Anthropogenic Water Use (CCI-AWU)

Deliverable 13:
Roadmap to derive operationally AWU from satellite data as ECV in the upcoming years

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1. Introduction

1.1. The CCI-AWU Project

The closure of the Earth's water cycle (as well as the energy balance and the carbon cycles) through satellite Earth Observation (EO) represents one of the outstanding scientific challenges highlighted by the Global Climate Observing System (GCOS). Required standards of accuracy are fixed to 5% and annual timescale. To this end, a suite of essential climate variables (ECVs) has been defined to understand the evolution of climate and to assess the potential derived risks. However, if targets at annual timescale can generally be reached, larger uncertainties are observed for sub-annual and sub-continental time and spatial scales, respectively (Dorigo et al., 2021). In this context, the development of an ECV that includes information on anthropogenic water use (AWU) can help in advancing the proper closure of the water cycle at higher spatial and temporal scales. In the ESA Climate Change Initiative Anthropogenic Water Use (CCI-AWU) precursor project, AWU is more specifically intended as agricultural water allocated for irrigation, which represents the largest anthropogenic water use, thus making irrigation the most impactful human activity on the hydrological cycle. FAO (2016) estimated that irrigation, worldwide, accounts for more than 70% of water withdrawn from the surface (i.e., rivers, lakes) and subsurface (i.e., groundwater) water sources and these estimates are expected to increase in the near future due to an increase in population and in food production, especially over arid and semi-arid regions (McDermid et al., 2023). In this context, the main data source identified by GCOS for tracking AWU is FAO's AQUASTAT. However, AQUASTAT provides survey-based irrigation estimates that do not meet the GCOS requirements, i.e., data are provided on a 5-year interval instead of yearly and are available every 2-3 years.

The overarching objective of the Climate Change Initiative - Anthropogenic Water Use (CCI-AWU) precursor project is to derive long-term (i.e., at least twenty years) AWU time series for selected regions using several approaches exploiting remote sensing observations, as a proof-of-concept of the feasibility towards a proper AWU ECV product.

The CCI-AWU project is led by a consortium coordinated by CNR-IRPI and includes the following institutions:

1. Vienna University of Technology (TU Wien) (TUWIEN)
2. KU Leuven, Department of Earth and Environmental Sciences, Division of Soil and Water Management (KULeuven)
3. University of Perugia (UNIPG)
4. Politecnico di Milano, Department of Civil and Environmental Engineering (POLIMI)

1.2. Scope of this Report

This document summarises the main achievements obtained during the CCI-AWU project and outlines the future steps that should be carried out in this activity.

1.3. Applicable Documents

- Proposal.
- Deliverable D2. Report explaining the criteria for selecting the test regions.
- Deliverable D3. Algorithm Theoretical Baseline Document (ATBD).
- Deliverable D4. Product Validation and Algorithm Selection Report (PVASR).
- Deliverable D6. Product Validation and Intercomparison Report (PVIR).
- Deliverable D7. Product User Guide (PUG).
- Scientific Paper #1: "Satellite based estimates of irrigation water use versus modeling reconstructions: how much do they differ?" by Dari et al, submitted to *Earth's Future*.
- Scientific Paper #2: "Assessing the suitability of global evapotranspiration products over irrigated areas" by Laluet et al, submitted to *Hydrology and Earth System Science*.
- Scientific Paper #3: "Comparing irrigation water demand from biophysical modelling with remote-sensing driven withdrawal estimates: insights on water use patterns" by Galli et al, submitted to *Agricultural Water Management.*
- Scientific Paper #4: "Long-term irrigation water use datasets from multiple Earth Observation-based methods in major irrigated regions" by Laluet et al, submitted to *Earth System Science Data.*

All deliverables mentioned here will be made publicly available at the following link: https://climate.esa.int/en/projects/anthropogenic-water-use/.

2. Summary of the main scientific results

The main achievements of the projects can be summarized in:

1. 1 scientific paper published (https://doi.org/10.3390/w16050644) and 4 more currently under review in international journals, with 2 of them early accessible as preprints: Laluet et al (https://doi.org/10.5194/egusphere-2025-5716) and Dari et al (10.22541/essoar.176218923.33215210/v1);
2. 45 open-access, long-term irrigation water use (IWU) data sets at 0.25° spatial resolution;
3. 3 use cases;
4. Project activities presented in several international conferences (ESA conferences, EGU , MedGU, etc.) during the project lifespan.

The CCI-AWU project generated a harmonised multi-method archive of IWU estimates over four major irrigated regions (CONUS, India, the Murray-Darling Basin, and the Ebro Basin) at monthly resolution and 0.25° spatial scale. Three EO-based approaches were implemented within a consistent processing framework: the SM-based Delta method, the SM-based Inversion method, and the Model-Observation Integration. A comprehensive description of the methods, input datasets, processing workflow, and the full set of scientific results, analyses, and limitations can be found in Laluet et al., (2025b), which represents the primary scientific output of the CCI-AWU project. The full IWU dataset collection is openly available on Zenodo (DOI: 10.5281/zenodo.14988198; Laluet et al., 2025c). Figure 1 shows a slide recently used to advertise the project and the developed IWU archive.

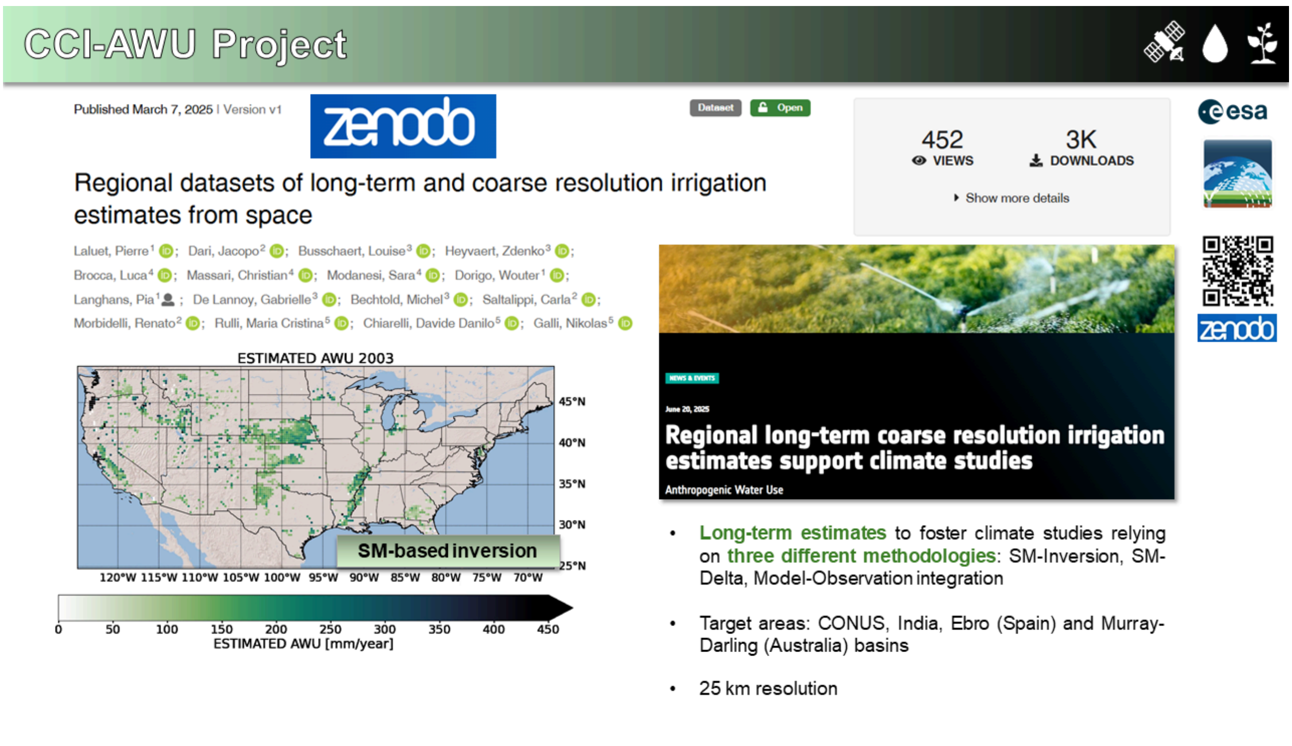

Figure 1. Overview of the IWU archive developed within the CCI-AWU project.

Across the study regions, all three approaches detect irrigation-related signals and reproduce the dominant seasonal patterns associated with major cropping cycles. In CONUS, several method-input combinations fall within the correct order of magnitude of official irrigation statistics and correctly identify main irrigated areas. In the Ebro and Murray-Darling basins, the timing of the irrigation season is broadly captured, although substantial differences in IWU magnitude are observed across methods. In India, where no in-situ irrigation data exist, the methods reproduce the main Rabi (November-March) and Zaid (April-June) seasonal cycles and identify the Ganges Plain (Northern portion of the country) as the principal irrigated region, although the spread between IWU estimates remains large.

The harmonised design enabled the first systematic multi-method comparison of EO-based IWU retrievals across multiple continents. This analysis revealed areas of consistency (such as the localisation of major irrigation hotspots and the representation of broad seasonal cycles) together with significant differences in absolute magnitudes, interannual variability, and spatial detail. These differences reflect both the sensitivity of IWU estimates to EO inputs (soil moisture and evapotranspiration) and the structural assumptions embedded in each retrieval approach.

In addition to producing the IWU archive, the project delivered several complementary scientific analyses. WP510 analysed complementary strengths and weaknesses between the developed IWU datasets and irrigation demand simulated the WATNEEDS agro-hydrological model, under the broader perspective of their synergistic use at large scale. The work is described in the paper “Comparing irrigation water demand from biophysical modelling with remote-sensing driven withdrawal estimates: insights on water use patterns" by Galli et al, submitted to Agricultural Water Management. WP520 assessed the behaviour of multiple global evapotranspiration products over irrigated areas, showing considerable variability across ET datasets and demonstrating that ET uncertainties translate directly into differences in IWU estimates, particularly for the Delta approach. The work is described in the paper “Assessing the suitability of global evapotranspiration products over irrigated areas” by Laluet et al, submitted to Hydrology and Earth System Science. WP530 compared EO-based IWU estimates with irrigation simulated by global hydrological and land-surface models, highlighting systematic structural differences and providing insight into model-satellite discrepancies.

Overall, the scientific results show that EO-based approaches have the capacity to represent large-scale irrigation dynamics and provide valuable regional information, while also highlighting several limitations, particularly related to spatial resolution, input-driven variability, and limited validation data, that must be addressed before EO-based IWU products can reach a level of robustness suitable for operational or climate applications.

3. Scientific and technical challenges

The scientific results obtained in CCI-AWU highlight several limitations that currently prevent EO-based IWU products from reaching a sufficient level of robustness for operational applications. These challenges mainly concern the EO input datasets and the limited availability of reference data, as well as the retrieval methods themselves.

3.1 Challenges related to input and validation datasets

The following limitations related to the EO inputs required by the three IWU retrieval approaches arise:

1. **Spatial resolution (0.25°) remains a major constraint.** The satellite-based IWU products developed in the CCI-AWU project rely on coarse resolution data (0.25°) capable of ensuring long-term records, as their main aim is to foster climate studies. One main limitation that arises from the intrinsic trade-off between spatial and temporal resolution of remote sensing retrievals is the limited capability of the developed data set in properly reproducing IWU over complex landscapes, where irrigation takes place at finer scales. At the adopted resolution (0.25°), irrigated and non-irrigated land are frequently mixed within a single pixel, which limits the detectability of irrigation signals and reduces spatial detail. All three retrieval approaches are affected by this limitation.
2. **Variability across soil moisture and evapotranspiration datasets.** Differences between soil moisture and evapotranspiration products (driven by retrieval errors, climate-dependent performance, and processing choices) translate directly into large differences in IWU magnitude and timing. WP520 (evaluation of ET products over irrigated areas) showed that ET inputs vary widely in irrigation regions, highlighting the need to better quantify how input uncertainties propagate into IWU estimates.
3. **Uncertainties in irrigated-area maps.** Errors in irrigated-area fractions propagate through all retrieval approaches, particularly the Model-Observation Integration method, whose spatial distribution of irrigation depends directly on these maps. Such uncertainties can introduce regional biases in IWU magnitude and spatial patterns. Recent evaluation and intercomparison efforts of irrigated-area products, such as the assessment reported in Zhu et al. (2026), provide an opportunity to better characterise these uncertainties and should be leveraged in future developments

4. **Limited availability of reference irrigation data.** Validation is constrained by scarcity of benchmark data. In CONUS, country-aggregated reference data are available only for two survey years. Despite several efforts in this sense, it was not possible to collect in-situ irrigation data In India. The Ebro and Murray-Darling basins represent more virtuous cases and likely even more information can be acquired. The uneven (and often scarce) amount of reference information across the different case studies affects independent evaluation and uncertainty quantification.

3.2 Challenges related to the retrieval methods

In addition to input-data limitations, the IWU retrieval approaches themselves present several methodological challenges:

1. **High inter-method variability.** The SM-based Delta, SM-based Inversion, and Model-Observation Integration approaches often produce divergent IWU magnitudes and interannual variations, even

when applied to the same region and using harmonised inputs. Nevertheless, the two SM-based methodologies are affected to a minor extent.

2. **Sensitivity to methodological assumption.** IWU estimates remain sensitive to the structural assumptions embedded in each retrieval approach. For the SM-based approaches, sensitivities arise from the indirect nature of the irrigation signal in soil moisture and evapotranspiration datasets, as well as from the reliance on parametrised soil and evapotranspiration formulations. For the Model-Observation Integration approach, uncertainties stem from model-embedded representations of plant water use, soil hydraulic properties, and irrigation timing and amounts, which may not capture regional irrigation practices or crop-specific management. These assumptions collectively contribute to differences in IWU magnitude, spatial patterns, and seasonal evolution across regions.

3. **Uncertainty quantification remains incomplete.** Uncertainty quantification remains incomplete across the different IWU approaches. While the project implemented uncertainty diagnostics for the Model-Observation Integration dataset, these analyses focus primarily on perturbations of the meteorological forcing and do not yet encompass key land-surface parameters or irrigated-area maps. Additionally, no formal uncertainty characterisation was developed for the SM-based approaches. Developing more comprehensive uncertainty frameworks, including ensembles or perturbation experiments that jointly account for input and structural sources of uncertainty, would provide a more robust basis for interpreting IWU estimates and comparing retrievals across regions and methods. Nevertheless, the implementation of common strategies to assess uncertainties of IWU retrievals from the two SM-based approaches is not straightforward because of the different number and type of inputs needed to run them and because of a substantial difference between the two. While for the SM-based Inversion approach there is the need to calibrate certain parameters, no calibration is needed for SM-based Delta.

3.3 Challenges related to extending the coverage of IWU estimates

On the basis of the limitations above, challenges in extending the spatial coverage of the IWU archive arise. In fact, scaling to global or near-global coverage requires additional testing, input harmonisation, and validation across a broader range of climates and cropping systems.

4. Scientific and technical roadmap

The scientific and technical limitations identified in Section 3 point to the need for higher-resolution and better-characterised EO inputs over irrigated areas, strengthened validation capacity, expanded spatial coverage, and enhanced integration with modelling initiatives. The roadmap outlined below describes a phased and targeted development plan, paving the way for the next phase of the project, CCI-AWU IMPRES (IMProved RESolution).

4.1 Near- and mid-term priorities

Focus: improving EO inputs, strengthening validation, reducing known uncertainties, and enabling more robust retrievals in key irrigated regions.

Improved EO inputs and spatial resolution. Testing Higher resolution EO inputs. Medium-resolution soil moisture products are good candidates to enhance irrigation detectability in heterogeneous agricultural landscapes without neglecting the climate perspective. The CCI SM v09.1, 0.1° and long-term downscaled products relying on the DISPATCH (DISaggregation based on Physical And Theoretical scale CHange) approach (Merlin et al., 2013) represent suitable options. Concerning ET, leveraging high-resolution datasets (e.g., PMLv2, FLUXCOM RS/X-BASE, GLEAM-HR, SSEBop) can be useful to better capture fine-scale irrigation dynamics.

Improved representation of irrigated areas. Integrate recent high-resolution irrigated-area products and uncertainty assessments (e.g., Zhu et al., 2026) to reduce spatial biases in IWU.

Progressive extension of geographical coverage. Begin extending IWU retrievals to additional irrigated regions, ensuring early testing across diverse climates and cropping systems.

Better integration of EO-based information in modeling platforms. Start some effort aimed at integrating EO retrievals into modeling platforms, e.g., by using them to derive ancillary information useful in models' schemes. In parallel, it is also meaningful to adopt model assumptions (e.g., on the spatiotemporal occurrence of irrigation) in satellite-based algorithms.

Comprehensive uncertainty frameworks. Provide a better quantification of how differences among soil moisture and evapotranspiration products propagate into IWU estimates. Develop ensemble or perturbation strategies that jointly account for input uncertainties and structural assumptions embedded in each retrieval approach.

Increase the amount of reference IWU information. Disposing of more IWU records is essential to properly assess the accuracy of the developed products. Under this perspective, the community initiative aimed at creating the first global IWU database recently launched by Jacopo Dari can be strategic. The flyer of the call for collaboration is provided in Figure 2.

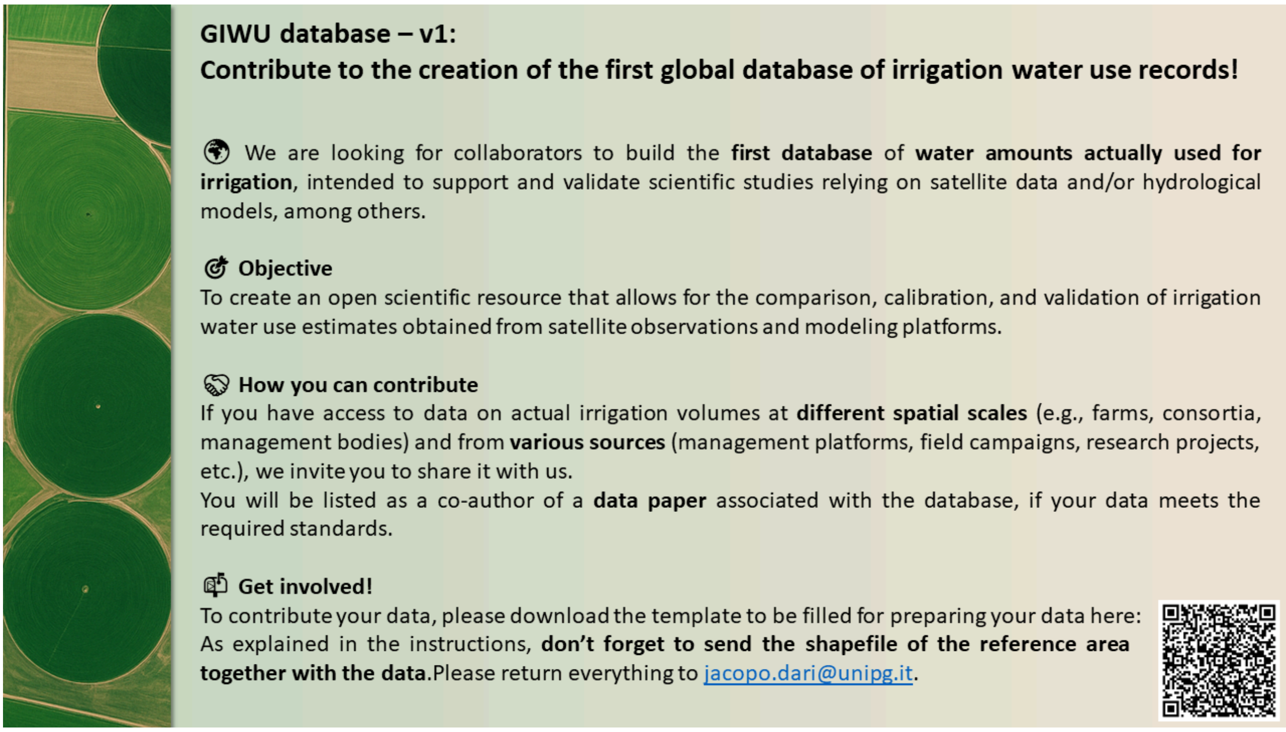

Figure 2. Open call to contribute to developing the GIWU (Global Irrigation Water Use) database.

4.2 Long-term priorities

Focus: global applicability, climate-model relevance, and integration with the wider CCI ecosystem.

Global coverage and scalability. Extend IWU retrievals to near-global domains while ensuring methodological consistency and avoiding regional artefacts. Prepare processing architectures and quality-control procedures for large-scale applications and potential transition towards operational production.

Integration with modelling and climate services. Strengthen synergies with Earth System Model initiatives enabling systematic comparison between EO-derived IWU and modelled irrigation and improving irrigation representation in climate models. Integrate complementary CCI ECVs (e.g., Soil Moisture, Land Cover, Land Evaporation, Vegetation Parameters, Biomass) to represent multidimensional irrigation impacts on land-surface processes. Support climate and adaptation services by enabling monitoring of irrigation pressures, water scarcity, and land-atmosphere feedbacks.

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