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Discussions

Interactive comment on "Storage and routing of water in the deep critical zone of a snow dominated volcanic catchment" *by* Alissa White et al.

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Storage and routing of water in the deep critical zone of a snow dominated volcanic catchment by Alissa White et al. Authors' reply to Anonymous Referee #1

General Comments This study employed physical measurements of stream discharge, groundwater heads, and vertical variability of water content, combined with hydrochemical and isotopic measurements to help understand the functioning of water in the critical zone at the Jemez CZO over a one-year period. The authors conclude, rather surprisingly, that a deep aquifer in fractured tuff is the principal contributor to streamflow and is better connected to recharge/discharge than shallower perched or soil-zone

water reservoirs. The study has a reasonably broad base of data from which to make inferences, and in general the reasoning is clear and the final inferences seem sound. My only real criticism is that the findings do not seem very generalizable. It is nice to know that this one, very small, catchment in the Jemez Mountains functions in this particular way, but what can we take away from this study that can be more generally applied? Does it help us, even in part, to answer larger questions that have been raised previously?

We appreciate the referee's thoughtful comments and helpful suggestions. We have addressed their specific comments by clarifying text relating to volumetric water content and oxygen and hydrogen isotopes, as well as, accepting their suggestions for more accurate word choice. We have also addressed their broader comment by adding paragraphs to our concluding remarks that stresses the implications, general utility, and potential application of our findings to other studies in mountain systems. Detailed responses to each of the referee's comments are below each comment.

Added to conclusions to stress implications: Surprisingly, deep groundwater from site 1 wells appear to be more chemically-representative of waters that contribute to La Jara stream and more representative of the structure (geology, fractured aquifer, and greater depth to water table) and function (hydrologic response, solute fluxes, and water routing) of the CZ in the greater La Jara catchment, suggesting that deep groundwater from the fractured aquifer, rather than shallow subsurface flow from the perched aquifer, sustains stream baseflow. Further, we suggest that the deep subsurface flow paths observed in the JRB-CZO are likely a signature of snow dominated volcanic catchments transferable to other deeply fractured extrusive bedrock systems. The dominant contribution of deep groundwater to surface flows and the hydraulic connection between the fractured bedrock aquifer and streamflow may suggest that deep groundwater stores in fractured bedrock aquifers are sensitive to changes in climatic drivers of streamflow like shifts in precipitation magnitude and timing, as predicted in the southwestern United States. We assert that this study emphasizes the utility of interdisciplinary research to discern the distribution of groundwater stores, their connection to streamflow, and the underlying impact of CZ architecture on hydrologic response to climatic drivers. Furthermore, we propose that it highlights the need to better characterize the deep subsurface of mountain systems by transferring this approach to other complex settings that challenge and advance the current understanding of subsurface hydrologic systems around the world. We hope that this study provides an example of how to bring together multiple lines of evidence to simultaneously examine both, CZ architecture and hydrology, through hydrometric, geophysical, geochemical, and residence time analyses.

Detailed Comments 137: "uplifted" is really not the best word to describe formation of rhyolite domes; "emplaced" would be better. "Uplift of" changed to "emplacement of"

140: Describing the Bandelier Tuff as "Pleistocene aged" is redundant; "Pleistocene" is a time interval and "aged" is not needed. We agree and "aged" has been removed.

198: "Isotopes" are defined as variations of an element characterized by different numbers of neutrons. Water is a molecule, not an element, and therefore water does not have isotopes. "Isotopologues" is the correct terminology Rather than using isotopologues of water, this text uses isotopes of both elements of water (oxygen and hydrogen stable isotopes) measured independently of one another; therefore, we do not believe that the suggested change to isotopologues should be made. However, we have clarified the use of "stable water isotopes" throughout the text to refer specifically to "d18O and d2H" instead.

245: Equations 4 and 6 do not actually give the corrected age until they are solved for "t". Equation 5 does not give the 13C fraction from carbonate dissolution; it gives the 13C fraction from atmospheric carbon. Equations 4 and 5 were solved for "t" and the title of Equation 5 was changed.

280: What principle does the Decagon EC-5 soil-moisture sensor work on? A few lines were added to the methods section 2.6 to explain the scientific principle underlying the

function of Decagon EC-5 sensors.

428: The statement "both Ca2+ and DIC concentrations of shallow groundwater increase simultaneously, which is consistent with calcite dissolution. . ." is puzzling. In general, calcite will dissolve more when Ca2+ and DIC concentrations decrease, not increase. If the system contains no calcite and it is introduced, then its dissolution will be marked by increases in concentration, but we are dealing here with a system where the calcite is presumably fixed in the rock matrix. We reworded this sentence to clarify. We find that both Ca2+ and DIC concentrations increase and suggest that those increases in concentration are the result of calcite dissolution. We posit that Ca2+ and DIC concentrations increase as calcite dissolves around the onset of spring snowmelt and return to lower concentrations as groundwater becomes saturated with respect to calcite causing Ca2+ and DIC to precipitate out of solution. We make this suggestion based on calcite saturation index calculations of shallow groundwater from previous work (Olshansky et al., 2018) at the JRB-CZO. Time series of the calcite saturation index of shallow groundwater display a marked increase from near equilibrium at the onset of spring snowmelt (coincident with the time that the current study notes increased Ca2+ and DIC concentrations) to saturated around April 1 (when the current study notes the onset of decreasing Ca2+ and DIC concentrations).

449: "Isotopologues" rather than "isotopes". . (Same thing for the Figure 9 caption). Also, the compositions of the isotopologues are plotted in terms of their deltaD/delta18O abundance, not "in space". See previous comment about the rewording of the phrase "stable water isotopes" throughout the text. The description of isotope values in space was corrected.

462-463: Note that the exponential ages are greater than the period over which the tritium input has remained constant (since 1992). The calculated ages are thus going to be biased young because the actual input TU was greater than the assumed. We agree that residence times calculated from tritium concentrations are biased towards shorter times and have added this note into the methods section 2.3 to accompany the description of residence time calculations.

532: The meaning of “cubic shape of the rising water table” is not clear. We more clearly direct the reader to Figure 3F to see the cubic shape of the well 2D hydrograph during snowmelt 2017 and describe the shape of the curve. This cubic shape is characterized by a gradual increase in groundwater level followed by an inflection point and subsequent more rapid rise in groundwater level as described by Sophocleous et al., 1988, 1991a, 1991b.

556-560: The idea is not well expressed. It is the drying out between precipitation events that inhibits the infiltration of water, not “episodic recharge”. We acknowledge the point that the reviewer is making here, but we argue that small and frequent rain events facilitate and exacerbate more frequent drying out events, which mirrors the “episodic recharge” scenario of Langston et al. (2015). Langston et al. (2015) found that less recharge reached the groundwater table when precipitation was spread over several, small events each followed by a period of evaporation as compared to one concentrated event that mimics seasonal melt and subsequent evaporation. They concluded that the timing of recharge exerted a strong control on the degree of saturation and flow paths within the subsurface and that frequent wetting and drying inhibits fluid flow deep into the subsurface. These modeled scenarios strongly resemble the differences our study sees in soil moisture content during NAM season and spring snowmelt.

568-570: I’m not clear on the reasoning here. The much higher water content observed between 1.5 and 4.0 m during the October survey (Well 2C; Fig. 6) has to be due to infiltration of precipitation over a long period of time. The difference in volumetric water content between October and the other surveys is roughly 0.25. Over 250 cm of vadose zone, this amounts to about 600 mm of water. What is the total July-October precipitation? I doubt that it amounts to 600 mm. Certainly the 0.25 mm immediately antecedent precipitation is irrelevant! So where this water came from is something of a mystery. We acknowledge that the 0.25 cm3 cm-3 change in VWC is large compared to the precipitation inputs immediately prior to the October NP measurement. We have

changed the precipitation inputs immediately prior to each NP event to cumulative precipitation since the last NP event. For instance, the cumulative precipitation between the June and August NP measurements is 168.13 mm while the cumulative precipitation between August and October NP measurements is 67.55 mm, making the total precipitation input between June and October NP measurements 235.68 mm. The 600 mm mentioned by the referee is very near the cumulative annual precipitation for WY 2017 of 637.5 mm and close to the average annual precipitation from 1981-2012 of 711 mm (Zapata-Rios et al., 2015b). Surprisingly, cumulative precipitation between June and August is greater than cumulative precipitation between August and October. Again, we return to our hypothesis that frequent wetting and drying inhibits infiltration into the subsurface. It is possible that the Redondo Weather Station, while only 1.5 km from the wells in the ZOB, does not capture representative precipitation inputs because of elevation differences (Redondo Weather Station at 3231 masl while site 2 wells at 3024 masl) and the sporadic nature of NAM storms. It is also possible that lateral subsurface flow contributes some quantity of water to well 2C between the August and October NP measurements; however, we think this is unlikely. The shape of the VWC curve gradually increasing from ground surface down to its max at 4 mbgs, the generally lower VWC (in 3 of 4 NP measurements) at the surface compared to the generally higher VWC below 4 mbgs not indicative of lateral flow, the increased shallow soil water content (Figure 4) during the time of the October NP measurement, and the fact that the shallow groundwater water table is rising during the time of the October NP measurement suggests vertical infiltration rather than subsurface lateral flow.

583: What is the value of the “depth corresponding to the gravel-like layer”? The depth of 1.5 to 2.3 mbgs was added to the text and Figure 6.

587: The text repeatedly refers to “lenses” of high water content. Given that these are evidenced only on 1-D vertical profiles, how can you know that they are shaped like lenses in 3-D? We did not mean to imply a 3D shape of the “lenses” and have changed to words like layer and zone that do not imply 3D shape.

600: What is meant by a “blind fault”? Usually this indicates a fault that does not outcrop at the surface, and thus would not appear on a geological map. We have changed the use of “blind fault” to “concealed fault” in the text. The authors used the term blind fault to refer a fault that is noted as certain and concealed in the geologic map of Goff et al. (2011). We have used the geologic map of Goff et al. (2011) in the analysis and figures herein; however, Goff et al. (2011) notes that they did not substantially change the primary fault patterns of previously maps from Smith and Bailey (1968) and Smith et al. (1970).

613: “positive Si concentration pulses” is very awkward. Why not say “found pulses of high Si concentration. . .” instead? The sentence is run-on and its meaning hard to decipher. This change was made and the sentence was reworded.

621-622: “are produced by calcite dissolution” is preferable to “are a function of calcite dissolution”. Calcite as a mineral may be present in the perched aquifer, but calcite dissolution is a process that is “active” or “operative” or some other active verb. Give the number(s) for the figure you are referring to in this paragraph. Changes were made.

650-653: If the Site 2 water is not found in La Jara Stream, then how does it discharge? It must leave the system somehow. We are unable to conclude where the site 2 water drains. Text detailing the possibility of the perched groundwater transmitting to streamflow was added (Lines 668-670).

656: “isotopologues” rather than “isotopes” See previous comment about the rewording of the phrase “stable water isotopes” throughout the text.

657: idem See previous comment about the rewording of the phrase “stable water isotopes” throughout the text.

679-684: By far the most diagnostic indicator of geothermal water in the Jemez is elevated Li. Was Li measured? Unfortunately, Li concentrations were not measured.

688: “isotopologues” See previous comment about the rewording of the phrase “stable

water isotopes” throughout the text.

688: I’m not sure that the extent and permeability of some of these “stores” qualifies them to be termed “aquifers”. We no longer refer to the site 2 deeper groundwaters as aquifers and reserve the use of that term for the perched aquifer (well 2D) and site 1 deep fractured aquifer.

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