Deliverable 4.4: MONITORING TOOLBOX PROTOTYPE

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Executive summary

The monitoring of water is critical for planning and policy, especially under climate and socio-economic change. Detailed information on the spatial distribution, quantity and variability of human and natural components of the hydrologic system is needed for informed decision making around allocation and management of scarce water resources, both at the local level – such as farm-level irrigation scheduling – and for crafting basin-to-national-scale policies and long-term strategic planning. Monitoring of water demand and supply is therefore central to the TRANSCEND project's aim of identifying, designing, and catalysing the adoption of Transformational Adaptation Policies (TAPs) to water scarcity. Despite these needs, as described in Deliverable D4.1 (White Paper), gaps in basin-scale monitoring impede our ability to design and implement TAPs. Monitoring data gaps have serious implications for the sustainability and effectiveness of water management, constraining efforts to allocate available water resources between competing uses, limiting the ability to effectively identify and assess environmental impacts of policy changes, and reducing overall trust in water management planning. There is a pressing global need to develop affordable, transferable and accurate methods to aid in the collection of policy-ready water availability data. In this deliverable, a set of research activities comprising the Monitoring Toolbox are described, as well as the decision-making process (including co-creation) that led to these research activities being selected. At the core of the Toolbox is the development of land use/land cover and irrigated area maps using Earth Observation (EO) data. EO data, combined with advanced data-driven modelling tools such as machine learning algorithms, provides a scalable and cost-effective solution to address gaps in agricultural land and water use monitoring that were identified as a common cross-cutting monitoring need across the majority of TRANSCEND's living labs and are of broader importance globally in water-scarce river basins. We outline the key features of the Toolbox, along with specific activities and timelines for a series of pilot applications planned in four of TRANSCEND's living labs spanning three continents and six countries: Titicaca Lake, Desaguedero River, Lake Poopo system in Latin America (Bolivia and Peru); Jucar River basin in Spain; Mahanadi River basin in India; and the Tympaki River basin in Greece. We also further document processes for ensuring that the Toolbox and the data it produces are impactful, actionable, and sustainable beyond the end of TRANSCEND, both within the pilot labs and in river basins globally. These include stakeholder engagement and partnership in co-design, open-access code/tools, and synergetic knowledge exchange, both within and beyond the consortium. In doing so, the TRANSCEND Monitoring Toolbox will be a vital vehicle supporting the development of TAPs to water scarcity, climate change, and socio-economic development in agriculturally intensive river basins worldwide.

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Contents

List of Tables

List of Figures

1 Introduction

The monitoring of water supply and demand is critical for planning and policy, especially under climate and socio-economic change. Detailed information on the spatial distribution, quantity and variability of human and natural components of the hydrologic system is needed for informed decision making around allocation and management of scarce water resources, both at the local level – such as farm-level irrigation scheduling – and for crafting basin-to-national-scale policies and long-term strategic planning. Monitoring of water demand and supply is therefore central to the TRANSCEND project's aim of identifying, designing, and catalysing the adoption of Transformational Adaptation Policies (TAPs) to water scarcity.

Despite these needs, as described in Deliverable D4.1 (White Paper), gaps in basin-scale monitoring impede our ability to design and implement TAPs. There is growing evidence that, globally, investment in in-situ monitoring is declining, particularly with regards to streamflow data (Crochemore et al., 2020; Ruhi et al., 2018). At the same time, only a small proportion of water abstraction volumes and locations are metered and officially verified, with significant monitoring gaps in groundwater and agricultural abstractions (Molle and Closas, 2020). These data gaps have serious implications for the sustainability and effectiveness of water management, constraining efforts to allocate available water resources between competing uses (Josset et al., 2019), limiting the ability to effectively identify and assess environmental impacts of policy changes (Deines et al., 2019; van Loon et al., 2022), and reducing overall trust in water management planning (Lin et al., 2023). There is a pressing global need to develop affordable, transferable and accurate methods to aid in the collection of policy-ready water availability data.

Satellite Earth Observation (EO) techniques have the potential to fill many monitoring gaps, enhancing and supporting existing or new systems of in-situ gauging and monitoring of water cycle dynamics to provide scalable solutions to tackle growing water scarcity challenges globally. EO techniques generally involve measurement of some property of the Earth – often, but not always, spectral-temporal characteristics – using a satellite-mounted sensor and interpreting these measurements to derive estimates of hydrological fluxes or storages. Some recent examples of the potential transformative impact of EO for water management include the use of Sentinel-2 data to develop global, 10 m resolution land cover maps (Karra et al., 2021); application of the SWOT sensor to generate a global database of streamflow information (Riggs et al., 2023); and leveraging GRACE satellite measurements to identify regional-to-continental groundwater depletion (Famiglietti et al., 2011).

In this context, the purpose of this deliverable is to outline a Monitoring Toolbox (hereafter "the Toolbox"), based on EO techniques and focused on water accounting , which will be developed and piloted within the TRANSCEND project to support TAP development in TRANSCEND's living labs and beyond. First, we outline and describe the co-identification process through which monitoring tool/data needs were identified for each living lab. Then, we identify and discuss common cross-cutting monitoring needs across TRANSCEND's living labs and globally, and how this – along with existing data and consortium expertise – have informed the final Toolbox design and proposed research applications. Finally, we describe the key features of the proposed Toolbox, followed by – where relevant – specific details of the implementation, science and policy research applications in each living lab. We conclude with a forward-looking consideration of how the Toolbox will support other TRANSCEND activities, with a review of linkages to TRANSCEND's broader goals beyond Work Package 4 including Modelling (Work Package 3) and capacity development of partners.

2 Co-identification of monitoring tools and data needs

During the first stages of the TRANSCEND project, there has been sustained work to engage stakeholders and co-identify gaps in monitoring in each living lab. This process has been continuous, occurring in both formal and informal channels. The first formal round of co-identification occurred during the first living labs Workshops, where living labs convened events bringing together local stakeholders to directly discuss monitoring gaps, among other issues (*Figure 1*).

Figure 1 Images of in-person co-identification of needs. a) Sticky notes containing monitoring priorities from the Titicaca Lake, Desaguadero River, Poopo Lake (TDP) lab's first workshop (October 2023); b) Stakeholders discuss water issues in the Mahanadi basin during their first workshop (October 2023).

Another key stage occurred during the preparation for Deliverable D4.3, "Monitoring and Implementation Status and Indicators", when a survey was circulated among the living lab leads to gather a written summary of the existing status of water supply and demand monitoring in each lab. Based on these survey responses, and in consultation with living lab partners, Deliverable D4.3 contained a summary of monitoring gaps in each living lab. A synthesis from D4.3, showing the relative monitoring levels in each living lab, is presented in *Figure 2*.

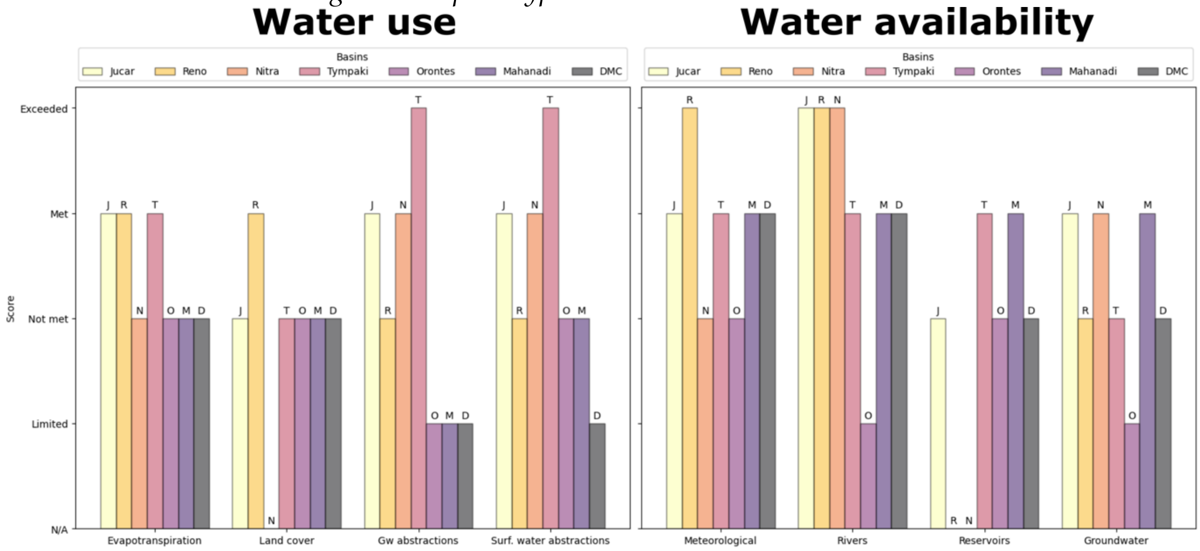

Figure 2 Reproduction of Figures 17 and 18 from D4.3, showing a comparison of the standard of water use (left) and water availability (right) monitoring across the living labs. See D4.3 for a detailed description of the y-axes scores.

Subsequently, a session was held at the 1st TRANSCEND General Assembly (Uppsala, 2024) where partners from across the consortium conducted group discussion to further refine evidence of monitoring gaps and define priority monitoring data needs to be addressed as part of TRANSCEND WP4 (Figure 3). It was found that this interactive setting allowed for a dynamic examination of each basin's needs that complemented the insights obtained from the survey. Finally, from March to May 2024, a series of video conference meetings were held to fine-tune the description of monitoring needs and flesh out details of potential monitoring work that could be designed to meet them.

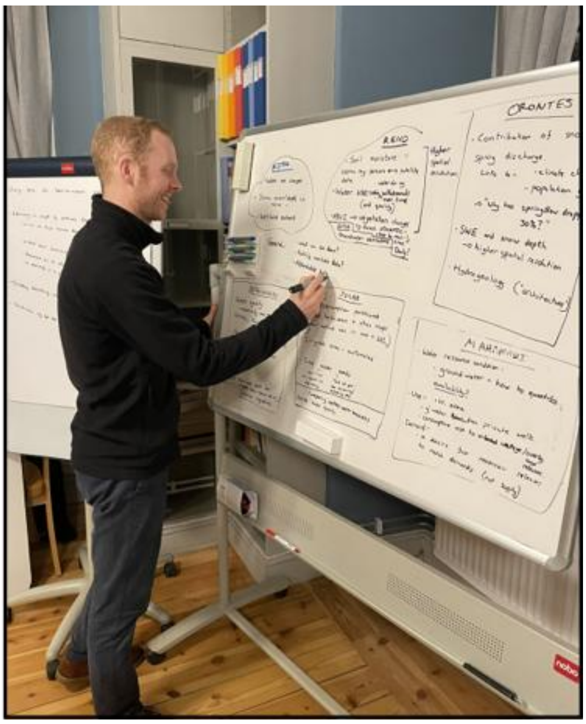

Figure 3 An image of whiteboard work during the 1st General Assembly (Uppsala, February 2024).

To summarize the outcome of the co-identification process, *Table 1* presents three key monitoring priorities that were identified by living lab leads in consultation with local stakeholders and consortium partners in each living lab. A wide range of different needs were identified, covering different aspects of the hydrologic system (e.g., water quality, water quantity, surface water, groundwater, agricultural practices), differing scales (ranging from counting of individual trees to basin-scale water use estimation), and capturing both natural (e.g. hydrological processes such as snow dynamics) and human components (e.g. water use for irrigated agriculture) of the water cycle.

Table 1 Identified monitoring needs across the seven living labs. This table is based on the needs which were identified during the TRANSCEND 1st General Assembly (Feb 2024) and fine-tuned in subsequent video conference meetings. The 'primary stakeholders' column indicates the main stakeholder(s) that were involved in these engagement activities to give a sense of the scope of the co-identification process. There are many more stakeholders who are not listed but made contributions to needs identification through other channels.

living lab	Identified Monitoring Needs/Priorities	Primary stakeholder(s)
Jucar	- Improved monitoring of the relative water consumption by herbaceous and citrus crops - Automated method to identify irrigated area - Improved monitoring of crop water needs: both 'real time' to support irrigation efficiency, and 'summative' to support annual reviewing and policy enforcement	Universitat Politècnica de València
Reno	- Soil moisture: linking cosmic ray sensors to satellite data - Monitoring surface water withdrawals over time - Dynamic monitoring of vegetation changes	Agenzia regionale per la prevenzione, l'ambiente e l'energia dell´Emilia-Romagna (ARPAE)
Nitra	- Water use changes - Snow cover/depth in mountain regions - Wetlands extent	Slovak Water Management Enterprise (VSP) Slovak Environment Agency
Orontes	- Contribution of snow to spring discharge - SWE and snow depth monitoring at higher spatial resolution - Hydrogeologic mapping of "the groundwater architecture"	American University of Beirut
Mahanadi	- Quantification of available groundwater	Institute for Resource Analysis and Policy

	- Irrigated area, groundwater abstractions through private wells, consumptive use - Better monitoring of irrigation demand to aid effective reservoir releases	
Titicaca Lake, Desaguadero River, Poopo Lake (TDP)	- Water quality monitoring (nitrates, phosphates) near major cities - Agricultural water use (abstractions) - Irrigated area mapping	The Stockholm Environment Institute (Latin America branch)
Tympaki	- Detection/monitoring of irrigated areas (potential olive tree counting) - Dynamic monitoring on crop water demand and soil moisture - Monitoring of snow cover/depth in the mountain area	SEVEN-Engineering Consultants Region of Crete

In addition to identifying the top three monitoring data needs and priorities for each lab, discussions also considered which monitoring needs were lower priority. In particular, we sought to identify where data needs raised by some labs were lab-specific, i.e. less relevant to other labs, or where existing systems of data collection were already strong. A common statement from discussions with all labs was that there was little desire for developing a generic toolbox that was not tailored to match the needs or water management challenges in individual specific river basins, nor a toolbox which duplicated existing tools that were already used for monitoring of water use and availability within a lab. These factors, alongside top three monitoring priorities, directly informed the decisions around focus and scope of the Toolbox, which are discussed in detail in the subsequent sections of this report.

3 Prioritisation of cross-cutting monitoring needs and capabilities

Designing the Toolbox required identification of research activities that would be innovative, impactful and transferable, while also being achievable in the context of the expertise, resources, and scope of the TRANSCEND project. As such, the proposed Toolbox and associated research applications is directly aligned to the monitoring gaps described in the previous section and identified by living lab leads and stakeholders.

We considered several criteria to inform and guide the focus of the Toolbox. First, we sought to focus the Toolbox on monitoring gaps that were cross-cutting across TRANSCEND's living labs (i.e. where the same/similar data gap was identified by stakeholders as a key data gap or need in multiple living labs). These cross-cutting needs are shown in *Figure 4*. Second, existing datasets were considered to assess whether living lab needs could already be met through supporting and strengthening use of existing data products. The diverse participants in TRANSCEND – spanning the academic and water management sectors – brought awareness of different existing datasets and their potential uses and this supported the identification of data that could meet living lab needs. Finally, the technical expertise existing within the consortium was considered. This involved targeting research activities to match the competencies included in the consortium, in particular to ensure effective use of the resources available within TRANSCEND to maximise impact and value added on the science, policy and management within and beyond TRANSCEND's living labs. Furthermore, we considered the nature and scope of the TRANSCEND project, specifically the focus on leveraging models and public data to strengthen river basin management and water allocation. This scope meant that monitoring work plans have been explicitly constrained to activities that do not require development of in-situ infrastructure (e.g. new stream gauges, groundwater monitoring wells, etc).

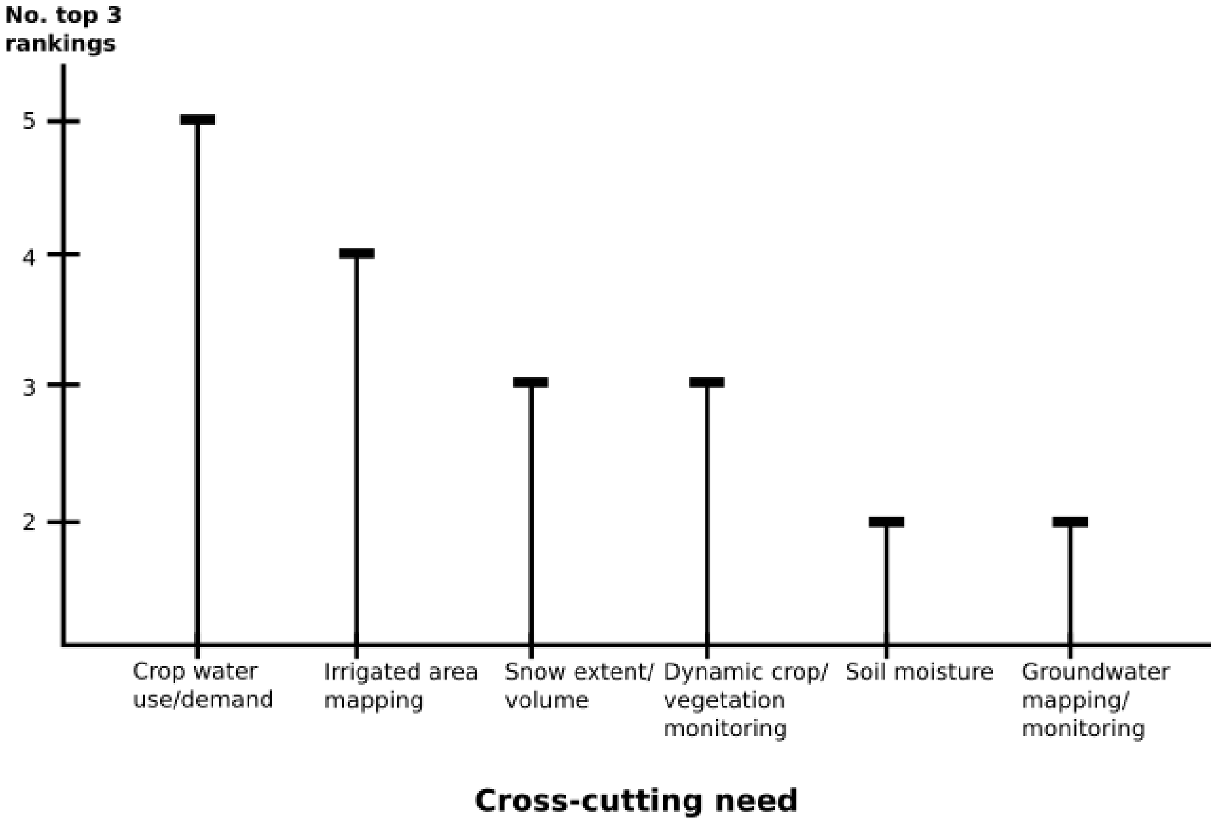

Figure 4 Line chart showing cross cutting needs and the number of basins in which they were ranked as a top three priority. This chart is based on the identified needs shown in Table 1.

On the basis of these criteria, we identified the Toolbox focus as monitoring and mapping of irrigated area dynamics, along with monitoring of water use (either directly through abstractions, or indirectly through crop water-use), especially within the agricultural sector. These data needs are significant monitoring challenges and gaps globally, as discussed in the Monitoring White Paper (Deliverable 4.1) produced in Year 1 of TRANSCEND, which are critical to address given the central role of agriculture as a sector that is both driving and being impacted by water scarcity. Designing research activities around cross-cutting needs for improved data on agricultural land and water use therefore has the potential to not only support collaboration and co-creation across TRANSCEND living labs, but also to support TRANSCEND's goals of generating impact on water management and policy in other water scarce regions globally.

Other common cross-cutting data needs that were identified through our participatory co-identification process were snow cover/depth and dynamic monitoring of in-season vegetation conditions or phenology. However, these were deemed to not be feasible or priorities to address within the constraints of TRANSCEND and project resources. While monitoring of snow depth and snow cover is feasible with EO data (Li et al., 2017; Schneider and Molotch, 2016) these approaches require specialist knowledge of snow hydrology and remote sensing which do not exist within the TRANSCEND consortium. The focus of TRANSCEND on strategic longer-term planning and policy related to water resource allocation as opposed to operational short-term management of water also means that real-time in-season vegetation and water demand monitoring was deemed to be out of scope. Finally, the focus of TRANSCEND is on management of water quantity rather than water quality, and hence monitoring of water quality – while a priority for some labs – was therefore not selected as a focus for the proposed Toolbox.

4 Monitoring Toolbox design and features

As outlined in the previous section, the monitoring Toolbox developed in TRANSCEND focuses on addressing a cross-cutting global need for tools for actionable and scalable monitoring of agricultural land and water use in support of strategic long-term river basin planning. Specifically, the focus will be on leveraging developments in satellite imagery and processing algorithms to provide tools to map spatiotemporal changes in agricultural land use/land cover (LULC), including irrigated areas and crop water consumption/use. The maps will be region-specific, which distinguishes them from existing global LULC mapping products (e.g. the Copernicus Land Monitoring Service or that of Karra et al., 2021) insofar as the mapped LULC categories will be specifically those that are important for a given region (including, where relevant, distinguishing different crop-types) and the accuracy of the maps will be high (> 90%).

In the following sections, we first describe the general methodological features and structure of the proposed Toolbox. We then discuss how the Toolbox will be applied in TRANSCEND living labs as part of WP4, as well as how data generated by the Toolbox will interface with and support other aspects of the project (e.g. WP3 – Modelling). As part of the work plan for WP4, we will conduct science-to-policy pilot applications of the Toolbox in four of the TRANSCEND living labs where agriculture is a significant component of water management planning and where there are currently the largest gaps in effective monitoring of agricultural land and water use: (1) Titicaca Lake, Desaguadero River, Poopo Lake (TDP) living lab in Peru, and Bolivia; (2) Jucar living lab in Spain; (3) Mahanadi living lab in India; and (4) Tympaki living lab in Greece.

For the other living labs in TRANSCEND, and other river basins globally where our consortium are active (e.g. Litani, Duero, Republican, Murray-Darling river basins), we will seek to build capacity amongst local stakeholders and actors to facilitate uptake of the Toolbox within and beyond the timeframe of the TRANSCEND project. In the Orontes and Reno river basins, this work will focus on developing capacity and opportunities to use the Toolbox to support and complement established datasets (Jaafar et al., 2022; Mhanna et al., 2023) and tools (Antolini et al., 2016; ARPAE, 2020) that are already actively being used to monitor agricultural land and water use as part of river basin planning and management. In the Nitra, agricultural land water use is currently not extensive and is not the primary driver of water scarcity challenges. However, expansion of irrigated agriculture elsewhere in central Europe suggests this dynamic could change in the future under climate change, and the improved land use monitoring provided by the toolbox will enable tracking of any future decline in industrial water use and increases in agricultural use. Therefore, building capacity within local partners in the Nitra lab (e.g. SAZP) will be a focus to ensure the Toolbox can support future water management decisions beyond the TRANSCEND project.

4.1 Methodological framework

There is a large and well-established body of literature describing the use of Earth observation data to map LULC (see, for instance, reviews by Hansen and Loveland (2012) and Talukdar et al., 2020). The 2008 decision of the United States Geologic Survey (USGS) and NASA to make the full LANDSAT data archive freely available accelerated growth in science and policy applications of EO data for monitoring dynamics and changes in land use and resulting impacts on the water cycle. Research has also demonstrated the significant value of other optical sensors including MODIS (Ambika et al., 2016) and Sentinel (CiVelek et al., 2023) for land use monitoring, while further studies have explored the potential benefits of satellite radar datasets especially in regions with significant or frequent cloud cover contamination of optical imagery (The European Space Agency, 2021).

Within the TRANSCEND consortium, there is significant expertise in LULC mapping, in particular related to changes in agricultural land and water management practices and decision-making. Examples of recent studies and methodological advances in EO-based agricultural mapping and its application for policy assessment by consortium members include Higginbottom et al. (2023), Sujud et al. (2021), Jaafar et al. (2022), and Sapino et al. (2024). The Toolbox will leverage this consortium expertise, along with recent advances in both satellite image composition (e.g. Brandt et al., 2020; K. Wang et al., 2022) and processing methods (e.g. S. Wang et al., 2022), to develop actionable tools that can be used to help river basin agencies in TRANSCEND living labs and beyond to plug gaps in monitoring of agricultural land and water use and facilitate transformational adaptation to water scarcity.

Figure 5 illustrates the generalised workflow that will be adopted for EO-based mapping of agricultural land and water use within the Toolbox. Below, we briefly outline the four key steps in the Toolbox workflow with subsequent sections of this deliverable providing details of specific research questions, expected outputs, and timelines for applications in selected TRANSCEND living labs.

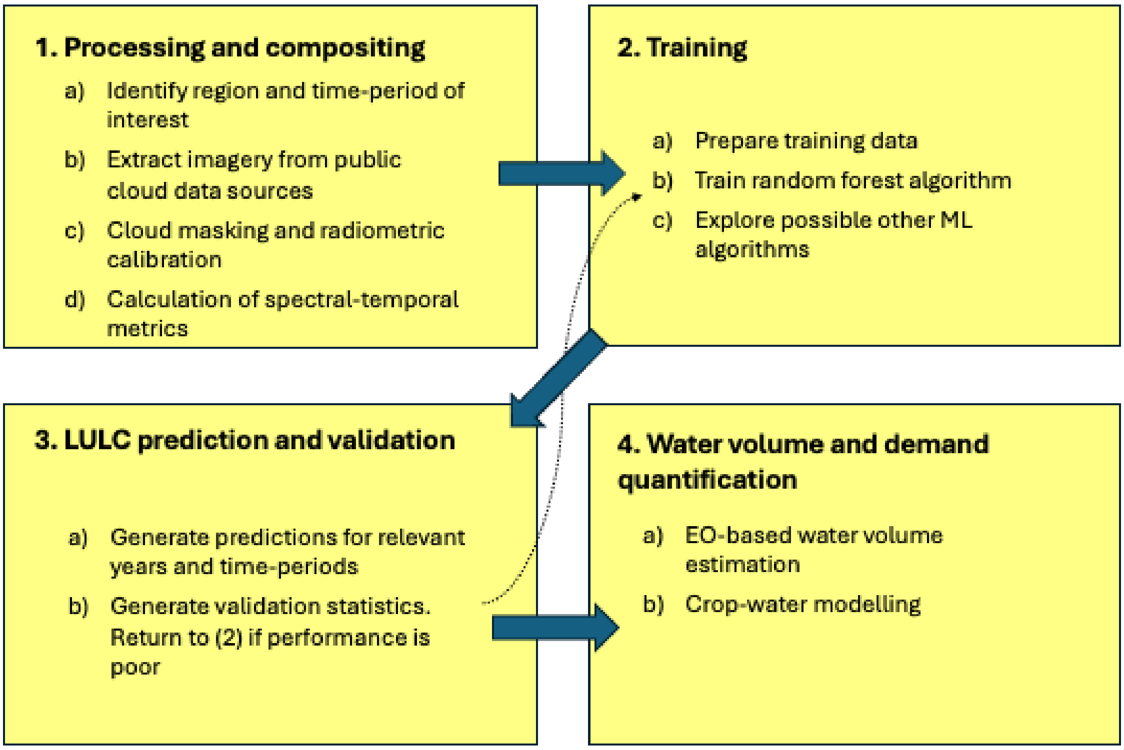

Figure 5 Generalized workflow diagram showing the four key steps, with sub-steps shown. The four key steps, and all sub-steps, are described in detail in the main body of the Deliverable.

4.1.1 Processing and compositing of EO data

The first step in the Toolbox workflow is extracting metrics from raw satellite imagery that can be used as inputs to data-driven machine learning models of agricultural land use and irrigation status. Imagery covering the region and time period of interest will be accessed from relevant public cloud data sources, which in most cases will be Google Earth Engine (GEE). All extracted imagery will be pre-processed in cloud environments to mask pixels with significant cloud cover or cloud shadow contamination. Where radiometric calibration has not been pre-performed, relevant calibration methods will also be applied at this stage.

After extraction and initial quality control has been performed on all EO data inputs, the Toolbox will then process imagery into spectral-temporal metrics (STMs). STMs composite available satellite imagery into a series of descriptive statistics to provide spatially gap-free information about the variations of different EO variables in a given region and period of interest. STMs provide a means of reducing the large feature space created by ever-increasing quantities and complexity of satellite imagery, and are robust to data noise, uncertainty, and sparse or irregular observations (Frantz et al., 2023). STMs have been shown to be reliable tools for LULC mapping, including for monitoring changes in cropping practices and irrigated areas (Deines et al., 2017; Higginbottom et al., 2023; Wang et al., 2020b).

The specific satellite sensors and STMs that will be considered and generated during this first phase of the Toolbox workflow will vary depending on the region, time period, and agricultural system(s) being studied, and will be informed by expert scientific and local agronomic knowledge. Common STMs used for LULC mapping in agricultural regions include intra-seasonal percentiles of vegetation indices such as Normalized Difference Vegetation Index (NDVI) or the Enhanced Vegetation Index (EVI), along with STMs generated for raw spectral bands and non-spectral variables (e.g. backscatter metrics) recorded by radar satellites.

4.1.2 Training of machine learning models

After raw satellite imagery has been processed and composited into a set of predictor STMs, the Toolbox will then train state-of-the-art machine learning algorithms to provide scalable models that can be used to relate EO STMs to agricultural land and water use (specifically crop type and irrigation status) across a specific region or river basin.

For the Toolbox, random forest (RF) classifiers will be the primary algorithm employed for predicting agricultural land and water use. RF classifiers have been shown to be reliable tools for estimating land use and land cover from satellite imagery (Sheykhmousa et al., 2020; Tariq et al., 2023; Wang et al., 2020b), and their high level of interpretability overcomes some of the challenges associated with more 'black box' machine learning algorithms such as neural networks (Bowden et al., 2023). However, as part of development and applications of the Toolbox, we will also test and benchmark the performance of alternative model algorithms. In particular, we will consider the potential value of emerging deep learning algorithms for mapping agricultural land and water use dynamics, especially in regions with either complex agricultural land use dynamics or more limited training data.

This multi-algorithm approach applied in the Monitoring workstream is consistent with TRANSCEND's commitment to multi-model approaches within the Modelling workstream, and we will explicitly quantify uncertainty associated with all land use maps and datasets produced by the Toolbox. Training of RF and other algorithms will leverage geolocated data on known LULC/irrigation status with the target study region.

These data will be collected either by living lab partners/stakeholders, digitized from very high-resolution satellite imagery (e.g. Google Earth), or sourced from relevant secondary datasets.

4.1.3 LULC prediction and validation

After machine learning classifiers have been trained, these model classifiers will then be used to generate spatially continuous maps of agricultural land use and irrigation status across the region or basin of interest. Maps will be generated for each relevant cropping season and across all historic years where sufficient satellite imagery is available for the specific target region or basin. Trained model algorithms will also be capable of ingesting new satellite imagery to generate maps of agricultural land use and irrigation status for future years, helping to address key needs of river basin agencies for monitoring future agricultural land use change and responses to water policies.

Before agricultural LULC maps are considered reliable and accurate for use as part of river basin planning, an important final step of the Toolbox will be to independently verify the accuracy of land use and irrigation maps ("validation"). The Toolbox will generate accuracy statistics for maps by comparing the land use and/or irrigation status from the machine learning classifier against geolocated ground-truth observations ("the validation dataset") that are unique and independent to observations used in model training. Validation within the Toolbox will follow established statistical guidelines and best practices (e.g. Olofsson et al., 2014) to ensure end users have transparent knowledge of map accuracy and uncertainty before data are used in water management policy or planning.

4.1.4 Water use and demand quantification

The primary output from the Toolbox is geospatial intelligence about where land is being used for agriculture and whether that land is being irrigated. However, TRANSCEND's living lab stakeholders and wider water policy communities have also highlighted the need to monitor how much water is being used by irrigated and rainfed agriculture. This information can support in-depth volumetric water accounting as part of river basin planning. To this end, the Toolbox will also provide functionality to integrate EO-derived agricultural land use and irrigation status maps with other EO and non-EO data and models including for:

a) Contemporary water accounting

The main workflow of the Toolbox described above focuses on mapping of agricultural land use dynamics, including the water management status (irrigated vs non-irrigated) of croplands. To further support accounting of agricultural water use, we will develop functionality to combine these LULC type maps with other existing satellite-derived data products to generate actionable information about rates of irrigation water consumption and use across agricultural landscapes.

Our approach will be broadly informed by established water accounting procedures, including the FAO Water Accounting+ framework (Karimi et al., 2013). Specifically, the Toolbox will enable users to link agricultural LULC maps with satellite-derived estimates of crop water consumption (i.e. actual evapotranspiration) from models developed by consortium partners at American University of Beirut (Jaafar et al., 2022) and datasets/tools provided by the wider research community (Elnashar et al., 2021; Garrido-Rubio et al., 2020). Through this, the Toolbox will provide estimates of the spatio-temporal dynamics of volumetric crop water use that provides a holistic understanding of agricultural water consumption within river basins or regions of interests.

Combining estimates of agricultural water consumption with other data sources (e.g. precipitation and soil moisture datasets, soil characteristics), the Toolbox will also provide functionality to support quantification of rates of abstracted or applied irrigation water – recognising that this is often the primary metric on which water rights are managed and allocated globally (Foster et al., 2020). Our approach to quantifying applied or abstracted irrigation water use will follow the broad methods outlined in Zipper et al. (2024) and Foster et al. (2019). Specifically, ET records for mapped irrigated agricultural land areas will be combined with meteorological (precipitation), vegetation (to define growing periods), and soil characteristics data to develop water balance models that quantify levels of expected applied/abstracted water. As part of this work, we will explore the potential added value of incorporating satellite-derived soil moisture information into water balance modelling alongside ET data, building off recent efforts to exploit satellite soil moisture for irrigation estimation (Massari et al., 2021; Zappa et al., 2024). In line with TRANSCEND key principles, we will seek to explicitly quantify and transparently acknowledge uncertainties, paying specific attention to impacts of input data choices and alternative model structures that can be used to estimate applied/abstracted rates of irrigation based on satellite data.

b) Future water demand projection

While satellite remote sensing can support quantification of volumetric agricultural water use for historic and contemporary time periods, water managers and agencies also need to plan for how agricultural water needs will evolve in the future which cannot be observed in satellite data alone. In particular, understanding how agricultural water needs will be impacted by changes in climate change or on-farm management practices/systems (e.g. irrigation technology choices) is a key need to support robust long-term management and allocation of water in agriculturally intensive basins.

To address this need, the Toolbox will integrate satellite-based mapping of agricultural land and water use with crop-water modelling tools that can be used to project and explore scenarios for future changes in water use/needs of agriculture. Specifically, we will leverage open-source crop-water modelling tools developed by the UoM team within the consortium (AquaCrop-OSPy – Kelly and Foster, 2021; Foster et al., 2017) and the wider research community (pyFAO56 – Thorp et al., 2024) for this goal. Where resources and required technical support are available, we will also seek to enable integration with other crop models developed beyond the consortium (e.g. DSSAT – Jones et al., 2003) to support TRANSCEND's efforts to consider multi-modelling approaches as part of TAP design.

We will build upon existing functionality to automate runs of crop-water models (e.g. AquaPlan – www.tinyurl.com/aquaplan) and provide simplified interfaces to key public domain input data sources (e.g. weather/climate conditions, soil characteristics). At the same time, the Toolbox will be designed to enable end users to customise model parameters and input sources to local contexts (e.g. to replace public regional or global data inputs with locally collected data products). Efforts will also be made to explicitly quantify uncertainty in future water needs projections, in line with the approaches and principles outlined above for contemporary volumetric water accounting aspects of the Toolbox.

5 Pilot applications in Living Labs

The general workflow and principles described above will be applied in each of the living labs for which a new LULC dataset will be generated (TDP, Jucar, Mahanadi, Tympaki). In addition, each lab has its own specific objectives, detailed workflow, and timeline, which are outlined below. It is important to also note that monitoring datasets developed through these pilot applications will also be important inputs to some of the planned modelling work as part of TRANSCEND WP3. Further details on use of monitoring data for modelling are provided in TRANSCEND Deliverable 3.2.

5.1 Titicaca Lake, Desaguadero River, Poopo Lake (TDP)Lab

In the TDP living lab, there is substantial concern around the health of the basin's surface water systems. There was a complete drying of Lake Poopo in 2015 and, in recent years, historically low water levels have been observed in Lake Titicaca, both events with significant environmental and human costs. These surface water declines have been associated with expansion of agriculture – both relating to the boom in quinoa that started in the 1990s and has accelerated since 2012 (Alandia et al., 2020) in addition to growth in more water intensive crops such as alfalfa and potatoes – and climate variability (Lima-Quispe et al., 2021; Torres-Batlló et al., 2020). There is further concern around possible changes in the basin's upland wetland areas, known as bofedales, which a large and vulnerable population of primarily indigenous farmers are dependent on for llamoid grazing. Additionally with more frequent and severe drought events, farmers are increasing irrigation using more infrastructure to divert from rivers which make more vulnerable Poopo and Titicaca lakes due to reduction of streamflow in recharge in more critical season from August to October.

The main objective of the Toolbox pilot in TDP is to generate improved intelligence about how agricultural land and water use is changing within the basin, and what impacts these changes have had on the hydrology, freshwater ecosystems, and water sustainability in the basin. Prior studies in the basin (e.g. Lima-Quispe et al., 2021; Torres-Batlló et al., 2020) have relied upon land use maps drawn from either global data products (e.g. ESA Land Cover) which often have variable performance at local scales and do not disaggregate land into specific local crop types, or have used land cover surveys from national agencies that are only conducted for specific snapshots in time and do not provide consistent spatially explicit data on land cover dynamics.

Our pilot application of the Toolbox will address these issues by producing long-term time series of annual agricultural land dynamics, disaggregated by crop type and growing season (rainy and dry), over at least the period of hydrologic change and potential agricultural expansion (early 2000s to present, extending further back in time if sufficient imagery is available). Specifically, working with local partners in the consortium at Stockholm Environment Institute (SEI) Latin America, we have defined two key data outputs from the pilot: the first a map of agricultural vs non-agricultural land, and the second a map of irrigated vs non-irrigated land. Initially maps will be developed as non-crop specific (i.e. a single 'crop' category), with later versions refining maps to breakdown agricultural land into key crop categories (e.g. quinoa, potatoes, alfalfa, dry beans, vegetables etc). Data products will cover the same time-period and will highlight important changes that influence agricultural land and water use dynamics within the TDP lab.

To support the pilot application of the Toolbox, we will leverage three sources of data for training and validation. The first comes from previously completed LULC mapping undertaken by the Peruvian and Bolivian governments, with the former corresponding to the year 2015 and the latter to 2010. These data are maps showing agricultural and non-agricultural land, with some additional breakdown into broad agricultural classes in the Bolivian case. Field data were collected by both governments to support production of these maps, and these raw input data are currently being requested by stakeholders who have good connections to relevant government ministries and local agencies. The second class of available data come from other, previous research projects in the area: the Veizaga study (Agua Sustentable local NGO) and the Global Environment Facility study (GIRH TDPS project of complementary studies on water demand), each of which gathered information on irrigation and cropping patterns, albeit both in limited sub-regions of the basin and/or with limited accuracy. The third class of available data is a proposed field campaign to obtain labelled crop-type data, with samples to be gathered in the rainy season of 2024 and the dry season of 2025. These data will support disaggregation of land into different crop classes. Together, these datasets will support the mapping and enable rigorous and robust conclusions to be drawn.

Impacts of agricultural land and water use changes on hydrology in the TDP lab will be assessed by linking maps of land cover changes with monitoring data on the extent and conditions of key features of the freshwater environment. Specifically, we will seek to assess connections of agricultural land and water use dynamics with: (a) downstream hydrological fluxes and conditions, in particular ecological flows in the Desaguadero River and areal extent of the sensitive downstream Lake Poopo; (b) water levels and potentially water quality status of the upstream Lake Titicaca system, which is also anecdotally being impacted by surrounding agricultural land. Where needed, additional EO imagery and products will be leveraged to explore these hydrological fluxes, such as the use of Landsat and/or Sentinel data to map lake extents, Landsat data to observe possible eutrophication events in the lakes, and SWOT data to observe changes in river flows. These data will complement in-situ measurements available through local partnerships.

The planned timeline for research activities in the TDP basin is as follows:

1. **May – July 2024**: Processing and quality control of EO imagery
2. **August – September 2024**: Training of an initial cropland classifier model; Collection of field data on crop types for dry growing season (confirmation of field data collection pending).
3. **October – December 2024**: Collection of field data on crop types and irrigation status for rainy growing season; Refinement of cropland classifier.
4. **January – May 2025**: Extension of maps to include of crop and irrigation status specific classifications.
5. **June – October 2025**: Application of maps to assess hydrologic impacts of agriculture in TDP basin
6. **November 2025 – March 2026**: Write-up and consolidation of final results; Training and capacity development amongst local agencies (e.g. ALT).

Immediate value will emerge from the workflows and data produced during this project. In addition to this, potential end users in local water governance will be identified early in the research timeline, to ensure that final products can be adapted to best serve these users' needs and to enable the training and/or capacity building identified in step 6. Every effort will be taken to ensure that the mapping tools and workflows can be used beyond the March 2026 end of this research pilot.

5.2 Jucar Living Lab

In the Jucar living lab, there is substantial concern around the basin's groundwater systems. The largest aquifer in the basin is the Mancha Oriental, in the south, where substantial agricultural activity occurs. The Mancha has been the focus of sustained study, considering the impacts of climate variability (Dountcheva et al., 2020), land-use changes (Pulido-Velazquez et al., 2015), and abstraction volumes (Sanz et al., 2011) on the groundwater resource of that aquifer. In the north is the Requena Utiel aquifer, which is relatively under-studied despite being designated as 'overexploited' by the Júcar River Basin Authority in 2016 (Uribe-Asarta et al., 2023) and supporting a productive and important agricultural area. "Overexploited" status has led to imposition of various restrictions such as irrigation limits within certain sub-areas of the aquifer, although there is some concern that compliance with these limits may not be absolute. Common stresses across both aquifers are recent droughts and an expansion of almond growth led by demand-supply market forces. Regulatory and land-use changes are therefore both having significant impacts on groundwater use in the Jucar basin.

Deliverable 4.4 – Monitoring Toolbox prototype

The main objective of the Toolbox pilot in the Jucar is to improve understanding of the interplay between regulatory, land-use and water-use changes in the under-studied Requena Utiel Aquifer system. This knowledge will be used to holistically explore the impacts of the 'overexploited' designation. First, changes in land and water use pre-and-post 2016 in the Requena Utiel will be compared with climate variability to explore the key drivers of changing practice, both over time and within the aquifer (e.g. within and outside 'official' irrigated designations). Second, there will be comparative analysis with the Mancha Oriental which is operating under a very different regulatory framework. Existing land-use mapping is not sufficient to achieve these objectives. The best available satellite product (SIOSE) identifies different crop types but is updated intermittently, with multi-year gaps, and does not distinguish between irrigated and non-irrigated land. Another database, SIGPAC, is based on farmer declarations, leading to issues around completeness and accuracy. Without improved land-use data, it will be difficult to untangle to complex policy/landuse/water use dynamics that are occurring in the Requena Utiel aquifer and the Jucar basin more widely.

The Toolbox pilot will address these data gaps by generating accurate maps of land use, including irrigated and non-irrigated status, in the Requena Utiel area. Specifically, two classes of map will be generated. The first will be an irrigated/non-irrigated classifier, which will cover the period 2013-present (Landsat 8 and Sentinel 1/2 era) and possibly further back in time, dependent on need. This class of map will be used to explore the extent to which irrigation limits imposed in 2016 have changed land and water practices of farmers, and the level of compliance with regulatory limits around irrigated areas. It will also be used to explore the relative importance of regulatory changes, market forces and climate variability on irrigation dynamics. The second class of map will include specific crop types, and this map will be used to support quantification of crop water use through integration with evapotranspiration data and crop modelling tools embedded within the Toolbox. Both maps will be produced at annual temporal resolution following the general procedures outlined earlier in this report.

To support the pilot application, we will leverage existing datasets for training and validation. The SIGPAC data will be used to train the irrigated vs non-irrigated classifier, with steps taken to incorporate the possible data errors in that dataset. An additional dataset collected by local partners two years ago will be used as validation: these data will be higher quality and will therefore be most appropriate for this purpose. There is also the possibility of collection of addition data during the project's lifetime through targeted field surveys, in particular where existing groundtruth data is insufficient (e.g. gaps in emerging crop types such as almonds, or in labels for irrigated/non-irrigated land). The SIOSE data, which do not contain irrigation labels, will be used primarily as training data for the crop-type mapping.

The research activities will be divided into five main phases, outlined below.

- **Phase 1 (July 2024 – November 2024:** Preparation and quality assurance of data: collecting data, preliminary analysis of available satellite data
- **Phase 2 (Dec 2024 – June 2025):** Training and development of classifier for predicting irrigated areas and crop types for Requena-Utiel; Analysis of policy impacts and drivers of land use dynamics
- **Phase 3 (July 2025 – December 2025):** Estimation of water use/abstraction through integration of land use dataset with crop-use modelling/ET datasets; Analysis against observed/reported abstraction records
- **Phase 4 (January 2026 – April 2026):** Comparative analysis between Requena-Utiel and Mancha Oriental aquifers

- **Phase 5 (May 2026 – August 2026):** Write up and consolidation of outputs; Training and capacity development amongst local agencies

There will be continued collaboration between UPV (acting as technical science lead) and UoM (providing technical support) which will take three forms: monthly webinars across all living labs on monitoring LULC, remote interactions between Matt/Tim and the UPV team, and in-person visits. There will be continued work to interact with local stakeholders to tailor products and workflows to be most application-ready, with emphasis on taking steps that ensure the products and/or workflows developed have usability beyond the duration of the TRANSCEND project.

5.3 Mahanadi Living Lab

In the Mahanadi basin, there is conflict around water management relating to the allocation and sharing of water between the upstream state of Chhattisgarh and the downstream state of Odisha (Ministry of Water Resources, River Development and Ganga Rejuvenation, 2023; Prava, 2021). On average, the Mahanadi basin is relatively water 'rich' with long-term aggregated basin supply exceeding demands. However, the Mahanadi experiences large variability in both inter-annual and intra-annual flows that are a source of conflict between the two states and between different water-dependent sectors (Kumar and Bassi, 2021). Water releases downstream to Odisha, where the Mahanadi's flows are essential to support both agriculture (especially paddy production) and growing urban centres (e.g. Bhubaneshwar), are controlled by the Hirakud reservoir, the 8^{th} largest dam in India by storage which was constructed and opened post-independence in 1957.

Over recent years, there has been growing concern about management of the Hirakud dam and its implications for downstream water risks in Odisha. Upstream expansion of water-intensive thermal power generation, mining and associated deforestation, and construction of new barrages and dams, coupled with increasing hydrological variability due to climate change, have been cited as impacting availability of water both within Chhattisgarh and downstream into the Hirakud reservoir (Chhattisgarh State Center for Climate Change, Raipur, 2019; Dsouza et al., 2017; Ratha, 2019). More volatile or even reduced flows into the Hirakud are particularly significant as they may affect the ability to meet agricultural water needs, especially during the dry season, in downstream Odisha. Increasing seasonal scarcity could, in turn, bring farmers into conflict with industrial water users in Odisha (Bassi, 2023).

Alongside these pressures, the Hirakud has also experienced a continual decline in storage capacity over time due to sedimentation. Current storage capacity is estimated to be as much as 30% lower than designed (Wetlands International South Asia and Chilika Development Authority, 2015). This has implications not just for the reservoir's ability to act as a buffer against periods of lower streamflow, but also for downstream flood protection. Farmers in Odisha have complained, for example, of being highly exposed to the damaging effects of floods, with blame in part being attributed to reduced storage capacity and inadequate coordination of reservoir operation between the two states. A further side effect of sediment trapping in the Hirakud and other reservoirs is reduced supply of sediment to the Mahanadi delta in Odisha (Bastia and Equeenuddin, 2016). Reduced sediment supply to the Delta has been cited as a driver of erosion, potentially exacerbating vulnerability of agriculture and other sectors to seasonal cyclones and flooding (Darby et al., 2020; Duncan et al., 2017). Given subsidence is an issue in similar deltaic systems facing restricted sediment supply, it is anticipated that subsidence may be further exacerbating the hazard in the Mahanadi delta (Dandekar and Thakkar, 2014).

Deliverable 4.4 – Monitoring Toolbox prototype
To support future planning of inter-state water allocation, the Toolbox pilot for the Mahanadi living lab will focus on assessing historic changes in agricultural scarcity and flood vulnerability in the downstream area of the basin. Specifically, we will seek to develop annual maps of both the downstream extent of cropland vs land fallowing (during the dry season) and flood inundation (during the monsoon season). Analysis will leverage a combination of medium resolution imagery with long-term time series (e.g. MODIS) together with more recent higher resolution sensors (e.g. Sentinel 1 and 2), which have been shown to be effective at monitoring both flood inundation (Bonafilia et al., 2020; Tellman et al., 2021) and land use dynamics in smallholder farming systems (Gumma et al., 2022). We will assess how dynamics of water scarcity and flood vulnerability have evolved over time, relating this to hydroclimatic variability in the basin, reservoir operations and capacity changes, and other changes (e.g. land and water use upstream) within the basin.

Training and validation of maps are currently anticipated to rely primarily on visual inspection of very high-resolution satellite imagery, sourced through Google Earth and public archives of microsatellite providers (e.g. Planet NICFI composites) combined with generation of validation labels through interpretation of satellite image time series records. While such imagery is expected to be sufficient for monitoring land fallowing, ability to support training and validation of flood inundation maps is currently unclear. Validation of flood maps can be strongly influenced by cloud-induced gaps in optical imagery around times of flood inundation and where there are multiple unique causes of flooding (e.g. coastal vs fluvial) with distinct signatures in EO imagery (Thomas et al., 2023). As a result, production of flood inundation maps will be conditional on first identifying if there is sufficient observational data to support map training and validation, considering also the time, expertise, and resource constraints for TRANSCEND's work in the Mahanadi living lab. In the event of insufficient data, work will focus solely on monitoring cropland and fallow dynamics in key areas of the basin (e.g. Hirakud command area).

The research activities for the Toolbox pilot in the Mahanadi will be divided into several main areas, outlined below.

- **July 2024 – December 2024:** Sourcing, preparation, and quality assurance of training and validation data; Decision-making about scope of mapping (fallow/inundation mapping or both)
- **January 2025 – December 2025:** Training and development of classifier for predicting cropland and land fallowing dynamics; Analysis of dynamics and drivers of observed cropland/fallowing.
- **September 2025 – March 2026 (subject to data availability):** Training and development of classifier for predicting flood inundation; Analysis of dynamics and drivers of inundation, including joint analysis with cropland maps.
- **May 2026 – August 2026:** Write up and consolidation of outputs; Training and capacity development amongst local agencies

The proposed pilot research will be delivered and led primarily by The University of Manchester (UoM). UoM will lead technical design and application of the Toolbox for the pilot. TRANSCEND partner the Institute for Resource Analysis and Policy (IRAP) in India will support work, including through helping to identify and source potential datasets for map evaluation and brokering connections with local stakeholders (e.g. state governments in Odisha and Chhattisgarh). Furthermore, the UoM team will also engage with other relevant local partners and existing collaborators in the region, in particular organisations such as the International Rice Research Institute (IRRI) and International Maize and Wheat Improvement Centre (CIMMYT) who are key agencies engaged in supporting agricultural intensification and monitoring in Odisha and eastern India.

5.4 Tympaki Living Lab

In the Tympaki living lab, there is substantial concern regarding water availability for irrigation and groundwater over-abstraction. The Tympaki area encompasses a basin of about 265 km^2, and comprises according to the WFD typology, of 7 river water bodies, and 6 groundwater bodies. The main land uses are agriculture (about 40% across the whole basin, and 88% in the central plain of Tympaki) and pasture (about 48.5%). About 40-50% of the agricultural land is irrigated. The main cultivated crops are olive groves, and greenhouses with fruits and vegetables. There are also some fruit trees. The chemical status of some of the groundwater bodies is poor. More specifically, 1 of the 6 groundwater bodies (namely EL1300082) is in poor chemical status, with significant pressures of over-abstraction for irrigation purposes, which has led to salinization and seawater intrusion, quantitative and qualitative deterioration. The other groundwater bodies are still characterized in good status, yet nitrate levels are found to be locally higher than the Maximum Acceptable Limits in different monitoring stations in 2 of these GWBs namely in EL1300081, EL1300086) reaching up to 60 mg/l in some locations, while local seawater intrusion is observed in the GWB EL1300250.

Rainfall in the Tympaki area is very low, less than 500 mm per year. The resultant moisture index Ih of 0.532, is in turn very low, bordering semi-arid conditions. Despite these unfavorable climatic conditions, the basin is the focus of intense agricultural activity. In the central plain of Tympaki about 7.5 mio m3 are annually abstracted from 3 groundwater bodies (EL1300081, EL1300082, EL1300086-part of) for irrigation purposes, to irrigate about 40 km2. Another 3 mio m3 are annually supplied from the Faneromeni Reservoir to the central plain of Tympaki, however unmet demands still prevail. The overexploitation of groundwater has reduced water availability, while the uncontrolled pumping and use also create tensions amongst the users. Soil degradation and salinisation are also important issues of the wider area, while desertification in becoming an issue as well. Simulation of seawater intrusion, has established that at the southern end of the coast, the toe of the saltwater intrusion front lies 550 to 600 m inland from the coastline.

The main objective of the Toolbox pilot in the Tympaki is to detect the irrigated and non-irrigated olive growing farms using remote sensing techniques. Currently, water abstraction and use permits are issued by the Water Directorate of the Decentralized Administration of Crete (WDC) to interested water users upon application. These beneficiaries can be either public stakeholders (Municipal Water Supply and Sewerage Companies - DEYA, Local Land Reclamation Organisation -TOEV, Municipalities) or private individuals. Each license specifies the annual quantity that can be used by the user, determined according to the use and are subject to a maximum limit. Furthermore, the farmers declare the type of crops that they cultivate in their farm, along with the irrigation method (in the case of irrigated farms) to the OPEKEPE (the Greek Payment Authority of Common Agricultural Policy Aid Schemes) in order to receive subsidies is applicable. Irrigating olive trees increases the production and hence the income of the farmers. Although some farmers may declare that they are not irrigating their olive trees, the reality may be different. Knowing exactly the irrigated olive tree areas will support the proper estimation of irrigation water use and related groundwater abstraction which is the main pressure in the Tympaki basin. This will reduce the uncertainty in the water balance calculations in the basin, and will allow for a better water allocation scheme.

Our pilot application of the Toolbox will address these issues by producing maps of irrigated vs. non-irrigated areas using earth observation data. This improved knowledge of the irrigated areas will in turn support a better estimation of the irrigation water use in Tympaki basin, and will further support the detection of illegal water use (i.e. by observing irrigation in farms that have been declared as rainfed). Understanding how irrigated areas change over time is also vital to effectively manage the water resources, currently under pressure, and also plan for future agricultural practices and policies to ensure sustainable water use and prevent environmental degradation (trend analysis if feasible).

To support the pilot application, we will leverage the following datasets for training and validation:

- Sentinel-2: High-resolution multispectral imagery with bands useful for vegetation analysis (e.g., NDVI).
- Landsat 8: Multispectral imagery for analysis and vegetation indices.
- Ancillary Data:

- Weather Data: Precipitation, temperature, and humidity data.
- Soil Moisture Data: Available from in-situ sensors.
- Topographical Data: Elevation, slope (from DEM)
- Field Survey Data: Ground truth data collected from field survey indicating irrigated vs. non-irrigated plots
- Agricultural Statistics: Historical data on olive production and irrigation practices.

The methodology to be applied is summarised as follows: multi-temporal Sentinel 2 and Landsat imagery will be processed to obtain specific vegetation indices such as RVI (ratio vegetation index) and NDVI (Normalized Difference Vegetation Index) which are indicative of active irrigation, temperature indices such LST (Land Surface Temperature) and BT (Brightness Temperature) to assess temperature, and drought indices such as the VCI (Vegetation Condition Index), the TCI (Temperature Condition Index), and VHI (Vegetation Health Index) which are basically based on the NDVI and LST. Ancillary data could also be used to enhance the features, but also for validation purposes (e.g. soil moisture data combined with weather data can indicate if irrigation is applied). Field survey data will be used to define the ground truth information that will be needed in order to train a classification model to distinguish the irrigated vs. non-irrigated areas. Common practices of machine learning will be utilized during the training in order to ensure the model robustness and generalization. Data will be split to training and test datasets, and cross validation on the training data will be used to tune the hyperparameters. The model's output will be the classification of a pixel as irrigated or non-irrigated. A further validation and refinement of the results will be conducted to ensure the accuracy of the results (e.g. looking into spatial relationships/ checking if adjacent pixels within the same plot are under the same class). The results of the classifications can be transposed over the fields' shapefiles to obtain a final information of the irrigated vs. non-irrigated fields and relevant statistics. As a final step, for operationalization purposes, training will be provided to the Region of Crete and/or other competent stakeholders to use and update the application in the future.

The following end users of the dataset have been identified:

- The Region of Crete – Directorate of Environment and Spatial Planning – Department of Hydroeconomy: they are responsible for the design and implementation of measures, the decisions on water use restrictions, pollution monitoring and environmental protection (e.g. ecological flows, good water quality status, etc.). A better estimation of irrigated areas will lead to a better estimation of the irrigation water demand facilitating them to identify unsustainable conditions (i.e. where demand exceeds availability) and plan for the appropriate measures and/or restrictions.

- The Region of Crete - Directorate of Agricultural economy & Veterinary: they are responsible for the development of the Regional Agricultural Development Plan (RADP). An enhanced knowledge of the irrigated areas and the capacity for automated calculations via EO data can support updating of the relevant aspects of the RADP.

- The Water Directorate of Crete Decentralized Administration (WDC): their main role is the development and implementation of the WFD River Basin Management Plans (RBMPs) and Programme of Measures. They are also responsible for monitoring of the water resources and data collection, for issuing water use licenses (the license describes the terms and conditions to use the water, the specific amount/volume of water to be abstracted and used within specific time, usually 10 yrs), and for regulation enforcement. A better estimation of irrigated areas will lead to a better estimation of the irrigation water demand, which when compared against water availability will facilitating them to identify unsustainable conditions, relevant caps for the water use licences, any possible illegal abstraction activity, and plan for the appropriate measures and/or restrictions.

- Local Land Reclamation Organization - TOEV of Zone A' of Messara: they are responsible to operate the water supply and distribution system for local farmers (i.e. provision of irrigation water to the farmers), including the maintenance of the pipeline network. They are also responsible to collect the water fees from the connected agricultural users and monitoring of the installed water meters. A thorough knowledge of the irrigated areas, and especially a detailed knowledge of the number of irrigated olives trees, is essential for them in order to better plan the distribution of the irrigation water according to the farmers' actual needs.

- The Hellenic Survey of Geology & Mineral Exploration (EAGME): they are responsible for the groundwater monitoring system, and also conduct research for water development. Better data on irrigated areas can support better estimations of groundwater abstraction needs and thus a better evaluation of the groundwater system.

- The Special Secretariat for Water (SSW) of the Ministry of Environment and Energy: they are the National focal point for the implementation of the Water Framework Directive and related EU legislation (i.e. Groundwater Directive, Nitrates Directive , etc.), responsible for the development and implementation of the National Programs for the Protection and Management of Water Resources of the country, and the coordination of agencies and national bodies regarding the protection and management of water resources. They can evaluate the added value of automated estimations of the irrigated areas via EO data and suggest its replication in other areas in Greece with similar needs.

- The Hellenic Agricultural Organization (ELGO Dimitra) - Institute of Olive Tree, Subtropical Crops and Viticulture, the Foundation for Research and Technology-Hellas (FORTH) - Institute for Mediterranean Studies, the Hellenic Mediterranean University- Department of Agriculture, the Technical University of Crete: they are all involved in research around water resources management and irrigation, so these data will be also valuable for applied research purposes

The planned timeline for research activities in the Tympaki basin is as follows:

- **Phase 1:** Planning and Data Collection (June 2024 – October 2024): Collect satellite imagery and ancillary data, conduct field surveys for ground truth data, quality assurance

- **Phase 2:** Preprocessing and Feature Extraction (November 2024 – December 2024): Preprocess satellite imagery (cloud masking, compositing), extract relevant features (vegetation indices, texture features).

- **Phase 3:** Model Development, Validation and Testing (January 2025 – June 2025): Develop and train machine learning model, perform hyperparameter tuning and model selection. Validate models using spatial and temporal cross-validation, refine models based on validation results.
- **Phase 4:** Operationalization (July 2025 – November 2025): Estimation of water use/abstraction through integration of the new maps/datasets in the WEAP model, analysis against observed/reported abstraction records
- **Phase 5:** Deployment and Training (December 2025 – March 2026): Write up and consolidation of outputs; Training and capacity development amongst local stakeholders

The proposed pilot research will be delivered and implemented jointly by TRANSCEND consortium members at SEVEN, Region of Crete and University of Manchester (UoM). SEVEN will lead the technical design and application of the Toolbox for the pilot. The Region of Crete will support the work through provision of field survey data for training and validation, along with leading engagements with local stakeholders engaged in monitoring and management of agricultural water use in the Tympaki system. The UoM will provide high-level ad-hoc technical expertise where necessary, as well as helping to integrate and share learning with work on irrigated area mapping in other TRANSCEND labs (especially the TDP lab in Latin America and Jucar lab in Spain).

6 Embedding the Toolbox in river basin planning

TRANSCEND's central goal is developing actionable science that has transformational impact on how water is allocated and managed in water-scarce regions globally. As already highlighted, strengthening monitoring of agricultural land and water use is essential to achieve this goal given that agriculture is commonly the sector that is the largest driver of, and has greatest exposure to, water scarcity. However, technical advances in monitoring will only contribute to real-world changes in management and policy if the tools are tailored to needs of local water planners and decision-makers, and if the design of tools allows for them to be easily and readily applied within resource- and time -constrained agencies such as river basin authorities, governmental environment agencies, and multi-lateral planning organisations. To this end, the development and piloting of the Toolbox for monitoring and accounting for agricultural land and water use will be underpinned by three key working practices and principles, which have been guided by barriers to adoption of data-driven monitoring solutions reported in Deliverable 4.1 and through our consortiums extensive experience of science to policy research.

1. Define end users early in design

Scientific research can often fall into the trap of seeking to generate "new" and "better" data, with the assumption that these data will be readily and willing adopted by end users for example to support policymaking around water planning and management (the technocentric mantra of "build it and they will come"). The reality is often quite different, with many advanced data-driven tools failing to achieve intended levels of impact and adoption after a research project finishes. An important first step in overcoming this innovation "valley of death" is identifying end user(s) who would take ownership over the scientific tool or dataset beyond the end of a project.

In each of our pilot projects for the Toolbox, we have worked closely with living lab leads to already identify target end user(s) for whom the Toolbox would add value in terms of their roles within water management and planning within the associated river basin. Identification of key end users for each of our four pilot labs is ongoing, and we therefore summarise below the key end user groups already identified

- *TDP living lab:* In addition to the Stockholm Environment Institute's Latin America Office, a key target end user will be ALT (binational authority of Titicaca Lake) who have an overarching trans-national responsibility for monitoring and management of water in the TDP living lab. SEI has an established MoU with ALT as part of TRANSCEND that will facilitate their close engagement in design and implementation of the Toolbox for the TDP lab, with ALT already having expressed a strong interest in being involved in the Toolbox pilot. In addition, further relevant stakeholder groups will include national water and agriculture Ministries in each of the two countries within the TDP basin system (Peru, and Bolivia), who each have respective responsibilities for agricultural monitoring and management in sub-areas of the basin.

- *Jucar living lab:* In the Jucar lab, primary potential end users would be the river basin authority and administration tasked with managing abstraction from the Requena-Utiel and Mancha Oriental aquifer systems who would benefit from improved capacity and tools for continuous monitoring of irrigated area and cropping dynamics to track policy compliance and outcomes. Opportunities also exist to develop capacity for adoption and application of the Toolbox to similar agencies in other parts of Spain, for example through linkages with other projects involving TRANSCEND collaborators (e.g. TALANOA-Water project focused on the Douro basin).

- *Mahanadi living lab:* As part of the proposed pilot, we will work to build capacity to adopt and extend the Toolbox within TRANSCEND's primary project partner in India (Institute for Resource Analysis and Policy – IRAP). Wider engagements have also highlighted interest from the International Rice Research Institute (IRRI) and International Maize and Wheat Improvement Centre (CIMMYT) in supporting the development of the toolkit, both of whom are organizations who are deeply embedded in supporting water management and planning in the Mahanadi Lab. Finally, a key user group identified through our scoping work is the Odisha State Government, in particular the Departments of Agriculture and Water Resources with whom we will seek to engage as end users as the pilot develops.

- *Tympaki living lab:* The outline of the pilot project for the Tympaki Lab outlines in detail a set of key user groups who would be active adopters of the Toolbox and its outputs. This includes The Region of Crete government and Water Directorate of Crete who have responsibility for monitoring and regulating water abstractions from agriculture; Local Land Reclamation and agricultural groups who would benefit from improved irrigated area monitoring to support planning and allocation of agricultural water; along with hydrological groups such as The Hellenic Survey of Geology & Mineral Exploration the Special Secretariat for Water (SSW) of the Ministry of Environment and Energy who can leverage mapping data as part of wider sustainable water management planning including supporting scaling to other regions in Greece.

2. *Tailor design for the needs of end users*

For the Toolbox to be useful for end users identified above, it is important that specific applications of the Toolbox are as closely aligned to and application-ready for end users needs around improved monitoring of agricultural land and water use in their specific living lab/river basin. A common disconnect between scientists and end users is that scientists design tools and models with primary goals of academic novelty, but neglect consideration of the real-world needs of end users (e.g. where the spatial/temporal resolution, geographic area, or LULC categories may not match what is needed in the context of regulatory and policy environments). This was reflected in the strong and consistent feedback in the co-identification of monitoring needs for TRANSCEND not to develop one generic tool that sought to simultaneously serve monitoring needs in all labs, and instead focus on generalisable methods that can be tailored to address specific local data gaps, monitoring challenges, and management issues related to agricultural land and water use dynamics.

To balance and address these sometimes-conflicting goals of scientific research and policy, for each pilot we will ensure continual engagement and dialogue throughout pilot applications between technical science leads, living lab coordinators, and key target end-users to ensure that both scientific and end-user needs are met. Alongside regular meetings between science leads and living lab coordinators, we will also hold regular engagements with end-users and relevant groups within wider stakeholder networks to provide space for continual feedback on the pilot of the Toolbox in each lab. These engagements will be held virtually (bi-monthly to quarterly), along with targeted in-person engagements around key TRANSCEND events planned within each living lab (Scenathons, International Workshops, Summer/Winter Schools). These engagements build upon already established dialogues, which, as outlined above, have been a core part of the development of this Deliverable and proposals for the Toolbox and its pilot applications.

3. *Build capacity to apply and maintain tools*

Another theme that will run throughout the Toolbox's work is making the outputs from the pilots in living labs as application-ready and sustainable as possible – especially beyond the end of TRANSCEND. Research projects can fall into the trap of producing "once and done" work that serves only limited use because it ceases to be updated once the scientific funding for a given project has expired, especially where the tool or dataset is specific and tailored to a particular application or local context. Alongside this, data-driven tools – especially those using complex data such as EO or processing methods such as machine learning – can languish after a project if constraints and limitations to technical capacity and expertise of end users outside academia are ignored. Deliverable 4.1 highlighted, for example, that use of EO data for monitoring water use has been limited in part to date by lack of time and geospatial analysis/data skills within agencies tasked with monitoring and regulating water use. To begin to address some of these challenges, three key actions will be taken.

First, we will ensure that all codes and workflows underpinning the Toolbox and its pilot applications are open source (e.g. in Python/R), thoroughly documented (commented code and supporting manuals), and made publicly available (e.g. via repository services such as GitHub). This will help ensure the Toolbox is reproducible by end users who are not necessarily EO specialists, and that pilot applications can be readily adapted to future needs and other contexts beyond the TRANSCEND labs. As far as possible, the LULC maps generated within the Toolbox will be annually updated throughout the life of the project, to streamline workflows and demonstrate the ability to readily update the product. This will increase the likelihood of the workflows being re-used and maintained by end users after the project ends.

Second, while open and reproducible workflows can help to streamline adoption, many EO mapping analyses can still be time and resource intensive enough to deter adoption by practitioners in water policymaking or governance. We will seek to minimise computational resource burdens by linking Toolbox workflows to public cloud computing resources, in particular Google Earth Engine due to its efficient interfacing to Earth observation data and optimized in-built algorithms for geospatial analysis. Additionally, we will identify steps in Toolbox workflows that are especially time consuming (e.g. digitisation of training data, model evaluation), and seek to develop tools to simplify these processes for time constrained end users. For example, research has demonstrated potential for self-supervision deep-learning methods to fully or partially automate training data labels for other water cycle components (Peña et al., 2023), while unsupervised or weakly supervised classification methods can also reduce upfront input costs of land use classification (Ragettli et al., 2018).

Third, recognising that geospatial and data science skills are often a major gap in water management agencies and organisations, we will develop and deliver training for staff of key end users in each pilot to embed more detailed knowledge and capacity to apply and adapt the Toolbox pilot in their region. To further support these activities, an internal monthly webinar/meeting will be held, led by UoM, to which TRANSCEND monitoring pilots will be invited to share knowledge, progress and technical expertise in the field of LULC mapping, and promote cross-fertilization of ideas between Toolbox pilots. Beyond the labs engaged in pilots, we will also engage other TRANSCEND labs, river basin agencies, and organisations involved in agricultural water management to facilitate wider adoption and impact of the Toolbox and its approaches. This will be achieved through dissemination of the Toolbox at key project events (e.g. International Workshops, General Assemblies) and international fora (e.g. Mediterranean Water Forum; World Water Week), alongside a platform of web-based training materials that leverages pilot projects in TRANSCEND to provide open and accessible training for water managers worldwide in how to use the Toolbox for agricultural monitoring in their own regions and river basins.

6.1 Moving from KPIs to Outcomes and Impacts

The above measures are collectively key pillars to support TRANSCEND's monitoring KPI ("Water accounting and monitoring toolbox using in-situ/satellite data adopted in 7+ labs"), leveraging the four pilots, wider training and capacity development to lay the groundwork for embedding and enabling the project across and beyond TRANSCEND's core labs and wider regions. Through these efforts, we will also support and ensure TRANSCEND's subsequent long-term outcome and impact goals linked to monitoring (*O4 – "Identify water efficiency deficiencies and achieve improvement by at least 50% by 2030, in regions under water stress, now or in the future, and for water bodies at risk of failing to meet good ecological/quantitative status"; O-5. "Reduce the water footprint of water-using sectors, especially agriculture, energy and industry"*; and *I3 – "Efficient monitoring, assessment and projections related to climate change impacts, mitigation and adaptation potential in order to bring out solutions for tackling emerging threats and support decision-making in climate change mitigation and adaptation policies at European and global level"*) by providing a globally scalable, replicable, and actionable Toolbox that addresses the primary driver of water sustainability and efficiency challenges – agricultural water demands.

7 Conclusions

In this deliverable, a set of research activities comprising the monitoring Toolbox have been described, as well as the decision-making process (including co-creation) that led to these research activities being selected. At the core of the Toolbox is the development of LULC/irrigated area maps using Earth observation data, with new maps being produced in the TDP, Mahanadi, Jucar and Tympaki basins. The technical details of that work have been set out, and in that regard, this document will serve as an essential reference point for the scientific/technical aspects of Work Package 4. However, as important is the continued emphasis on application-readiness which is found in all aspects of the Toolbox. Stakeholder engagement, open-access code/tools, and synergetic knowledge exchange, both within and beyond the consortium, are vital elements of the Toolbox and key to its success in furthering the wider goals of TRANSCEND. This Toolbox will be a vital vehicle in the development of TAPs, with this document serving as the blueprint that defines Work Package 4 activities for the remainder of the project.

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