

Interactive Discussion: Author Response to Referee #1

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

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Dear Referee,

We would like to thank you for your critical remarks and feedbacks on this study. Please find below our detailed responses to the points that you raised, and we hope this will fulfill the requirements of the concerns.

1. [...] This a regional study that uses only existing methods, both in terms of measurement and methodology, so the results have no fundamental scientific added value outside the study area. Therefore, this work does not fit in this journal. Alternatively, there are many journals where regional studies like this can be published.

The present manuscript describes the first order attempt to use both the ground-based soil moisture (20 spatial points) and depth to groundwater table (DTGT) (58 observation well) datasets in the newly established Critical Zone Observatory (CZO, the second one in India) in the central Ganga plain, North India. This CZO is one of the very few CZOs across the world that is located in an intensively managed landscape, and therefore the findings from this paper have significant implications to advance the critical zone science, which is a fast-emerging topic in earth surface processes (Brantley et al., 2017; Gaillardet et al., 2018; Guo and Lin, 2016; Li et al., 2018). Further, the present CZO was established to understand the baseline conditions and sub-surface hydrodynamics, as a representative of the Ganga basin in North India (Gupta et al., 2019), which is considered as the ‘food basket’ of India. Therefore, outcomes of this study would be highly beneficial for designing the sampling strategies and understanding the primary control on the major variability of the hydrologic components outside the CZO network. In addition, the selection of an optimal number of points would not only provides a baseline for short-term remote sensing evaluation studies and upscaling sensor network but also help in managing the concurrent water resources for effective management. In view of the concerns from the reviewer, we would be happy to revise manuscript accordingly to emphasize these points.

2. The temporal resolution of the data is rather poor. This is outdated nowadays, when sensors and data loggers can be acquired and operated for relatively little money.

We agree with your concerns regarding the sensor and data logger based measurements for the spatiotemporal dynamics. However, we would like to highlight that numerous recent studies have

documented such analysis with limited number of space-time networks for demonstration of interdependent observational variability ([Dari et al., 2019](#); [He et al., 2020](#); [Li and Shao, 2014](#); [Zhang et al., 2016](#)). In fact, we are continuing the observations in the study region, which could potentially supplement the ground-based measurements in the Ganga basin in near future. It is also worth pointing out that installation of automated sensors and data loggers in a rural but densely populated and intensively agriculture area is not a trivial issue, and there are serious problems with safety of the sensors and network connectivity. So, the manual data collection in such areas works best to capture the temporal variability.

Another important aspect here is that we represent the observational data based on two categories, (1) spatially limited and temporally dense and (2) temporally limited and spatially dense. The first category corresponds to the surface soil moisture observations (20 location and 62 days) whereas the second category include the DTGT observation (58 well and 22 days). The novelty here is that even though the temporal resolution of the groundwater level data is relatively less, results of this study comprehensively represent the spatial variability of the groundwater dynamics as suggested by EOF analysis. Our analysis has also identified a single representative monitoring well in the CZO based on temporal stability analysis. Furthermore, the results of statistical analysis of soil moisture including random combination and temporal stability are found to be coherent with previous studies (please see Section 5.2 of the manuscript).

3. The evaluation of groundwater levels with statistical methods is problematic because groundwater level measurements are usually not independent of each other, since they observe the same groundwater body. Unless the measurements took place in clearly delimited aquifers, but this was not explained in the text.

Thank you for this thoughtful comment and careful interpretation. Yes, you are correct on the interpretation of statistical analysis for a single groundwater body. We missed to highlight this point in our manuscript about the groundwater level measurements of various delimited aquifers of this region. We are monitoring water level for the shallow aquifers (< 8 m bgl) in an interfluvial region of the Ganga plains. Previous studies have clearly established that these aquifers exist as narrow sand ribbons in the subsurface (please see Figure 4 and 5 of [Yadav et al., 2010](#)), and therefore are clearly delimited. The study by Yadav et al. (2010) was based on a large number of resistivity soundings across the Ganga-Yamuna interfluvial region which covered our study area as well (near IIT Kanpur to the east of Pandu River). Resistivity surveys supplemented with lithology data show the presence of laterally disconnected narrow aquifer sand bodies in shallow sub-surface whereas an extensive sand body exists only at a deeper level ([Yadav et al., 2010](#)). Therefore, our statistical analysis holds good for this setting. Thank you again for raising this point, we will add this information in the revised manuscript.

4. The statement that topography and the clay content of the soils are considered the most important factors determining the spatial pattern is not tenable, as the study area consists of

irrigated agricultural fields. Therefore, the spatial pattern will strongly depend on the amount of water applied locally and the crops. Without taking this into account, the general statements cannot be made.

Thank you again for your concern. Yes, we agree with your statement regarding the control of watering and crop type on spatial dynamics of soil moisture and groundwater. The study region typically belongs to a monsoon-fed irrigation system with primary dependence of monsoonal precipitation for rice crops. However, the wheat crop in post-monsoon is typically irrigated through periodic wetting and drying through local watering, based on soil moisture assessment by the farmers. Therefore, as a concern of the #Reviewer-1, we segregated the entire soil moisture sampling window into two parts, rice crop cycle (Mid-June–October) and wheat crop cycle (November–April) and subsequently analyzed their spatial EOFs correlation with time-invariant properties (please see the figure below).

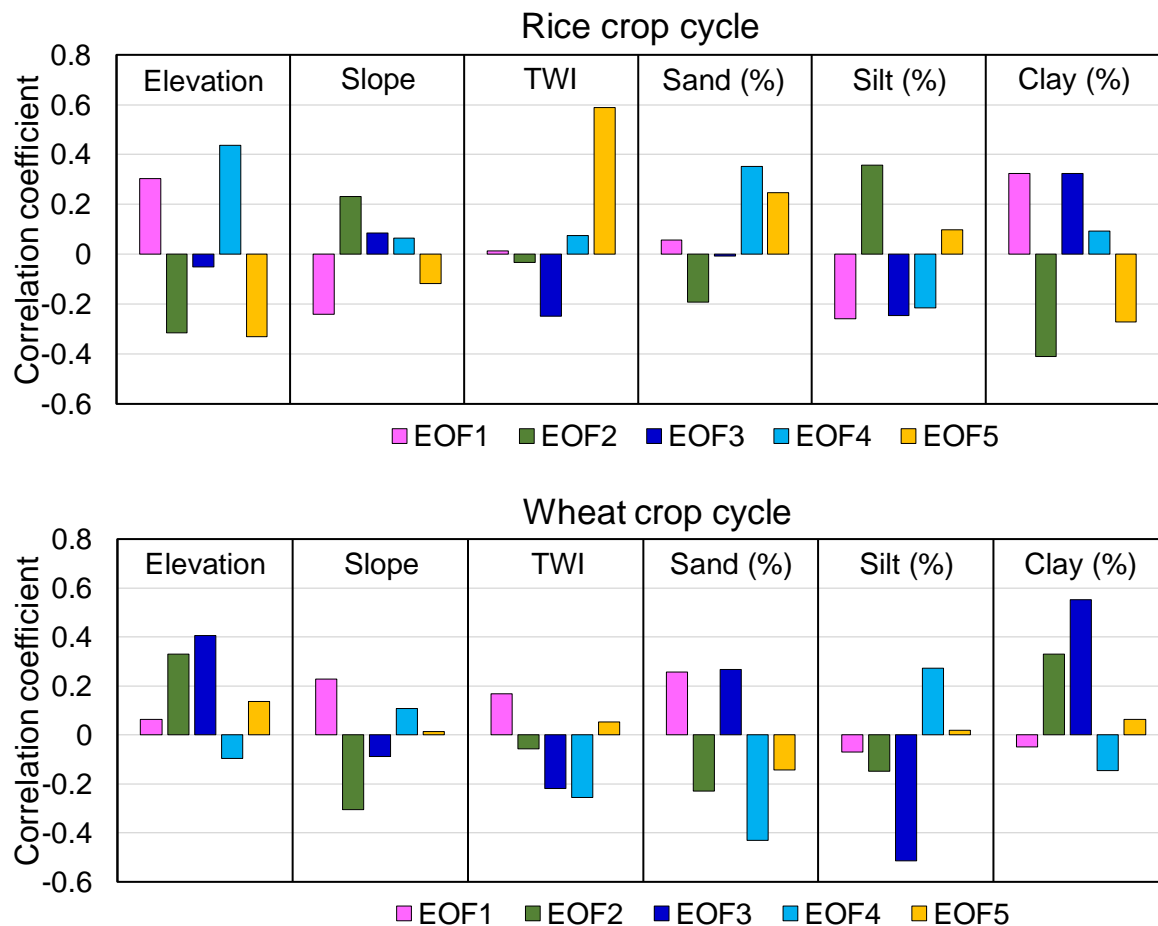


Figure: Relationship between the first five spatial EOFs of soil moisture with the time-invariant in-situ physical properties for the rice cropping cycle (upper) and for the wheat cropping cycle (lower).

As the figure shows, clay and topography followed by silt fraction are the prime factors for the spatial variability of soil moisture during rice crop cycle, whereas these factors are not able to control during wheat cycle, when the watering is periodic. In the wheat crop cycle, sand (%) and slope have a moderate correlation with EOF1, suggesting partial influence on the spatial SM variability. However, a mixed control of topography, clay (%), sand and slope contribute to most of the spatial SM variability during wheat cycle. This is visible here with a satisfactory correlation of EOF1 and EOF2 with the above factors.

We would also like to highlight that the soil moisture measurements were usually avoided during local crop watering. Additionally, SM measurements are conducted with a weekly sampling interval, therefore, actual watering day might be insignificant to the mean SM variability.

We would be happy to include this information, supplement with figures in the revised manuscript to address the Reviewer's concern.

5. Finally, strategies for efficient irrigation water management are proposed that not based on the statistical analyses in this paper.

We understand the concerns of the reviewer, but we beg to differ. In this study, we have made an effort to combine several stakeholder surveys to the understand SM and DTGT spatiotemporal variability, although the analysis includes primarily the natural hydrometeorological components. We have not made any specific recommendations, but this study has strong implications for developing future monitoring and sustainable irrigation strategies. Apart from providing guidance for selection of optimum network for soil moisture and groundwater monitoring, we found a significant correlation of monsoonal variability of soil moisture between multiple annual cycles (please see Figure 9a of the manuscript). This information can potentially be used to harvest rainwater to the abandoned/unused local depressions in the study region, which will ultimately lead to efficient irrigation water management. Further, our findings on the identification of representative time stable monitoring locations, adjacent mostly to the presence of water bodies (please refer to Figure 12 of the manuscript), would help further in restoring several unused channel network and canal to maintain a threshold soil water content in the crop field. We also recommend to minimize extensive groundwater extraction by planting moderate water intensive crops depending upon the textural characteristics of soil which primarily governs the groundwater variability (please see figure in #comment-4 above). We would be happy to expand this section a bit more to highlight these points more explicitly.

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