Response to the reviewers' comments

The authors of this study wish to thank the reviewers for their accurate and useful comments. We believe that the expert reviewers' opinions will provide us guidance to improve the manuscript. A detailed response is provided in the following. In black, we have reported the reviewers' comments, in red, the detailed replies, and in blue, the sentences that will be changed and/or added in the revised manuscript to address reviewers' comments.

Reviewer #1: Summary -

Irrigation water has been a majority portion of human total water use but detailed information at high-resolution for water resource instructions has been limited. In this study, the authors presented high-resolution regional datasets derived from remote sensing through SM-based method (water balance equation) for three basins, Erbo and Po basin (1-km) in Europe, and Murray basin (6-km) in Australia. The products are evaluated through detailed benchmark irrigation rate data collected in these three basins. The results are valid and valuable for Erbo and Murray basin, as for Po basin, large uncertainty exist due to limited length of benchmark data. The authors highlighted the limitations of this method and proposed ideas for future studies. The manuscript presented has great significance for remote sensing and land model communities and has great potential to achieve large-scale application. Despite its importance, some comments and issues need to be addressed before it can be accepted for the journal. Please see my comments and questions below:

We wish to thank the reviewer for appreciating our work and for the useful suggestions provided.

General comments -

1. Eq (1) shows the water balance terms used in the SM-based method. Does any of these three basin would have snowfall and snowpack in winter and snowmelt contributing to soil moisture water balance in spring? As no word of snow is mentioned in the manuscript, would it be possible that the overestimated high irrigation rate in winter and early spring peak due to a missing (snow) component in Eq (1).

We thank the reviewer for this interesting comment. Actually, the source for rainfall input we are using is the total precipitation from the ERA5-Land data set that involves snow as well. Nevertheless, the contribution of snowfall (if any) is definitely not conclusive, as for each basin the algorithm is run over flat agricultural valleys only. For similar reasons, as explained in the manuscript at lines 164-165, the surface runoff is neglected and the assumption is valid for runoff generated by snowmelt as well.

2. Another possibly neglected component would be the groundwater contribution to soil moisture, the g(t) term, if the groundwater table is shallow, it would be possible that rainfall from other area could drain to river and groundwater aquifer which provides lateral transport of moisture, contributing to soil moisture.

We thank the reviewer for the suggestion. We wish to highlight that in our approach the g(t) term represents the amount of water exiting from the bottom of the soil layer. Hence, it is a term quantifying groundwater recharge, not considering potential groundwater contribution to soil moisture. It is important to underline that in case of remote sensing soil moisture the information refers to the soil surface (generally less than 5 cm). Hence, soil moisture alterations due to shallow groundwater may occur very close to river reaches and/or deltas only, namely areas that are masked out. Hypothetical border effects over pixels adjacent to water bodies (if any) are expected to be negligible.

3. 3.2 Input data sets, the authors used different sources of input data sets with various resolution, soil moisture (1-km), PET (0.25°) and precipitation (9-km), can the authors also provide a discussion on the way of spatial aggregation, would it affect the results obtained in the dataset?

We thank the reviewer for this comment, however, believe that the spatial resolution of the ERA5-Land reanalysis used to derive rainfall rates (~9 km) does not represent an important limitation for the proposed methodology. Conversely, the spatial resolution of the PET term surely has a more important role in determining the algorithm output, considering also that the product currently used for PET rates is characterized by a spatial resolution pretty coarser with respect to the target of this application. Hence, we will further specify the importance of future implementations using higher resolution PET rates from GLEAM (which were not available at the time of our implementations) at the third point of the "Future plans" section (line 443), which will read as follows:

"Exploitation of high-resolution evapotranspiration input data. Along with soil moisture, the evapotranspiration term plays a fundamental role in determining the output of the SM-based inversion approach (Dari et al., 2020). Hence, the exploitation of evapotranspiration estimates at a spatial resolution matching the scale at which irrigation occurs is expected to bring benefits to the outcomes of the SM-based inversion approach. For this reason, the use of higher resolution input PET rates for computing the evapotranspiration term of Eq. (3) (e.g., from a 1 km resolution version of the GLEAM data set over the Mediterranean, which will be developed within the abovementioned 4DMED-Hydrology project) is among the future perspectives of this study."

We wish to highlight that the implementation of the methodology with 1 km PET rates from GLEAM is a process already running over the two European basins that will likely lead to a version 2 of the irrigation data sets for the Ebro basin and the Po valley.

4. The authors also highlighted the uncertainty and future exploitation of ET data, would it be possible to apply a physical process-based land surface model (LSM), which has more sophisticated ET calculation, to obtain SM-based irrigation rate, rather than the soil moisture balance Eq (1)?

The evapotranspiration term of Eq (1) relies on potential evapotranspiration rates, PET, which can be derived from different sources, involving the output of LSMs. In previous works, the method was implemented with evapotranspiration data coming from several sources and modeling approaches (see, e.g., Dari et al., 2022). Nevertheless, we believe that maximizing the use of data sets relying also on observations is an added value for our purpose, as irrigation is a human-induced process which is usually missed or poorly parameterized by models.

5. The scatter plot in Figure 5,7,9. It seems that there are some systematic underestimation in Ebro basin and Murray baxin, and overestimation in Po basin. Any speculation on these, would it be due to the physical landscape, i.e. missing processes in Eq (1) used to estimate SM? If this is true, what caution would the authors recommend to users when propogating this method to use in large regional application in other regions of the world?

In our opinion, the main reason for the different performances obtained over the Po valley as compared to the other two pilot areas is attributable to the climatic features. In fact, systematic underestimations over the pilot areas characterized by an arid or semi-arid climate (water-limited regimes) are obtained independently on the soil moisture product used (RT1 Sentinel-1 for the Ebro basin and CYGNSS for the Murray-Darling basin). Conversely, irrigation overestimates over the Po valley can be attributed to rainfall overestimates in a humid context, as specified at lines 424-425 of the manuscript. However, given the high novelty degree of the research topic and the very scarce knowledge about irrigation dynamics worldwide (and consequently scarce availability of benchmark data for validating the proposed estimates) we prefer not speculating too much on the aspects mentioned by the reviewer, but we encourage the scientific community in checking, testing, and validating the developed products. We think that potential users are properly informed about the caution to be adopted by reading the "Limitations" section (lines 396-425 of the manuscript).

6. Do these three basins in pilot areas use the same irrigation method? If different irrigation methods are used in these three basins, would these affect the SM-based inversion approach, reflected on the results? The authors could provide a discussion on the irrigation methods and also

7. The authors mentioned applying irrigation map and crop calendar to constrain irrigation dataset in Discussion. When applying these constrains, would it affect the calibration parameters, i.e. these parameters would need to re-calibrate?

We merge the responses to points 6 and 7. The reviewer is right, different irrigation techniques can be differently detected by satellite soil moisture and, in turn, lead to different performances in estimating water amounts through the SM-based inversion approach. Surely, different techniques are adopted across basins and within each basin. In order to clarify potential issues due to the adoption of different irrigation techniques, we will add the following sentence referring to studies in which this issue is deepened at line 356.

"Previous studies highlighted how the irrigation method affects the capability of remotely sensed soil moisture products to detect irrigation-driven changes (see, e.g., Gao et al., 2018; Dari et al., 2021)."

The following reference will be added in the proper section:

Gao, Q., Zribi, M., Escorihela, M.J., Baghdadi, N., and Quintana-Seguí, P.: Irrigation mapping using Sentinel-1 time series at field scale, Remote Sens., 10, 1495, https://doi.org/10.3390/rs10091495, 2018.

Regarding the spatial and temporal constraints for refining the irrigation estimates, no, there is no need to re-calibrate the algorithm parameters. What we suggest is a postprocessing of the results, as specified at lines 448-453 of the manuscript.

Specific comments -

1. In general, the presentation of the manuscript is good. But there are several places where paragraphs are too long. For example, the first paragraph of Introduction is too long, the authors may divide it into separate paragraphs that may be helpful for readers.
   We will separate the first paragraph of the introduction as suggested by the reviewer.
2. L307: "… to the Urgell district" could use a separate paragraph
   We will separate the paragraph as suggested by the reviewer.

References:

Dari, J., Quintana-Seguí, P., Morbidelli, R., Saltalippi, C., Flammini, A., Giugliarelli, E., Escorihuela, M.J., Stefan, V., and Brocca, L.: Irrigation estimates from space: Implementation of different approaches to model the evapotranspiration contribution within a soil-moisture-based inversion algorithm, Agric. Water Manag., 265, 107537, https://doi.org/10.1016/j.agwat.2022.107537, 2022.