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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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Received and published: 5 October 2015

Response to Reviewer 2:

First of all, we thank Reviewer 2 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 2's comments.

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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 2's comments:

Reviewer 2 Comment: 1) The paper contains a lot of material and information which is good from a scientific perspective but that forced the authors to not go into much details of some important concepts and descriptions. I suggest to focus on the most important results (the authors could follow the suggestions of Reviewer 1).

Author Response and Actions Taken: We agree with Reviewer 2 on the need to present a lower number of results with a higher level of detail. We addressed this as follows:

1. We better focused the main analyses and results of the manuscript in order to focus the reader's attention on a few important points, which can be summarized as follows: a. Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing. b. 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. The motivations for these studies have been discussed in the Introduction from page 3, line 18 to page 5, line 5..

2. We reduced the analysis on the relations between spatial variability and mean of soil moisture and we used it as further confirmation of the correspondence between soil moisture measurements from the distributed sensors and CRNS. As a result, this part was moved in Section 3.1 in the Methods (page 12 and line 17 on the new manuscript version) and to Section 4.1 in the "Results and Discussion" (page 17 and line 11 on the new manuscript version). In addition, Fig. 9 of the first draft is now Fig. 6.

3. We removed the analysis and discussion of the relations between spatial variability of soil moisture and ET. As a result, Fig. 11 was removed.

Reviewer 2 Comment: 2) Related to the previous point, I would emphasize and improve the "closing the water balance approach" through a better description of the concepts behind it. There a number of assumptions and contradictions that need to be addressed and justified otherwise it is difficult to follow this part (e.g., L=0 assumption and its consequences on the subsequent analysis should be better explained). Establishing a clear method of analysis prior to present the results, other than improving the comprehension of the paper, would add value to it and to its alternative approach.

Author Response and Actions Taken: In the revised manuscript, we modified the text to clearly explain each step of our methodology, thus avoiding any potential misunderstandings. Specifically, in section 3.2, we distinguished the application of the water balance in an event-based and in a continuous fashion. For each of these two cases,

we explained and justified our assumptions related to the leakage:

The event-based application of the water balance is focused on the rising limb of the soil moisture response. In this period, it is very unlikely that percolation to deeper layers occurs. As a result, for this case we assumed a leakage equal to zero (i.e., $L = 0$). This assumption has been tested at each site by checking the soil moisture measurements of sensors installed along a 1-m profile next to the EC tower. Note that z^* is always above 1 m. We found that the percolation beyond a depth of $\sim$40 cm is infrequent at both sites during the duration of summer monsoon storms. This has now been explained in page 14, lines 1-5. When we applied the water balance at JER, we found 5 events where leakage occurred (i.e., the change in soil moisture at the 30-cm depth sensors is not negligible). This can be explained by the combination of a high starting soil moisture due to the occurrence near the end of the monsoon season, and the large amount of rainfall for these storms.

Percolation can occur on a time scale of several days during winter precipitation (e.g., Franz et al., 2012b; Templeton et al., 2014; Pierini et al., 2014). Thus, in the continuous application of the water balance, L is not assumed to be 0 and is instead obtained as $L= O - ET$, where O is the CNRS flux (fCNRS) out the depth z^*, and ET is the evapotranspiration measured by the EC tower. This has been explained in page 14, lines 4-5.

Reviewer 2 Comment: 3) The role of z^* and its relation with z_m and the maximum measurement depth of the probes requires a more clear description. The authors should deserve at least a brief paragraph to this issue. Indeed, it looks like that z^* has a strong influence on the results so I suggest for instance to analyze the z^* time series and discuss further the limitations associated to its time variability ant its potential effects on the result interpretation.

Author Response and Actions Taken: In the computation of the event-based water balance, we modified the assumptions concerning z_m and we adopted a different

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measurement depth (z*) for each event. This change is reflected in Fig. 6 and in Table 4, as well as the text presented in page 13.

The temporal variations in z* have also been included in Fig. 3. Such variations should have little effect on the comparison between the sensor network and the CRNS method, because the soil moisture data from the sensor network were averaged through a method that accounted for the variation in time of the CRNS measurement depth as discussed in page 12, line 15.

In the application of the water balance in a continuous fashion, temporal variations in z* do affect our estimate of the flux of water into and out of the CRNS measurement footprint. This is why we use the minimum value of z* over the two day period, this ensures that we are using the same control volume for the calculation. These concepts have been clarified on page 14, lines 13-14 of the new manuscript version.

Reviewer 2 Comment: P5345 L. 14-18. Many satellite SM missions are now available and include not only passive sensors (Kerr et al. 2001) but also active (Bartalis et al. 2007) and combined (passive plus active, Entekhabi et al. 2010) sensors. I suggest to add this references to the manuscript.

Author Response and Actions Taken: These citations have been added on page 3, line 15.

Reviewer 2 Comment: P5346 L5. I would move Eq. (6) and its description to the method block. It is ok to say something but putting details in the method avoids to jump from one page to another and improves the readability of the manuscript. More-over, in this case the "closing the water balance approach" will be presented in a more consistent and general manner.

Author Response and Actions Taken: We assume this is in reference to Eq. (1). We have moved it to the methods block and created a single section in the Methods ("3.2 CRNS Water Balance Analyses Methods") regarding the water balance. These sug-

gestions have helped clarify the manuscript.

Reviewer 2 Comment: P5350L19: could you provide a brief justification for these choices? (i.e. the method used for averaging SM time series). I guess some info is contained in the references added but it would be beneficial to have something in the manuscript since the spatial mean of the probes is used as a benchmark for the comparison.

Author Response and Actions Taken: The soil moisture sensors in the transects were installed prior to this experiment in order to examine different hydrologic processes at the two sites. 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 vegetation distribution, rather than distance to the CRNS sensor because this will provide a more accurate estimation of large scale soil moisture. 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 presented in Templeton et al. (2014). We added this information to clarity the concern in the text on page 8, lines 8-12.

Reviewer 2 Comment: P5352 L12: boxcar filter. Please add a reference.

Author Response and Actions Taken: Since the description of this relatively popular averaging technique is available in textbooks, we decided not to add a reference. However, we have added some extra text to explain the details on how we applied this filter.

Reviewer 2 Comment: P5352 L23: Could you provide a clearer justification for limiting the analysis to the 50% of the source area? Which are the effects of considering smaller or larger contributions?

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Author Response and Actions Taken: The main reason that we used the 50% footprint is that larger footprints (i.e. 86% or 100%) for the EC tower and the CRNS sensor will extend well beyond the watershed domains, as could be discerned from Fig. 2. In addition, the 50% footprints fully contain the soil, terrain and vegetation layers available to characterize the sites and avoid large variations introduced by nearby channels outside of the sensor network sampling areas. Page 11, lines 9-11 have been updated to explain this.

Reviewer 2 Comment: P5354 Section 2.4. This section is particularly important and should be explained better. Examples are: L=0 for short rainfall events could be reasonable but later in the manuscript L is supposed different from zero in many cases. If understand well this refers to a longer analysis period, however, I found this a bit confusing. Could you improve this part and make the text more clear?

Author Response and Actions Taken: We significantly revised this section (now Section 3.2) to make this distinction more clear. See response to comments #2 and #3 from this review.

Reviewer 2 Comment: P5354 L8-10. Z_m=40 cm. Which are the potential consequences of this assumptions?

Author Response and Actions Taken: See response to point #3. We have removed z_m and only use z^* now to eliminate unnecessary assumptions.

Reviewer 2 Comment: P5354L15-18. Describe the performance metrics in separate section and remove them from the caption of Table 3.

Author Response and Actions Taken: We have removed the performance metrics from the caption and provided a citation to an in-depth discussion of the metrics we used (Vivoni et al. 2008b) in the caption to table 4.

Reviewer 2 Comment: If this is true that fCRS>0 implies infiltration, it cannot be generally said that f=I. Indeed, at daily temporal resolution the effect of others water balance

components cannot be neglected, e.g., the effect of the deep percolation, especially for JER site

Author Response and Actions Taken: We thank Reviewer 2 for pointing this out. We have changed this to be called "Net Infiltration into the surface soil". The change is on page 14, line 15.

Reviewer 2 Comment: It is not sufficiently clear how the authors compare the two SM measurements (CRS and probes) with the water balance components. For instance it is said at P5354 that Q can be derived from P-I when fCRS>0 and can be compared with Q measured but I did not find any of this comparison in the result section.

Author Response and Actions Taken: As clarified in the new manuscript, the water balance was applied in an event-based approach and in a continuous fashion. In both cases, only the CRNS soil moisture estimates were used. Soil moisture measurements from CNRS and sensor networks were compared prior to the application of the water balance through a scatterplot (Fig. 5). We have updated the "Method" sections to make each of these points clearer.

In the application of the water balance in a continuous fashion, we use the CRNS measurements to compute fCRNS. This, in turn, is used to derive an estimate of the surface runoff (Q) from measurements of precipitation (P) as $Q = P - I$ (where $I = $ fCRNS when fCRNS > 0). The comparison against the observed runoff is performed in Table 4 via the runoff coefficient Q/P.

Reviewer 2 Comment: I cannot well understand from this part how the "closing the soil water balance approach" is finally used. I think the authors should significantly improve this part

Author Response and Actions Taken: The expression "closing the soil water balance approach" has been used to indicate the use of the water balance equation to (i) validate the CRNS method and (ii) show how the soil moisture estimates from CRNS can

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be used to quantify its components.

Reviewer 2 Comment: P5356 L13-19. " Relative. . .at JER". I would move this part from the results to the section 2.2

Author Response and Actions Taken: Since Fig. 4 and related comments show a first comparison between CNRS and sensor networks, we prefer leaving this part in the "Results" section that is dedicated to such comparison.

Reviewer 2 Comment: P5356 L21-26. Why not using the SSE to quantify the seasonal differences?

Author Response and Actions Taken: Given the fairly small differences between the two estimates reported in Fig. 4, we decided not to add the SEE in the text.

Reviewer 2 Comment: P5358 L10. "This suggest that the three approaches" The sentence is not clear, consider revising. Three approaches?

Author Response and Actions Taken: The three approaches are the sensor network, the CRNS method, and by closing the water balance. We have updated the text on page 18, lines 11-12 to reflect this change.

Reviewer 2 Comment: P5358 L14. "A closer revealing". Remove this sentence it is not clear.

Author Response and Actions Taken: This sentence has been modified, page 18, lines 15-16.

Reviewer 2 Comment: P5359 L 1-30 – P5360 L1-8. I found this part really hard to follow. It is overall clear that the two sites show strong ecosystem differences but I am expecting a larger discussion on whether theta_CRS is able to close the water balance or not with respect to theta_SN. (in the title the authors claim this). Something is provided at P5360 L1-8 but I think it has to be expanded.

Author Response and Actions Taken: We have clarified this section by adding materials

requested in the revisions. This discussion section is linked to the analyses presented in Fig. 9 and Table 5 which now are more clearly labeled as a section addressing the utility of CRNS for hydrologic process investigation. We have also clarified how the soil water balance is used in this study to: 1) derive an independent soil moisture estimate to compare to CRNS and the sensor network and 2) to make inferences on water balance fluxes through CRNS observations.

Reviewer 2 Comment: Table 2 information can be put in Table 1.

Author Response and Actions Taken: Given the relatively large content of the caption of Table 2, we decided to leave it as a separate Table. In addition, the two topics are fairly different and thus warrant separate treatment.

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