roles in runoff generation.

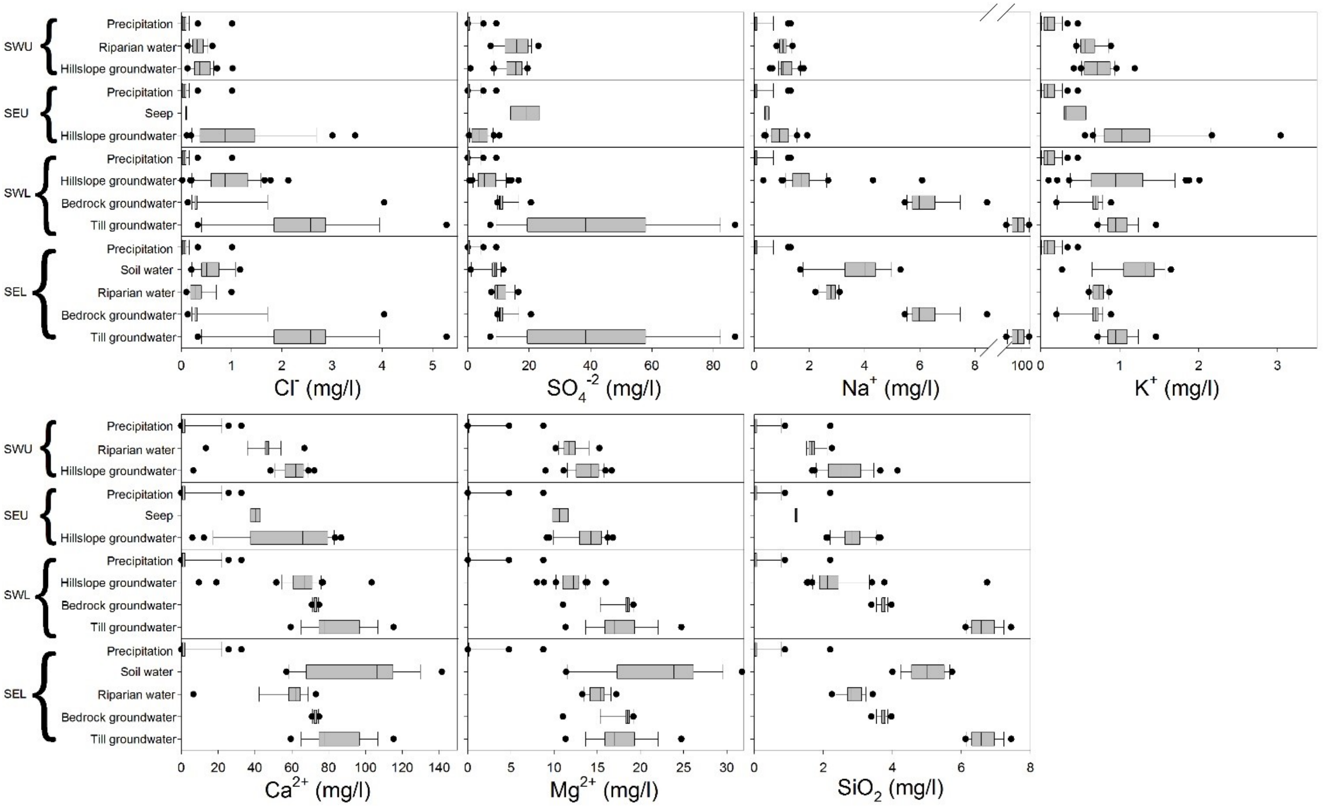


Figure 3: Box plots for Star West Upper (SWU), Star East Upper (SEU), Star West Lower (SWL), and Star East Lower (SEL) showing the ranges in chemistry for potential sources.

4 Data Processing

End-member mixing analysis (EMMA) was used to visualize multi-variate source water and stream chemistry by reducing the dimensionality of the data with principal component analysis (PCA; Christophersen and Hooper, 1992). ~~The key assumptions for EMMA are: 1) the tracers are conservative; 2) the mixing process is linear; 3) source chemistry does not change temporally or spatially over the period or area studied (Inamdar, 2011; Hooper, 2003), and; 4) all sources have been identified and have the potential to contribute to streamflow.~~ In addition, there were multiple subjective decisions required prior to running EMMA, such as choosing tracers/ions and defining sources. Although others have often used the selection criteria presented in Barthold et al. (2011), an inability to run the unmixing routine (stream water fell outside the bounds of the source water; see Results) hindered the use of these methods. Rather, the tracer variability ratio (TVR; explained below) and linear discriminant analysis (LDA; explained below) have been presented as effective parameters to subjectively determine if tracers are included in the analysis and if sources are well separated or grouped appropriately, respectively (Pulley et al., 2015; Pulley and Collins, 2018; and others – see comprehensive review in Collins et al., 2017). These methods have been automated in the SIFT (SedIment Fingerprinting Tool) open source R shiny software described in Pulley and Collins (2018). We extracted this portion of the SIFT routine.

Two methods were used to determine if tracers were appropriate to use in the analysis, bivariate plots and TVR. First, ~~A~~a matrix of bivariate plots of stream chemistry data (ion concentrations), used most commonly in geographical hydrograph separations, was used to determine if ions were conservative in nature (Hooper, 2003). A linear relationship between tracers can be interpreted as a sign of conservative relationships. Second, T~~he tracer variability ratio (T~~VR~~)~~, used most commonly in sediment source apportionment studies, was used to determine if the difference in ion concentrations between groups was larger than the variation within a source group (Pulley et al., 2015). ~~The~~ TVR was calculated using the following equation: the percent difference between source group median divided by the average coefficient of variation between group pairs, ~~was calculated~~ for each tracer pair and compared between each group (Pulley et al., 2015) ~~as the percent difference between source group median divided by the average coefficient of variation between group pairs (Pulley et al., 2015)~~. TVR should be greater than 2 to be considered appropriate for use in mixing calculations (Pulley and Collins, 2018), although depending on the dataset in question, a greater threshold may be adopted to make the tracer selection more stringent and to help reduce the numbers of tracers included in further data processing.

Box and whisker plots and ~~linear discriminant analysis (~~LDA~~)~~ were used to remove the subjectivity of defining sources (Ali et al., 2010; Pulley and Collins, 2018). Box and whisker plots were used as a visual means of discriminating between sources. LDA was then used to determine if the combined sources exhibited sufficiently robust statistical separation (Pulley and Collins, 2018). LDA optimizes separation between the centroid of group clusters by partitioning the variation across each tracer and weighing that variation into two axes (reducing the dimensionality). Other statistical classification methods, such as hierarchical clustering or k-means clustering, were not appropriate because source categories were known a priori. The data were processed ~~using~~in R (R Core Team, 2014) using 'lda' function ~~LDA~~ in the MASS package~~('lda' function;~~ (Venables and Ripley, 2002) to reduce dimensionality and assess the separation visually and the klaR ('stepwise' function; Weihs et al., 2005) package to model the data and determine the ability to separate groups statistically~~s in R (R Core Team, 2014)~~. The 'stepwise' function models the data while removing individual tracers iteratively. ~~was used with t~~The 'backwards' direction was used in an attempt to maintain the most tracers with the ~~;~~ 'lda' method, and 'ability to separate' criterion.

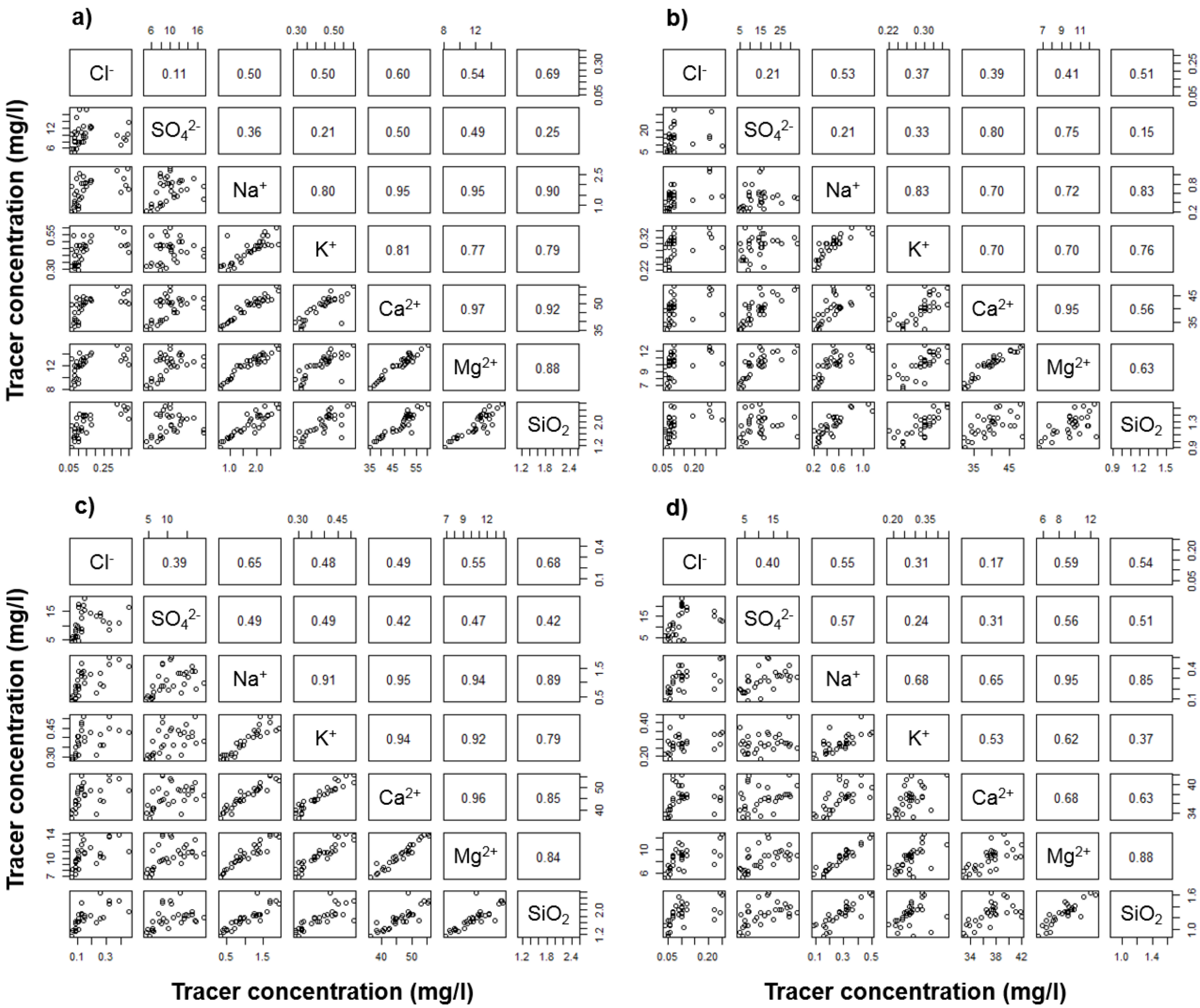
After the sources were characterized, the stream water was processed using principal component analysis (PCA; 'prcomp' function in R; R Core Team, 2014) as a method of dimensionality reduction to create a two-dimensional (2D) mixing space (Christophersen and Hooper, 1992). Stream water was standardized (subtracting the mean and dividing by the standard deviation for each sampling point), for each tracer, to create equal variance between chemical components and used to create a correlation matrix. PCA was conducted on the correlation matrix to calculate eigenvectors and eigenvalues. Standardized stream water was then projected into the end member mixing-space by multiplying by eigenvectors. Ideally, two principal components (PCs) explained most of the variation in the data and were used to generate a 2D mixing space, which corresponds to three sources in EMMA (Hooper, 2003). Other studies have used the 'Rule of 1' to determine how many dimensions, and therefore sources, should be used to create the mixing space (Ali et al., 2010; Barthold et al., 2011). For this study, the mixing space was set to two dimensions for ease of visualization but used all appropriate sources as presented by Inamdar et al. (2013) to provide a full description of potential source contributions. Source water was then standardized using stream water means and standard deviations for each ion and projected into the 2D mixing space as defined by the stream water (Christophersen and Hooper, 1992; Hooper, 2003). Stream water sources should create an outer boundary or polygon around all stream water samples if all sources were correctly identified and adequately sampled.

5 Results

5.1 Tracer and source water group selection

Bivariate plots were created and TVR was calculated to determine which tracers were appropriate for use in EMMA. Pearson correlation coefficients were calculated between all stream bivariate plots for stream water at each sub-watershed (Figure 4). These showed that all tracers exhibited acceptable linear trends with at least one other tracer (Pearson's $r > 0.5$) and were thereby likely conservative in nature. Average TVR for almost all tracers at all sites (exception Si at SW and SE) were below 2, which suggested that the within-group variation exceeded the between-group variation. Greater variation within- compared to between-source groups violates assumption 3) for EMMA (source water does not change) ~~and~~ and ~~were~~was considered unacceptable. As a result, rather than calculating mixing ratios or percent contribution~~s~~ of sources to stream water on the basis of an un-mixing routine in EMMA, trends in stream water distribution were described in relation to source water dynamics and runoff processes. ~~, as suggested by Inamdar et al. (2013).~~

The a priori classification of water sources was rain, snowmelt, soil water, ~~riparian water, toe slope water, upper~~ hillslope groundwater, ~~groundwater seeps~~till groundwater and bedrock groundwater; however, not all sites conformed to these categories. ~~b~~Box and whisker plots showed that the distribution of rain and snowmelt were ~~similar as well as the distribution of soil water, riparian water, toe slope water, and hillslope water for most sites~~too similar to be considered as separate groups. Although riparian water mixes with stream water and should be chemically different from hillslope water as a source, soil water, toe slope water, and upper hillslope water were grouped with riparian water for most sites because the distribution of these samples were too similar to be considered separate sources. The exception was SEL and SWU in which riparian water was considered as a separate source. Final source water groups ~~(Figure 3)~~ are described below for each sub-watershed. LDA plots indicated that LD1 and LD2 explained 88.5 % and 11.5 %, 95.3 % and 4.7 %, 81.1 % and 15.5 %, and 77.6 % and 22.4 % of the variance of the centroids for SWL, SWU, SEL, and SEU sites, respectively. Stepwise analyses were also used in attempt to reduce the redundancy of the tracers and to ensure that samples were well separated; on this basis, 99.7 %, 91 %, 98.6 %, and 99.9 % of samples were well separated in SWL, SWU, SEL, and SEU, respectively. In all sites, all tracers were retained to maximize the ability to distinguish between the source groups. Overall, these results support the conclusion that there was good separation between source water groups as re-categorized for the individual sites.



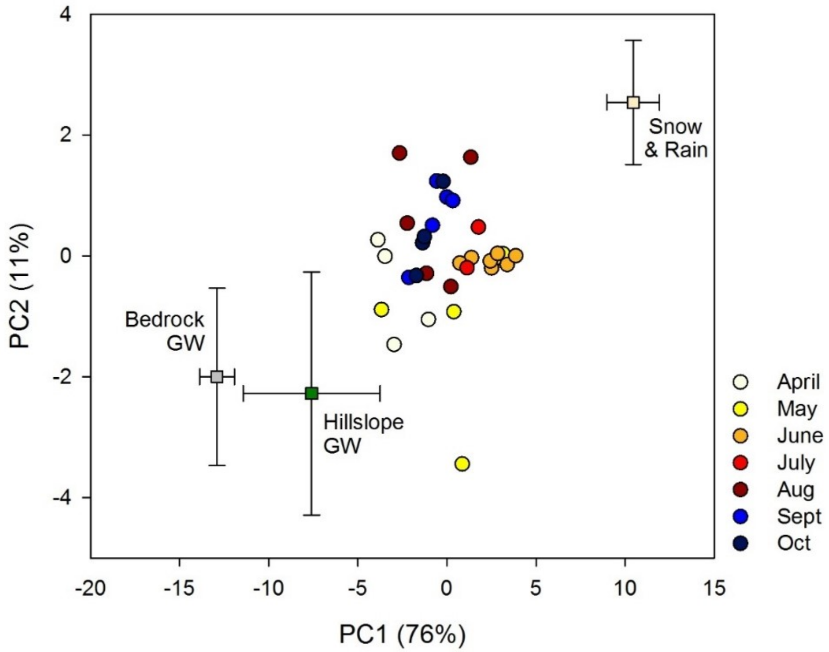
~~Figure 4: Bivariate plots of stream water chemistry at a) Star East Lower, b) Star East Upper, c) Star West Lower and d) Star West Upper. Top half of plots represents the Pearson's correlation coefficient (r) for the linear relation between each solute.~~

At the outset of this research, ~~G~~groundwater seeps were sampled in lieu of bedrock and~~or~~ till groundwater wells to characterize the variability in the chemical signature of groundwater throughout Star Creek. Most~~The~~ ion concentrations of the groundwater seeps were not chemically distinct because they were generally similar to stream water or hillslope groundwater in the PCA analyses (data not shown). However, the water temperature of ~~examination of~~ groundwater seeps ~~temperatures~~ from spring to fall revealed that some seeps ~~had~~were consistently cool ~~temperatures and~~while others had larger fluctuations in temperature. This suggests that some seeps were potentially groundwater-fed and others were fed by shallow subsurface water, respectively. For example, in SEL, the temperature of a ~~a~~ groundwater seep ranged between 2.2-3.7 °C throughout the summer (Figure 5), which is indicative of a bedrock groundwater source because the temperature range was muted and was largely not influenced by radiative warming (Taniguchi, 1993). ~~Similarly, i~~In SEU, the temperature of a groundwater seep ~~-~~ranged from 2.5-3.5 °C (Figure 5), also indicating a bedrock groundwater source. Temperatures in the till groundwater well ranged between 2.7-9.7 °C, displaying some radiative heating and cooling, whereas~~and~~ the bedrock groundwater ranged between 5.1-5.8 °C, displaying little radiative effects (Figure 5). The~~Both~~ groundwater seeps mentioned above had low variability like bedrock groundwater but were cooler suggesting potentially~~a~~ deeper bedrock groundwater sources than in the well. Temperatures of ~~the~~ some other groundwater seeps were more similar to bedrock groundwater although more variable, ranging from 3.6-5.4 °C (data not shown), while~~and~~ others were more similar to ~~surface water sources~~till groundwater, ranging from 4~~3~~.8-7.1~~9.4~~ °C (Figure 5). The corresponding specific conductivity measurements add further complexity to these patterns. The cool, temporally more stable seeps had low conductivity from April to September, which was not reflective of the specific conductivity in the bedrock groundwater well. Rather, the other seeps with greater variability in temperatures had high specific conductivity, more consistent with the bedrock groundwater wells (Figure 5). Unfortunately, the till well specific conductivity could not be used due to the contamination mentioned above so it was unclear if the till groundwater had similar specific conductivity.

5.2 Source water characterization

5.2.1 Star West~~ Lower~~

Water s~~S~~ources for the Star West Lower sub-watershed were grouped as precipitation (rain and snow), hillslope groundwater (soil water, riparian water, and toe slope water), and bedrock groundwater and plotted in PCA mixing space (Figure 6~~5~~). PC1 was mainly driven by cations and PC2 was driven by anions (Table 1). Minimal variation in chemistry across all precipitation samples (standard deviation (SD) of 2.4 and 1.1 for PC1 and PC2, respectively) and overlap of snow and rain samples in the mixing

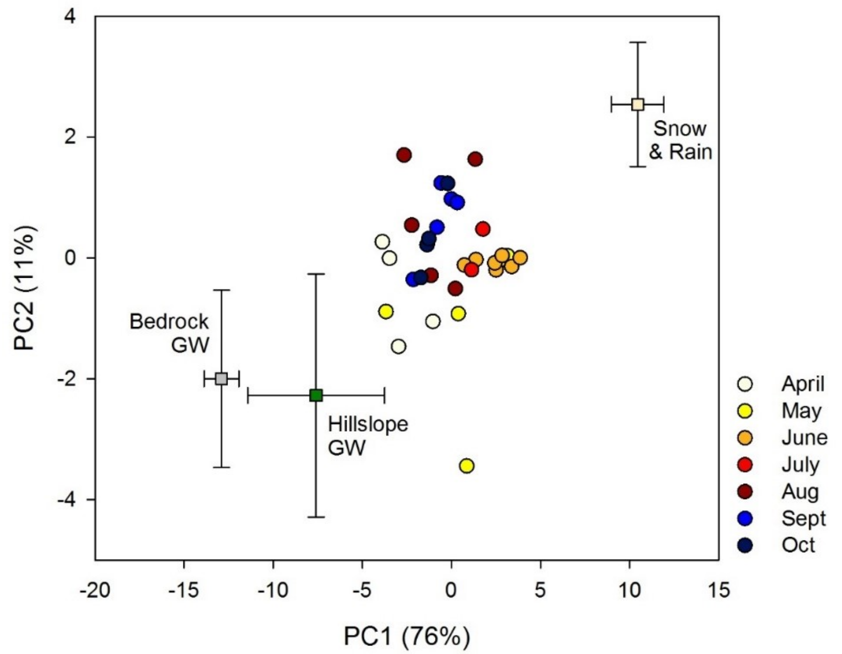


~~Figure 5: Star West Lower stream water chemistry from April to October in 2-D mixing space, which was derived from principal component analysis. Source water (precipitation, hillslope groundwater, and bedrock groundwater) was projected into the stream water mixing space. PC1 and PC2 represent the first and second principal components, which explain 87 % of the variation in stream water. Error bars represent the standard deviation of the source waters for PC1 and PC2.~~

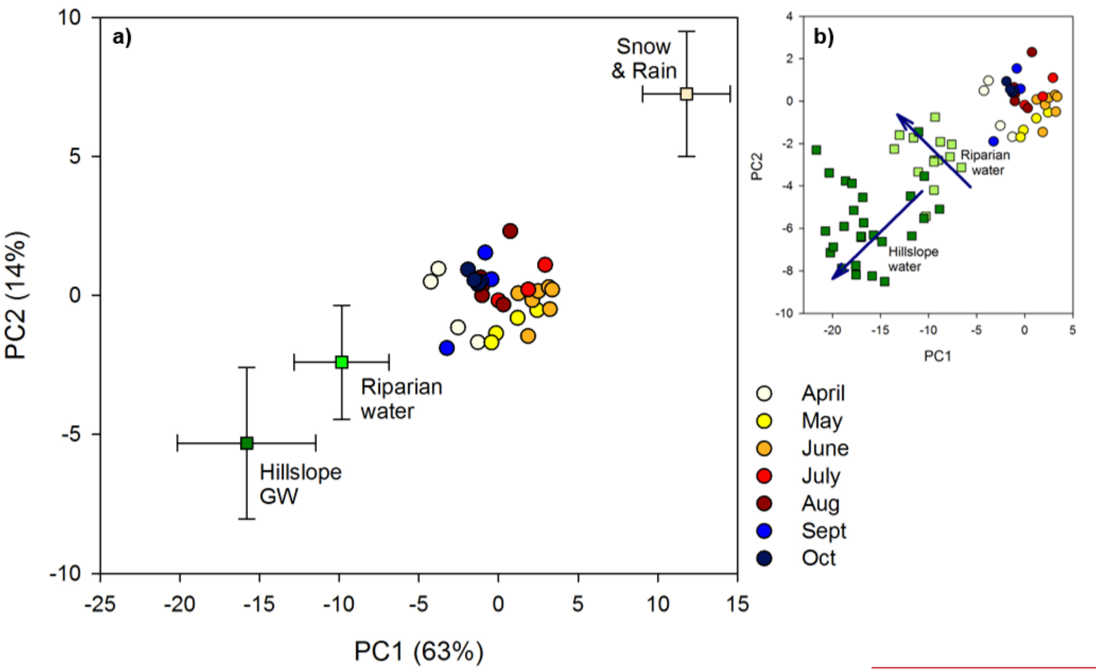
space confirmed that it was appropriate to aggregate all samples (snow and rain) taken across all sites (Star Creek, York Creek, and Coleman). Hillslope groundwater exhibited greater chemical variation across samples (SD of 3.8 and 2.0 for PC1 and PC2, respectively) compared to bedrock groundwater (SD of 2.9 and 4.8 for PC1 and PC2, respectively), but no clear temporal pattern was observed. Bedrock groundwater chemistry showed slight temporal variation~~,~~ with more positive values in PC2 in the spring than in the fall ~~(SD of 2.9 and 4.8 for PC1 and PC2, respectively)~~.

~~5.2.2 Star West Upper~~

Water sources for the Star West Upper sub-watershed were similarly grouped as precipitation (rain and snow) and~~,~~ hillslope groundwater (soil water, toe slope water, and upper hillslope water), but here~~and~~ riparian water displayed greater separation from hillslope groundwater and was considered as a separate source (Figure 6~~a~~). Bedrock groundwater samples were collected from a lower elevation in the watershed and may not be representative of higher elevation groundwater chemical composition~~signatures~~; therefore, they were excluded ~~as a source~~from the analysis for ~~at~~ the upper sites. Further, there were only two seeps identified in the upper watershed, but the temperature and chemical composition of these seeps were not reflective of bedrock groundwater. While this did not exclude bedrock groundwater contributions to streamflow in the upper regions of the watershed, it showed the chemical composition of the bedrock well and the two seeps may not have been representative of the bedrock groundwater chemistry in the Star West Upper sub-watershed. Precipitation clustered tightly in one location except for four snow~~a couple~~ samples ~~of snow~~ and one rain sample, which increased the SD for precipitation (SD of 2.7 and 2.3 for PC1 and PC2, respectively). All sources showed similar variation as precipitation; hillslope groundwater had a SD of 4.3 and 2.7 for PC1 and PC2, respectively and riparian water had a SD of 3.0 and 2.0 for PC1 and PC2, respectively. A temporal pattern was observed for hillslope water in which hillslope water became less like precipitation from spring to fall (Figure 7) ~~(Figure 6b)~~. Temporal variation was also observed across months for riparian water, in which SO_4^{2-} concentrations increased from spring to fall (~~Figure~~ Figure 7~~6b~~).



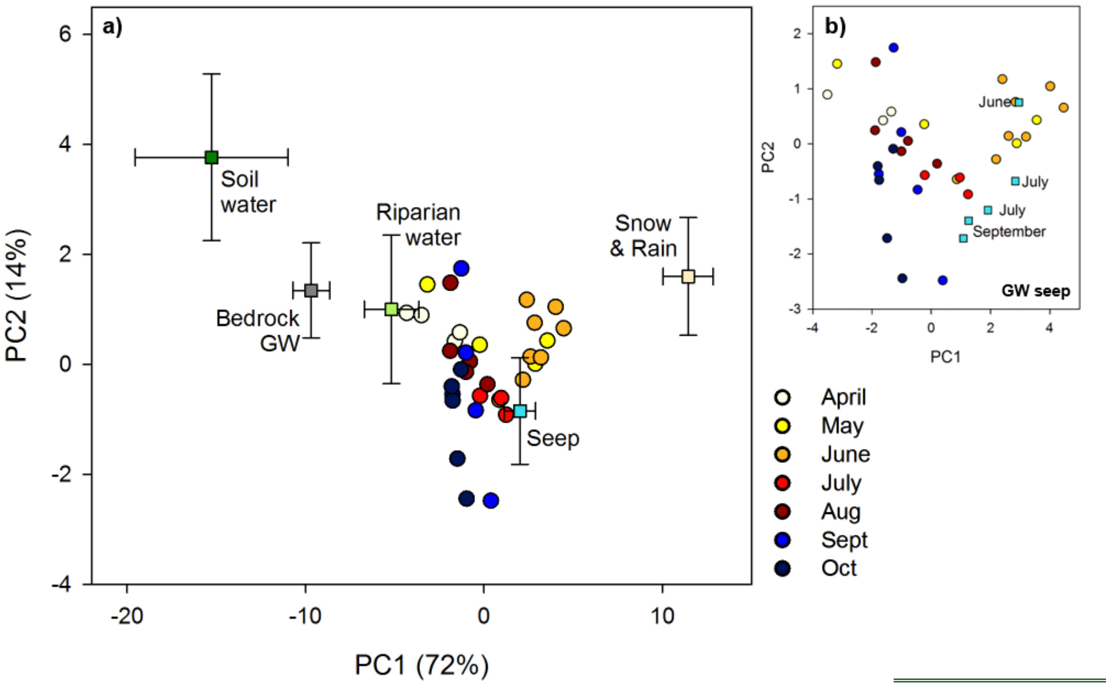
~~Figure 5: Star West Lower stream water chemistry from April to October in 2-D mixing space, which was derived from principal component analysis. Source water (precipitation, hillslope groundwater, and bedrock groundwater) was projected into the stream water mixing space. PC1 and PC2 represent the first and second principal components, which explain 87 % of the variation in stream water. Error bars represent the standard deviation of the source waters for PC1 and PC2.~~



~~Figure 6: a) Star West Upper stream water chemistry from April to October in 2-D mixing space, which was derived from principal component analysis. Source water (precipitation, riparian water, and hillslope groundwater) was projected into the stream water mixing space. PC1 and PC2 represent the first and second principal components, which explain 77 % of the variation in stream water. Error bars represent the standard deviation of the source waters for PC1 and PC2; b) shows the variation in riparian water and hillslope water samples from spring to fall (direction of arrows).~~

5.2.2~~3~~ Star East~~ Lower~~

Water sources for the Star East Lower sub-watershed were grouped as precipitation (snow and rain), soil water, riparian water, groundwater seep and bedrock groundwater (~~Figure 7~~Figure 8~~a~~). Precipitation (SD of 1.4 and 1.1 for PC1 and PC2, respectively) and bedrock sources (SD of 1.0 and 0.9 for PC1 and PC2, respectively) were the same as those used in SWL~~. Again, precipitation was tightly clustered in the PCA biplot for SEL (SD of 1.4 and 1.1 for PC1 and PC2, respectively)~~. Hillslope groundwater samples were initially grouped together as a single source but high standard deviations and clustering within the group suggested the separation of riparian water (SD of 1.0 and 1.5 for PC1 and PC2, respectively) and soil water (SD of 4.3 and 1.5 for PC1 and PC2, respectively) as individual sources. Soil water was most different from stream water and varied from spring to fall (increased Ca^{2+} and Mg^{2+} concentrations; Figure 9). Riparian water was most similar to stream water and did not vary over the season. ~~Bedrock groundwater was clustered in a linear pattern, but no temporal variation was observed.~~ A single groundwater seep that was chemically similar to stream water but temperatures were consistently cool was retained to aid in the explanation of stream water dynamics (~~Figure 7~~Figure 8~~b~~).



~~Figure 7: Star East Lower stream water chemistry from April to October in 2-D mixing space, which was derived from principal component analysis. Source water (precipitation, soil water, riparian water and bedrock groundwater) was projected into the stream water mixing space. PC1 and PC2 represent the first and second principal components, which explains 86 % of the variation in stream water. Error bars represent the standard deviation of the source waters for PC1 and PC2; b) shows the variation in the groundwater seep from June to September.~~

~~5.2.4 Star East Upper~~

Water sources for the Star East Upper sub-watershed were grouped as precipitation (rain and snow), hillslope groundwater (soil water, riparian water, and toe slope water), and groundwater seep (~~Figure ~~Figure 8~~8a~~). Precipitation ~~was clustered in a linear pattern~~displayed little variation (SD of 2.4 and 1.1 for PC1 and PC2, respectively)~~ but did not vary temporally~~. Large variation was observed for hillslope groundwater (SD of 9.3 and 7.3 for PC1 and PC2, respectively). Toe slope water and riparian water had some chemical dissimilarities but were not different enough from each other, or soil water, to be considered as different groups. ~~No temporal pattern was observed for toe slope water or riparian water chemistry.~~Some temporal variability was observed in riparian water compared to Star East Lower; however, s~~ S~~oil water had much larger~~varied~~ temporal~~ly~~ variability~~ where it was more similar to~~ than riparian water ~~and stream water in the spring and less like all stream water and all other samples (higher concentrations of ions) in the fall~~(Figure 9). ~~As in SEL, a ~~A single groundwater seep was identified in SEU. The seep~~ that~~ was chemically similar to stream water but temperatures were consistently cool and indicative of a deep groundwater source so it was retained to aid in the explanation of stream water dynamics (~~Figure ~~Figures 8 and 9~~8b~~).

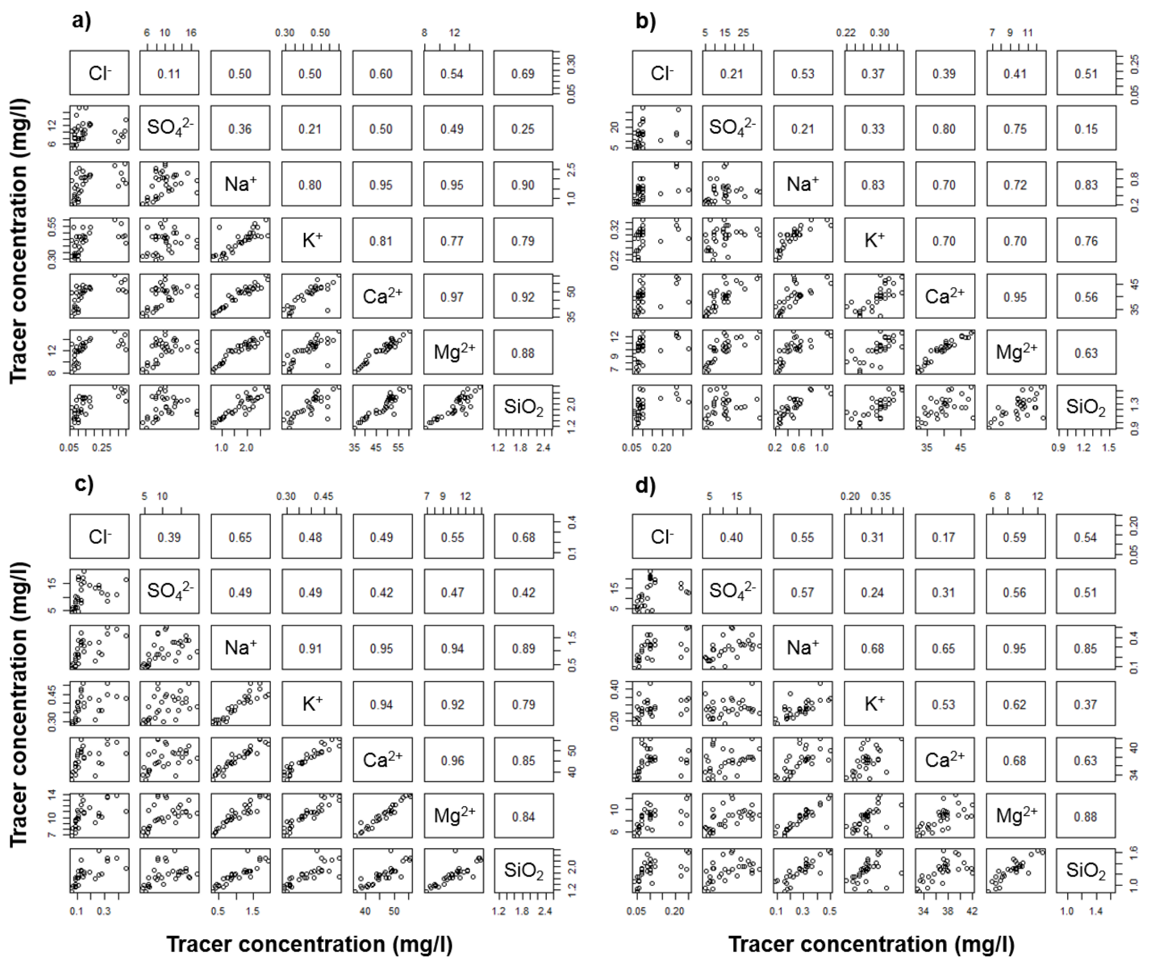


Figure 4: Bivariate plots of stream water chemistry at a) Star East Lower, b) Star East Upper, c) Star West Lower and d) Star West Upper. Top half of plots represents the Pearson's correlation coefficient (R~~r~~) for the linear relationship between each solute.

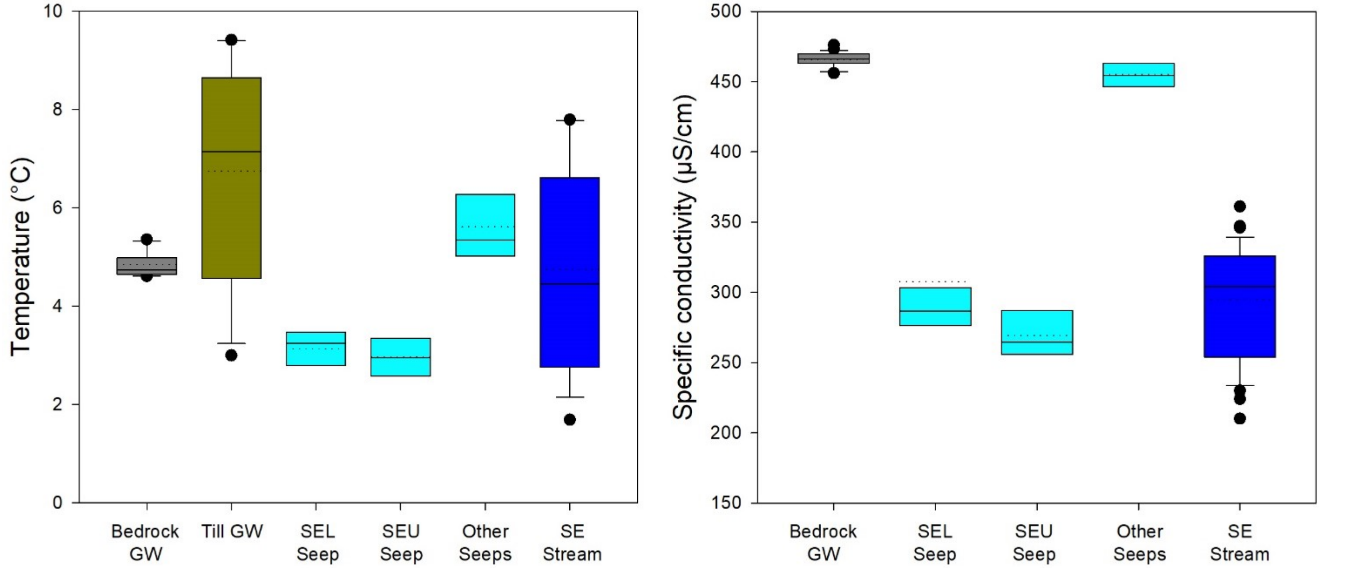


Figure 5. Box and whisker plot of groundwater, seep, and stream water temperature (left) and specific conductivity (right). Solid line indicates the median and the dashed line indicated the mean. The box indicates the 25th and 75th percentiles, the whiskers indicate the 10th and 90th percentiles, and the circles indicate points within the 5th and 95th percentiles. "Other seeps" is shown here as an example of the temperature and specific conductivity in many of the other seeps that were identified in the watershed but not used in the PCA biplots.

Table 1. Ions that explained the most variation in PC1 and PC2 for each sub-watershed in Star Creek.

	PC1	PC2		PC1	PC2
SEL	Mg (-)	SO_4 (-)	**SWL**	Na (-)	K (-)
	Si (-)	Cl (+)		Mg (-)	SO_4 (+)
	Ca (-)			Ca (-)	Cl (+)
	Na (-)			Si (-)	
	K (-)				
SEU	Mg (-)	SO_4 (-)	**SWU**	Mg (-)	Cl (+)
	Ca (-)	Si (+)		Na (-)	Ca (-)
	Na (-)			Si (-)	K (-)
	K (-)				SO_4 (+)

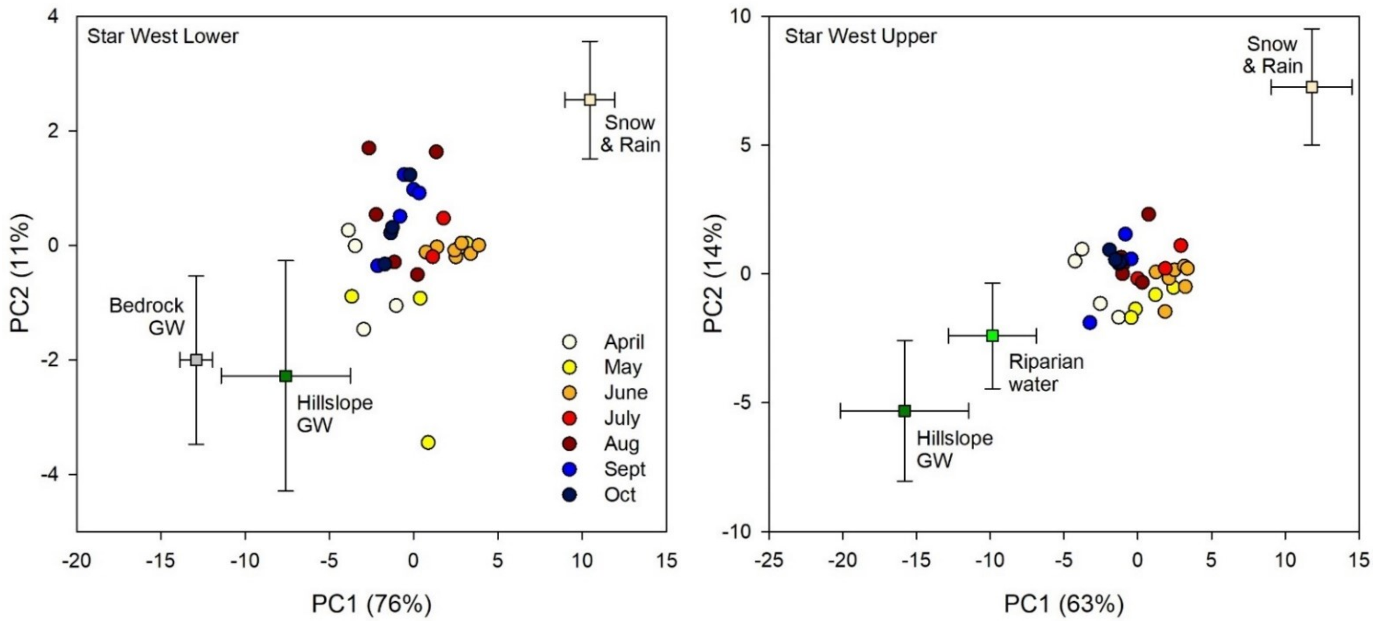


Figure 6: The first two principal components (PC) of variation in stream water chemistry in Star West Lower (left) and Star West Upper (right) from April to October (values in brackets indicate the percent variation explained by each PC). Square symbols indicate the mean chemical composition (+/- 1 standard deviation) of stream water sources for each sub-watershed.

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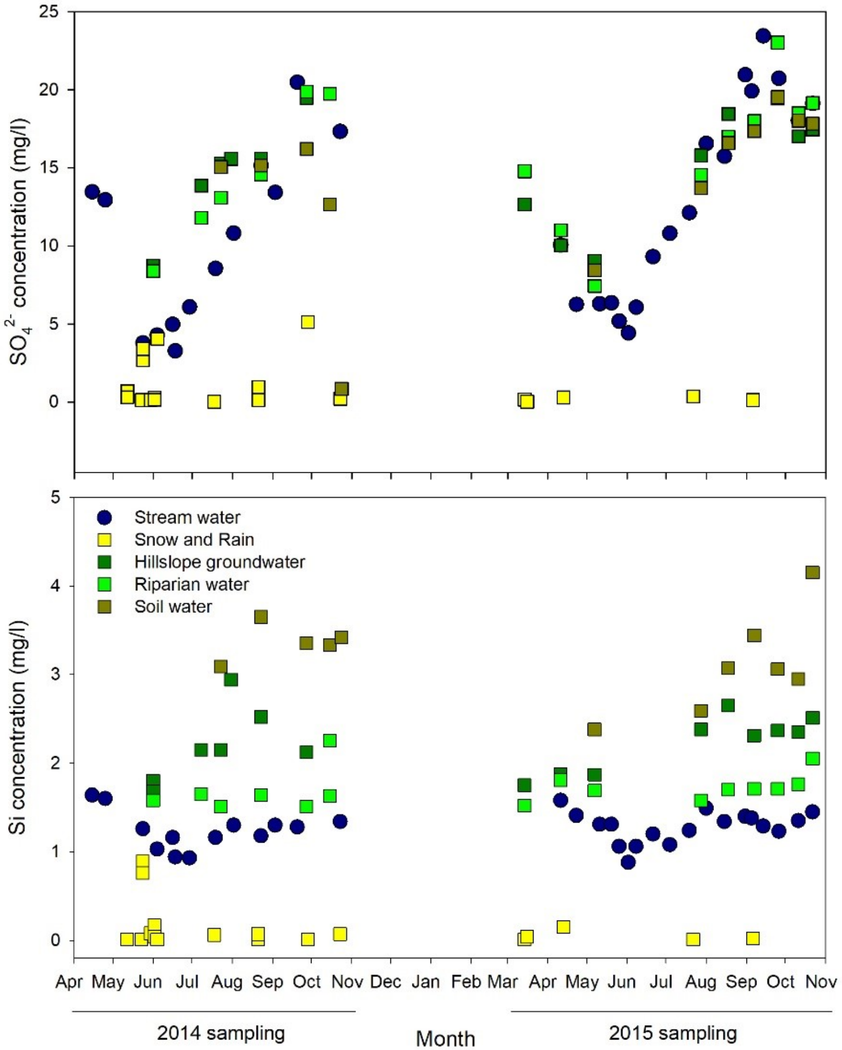
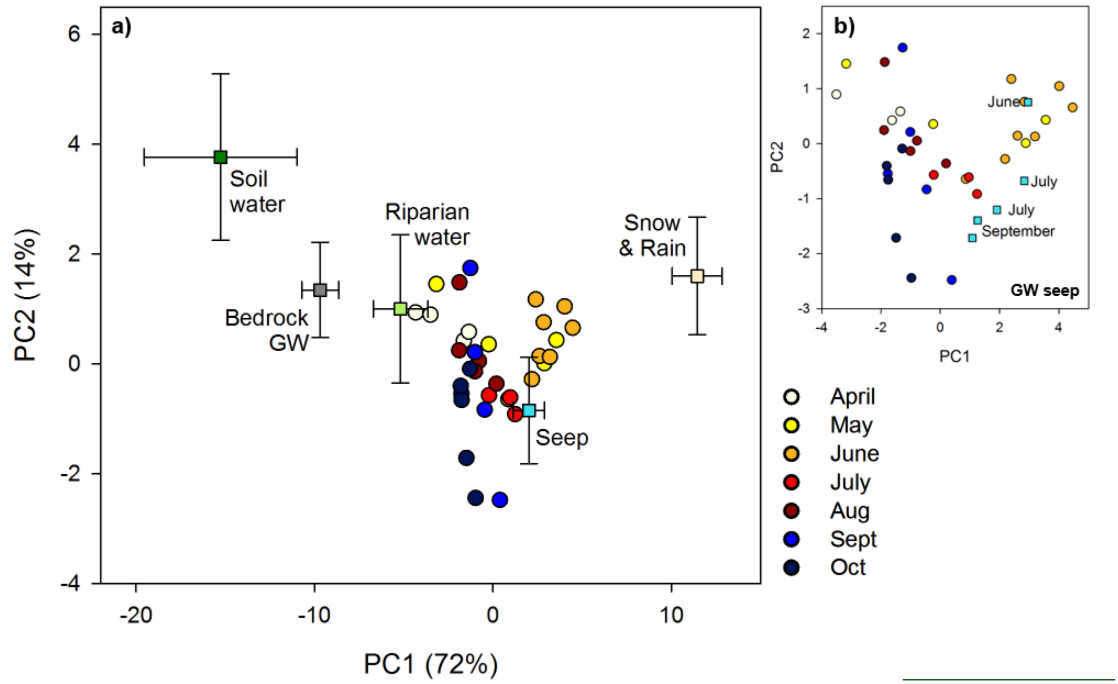
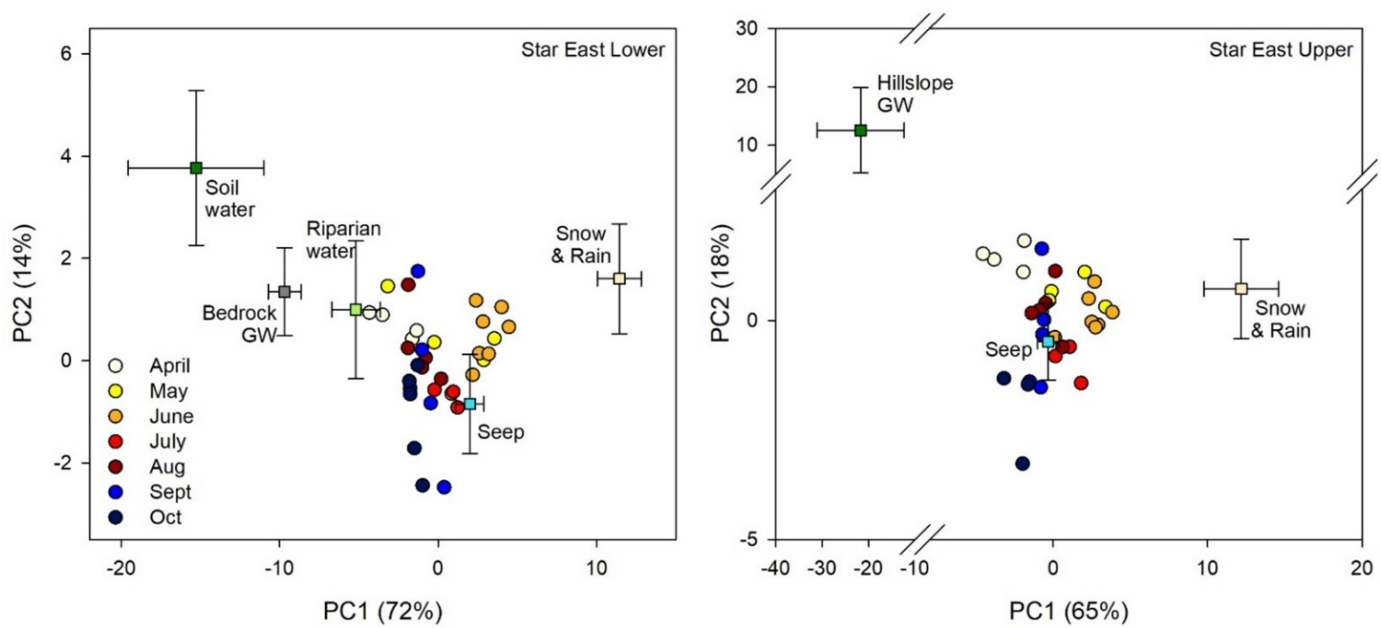


Figure 7: Time series of Si and SO_4^{2-} concentration in Star West Upper stream and source water in 2014 and 2015.

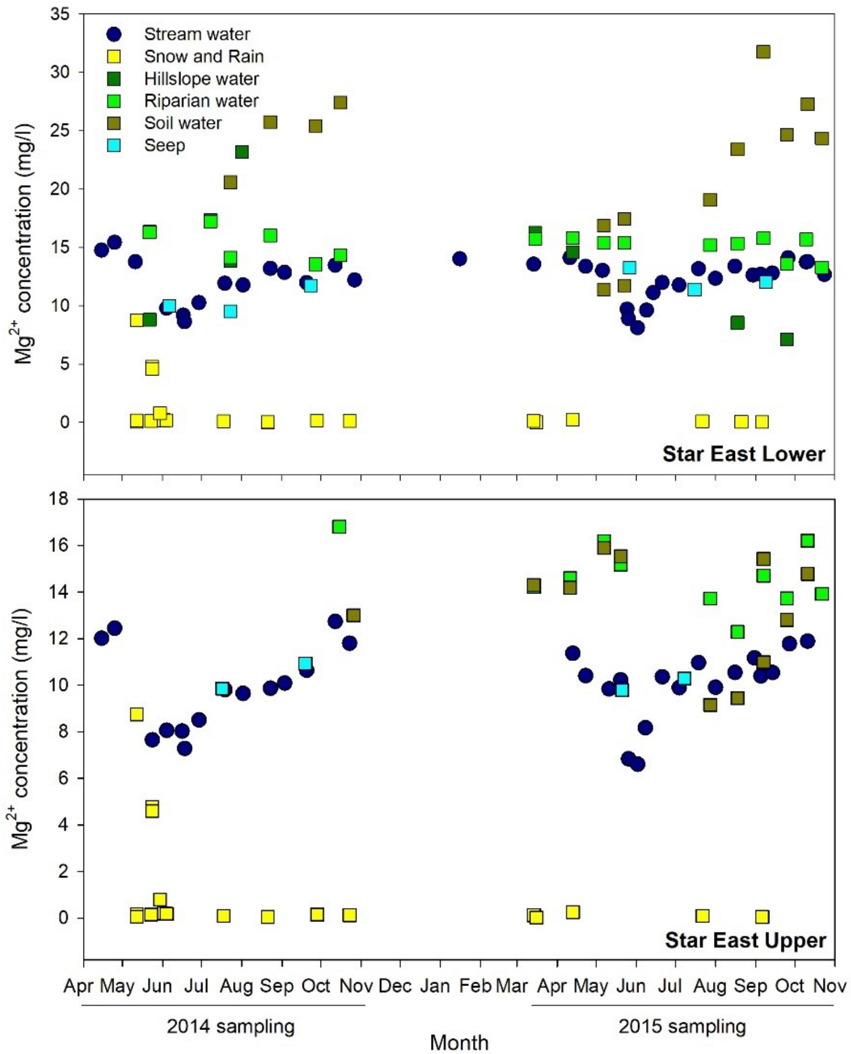




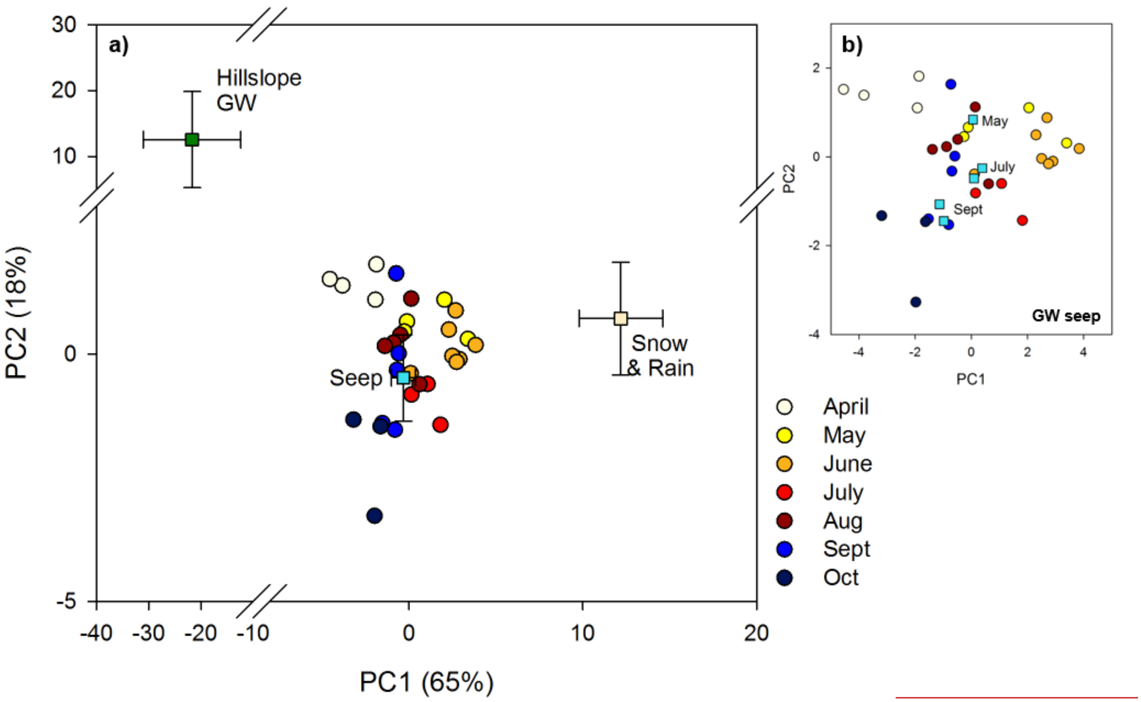
~~Figure 7~~Figure 8: The first two principal components of variation in stream water chemistry in Star East Lower (left) and Star East Upper (right) ~~stream water chemistry from April to October in 2-D mixing space, which was derived from principal component analysis~~(values in brackets indicate the percent variation explained by each PC). Square symbols indicate the mean chemical composition (+/- 1 standard deviation) of stream water sources for each sub-watershed.~~Source water (precipitation, soil water, riparian water and bedrock groundwater) was projected into the stream water mixing space. PC1 and PC2 represent the first and second principal components, which explains 86 % of the variation in stream water. Error bars represent the standard deviation of the source waters for PC1 and PC2; b) shows the variation in the groundwater seep from June to September.~~

Table 2. Streamflow and precipitation metrics for 2014 and 2015 water years.

	2014		2015	
	SW	SE	SW	SE
Annual discharge (mm)	944	648	719	468
Proportion of discharge May-July	0.69	0.74	0.45	0.54
Peak discharge (m^3/s)	1.20	0.75	1.14	0.72
Annual precipitation (mm)	1149	1089	1091	1090



470 **Figure 9: Time series of Mg^{2+} concentration for Star East Lower (top) and Star East Upper (bottom) stream and source water in 2014 and 2015.**



~~**Figure 8: Star East Upper stream water chemistry from April to October in 2-D mixing space, which was derived from principal component analysis. Source water (precipitation, hillslope groundwater, and groundwater seep) was projected into the stream water mixing space. PC1 and PC2 represent the first and second principal components, which explains 83 % of the variation in stream water. Error bars represent the standard deviation of the source waters for PC1 and PC2; b) shows the variation in the groundwater seep from May to September.**~~

5.3 Stream water characterization

Stream water chemistry for all four sites showed high temporal variation throughout the months of open-water flow (Apr-Oct) but little variation between years. As a result, the temporal pattern of stream water was characterized for each site in general for both 2014 and 2015 combined. Further, due to the lack of source water samples during winter months, the temporal pattern of stream water was characterized from April to October, which represents the most dynamic hydrologic period from the beginning of snowmelt through to the start of the next year's snow accumulation period. Hydrologic characteristics of the 2014 and 2015 water years are indicated in Table 2.

5.3.1 Star West ~~Lower~~

The first two principal components (PCs) from the PCA analysis ~~indicated that~~explained 87 % and 77 % of the variation in ~~the data was explained by the first two PCs~~stream water chemistry in Star West Lower and Star West Upper streams, respectively. Temporal variation of ~~S~~stream water ~~samples~~chemistry ~~were~~ was constrained within the broader multi-variate mixing space created by the variation in ~~an outer boundary created by~~ source water chemistry, ~~when the temporal variation in source water was considered,~~ but not ~~if mean values of source water were considered~~within the more constrained mixing space of the mean composition (+/- 1 std. dev.) of these sources (Figure ~~5~~ 6). In April, stream water was most similar to the hillslope groundwater (and riparian water in SWU). Stream water transitioned through May to become most similar to precipitation source water in June (and July in SWU). In SWL~~In July~~, stream water was slightly more similar to hillslope groundwater and bedrock groundwater in July. In August, September and October, stream water chemistry was more variable and was similar to precipitation and hillslope and bedrock groundwater. The temporal pattern associated with variation in stream water ~~variation~~chemistry through the fall was perpendicular to the direction of the bedrock temporal pattern, suggesting that hillslope groundwater (soil water, toe slope water and riparian water), rather than bedrock groundwater, was driving variation in stream water chemistry in the fall in SWL. Time series of Ca^{2+} and SO_4^{2-} show that hillslope groundwater was most similar to stream water (Figure 10). S

~~5.3.2 Star West Upper~~

~~PCA analysis indicated that 77 % of the variation in the data was explained by the first two PCs (Figure 6a). Sources formed two ends of a spectrum for stream water mixing rather than a triangle or polygon defining the mixing space. It is possible that a source was missed in the sampling campaign but when the variation in sources was considered, the stream water was bounded by the two points. In April, stream water was most similar to hillslope groundwater and riparian water. Stream water transitioned through May and was more similar to precipitation in June and July. S~~tream water in SWU was again more chemically similar to hillslope groundwater and riparian water~~again~~ through August, September, and October, but~~-~~ stream water chemistry differed slightly from ~~did not follow the same pathway as i~~its chemical composition~~n~~ in the early summer months. Riparian water chemistry had a similar temporal shift from April to October as stream water chemistry whereas ~~These temporal differences in stream water between spring and fall are similar to the temporal differences observed in riparian water from April to October rather than~~ hillslope groundwater and soil water had greater temporal variation (Figure ~~6~~ 7~~b~~). Further, water table depth in the hillslope well indicates that the upper hillslope is largely disconnected from the stream in the fall in both SWL and SWU (Figure 11) so it is more likely that the riparian area is contributing flow to the stream in the fall. ~~It is likely that there was mixing between riparian water and stream water producing a similar temporal variation in their chemical signature.~~

5.3.2~~3~~ Star East ~~Lower~~

Temporal patterns of variation in stream water chemistry observed for Star East Lower and Star East Upper were very consistent with each other, again with the exception of the bedrock groundwater well which was only sampled at a lower elevation site and therefore not included in the PCA analysis in Star East Upper. However, seeps that displayed temporal stability in water temperature typically characteristic of deep groundwater (Figure 5) were used in the analysis for both SEL and SEU. ~~PCA analysis indicated that~~The first two PCs explained 86 % and 83 % of the variation in ~~the data~~ stream water chemistry in Star East Lower and Star East Upper, respectively~~was explained by the first two PCs~~ (~~Figure 7~~Figure 8~~a~~). For both sub-watersheds, temporal variation in ~~S~~stream water chemistry~~samples~~ were mostly constrained within the mixing space produced by ~~an outer boundary created by~~ the variation in source water chemistry, ~~when the temporal variation in source water was considered with the exception of~~except during September/October when stream water~~, which~~ plotted outside this boundary. In April, stream water was most similar to the riparian/hillslope water (or bedrock groundwater for Star East Lower). The chemistry of ~~S~~stream water transitioned through May and was most similar to precipitation in June. In July and August, stream water became dissimilar from precipitation and was once again similar to riparian/hillslope water or bedrock groundwater. In September and October, stream water was less similar to riparian~~/ water~~ hillslope water and plotted outside the mixing space of ~~boundary created by~~ the identified sources. Since stream water was not contained within the boundary created by the source water, it is likely that an additional source was ~~missed from the analysis~~not captured by field sampling. However, ~~T~~the temporal variation in ~~the~~the chemistry of the groundwater seep followed the same pattern as the September/October stream water in both sub-watersheds, suggesting the same source water for the groundwater seep and late fall baseflow (~~Figure 7~~Figure 8~~b~~). Consistently cool temperatures of the seep in Star East Lower (2.2-3.7 °C) and Star East Upper (2.5-3.5 °C) suggest a deeper groundwater source.

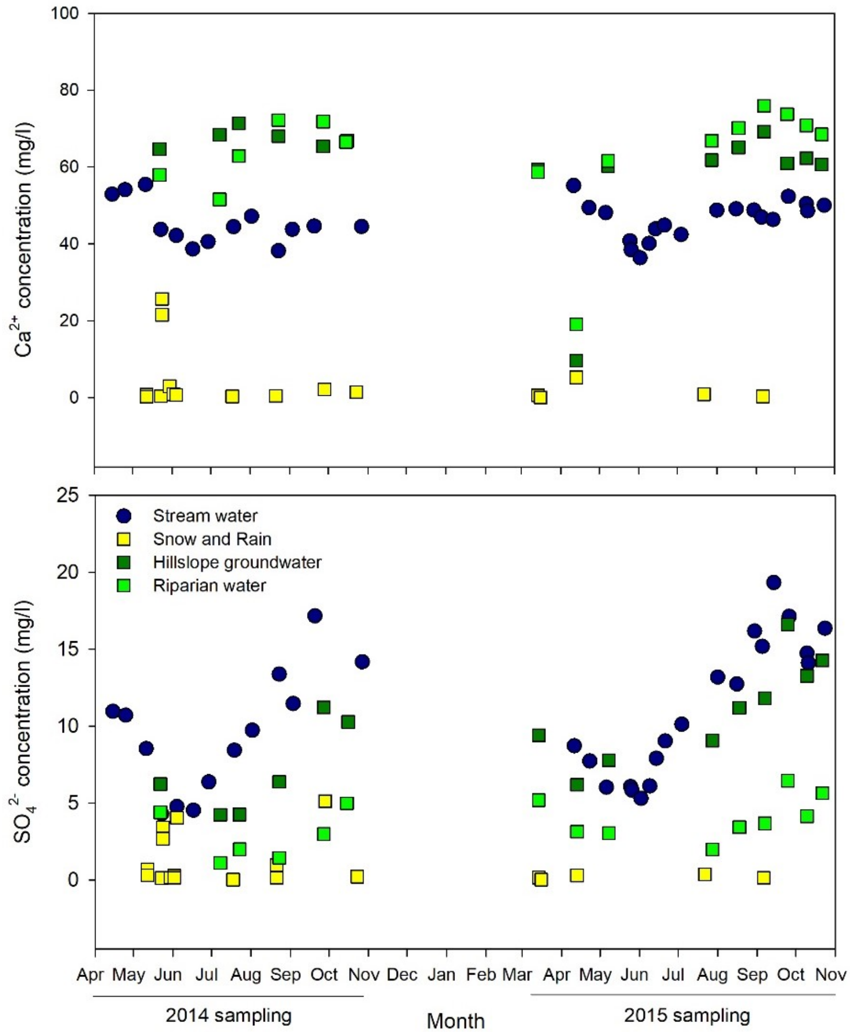


Figure 10: Time series of Ca^{2+} and SO_4^{2-} concentration in Star West Lower stream and source water in 2014 and 2015.

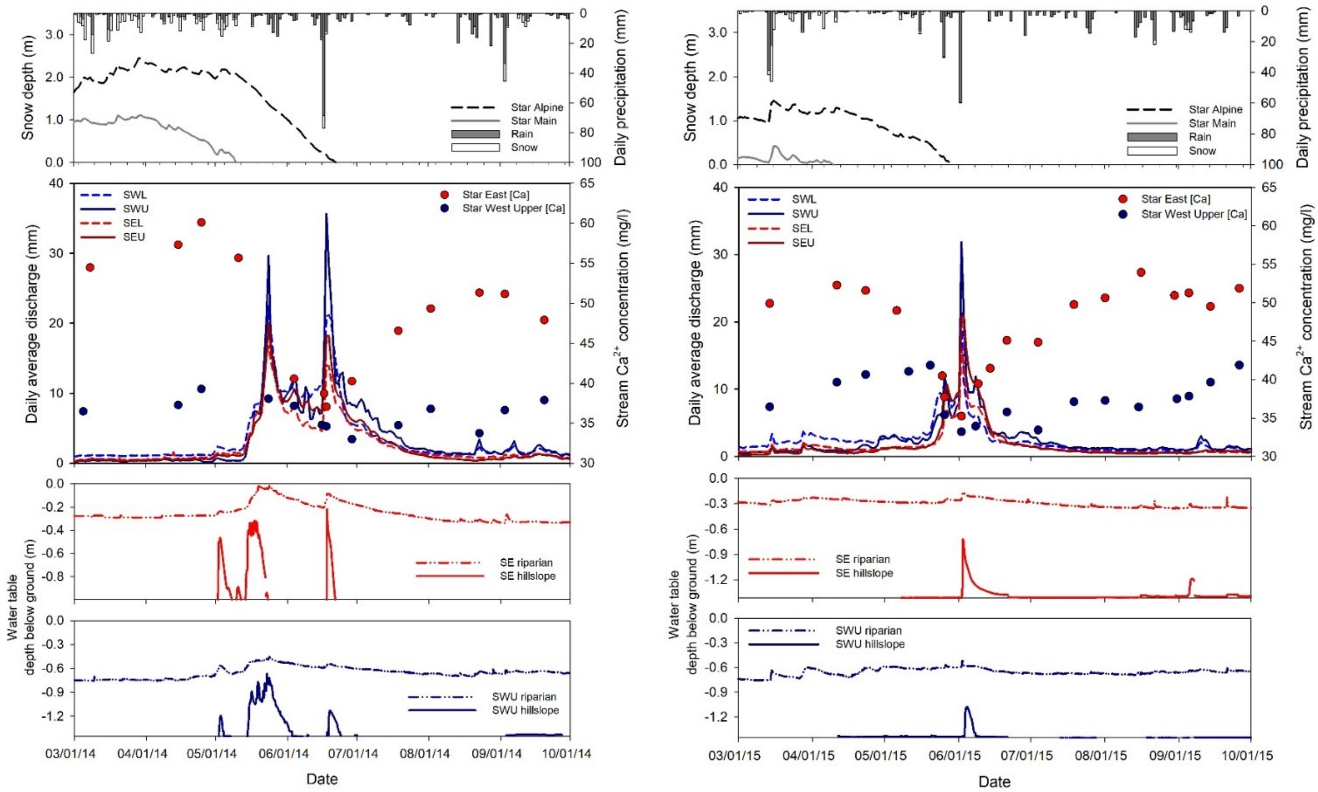


Figure 11: Observed inputs (snow depth and daily precipitation – estimated snow and rain proportions) and responses (stream discharge, stream Ca^{2+} concentration, shallow groundwater wells – hillslope and riparian) for Star Creek sub-watersheds in 2014 (left) and 2015 (right). Precipitation phase was separated into snow and rain after Kienzle (2008).

~~5.3.4 Star East Upper~~

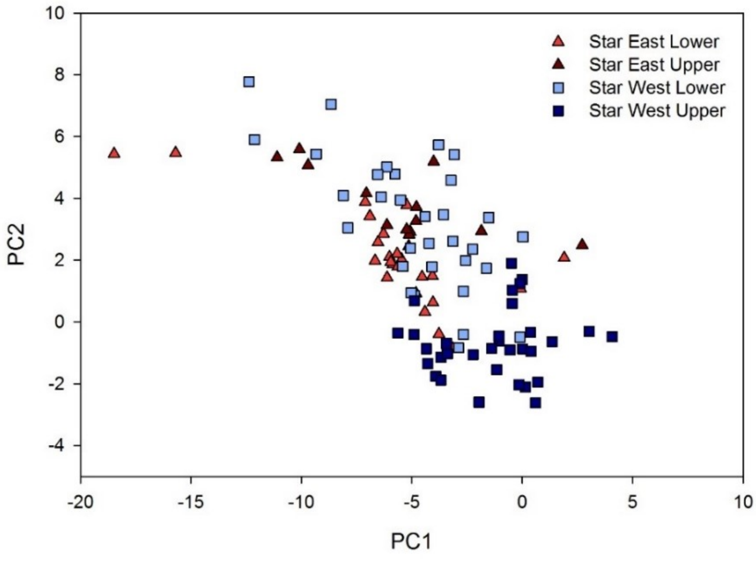
~~PCA analysis indicated that 83 % of the variation in the data was explained by the first two PCs (Figure 8a). Similar to SEL, some of the stream water samples were outside the boundary formed by the stream water sources. In April, stream water was most similar to hillslope water. Stream water was similar to precipitation in May and June. In July and August, stream water was similar to hillslope groundwater but not as much as in April. In September and October, stream water became chemically dissimilar from all identified sources and plotted outside the boundary created by these sources. As in SEL, the temporal variation observed in the stream in September and October was also observed in the groundwater seep (spring to fall; Figure 8b). Again, it is likely that there was another source contributing to streamflow in the fall that was not captured by the field sampling. This was likely a deeper groundwater source due to consistently cool temperatures (2.5-3.5 °C) observed for the groundwater seep.~~

6 Discussion

Twice monthly stream water and source water samples collected in Star Creek from April to October in 2014 and 2015 have been used here to conceptualize runoff generation in Alberta's Rocky Mountains. Results from this study allow for detailed examination of temporal patterns in source water chemistry and a qualitative description of source water contributions to stream water. While our intention was a quantitative estimate of source water contributions to streamflow using an un-mixing routine, two of the key assumptions for EMMA, the chemical composition of sources does not change over 1) the time scale considered or 2) with space (Hooper, 2003; Inamdar, 2011), were violated in this dataset. Source water chemistry varied greatly across the watersheds. For example, when all hillslope samples from each sub-watershed were projected into the mixing space created by stream water at the watershed outlet (SM), large variability was evident between sites (Figure 12). While there was some overlap between some sites (SWL and SEU), SWU was clearly different than the other hillslope samples. As a result, source water from within individual sub-watersheds was used to reduce the uncertainty associated with large spatial variability in source water chemistry. However, the variability within sites was also quite large. The coefficient of variation (CV) of source water was often larger than the CV of the stream water (there should be little to no variation in source water over time; James and Roulet, 2006; Inamdar, 2011), particularly for K^+. The occasions where source water CV were smaller than stream water CV for most ions were for seeps in SEU and SEL, bedrock groundwater in SWL and SEL, and hillslope and riparian water in SWU. ~~**6.1 Temporal and spatial variation in source water signatures**~~

Chemical signatures of source water have been shown to vary seasonally and annually (Rademacher et al., 2005) as well as spatially across sub-watersheds in southern Quebec, Canada (James and Roulet, 2006). As a result, James and Roulet (2006) suggested that only source water from within individual sub-watersheds of interest should be used in un-mixing calculations. Inamdar et al. (2013) further argued that mixing proportions should not be calculated because multiple assumptions are often violated and can lead to significant errors in un-mixing proportions. Rather, temporal and spatial variation in stream water and source water should be examined and used to describe or to develop a physically-based conceptualization of runoff mechanisms.

~~Two of the key assumptions for EMMA, the chemical composition of sources does not change over 1) the time scale considered or 2) with space (Hooper, 2003; Inamdar, 2011), were violated in this dataset. Source water chemistry varied greatly across the watersheds. For example, when all hillslope samples from each sub-watershed were projected into the mixing space created by stream water at the watershed outlet (SM), large variability was evident between sites (Figure 9). While there was some overlap between some sites (SWL and SEU), SWU was clearly different than the other hillslope samples. As a result, source water from within individual sub-watersheds was used to reduce the uncertainty associated with large spatial variability in source water chemistry. However, the variability within sites was also quite large. The coefficient of variation (CV) of source water was often larger than the CV of the stream water (there should be little to no variation in source water over time; James and Roulet, 2006; Inamdar, 2011), particularly for K^+. The occasions where source water CV were smaller than stream water CV for most ions were for seeps in SEU and SEL, bedrock groundwater in SWL and SEL, and hillslope and riparian water in SWU.~~



~~**Figure 9: Hillslope groundwater from all sub-watershed sites in 2-D mixing space, which was derived from principal component analysis of Star Main (Figure 1) stream water. PC1 and PC2 represent the first and second principal components**~~

~~Despite the violation of assumptions, interesting and interpretable temporal trends in source water chemistry were observed. For example, temporal variations in riparian water in SWU were observed from spring to fall and followed the same pattern observed in stream water chemistry in May compared to September/October (Figure 6b). It is not clear if the stream chemistry responded to variation in riparian chemistry or if riparian water responded to stream chemistry, but these pools of water were likely mixing to create the same temporal pattern rather than the variation in hillslope water chemistry influencing the stream. Other studies have also shown the importance of the riparian zone for "buffering" water chemistry and influencing stream water contributions, although often at the event scale (McGlynn and Seibert, 2003; Grabs et al., 2012). Spencer et al. (2019) presented water table dynamics in hillslope groundwater wells and suggested that the upper hillslope and the stream were only connected during the spring freshet. This would suggest that hillslope water chemistry should reflect the dilution from snowmelt and the subsequent drying of the hillslope, which should increase the concentration of water held in the soil from spring to fall. The corresponding temporal pattern in hillslope water chemistry was observed in SWU (Figure 6b) and for soil water chemistry in SEL and SEU.~~

~~Bedrock groundwater was consistent between years, but there is uncertainty around the variability of bedrock groundwater across the watershed. Although most of the stream is situated within the same geologic formation, there may be differences in bedrock groundwater chemistry associated with heterogeneous sedimentary layers or contact time (Freeze and Cherry, 1979). Groundwater seeps that were sampled along the stream length could be used as a potential indicator of groundwater variability because they may flow through various formations or flow pathways. Temperature signals from seeps suggested some were groundwater-fed (consistent cool temperatures) and others were fed by shallow subsurface water (larger fluctuations in temperature; Taniguchi, 1993). However, ion concentrations of the seeps were not chemically distinct because they were~~

~~generally similar to stream water or hillslope groundwater. This suggests that there are likely many complex subsurface flow pathways making it difficult to differentiate between subsurface sources. Other tracers such as oxygen and hydrogen isotopes or non-conservative tracers such as nitrogen and dissolved organic carbon may help to better differentiate between seeps, hillslope groundwater, and bedrock groundwater (e.g., Cowie et al., 2017; Ali et al., 2010; Orlova and Branfireun, 2014). More wells in the bedrock and till are also required to characterize the variability in groundwater more robustly across the watershed (Rinderer et al., 2014) and improve the EMMA results.~~

~~6.2 Temporal variation in stream water contributions~~

Despite the violation of assumptions, notable temporal trends in source water chemistry were observed in snowmelt, riparian water, hillslope and soil water, and bedrock groundwater and their contributions to ~~S~~stream water ~~contributions~~ can be generalized for all sub-watersheds in Star Creek in a number of ways. The water that was stored in the hillslope overwinter (or "reacted water") was likely the first to reach the stream in the early spring prior to high flow as snowmelt started to saturate the landscape (Figures 6 and 7). T~~.~~emporal patterns in stream water chemistry also showed a spike in concentrations of some ions (e.g., Ca^{2+} concentration in Figure 11) in the stream in the early spring as this reacted water mobilized prior to the onset of the snowmelt freshet. Although three snowmelt samples in 2014 showed similar ionic pulses early in the snowmelt season to those reported in the Colorado Rocky Mountains (Williams et al., 2009), the concentrations were notably less than from all other sources and thus not likely an important source of the observed early season increase in stream water concentration of some ions. Rather, t~~T~~he delivery of reacted water~~old water~~ to the stream at the onset of snowmelt is likely similar to the flushing mechanism observed in the Turkey Lakes Watershed in central Ontario, Canada (Creed and Band, 1998) where high nitrogen concentrations were observed prior to peak streamflow. McGlynn et al. (1999)~~also~~ observed the displacement of old water to the stream at the onset of snowmelt in Sleepers River Research Watershed in Vermont, USA and suggested this was due to a small volume of snowmelt being added to a large storage of water already in the subsurface.

This initial displacement of ~~old~~reacted water was~~likely~~ followed by a dilution effect, where large volumes of low concentration snowmelt mixed with soil water and contributed to streamflow. ~~S~~Snowmelt was the major event that produced a water table response in all hillslope wells and connected the hillslopes to the stream (Figure 11; Spencer et al., 2019)~~(Spencer et al., 2019)~~. The initial snowmelt period was also the only time overland flow was observed at the study site. Other studies have also reported that snowmelt creates a dilution response in the stream (Rademacher et al., 2005; Cowie et al., 2017). Conversely, the opposite has ~~also~~ been observed whereby a previously disconnected source was connected to the stream and caused an increase in solute concentrations (McNamara et al., 2005). Although this was the main period of hydrologic connectivity in Star Creek (Figure 11), we did not observe an~~the~~ increase in stream water ion concentrations~~chemistry~~ associated with newly connected sources. Hillslope groundwater and soil water chemistry should reflect the dilution from snowmelt and the subsequent drying of the hillslope, thereby increasing ion concentrations in the soil water from spring to fall. This corresponding temporal pattern in hillslope groundwater chemistry was observed in SWU (Figure 7) and for soil water chemistry in SEL and SEU (Figure 9).

Source ~~tream~~ water contributions to the stream were more similar within Star East (SEL and SEU) and Star West (SWL and SWU) sub-watersheds than between alpine/sub-alpine (SEU and SWU) and upper montane (SEL and SWL) sub-watersheds. PCA plots for SEL and SEU showed that stream water chemistry was most ~~like~~similar to precipitation in May and June, whereas a~~this~~ dilution effect from snowmelt occurred in June and July in SWL and May to July in SWU. It should be noted that although dilution was observed, stream water was less dilute than snowmelt alone. Snowmelt water interacts with the soil as it moves through the subsurface to the stream directly influencing the chemical composition of the snowmelt contributions to streams (Sueker et al., 2000). The delayed response in SWL and SWU is consistent with the watershed storage estimates from baseflow recession analysis (Spencer et al., 2019) that suggested that the west fork sub-watersheds had a larger storage capacity than the east fork sub-watersheds. Accordingly, more water would be required to fill storage before saturation or hydrologic connectivity occurred.

Differences in the east and west forks were also evident ~~later~~ in~~in~~ ~~the year~~the hysteresis pattern in stream water chemistry from spring to fall. Star West sub-watersheds had a counterclockwise pattern, whereas Star East sub-watersheds had a clockwise pattern. In general, this is an artefact of the PCA analysis driven by the specific ions that defined each PC (Table 1). In Star East, the first PCs were dominated by anions and the second PCs were dominated by SO_4^{2-} (negative relationship). While the first PCs for Star West were dominated by anions, the second PCs included a mix of anions and cations and SO_4^{2-} with a positive correlation thereby producing an opposite hysteresis pattern. Although this is an artefact of the PCA analysis, it was ultimately due to slight variations in the sources contributing to the streams at different times during the flow season. For instance, ~~I~~in SWL and SWU, stream water was chemically similar to ~~hillslope ground~~riparian water in the fall (Figure~~s 5 and~~ 6~~a~~); whereas~~. I~~ in SEL and SEU, stream water was similar to hillslope groundwater in August but fell outside the boundaries created by the identified sources in September and October (Figure~~s~~ 7~~a and 8a~~). Details on the possible processes underlying these differences are described below.

Temporal variations in riparian water in SWU were observed from spring to fall and followed the same pattern observed in stream water chemistry in May compared to September/October (Figure 7). It is not clear if the stream chemistry responded to variation in riparian chemistry or if riparian water responded to stream chemistry, but these pools of water were likely mixing to create similar temporal patterns rather than reflecting those of hillslope water chemistry influencing the stream. Timing of riparian and stream water level responses may be used to help clarify these patterns in future research. Other studies have shown the importance of the riparian zone for "buffering" stream water chemistry from inputs from other sources particularly for individual hydrologic events (McGlynn and Seibert, 2003; Grabs et al., 2012). Further research needs to be conducted to estimate the extent of the riparian area and the potential volume of water that may contribute to streamflow in Star East compared to Star West.

A groundwater seep in SEL and SEU followed similar temporal patterns as stream water from spring to fall (Figure~~s~~ 7~~b and 8b~~) and may provide insights into the sources of stream water in ~~the fall~~September and October. Consistently cool, ~~temperatures~~ but low specific conductivity of the groundwater seeps suggest they likely reflected ~~have~~ a deeper bedrock groundwater source different than the bedrock groundwater well. ~~Star Creek has spatially heterogenous surficial deposits and~~

~~geology (AGS, 2004) which likely has a large influence on groundwater chemistry throughout the watershed~~Although most of the stream is situated within the same geologic formation, there may be differences in bedrock groundwater chemistry associated with heterogeneous sedimentary layers or contact time in the upper versus lower watershed (Freeze and Cherry, 1979). Temperature signals from other seeps suggested some were fed by shallow subsurface water or till groundwater (larger fluctuations in temperature; Figure 5; Taniguchi, 1993), yet they had high specific conductivity and similar ion concentrations as bedrock and hillslope groundwater. This suggests that there are likely many complex subsurface flow pathways making it difficult to differentiate between subsurface sources, but i~~. I~~t is possible, therefore, that additional bedrock groundwater sources were contributing to streamflow in Star ~~Creek~~East in September and October. Other tracers such as oxygen and hydrogen isotopes or non-conservative tracers such as nitrogen and dissolved organic carbon may help to better differentiate between seeps, hillslope groundwater, and bedrock groundwater (e.g., Cowie et al., 2017; Ali et al., 2010; Orlova and Branfireun, 2014). Additional observation wells in the bedrock and till would be required to characterize more thoroughly the variability in groundwater across the watershed (Rinderer et al., 2014).

Topographic transitions and convergent zones have been associated with groundwater contributions to streamflow (Covino and McGlynn, 2007; Hjerdt et al., 2004). While minimal groundwater discharge occurred over the mountain front recharge zone in Humphrey Creek, southwest Montana, USA, considerable groundwater discharge was observed in the valley bottoms (Covino and McGlynn, 2007). Large increases in the concentration of stream water ions that may be associated with strong groundwater upwelling were not evident between April and October or along the length of the stream. However, chemical signatures of groundwater seeps suggest that some bedrock groundwater may not be distinguishable from stream water. Consequently, these transitions may not be visible in water chemistry along the length of the stream.

Although contamination of the till groundwater well ~~has~~ limited the inferences that could be made from its water chemistry, water levels in the bedrock and till groundwater wells do provide some insights into ~~their~~potential contributions of till groundwater to streamflow. Water table depth in the till groundwater was more responsive than bedrock groundwater level in the spring, though the overall rise in water level in the bedrock was slightly greater. Despite the flashier response earlier in the year, till groundwater levels remained elevated longer than bedrock groundwater resulting in a slower recession (slower drainage) in the till groundwater well in the summer~~The till groundwater well showed consistently slower recession curves compared to the bedrock groundwater well~~ (~~Figure 10~~Figure 13). Similar to the post-glacial landscape in Sleepers River watershed (Shanley et al. 2015), slower drainage from till groundwater may be partly responsible for maintaining streamflow during late summer or fall. The temperature range of some seeps sampled along the stream length were similar to till groundwater, but ion concentrations were similar to hillslope and bedrock groundwater. It is likely that glacial till chemistry is similar to hillslope and bedrock groundwater given that they are situated above and below the glacial till layers. Heterogeneous glacial till deposits with different physical characteristics were also linked to the variable release of stored water, and thus the variability in baseflow, in the Scottish Highlands (Blumstock et al., 2015). Glacial till in the Rocky Mountains can be highly spatially ~~heterogenous~~variable ~~and~~ likely ~~has~~promoting multiple flow pathways ~~within it~~ (Langston et al., 2011). Clay lenses can create perched water tables that have different response times than the rest of the till matrix

(Evans et al., 2000) or create complex groundwater flow pathways (Freeze and Witherspoon, 1967). Further research is needed to help differentiate between bedrock groundwater and till groundwater and their contribution to stream water during low flows.

~~The complexity in subsurface flow pathways that appears to influence runoff generation in Star Creek watershed may be important in evaluating watershed resilience to disturbance. Primarily vertical percolation or groundwater recharge (Spencer et al., 2019) and delayed or variable release of stored water could mute the impact of disturbance on peak flows. However, excess water associated with forest disturbance would infiltrate into the subsurface, which may subsequently increase baseflows. Star Creek sub-watersheds have a large storage capacity (300-450 mm) in glacial till and fractured bedrock (Spencer et al., 2019). When compared to average annual precipitation (950 mm), it is possible that storage can mitigate the effects of the increased net precipitation reaching the ground following disturbance by temporarily holding and slowly releasing the excess water. Harder et al. (2015) also postulated that complex subsurface flow pathways and large storage capacity may be partly responsible for the resiliency observed in Marmot Creek watershed (Alberta, Canada) following disturbance; however, more research is needed to determine the influence of disturbance on groundwater.~~

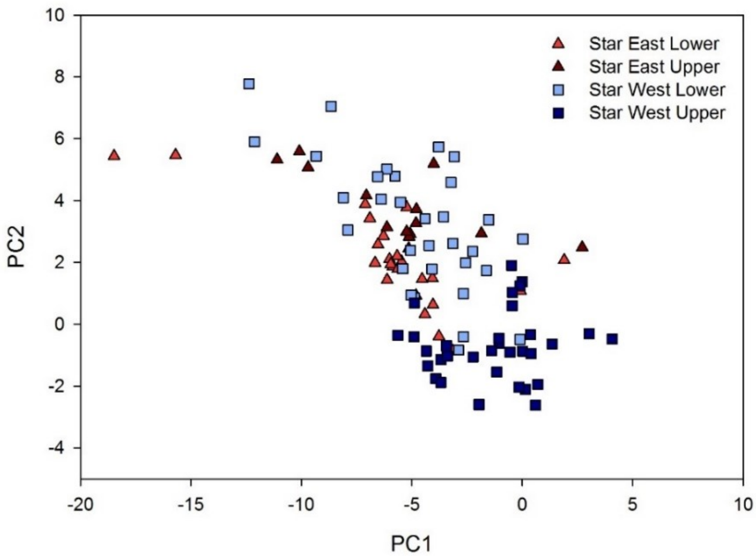
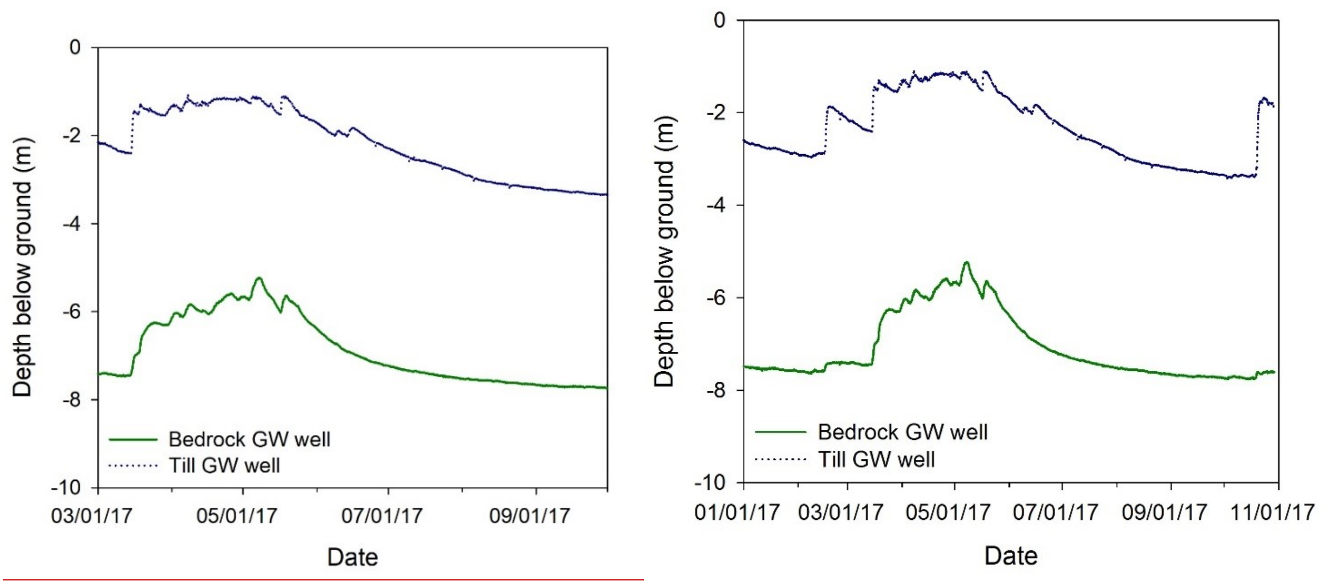


Figure 12: Hillslope groundwater from all sub-watershed sites in 2-D mixing space, which was derived from principal component analysis of Star Main (Figure 1) stream water. PC1 and PC2 represent the first and second principal components



~~Figure 10~~Figure 13: Bedrock groundwater and till groundwater well responses (depth below ground, m) over the 2017 calendar year. ~~Till groundwater is more responsive but has slower recession slopes in the summer.~~

7 Conclusions

Stream and source water were collected over the 2014 and 2015 water years and visualized using principal components analysis to conceptualize runoff generation processes in the Canadian Rocky Mountains. While strong variability in source water chemistry limited our ability to quantitatively estimate the relative contributions of multiple water sources to the stream using an un-mixing routine, the analyses used here enabled a strong qualitative description of precipitation, hillslope water and bedrock groundwater source contributions to streamflow. This allowed us to both indirectly observe and infer key runoff generation processes in watersheds with a complex lithological structure characteristic of the highly permeable bedrock and glacial till of the Alberta Rocky Mountain region.

Stream water chemistry in four sub-watersheds of Star Creek showed that Star East (SEL and SEU) and Star West (SWL and SWU) sub-watersheds were more similar than alpine/sub-alpine (SEU and SWU) and upper-montane (SEL and SWL) physiographic zones. ~~PCA plots were used to conceptualize runoff generation.~~ In general, higher concentration “reacted” water~~old water~~ reached the stream first at the onset of spring melt in all sub-watersheds. This was followed by a dilution effect as the snowmelt saturated the landscape and the hillslope was connected to the stream. Fall baseflows differed between Star East and Star West forks. Star West stream water was once again similar to hillslope water or riparian water, but Star East stream water plotted outside the boundary of the measured sources~~was unlike all measured sources~~. Seep water temperatures were cool and had low variability suggesting it may be deeper bedrock water contributing to the stream. Slower recession rates (and likely lower hydraulic conductivity) in the till groundwater well than in the bedrock groundwater well suggest that water recharged into the till groundwater may be slowly released to the stream. Contamination of the till groundwater well made it unclear when it was contributing to the stream, but groundwater table fluctuations suggested it is likely contributing during late summer or fall.~~, thereby muting the effects of disturbance on peak flows. While this large storage zone may be an important factor in watershed resilience to disturbance that has been observed in front-range Rocky Mountain watersheds in Alberta, the influence of disturbance on groundwater dynamics is not well understood.~~ More research on the variability of bedrock and till groundwater chemistry is needed to clarify the difference between these sources and their contributions to streamflow throughout the year. However, it is clear from this research that multiple subsurface flow systems lead to the slow leakage of bedrock and till groundwater to the stream promoting higher baseflows in this region compared to regions with shallow soils and impermeable bedrock where groundwater stops flowing in the summer.

Author contributions

US and AEA secured funding enabling this research and supervised the research project. SS designed and carried out the field research. SS analysed and interpreted the data with assistance from all co-authors, particularly ALC with statistics and R code. SS prepared the original draft of the manuscript with contributions in review and editing from all co-authors.

Data availability

Please contact the corresponding author for data availability.

Competing interests

The authors declare no conflicts of interest.

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