**Author response to Anonymous Referee #1:**
**Our replies to referee comments (black italics) are provided below in blue.**

*<u>Anonymous Referee #1 comments:</u>*

*<u>General comment</u>*

*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 appreciate the referee's concerns about the lack of linkage between resilience and the research presented in our draft paper. To address the concerns of the referee, the Introduction will be reformulated to focus on understanding runoff generation in regions with permeable bedrock and deep soils/glacial till because this was ultimately our intention. All references to watershed resilience will be 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 describes precipitation-runoff and storage dynamics in Star Creek using hydrometric data and suggests a conceptualization of runoff generation at the end of the manuscript (Spencer et al. 2019). Another manuscript (currently in prep) will use additional lines of evidence to further link these factors to water table responses, hydrologic connectivity, and structural controls on stream water contributions in Star Creek. While the hydrometric analysis/results presented in Spencer et al. (2019) were able to inform some aspects of runoff generation in the study region, the component of our research presented in our submission to HESS is meant to help clarify their conceptualization of runoff generation. Some suggestions from Referee #1 to add hydrometric and water table data will be incorporated into this manuscript, but there will be limits on what can be included based on the data already published in Spencer et al. (2019). We also worry that the addition of too much extra data will make the manuscript too dense, resulting in an overall loss of clarity (or less easily digestible by readers).

*Specific comments:*

*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:** The abstract will be heavily revised to reflect the changes in the 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:** The draft Introduction will be expanded and revised to better clarify research gaps and the concomitant rationale for this study.

The eastern slopes of Canada's Rocky Mountains have complex geology/surficial geology composed of permeable, fractured sedimentary bedrock overlain by deep glacial till (3 m on average). Others have hypothesized that these complex subsurface flow pathways may be responsible for the muted response in streamflow following disturbance (Harder et al., 2015; Goodbrand and Anderson, 2016) but a bespoke conceptualization of runoff generation is needed. The local geology may control runoff generation and subsurface flow pathways in ways not consistent with broadly accepted paradigms of runoff generation applicable to regions with largely unfractured bedrock overlain by thinner surface materials. While there are many studies in regions with permeable bedrock or deep soils/glacial till, few exist in regions with both features in series. As a result, while some implications can be drawn from regions with either permeable bedrock or deep soils or till, more research is needed to conceptualize runoff processes in these systems.

- *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 will be revised to specify why the approach used here was preferred over the method outlined in Barthold et al. (2011). The explanation of how TVR and LDA work will be expanded.

We are aware of the work by Barthold et al. (2011) and did consider the methods presented in the paper at the onset of this research. However, the stream water falls outside the bounds of the sources, which violates the EMMA assumption that there are no missing sources (Figures 7 and

8). This and the larger variability in source water than stream water (quantified by coefficient of variation) indicate that EMMA could not be run in its entirety to determine percent contributions from each stream water source. The inability to run the unmixing routine hindered the used of the methods outlined in Barthold et al. (2011) because the second criteria in the automated procedure requires running many iterations of source water contributions.

Other methods that could be used to indicate whether sources were well separated and if tracers showed minimal variation were evaluated. TVR and LDA 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 (Pulley et al., 2015; Pulley and Collins, 2018; and others – see comprehensive review in Collins et al., 2017 – Journal of Environmental Management). These methods have been automated in the SIFT (SedIment Fingerprinting Tool) open source R shiny software described in Pulley and Collins (2018). We used this portion of the SIFT routine.

*- 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:** We agree that this will streamline the Results and Discussion and will revise 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:** We will consider adding a time series plot of water sources and stream water as suggested. These plots would show the patterns we are describing in the insets in Figures 7 and 8 with more clarity. They will also help with other discussion points made here (as indicated in reply to the comment below: line 417-418) and by Referee #2.

*- 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. There is also evidence in our time series of stream water, where concentrations of some chemical constituents increase in the early spring just as snowmelt starts, which appears to be similar to the piston flow observed in other watersheds. Text and time series plots will be added to clarify this point.

*- 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 will be removed as suggested.

*Minor comments and technical corrections:*

*1. The title is long and complex. I suggest making it more compact and clearer.*
**Reply:** Revision of the title will be considered.

*11. I suggest to change as follows: "A lack of : : :but mechanisms governing: : :".*
**Reply:** Sentence will be revised as suggested.

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

*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 will be revised. See reply to general comment and Introduction comment above. The abstract will be 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:** This statement will be clarified.

*29: Perhaps put it more general, mentioning pathogens.*
**Reply:** This will be revised as suggested.

*35. What do the Authors refer to by "features"? Please explain.*
**Reply:** This will be revised for clarification: "features" was referring to "watershed features (e.g., bedrock, surficial geology, wetlands)" and will be added 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 will be clarified in the text.

*193. TVR: please report the definition and possibly the equation to let the reader immediately understand it.*
**Reply:** The text will be re-arranged and the definition and equation will be 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:** Sentence will be revised for clarification.

*245. leu?*
**Reply:** This is a typo and will be corrected.

*269: Perhaps add "compared to bedrock groundwater".*
**Reply:** We prefer not to change this sentence as it is a stand-alone statement. There was no clear temporal pattern observed… not compared to the other sources. However, we will revise the text to ensure our meaning is clear.

*Fig. 6b). Could the Authors perhaps colour-code samples for season (spring, summer, fall)?*
**Reply:** Colour-coding for season will be considered. However, with the addition of time series as suggested above, the new time series will likely be referenced and insets removed. Time series will show the same pattern the authors are pointing out here, making the insets redundant.

*322. Which are these months?*
**Reply:** Months will be added to the text: '…months of open-water flow (Apr-Oct)…'

*340. Why a source might be missing? Please, explain.*
**Reply:** Text will be added for clarification: '…because some samples fell outside of the mixing space defined by the mean and standard deviation of the sampled sources…' This logic is well established in the international literature.

*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. We will explore this suggestion and include this comparison in revisions if this helps strengthen the revised narrative.

*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:** This will be revised to "increase in stream water ion concentrations".

These water chemistry observations are taken in conjunction with observations published in Spencer et al., 2019 and another manuscript that is currently in prep. The other manuscripts contain hydrometric, meteorological, and groundwater data that help infer connectivity.

Text will be revised to clarify that these inferences are being made in conjunction with other studies that were carried out in the same watersheds during the same time as in the current study.

*431. Contributions to what? Please specify.*
**Reply:** Text will be 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 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, not to suggest that the water entering the stream is pure snowmelt or rain. Water chemistry of rainfall and snowmelt are essentially identical so there is no way to separate the contribution of rain and snow.

Our draft text will be modified to clarify these points.

*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. https://doi.org/10.5194/hess-15-2007-2011*
*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 will be incorporated where applicable.