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Hydrology and Earth System Sciences
Discussions

# *Interactive comment on* "Closing the water balance with cosmic-ray soil moisture measurements and assessing their spatial variability within two semiarid watersheds" *by* A. P. Schreiner-McGraw et al.

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Response to Reviewer 3:

First of all, we thank Reviewer 3 for her/his comments that significantly helped us to improve the quality of our manuscript. In the following, we first describe the main changes that we made on the text based on the suggestions of all three reviewers and, then, we provide point-to-point answers to Reviewer 3's comments.



A. We separated the "Methods" section into "Study Area and Datasets" and "Methods".

B. We better focused the main analyses and results of the manuscript, which can be summarized as follows: 1. Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing. 2. Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture. These changes implied significant modifications in the Introduction, Methods and Results sections.

C. To give more importance to the main results reported in the previous point: 1. We reduced the part focused on the spatial variability of soil moisture and moved it to the section on the validation of the CRNS method through the distributed sensor network of soil moisture probes. 2. We completely removed analysis, discussion and one figure about the relations between spatial variability of soil moisture and ET.

D. We improved the description of the water balance approach for (i) validating the CRNS method and (ii) studying the fluxes at the CRNS footprint in continuous fashion. In doing so, we carefully explained each assumption to avoid any misunderstandings.

E. In the computation of the event-based water balance, we adopted a different measurement depth (z*) for each event, as requested by all reviewers. This implied an update of two figures and metrics reported in Table 4.

Point-by-point responses to Reviewer 3's comments:

Reviewer 3 Comment: There are a lot of analyses and approaches proposed in the manuscript but they are presented and discussed rather superficially which makes the manuscript very hard to follow, and sometimes not very well connected. What is/are the scientific question/s the authors are trying to answer? What is the main motivation? It is not clear to me what exactly the authors are trying to show (i.e., comparison of CRS with SN at both sites; relationships of within-footprint variability; evaluating use of CRS

with EC fluxes; testing a simplified water balance approach with the data). This needs to be better clarified and organized in the revised version, hence I recommend major revisions.

Author Response and Actions Taken: We agree with Reviewer 3 on the need to make clearer the scientific motivation of our work. As outlined above, we have significantly modified the manuscript to address this comment. Specifically, we clarified that the main focus of our analyses are two issues:

1. Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing. 2. Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture.

All sections of the papers have been modified to reflect these changes.

Reviewer 3 Comment: 1. The water balance approach employed in the paper assumes the control volume is defined by the effective depth of the CRS (âĹij 40cm). However, we usually assume the control volume to be defined by the layer containing contribution from active roots, in the process of root water uptake - evapotranspiration. Authors should comment on the potential limitations of using a control volume represented by the measurement directly. Also, how about the lack of energy closure by the EC method (80% closure calculated)?

Author Response and Actions Taken: Since the application of the water balance of equation (6 in the new manuscript version) is made for rainfall events, ET is negligible. As a result, the use of z* instead of the plant rooting depth is justified. We clarified this point in page 13, lines 20-21.

The error inherent to the EC method that is reflected in the estimates of energy balance closure also plays a negligible role in the validation of the water balance approach



applied for events since ET is very low at the scale of the single event. We have updated the text in the methods section page 13, lines 20-21 to explain this. At longer time scales (weeks to years), ET is an important part of the watershed water balance. For these applications, the errors in the energy balance closure are important. Unfortunately, the error balance closure error from the eddy covariance technique is unavoidable. Our estimates are well in line with eddy covariance studies across a wide range of ecosystems.

Reviewer 3 Comment: 2. The authors justify the use of Eq. 2 in its simplest form (i.e., without accounting for additional hydrogen sources). However, lattice water is then accounted for when calculating the CRS measurement depth (z*) in Eq. 4. Can the authors explain why lattice water does not matter for theta(N) but seems to matter for z*(theta)? This seems to be rather inconsistent!

Author Response and Actions Taken: Thanks for pointing this out. We updated the methods section to clarify this. The lattice water does not need to be accounted for when applying Eq. 2 because it was accounted for during our local calibration process. It is unlikely that the lattice water will change over time due to the low clay contents. Furthermore, since the CRNS method measures relative differences in soil moisture (calibrated to obtain an absolute soil moisture), the lack of inclusion of the lattice water does not represent an issue for obtaining soil moisture.

When calculating the z* measurement depth, however, we need to have estimates of the absolute values of hydrogen in the soil because there is not a way to locally calibrate the measurement depth. As a result, we utilize values for lattice water for that calculation. To address this comment, we have updated the text on page 11, lines 4-6, and page 11, lines 22-23.

Reviewer 3 Comment: 3. As pointed out by the authors, there are already studies that focused on understanding the use of CRS in semi-arid sites. In this case, the good agreement between CRS and SN is not necessarily novel (in fact, SRER has been used

quite extensively for such comparison). According to the authors, most of this good agreement happens under relatively dry conditions, as “the CRS method was not able to capture the soil moisture conditions during large rainfall events”. Can the authors comment on possible limitations on the use of CRS for monitoring and predicting (in combination to hydrological models) flash floods events in semi-arid region?

Author Response and Actions Taken: The CRNS performs well as compared to the sensor network over a full range of different soil moisture conditions, though the errors tend to increase asymptotically with the soil moisture content. In the water balance approach, the major limitation for the large storm events was due to our assumptions on z* and not to the CRNS measurement itself. We have modified the sentence quoted here because it did not accurately reflect our conclusions. We changed line 13, on page 22 to say: “In the water balance comparisons, we identified that our assumptions of no leakage beneath z* were not met during large rainfall events, therefore the CRNS method was not able to capture all of the soil water in its measurement. We attribute this to rapid bypassing of the measurement depth promoted by soil and terrain characteristics.” With regard to the application of CRNS for flash flood studies in arid and semiarid regions, we believe it is too premature in this work to comment or speculate on this aspect. Nevertheless, the reviewer brings up an interesting point that we might pursue in the future through the use of a hydrologic model and a data assimilation scheme using the CRNS as a spatially-aggregated observation.

Reviewer 3 Comment: 4. Figure 2a: The land cover within the EC footprint suggests less bare soil fraction than the area covered by both CRS and SN. Figure 2b: How strongly do the authors consider the SN placement to be representative of the entire watershed? In addition, there is little overlap between EC footprint and CRS and SN spatial coverage. Can the authors comment on possible impacts and limitations in the analyses due to those issues?

Author Response and Actions Taken: The land cover in the watershed, EC footprint, and CRNS footprint is actually quite similar, as showed in a previous paper through



UAV images (Vivoni et al., 2014). Thus, we made explicit reference to that paper on page 11, line 15. The soil moisture sensors were installed to examine different hydrologic processes at the two sites. We improved the explanation of the motivation in the revised manuscript.

1. At SRER, the soil moisture sensors were distributed under different vegetation cover. Here, the differences in soil moisture responses among different vegetation covers are larger than the horizontal spatial variability of soil moisture within the same vegetation class. Thus, we weighted the sensor network based on the amount of certain vegetation types, rather than distance to the CRNS sensor because this will provide a more accurate estimation of large-scale soil moisture. 2. At JER, topography plays an important role in the soil moisture due to a more incised watershed. This results in soil moisture redistribution, as well as sharp differences based on aspect. We therefore weighted the sensor network based on an aspect-elevation relation shown in Templeton et al. (2014).

Regarding the question on the overlap between EC footprint and CRNS and SN spatial coverage, we think that differences in footprints and lack of overlap do not significantly affect our results, because:

1. The vegetation distribution does not significantly change at the scales of watersheds and footprints. In other words, it can be considered homogeneous at both scales (see Vivoni et al., 2014). This is stated on page 11, line 13-16. 2. While the soil may have different features within the channels, the only channels outside of the watershed are on the fringes of the footprints and are not expected to have a large influence. In addition, Anderson (2013) performed a soil texture analysis in the footprint of the EC tower at both sites and found small variations. This has been now stated on line 15, page 11.

Reviewer 3 Comment: 5. Authors need to explain exactly what they are trying to show in Figure 11. Is there any strong relationship when individual points? There is only one

case in which ET seems to respond to sigma (JER) but the error bars for individual bins are quite large.

Author Response and Actions Taken: We appreciate the reviewer comment. However, we decided to remove the analyses on the relationship between soil moisture heterogeneity and ET. Thus, Fig. 11 is no longer in the manuscript.

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 5343, 2015.