Response to the reviewer's comments

The authors of this study wish to thank the reviewer for the useful comments.

In black, we have reported the reviewer's comments, in red, the detailed replies, and in blue, the sentences that will be changed and/or added in the revised manuscript to address the reviewer's comments.

R1C1. The manuscript titled "The development of an operational system for estimating irrigation water use reveals socio-political dynamics in Ukraine" introduces a system that leverages remote sensing data to estimate irrigation water use. This system is notably valuable for providing crucial data in water resource management, such as for modeling and monitoring. The application of this system is demonstrated using a timely case study of the Russian-Ukraine conflict. However, while the system shows great promise, the manuscript falls short in certain areas:

- The background research that led to the development of the system is inadequately detailed, particularly regarding the estimation of irrigation water use.
- The methodology section is too concise, lacking a comprehensive introduction or synthesis (if some methods are previously published) of the key methods or algorithms employed in this system.

R1A1. We are glad that the reviewer recognizes the significance of the work and we appreciate the comments provided for improving the manuscript quality. One main concern raised by the reviewer is the lack of background on the methodology adopted for estimating the irrigation water use, i.e., the SM-based inversion approach. This was our explicit intention, as the method is currently well-established after several development steps described in the following papers: Brocca et al. (2018), Dari et al. (2020, 2022, 2023). In this case, we decided to demonstrate our ability to implement an operational application that deals with a timely topic. Note that the reader is referred to the papers mentioned above for details on the method (see, e.g., lines 29, 34-41, 57, 69 or the sentence "the details for the implementation of the method are fully described in Dari et al. (2023)" at lines 72-73. Nevertheless, in order to meet the reviewer requirements, we will expand more on the method background in Section 3. The new Materials and Methods section will read as follows (added parts are underlined):

"3 Materials and Methods

3.1 The SM-based inversion approach

Irrigation water use has been estimated through the SM-based inversion approach (Brocca et a., 2018; Dari et al., 2020; 2023) over a time span ranging from January 1, 2015 to September 30, 2023. The core idea behind the method is the inversion of the soil water balance for backwards estimating the total water input, generally represented by rainfall plus irrigation. By expressing the soil water balance as:

$$Z^* \frac{dS(t)}{dt} = i(t) + r(t) - g(t) - sr(t) - e(t) \qquad (1)$$

where Z^* [mm] is the water capacity of the soil layer, $S(t)$ [-] is the relative soil moisture (i.e., ranging between 0 and 1), t [days] indicates the time, $i(t)$ is the irrigation rate [mm/day], $r(t)$ [mm/day] is the rainfall rate, $g(t)$ [mm/day] is the drainage term, $sr(t)$ [mm/day] is the surface runoff, and $e(t)$ [mm/day] is the evapotranspiration rate. Eq. (1) is equivalent to:

$$Win(t) = Z^* \frac{dS(t)}{dt} + g(t) + sr(t) + e(t) \qquad (2)$$

where $Win(t)$ is the total amount of water entering into the soil, i.e., rainfall plus irrigation. As thoroughly explained in previous studies by the authors, the following assumptions can be adopted: (i) $g(t) = aS(t)^b$ (Brocca et al., 2014), (ii) $sr(t) = 0$ (Brocca et al., 2015), (iii) $e(t) = F \cdot S(t) \cdot PET(t)$ (Dari et al., 2023). Hence, Eq. (2) can be rewritten as:

$$Win\ (t) = Z^* \frac{dS(t)}{dt} + aS(t)^b + F \cdot S(t) \cdot PET(t) \quad (3)$$

After estimating the total amount of water entering the soil, irrigation rates can be derived by removing rainfall rates from the total, $i(t) = Win\ (t) - r(t)$. Negative irrigation rates, if any, are imposed equal to zero (Jalilvand et al., 2019). A threshold value for the ratio between weekly estimated irrigation and weekly rainfall equal to 0.2 is adopted to discard negligible irrigation amounts due to random errors.

The parameters a, b, Z^*, and F of Eq. (3) are the model parameters. a, b, and Z^* have been calibrated against rainfall (i.e., by optimizing the method performances in properly reproducing rainfall amounts) by masking out days with no rainfall rate during the irrigation seasons (hence, potential irrigation days). The F parameter has been set equal to 0.3 as explained in Section 3.2. For further details on the method, the reader is referred to Dari et al. (2023).

3.2 Data and processing

The algorithm requires soil moisture, rainfall and potential evapotranspiration (PET) data as an input. We have used Sentinel-1 surface soil moisture observations from the Copernicus Global Land Service (https://land.copernicus.eu/global/products/ssm) (Bauer-Marschallinger et al., 2019) having a spatial resolution of 1 km and 2 to 6 days revisit time depending on the region of interest and the number of satellites available in orbit (2 satellites from October 2016 to December 2021, and 1 satellite from October 2014 to October 2016 and from January 2022 to September 2023 due to failure of Sentinel-1B). Before running the algorithm, the noise in the soil moisture signal has been reduced by computing the Soil Water Index (SWI) according to the exponential filter proposed by Albergel et al. (2008). Precipitation and PET have been obtained from the 5th land reanalysis of the European Centre for Medium-Range Weather Forecasts (ERA5 Land, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview), characterised by a native spatial resolution of 9 km and hourly temporal resolution (Muñoz-Sabater et al., 2021). As PET from ERA5 Land represents pan evaporation, i.e., open water evaporation, we have rescaled the data, i.e., to obtain the same mean value in the common period, by using potential evaporation from the Global Land Evaporation Amsterdam Model (GLEAM v3.6a, https://www.gleam.eu/) (Miralles et al., 2011; Martens et al., 2017) that was used in previous studies (e.g., Dari et al., 2023) but it is not available with short latency. The applied scaling value is equal to 30%. Precipitation and PET data have been resampled over the same spatial grid of Sentinel-1 with the nearest neighbouring approach and aggregated at daily time scale. Therefore, irrigation water use estimates have been produced on the 1 km grid of Sentinel-1 surface soil moisture data with a temporal resolution of 15 days. "

R1C2. I recognize the potential of the system proposed, but believe the manuscript requires substantial improvement to effectively showcase this important work. Given the extent of revisions needed, I recommend rejecting its current version. However, I strongly encourage resubmission of a revised version. I provided detailed thoughts and suggestions below which might guide these improvements.

First, the introduction section of the manuscript currently offers a limited synthesis of the research context. While there is an abundance of references to studies in remote sensing algorithms, the manuscript fails to adequately address the background in estimating irrigation water use. Given that the primary objective of your system is to estimate and monitor irrigation water use, the absence of a thorough discussion on the research gaps in existing systems for estimating irrigation water use significantly weakens the presentation of your proposed system. To enhance this aspect, I recommend the following revisions for the introduction: (1) incorporate a comprehensive literature review that emphasizes the significance of estimating irrigation water use in water resource management and identifies existing research gaps; (2) establish a clear connection between these identified research gaps and your proposed system, highlighting how your system aims to bridge these gaps.

R1A2. We will revise the Introduction according to the reviewer's suggestions. We remark that estimating irrigation water use from satellite data is in itself an open challenge, but here, based on the authors previous works, we set ourselves an even more ambitious goal, which is the building of an operational system. Under this perspective, we balanced the introduction in order to not put too much focus on details of other methods to estimate irrigation water use available in literature (which are mentioned anyway), but emphasising the background of the SM-based inversion approach, here used to develop an operational system. The importance of estimating irrigation water use in water resource management and the existing research gaps (i.e., the total absence of operational systems) will be further emphasised. The new Introduction will read as follows (added parts are underlined):

"1 Introduction

In recent years, Europe has experienced a number of catastrophic events, including the COVID-19 pandemic and the conflict in Ukraine. The effects of these events are far-reaching and impact all sectors of society, including agriculture and food production (Van Tricht et al., 2023). Ukraine is among the largest wheat producers in Europe, and is indeed known as the breadbasket of Europe. It is crucial to comprehend the impact of these catastrophic events on crop production in Ukraine, particularly in the conflict-affected Kherson region. Crop production in the Kherson area south of the Kakhovka dam heavily depends on irrigation that is facilitated by the Kakhovka reservoir. As the Kakhovka dam's collapse on June 6, 2023 is anticipated to have had a significant impact on crop production, it could be evaluated by examining the variability over time of irrigation water use in the area.

Thanks to the advance in satellite technology, as for instance the launch of the Sentinel constellation under the Copernicus Programme, remote sensing has recently enabled the acquisition of irrigation water use measurements (Massari et al., 2021; McDermid et al., 2023), enabling large areas to be monitored in a consistent and equitable manner. <u>This circumstance opens unprecedented perspectives in water resources management over human-altered basins. In fact, irrigation represents the largest component of the anthropogenic water use (Foley et al., 2011; Dorigo et al., 2021), with impacts on several components of the Earth system and social dynamics (McDermid et al., 2023; Dari et al., 2024). In general, satellite observations of hydrological variables that can be a proxy of irrigation occurrence are used to estimate irrigation volumes, as long as the condition of a matching between the spatio-temporal resolution of the observational data and the spatial and temporal scales of irrigation dynamics is satisfied (Dari et al., 2022; Zappa et al., 2022)</u>. Specifically, approaches based on satellite soil moisture (e.g., Lawston et al., 2017; Brocca et al., 2018; Dari et al., 2020) and evaporation (e.g., Bretreger et al., 2022; Brombacher et al., 2022; Kragh et al., 2023) products have been developed in recent years. An example integrating both soil moisture and evaporation products is the soil moisture based (SM-based) inversion approach developed by Dari et al. (2023) as an evolution of the SM2RAIN (Soil Moisture to RAINfall) algorithm originally designed to estimate rainfall from satellite soil moisture (Brocca et al., 2014). Preliminary promising results were shown by Brocca et al. (2018) and Filippucci et al. (2020) by means of coarse resolution satellite and in-situ soil moisture, respectively. Concurrently, a few studies deepened the role of the evapotranspiration term within the algorithm structure (Jalilvand et al., 2019; Dari et al., 2020; 2022b). The first implementation with high-resolution satellite soil moisture as an input has been proposed by Dari et al. (2020). The authors produced a data set of irrigation estimates at 1 km spatial resolution over a heavily irrigated portion of the Ebro basin, in Spain, covering the period 2011-2017. Recently, the SM-based inversion approach has been implemented under the European Space Agency (ESA) Irrigation+ project for producing the first regional-scale, high-resolution data sets over three major basins worldwide (Dari et al., 2023). In a nutshell, the SM-based inversion approach proved itself to be a useful tool for estimating irrigation water use across scales; the following natural step is the exploration of the possibility of building an operational system based on it, as currently no operational services for monitoring large-scale irrigation are available.

In this study, we have developed for the first time an operational system for monitoring irrigation water use with 10 days latency relying on the SM-based inversion approach forced with operational satellite-based surface soil moisture data and precipitation and evaporation data from reanalysis. "

R1C3. Second, Section 3 on Materials and Methods currently provides insufficient information for readers. The section appears to predominantly describe the necessary data and data sources, yet it neglects to adequately detail the critical methods or algorithms that underpin the system. Consequently, while the data requirements for the system are clear, its structure (such as the system components, modules, and data flows) and the core algorithms that facilitate its operation remain obscure. Additionally, the results and discussion sections indicate the application of the system to a real-world scenario for demonstration purposes, yet the method section lacks a comprehensive overview of the chosen case area. I recommend that the authors thoroughly reevaluate and substantially revise the methodology section to provide a clearer and more detailed presentation of the proposed system. This revision should aim to explain in detail for both the system architecture and its foundational algorithms, as well as incorporate a more detailed description of the case study area within the methodological framework.

R1A3. We believe that we already responded about changes to be done to better describe the methodology in R1A1. We will also improve the description of the study site, adding more details on the irrigation infrastructure of the Kakhova system. The revised version of the Study Area section will read as follows (added parts are underlined):

"2 Study area

As a proof of concept, the operational system for monitoring irrigation water use from satellite data has been implemented over a cold semi-arid area (Beck et al., 2018) enclosing a heavily irrigated portion fed by the Kakhovka reservoir on the Dnipro river, in Ukraine, collapsed on June 6, 2023. More in detail, we have selected a box of almost 4000 km2 whose extension ranges from longitude 33.30° to 34.45° and from latitude 46.15° to 46.50°. This is the area fed by the Kakhovsky canal, which originates just upstream the dam and delivers water to five irrigation districts through an efficient and automated network; the districts are equipped with a dense system of centre pivot that was mainly realized between the late 1970s and 1980s as part of the development of the Kakhova system, completed in 1990 (Kuns, 2018) and representing one of the largest irrigated areas in Europe. The dense system of center pivot irrigation equipment can be observed by visual inspection of satellite maps (see, e.g., Fig. 1a). For the selected area, the latest version of Global Map of Irrigated Areas (GMIA) (Mehta et al., 2022) reports peaks up to 60% in terms of percentage of area equipped for irrigation. The data set refers to cells characterised by a spatial resolution of 5 arc-minutes (about 10 km at the Equator). Reznik et al. (2016) report a percentage of irrigated areas equal to 83.3% of the total available area in 2015. Based on statistical surveys, the main cropping season for cereal and other annual crops in Ukraine is from May to August (Portmann et al., 2008)."

R1C4. I would like to reiterate that the topic and the proposed system are both valuable and of great interest to me. However, the current presentation of the manuscript does not do justice to the value of the work. It is essential that the content and delivery are refined to effectively convey the significance of your research. I look forward to having the opportunity to review a revised and resubmitted version of this manuscript in the future, hoping it will fully reveal the potential and importance of the work.

R1A4. We thank the reviewer.

References

Brocca, L., Tarpanelli, A., Filippucci, P., Dorigo, W., Zaussinger, F., Gruber, A. and Fernández-Prieto, D.: How much water is used for irrigation? A new approach exploiting coarse resolution satellite soil moisture products. International Journal of Applied Earth Observation and Geoinformation, 73C, 752-766, doi:10.1016/j.jag.2018.08.023, 2018.

Dari, J., Brocca, L., Quintana-Seguí, P., Escorihuela, M.J., Stefan, V. and Morbidelli, R.: Exploiting high-resolution remote sensing soil moisture to estimate irrigation water amounts over a Mediterranean region. Remote Sensing, 12(16), 2593, doi:10.3390/rs12162593, 2020.

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. Agricultural Water Management, 265, 107537, doi:10.1016/j.agwat.2022.107537, 2022.

Dari, J., Brocca, L., Modanesi, S., Massari, C., Tarpanelli, A., Barbetta, S., Quast, R., Vreugdenhil, M., Freeman, V., Barella-Ortiz, A., Quintana-Seguí, P., Bretreger, D. and Volden, E.: Regional data sets of high-resolution (1 and 6 km) irrigation estimates from space. Earth System Science Data, 15(4), 1555-1575, doi:10.5194/essd-15-1555-2023, 2023.