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.

R3C1. In this work, the authors discuss the importance of building an operational system for monitoring water-use quantity for large-scale irrigation purposes (for example, during high-impact dam-destructions, big-scale pandemics or wars), through satellite images, with spatial resolution of 1 km, of soil-moisture, precipitation and potential evapotranspiration (through ERA5 reanalysis data and GLEA models), and with application south of Kakhova in Ukraine and during the period 2015-2023. Although the idea seems interesting, further analysis and validation are required to support it. Please see some major issues that I hope they can be of help to the authors:

R3A1. We are glad for the reviewer's positive feedback. Please find a detailed response as follows.

R3C2. 1) I would recommend the Abstract and Introduction focus on the idea of "developing an operational system for monitoring water-use quantity for large-scale irrigation purposes", and mention to the end something like that "to support this idea, we select for application the largest scale events of the last decade in Europe, which is the COVID and the conflict in Ukraine that led to the destruction of high-impact irrigation dam", since there seems to be much emotion and focus on the application area (that, although justified, it is not the purpose of this paper).

R3A2. We agree with the reviewer, the case study has been chosen because it allows us to depict timely socio-political dynamics, but the paper's main intent is to develop an operational system for monitoring water-use quantity for large-scale irrigation purposes. We will rephrase the abstract as follows:

"Irrigation is the main driver for crop production in many agricultural regions across the world. The estimation of irrigation water has the potential to enhance our comprehension of the Earth system, thus providing crucial data for food production.

In this study, we have created a unique operational system for estimating irrigation water using data from satellite soil moisture, reanalysis precipitation and potential evaporation. As a proof of concept, we implemented the method at high-resolution (1 km) during the period of 2015-2023 over the area south of the Kakhovka dam in Ukraine, which collapsed on June 6, 2023. The selected study area enabled us to showcase that our operational system is able to track the effect of the pandemic and conflict on the irrigation water supply. A significant decrease of 63% and 44% in irrigation water compared to the mean irrigation water between 2015-2023 has been identified as being linked to the collapse of the dam and, potentially, to the COVID-19 pandemic, respectively."

R3C3. 2) I do not comprehend the sentence "Concurrently, a few studies deepened the role of the evapotranspiration term within the algorithm structure"; please consider further explaining it or maybe rephrasing it, and present what exactly these other studies' advantages and disadvantages.

R3A3. We will change the sentence as follows:

"Concurrently, a few studies demonstrated the importance of considering the evapotranspiration term within the algorithm structure together with SM (Jalilvand et al., 2019; Dari et al., 2020; 2022b)."

In addition, we believe that details on the methodology added to address R3C5 will further clarify the sentence in the context of the model's structure (see R3A5).

R3C4. 3) Please add more information for the study area (for example, why the dam collapsed, dimensions of the dam and its reservoir, temperature, PET, precipitation, soil-moisture, streamflow, etc.), so that the readers are familiarized with the area's social, climatic and hydrological conditions.

R3A4. The climatic context is mentioned at line 48 of the manuscript. We will add more information on the study area. The revised version will read as follows (added parts are underlined):

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 <u>on the Dnipro river (approximate length of 2200 km and average flow at the outlet of 53 km^3/year under natural conditions)</u> in Ukraine, collapsed on June 6, 2023. <u>Under operating conditions, the store capacity was of 18.2 km^3, corresponding to an extent of water surface equal to 2155 km^2</u>. We have selected a box of almost 4000 km^2 whose extension ranges from longitude 33.30° to 34.45° and from latitude 46.15° to 46.50°. <u>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</u>. 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). <u>Reznik et al. (2016) report a percentage of irrigated areas equal to 83.3% of the total available area in 2015.</u> 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).

R3C5. 4) It is mentioned that "To assess irrigation water use from satellite observations of soil moisture (or evaporation), the observations must detect the increase in soil water associated with irrigation application."; however, it is not clear what exactly the methodology is, and how evaporation can be used instead of the soil-moisture. Please consider presenting the methodology in further detail and how exactly one can estimate soil-moisture or evaporation from the satellite image processing.

R3A5. In our method soil moisture is used together with evaporation. We hope this will be clarified by a detailed description of the method that will be added. The revised version of the section will read as follows (added parts are underlined):

"3 Materials and Methods

<u>3.1 The SM-based inversion approach</u>

<u>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:</u>

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

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:

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

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:

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

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).

R3C6. 5) Some of the main conclusions of this study (i.e., "Consequently, we can confidently stipulate that Sentinel-1 soil moisture data is capable of detecting the irrigation signal in space with good precision." or "The possible impact of COVID-19 pandemic is also highlighted.") are not fully supported, in my opinion, from the analysis, due to (a) the small range of data from 2015-2023 (at least 30 years of data is required to include the intrinsic uncertainty of the key hydrological-cycle processes, traced in their short-term dependence and long-term persistence), and (b) more data and different climatic and seasonal conditions need to be examined to support the above conclusions and exclude other factors that may result in the same impacts and similar images (for example, how do you take into account the type of irrigation and land-use in the area; is there a change during the 2015-2023 period?).

R3A6. The limited range of data is due to the temporal coverage of satellite data, which represents the essential tool on which the approach relies. We honestly believe that this is not a strong limitation to our study, as it is a natural issue in emerging applications relying on recent satellite retrievals. However, we will add the following sentence in the conclusions:

"The current temporal coverage of Sentinel-1-derived observations may be a limitation, but the continuity foreseen for the mission will offer the possibility of creating long-term time series of irrigation water use in the upcoming years."

It is important to highlight that the reliability of the retrieved irrigation amounts is consistent with precipitation dynamics. In the new "Study Area" section we will explain that the system has been working from 1990s onwards, adopting an automated network of centre pivot, thus reasonably implying a static scheme working through sprinkler irrigation. The recurrence of irrigated areas is also clear by the following maps of average LAI (Leaf Area Index) during the various irrigation seasons (see Figure R1 and Figure A4 in the Appendix to the manuscript).

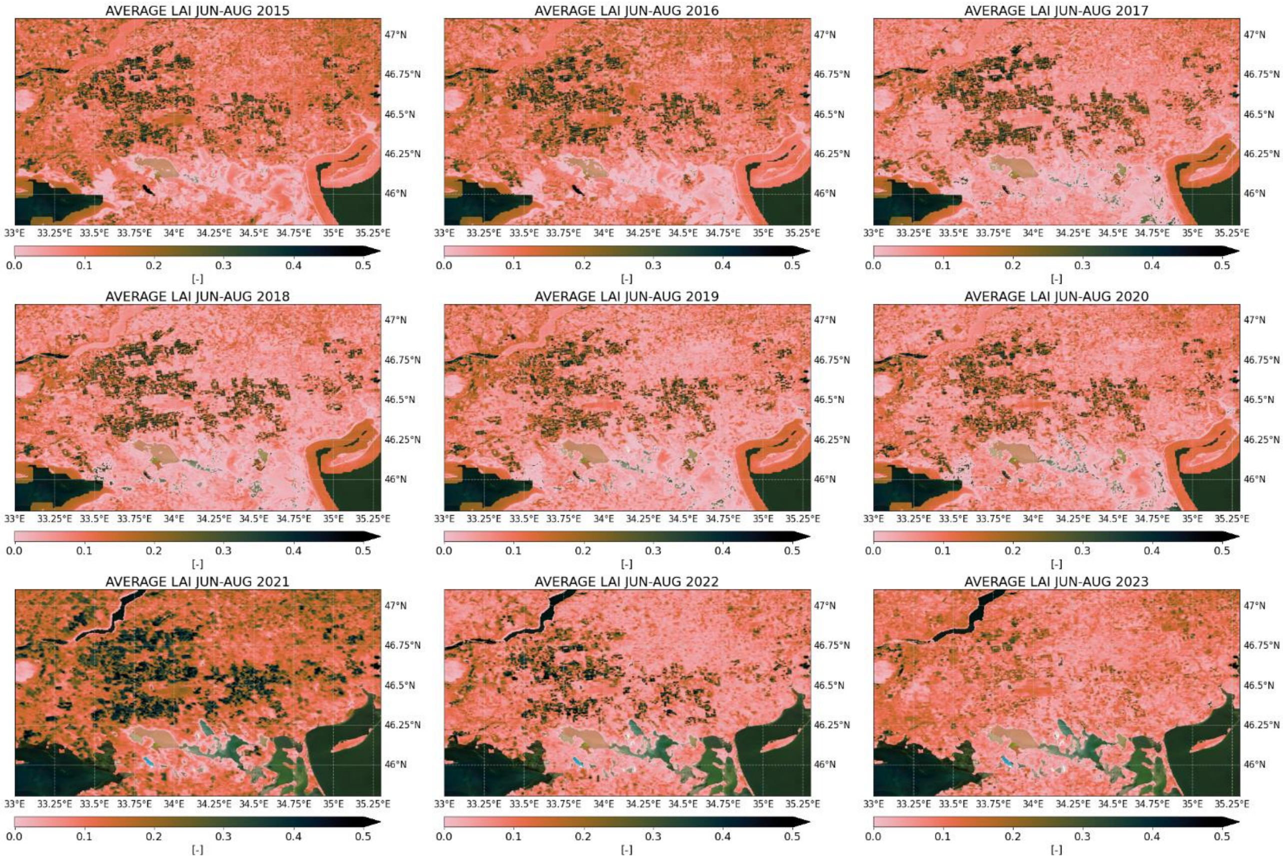

Figure R1. Average LAI during the various irrigation seasons considered.