A Roadmap for Copernicus water services

Water-ForCE

2024

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Executive summary

There is no life on Earth without water and we are increasingly feeling the effects of climate change through water extremes. The provision of high-quality data and information on water quantity and quality should therefore be a key aim of the Copernicus Programme and the Copernicus Services. This Roadmap informs the Copernicus Services how to improve their impact in the inland water domain. The Copernicus Services could be a powerful tool for understanding the water related processes on Earth, supporting water management, supporting Sustainable Development Goal's (SDG), System of Environmental-Economic Accounting (SEEA), climate adaptation, and boosting European markets. To realise this opportunity, there is a need to demonstrate commitment to requirements of current and future users, as proposed through the recommendations in this Roadmap.

The Water-ForCE project, using internal expertise of 20 partners and engagement with over 800 current and potential users, assessed the current water-related service elements and how they satisfy the needs of different stakeholders and user groups. This led to the identification of 8 main bottlenecks (Figure ES1) which limit the success of Copernicus Services in the water domain. Solving these bottlenecks is the main recommendation to improve the impact of the Copernicus for Water.

Figure ES1. *Summary of bottlenecks to Copernicus Services for Water that need to be overcome.*

There are multiple ways to solve the identified bottlenecks an reach the expected impacts identified by the European Commission in the Space call. The Water-ForCE consortium developed and analysed

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four scenarios to provide the European Commission, the Entrusted Entities and the Member States with possible ”pathways” towards a coordinated, coherent and trusted monitoring system for inland waters (Figure ES2). The first scenario is to keep Copernicus Services as they are now and continue the gradual progress that has taken place in the last decade. The second scenario, Thematic Hub, can also be considered as an ongoing development as the first four Thematic Hubs (Health, Coastal, Energy, Arctic) were officially launched on November 8, 2023. According to the current documentation the Thematic Hubs are “single entry points to data and products generated by different Copernicus services on specific thematic areas”. Such data portals cannot help to overcome the bottlenecks identified by the Water-ForCE or reach the expected impacts raised by the European Commission. Therefore, the consortium sees greater potential in Scenarios 3 and 4. The Scenario 3: “Water as a Virtual Service” foresees creating an entity under one of the existing Services responsible for coordination of all inland and near-coastal (to allow monitoring water as a continuum) water products and services. This includes creating an in situ component that actually collects necessary data for calibration and validation of Copernicus products rather than relies on what is collected by other organisations. The Scenario 4 goes a step further and develops a dedicated Copernicus Water Service. This can be achieved through establishing a new Service, expanding responsibilities of one of the current Services or merging some of the current Services.

Figure ES2. *Scenarios for Copernicus Services for Water.*

For the Copernicus programme to overcome the bottlenecks and realise its ambition within the water domain, a series of recommended actions were suggested for either implementation or endorsement by the Copernicus Services. These recommended actions are independent of the scenario selected for Copernicus for Water, but the scenario will greatly influence the timeframe in which actions can be implemented. These recommended actions are targeted towards the different

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stages of the Copernicus value change, from Copernicus as a data provider, Copernicus as a product provider, Copernicus as a service provider, and Copernicus supporting downstream. The recommended actions are designed to lead the Copernicus programme to delivering the necessary data, products and services that are coordinated, coherent, validated, trusted and accessible. Additionally, these recommended actions will help the Programme deliver a framework and confidence for the data to be used increasingly in policy implementation and inform decision making in environmental contexts under increasing threat from a rapidly changing environment and climate extremes.

Based on an extensive consultation, our conclusion is that the Roadmap should be used by the European Commission, supported by the findings from the Water-ForCE deliverables to establish a strategic plan for addressing the bottlenecks. We propose the following recommendations be taken up in the short-term:

1. The Commission is recommended to use this Roadmap and the findings from Water-ForCE deliverables to conduct a cost-benefit analysis of the scenarios developed, including knowledge of budgets.
2. EUSPA is recommended to consider the inclusion of Water as an identifiable market sector to fully comprehend the relevance of the EO water sector in Europe.
3. The Commission is recommended to conduct investigation into products which Water-ForCE identifies with high Technology Readiness, to make them fit-for-purpose for policy, downstream user and business.
4. It is recommended that EO be considered as a possibility for monitoring in future water-related EU legislation.
5. Member States to champion the integration of Earth Observation with in situ national monitoring.
6. The Commission, Member States and the European Environment Agency are recommended to establish a taskforce to address the in situ needs for water products and services, using the options provided by Water-ForCE (e.g., establish supersites).
7. The Commission is recommended to elaborate the scenario analysis provided by including

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knowledge of budgets, into a full impact assessment.

8. The Commission is recommended to take the findings presented by Water-ForCE in consideration if taking forward the proposed 'Water Management' Thematic Hub.

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1. Introduction

1.1 Copernicus role in the Water domain

The potential uses of Copernicus Services within the Water domain (policy, research, commercial) are vast and can be greatly advanced over the coming few decades. Earth Observation (EO) can help to overcome some of the limitations of conventional monitoring methods, to provide whole system information on the water cycle and in turn advance water management. EO data are essential in a future water-smart society, to ensure access to clean water and sanitation for all (Sustainable Development Goal (SDG) 6) and will contribute to a fair and visible Water market segment (**D1.5** and **D6.3**[1]). As the largest provider of EO data in the world, the majority of which is free-to-access, the Copernicus Programme is designed to support EU policy goals and implementation, contribute to the SDGs and the System of Environmental Economic Accounting, to boost upstream and downstream economic growth within the EU space and EO industry. The beneficiaries of a Copernicus Programme that fully embraces the importance of water, include decision and policy makers who are enabled with actionable tools, EU member states who can meet reporting requirements, water agencies that can access reliable and timely data on their waterbodies, companies that can provide customers with water-smart information and individuals that are informed on the value of water. The purpose of this document is to describe the pathway towards this future for Copernicus for Water, and to determine the necessary steps to get there.

Figure 1. *From left to right; Smart water society (Water Europe), FAIR water segment (watercalculator.org) and SDG6 Clean Water and Sanitation (United Nations).*

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[1] The numbers here and below indicate respective Water-ForCE deliverables available in www.waterforce.eu, CORDIS and ZENODO

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__Figure 2.__ Future role of Copernicus Water products and services across end-users.

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1.2 Background and context

In 2001 the European Union and the European Space Agency (ESA) launched a joint initiative: the Global Monitoring for Environment and Security (GMES), to fill a gap in the availability of environmental observation data and to guarantee independence of Europe in collecting such information. The GMES initiative evolved into the Copernicus Programme and the delivered services from the Framework Programme 7 (FP7) funded pre-operational services (from 2008-2009) to fully operational Copernicus Services since 2012.

The launch of the Sentinel satellites under the Copernicus Programme was a paradigm change for EO satellites capacities in Europe and around the world. Environmental data was no longer limited to one-off scientific missions. The Copernicus Programme gave users from across domains unprecedented access to free and open satellite data.

Today there are six Copernicus Services: Atmosphere Monitoring Service (CAMS), Climate Change Service (C3S) , Emergency Management Service (CEMS), Marine Service (CMEMS), Land Monitoring Service (CLMS), and Security Service (CSS). Each Service has an entrusted entity with responsibility for implementing the Service, including managing the budget. Five of the Services, the Atmosphere Monitoring, Climate Change, Emergency Management, Marine and Land Monitoring Services, provide products related to water quantity or water quality in their respective domains. The implementation of these five Services has been entrusted to different entities: the European Centre for Medium-range Weather Forecasts (ECMWF) for the atmosphere monitoring and climate change services, the European Environment Agency (EEA) for the Land Monitoring Service (CLMS), the Joint Research Centre for the Emergency Management Service (CEMS) and Mercator Ocean International for the Marine Service (CMEMS).

1.3 The need to assess the Copernicus Services for water

The Copernicus Services provide water related products and services, but the wide community of the water sector have drawn attention to a suboptimal availability of products as well as organisation of the Copernicus Services from their perspective. In response to this feedback, the European Commission launched a Horizon 2020 call “LC-SPACE-24-EO-2020: Copernicus evolution: Mission

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exploitation concept for WATER"[2]. The responding Water-ForCE consortium was selected to carry out this 3-year project, which is summarised in this document.

The main challenge identified was that each Copernicus Service develops separately from each other, for their own specific purposes. These separate developments do not consider the global understanding and representation of the water cycle from regional to global scales. As a result, support to water related policy development and implementation in the EU, contributions to UN water coordination mechanisms, achieving Sustainable Development Goals, contributing towards the System of Environmental Economic Accounting, or addressing climate change is below the level that Copernicus Services could deliver. The aim of the Coordination and Support Action awarded to the Water-ForCE consortium was to develop a scenario in which the Copernicus Services could reach to the following expected impacts for the water domain:

- Improving coordination and integration of Copernicus Services to allow understanding of the water cycle as a whole
- Expand the Copernicus Services inland water portfolio to satisfy the needs of different user groups and stakeholders
- Reach minimal duplication of effort between the Services,
- Inclusion of higher-level biogeochemical products in the Copernicus portfolio for water quality and food web modelling and analysis
- Providing all water products with forecast and hindcast features
- Achieve consistency between inland and coastal products to allow studying water quality as a continuum
- Providing change detection tools for water quantity and water quality products
- Provide all water products with uncertainties
- Improve the Services interactions with non-EO communities in the inland water domain.

The Water-ForCE project made an assessment of the current water-related service elements, analysed how they satisfy the needs of different stakeholders and user groups, identified main

[2] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/lc-space-24-eo-2020

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bottlenecks that limit the success of Copernicus Services in the water domain and proposed priority actions that should help to overcome these main bottlenecks. Selecting an optimal future scenario for the inland water part of Copernicus Services is constrained by political, financial and technical conditions. The decision about the way forward has to be made by the Member States. Water-ForCE assessed four possible future scenarios based on how they help to solve the expected impacts raised by the European Commission in the H2020 Space call (above) and the main bottlenecks identified during the project. This assessment should help to guide the Member States to make the decision about how to improve the Copernicus inland water domain in the coming years. Water-ForCE consortium acknowledges that some of the proposed scenarios are also quite broad and contain multiple options for future development.

1.4 Water-ForCE consortium & engagement

Water-ForCE is a consortium of water quantity and quality experts, including 20 partners from 10 countries (List in Annex 1). Water-ForCE partners comprise knowledge in different fields (policy, water quantity, water quality, in situ measurements, remote sensing, modelling, etc), and through engaging global community through thematic scientific working groups (27 countries and many sectors), webinars and workshops (+250 registrants from 50+ countries) as well as public surveys (500+ responses from 5 continents). For more information on the consortium and the consultation process please refer to Annex 1 and Annex 2. Over 50 project deliverables contributed to the formation of the Roadmap and are available at www.waterforce.eu, or listed with links in Annex 5.

1.5 Document scope

This document is focused on inland waters. However, the expected impacts listed above require products that allow monitoring of inland and coastal waters as a continuum. Consequently, we had to include near-coastal waters in the analysis when considering the water quality domain. The near-coastal implies waters whose optical properties (i.e. those detectable by remote sensing) are directly impacted by the nearby land. These water bodies will be referred to as “coastal” in this text.

This document was written primarily to advise the Copernicus Services on how they can improve their impact across the water domain in the future. The document should also be relevant to policymakers and stakeholders in the water domain to understand the current state of play and to

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define the associated research and development agenda. As a public document, technical jargon is avoided as much as possible. Alongside this document, Water-ForCE has produced detailed technical analysis reports, which are referred to in this text by their Deliverable abbreviation (e.g. **Dx.y**), where the first number refers to a package of work focussed on a specific domain (water quantity, quality, modelling, in situ observation, etc) and the second marks the specific report number within that domain.

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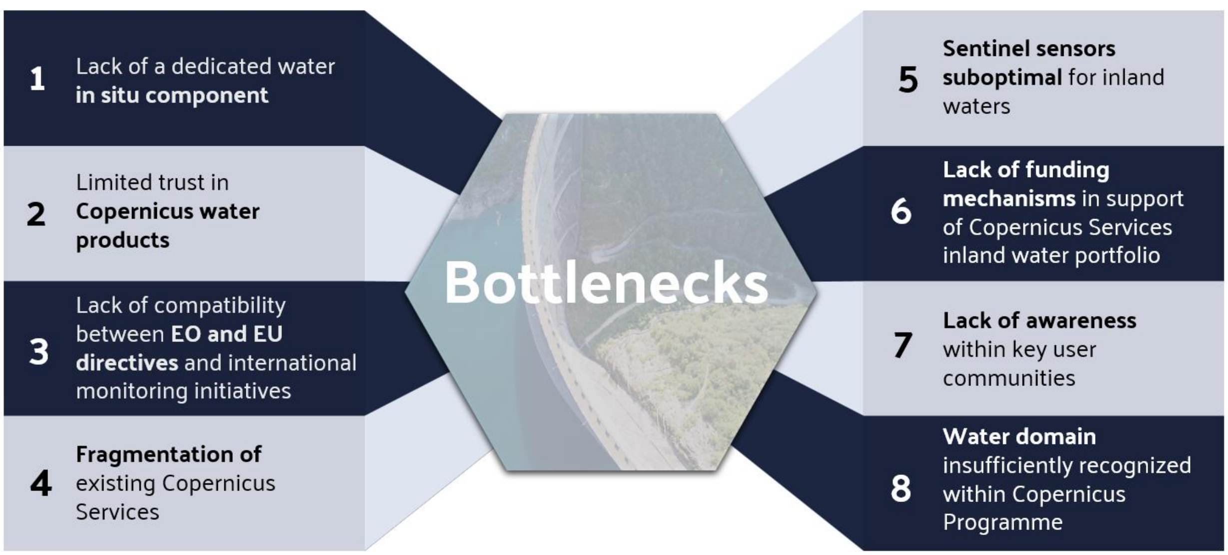
2. Bottlenecks to uptake

While the Copernicus Programme is undoubtedly a successful investment, analysis by the Water-ForCE consortium and extensive user consultation, reveal a number of critical bottlenecks. Bottlenecks are blocking, insufficient or missing processes, products or technologies that need to be resolved to achieve the desired impact. Here, we present the most critical bottlenecks, found to be stalling progress of Copernicus water-related services across user and policy domains (Figure 3). Each bottleneck is detailed below, which then leads to the future scenarios for Copernicus Services and their potential to overcome them.

For a summary of the current Copernicus portfolio see Annex 3, including the portfolio for water quantity products, water quality products, the in situ component, the portfolio for EU legislation, and the portfolio for Sustainable Development Goals, and FAIR principles in Copernicus infrastructure. For more thorough analysis, please refer to the full list of deliverables (Annex 5).

Figure 3. *Summary of bottlenecks to Copernicus Services for Water that need to be overcome.*



2.1 Lack of a dedicated in situ component

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Who is directly impacted?	Which processes are affected?
Copernicus Services	Development of water portfolio for new applications
Research and innovation community	
Potential users	

In situ data is an absolute necessity for developing and validating remote sensing and modelled products. Currently there is no dedicated in situ component in the Copernicus Programme. The Copernicus Services do not collect in situ data for water products, nor directly coordinate their collection. Consequently, the Copernicus Services do not have any control about the in situ data that is needed to develop new products, validating existing ones, providing uncertainties with the remote sensing and modelled products and increase the user confidence in the Copernicus products. This bottleneck impacts the Copernicus Services at the most fundamental level. To achieve its desired impacts for water, the Copernicus Programme must implement state of the art Earth observation and therefore products must be validated at the appropriate geographic and temporal (e.g. multi-seasonal) scale. Section 80 of the European Union Space Programme[3] issued in 2021 states that "The Commission and Member States should work together to develop the in situ component of Copernicus and to facilitate the integration of Copernicus in situ data with space datasets for upgraded Copernicus Services." Thus, it can be assumed that a coordinated effort can and will be made to evolve the Copernicus in situ component to the point that it can support validation and further evolution of the water product portfolio.

At present, the Copernicus In Situ Component, is responsible for mapping the landscape of in situ data availability to assist the Services (D4.3 & Annex 3). A step further would be to coordinate EU and international collaboration of in situ observation data collection and sharing. The Water-ForCE water quality and water quantity working groups noted various stages of community coordination for in situ data. For water quantity variables, a global network of hydrometeorological stations, funded by national governments and standardised and curated by the WMO, provides key variables for development and validation of Copernicus water quantity products (Annex 3). Despite this existing network, there remains a demand for improvement in spatial coverage and data availability (not all countries provide their water quantity data, or with substantial delays, or consistent licensing), an

[3] https://eur-lex.europa.eu/eli/reg/2021/696/oj

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increase in the number of variables collected (particularly soil moisture, groundwater levels and evapotranspiration, see D3.2 and D3.3) and locations of monitoring sites (e.g. alignment with altimeter tracks). Globally, there are also challenges for data collection and metadata harmonisation, as well as data sharing practices.

Although both water quantity and water quality products need dedicated in situ data the lack of in situ data for water quality is the most critical. A key source of in situ data for water quality products is via the monitoring programmes of EU Member States which are primarily designed to fulfil policy needs, such as the Water Framework Directive, and overseen by the EEA. These data collections, for the small part where they overlap with remote sensing capabilities, could be more strategically organised for maximum synergy, noting sample locations and coincident observations as key improvements. Additionally, further optical proxies of water quality could be systematically collected by the Member States, most notably radiometric observations of colour and temperature. Due to the lack of a dedicated in situ component, alternative sources of in situ data are also heavily relied upon, such as research projects, citizen science and high-frequency observation stations (D4.2, D4.3). These data collection efforts are not coordinated by Copernicus, are often short-term, do not cover the whole spatial and temporal extent necessary for proper validation of Copernicus products. Moreover, the collected data is usually retained in unfunded data repositories and/or is not publicly available (D4.3).

Lastly, there is also a lack of Fiducial Reference Measurements (FRM) which limits the improvement of uncertainty estimation of any water quality products. FRM are a specific suite of in situ observation data used to provide independent traceability and uncertainty budgets for satellite observations. ESA and EUMETSAT support FRM data collection to validate upstream radiometric (L1) data. Developing and validating global Copernicus products to FRM standards requires a far greater degree of standardisation, but is arguably needed to provide confidence in satellite products for climate modelling, and to achieve the highest possible standard in statutory use of observation data (D2.2 and D2.3).

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2.2 Limited trust in Copernicus water products

Who is directly impacted?	**Which processes are affected?**
Current users and potential users	Uptake of existing products and services

A prominent bottleneck to the uptake of satellite EO-derived water products is limited trust or confidence in the quality of the products (D1.3, D2.3, D4.4, D2.2, D1.4, D6.3). The term trust combines subjective and objective components. Some potential users believe that satellite based and modelled products are not accurate and reliable.[4] There is also an objective part of limited trust - many Copernicus Services products are not fully validated and/or do not have uncertainties attached to the products.

In some cases, product quality can be further improved through further R&D, bolstered by strategic data collection. In situ data are required to validate satellite EO and modelled products and to characterise the product uncertainties, and hence this bottleneck is largely contingent on bottleneck 1, lack of dedicated in situ component. Additionally, the optical, morphological and biogeochemical diversity of inland and coastal waters is very high. Therefore, remote sensing methodologies as well as modelling tools need to be developed and tested in representative environments and under a range of observation conditions (e.g. different seasons). Introducing new products into the Copernicus portfolio requires in situ validation data that are (ideally) independent of training datasets, and representative for the product region of interest, which can be regional or global. Collecting such dataset relying on seldom research projects is basically impossible and the Copernicus Programme will require a dedicated in situ component to cover the need in training and validation data.

2.3 Lack of compatibility between EO methods, and EU legislation and other international initiatives

[4] Agnoli, L., Urquhart, E., Georgantzis, N., Schaeffer, B., Simmons, R., Hoque, B., Neely, M.B., Neil, C., Oliver, J. and Tyler, A., 2023. Perspectives on user engagement of satellite Earth observation for water quality management. *Technological Forecasting and Social Change*, *189*, p.122357.

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Who is directly impacted?	Which processes are affected?
Member states	Policy support, development and monitoring
Copernicus Services	

The implementation of water related EU policy and legislation includes monitoring changes in indicator values against defined targets. These indicators may be physical variables, like lake water temperature, or aggregated indicators such as the Marine Biotic Index (AMBI) or biological quality index (BQI). The majority of indicators in relevant policy frameworks cannot be monitored using remote sensing. On the other hand, those indicators that could be mapped with remote sensing are not in the Copernicus water portfolio (See Annex 3.4: The current Copernicus portfolio for implementing EU policies). It has to be stressed that many of the EU legislation documents came into power before the Copernicus Services were launched. Consequently, they do not mention the Copernicus Services and do not contain indicators that can be monitored by remote sensing methods, but amendment of this is long due.

From the side of satellite remote sensing, the main limiting factor for uptake in a policy monitoring capacity lies in the translation from the scientific state of the art to validation at the scale of deployment within the Copernicus Services, i.e. the European or global scale. There are a number of relevant water products that are successful at regional scale (see D2.2. and D2.4), but cannot be included in the Copernicus portfolio as there is no in situ data to validate these products over a larger scale (Bottleneck 1). For river monitoring, the spatial resolution of MSI (10 m) theoretically allows for monitoring water quality aspects of wide rivers, and some transitional waters, although this has not been translated into operational products yet. Notably, the uptake of remote sensing products in monitoring practices also requires investment by users. The voluntary uptake of Copernicus products by national agencies may be limited by budgets or data expertise. For an example of the latter, water quantity and quality products are not delivered individually per water body, which is ultimately required for monitoring (D3.3 and D3.4).

In turn, policy and legislation can be a driver for new data and product development either by setting stricter standards (such as emissions) or by expressly referring to satellite-derived information as an accepted method for monitoring the implementation. Only a few of the policy and regulatory instruments we investigated explicitly refer to the use of satellite-derived information (D5.4). In some

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cases this is a logical effect of the fact that the legislation precedes operational Copernicus Services - such as the Water Framework Directive (2000) - but even more recent EU Green Deal instruments show a mixed picture. A positive exception is the Common Agricultural Policy (CAP), which expressly encourages the use of modern technologies, including Copernicus data and Services, to monitor and report on the performance of CAP implementation through a set of indicators including for water sustainability. Resolving the above issues may be expected to deliver much wider uptake in the implementation of policy directives.

This compatibility issue is not limited to EU legislation but also hinders the uptake of EO within international reporting, such as the Sustainable Development Goals (see Annex 3.5). For indicator 6.3.2 ambient water quality, reporting only recently, in 2023, permitted EO as a level 2 contribution (supporting the in situ report), there is also a limited offering from Copernicus to deliver information on water-related indicators. For global application, there is an additional issue that many products are not validated globally due to lack of in situ data (Bottleneck 1) and hence a trust issue (Bottleneck 2). Additionally, Essential Climate Variables (ECVs) are internationally recognised variables necessary for monitoring to systematically observe the changing climate. The Global Climate Observing System (GCOS) operating under the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), the United Nations Environment Programme (UN Environment), and the International Science Council (ISC) regularly assesses the status of global climate observations of the atmosphere, land and ocean. All hydrosphere and cryosphere ECVs (Groundwater, Lakes, River discharge, Terrestrial water storage, Glaciers, Ice sheets and ice shelves, Permafrost, Snow) are directly related to inland and coastal water quality and water quantity, and should be offered by the Copernicus Services.

2.4 Fragmentation of existing Copernicus Services

Who is directly impacted?	**Which processes are affected?**
All beneficiaries of water-related Copernicus Services	Uptake of Copernicus products and services
	FAIR use principles
	Understanding of the water continuum

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The independent delivery of each of the Copernicus Services by their entrusted entities has led to fragmentation of effort and lack of coordinated development and harmonisation of products across the land-sea continuum, for water cycle monitoring, and climate modelling. One of the consistent outcomes from user and expert engagement activities was that users were sometimes not sufficiently aware of the Copernicus Services water portfolio, and where to find relevant products (D6.1, D3.1). This is, in part, due to low FAIR (Findability, Accessibility, Interoperability, and Reusability) scores, and part lack of user-driven design. The harmonisation of existing products and Services would allow new and existing users to optimally exploit and benefit from the Copernicus Services, stimulating the uptake of EO data and strategies by new sectors (see D1.4, D1.5 and D6.3). Fragmentation is not exclusive to the Copernicus Services but is also evident across the water domain, with communities operating in silos to address specific water issues, by region or by specific type of water body (e.g. lakes) without sufficient interaction with other groups tackling similar challenges[5] .

2.5 Sentinel sensors are suboptimal for inland waters

Who is directly impacted?	**Which processes are affected?**
Beneficiaries of water	Development of water products
Copernicus Services	Uptake in management and monitoring
	Climate adaptation and mitigation

There exists a large technology gap between the high-resolution Sentinel-2 MSI sensors and the Sentinel-3 land/ocean sensor OLCI. Arguably, the optimal balance between spatial, temporal and spectral resolution required to observe biogeochemical processes in inland and inshore water bodies are met by neither the land-observation oriented MSI with 3-5 day revisit, radiometric resolution not sufficient for water bodies, and absent glint avoidance, nor the daily revisiting OLCI operating at 300m over a larger number of spectral bands and with otherwise excellent radiometric sensitivity. Daily observations are desirable to monitor potentially harmful blooms, pollution events, and

[5] Michalak, A.M., 2016. Study role of climate change in extreme threats to water quality. *Nature*, *535*(7612), pp.349-350. Doi: 10.1038/535349a.

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flooding. High-resolution temperature observations are not currently available from the Sentinel missions, which are critical to water quality and water quantity monitoring (e.g. evapotranspiration and water stress). TIR (thermal infrared) is only provided at medium resolution, Sentinel-3, however it is missing in Sentinel-2 (D3.5). Various water quality applications, such as monitoring harmful algal blooms, require extra spectral bands (that should be available on S2NG around 10 years from now) (D2.4). Despite substantial limitations, Sentinel-2 MSI marks significant progress compared to earlier high-resolution optical sensors in the Landsat series. It is currently used to deliver the two inland water quality (by the Land Monitoring Service (CLMS)) and four coastal products (by the Marine Service, CMEMS) (Annex 3.2, D2.2, D2.4). It is important to note that, even with the current Sentinel-2 mission, many other products are possible (see for products Bottleneck 3), and are primarily missing due to the lack of appropriate in situ data (Bottleneck 1), rather than the sensor capabilities. Availability of satellite sensors designed specifically for inland water purposes would allow to increase the number of products in the Copernicus portfolio and reduce the uncertainty of existing products. Furthermore, a constellation of satellites would also meet the spatial and temporal resolution desirable for inland waters.

Copernicus Sentinels at this stage do not provide sufficient data for river dynamics (e.g., river runoff), hydrological dynamics or under-water systems. Sentinel-3NG-T and ROSE-L will likely fill the current gaps on river dynamics, monitoring of glaciers and ice caps (D3.5). In terms of radar altimetry for inland water quantity monitoring, the recent SWOT mission (a NASA/CNES collaboration) is heralded as a breakthrough mission allowing far greater coverage than previous missions and improved synergy with SAR imagery. Newly available SWOT data will help fill the gap including monitoring of transboundary river basins (e.g., water storage and river discharge). There remains, however, a lack of clarity on the long-term consistency of future gravimetry missions (e.g., ESA GOCE, NASA/DLR GRACE and GRACE-FO) (D3.5)[6].

[6] Haagmans, R., Siemes, C., Massotti, L. et al. "ESA's next-generation gravity mission concepts". Rend. Fis. Acc. Lincei 31 (Suppl 1), 15–25 (2020). https://doi.org/10.1007/s12210-020-00875-0

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2.6 Lack of funding mechanisms to support enlargement of the Copernicus inland water portfolio

Who is directly impacted?	Which processes are affected?
Researchers	Development of Copernicus products
Policy	Downstream information services development
Downstream value adders	

Current national and EU level funding mechanisms offer a wide range of opportunities (D1.5) but do not sufficiently support the addition of new operational water quality products in the Copernicus Services portfolio. To be added to the portfolio, the candidate methods need to reach a validation threshold to warrant investment in a demonstration capability at regional, continental or global scale (see Bottleneck 1) and a realistic expectation of future user uptake. Existing funding opportunities include research and development projects that demonstrate the feasibility of new remote sensing products, and development projects that produce service demonstrations. However, such remote sensing products and services have limited geographic scope (e.g. a small number of lakes) due to the huge variability in optical properties of inland waters. These new products have to be validated at relevant geographic scales (European, global) i.e. cover all main water types in the geographic area, in order to include them in the Copernicus portfolio. There is a funding gap to do this. Whether the funding gap should be overcome by long term funding to Copernicus inland water calibration and validations supersites or by large research projects that collect currently missing in situ data at pan-European and/or global scales and validates the new products, needs further cost benefit analysis.

2.7 Lack of awareness within key user communities

Who is directly impacted?	Which processes are affected?
Copernicus Programme	Prevents full uptake of Copernicus products and services.
Downstream EO providers	

Copernicus is a user-driven Programme. It is one of the largest data providers in the world, offering free data as a public good. Many products (both remote sensing based and modelled) have been developed based on user needs. However, there remain many potential users that are not aware that

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there are Copernicus products and services they can benefit from (D6.1). In addition to being unaware of the products available, users may not be aware of the open access policy, lack confidence to use these products and services (Bottleneck 2), or remain unaware of the information available to develop the skills to use products and services (D6.1). Lack of awareness was noted in multiple stakeholder engagement activities within Water-ForCE (D3.3, D1.2). It is particularly important that key actors of change and decision makers (see Annex 4) are aware of the capabilities of EO based water information and the current limitations of the Copernicus programme for water domain users and other end-users. Various external sources, including the London Economics 2018 and EARSC 2021, also evidence a lack of skilled personnel to work with EO downstream providers in Europe.

2.8 Water domain is insufficiently recognised within the Copernicus Programme

Who is directly impacted?	Which processes are affected?
Potential water users Copernicus programme	Copernicus Programme products and Services do not meet desired impact in the water domain

This bottleneck is closely related to the Bottleneck 4 - the fragmentation of water across the different Services. Water is a transversal sector on which many other sectors rely or exist. Most of the time, this market is hidden within other market sectors (e.g. agriculture, natural resources, emergencies). Information provided in market and trend reports available for Space and EO imply that the role of EO in the water sector is currently limited to a few specific applications, but currently there is no specifically identified EO market for water (WP1, D1.3). Moreover, the Copernicus Programme is supposed to support the development and implementation of EU policies. However, the current contribution is very minimal (see Bottleneck 7). Thus, despite the importance of water on all life on Earth it does not have a proper position in the framework of Copernicus Services (Bottleneck 4).

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3. Scenarios for Copernicus Services for Water

The European Commission listed nine expected impacts that the Copernicus Services should reach in the inland water domain (Chapter 1.3) and the Water-ForCE consortium identified eight main bottlenecks (Chapter 2) that prevent the Copernicus programme from fulfilling its potential. To assess which evolution pathway would be able to overcome most or all of these issues, we have developed four scenarios and carried out a strengths-weaknesses-opportunities-threats (SWOT) analysis for each. The scenarios are in part a route to be taken starting from past and current actions (Business-as-Usual and Thematic Hub Water) and in part a horizon scan of actions to be taken to achieve the 'ideal' situation (Water-as-a-Virtual-Service and Water as a Copernicus Core Service) (**Figure 4**). It should be noted that these scenarios have been developed from a scientific, technical, and (policy and business) user perspective while we recognise that some more advanced choices will require political decision-making.

Figure 4. *Scenarios for Copernicus Services for Water.*

3.1 Business as Usual

Business as Usual implies that the evolution of Copernicus follows the path set in motion from the outset, with the six operational Services providing information about the Earth's land, ocean, and atmosphere, monitoring climate change, supporting European emergency management and safeguarding civil security. Water related products are scattered among these Services. The SWOT analysis for this scenario assumes no change to this pathway.

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Strengths	Weaknesses
* Copernicus has been an operational service since 2012 and pre-operational (funded from the FP7 Programme) since 2008, delivering inland and coastal water related products.	* The European Commission identified nine issues that need improvement in the inland water domain (Chapter 1.3). Some of them can be solved within this scenario over longer period of time. However, it is unlikely that some of them (understanding the water cycle as a whole, minimising duplication between the Services, achieving consistency between the inland and coastal water products, etc.) can be solved within this scenario. * Structural barriers to uptake (bottlenecks 1, 2, 3, 4, 5, 6, 8) are not addressed in this scenario. * The current pace is two inland water quality products in 15 years. Clearly not sufficient to satisfy the user's needs. * Without an in situ component it will not be possible to expand the products portfolio and to provide uncertainties of the products.
Opportunities	**Threats**
* The Horizon 2020 call to which Water-ForCE responded (LC-SPACE-24-EO-2020: Copernicus evolution: Mission exploitation concept for	* By not addressing the most pressing Bottleneck 1, "Lack of a dedicated water in situ component", Copernicus Services are unable to

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WATER) recognised the gaps and shortcomings, asking for an analysis and recommendations. * The Commission has initiated the development of Thematic Hubs (see the next scenario) to increase the awareness about the available water products and provide a single point of entry for accessing thematic products.	provide new products in order to meet the needs of EU policies, the SDGs, and business and the wider water sector. * Inland water is not a priority in the Copernicus Services ecosystem.

3.2 Water Thematic Hub

To overcome the thematic fragmentation and bring products and services closer to the target audiences, the European Commission introduced the concept of Thematic Hubs. Some 28 policy areas were identified, of which 15 were identified as a potential Thematic Hub. The first four - Coastal, Health, Energy, and Arctic - were officially launched on November 8, 2023 with Biodiversity, SDGs, Cultural heritage, International development, Agriculture-food security, Environmental compliance assurance, **Water management**, and Extreme events are planned to be launched. The SWOT analysis for this scenario assumes the establishment of a Hub (data portal) to be the only change compared to the Business as Usual scenario.

Strengths	Weaknesses
* Copernicus has been an operational service since 2012 and pre-operational (funded from the FP7 Programme) since 2008, delivering inland and coastal water related products. * A Thematic Hub Water Management would	* Structural barriers to uptake (Bottleneck 1, Bottleneck 2, Bottleneck 3, Bottleneck 5, Bottleneck 6) are not addressed by setting up a Thematic Hub which is, by the current definition, “a single access point to existing products” i.e. a

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provide a cross-cutting user-facing portal, potentially helping to overcome fragmentation (Bottleneck 4), and increase awareness by being more visible (Bottleneck 7 & Bottleneck 8). * A single entry point should help users to find relevant water quantity products from 800+ currently available.	data portal. * Solving the issues raised by the Commission (Chapter 1.3) will not be improved compared to the Business as Usual scenario. * The current pace is two inland water quality products in 15 years. Clearly not sufficient to satisfy the user's needs. The Thematic Hub will not make any progress in this domain. * Without an in situ component it will not be possible to expand the products portfolio and to provide uncertainties of the products. * It is likely that most of the planned 15 potential Thematic Hubs will contain some inland water products. This may even increase confusion among the potential users not reducing it. * Background information about the portals that have been launched or will be launched is not available, leaving the exact form and format (scope, governance, resources, mandate) and indicators for success unclear. The planning for launching further Hubs is unknown.
Opportunities	**Threats**
* While structural barriers between the Services will not be eliminated, the Hub can at least start	* Thematic Hub *Water Management* is not selected as priority from the list of 15 potentials

the dialogue to address coordination between the Services (bottleneck 4) related to inland water products allowing to reduce unnecessary duplication and user confusion. * Thematic Hub *Water Management* may raise awareness about the available water products in key user communities (bottleneck 7) and to a certain extent make the inland water domain more visible in the Copernicus Programme (bottleneck 8).	during this budget period (2021-2027) or the start of the next budget period (2028-2034), with any impact expected from this scenario therefore under threat of such a decision. * By not addressing the most pressing Bottleneck 1 "Lack of a dedicated water in situ component" the Copernicus Services are unable to provide new products in order to meet the needs of EU policies, the SDGs, and business and the wider water sector. * The new portal risks becoming one of the many and thus add confusion for users rather than reducing it. * Inland water is not a priority in the Copernicus Services ecosystem.

3.3 Water as a Virtual Service

In order to make significant progress in inland water domain the Copernicus Programme needs an entity responsible for coordinating and managing of all water related activities like establishing an in situ component that allows development of new inland (and coastal) water products, achieving consistency between the products to allow understanding of the water cycle as a whole and water quality as a continuum from inland to coastal waters, as well as providing water products with uncertainties and forecast/hindcast features. This entity would be very similar to the current Entrusted Entities and the work structure close to the current six Services. The current legal framework allows six Services and changing it requires agreement of all EU Member States.

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Therefore, it should be easier and faster to establish a virtual service under one of the existing Services. Bringing all inland water related activities under one governing body should enable faster solving of all the issues raised by the European Commission (Chapter 1.3) and overcoming the bottlenecks (chapter 2) identified by the Water-ForCE.

A key component of this scenario will be establishing an in situ component for inland and near-coastal waters that is collecting the data that is critical for calibration and validation of new and existing Copernicus products and defining their uncertainties. This will be a major change in the Copernicus Programme as currently Copernicus Services only search and collate data collected by other institutions. Consequently, the Virtual Service will become an active player that can guarantee high quality of it's products rather than being a passive player who's product portfolio and accuracy of the products is relying on seldom data coming from different sources with variable quality.

Strengths	Weaknesses
* Gives inland waters a more important position in the Copernicus Programme. * Allows to achieve all the expected impacts listed in the Space call (Chapter 1.3) and solve all the bottlenecks identified by the Water-ForCE project in Chapter 2. * Building an in situ component that collects necessary calibration and validation data (instead of harvesting what has been collected by other institutions) will allow to ensure expansion of the Copernicus inland water product portfolio and provide the products with	* Requires extra funding for establishing the entity responsible for the Virtual Service * Requires extra funding for collecting in situ data (e.g. network of cal/val supersites or large (global) validation projects).

guaranteed accuracies and uncertainties, that is not possible at present.	
Opportunities	**Threats**
* Adding the Virtual Service to one of the main players in the inland water domain (CEMS, CLMS, C3S) will not only advance the inland water domain, but will strengthen also the existing service by utilising the potential synergies from linking water quality and water quantity products more closely with the core products of the "host" Service.	* Several of the currently planned Thematic Hubs may also want to become virtual services with all it's elements rather than staying just data portals (single entry points of thematic products) as they are planned now. This will create instability in the whole Copernicus Programme. * May face resistance from current Entrusted Entities.

3.4 Water as a Copernicus Core Service

The fourth scenario is built on having a dedicated Copernicus Water Service, comparable to the existing six Services. It will have an Entrusted Entity who is coordinating all the water related activities and it will have an in situ component responsible for collecting calibration validation data rather than harvesting what is available around the world. Creating a Copernicus Water Service will not mean that production of all water related products must be moved under it. In order to avoid duplication of effort production of some water products may remain under the current Services. The Water Service does not have to be "a new" (seventh) Service. It can be built by expanding responsibilities of one of the existing six Services or even by merger of two existing Services (i.e. reducing the number of Services to five).

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Strengths	Weaknesses
* This is the ultimate scenario with the political status and commitment fitting the urgency of the need for better monitoring and improved management of scarce freshwater resources. * Will allow to achieve all the expected impacts listed by the European Commission in the Space call (Introduction) and solve all the bottlenecks identified by the Water-ForCE project in Chapter 2. * Will have stronger impact on the space component (i.e. on the launch of sensors dedicated to inland water monitoring) than any of the other scenarios. * Will have stronger impact globally on what kind of in situ data is collected, where and when in order to ensure the highest quality of Copernicus inland water products.	* Setting up a Water Service requires a legislative change, which first requires political will of the Member States, an impact assessment by the European Commission and a lengthy procedure to go through the co-legislation process (Council and Parliament). This would cause delay where speed is required. * Requires extra funding (starting and running a new Entrusted Entity or expanding one of the existing ones). * Requires extra funding for collecting in situ data (e.g. network of cal/val supersites, large (global) validation projects, agreements with other countries or institutions).
Opportunities	**Threats**
* Stronger political mandate will help to create a global in situ component required for calibration and validation of global products (i.e. covering all the main water types present on Earth) rather than relying on random project data collected	* Opening the discussion about a new service will open the Pandora's box about reorganising all existing Services as there are currently many thematic areas (see the list of potential Thematic Hubs above) that may request to

outside the Copernicus Programme. * The Water Service does not have to be a new (seventh) Service. It can be built by extending the mandate of one of the existing six Services or even by the merger of some existing Services.	become a Service. This may create short term instability of the whole Copernicus Programme (although a better Programme in the long term). * May face resistance from current Entrusted Entities.

4. Recommended Actions

Recommended Actions are actions that can be undertaken or endorsed by the Copernicus Services which can improve the impact of Copernicus Services for water. These recommended actions (Figure 5) range from actions that influence the data provision of Copernicus to the support of downstream providers and end-users. The Recommended Actions presented here are not ranked in terms of importance. From a long list of actions (Annex 4), the ones presented here were selected by the consortium and a stakeholder consultation process. The following section comprises a description of each action and what steps may need to be taken prior. They are also linked to the bottlenecks which they contribute towards overcoming. These recommended actions are independent of the scenario, although the scenario for the Copernicus Services will certainly influence the effectiveness and pace at which the actions can be implemented.

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Figure 5. *Summary of Recommended Actions to improve the impact of the Copernicus Services on the water domain.*

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4.1 Actions to build trust and capacity among users resulting in a water-smart society

The success of the Copernicus Programme for water is critical to developing a water-smart society within the EU. A water-smart society is one where the true value of water is realised by all and hence water is managed in such a way to reduce pollution and scarcity, and fosters a circular economic model (Water Europe, 2023). As identified in previous work (WP1, D6.1), there is a lack of awareness about the benefits of EO for water quantity and quality purposes at all levels of society (See Bottleneck 7 and Bottleneck 8). Hence, increasing the uptake of Copernicus products and services and raising awareness of the capabilities of EO for understanding water-related issues, are critical to realising the benefits of the Copernicus Programme for all beneficiaries of water. Actions summarised below are aimed at increasing the realised benefits of water products and services which are already provided by Copernicus Services, while also enriching the potential engagement of the downstream private sector, water domain and various other sectors with future Copernicus products and services. These are primarily coordination and engagement activities which can commence in the short-term and establish the pre-conditions for some of the other recommended actions.

4.1.1 Increase "satellite literacy" at all levels of society

"Satellite literacy" is related to individual and organisational -level capacity building, including building awareness of Copernicus, and education and training to build knowledge and skills to use EO products (D6.1). This is directly related to addressing Bottleneck 7, Lack of awareness of Copernicus products and Services, which could also contribute towards addressing Bottleneck 2, regarding the lack of trust in water products. The increase in satellite literacy is needed across all levels of society (D1.2). This ranges from key stakeholders such as policymakers at EU and Member States, to secondary and tertiary levels of education, as the next generation of EO professionals and the Copernicus Programme as an important European achievement. To increase satellite literacy, Copernicus Services are encouraged to launch campaigns which increase awareness of the Copernicus offerings through social media, increase educational outreach, and provide tailored support for decision makers and the private sectors (D6.3). One of the biggest concerns for the downstream EO sector in Europe is a lack of skilled personnel to work with EO data (e.g., EARSC 2021). Incorporating EO into formal education (e.g., MSc programmes) therefore has a clear benefit for

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the growth of this sector (D6.3). The Copernicus academy and Space4GEO are important existing initiatives which could be leveraged to reach more people and offer theoretical and practical introductions to EO.

Water managers and national statistic agencies also have much to gain from learning more about Copernicus, since EO has the capability to improve their management and reporting practices (D1.6, D3.3). Training for water managers, globally, may include tailored training and also provision of other resources (e.g., IT capacity and infrastructure) which can be barriers to the use of EO (D3.3, D5.4, D6.1). Particular calls have come from the water quantity communities for training of engineers at national response bodies in areas that do not have their own forecasting systems and more generally for training and operational products from European Flood Awareness System (EFAS) (D3.3). It is recommended that training agendas be co-developed with the trainees to ensure they are relevant and useful. It is also important to clearly demonstrate the added value of using EO and future uses of satellite products (e.g. from Copernicus portfolio). For many potential users, a lack of validation of the products is an obstacle to generating trust (Bottleneck 1, Bottleneck 2). Therefore, training in EO skills should encompass the complementary value of satellite and in situ observation.

An example can be taken from ESA EO4SD (Earth Observation for Sustainable Development). In this programme, capacity building was carried out at multiple levels, from donors/investors (The World Bank, Asian Development Bank) to plan their missions and monitor the outcomes using remote sensing, to national ministries and agencies on using remote sensing at country level, and to researchers and students on how to create and use tools like the Copernicus Services. Other projects have been completed under the Framework Partnership Agreement on Copernicus User Uptake (FPCUP), but there are few training opportunities specifically offered to the water domain (D6.1).

4.1.2 Foster synergy between water research, management and governance communities

Synergies should be fostered between research communities. In particular, synergies between in situ, satellite EO and modelling communities, with management and governance bodies such as Member States, national agencies, and regional/provincial authorities. This is a critical precursor for many of the more technical priority actions. Coordination among stakeholders and communities of practice is an action that can start immediately, even without specific funding to do so. This type of coordination

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is critical in overcoming the fragmentation of different actors of the water system (e.g. drinking water managers, ecological scientists, governance, enforcement) and the different components of the water cycle (e.g. lakes, rivers) (Bottleneck 4). It is also critical to developing the dialogue that will help to overcome Bottleneck 1, Lack of dedicated in situ component, and is a necessary preparatory step in aligning in situ and remote sensing EO monitoring (Recommended Action 3).

Long-lasting, effective synergies include regular knowledge exchange, consultation on the planning and agenda-setting, transparency, and updates on the activities of each community, and generally engaging in a back-and-forth collaboration. The development of synergies requires that communities are well defined and that there are relatively formal channels of communication or feedback loops between the communities.

Important to this action is ensuring that water users are sufficiently represented in the Copernicus user forum, or establishing a specific role for this. Existing networks should be a starting place for establishing these synergies (e.g., GLEON, GeoAquaWatch, WWQA, Water Europe, Water4All Partnership, water-related Horizon projects). The entrusted entities can lead the charge of linking these groups, setting priorities could be addressed in the Knowledge Center on Earth Observation (KCEO) which compiles resources that can help EU policymakers to fully exploit EO, and also brings together research and policy and governance communities. Another example is to move water research communities from R&D of new products into providing actionable data through co-design.

4.1.3 Co-develop products with professionals in the water industry and other end-user sectors

While the Copernicus programme is user driven, there are a number of opportunities for co-developing products which have not been realised. In particular, there are clear opportunities to work with private end-user sectors to curate products that have commercial viability and existing customership (D6.3). Such projects, particularly with sectors that have been resistant to adopting new technologies, may be an important way to gain trust in EO. The Copernicus Programme is dedicated to enabling the downstream private sector that benefits from free data provisions, as well as establishing a competitive space industry within the EU (See D1.5, D2.4, and D6.3). In order to strike a balance between upstream and downstream goals, it is critical to analyse the most suitable delivery mechanisms, determining which will provide the greatest benefits to both the EU

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economy and policy objectives. Co-developing products with sectors is key to using resources and tailoring technological advancement towards products and services which are likely to have the greatest benefits within Europe. An initial step towards this would be to recognise the EO water market segment within future EUSPA market report. This would include the Copernicus-enabled economic impacts within the EU, but also includes social impacts, towards a fairer water segment and also a circular water economy. One of the most promising collaborations as per the Water-ForCE engagement and research would be to develop near real-time flooding and immediate risk products that use scales directly relevant to the assurance and insurance sector (WP1, D6.3). It would also benefit Europe greatly to develop next generation products with professionals from the utilities and drinking water sectors. Member States are predicted to require between 20% and 170% increases in water utility expenditure to meet current standards by 2030, according to the OECD (2020). Hence, there is a great potential economic gain from products which can reduce these costs. There may also be commercial opportunities within high-revenue end-users such as the agriculture and energy sectors if products are a good problem-solution fit (D6.3).

4.1.4 Develop seamless integration into Digital Twins, Decision Support and GIS-based knowledge management for decision making

Incorporating Copernicus products into actionable information systems is required to realise ambitions of the programme across the water sector. Such systems can take a data-driven information approach through existing GIS tools, a data-driven impact modelling approach such as in decision support systems, or even include feedback mechanisms towards data collection and management such as typical of Digital Twins. Enabling the development of these approaches as a seamless extension to existing Copernicus products requires interoperable data access interfaces and data harmonisation (grids, formatting). To go further, the integration of analytical services within the Copernicus service landscape may be considered, which would enable a wider user base (D6.1). It is important, then, that some cohesive analysis is done to review the development of data and analysis portals to prevent duplication and user fatigue. A few digital twin projects are already underway, including the (European Digital Twin of the Ocean - DTO, Mercator Digital Twin of Ocean, and ESA's Destination Earth). Whilst these are likely to deliver powerful demonstrators, Digital Twins working at a variety of spatial scales and with varying degrees of data-model interaction across water management disciplines still require extensive demonstration effort. Both the development of such

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analytical services as an extension to the Copernicus product portfolio, and their integration into the Copernicus service offering should be the subject of feasibility, demonstrator, and application-specific studies. Example application areas may be found in ongoing 'lighthouse' projects.

4.2 Actions to develop a comprehensive suite of water products within the Copernicus Portfolio

Developing a suite of water products with the Copernicus Portfolio is essential for the future use of satellite EO within the water domain. Development of a comprehensive water portfolio will contribute to overcoming the incompatibility between the Copernicus portfolio and EU and global legislation (Bottleneck 3). In this section, the key variables that are desired are presented, based on user requirement analysis and consultation (see D2.4, D3.5). For each of these suggested products their maturity is assessed. The technological readiness (TRL) and implementation readiness (IRL) levels combine our analysis of scientific literature, the landscape of downstream service providers, and available resources. The integration readiness (IRL) should be interpreted here as the readiness of the concept to scale up, where low scores indicate remaining R&D elements, intermediate scores may indicated challenges in achieving validation (e.g. due to data scarcity), and high scores only require incorporation into the service portfolio (i.e., funding for data production).

The overall recommended action for this section is to expand the Copernicus water quality and -quantity portfolio. Many water products are already at a relatively high TRL level. However, properties of inland water bodies are highly diverse. As a result remote sensing methods developed for a certain type of waterbodies may not work in other waterbodies. Consequently, adding new products in the Copernicus portfolio requires validating the products over the whole range of water types available globally. However, this cannot be done due to a lack of in situ data for global validation. The lack of in situ component (Bottleneck 1) does not allow to characterise product uncertainties (Bottleneck 2) and expand the Copernicus inland water products portfolio. The actions needed to establish a dedicated in situ component are covered in Recommended Action 3. There are also a number of products that are dependent on new Sentinels to be fully realised, as covered by the recommended actions in Recommended Action 4.

4.2.1 Deliver products supporting monitoring and management under EU legislation

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There is a relatively narrow intersection between variables that can be obtained from remote sensing (as determined by physics) and those currently identified as indicators in EU legislation (as derived from water management practices, across physics, chemistry and hydrology). This is one of the reasons why the Copernicus Services deliver just a few products for the needs of EU legislation development and implementation. Nevertheless, there are multiple products which have been demonstrated at limited scale, but which require pan-European or global validation in order to be added to the Copernicus Services portfolio. It is recommended that action should be taken to collect necessary in situ data to allow inclusion of these high TRL level products in the Copernicus portfolio.

Water Framework Directive (WFD)

The WFD provides quality elements that are monitored for rivers, lakes, groundwater, transitional and coastal water bodies. To a large extent the quality elements are the same for all types of waterbodies and it is recommended that Copernicus Services deliver these products where feasible. At the moment Copernicus Services deliver only lake water surface temperature for the WFD (See Annex 3 for review of the Current Water-Related Service Elements). However, there are multiple quality elements in the Table below which are theoretically feasible and/or have already been demonstrated at a local scale, but require large scale validation (i.e. in situ data, Bottleneck 1).

Table 5. *Variables from the Water Framework Directive and the maturity of EO-derived estimation.*

WFD element	TRL	IRL	Comments	Action required	Delivery
Composition of aquatic flora	6	6	Broad groups of macroalgae and plants	in situ datasets for cal/val Research and development of product	Core
Abundance of aquatic flora	6	6	Percentage cover of benthic vegetation	in situ datasets for cal/val	Core
River continuity	7	6	Limited by spatial resolution of sensors	Deploy higher resolution satellite sensors (e.g. S2NG) in situ datasets for cal/val	Core
River width	7	6	Limited by spatial resolution of sensors	Deploy higher resolution satellite sensors in situ datasets for cal/val	Core
Depth (bathymetry)	7	8	Limited by water transparency	in situ datasets for cal/val	Core
Biomass of phytoplankton; frequency and intensity of blooms	7	8	In terms of chlorophyll-a	in situ datasets for cal/val	Core

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Quantity, structure and substrate of water bed	6	8	Limited number of benthic and substrate classes. Limited by water transparency	in situ datasets for cal/val	Core
Transparency	7	8	Secchi depth or vertical diffuse attenuation coefficient.	in situ datasets for cal/val	Core
Nutrient conditions	5	4	No direct observation possible; feasible in water bodies where optical proxies for nutrients exist, or through model-data assimilation; localized calibrations are essential.	in situ datasets for cal/val Research and development of product	Downstream or Core depending on scale
Structure of intertidal zone	6	6		in situ datasets for cal/val	Core

Bathing Water Directive (BWD)

Whilst the two major microbial indicators (intestinal enterococci and *Escherichia coli* counts) are not observable from satellite, assessment of the potential for proliferation of cyanobacteria and macro-algae is feasible, and some indicators for pollution risk may be considered.

Remote sensing of cyanobacteria may be considered mature, and is implemented in various countries and offered by several commercial providers. Product uncertainties have been described and tend to be high at low cyanobacteria biomass compared to other phytoplankton, thus the potential for early warning should not be overstated. At present the potentially toxic cyanobacteria can be monitored in large lakes only as Sentinel-2 does not have spectral bands necessary to detect the dominance of cyanobacteria in water. Sentinel-2NG will have the necessary spectral bands, but will not be launched in the coming decade.

The possibility of mapping macroalgae floating at or near the water surface has been widely demonstrated (see references in D2.4). Macroalgae washed onto beaches are likely quantifiable from high resolution imagery and/or using change detection methods. Improved spectral and spatial resolution of Senetinel-2NG will enhance the capabilities of future Copernicus Services.

Pollution risks associated with elevated turbidity or organic matter, such as common for sewage spills following heavy rain, may be identified using well established optical indicators, particularly turbidity and the concentration of chromophoric dissolved organic matter (CDOM). The former is already a

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mature product at regional scales whereas global validation of CDOM estimates is underway for lakes and would need extending to rivers, transitional and coastal water bodies. In rare cases, chemical pollution may result in increased transparency by removing phytoplankton. Thus, the result of elevated pollution may actually be clearer water. Other pollutants, such as plastic and other litter, or oil, can be found to float on the water surface, and studies exist proving their detectability in specific aquatic environments. Thus, methods targeting identifiable pollutants are within scope for wider implementation following further investment in R&D.

Table 6. *Variables from the Bathing Water Directive and the maturity of complementary satellite EO methods.*

Variable	TRL	IRL	Comments	Action required	Delivery
Cyanobacterial proliferation	6	6	Identification of blooms; limited early-warning potential without model forecasting.	in situ datasets for cal/val Deploy NG satellite sensors Research and development	Core
Proliferation of macroalgae	6	6	Near and at the water surface, beaches.	in situ datasets for cal/val Research and development	Core
Risk of short-term pollution					
Particulate matter	7	6	Turbidity, transparency and suspended solids feasible.	in situ datasets for cal/val Research and development	Core
Coloured dissolved organic matter	6	5	CDOM algorithms	in situ datasets for cal/val Research and development	Core
Floating matter	7	6	Floating matter algorithms	in situ datasets for cal/val Research and development Deploy NG satellite sensors	Core

Urban Wastewater Directive (UWWD)

The UWWD requires monitoring of variables which are mostly not observable through remote sensing. Total suspended solids (TSS) concentration is observable with remote sensing through interpretation of light (back)scattering by particles, which is closely related to the turbidity product included in the Land Service. Thus, the TSS product is feasible, but requires additional in situ observation data to be fully characterised.

Total phosphorus and total nitrogen are products that are highly desirable not only for the UWWD monitoring. At the local scale, correlations between TSS, phytoplankton biomass or CDOM, and total

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nutrient concentrations may be apparent, providing some opportunities for data-model assimilation to better interpret the nutrient fluxes and microbial transformations. However, mapping nutrients over large geographic areas is speculative and needs further research.

Table 7. *Variables from the Urban Wastewater Directive and the maturity of EO-derived estimation.*

Variable	TRL	IRL	Comments	Action required	Delivery
Total suspended solids	7	6	Closely related to the turbidity product delivered by the Land Monitoring Service.	in situ datasets for cal/val	Core
Total phosphorus			May be feasible in certain types of waterbodies	in situ datasets for cal/val Research and development	Downstream
Total nitrogen			May be feasible in certain types of waterbodies	in situ datasets for cal/val Research and development	Downstream

Floods directive (FD)

The FD was developed for assessment and management of floods risks and is aiming at reduction of the adverse consequences. The products delivered by the Copernicus Emergency Management Services have been developed to respond to the needs of this directive.

Directive on the quality of water intended for human consumption

The directive on the quality of water intended for human consumption aims to protect human health from the adverse effects of any contamination of water intended for human consumption. There are microbiological parameters, chemical parameters, and other indicator parameters to determine the risks. Turbidity, Total organic carbon and colour are the indicators that can potentially be mapped with remote sensing. Only turbidity is currently provided for around 4200 largest lakes by the Copernicus Land Services. The other indicators, and lack of the relevant products in the Copernicus Services portfolio, has been discussed above.

4.2.2 Deliver an extended set of water quality and - quantity products for ecosystem management

Water-ForCE identified more than 40 desired inland and near-coastal water quality and water quantity remote sensing products (D2.2, D2.4, D3.2) which occur at different levels of maturity and could potentially be included in the Copernicus portfolio after extensive validation effort (Bottleneck

1). This is an order of magnitude higher than the number of core products currently provided in the water quality domain. Thus, the priority is to expand the Copernicus water quality and water quantity portfolio. Some of the desired products are considered 'higher-level biogeochemical products', which may require combining observation and modelling disciplines, such as aquatic primary production (D2.4).

Eight broad groups of desirable products were identified (D2.2, D2.4, D3.2):

- Carbon fractions (dissolved organic carbon, coloured dissolved organic carbon, particulate organic carbon, total organic carbon, total inorganic carbon.).
- Shallow water products (bathymetry, benthic vegetation cover, benthic habitat types, carbon fixed by benthic habitats).
- Floating material products (plastic and other marine litter, floating cyanobacteria, macroalgal mats (e.g. *Ulva* or *Sargassum*), tree pollen, invasive nuisance plants (e.g. water hyacinth, duckweed)).
- Water bodies characteristics (lake area, -extent, and -circumference, river and lake morphology).
- Water level and river discharge products (partially available in Copernicus, though more elaborated products required by the end user).
- Soil data products (groundwater flow, hydraulic properties soil).
- Drought & flood products (temporality of streams, flood defence systems (implemented structures), elaborated evapotranspiration products).
- Interaction products (providing information on the interaction between sea-river, groundwater-river).

Observable variables that would complement WFD monitoring and reporting, as well as other variables mentioned in the preceding sections, should be considered relevant for management, but are not repeated in Table 8.

Table 8. *Variables for ecosystem management and the maturity of EO-derived estimation.*

Variable	TRL	IRL	Comments	Action required	Delivery
Dissolved organic carbon (DOC)	6	6	Not directly observable, but closely coupled with CDOM in inland water bodies. Relevant to carbon cycle	Research and development in situ datasets for cal/val	Core

			studies, drinking water industry.		
Coloured dissolved organic matter (CDOM)	6	6	The main proxy for DOC and TOC	Research and development in situ datasets for cal/val	Core
Total organic carbon (TOC)	6	6	Can be estimated from DOC/CDOM	Research and development in situ datasets for cal/val	Core
Particulate organic carbon (POC)	6	6	Well developed in ocean remote sensing, larger uncertainties likely in inland/coastal waters. Critical for aquatic carbon pump studies.	Research and development in situ datasets for cal/val	Core
Primary productivity	5	4	More developed in ocean studies. Studies in different lake environments needed. Combined observation/modelling.	Research and development in situ datasets for cal/val	Core
Floating aquatic plants (water hyacinth, duckweed etc)	7	6	Mapping of nuisance species requires further R&D.	Research and development In situ datasets for cal/val	Downstream
Benthic carbon	3	3	Currently missing in carbon budgets. Needed for carbon cycle studies and carbon accounting (SEEA). Low conceptual maturity.	Research and development in situ datasets for cal/val	Core
Benthic primary production	3	3	Low conceptual maturity. Coupled observation/modelling studies.	Research and development in situ datasets for cal/val	Downstream
Existing variables aggregated per waterbody.	8	8	Technically feasible	Ready	Core
Water bodies characteristics	7	4	Parameters missing for ecosystem monitoring and management are lake area, -extent, and -circumference, river and lake morphology	Research and development in situ datasets for cal/val	Core
Water level and river discharge	8	8	More detailed products needed to perform accurate monitoring and assessment.	Research and development in situ datasets for cal/val	Core
Soil data	7	6	Groundwater flow and hydraulic properties necessary to get a proper understanding of the complete water balance cycle.	Research and development in situ datasets for cal/val	Core
Drought and flood products	8	8	More detailed/accurate drought and flood assessments when incorporating parameters as temporarity of streams and flood defence structures.	Research and development in situ datasets for cal/val	Downstream

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Interaction products	3	1	Products reflecting the interaction between various sub systems (e.g. groundwater-river) are lacking though they may add valuable information on how to interpret data.	Research and development in situ datasets for cal/val	Downstream

4.2.3 Deliver products to support monitoring progress towards the Sustainable Development Goals

The EU has demonstrated dedication to achieving the Sustainable Development Goals and satellite EO products can be used to monitor and implement efforts. The recommended actions listed in Table 9 are directly relevant to SDG indicators or reporting tools (see D1.6 and D6.1). Various indicators that are achievable from satellite EO are relatively mature, whilst others require R&D or in situ data collection and are, therefore, less likely to contribute to the 2030 SDG agenda.

Table 9. *Sustainable Development Goal indicators and the maturity of relevant satellite EO-derived products.*

Indicator	TRL	IRL	Comments	Action required	Delivery
1.5.2 Direct economic loss attributed to disasters in relation to global gross domestic product (GDP).	2	5	Products that can help to determine water-related disaster range etc	Research and development Build trust & capacity in national departments	Unspecified
2.4.1 Proportion of agricultural area under productive and sustainable agriculture.	2	5	Determining if agriculture is sustainable relies on understanding of water availability in the catchment.	Research and development Build trust & capacity in national departments	Unspecified
3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services).	2	5	Determining the quality of water in the region.	Research and development Build trust & capacity in national departments	Unspecified
6.1.1 Proportion of population using safely managed drinking water services.	2	5	To determine the quality of water in the area - water extent, quality.	Research and development Build trust & capacity in national departments	Unspecified
6.3.1 Proportion of wastewater safely treated.	2	5	To determine the discharge of wastewater flow into	Research and development of product Build trust & capacity in national departments	Core

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			the environment, and water quality after treatment.		
6.3.2 Proportion of bodies of water with good ambient water quality.	6	7	Any observable water bodies can be included - uncertainties high for small water bodies. Groundwater excluded.	Innovation (upscaling) Build trust & capacity in national departments	Core
6.4.1 Change in water-use efficiency over time.	2	5	Reported per volume of water, considers water use by all economic activities (e.g., agriculture, industry and service sector). Requires modelling.	Research and development of product Build trust & capacity in national departments	Core
6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources.	7	7	Requires a modelling component.	Ready Innovation (high-resolution)	Core
6.6.1 Change in the extent of water-related ecosystems over time.	7	7	Multidecadal water body extent observations mature. Smaller water bodies possible with SWOT.	Ready Innovation (high-resolution)	Core

4.2.4 Deliver products for all Essential Climate Variables

It is recommended that Copernicus deliver products for missing water-related Essential Climate Variables, as requested by users and stakeholders (D3.5). While some products are already provided by the Copernicus Services through the Climate Service (C3S), other products only exist in their operational delivery format (e.g. Lake water-leaving reflectance, soil moisture). Some ocean ECV products, where synergy across the land-marine interface is required, include phytoplankton diversity, phytoplankton biomass, seagrass cover (areal extent), macroalgal canopy cover and composition, hard coral cover and composition, and pCO2.

4.2.5 Atmospherically corrected 'analysis-ready' data

It is recommended that Copernicus work towards offering analysis-ready data, and in particular, a validated water reflectance product. At present, many users (including national monitoring institutions) are not satisfied with the Copernicus products. First of all there are only two water quality products (turbidity and trophic state index) that are not indicators of any directives and usually not a

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part of any monitoring programs. There are many products that are locally feasible (see the tables above) and could be calculated from the water reflectance provided by the Copernicus Services. However, usually the reflectance product does not have sufficient accuracy at regional and local scale. Consequently, the users download L1 Sentinel imagery, select the best performing (for their area) atmospheric correction and then apply local water quality variable algorithms. Since atmospheric correction is the largest source of uncertainty in inland water remote sensing (D2.4), this would contribute to overcoming Bottleneck 2, limited trust in Copernicus water products. However, it cannot done before the Bottleneck 1 is solved.

A long term solution for the problem would be collection of necessary radiometry data by the respective Copernicus Services (e.g. establishing a network of supersites). A short term recommendation is coordinating and supporting atmospheric correction round robin exercises for AC validation under a wide range of atmospheric and water conditions (D2.2, D2.3). Finally, it would be important to encourage harmonisation between the atmospheric correction methods used by different Services as this will allow studying the water continuum (from lakes to rivers to seas). For example, Sen2water analysis-ready product is currently developed for Sentinel-2 MSI for both inland and coastal water applications.

4.3 Actions to better align in situ and remote sensing EO monitoring

The relationship between EO and in situ data collection has been extensively discussed among the Water-ForCE consortium, Copernicus users, and water professionals. The absence of data collections designed to support and improve Copernicus Services, alongside conventional monitoring and reporting, is arguably the most fundamental bottleneck of the current Copernicus Services to fulfil the needs of the water domain (Bottleneck 1). The reason for the prioritisation is that overcoming many of the other bottlenecks is contingent on the improvement of the availability of in situ data. For example, greater amount of in situ data is critical for developing necessary products to support EU and global legislation (Bottleneck 3), and to build trust among current and potential users (Bottleneck 2). To address Bottleneck 1, we promote four priority actions, listed below.

4.3.1 Establish cal/val supersites around the world covering the optical variability in water bodies

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The creation of a dedicated in situ component for inland and coastal water bodies is widely recognised through our investigation and stakeholder consultation as the highest priority action. The consortium suggests the establishment of a network of supersites representing global optical-biogeochemical diversity. This recommended action would require long-term funding, a consistent set of instrumentation, unified sampling and data protocols, uncertainty characterisation in line with FRM standards and coordinated data management. There are already various candidate sites around the world where physical and biogeochemical data are collected routinely and where expert support is available. There are also dedicated coastal/ocean sites such as MOBY and BOUSSOLE, from which expertise can be shared, which receive some support from space agencies. ESA supports for a couple of years HYPERNET network containing a couple of inland and coastal water sites. Additional sites may be part of existing networks with complementary aims (e.g. LTER, GLEON), and could form a core from which the network of supersites can grow. Coordination between Copernicus and space agencies is essential to ensure combined requirements for radiometric and downstream product validation can be met. Organising meetings among Entrusted Entities and decision makers to propose the benefits of supersites is a necessary step towards this action.

4.3.2 Adapt monitoring schemes to increase compatibility with satellite Earth Observation

Developing indicators for EU directives that can be supported through the Copernicus portfolio will enable natural use of remote sensing in monitoring and reporting. For example, such complex indicators may integrate data from remote sensing, in situ and modelling components. Reciprocally, the directives should encourage the use of satellite EO to complement in situ observations.

A current opportunity towards this action is evident in the Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2000/60/EC establishing a framework for Community action in the field of water policy, Directive 2006/118/EC on the protection of groundwater against pollution and deterioration and Directive 2008/105/EC on environmental quality standards in the field of water policy (COM(2022) 540 final 2022/0344 (COD)). Within the Common Implementation Strategy (CIS) for the Water Framework Directive the Working Group on Ecological Status (ECOSTAT) discusses e.g. innovative monitoring and assessment methods (remote sensing), best practice on monitoring, etc.

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4.3.3 Coordinate and agree on the collection of observation data to support enhanced and new satellite-based products

In addition to the establishment of cal/val supersites to support a range of water products, there is an opportunity to agree on a core set of reference variables and data collection strategies that will help develop and sustainably validate new satellite-based products. Coordination between experts is required to agree on international standards for in situ data collection, so that the data can be leveraged towards satellite products. Protocols are needed to describe both collection methods, including best practices for where and when to collect observations (D4.2). Of equal importance is establishing clear guidelines for metadata to ensure correct use and traceability of the data, e.g. to prevent duplication of records, to appropriately acknowledge data producers, and to provide feedback on data quality. Establishing these standards requires coordinated efforts of expert users, international monitoring programmes, organisations responsible for informing in situ communities and standardisation bodies. It is not suggested here to prioritise satellite EO development in data collection strategies, but to ensure the best return on investment. To start this process, a coordinating body must be identified. In the case if the Virtual Service or Copernicus Water Service scenarios will be chosen then the body will exist while in the case of other scenarios such a body has to be identified.

4.3.4 Build FAIR data repositories to store and share relevant in situ observation data

Currently, no in situ data is collected by the Copernicus Services (bottleneck 1). The Services are fully relying on data collected by other institutions (monitoring agencies, research projects, etc.). Decentralised data can only be used efficiently if they are shared under permissive licences, updates are readily accessible and reformatting or other interpretation requires relatively minor effort. This requires advocacy of FAIR principles at global scale. In addition, centralised data infrastructure could improve the efficiency of collecting and curating reference data for a wider range of services and products. There are data repositories (e.g., GEMStat, LIMNADES, GLORIA) which collate global datasets and attempt to provide a harmonised point of access, which could be further improved to increase their FAIR compliance. Water quantity and quality information may be considered sensitive, and the timely sharing of relevant data presents a (political) challenge in itself, where Europe could set a leading example. Coordination and consultation with existing data repositories and stakeholders (e.g., GEMstat, WWQA, GLEON) would be a necessary step towards this action.

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4.4 Actions towards a comprehensive satellite observation capability for exploitation within Water products and services

An identified bottleneck is the sub-optimal nature of existing Sentinel satellite missions for water products and water monitoring (Bottleneck 5). Better spectral, radiometric and spatial resolution as well as revisit time (i.e. sensors optimal for inland and coastal water research) would allow both development of new products and reduce the uncertainties of the current ones. Therefore, the following actions are designed to improve Copernicus space assets, based on requirements voiced by users and hence likely to improve the uptake of products within the water domain and other industries. For more detail on these recommendations, please refer to D2.5: Technical needs for future Sentinels. These recommendations have been relayed to the Sentinels Next Generation development team.

4.4.1 Sufficient spatial, temporal and radiometric resolution to resolve aquatic systems

Spatial, temporal and radiometric resolution are all important for water quantity and quality products and there is a need to increase the resolution of all parameters in the Next Generation (NG Sentinel missions (D2.4, D3.2, D3.5, D6.2; Bottleneck 5). Optimisation of radiometric, spatial and temporal resolution, in a single instrument and orbit, is a trade-off limited by the technical envelope of instrument design. The planned increase in NG Sentinels may be suitable for the needs of the water quantity community (D3.5). A spatial resolution from 5 up to 33 m across optical, thermal and radar altimetry sensors may be satisfactory to enhance the water quality and water quantity monitoring potential for inland and coastal water bodies (D2.4, D3.2, D3.5). An important option for obtaining a higher temporal resolution for water quantity and quality products can be obtained by a constellation of EO sensors (D2.5, D3.5). Both optical and radar missions which are formed of multiple satellites, are also recommended for increasing revisit times, and mitigating the risks of technical permanent problems (D3.5). It is known to the consortium at the point of writing this that both S2 and S3 satellites are not likely to launch for 10 to 15 years, but that ensuring that inland water monitoring is a key target for these satellites is a critical short-term recommendation.

4.4.2 Appropriate wavebands for water quality and corresponding water quantity evapotranspiration estimates

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Key wavebands have been identified (D3.5) to enhance optical multispectral sensors for water applications, including higher-level biogeochemical products (e.g., cyanobacteria specific pigment phycocyanin). Ideally, future satellite constellations will include instruments with continuous narrow-band (5 - 8 nm) UV to NIR hyperspectral capability and SWIR bands (D2.4, D2.5). Water quantity users also benefit from a higher resolution thermal band for evapotranspiration monitoring (D3.5). See more in D6.2. Recommendations from the Water-ForCE consortium were forwarded to respective ESA teams responsible for the next generation missions.

4.4.3 Appropriate sun glint avoidance across all optical instruments

Optical satellite missions designed for water applications have opted for either tilt or roll for sun glint avoidance. For example, OLCI has a 12-degrees westward roll to avoid sun glint. For future instruments, a 4° - 5° fixed westward tilt has been recommended (D2.4). Sentinel-2 MSI is not tilted, and Sentinel-2 NG is planned to point to nadir as well. Thus, there is scope to optimise the suitability of future Sentinels for water applications.

4.4.4 Continuity of gravimetric missions for groundwater monitoring

Groundwater monitoring is increasingly important as groundwater depletion has increased in recent decades and there is strong user demand for ground water products (D5.2, D3.5, D3.2). Groundwater quality is a part of SDG indicator 6.3, although remote sensing means are lacking to address this. Gravimetric missions can, however, facilitate monitoring of groundwater quantity and understanding the transfer process between surface and ground levels.

The recommended action is to provide consistency across different gravimetric missions[7]. GOCE (ESA mission) ended in 2012, NASA launched the GRACE-FO mission in 2018 as the continuity of GRACE (2012-2017). Designed as a 5-years mission GRACE FO is still in good shape. However, the next ESA gravimetry mission, MAGIC, which is developed in cooperation with NASA, is planned for 2032, potentially leaving a gap between GRACE-FO and MAGIC. It would be beneficial for the user community to have reassurance on the continuity for groundwater monitoring and the long-term plans for next generation gravimetric missions (D3.5).

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[7] Bonsor, H.C.; Mansour, M.M.; MacDonald, A.M.; Hughes, A.G.; Hipkin, R.G.; Bedada, T. "Interpretation of GRACE data of the Nile Basin using a groundwater recharge model." Hydrol. Earth Syst. Sci. Discuss. 2010, 7, 4501–4533.

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4.4.5 Virtual constellations to aid data integration and harmonisation

Virtual satellite sensor constellations are the seamless integration of data delivered from multiple satellite missions, including those from different providers, offering complementary properties. Thermal remote sensing (e.g., Copernicus LSTM Expansion mission, Landsat), dedicated satellite missions (e.g., FLEX) and additional instruments (multi-angular polarimeter, PAN camera) collected in synergy with optical observations are encouraged to support new applications, services and to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness (D2.3). Mission cooperation (e.g., CHIME and SBG) to attain complementary orbits can also vastly improve the temporal resolution for innovative water products. Night-time observations (e.g., proposed GALENE, the first dedicated inland and near-coastal water satellite) and geostationary satellites (e.g., GLIMR) would also support valuable applications and new services in an improved temporal domain. This also helps to reduce the risk of technical problems and data gaps (D3.5). To build virtual constellations, inter-agency cooperation is required on data formats and delivery, and on joint analysis of observation uncertainty properties.

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5. Conclusion and overall recommendations

Water is central to life and our economy, yet is also the medium through which we feel the impacts of climate through floods and droughts. Water, therefore, has direct intersections with biodiversity declines, carbon losses, food security threats, and complex human health, social and economic impacts. Climate extremes are only set to intensify in the future. At the same time we need catchment wide intelligence on water continuum to find and optimise nature-based solutions to mitigate these climate extremes, whilst also addressing the challenges of the Green Deal and driving opportunities in the Blue Economy. Satellite based Earth observation, coupled with in-situ data and predictive modelling has a key role to support society and the wider water sector in tackling these water related challenges and opportunities.

The Copernicus Services (then GMES Services) were launched more than 15 years ago and the space component (Sentinel satellites) has been operational now for a decade. The storage and processing of satellite data required large infrastructure, fast internet connections for imagery download and dedicated teams of specialists to run all these activities at the times when GMES and Copernicus Services were launched. In the present day, however, the economic and business environment in which the Copernicus Services are operating has changed profoundly. For example, a decade ago, launching satellites was the prerogative of large countries or international organisations like the ESA, whereas nowadays there are an increasing number of satellites being launched and operated by the private sector. The private sector operates constellations of satellites, ranging from a few to a few hundred satellites, including radar and very high spatial resolution satellites as well as hyperspectral sensors. Today, EO data storage is largely cloud-based and delivered through commercial providers. Data processing has also been moved to the cloud, reducing the need in downloading and storage from users side. Anyone with access to cloud services and a few (often freely available) software tools can perform tasks that only recently would have had to be delivered by organisations like the Copernicus Services. Now only a few services remain out of reach for private providers, such as near-real-time services, like the EFAS and GloFAS. However, these services may also become financially and technically feasible in the not too distant future. In response to this changing landscape, the

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Copernicus Services have a need to think long-term about maximising the sustainability and relevance of their contributions in the future.

The investments made in the innovative development of the Copernicus Programme have been returned through significant economic benefits, estimated between EUR 16.2 and 21.3 billion in 2019 (PwC, 2019), as well as important social, environmental and strategic impacts. These impacts include reducing casualties in natural disasters, reducing areas burnt by wildfires through better civil protection responses and strengthening the collaboration between states at a global scale for civil protection. While many benefits of the Copernicus programme have been realised, the Water-ForCE consortium have analysed the impact of water-related Copernicus products and services on the water domain and other related end-user sectors, and found it was not reaching potential, and meeting desired impacts (Annex 3, D2.2, D3.2, D4.2, D5.2). The need to invest in technology and processes is critical to protect Europe against future changes, particularly given the substantial increase in Member State expenditure on water management to maintain current water quality standards in the near future (Recommended Action 3). There is, therefore, a need for the Copernicus Services to adapt to the changing world in order not to lose its relevance but also to ensure that it provides the data and intelligence for society to adapt to climate extremes, to support the Green Recovery, and for Blue Growth opportunities.

This Roadmap is a guide and starting point for the European Commission and Copernicus Service to develop a plan for Copernicus impact on water. The document provides insight into the user needs and potential benefits of improving the Copernicus portfolio for water products and services, as well as suggested actions and a pathway to get there. The roadmap has been developed by a consortium of over 20 partners, including research, private and downstream EO providers, and over 800 stakeholders and experts have been consulted on its content. User engagement and expert analysis led to the identification of 8 main bottlenecks which limit the success of Copernicus Services in the water domain. In its most distilled form, the key recommendation to improve the impact of the Copernicus for water is to solve these bottlenecks. The sooner these bottlenecks are overcome the faster the ambition of the Copernicus Programme for water will be realised. In particular, reflection on the bottleneck highlights a huge dependency on one single bottleneck: the lack of a dedicated in situ component (Bottleneck 1), which substantially contributes to the lack of trust in water products

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and services (Bottleneck 2), and the lack of compatibility between the Copernicus portfolio and EU and global legislation (Bottleneck 3). This bottleneck is applicable to both water quantity and water quality, but water quality was identified as most critically limited. Further bottlenecks include fragmentation of the existing Copernicus Services (Bottleneck 4), sub-optimal Sentinels sensors for inland waters (Bottlenecks 5), and a lack of funding mechanisms in support of Copernicus inland water portfolio (Bottleneck 6). User engagement also highlighted a lack of awareness within key user communities of the Copernicus offering (Bottleneck 7) and that water has been insufficiently recognised within the Copernicus Programme thus far (Bottleneck 8).

As a next step, four scenarios for the next generation of Copernicus Services were developed which provide the European Commission, the entrusted entities and the member states with possible "pathways" towards a coordinated, coherent and trusted monitoring system for inland waters. Through SWOT (strengths-weaknesses-opportunities-threats) analysis, two were found to make a substantial improvement towards addressing the bottlenecks, at a pace befitting the urgency of the need for better monitoring and improved management of scarce freshwater resources within the EU and globally. These were the "Water as a virtual Service" scenario, and "Water as a core Copernicus Service". In the Water as a virtual Service scenario, Copernicus water products and services are presented as a service where users are the "value creator" and the virtual service becomes the "value facilitator". This scenario has a great potential to address most of the bottlenecks and improve the support of Copernicus within the water sector in Europe and globally, but this is contingent on the execution and maintenance of the virtual service, which can determine how adaptive it is to evolving user requirements and sustain a useful role within the water sector. The "Water as a core Copernicus Service" scenario is the ultimate scenario, where water is a dedicated Copernicus Service, equal to the existing six core Services. This scenario would demonstrate strong political will towards placing water on the agenda for Copernicus and Europe, and hence has potential to address all the bottlenecks, to a large degree. Although requiring substantially more restructuring of the Copernicus Programme, and legally challenging to implement, it is expected to have a substantial benefit in both upstream (data provision) and downstream (EO uptake) processes within Copernicus and certainly a beneficial impact in the water domain and water related sectors. The Copernicus Thematic Hub is the option that has been selected by the Commission as a step forward. However, it does not solve

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almost any of the issues listed in the Space call (Chapter 1.3) and is lacking the potential to overcome any of the bottlenecks identified by the Water-ForCE consortium. It does offer some improvement on the Business as Usual scenario, particularly if the opportunities of this scenario are fully utilised and the Thematic Hub will advance towards the Virtual Service rather than remaining a data portal as it is currently planned.

Lastly, for the Copernicus programme to overcome the bottlenecks and realise its ambition within the water domain, the Water-ForCE consortium also offers a series of recommended actions, which are necessary at different stages of the Copernicus value change. Although these recommended actions are independent of the scenario, the scenario for the next generation of the Copernicus Services will influence the pace at which actions can be implemented and the political will behind them. The recommended actions have been thought out to lead the Copernicus programme towards delivering the necessary data, products and services for water, that are coordinated, coherent, validated, trusted and accessible. Additionally, these recommended actions will help the Programme deliver a framework and confidence for the data to be used increasingly in policy implementation and inform decision making in environmental contexts under increasing threat from a rapidly changing environment and climate extremes. Thus, resulting in a far greater impact on the water domain and water related sectors.

Finally, to show commitment to Copernicus for water, the following recommendations are advised, to various actors, as initial steps to take the Roadmap further;

1. The Commission are recommended to use this Roadmap and the findings from Water-ForCE deliverables to conduct a cost-benefit analysis of the scenarios developed, including knowledge of budgets.
2. EUSPA is recommended to consider the inclusion of Water as an identifiable market sector to fully comprehend the relevance of the EO water sector in Europe.
3. The Commission is recommended to conduct investigation into products which Water-ForCE identify with high Technology Readiness, to make them fit-for-purpose for policy, downstream user and business.

4. Future water-related EU legislation to consider Earth observation as a possibility for monitoring.
5. Member States to champion the integration of Earth Observation within situ national monitoring.
6. The Commission, Member States and the European Environment Agency to start to establish a taskforce to address the in situ needs for water products and services, using the options provided by Water-ForCE (e.g. establish supersites).
7. The Commission is recommended to elaborate the scenario analysis provided by including knowledge of budgets, into a full impact assessment.
8. The European Space Agency and other space agencies are to discuss providing 'analysis-ready' data (i.e. water reflectance) for water targets.

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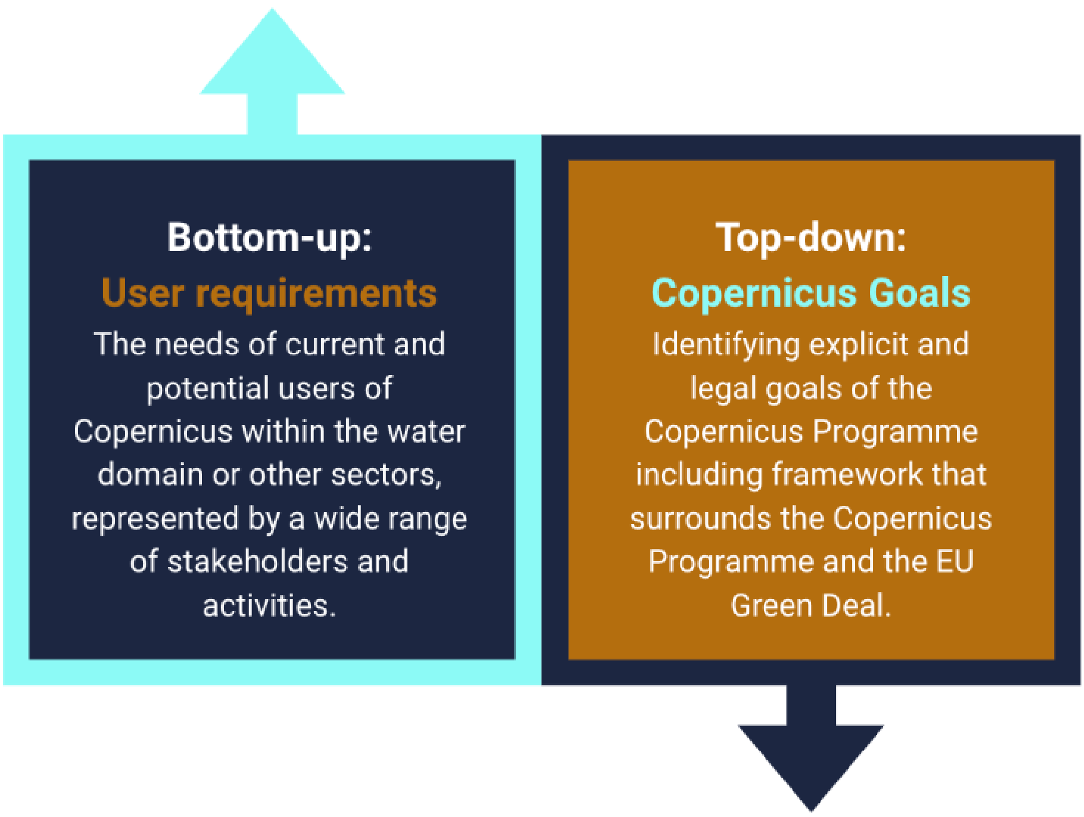
ANNEX 1: Water-ForCE Methodology

The impacts of the Copernicus Programme for the water domain are considered from both a bottom-up and top-down perspective (Figure 1). This meant consulting 800+ stakeholders of the Copernicus Programme from within the water domain and relevant sectors to determine the requirements of different users (see D1.2, D6.3, Annex 1), while also investigating the legal and regulatory framework of the Copernicus Programme and wider EU documentation to understand what goals need to be met. These two approaches are explained in the sections below.

Figure A1. *Schematic showing the bottom-up and top-down approach.*



The objectives of the Copernicus Programme have been interpreted within the context of the water domain (D1.3). The role of the Copernicus Programme is outlined in law (see Regulations (EU) 2021/696). Water-related issues and the broader water domain are integrated into many of the

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Copernicus objectives. Additionally, the European Green Deal is an overarching guide for the EU response to climate change, setting clear priorities for a sustainable future. Combining these, we can summarize the role of the Copernicus Programme within the Water domain through the following objectives:

- Support the **development of Union and Members States' policies**: Water Framework Directive, Bathing Water Directive, Flood Risk Directive, Marine Framework Directive, and future policies.
- Support the **monitoring and implementation of policy** in related fields such as agriculture, transport, food security, and energy.
- Support of the Union's external and development cooperation policies including the United Nation's **Sustainable Development Goals**.
- Improve **scientific understanding** of the global water cycle, benefits and effectiveness of climate adaptation, pollution, carbon and nutrient cycles and biodiversity / fragmentation / water continuum governance.
- Enable **innovative environmental applications** in fields such as agriculture, water resources and cultural heritage.
- Increase **Copernicus-enabled economic growth** within water-related value chains particularly those that contribute towards clean and circular economies.

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ANNEX 2: Water-ForCE consortium

Water-ForCE is a consortium of water quantity and quality experts, including 20 partners from 10 countries (Figure 2A, Table A1.). The analysis presented in this Roadmap were performed based on the extensive knowledge of the Water-ForCE partners in different fields (policy, water quantity, water quality, in situ measurements, remote sensing, modelling, etc), and through engaging global community through thematic scientific working groups (27 countries and many sectors), webinars and workshops (250+ registrants from 50+ countries) as well as public surveys (500+ responses from 5 continents). Engagement included all major sectors of both water and EO domains, including National Space Agencies, European and Member States Institutions (e.g Member States' Water Authorities), International Organisations, the private sector, operators of in-situ measurement stations, and leading scientific experts in the identified fields such imagery processing, aquatic optics, data fusion and data assimilation for hydrodynamic modeling. The project deliverables that led to the formation of the Roadmap are available on the Water-ForCE website (www.waterforce.eu,), the Water-ForCE Zenodo (https://zenodo.org/communities/waterforce_2020) and the EU Cordis Project page (https://cordis.europa.eu/project/id/101004186).

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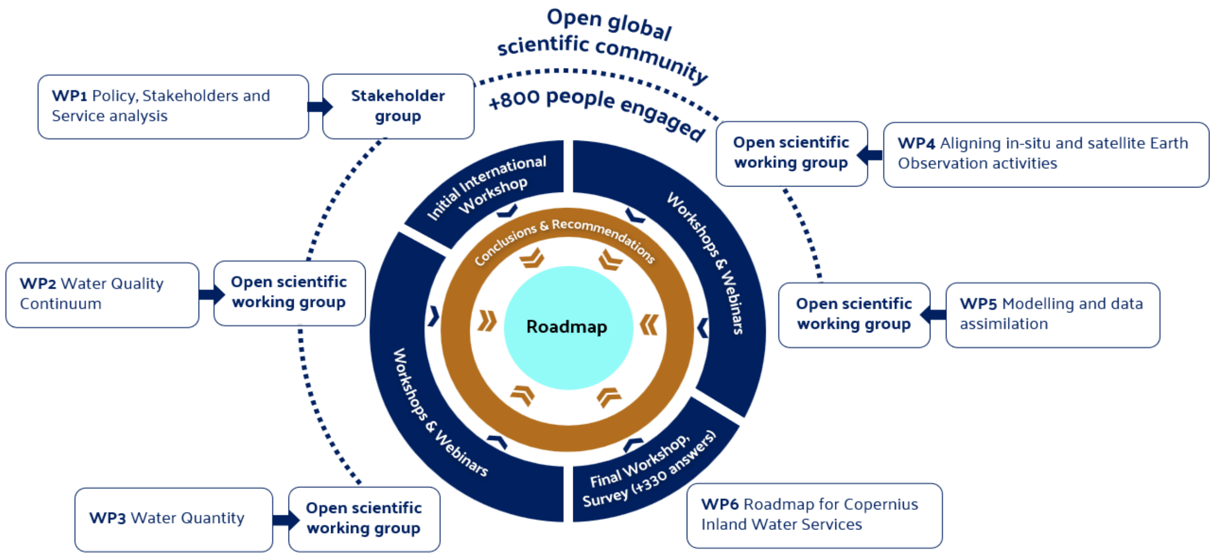
Figure A2. *Summary of the Water-ForCE project and process.*



Water-ForCE Consortium

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__Table A1.__ List of contributors of the Water-ForCE project

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		Eva Feldbacher
		Martin Tschikof
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		Ester Prat
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SINERGISE LABORATORIJ ZA GEOGRAFSKEINFORMACIJSKE SISTEME DOO	Slovenia	Grega Milcinski
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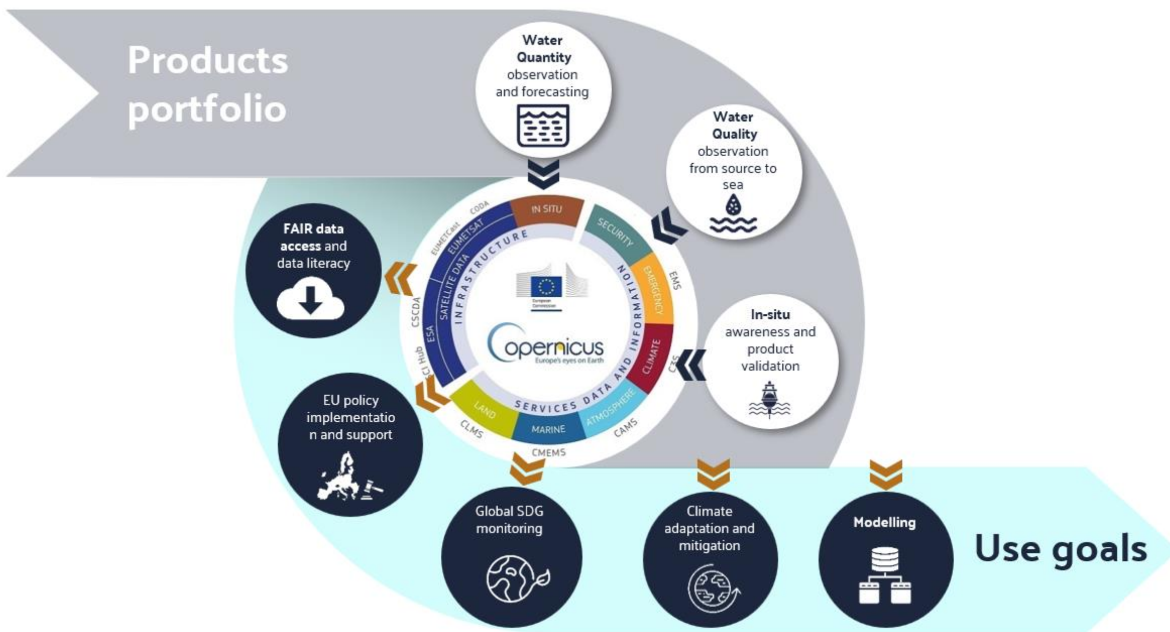
ANNEX 3: Current Water-related Service elements

Water products are an essential part of the Copernicus data and information services and found across the Land (CLMS), Marine (CMEMS), Climate (C3S), Atmosphere (CAMS), and Emergency (CEMS) services. To support the impact objectives, implementing the Findable, Accessible, Interoperable and Reusable (FAIR) data access principles to current (and future) service elements is instrumental. However, a harmonised 'water-related' service layer does not currently exist and the relevant data and information elements found across the Services and the Copernicus Programme follow a range of designs. The individual components are highlighted in the following sections.

Figure A3. *Summary of Copernicus Services Water-related elements.*



3.1 Water Quantity portfolio

Water quantity related products are provided by Land, Marine, Atmosphere, Climate and Emergency Services. The Copernicus Services already offer a wide variety of data products and tools related to water quantity and the hydrological cycle (D3.2). Counting all regional variants, 844 products are currently offered (Table A2). There are also many external data platforms (ESA, JAXA, NOAA) outside the Copernicus Services. While water quantity products are numerous (see D3.2 for full list), they do not adequately meet the needs of users (including modelers) nor the requirements to achieve the desired Copernicus outcomes. A summary of our findings is presented below (see **D3.5**, **D5.2** and **D3.2** for additional detail).

Products: Data products related to water storage, precipitation and/or snow & ice variables are highly represented, while evapotranspiration, soil moisture, soil maps, groundwater, and discharge are poorly represented (D3.5, D5.2). Most evapotranspiration products are generated by C3S reanalysis models (they don't derive directly from satellite observations). Absent variables notably include inland water bathymetry. A summary of water quantity products available from Copernicus are shown in Table 1 (D3.2).

Table A2. *List of water quantity product types separated by major theme.*

Product Type	Climate (C3S)	Atmosphere (CAMS)	Emergency (CEMS)	Land (CLMS)	Marine (CMEMS)	Total
Anthropogenic			1			1
Drought	4		8	7		19
Evapotranspiration	45	2				47
Floods			41			41
Geographic zones				10		10
Ground motion				3		3
Humidity	23	1				24
Hydrology	55		5	2		62
Land cover/Land use	10	10		59		79
Precipitation	68	8	19			95
Snow & Ice cover	159	6	7	10	41	223
Soil/Soil Moisture	36		11	6		53
Water storage	107	34				141
Waterbodies	24	2	1	19		46
Total	531	63	93	116	41	844

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Spatial resolution: The spatial resolution varies between observation disciplines and resulting products. A higher spatial resolution than currently offered is often desired by users. For example, snowmelt products (snow melt and snow cover) would be appropriate at 10-1000 m resolution for hydrological applications, surface water variables are needed at <1 km, and soil moisture is needed at higher resolution and evapotranspiration products for agriculture applications demand 20-30 m resolution, an order of magnitude finer than current Sentinel-3 capabilities (See D3.3, D3.5).

Temporal resolution: The temporal resolution of products varies between products, and is generally at the required level, with some exceptions such as hourly/daily groundwater recharge and daily soil moisture products.

Long-term continuity: Long time series are crucial to build time trends of several essential variables and to understand the impact of climate change in all components of the water cycle. Products such as those derived from gravimetry missions are only available in shorter time series (D3.5), decreasing their relevance for groundwater storage monitoring.

Spatial coverage: Global products are available for nearly all relevant variables, however, in general, they have lower spatial resolution than the equivalent regional products (D3.2).

Validation: The level of validation and maturity of products varies. Products with low validation include precipitation run-off, air temperature, drought, and water storage (D5.2).

Uncertainty: The characterisation and propagation of observation uncertainty is variably included in the water quantity product portfolio. Products specific to a particular lake or region may lack documented validation entirely. Of all assessed products, soil moisture has the lowest presence of product uncertainty information (D5.2).

3.2 Water Quality portfolio

There are currently only two water quality products (turbidity and trophic state index) for inland waters (Copernicus Land Service) and four (chlorophyll-a, turbidity, total suspended matter and light

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backscattering) for coastal waters, from the Marine Service. Both inland and coastal water quality products include water reflectance, an Essential Climate Variable and analysis-ready product for downstream production of additional optical water quality variables. In addition, skin temperature is provided across inland water bodies of sufficient size in the Land and Climate Services and for marine areas in the Marine Service.

The Services do not allow continuous observation of any parameters as continuum from inland to coastal waters. The only product provided for both inland and coastal waters is turbidity. However, the processing chains and algorithmic assumptions used between the Marine (CMEMS) and Land (CLMS) services are also differently optimised (D2.2, D2.3), although the high-resolution component of the Marine Service (HROC) blends atmospheric correction approaches used in marine and inland water domains, for the 20-km coastal zone.

Products: The key optical and thermal products that are observable from satellites, and for which globally validated approaches exist, are covered between the Land and Marine Services, with water surface temperature also offered through the Climate Service. A summary of the distribution of these products is given in Table A3 (D2.2).

Table A3. *List of water quality product types.*

	Climate (C3S)	Atmosphere (CAMS)	Emergency (CEMS)	Land (CLMS)	Marine (CMEMS)	Total
Chlorophyll-a					1	1
Light backscattering					1	1
Total suspended matter					1	1
Turbidity				1	1	2
Trophic State Index				1		1
Skin temperature	1			1	1	3
Total	1	0	0	3	5	9

The gap analysis carried out (D2.2) showed that higher level biogeochemical products (e.g. primary production) can only be developed once “lower level” satellite products are established as inputs. D2.4

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identified that there are three broad groups of remote sensing products that are critically lacking from user perspective:

- Carbon related products (e.g. coloured dissolved organic matter, (CDOM), dissolved organic carbon (DOC), total organic carbon (TOC), dissolved inorganic carbon (DIC), total inorganic carbon (TIC), CO2).
- Shallow water products (e.g. bathymetry, benthic habitat cover (%) and type, benthic primary production, benthic carbon).
- Floating matter products (e.g. plastics and other litter, cyanobacterial surface scum, macroalgae (Sargassum, Ulva) or floating plants (water hyacinth, duckweed), pollen, nuisance plants like water Hyacinth, etc.).

It was found (D2.4) that candidate methods to address additional water quality products have been developed at local or regional scale, with some available as (local) services outside Copernicus. Some of these products and services (e.g. areas blocked by water Hyacinth) are well-suited to local-scale delivery by downstream EO industry. Other products, particularly those with policy relevance (carbon and nutrient cycle, climate) are suitable for development at continental to global scale within the Copernicus Services. This will require a variable degree of product development and validation, and suitable in situ reference data collection efforts (D2.4, D6.2) however is hard to solve without solving the Bottleneck 1.

The retrieval of some additional variables might further be facilitated by the next generation of Sentinels, for example a set of additional bands (e.g. 'phycocyanin' bands at 620 nm and 650 nm as proxy for cyanobacteria biomass) proposed for Sentinel-2 NG (D2.5). However, the launch of Sentinel-2NG is not foreseen in the next decade. A dedicated inland water satellite mission (e.g. GALENE proposed for the ESA Earth Explorer 12 FutureEO call, D2.5) could make a pivotal contribution for monitoring the water continuum. But again, the launch of the first dedicated inland and near-coastal water satellite is also not foreseen in the next decade. These developments will gain relevance in future Copernicus funding cycles corresponding to post-2030 satellite launches.

Spatial resolution: The spatial resolution of Copernicus water quality products ranges from 100 m to 1 km. The spatial resolution is too coarse to fully match user needs and particularly the size

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distribution of inland water bodies. At present, the 300 m spatial resolution lake water quality products allow study of 4200 of the world's largest lakes, out of an estimated 117 million lakes on Earth that are larger than 50 m in diameter. These 4200 lakes cover >90% of the inland water volume, but smaller water bodies are particularly sensitive to environmental change, and globally important to water security. Water-ForCE analysis (D2.2, D2.4, D2.5) showed that spatial resolutions from 5-30 m are desirable. This resolution would conceptually make all small water bodies on Earth observable, although the physical limitations of estimating optical water quality of small water bodies are insufficiently known to assess the possibilities (with acceptable product uncertainty) at this scale.

Temporal resolution: Temporal resolution of the products ranges from 10 days for CGLS lake water products to daily-monthly for CMEMS coastal products (D2.2). The CGLS products are aggregated from up-to-daily 300 m resolution observations (based on OLCI), whereas coastal water quality products with 100 m resolution are provided as covered with Sentinel-2 imagery (i.e. full coverage every 3-5 days). Relevant biogeochemical and mixing processes in inland and coastal waters occur at hourly to daily time scales. There is, therefore, a gap between the user requirement and the service provision.

Spatial coverage: The 100 m CGLS lake water quality products are available for all lakes in Europe and Africa which are also included in the 300 m product, plus any surrounding smaller water bodies found in the same satellite scenes. Products at 300 m are available for over 4200 lakes globally, representing >70% of global freshwater surface area (and >90% by volume). Lakes ECV monitoring is covered by the ESA CCI which in part (water level and temperature) also feeds into C3S. CMEMS high-resolution coastal products, available in Copernicus Coastal Hub, are for coastal stripes of 20 km for all European seas (D2.2).

Validation: The level of validation and maturity of products is highly variable. Validation reports for the CGLS and CMEMS products are accessible at the respective portals. For example, most of CMEMS coastal products are not validated. The only validated product - chlorophyll-a, shows poor performance in optically complex coastal waters (e.g. R^2 for Chl-a ranges 0.04 - 0.22 in European seas except the Mediterranean). The two 100 m Sentinel-2 MSI CGLS water quality products (turbidity and trophic state index) are validated against corresponding 300 m Sentinel-3 OLCI satellite products rather than independent in situ observations.

Uncertainty: The largest source of uncertainty of aquatic remote sensing products is the atmospheric

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correction. All water quality products are derived from water reflectance obtained after applying atmospheric correction. Adequate atmospheric correction methods are therefore crucial. However, in situ radiometric observation data, which are needed to develop and validate these methods, are primarily collected in research projects, and fail to cover the whole range of optical variability present in inland and coastal waters. Moreover, remote sensing reflectance uncertainty is higher in the vicinity of land, due to strong optical contrasts and signal interference in the atmosphere, and in optically shallow conditions where water bottom reflectance may interfere (D2.2, D2.3). Consequently, more and varied in situ data are needed to characterise and propagate uncertainties due to algorithm, sensor, water type, observation angle, and adjacency effects, modulated by atmospheric composition.

3.3 In situ component

The Copernicus in situ (CIS) component collates water quality data collected by the EU member states as part of their monitoring programmes, and water quantity data collected by hydrometeorological stations around the world (D1.3). Additionally, data from research projects that share results publicly are included in the CIS data collections.

The global network of hydrometeorological stations is wide, equipped with standardised instruments, using consistent methodology, and largely funded by national governments or their sponsors. Therefore, water quantity data needed to develop and validate remotely sensed or modelled Copernicus products has relatively good availability. Geographic and thematic gaps can nevertheless be observed (e.g. on soil moisture in Africa).

A larger discrepancy is observed in the water quality domain. Sample data collected in national monitoring programmes (e.g. for WFD reporting) contains relatively few variables that overlap with the observation potential from remote sensing. Reflectance and other key bio-optical data are only collected by research projects.

Our key findings concerning the in situ component are summarised below (see D4.2, D4.3, D4.4, D4.5 and D4.6 for additional detail);

Variables provided: Currently many water quantity and some water quality variables are being collected by players outside the Copernicus Programme. However, most of the water quality data collected in Europe in the frame of different directives is irrelevant for Copernicus as a large number of the variables cannot be mapped with remote sensing (e.g. river fish species composition, lake biological oxygen demand, etc.). On the other hand, optically active water constituents, like total suspended matter or coloured dissolved organic matter, are not measured by conventional in situ monitoring programs. The three broad groups of missing (mainly due to the lack of in situ data) products (D2.4) were listed in the Chapter above. There is also a lack of water leaving reflectance data needed for improving atmospheric correction, removing the adjacency effects (D2.2) or to allow cal/val of different water quality products (D4.3).

Compatibility with EO data: Of the > 80 water quality elements monitored for the WFD, around ten show promising overlap with remote sensing technology[8]. To optimise compatibility between conventional and satellite observation, sampling locations and times (ideally within several hours) require strategic planning, whilst weather conditions (cloud cover) may still limit their uptake (D4.5). Water quantity data collection would benefit from strategic placement of in situ stations (e.g. river gauges) to match altimeter tracks.

Spatial coverage: To optimally support global Copernicus products, in situ data collections should also be globally representative. Water quantity data collections are globally coordinated, whereas equivalent action for water quality data sources has been limited to community initiatives (LIMNADES, GLORIA) without sustained support. Geographic gaps are evident, particularly in Africa. This scarcity has an impact on the uncertainty assessment of Copernicus remote sensing and model-based products.

Spatial and temporal resolution: Water quality data are typically collected at one location of a water body 8e.g. in the deepest point of the lake). Shore-based sampling is problematic due to the higher expected product uncertainty from remote sensing coupled with higher temporal variability along coasts. Spatial and temporal variability of water quality parameters is very high in lakes and coastal waters. However, high-frequency sampling to overcome this inherent variability is relatively uncommon.

Automated monitoring platforms (e.g. bay or lake buoys, river stations) and associated data collection,

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[8] Papathanasopoulou et al. (2019). Satellite-assisted monitoring of water quality to support the implementation of the Water Framework Directive (1.1). Zenodo. https://doi.org/10.5281/zenodo.3556478

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storage and sharing are largely arranged within research projects and hydrological networks. Further harmonisation would be needed to fully support the Copernicus Services from these sources.

Uncertainty: In situ data collection typically relies on traceability to national standards in the form of measurement protocols, and not consistently accompanied by measurement uncertainty information. This limits the applicability of in situ data in assessing satellite-based or modelled products.

3.4 The current Copernicus portfolio for implementing EU policies

Surface water temperature (WFD QE3-1-2) for large lakes and coastal waters is currently the only parameter provided by the Copernicus Services for the **Water Framework Directive (WFD)** out of more than 80 quality elements for rivers, lakes, transitional and coastal waters. Less than half of the 80 quality elements could theoretically be mapped by remote sensing methods. Concentration of chlorophyll-a, typically used as a proxy of phytoplankton biomass, also in the context of the WFD is available in CMEMS. However, the correlation of this product with in situ data is very poor in all European seas except the Mediterranean as was noted above. Several EU Member States have their own inland and coastal water monitoring programmes using raw Copernicus data and local remote sensing products (as Copernicus products are not available or are unreliable), and some countries use these products for WFD reporting purposes.

In the **Urban Waste Water Treatment Directive (UWWT)**, monitoring of total suspended solids is most closely associated with turbidity estimates provided by the Land and Marine services. However, currently the Copernicus Services do not provide any means to monitor implementation of the UWWT directive. Total nitrogen and total phosphorus have been mapped in some inland and coastal waters using remote sensing despite the fact that they cannot be directly observed and require intermediate hydrodynamic and/or biogeochemical modelling efforts to leverage remote sensing observations. However, extensive studies on possible optical proxies of the nutrients are needed before nutrients could be included in the Copernicus Services portfolio and it is not guaranteed that methods for mapping total nitrogen and total phosphorus over a large number of lakes and coastal waters are feasible at all.

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The **Bathing Water Directive (BWD)** focuses primarily on bacterial contamination of waters. Bacterial contamination cannot be assessed directly by remote sensing. Thus, it is not surprising that the Copernicus portfolio does not contain any products relevant to the BWD, On the other hand, the BWD further mentions proliferation of cyanobacteria and macroalgae as indicators of deteriorated water quality. Some cyanobacteria may release toxins sometimes and massive amounts of macroalgae (freely floating fragments) can damage coastal ecosystems by reducing underwater light for other marine organisms or causing anoxia during decomposition in shallow waters. Remote sensing of cyanobacteria and macroalgal blooms is relatively mature. However, no attempt has been made to develop robust remote sensing products that could be included in the Copernicus Services portfolio, as this requires massive amounts of in situ data over the whole range of inland and coastal waters used for bathing.

The directive on the **quality of water intended for human consumption** aims to protect human health from the adverse effects of any contamination of water intended for human consumption. There are microbiological parameters, chemical parameters, and other indicator parameters to determine the risks. Turbidity, Total organic carbon and colour are the indicators that can potentially be mapped with remote sensing. Only turbidity is provided for around 4200 largest lakes by the Copernicus Land Services.

As a summary, it can be said that the current six Copernicus Services do not deliver almost anything for the development and implementation of the EU water quality related directives.

The **Floods Directive (FD)** was developed for assessment and management of floods risks and is aiming at reduction of the adverse consequences. The products delivered by the Copernicus Emergency Management Services have been developed to respond to the needs of this directive.

3.5 Current portfolio for supporting Sustainable Development goals

There are 247 indicators under the UN Sustainable Development Goals. Water-related EO products have relevance for many of these (D1.6), either as a direct method for reporting on a specific indicator or as a supporting dataset. Currently, Copernicus products are known to contribute only to indicator: 6.6.1 *Change in the extent of water-related ecosystems over time*.

The relevance of Copernicus products to **water quantity indicators of the SDGs.** includes 5 indicators. Two of these, 6.4.2 *Level of water stress: freshwater withdrawal as a proportion of available*

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freshwater resources and 6.6.1 *Change in the extent of water-related ecosystems over time*, could be addressed using existing water level and water extent products.

Among the **water quality indicators of the SDGs**, indicator 6.3.2 *Proportion of bodies of water with good ambient water quality* requires a baseline water quality estimate per water body, and subsequent assessment of change (improving or declining). With current Copernicus capabilities, this is possible for larger and medium sized lakes using water quality variables of turbidity, lake trophic state index and chlorophyll-a (in coastal waters) derived from water-leaving reflectance. Additionally, remote sensing could deliver on SDG 14.1.1 *Index of Coastal Eutrophication and floating plastic debris density, but a suitable contribution is not currently included in* the Copernicus Services. Water quality products have further relevance as a contributing indicator for SDG 14.4.1 *Proportion of fish stocks within biologically sustainable levels, with contributed modelling efforts*..

There are many **other water-related indicators** for which EO products from Copernicus could be used in combination with other forms of information or within models. Flood and drought products are typical examples, and combined with socio-economic modelling, indicators such as SDG 1.5.2 *Direct economic loss attributed to disasters in relation to global gross domestic product*, may find benefit.

3.6 FAIR principles in Copernicus Infrastructure

An assessment of FAIR principles across the Copernicus Core Services highlighted several issues, as shown in Table A4 (for detail see D4.6). Only Accessibility in the Marine Service scored satisfactory.

Table A4. *FAIRness scores for four of the Copernicus Services.*

Service	**F**indable	**A**ccessible	**I**nteroperable	**R**eusable	Overall score
Marine	0.48	0.89	0.22	0.14	43%
Atmosphere	0.41	0.33	0.33	0.22	32%
Climate	0.41	0.33	0.33	0.22	32%
Land	0.24	0.33	0.1	0.1	14%

The Copernicus Data Space Ecosystem (CDSE, https://dataspace.copernicus.eu/), launched in

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2023, is designed to align with the FAIR principles and represents a notable step towards enhancing findability, accessibility, interoperability, and reusability of EO data. The CDSE "one-stop-shop" approach is designed to streamline the data experience, addressing the fragmentation problem of previous platforms, and enabling access to Copernicus geospatial assets through new visualisation and processing tools.

An important aspect of the CDSE design is its integration of the openEO platform and the SpatioTemporal Asset Catalog (STAC), which ensure that data stored within the ecosystem is well-described, facilitating effective search and discovery. This aligns with the Findability principle of the FAIR framework. By implementing openEO, the platform allows users to process and analyse data using standardised APIs, contributing to the Interoperability and Reusability principles of FAIR. Water-ForCE did not assess the new platform in detail, but the CDSE may be considered a significant advance in meeting user concerns on EO data accessibility and user friendliness.

Data access: In situ data sharing is not managed by Copernicus and is not harmonised across sources, posing a specific challenge for data curation and data users (D4.3). FAIR principles are not uniformly followed (D4.6).

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ANNEX 4: Addition to Recommended Actions

The Recommended Actions presented in the main Roadmap are further summarized in the table below which includes the addition of Delivery references, Technology Readiness Levels, Implementation Readiness Levels, Timeframe and link to the bottlenecks (Table A5).

Table A5. *Summary of Priority Actions, their state of technological maturity (TRL) and implementation readiness (IRL), likely timeframe for implementation, and notable existing bottlenecks.*

PA	Priority actions	Ref Del.	TRL	IRL	Timeframe (yrs)	Existing bottlenecks and precursors
5.1.1	Sufficient spatial, temporal and radiometric resolution of Sentinels to resolve aquatic systems	D2.2, D2.4, D2.5, D3.2, D5.2	**5**	**4**	10 - 15	5. Sentinel sensors suboptimal for inland waters coordination, advocacy of benefits 6. Lack of funding mechanisms
5.1.2	Appropriate wavebands (up to hyperspectral) for water quality and corresponding water quantity evapotranspiration estimates	D2.4, D2.5, D3.5	**6**	**3**	10 - 15	5. Sentinel sensors suboptimal for inland waters
5.1.3	Appropriate sun glint avoidance across all optical instruments	D2.4, D2.5, D3.5	**3**	**3**	10 - 15	5. Sentinel sensors suboptimal for inland waters
5.1.4	Gravimetric missions for groundwater monitoring	D3.5	**3**	**NA**	10 - 15	5. Sentinel sensors suboptimal for inland waters
5.1.5	Virtual constellations to aid data integration and harmonisation	D2.5, D3.5	**8**	**5**	10 - 15	4. Fragmentation of existing Copernicus Services 8. Water domain insufficiently recognized within Copernicus Programme
5.2.1	Establish cal/val supersites around the world representative of optical variability in water bodies, observing variables that are also observable by satellites	D4.3, D2.2, D2.3, D2.4	**6**	**5**	**10 - 15**	1. Lack of a dedicated in situ component
5.2.2	Adapt Member States monitoring schemes to increase compatibility with satellite Earth Observation	D4.3, WP1 synthesis	**2**	**1**	10 - 15	1. Lack of a dedicated in situ component PA02
5.2.3	Coordinate and agree on the collection of observation data to support enhanced and new satellite-based products	D4.2	**8**	**7**	5 - 10	1. Lack of a dedicated in situ component PA02

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5.2.4	Build FAIR data repositories to store and share relevant in situ observation data	D2.3, D4.3, D4.2	**6**	**4**	5 - 10	1. Lack of a dedicated in situ component 7. Lack of awareness within key user communities
5.3.1	Products supporting monitoring and management of EU policy and legislative instruments	D3.3	**5-7**	**4-8**	0 -15	3. Lack of compatibility between EO and EU legislation and international monitoring initiatives. Coordination, funding, technology NG sentinels 5. Sentinel sensors suboptimal for inland waters 6. Lack of funding mechanisms in support of Copernicus Services inland water portfolio 7. Lack of awareness within key user communities
5.3.2	An extended set of water quality products for ecosystem management	D2.2, D2.3, D2.4	**3-7**	**4-6**	0 - 15	
5.3.3	Products to support monitoring progress towards the SDGs	D1.6	**2-7**	**5-7**	0 - 15	
5.3.4	Products for all Essential Climate Variables	D1.6	**5**	**6**	5-10	
5.3.5	Atmospherically corrected 'analysis-ready data' products	D2.2, D2.3	**8**	**7**	0 - 10	??Coordination, currently ongoing.
5.4.1	Increase "satellite literacy" in relevant agencies within all levels of environmental management	D2.2, D2.3, D5.4	**7.**	**3**	0 - 5	2. Limited trust in Copernicus water products 7. Lack of awareness within key user communities. Advocacy and getting key people on board, training
5.4.2	Foster synergy between water research, management and governance communities → Fig 5 Foster synergy between in situ and satellite EO activities with member states and national agencies	D3.3, D1.3	**7.**	**3**	0 - 5	4. Fragmentation of existing Copernicus Services 7. Lack of awareness within key user communities Coordination project Improve Copernicus portfolio for inland and coastal water 8. Water domain insufficiently recognized within Copernicus Programme
5.4.3	Co-develop products with professionals in the water industry and other end-user sectors (insurance, water utilities, energy etc)	D3.3, D6.3	**6**	**1**	5 - 10	
5.4.5	Develop projects on Digital Twins, Decision Support Systems, GIS-based knowledge management systems for decision making	WP1 synthesis	**6**	**6**	5 - 10	3. Lack of compatibility between EO and EU directives and international monitoring initiatives 7. Lack of awareness within key user communities Coordination project Improve Copernicus portfolio for inland and coastal water 8. Water domain insufficiently recognized within Copernicus Programme Intergovernmental funding, collate previous work

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ANNEX 5: Water-ForCE deliverables

The Water-ForCE project has resulted in a wealth of output documents that are made available through the Water-ForCE Zenodo and on the Water-ForCE website.

Table 2. *List of deliverables*

Title	Link
Stakeholder list (Deliverable 1.1)	https://zenodo.org/records/10361215
Public domain and business identification (Deliverable 1.2)	https://zenodo.org/records/10363751
Links between mission-services-applications (Deliverable 1.3)	https://zenodo.org/records/10444804
End-user needs and requirements (Deliverable 1.4)	https://zenodo.org/records/10444843
Innovation needs and opportunities (Deliverable 1.5)	https://zenodo.org/records/10444881
Links with water SDGs and ECVs (Deliverable 1.6)	https://zenodo.org/records/10444917
Work package 1 Synthesis document	https://zenodo.org/records/10719577
Water quality working group (Deliverable 2.1)	https://zenodo.org/records/10719637
Analysis of current Copernicus water quality portfolio (Deliverable 2.2)	https://zenodo.org/records/10718669
Atmospheric corrections (Deliverable 2.3)	https://zenodo.org/records/10357236
Water-ForCE Atmospheric Correction Workshop. Questionnaire Results	https://zenodo.org/records/7540303
Higher-level biogeochemical products and gaps in current Copernicus water quality portfolio (Deliverable 2.4)	https://zenodo.org/records/10069459
Technical needs for future sentinels (Deliverable 2.5)	https://zenodo.org/records/10718824
Workshop - Water quantity and modelling and data assimilation (Deliverable 3.1)	https://zenodo.org/records/10693638
Review document on Copernicus products related to the hydrological water balance (Deliverable 3.2)	https://zenodo.org/records/10693666

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Review document and recommendation on the use of Copernicus products and services supporting water management (Deliverable 3.3)	https://zenodo.org/records/10666363
Review of state of the art use of models and satellite EO observations for water resources modelling (Deliverable 3.4)	https://zenodo.org/records/10650692
Sentinel missions for inland water quantity (Deliverable 3.5)	https://zenodo.org/records/10663715
An international "live" working group for in situ and satellite EO monitoring (Deliverable 4.1)	https://zenodo.org/records/10589486
Standards-of-practice for in situ networks and data-intensive monitoring devices (Deliverable 4.2)	https://zenodo.org/records/10649381
Report on the organisation and storage of in situ data (Deliverable 4.3)	https://zenodo.org/records/10719647
Outcomes of the Water-ForCE Workshop on Citizen Science for validation of water related satellite products (Deliverable 4.4)	https://zenodo.org/records/7361601
Potential new higher-level products for Copernicus water research (Deliverable 4.5)	https://zenodo.org/records/10589743
Guidelines to enable interoperability of in situ networks and connection with GEOSS (Deliverable 4.6)	https://zenodo.org/records/10717437
Training course materials: Introduction to Remote Sensing of Water Quality in Lakes	https://zenodo.org/records/6517601
Outcomes of the Expert Workshop on in situ calibration and validation of satellite products of water quality and hydrology	https://zenodo.org/records/5789232
Survey response of the H2020 Water-ForCE expert meeting on In situ calibration and validation of satellite products of water quality and hydrology	https://zenodo.org/records/5119010
Copernicus EO needs assessment for modelers and decisionmakers (Deliverable 5.1)	https://zenodo.org/records/10651070

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Survey Results: Identifying the needs of Copernicus Services for modelling water quantity and water quality	https://zenodo.org/records/7734657
Copernicus Services and Products - Modelling (Deliverable 5.2)	https://zenodo.org/records/10654446
Review document on Exploring the user of Artificial Intelligence (AI) to Optimize the Exploitation of satellite EO and modeling data (Deliverable 5.3)	https://zenodo.org/records/10693487
Value of satellite EO-enhanced models for policy and decision making (Deliverable 5.4)	https://zenodo.org/records/10654828
Capacity building requirements for Copernicus Inland Waters (Deliverable 6.1)	https://zenodo.org/records/10719668
Priorities for Research and innovation for Copernicus (Deliverable 6.2)	https://zenodo.org/records/8191712
Opportunities for Business Innovation and Service Delivery for Policy (Deliverable 6.3)	https://zenodo.org/records/10719626
Project dissemination and communication plan (Deliverable 7.1)	https://zenodo.org/records/10719680
Report on the Project Web page (Deliverable 7.2)	https://zenodo.org/records/10717949
Workshop materials (Deliverable 7.3)	https://zenodo.org/records/10717995
Events dissemination and communication (Deliverable 7.4)	https://zenodo.org/records/10718013
Management Structure Executive and Advisory Board (Deliverable 8.1)	https://zenodo.org/records/10716724
Interim Technical Report (Deliverable 8.2)	https://zenodo.org/records/10716804
Technical progress and Planning templates (Deliverable 8.3)	https://zenodo.org/records/10716848
Project implementation plan and milestones (Deliverable 8.4)	https://zenodo.org/records/10716897
Templates for task planning and WP Progress Reports (Deliverable 8.5)	https://zenodo.org/records/10716926
Project implementation plan and milestones (Deliverable 8.6)	https://zenodo.org/records/10716941
First data management plan (Deliverable 8.7)	https://zenodo.org/records/10716974

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Second data management plan (Deliverable 8.8)	https://zenodo.org/records/10717007

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