Replies to Reviewer 1

The authors present a useful study on soil moisture network design for use in catchment modelling studies. The approach is fairly novel although the authors fail to cite some key parts of the literature on soil moisture networks and spatial scaling. Much work has been done through various NASA soil moisture campaigns (SMEX, SMAPVEX, etc.) that have provided a wealth of publications. In addition, the approaches of temporal stability analysis and Empirical Orthogonal Functions have been used in the soil moisture community for many years to address key issues on scaling and design. The paper is generally well written but needs greater tie in to the existing soil moisture community literature before publication. Additional grammar editing is also needed, see minor comments for some edits.

Reply: We thank the reviewer in acknowledging the usefulness and novelty of the proposed soil moisture network design scheme for catchment modelling studies.

The NASA soil moisture campaigns and other similar projects are mainly focused on satellite soil moisture evaluations and algorithm improvements, so the in-situ sensors are purposely designed to best match satellite's observational footprint. Therefore their target is different to this study's which is focused on large catchment scale application. However, we agree with the reviewer that these researches should be cited and described. We will add them in the updated manuscript. Regarding the different statistical approaches mentioned by the reviewer, they will also be added in the manuscript.

Major Comments

1. The authors fail to identify the depth of soil moisture information used in the WRF NoahMP analysis! I assume this is the root zone integrated product from NoahMP 4 soil layers? Given the large difference between surface and rootzone soil moisture dynamics in space and time I would suggest doing the analysis for both a surface and rootzone layers. I suspect the network design will be different depending on which depth is of interest. Also what are the depths of sensors for the in-situ network?

Reply: The soil depth used in this study is the surface layer from the WRF NoahMP (top 10 cm). We agree with the reviewer that the result of the network design could be different depending on which depth is used for the analysis. The sensor depths in the in-situ network varies, but the majority are centred at 10 cm, 25 cm, 45 cm and 70 cm. The NoahMP provides soil moisture centred at 10 cm, 25 cm, 70 cm, and 150 cm. We will add the analysis of using the root zone soil moisture in the updated manuscript as suggested by the reviewer. And based on the common depth between the in-situ sensors and the NoahMP, 25 and 70 cm will be integrated to calculate the overall root zone soil moisture.

2. The authors fail to cite key soil moisture techniques for scaling (see Crow 2012 for general review paper, Mohanty 2001 and Famiglietti 2008), mainly the approaches of Temporal Stability Analysis (TSA, Vachaud 1985) and Empirical Orthogonal Functions (EOF, Perry and Niemann 2007). I also suspect the EOF approach and comparison with environmental covariates is very similar to the PCA and CA approach used here (see Wang 2017). Moreover, I am concerned about the influence of temporal variation in the covariance analysis here. While EOF is very similar to PCA, EOF notably splits the variance into time and space components. Wang 2017 find the analysis of the regional NE Mesonet soil

sensors that the spatial variability is dominated by the first EOF/PCA and that EOF is highly correlated to clay/sand fraction. I suspect the EOF approach would be enlightening here to show that topographic relief and/or soil texture dominated the 1st EOF from the NoahMP output. Also the map of 1st EOF coefficients will act as a form of spatial clustering analysis. I suspect that the alluvial plains will have similar EOF coefficients, similar to what was found with the clustering analysis here?

Vachaud, G., A. P. Desilans, P. Balabanis, and M. Vauclin (1985), Temporal stability of spatially measured soil-water probability density-function, Soil Sci. Soc. Am. J., 49(4), 822-828.

Perry, M. A., and J. D. Niemann (2007), Analysis and estimation of soil moisture at the catchment scale using EOFs, Journal of Hydrology, 334(3-4), 388-404. doi:10.1016/j.jhydrol.2006.10.014.

Famiglietti, J. S., D. R. Ryu, A. A. Berg, M. Rodell, and T. J. Jackson (2008), Field observations of soil moisture variability across scales, Water Resources Research, 44(1), 16. doi:W01423 10.1029/2006wr005804.

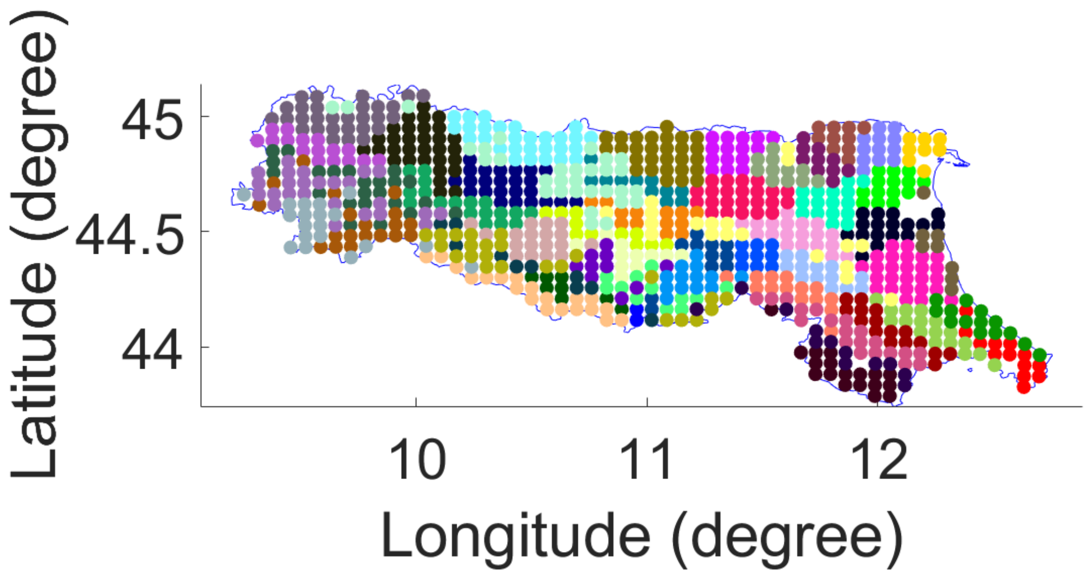
Mohanty, B. P., and T. H. Skaggs (2001), Spatio-temporal evolution and time-stable characteristics of soil moisture within remote sensing footprints with varying soil, slope, and vegetation, Adv. Water Resour., 24(9-10), 1051-1067. doi:10.1016/s0309-1708(01)00034-3.

Crow, W. T., A. A. Berg, M. H. Cosh, A. Loew, B. P. Mohanty, R. Panciera, P. de Rosnay, D. Ryu, and J. P. Walker (2012), Upscaling Sparse Ground-Based Soil Moisture Observations For The Validation Of Coarse-Resolution Satellite Soil Moisture Products, Rev.Geophys., 50. doi:10.1029/2011rg000372.

Wang, T., T. E. Franz, R. Li, J. You, M. D. Shulski, and C. Ray (2017), Evaluating climate and soil effects on regional soil moisture spatial variability using EOFs, Water Resources Research, 53. doi:10.1002/2017WR020642.

Reply: We agree with the reviewer that PCA/CA combination might not be the only approach that could be explored for the soil moisture network design. The mentioned studies will be added and described in the updated manuscript.

Regarding the temporal variation factor, it should be noted that the information we used for the PCA/CA is based on the soil moisture temporal variations (e.g., the 10-year time series data), so that areas following similar soil moisture temporal variations can be identified and only one sensor will be needed to represent them. Location information is not used for the PCA/CA analysis. However, due to the influence of local characteristics, the resultant clusters should more or less reflect the geographical feature. This information was not included in the manuscript, which will be updated. We had plotted the clusters in the following figure. It can be seen that most of the clusters are geographically connected. Whilst k-means has issues dealing with nonconvex clusters and geographically we might have nonconvex shaped clusters, but in terms of the result, k-means indeed is very useful for the soil moisture network design. We have tried EOF, however, we found it very difficult in dealing with a large array of datasets (828 points, and each with 3652 datasets), which was therefore not considered in this study.



3. The scaling of a point sensor to a 5 km grid is not trivial (see Crow 2012). Additional geophysical approaches like GNSS or CRNS can provide integrated soil moisture data at a scale of tens to hundreds of meters as opposed to having a network of point sensors. The CRNS has been implemented with the COSMOS and COSMOSUK networks (Zreda 2012, Evans 2016). COSMOSUK network moving towards integration with operational weather forecasts. CRNS better suited for use in complex terrain and may be a good option to use for a national network as compared to in-situ point sensors. Cost over 10 years probably similar to point sensors with increased maintenance replacement etc. The sensor networks would provide different data for different purposes.

Zreda, M., W. J. Shuttleworth, X. Xeng, C. Zweck, D. Desilets, T. E. Franz, and R. Rosolem (2012), COSMOS: The COsmic-ray Soil Moisture Observing System, Hydrology and Earth System Sciences, 16, 4079-4099. doi:10.5194/hess-16-1-2012.

Evans, J. G., H. C. Ward, J. R. Blake, E. J. Hewitt, R. Morrison, M. Fry, L. A. Ball, L. C. Doughty, J. W. Libre, O. E. Hitt, D. Rylett, R. J. Ellis, A. C. Warwick, M. Brooks, M. A. Parkes, G. M. H. Wright, A. C. Singer, D. B. Boorman, and A. Jenkins (2016), Soil water content in southern England derived from a cosmic-ray soil moisture observing system - COSMOS-UK, Hydrological Processes, 30(26), 4987-4999. doi:10.1002/hyp.10929.

Reply: Indeed. We agree with the reviewer, that the scale mismatch between the footprint of a point-based in-situ soil moisture station and a 5-km model gird would be expected to degrade the performance of the resulting network. The advanced soil moisture sensors based on GNSS and COSMIC-RAY could provide alternative solutions to overcome the mismatch problem. We will add a discussion in the updated manuscript.

4. Much work has been done on soil moisture network design and implementation. See the NSMN for USA and ISMN databases for globe. These networks and efforts should be better acknowledged.

http://nationalsoilmoisture.com/ and papers by S. Quiring. Dorigo, W. A., A. Xaver, M. Vreugdenhil, A. Gruber, A. Hegyiova, A. D. Sanchis-Dufau, D. Zamojski, C. Cordes, W.

Wagner, and M. Drusch (2013), Global Automated Quality Control of In Situ Soil Moisture Data from the International Soil Moisture Network, Vadose Zone Journal, 12(3), 21. doi:10.2136/vzj2012.0097.

Reply: Agreed. They will be added in the updated manuscript.

5. What do the CA clusters look like, that is are they nonconvex? How did you chose the optimal number of clusters (see Amiri 2019)? Please add more information on the CA approach used here.

Amiri, S., B. S. Clarke, J. L. Clarke, and H. Koepke (2019), A General Hybrid Clustering Technique, Journal of Computational and Graphical Statistics, 28(3), 540-551. doi:10.1080/10618600.2018.1546593.

Reply: Regarding the nonconvex clusters, please see the reply to comment 2.

On choosing the optimal number of clusters, the methodology part regarding the use of PCA, and CA in the existing manuscript is not very well structured. It will be reorganised and rewritten to improve its clarity. In essence, PCA is used for network redundancy analysis. Since the number of components from the PCA do not directly represent the physical number of grids, we propose to use the elbow method to find the corresponding number of grids. The elbow method is based on K-means clustering and looks at the variance contribution rate as a function of the number of grids. Generally, the required number of grids increases when the variance contribution rate increases. However, the growth rate is not constant that normally changes significantly at a critical point (threshold), which is used in this study as the desired rate for the soil moisture network design. And the corresponding number of clusters will be used. The threshold is found through visual recognition (Figure 5), and comparison of statistical performances of NSE and r (i.e., Table 3 and 4, Figure 8).

Minor comments

L 14. “variable in hydrological”

Reply: This will be updated.

L 53. “for hydrological research”

Reply: This will be updated.

L54. Large space? Sentence needs editing.

Reply: This will be updated.

L62. NSMN and ISMN address are key sources of soil moisture information. In USA state Mesonets are designed to fill such gaps. See http://nationalsoilmoisture.com/ and OK Mesonet, NE Mesonet, SCAN, CRN for some networks available etc.

Reply: Agreed. As to comment 4, this will be added in the updated manuscript.

L71. “of soil moisture”

Reply: This will be updated.

L72. Would disagree. TSA and EOF approaches have been used for such purposes.

Vachaud, G., A. P. Desilans, P. Balabanis, and M. Vauclin (1985), Temporal stability of spatially measured soil-water probability density-function, Soil Sci. Soc. Am. J., 49(4), 822-828.

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Crow, W. T., A. A. Berg, M. H. Cosh, A. Loew, B. P. Mohanty, R. Panciera, P. de Rosnay, D. Ryu, and J. P. Walker (2012), Upscaling Sparse Ground-Based Soil Moisture Observations For The Validation Of Coarse-Resolution Satellite Soil Moisture Products, Rev. Geophys., 50. doi:10.1029/2011rg000372.
Reply: Agreed. As to comment 2. These existing studies will be added in the updated manuscript.

L108. Sentence is awkward, please revise.
Reply: This will be modified.

L114. What are soil depths for model? Surface or rootzone?
Reply: The surface soil moisture at 0-10m is used for the analysis. As to comment 1, additional analysis based on root zone soil moisture will be added in the updated manuscript.

L 180. section 3.2.1. How do you deal with temporal component of variation in PCA? EOF splits temporal and spatial components to identify dominant spatial structures.

Perry, M. A., and J. D. Niemann (2007), Analysis and estimation of soil moisture at the catchment scale using EOFs, Journal of Hydrology, 334(3-4), 388-404. doi:10.1016/j.jhydrol.2006.10.014.
Reply: Please see the reply to comment 2.

L 217. How do you deal with nonconvex clusters and selection of number of clusters (Amiri 2019)? PCA + CA seems similar to EOF approach used by others.

Amiri, S., B. S. Clarke, J. L. Clarke, and H. Koepke (2019), A General Hybrid Clustering Technique, Journal of Computational and Graphical Statistics, 28(3), 540-551. doi:10.1080/10618600.2018.1546593.
Reply: Please see the reply to comment 2 and 5.

L257. KGE criteria has been shown to be superior to NSE (Gupta 2009). KGE uses correlation, bias in mean and standard deviation. Here you use both NSE and correlation, why not switch to KGE for simplicity?

Gupta, H. V., H. Kling, K. K. Yilmaz, and G. F. Martinez (2009), Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, Journal of Hydrology, 377(1-2), 80-91. doi:10.1016/j.jhydrol.2009.08.003.

Reply: We thank the reviewer on suggesting KGE for the performance assessment to replace the combinational use of NSE and r. We have found a recent paper written by Knoben, which compares NSE and KGE, it has suggested that “a strong case can be made for moving away from ad hoc use of aggregated efficiency metrics and towards a framework based on purpose-dependent evaluation metrics and benchmarks that allows for more robust model adequacy assessment”. Although there is the advancement of using KGE over the NSE, it may still not be sufficient to use the KGE on its own. Therefore the combination of NSE and r will be kept in this paper.

Knoben, Wouter JM, Jim E. Freer, and Ross A. Woods. "Inherent benchmark or not? Comparing Nash–Sutcliffe and Kling–Gupta efficiency scores." Hydrology and Earth System Sciences 23.10 (2019): 4323-4331.

L411-413. I would disagree. See comments above about work on soil moisture scaling and implications to network design, like NSMN or USA state Mesonets.

Reply: This will be added, and the manuscript will be updated.

L458. CRNS good option for long-term deployment in complex terrain.

Zreda, M., W. J. Shuttleworth, X. Xeng, C. Zweck, D. Desilets, T. E. Franz, and R. Rosolem (2012), COSMOS: The COsmic-ray Soil Moisture Observing System, Hydrology and Earth System Sciences, 16, 4079-4099. doi:10.5194/hess-16-1-2012.

Evans, J. G., H. C. Ward, J. R. Blake, E. J. Hewitt, R. Morrison, M. Fry, L. A. Ball, L. C. Doughty, J. W. Libre, O. E. Hitt, D. Rylett, R. J. Ellis, A. C. Warwick, M. Brooks, M. A. Parkes, G. M. H. Wright, A. C. Singer, D. B. Boorman, and A. Jenkins (2016), Soil water content in southern England derived from a cosmic-ray soil moisture observing system - COSMOS-UK, Hydrological Processes, 30(26), 4987-4999. doi:10.1002/hyp.10929.

Reply: This will be added in the updated manuscript.