

## **Interactive Discussion: Author Response to Referee #2**

### **Spatiotemporal dynamics and interrelationship between soil moisture and groundwater over the Critical Zone Observatory in the Central Ganga plain, North India**

Dash S. K. and Sinha R.,  
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Dear Referee,

We appreciate for your time to review our manuscript and providing your thoughtful comments and suggestions. Please find below our detailed responses to your concerns.

Based on multi-year observations of soil moisture and groundwater table at spatially distributed sites over an agriculture-driven critical zone observatory, the authors investigate the spatiotemporal dynamics of both variables, using a series of analysis methods (incl. EOF, random combination, temporal stability analysis, etc). Based on the findings of these analyses combined with stakeholders' surveys, some water management strategies were proposed. The paper is very well written, structured, and clear.

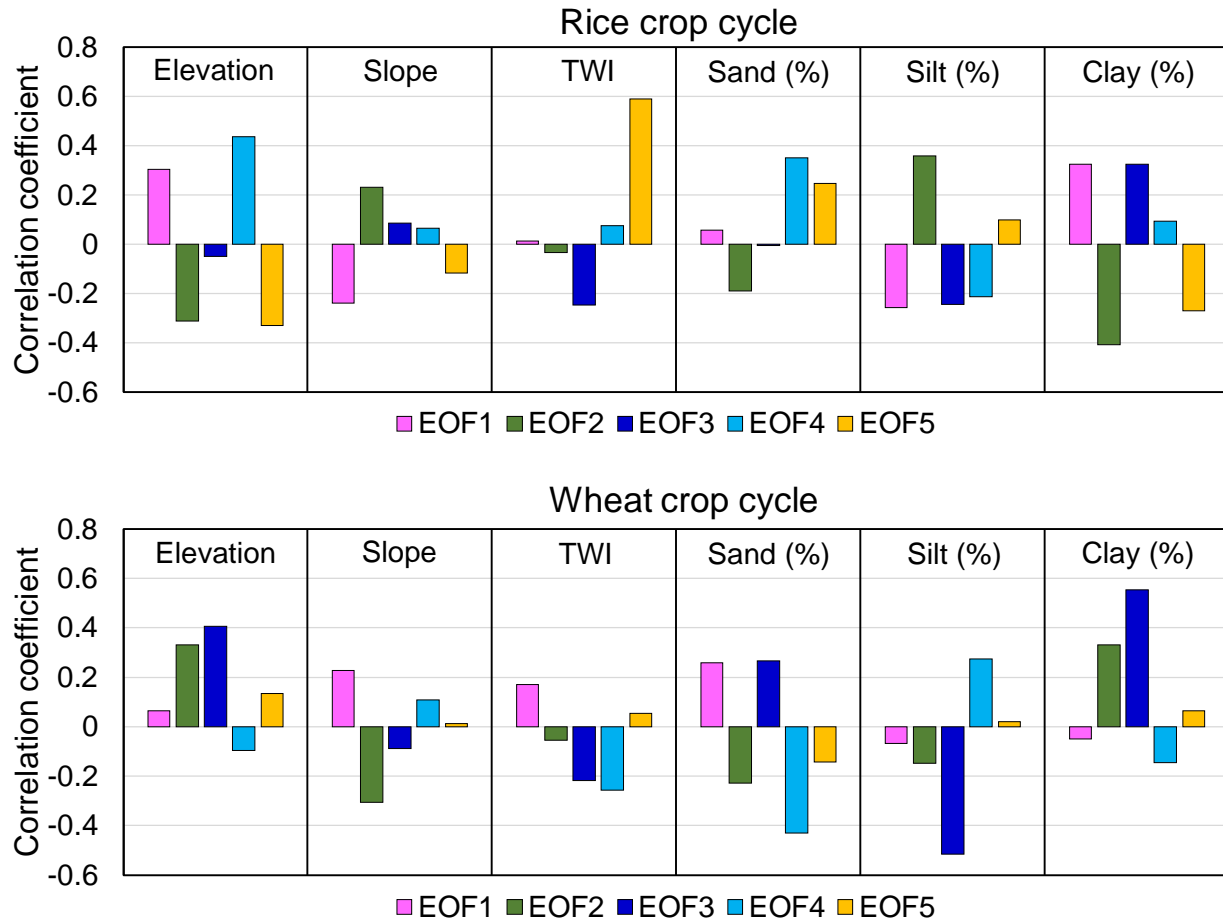
Thank you for your constructive comments and feedback. We hope that the analysis carried out in this study would help in designing sampling strategies for water resource management.

#### **Below please find some main concerns:**

1. Although the analysis carried out is very convincing in terms of finding representative sites/wells for understanding the spatial mean of the CZO, it is however not clear how the human activities (irrigation/groundwater extraction) will impact such analysis. There were several places the author indicate some spatiotemporal patterns to irrigation and pre-monsoon, post-monsoon precipitations. However, this information cannot be explicitly found in the manuscript. Please the authors try to clarify this information and explain their potential impacts on their findings.

We thank the reviewer for bringing up this point. To understand the control of irrigation watering on spatiotemporal control of soil moisture, we segregated the entire temporal window into rice and wheat crop cycle. This is because the farmers in the study region primarily grow rice in monsoon and wheat during non-monsoon months with limited summer crops. The rice cropping is usually dependent on the atmospheric precipitation whereas non-monsoon month crops are typically irrigated through periodic wetting and drying through local watering, based on soil moisture assessment by the farmers. The EOF analysis (Figure below) for each cycle shows that clay and topography remain as prime driver of SM spatial dynamics in rice cycle, when natural variability contributes most. But SM spatial dynamics during the wheat crop cycle is controlled with a

combined effect of topography–clay and sand–slope. These are shown in the figure below as correlations of first few EOFs with corresponding physical properties. Considering the irrigation scheduling to be a representative of the central Ganga plain, our findings on representative sites for rice and wheat cycles are the salient outcomes of this study.



**Figure:** Relationship between the first five spatial EOFs of soil moisture with the time-invariant in-situ physical properties for the rice cropping cycle (upper) and for the wheat cropping cycle (lower).

Secondly, for groundwater observations, although effect of any seasonal or timely pumping activities influence its temporal pattern, any specific variation due to pumping activities is apparently unnoticeable on its spatiotemporal dynamics (Figure-3b of the manuscript). This is because the mean interannual variation of groundwater level within the CZO strongly follows with natural seasonal forcings (please see Figure-3b of the manuscript) and we don't observe any trend of groundwater decline due to human impact within its study period. This suggests that extraction of groundwater is currently balanced through recharge within this region.

We also have taken care of the sampling of both components (SM and DTGT), not to be simultaneous with any of the pumping/watering activities. Also, the sampling intervals for SM and

DTGT are mostly weekly and bi-weekly respectively, so that any specific watering activities become minimal during the sampling. We hope this could potentially address the Reviewer's concern and we will revise the manuscript accordingly to include this information.

2. The satellite data SMAP was mentioned in the manuscript. However, there is no satellite SM data used in this study. This reviewer thinks this is a miss of the opportunity. It would be great to link the in-situ measurement to remote sensing data, as such, it is more operational in a sense to monitor the impact of water management strategies on soil moisture, or even groundwater storage change. It is understandable that for GW storage, the current GRACE product is too coarse. However, for SMAP soil moisture data, you do can find 1km and 3km resolution products. Also from Sentinel-1 SM, it is 1km. As such, this reviewer would encourage the author to include satellite data in their analysis.

Thank you for your encouraging suggestion on linking our ground measurements to remote sensing data. We would like to mention that the ground-based measurements on the soil moisture were mostly planned as per the revisit time of SMAP satellite. However, a detailed evaluation of the SMAP soil moisture products vis-a-vis in-situ datasets has just been published by us for the study area ([Dash and Sinha, 2022](#), Remote Sensing, 14, 1629; <https://doi.org/10.3390/rs14071629>). Therefore, we have, made an effort to characterize the CZO hydrodynamics in this paper based on only the ground-based available spatiotemporal datasets. We propose to add the following information in the revised version:

*“Selection of the representative site(s) can be used for remote sensing evaluation studies or upscaling the soil moisture network ([Schneider et al., 2008](#)), more specifically during the wet season. Recently, the present network has been used for the evaluation of passive remote sensing SMAP soil moisture products, reporting a high accuracy level and minimal random error in comparison to C and X-band microwave SM products based on the annual and seasonal scale variability ([Dash and Sinha, 2022](#))”*

**Some minor comments as below:**

a. On page 10, line 230, this reviewer is wondering if you have the data about 'watering by farmers'?

Thank you for your query. The study region, which could potentially represent the overall agricultural pattern in the Ganga plain, typically uses 4–5 hours of groundwater pumping (3–4-inch diameter pipe) for a 2040 sq. meter crop field (information from community surveys). The pumping interval is usually 3–4 times (mostly on a monthly interval) during a wheat crop cycle whereas the rice crop significantly depends on monsoonal rainfall with around 7–8 times watering for an adverse monsoon period. We would be happy to add this information in the revised version.

b. Page 10, line 234-235, this reviewer think this is only happening when the GW table is shallow, right? Please clarify and provide some more discussions on this.

Thank you for your thoughtful interpretation. You are correct that our data represents shallow groundwater table ( $< 8 \text{ mbgl}$ ). The characteristic shallow aquifer in this interfluvial region exist as narrow sand ribbons in the subsurface (please see Figure 4 and 5 of [Yadav et al., 2010](#)), and therefore are clearly delimited. Here we would also like to highlight that the  $CV_j$  stands for temporal coefficient of variation and we noticed the mean value (0.36) is same for both the SM and DTGT. This suggests that although, the spatial variability of both observations is different (SM is highly heterogenous compared to DTGT), the annual temporal mean variability is consistently interdependent. We will add this information for clarification in the revised manuscript.

c. Line 265 'PC' should be 'EC'

Thank you for noticing this. We will correct this accordingly.

d. Line 338, it would be convenient for readers if equations were given.

Thank you for your suggestion. We will add the Spearman's correlation equation in the revised manuscript as follows:

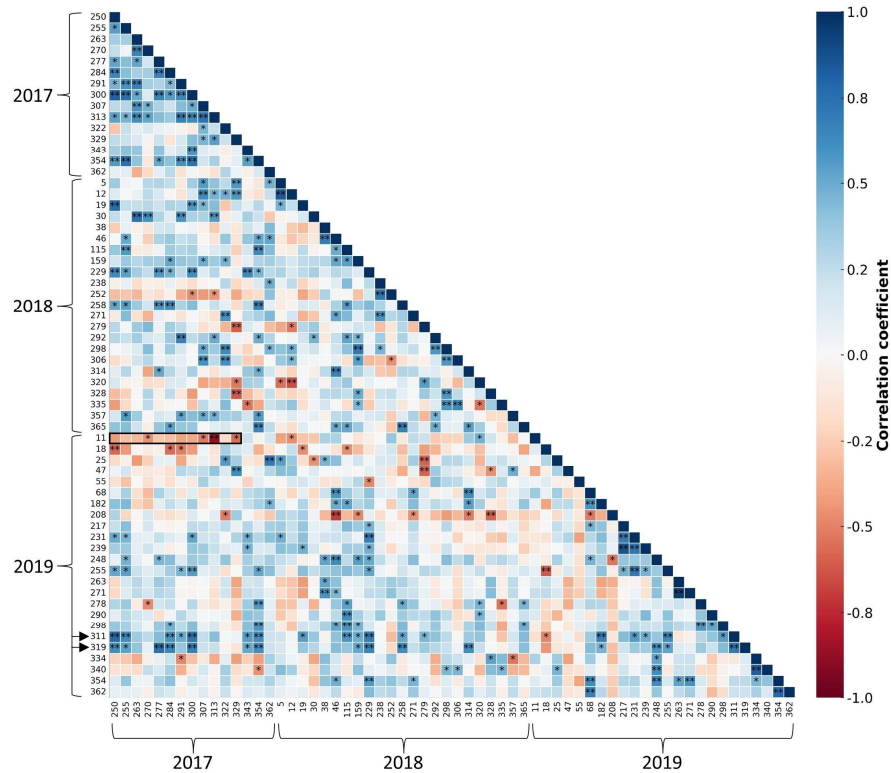
*“To analyze the similarity in the spatial mean between the sampling days, the Spearman rank correlation coefficients,  $R$ , has been computed and presented in Fig. 9a and 9b for SM and DTGT, respectively. The Spearman's correlation ( $R$ ) was obtained based on the two ranked variables according to the following expression:*

$$R = 1 - \frac{6 \sum_{i=1}^n (R_{X_i} - R_{Y_i})^2}{n(n^2 - 1)}$$

*where  $R_{X_i}$  and  $R_{Y_i}$  are the ranked variables of  $X_i$  and  $Y_i$  ( $i = 1, 2, 3, \dots, n$ ), respectively, and  $n$  is the total number of elements for each variable. A rank correlation close to 1 indicates a stronger tendency of similarity between the variables.”*

e. Line 344, these 'signals' should be marked out explicitly in Figure 9a

Thank you for your suggestion. These signals are now marked explicitly as rectangular box in the revised figure (as shown below). We have also marked the two arrows in the y-axis (revised figure here) to support the statements in Line-344. In addition, we also renamed the axis labels as 'Day counts' of a year for better clarity.



**Figure:** Spearman rank correlation coefficient of the observed values during the measurement campaigns of a) soil moisture, where the x and y-axis represents the day of the year. The box represents negative correlations of 11<sup>th</sup> Jan 2019 soil moisture with 2017 monsoon days. Also, the two arrows are shown which represents the 2019 November samplings with the monsoon of previous years. The correlation coefficients are shown as the triangle where the value is represented as generic boxes identified by  $i_{th}$  row and  $j_{th}$  column and each of the row/column are the sampling dates of the corresponding field campaign. \* Indicates significance at  $p < 0.05$ , \*\* Indicates significance at  $p < 0.01$

f. Line 414, 'in compared to' should be 'in comparison to'

Thank you for your suggestion. We will replace this accordingly.

## References

1. Dash, S.K. and Sinha, R., 2022. A Comprehensive Evaluation of Gridded L-, C-, and X-Band Microwave Soil Moisture Product over the CZO in the Central Ganga Plains, India. *Remote Sensing*, 14(7), p.1629. <https://doi.org/10.3390/rs14071629>
2. Schneider, K., Huisman, J.A., Breuer, L., Zhao, Y. and Frede, H.G., 2008. Temporal stability of soil moisture in various semiarid steppe ecosystems and its application in remote sensing. *Journal of Hydrology*, 359(1-2), pp.16-29. <https://doi.org/10.1016/j.jhydrol.2008.06.016>
3. Yadav, G.S., Dasgupta, A.S., Sinha, R., Lal, T., Srivastava, K.M. and Singh, S.K., 2010. Shallow sub-surface stratigraphy of interfluvial inferred from vertical electric soundings in western Ganga plains, India. *Quaternary International*, 227(2), pp.104-115. <https://doi.org/10.1016/j.quaint.2010.05.030>