SDG Indicator 6.6.1 – EO Support Sheet
November 2022

Indicator	**6.6.1** Change in the extent of water-related ecosystems over time		
Target	6.6. By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.		
Custodian(s)	UN Environment Programme (UNEP) and the Secretariat of the Ramsar Convention on Wetlands	Tier	I (since Nov 2018)

Current approach and challenges

The SDG indicator 6.6.1 has two custodian agencies (UNEP and Ramsar Secretariat), with the implication that two SDG Indicator metadata files are provided with different methodologies. Although the two custodian agencies have made some efforts to align their monitoring and reporting guidelines, there are still some differences between both methods, which explains why the 2 methodologies are handled separately in this EO support sheet. Commonalities between both approaches are highlighted when needed.

SDG Indicator Metadata 6.6.1a. (UNEP)

A brief description of the UNEP monitoring and reporting methodology for SDG indicator 6.6.1 is provided in the SDG Indicator Metadata 6.6.1a (latest update in July 2022), while the full monitoring details are described in the "*Monitoring Methodology Indicator 6.6.1, Measuring change in the extent of water-related ecosystems over time"* and in the on-line documentation available on the *Freshwater Ecosystems Explorer* of the SDG 6.6.1a data portal (www.sdg661.app).

The UNEP SDG 6.6.1 indicator tracks changes over time in the extent of water-related ecosystems, as well as in the quantity and quality of water within them. The indicator has several sub-indicators capturing different changes on different types of water-related ecosystems:

1) lakes (surface areas and water quality),
2) rivers (surface areas and river flows),
3) reservoirs (surface areas and water quality),
4) vegetated wetlands (surface areas),
5) mangroves (surface areas),
6) aquifers (ground water levels).

Changes in extent of water-related ecosystems include three components, which are changes in the spatial extent (or surface areas), changes in the quality, and changes in the quantity, as per below:

	Water-related ecosystems					
	Lakes	**Reservoirs**	**Rivers**	**Wetlands**	**Mangroves**	**Aquifers**
Spatial extent	▨	▨	▨	▨	▨	N/A
Quality/Condition	▨	▨	N/A	N/A	N/A	N/A
Quantity/Flow	N/A	N/A	▨	N/A	N/A	▨

N/A = No requirement to be monitored for SDG Indicator 6.6.1a

The SDG Indicator methodology uses a monitoring approach divided in 2 levels, with a total of 9 sub-indicators (note that the spatial extent and water quality of reservoirs are addressed together in the UNEP *SDG Indicator Metadata 6.6.1a)*.

The numbering scheme provided below has been added for clarity purposes but is not used in the SDG indicator metadata file from UNEP.

Level 1: sub-Indicators based on globally available datasets from Earth Observation, which are requested to be validated by countries against their own methodologies and data:

Sub-Indicator 1.1: spatial extent and change of lakes and rivers (permanent surface water areas)

Sub-Indicator 1.2: spatial extent and change of lakes and rivers (seasonal surface water areas)

Sub-Indicator 1.3: spatial extent and change of reservoirs (minimum and maximum areas)

Sub-Indicator 1.4: water quality of lakes (turbidity and trophic state)

Sub-indicator 1.5: water quality of reservoirs (turbidity and trophic state)

Sub-Indicator 1.6: spatial extent and change of inland vegetated wetlands

Sub-Indicator 1.7: spatial extent and change of mangroves

Level 2: sub-indicators based on data collected by countries, from national in-situ measurements or modelled data:

Sub-Indicator 2.1: quantity of water in rivers and estuaries (river discharge)

Sub-Indicator 2.2: quantity of groundwater within aquifers (groundwater levels)

Data from each sub-indicator are aggregated in a second step into national statistics on water-related ecosystem changes, using 2 levels of aggregation: at country levels and at watershed / river basin levels.

It should be noted that inland vegetated wetlands include marshes, peatlands, swamps, bogs and fens, vegetated parts of floodplains as well as rice paddies and flood recession agriculture, but not coastal mangroves which are handled separately. This implies that the UNEP methodology for the SDG 6.6.1 indicator does not strictly apply the definition of wetlands from the Ramsar Convention on wetlands.

SDG Indicator 6.6.1 baseline, monitoring and reporting methodology:

1. Level 1 sub-indicators

The level 1 sub-Indicators are based on globally available datasets derived from satellite observations, which are requested to be validated by countries against their own methodologies and datasets.

Each Level 1 sub-indicator (i.e. permanent water areas in lakes and rivers; seasonal water areas in lakes and rivers; reservoir minimum and maximum areas; inland vegetated wetland areas; mangrove areas; reservoir water quality; lake water quality) is computed separately from different existing EO-based global datasets, which are produced independently using different computational methods.

All Level 1 sub-indicators (including their aggregations into administrative and watershed statistics) are available, with supporting documentations, on the *Freshwater Ecosystems Explorer* of the UN Water SDG 6.6.1 data portal (www.sdg661.app).

The Level 1 methodological guidelines proposes a progressive monitoring approach, which means that countries can benefit from the availability of global data products (i.e., EO global datasets) on water-related ecosystems, but can also (when data and capacity exists in the countries) use nationally produced data to complement and/or augment the quality of the national extracts from existing global EO datasets.

1.1. Level 1 sub-indicators on spatial extent and change

(to be computed on rivers & lakes, reservoirs, vegetated wetlands and mangroves)

The sub-indicators on the spatial extent and change of water related ecosystems (5 sub-indicators in total) have to be computed separately for each of the ecosystem types:

- spatial extent and change of natural open water bodies (lakes, rivers, and estuaries)[1],
- spatial extent and change of reservoirs (dams, flooded areas such as opencast mines and quarries, water bodies created by hydro-engineering projects),
- spatial extent and change of inland vegetated wetlands (swamps, bogs and fens, peatlands, marshes, rice paddies, and flood recession agriculture),
- and spatial extent and change of mangroves.

Sub-Indicators 1.1 and 1.2 (spatial extent and change of permanent and seasonal surfaces waters in lakes and rivers) are based on the Global Surface Water dataset from the Joint Research Centre of the European Commission (EC), which provides monthly occurrences of surface waters for the last 38 years (starting in 1984). National extracts of the JRC Global Surface Water dataset are requested to be validated by countries against their own methodologies and datasets. Once validated, the datasets are used to calculate the changes in the spatial extent over time, in five-year intervals, using the 5 years of 2000-2004 as a baseline

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[1] The spatial extent of natural open water bodies (rivers and lakes) has 2 sub-indicators: one sub-indicator on the changes to permanent waters, and on sub-indicator on the changes to seasonal waters.

period and to be compared against any subsequent 5-year target period. For each 5-year period the water state (permanent, seasonal or no water) is decided by a majority rule, and the water transitions between the baseline and the target period is subsequently used to compute the percentage change (Δ) in the spatial extent of permanent and seasonal waters (cf. equation 1):

$$Equation\ 1\text{:}\ \Delta = \frac{(\alpha - \beta) + (\rho - \sigma)}{\varepsilon + \beta + \sigma} \times 100$$

with the following parameter for computing **permanent surface water dynamics**:

Δ – percentage change in spatial extent
α – New permanent water (i.e. conversion of a no water place into a permanent water place)
β – Lost permanent water (i.e. conversion of a permanent water place into a no water place)
ρ – Seasonal to permanent (i.e. conversion of seasonal water into permanent water)
σ – Permanent to seasonal (i.e. conversion of permanent water into seasonal water)
ε – Permanent water surfaces (i.e. area where water is always observed)

and the following parameters for computing **seasonal water dynamics**:

Δ – percentage change in spatial extent
α – New seasonal water (i.e. conversion of a no water place into a seasonal water place)
β – Lost seasonal water (i.e. conversion of a seasonal water place into a no water place)
ρ – Permanent to seasonal (i.e. conversion of permanent water into seasonal water)
σ – Seasonal to permanent (i.e. conversion of seasonal water into permanent water)
ε – Seasonal water surfaces (i.e. area where seasonal water is always observed)

It is well noted that the resulting impact of a gain or loss in surface areas need to be locally contextualized, which implies that gain or loss of surface waters can be beneficial or detrimental, depending on the local context.

Sub-Indicator 1.3 (spatial extent and change of reservoirs) is also based on the Global Surface Water dataset from the EC Joint Research Centre, combined with other global datasets such as the Global Reservoirs and Dam Database (Lehner et all, 2011), and Global Digital Surface and Elevation models (such as 30m ALOS World 3D and 30m SRTM DEM).

Although conceptually clear, in practice differentiating artificial water bodies from lakes in satellite imagery is a non-trivial task. JRC applied an expert system classifier to separate natural and artificial water bodies and to produce a global reservoir dynamics dataset, which today consists of 8,869 reservoirs, and which will be continuously updated as new reservoirs (e.g. new dams) are built.

The changes in reservoir area is calculated both as a change in minimum reservoir extent and as change in maximum reservoir extent. The calculation of minimum water extent is like the calculation of permanent surface water dynamics (Equation 1) but performed only for water bodies identified as reservoirs. The calculation of maximum reservoir extent also relies on Equation 1 but using an extended set of parameters presented in Equation 2:

$$Equation\ 2\text{:}\ \Delta = [((\alpha - \beta) + (\rho - \sigma))\ /\ \gamma] \times 100$$

Where:

Δ – percentage change in spatial extent
α – New permanent water (i.e. conversion of a no water place into a permanent water place)
β – Lost permanent water (i.e. conversion of a permanent water place into a no water place)
ρ – New seasonal water (i.e. conversion of a no water place into a seasonal water place)
σ – Lost seasonal water (i.e. conversion of a seasonal water place into a no water place)
ϑ – Permanent to seasonal (i.e. conversion of permanent water into seasonal water)
∂ – Seasonal to permanent (i.e. conversion of seasonal water into permanent water)
ε – Permanent water surfaces (i.e. area where water is always observed)
ϵ – Seasonal water surfaces (i.e. area where seasonal water is always observed)
$\gamma = (\varepsilon + \beta + \vartheta) + (\epsilon + \sigma + \partial)$

Sub-Indicator 1.6 (spatial extent and change of inland vegetated wetlands)

In the SDG 6.6.1a methodology, inland vegetated wetlands include areas of marshes, peatlands, swamps, bogs and fens, vegetated parts of flood plains as well as rice paddies and flood recession agriculture, but not coastal mangroves, which are handled in another level 1 sub-indicator. Intertidal and sub-tidal wetlands (e.g. tidal flats, seagrass meadows, coral reefs, etc.) are also excluded from the inland vegetated wetlands and are not considered in SDG indicator 6.6.1.

Despite the existence of international efforts to develop automated robust approaches for global wetland inventories, at this stage there is still no global dataset available on inland vegetated wetlands, at appropriate scale (at least 30m spatial resolution) and with the required accuracies. As part of the UNEP SDG 6.6.1a monitoring methodology, a high resolution global map of in-land vegetated wetlands has been produced by DHI to support countries monitoring the spatial extent on wetlands and reporting on SDG 6.6.1. The main objective was to fill the existing global data gap in the availability of wetland inventories (see also the *SDG indicator Metadata 6.6.1b* on the status of national wetland inventories in the Ramsar Convention).

The global map on inland vegetated wetlands was produced for the year 2017, using satellite observations from a 3-year period (2016-2018) to cope with the inherent annual variations in wetland dynamics and avoid annual biases (which can happen for example during dry years). The global map on inland vegetated wetlands represents a first rapid assessment of the global distribution of vegetated wetlands.

The current availability of global wetland datasets doesn't allow yet to compute percentage changes in the gain and loss of inland vegetated wetlands. Future updates will enable change statistics to be computed and displayed on the Freshwater Ecosystems Explorer (cf. www.sdg661.app).

Once updates will be available, it will be possible to calculate the changes in wetland areas from the baseline reference period:

$$Equation\ 2: \quad \Delta = \frac{\gamma - \beta}{\beta} \times 100$$

Where:

Δ – percentage change in the spatial extent of vegetated wetlands;
β – the spatial wetland area for the baseline reference period;
γ – the spatial area for the reporting period.

Sub-Indicator 1.7 (spatial extent and change of mangroves) is based on the Global Mangrove Watch (GMW) dataset (GMW v.3.0), which was produced in 2 phases: first with the computation of a global map showing mangrove areas for the year 2010, and then by producing ten additional and consistent annual data layers (for years 1996, 2007, 2008, 2009, 2015,2016, 2017, 2018, 2019, 2020) from the detection of mangrove changes (gains and losses) with respect to the year 2010. The current method is based on L-band SAR data (JERS-1, ALOS PALSAR and ALOS-2 PALSAR-2) and multispectral optical data (Landsat 5-7).

For the production of national statistics on SDG indicator 6.6.1, the year 2000 has been chosen as the baseline year to ensure consistency with the baseline year used for the surface water dynamics in rivers, lakes and reservoirs. The GMW 1996 annual dataset has been used a proxy for the 2020 baseline year.

The percentage changes (Δ) in the spatial extent of mangroves (sub-indicator 1.7) are computed by comparing annual mangrove extents to the baseline year:

$$Equation\ 3: \quad \Delta = \frac{\gamma - \beta}{\beta} \times 100$$

Where:

Δ – percentage change in the spatial extent of mangroves;
β – the spatial mangrove area for the 2000 baseline reference year;
γ – the national spatial extent of any other subsequent annual period.

1.2. Level 1 sub-indicators on water quality

(to be computed on lakes and reservoirs)

Sub-Indicator 1.4 and 1.5 (water quality of lakes and reservoirs) are based on the Lake Water Quality (LWQ) products from the Copernicus Global Land Service (CGLS) of the European Commission.

Earth Observation can only provide information on concentrations of in-water materials that affect the colour of water, i.e. its optical properties. Although there are many other water quality parameters such as dissolved oxygen, electrical conductivity, nitrogen, phosphorus, and pH, that determine overall water quality, they do not change the optical properties of the water body and are not included in these sub-indicators.

The CGLS LWQ global dataset provides two water quality parameters in lakes and reservoirs:

- Turbidity (derived from the measurements of suspended solids)
- Trophic State Index (derived from the measurements of chlorophyll-a used as a proxy of phytoplankton biomass).

Both parameters are measured at 300m spatial resolution and are available for a total of 4,265 lakes (including reservoirs) and have been made available on a yearly basis for the periods 2006 - 2010 (based on observations from the Envisat MERIS sensor) and 2017-2022 (based on observations from the Sentinel 3 OLCI sensors).

The reference baseline is identical for both trophic state and turbidity parameters, and is computed from monthly averages across a 5 year period (2006-2010).

The percentage changes (Δ) in turbidity and trophic state for a given month are computed for every year by comparing annual monthly data, starting in 2017:

$$Equation\ 4{:}\quad \Delta = \frac{Monthly\ average - Monthly\ baseline}{Monthly\ baseline} \times 100$$

The final statistics to be reported represent the number of lakes impacted by a degradation of their environmental conditions (i.e., showing a deviation in turbidity and trophic state from the baseline) compared to the total number of lakes within a country.

Each event (i.e., a lake/reservoir affected by environmental degradation) is considered indicative of a degradation in water quality and is meant to encourage countries to investigate why such event occurred and determine if any remedial action is required. The locations where percentage change is excessive can be targeted for increased water quality monitoring and management.

2. Level 2 sub-indicators

The level-2 sub-indicators are based on in-situ data collected from national in-situ measurements, complemented by modelled data.

2.1. Level 2 sub-indicator on river discharge

(to be computed on rivers)

Sub-Indicator 2.1 measures the changes in the volume of water flowing downstream in rivers and estuaries, also called river discharge.

Although the methodology provided for this sub-indicator is flexible, depending on the specificities of countries, the state of their river basins and the national resources available, countries should adhere to the following basic monitoring and reporting guidelines:

- Countries are required to provide the total annual discharge for all major rivers and monitor changes in river discharge across years.
- Discharge data from each major river monitored should be collected at least once per month. This data should then be averaged to obtain an annual average discharge per river.
- Each basin should have a minimum of one sampling location, at the point where its water exits into another basin or at the exit point from major tributaries.

The in-situ monitoring methods for river discharge are flexible and can include gauging stations, current meters, or even modelled discharges from hydrological/hydraulic models (preferably complemented with in-situ data, where possible, to ensure accuracy).

Countries are requested to report on the changes in river discharge by submitting 5 years of data on annual average discharges per major river. The data from these 5 years are averaged to smooth short-term variability. To generate percentage change of discharge over time, a common 5-year reference baseline for all river basins must be established. This baseline period will be used to calculate the percentage change of discharge for any subsequent 5-year period.

To calculate percentage change in discharge for each five year period with respect to the reference period, the following formula is used:

Where:

$$Equation\ 5\text{: Percentage Change in Discharge}=\frac{(\beta-\gamma)}{\beta}\times 100$$

Where
β = historical 5-year reference discharge (to be determined by countries based on their data)
γ = the average discharge over the 5 year period of interest

2.2. Level 2 sub-indicator on groundwaters

(to be computed on aquifers)

Sub-Indicator 2.2 measures the changes in the quantity of groundwaters within aquifers.

Although the methodology provided for this sub-indicator is again flexible to the specificities of the countries, to the status of their watersheds and to the national resources available, countries must adhere to the following basic monitoring and reporting guidelines:

- Countries are recommended to measure the level of groundwater within an aquifer using boreholes. The number and location of boreholes must adequately represent the total groundwater situation within an aquifer.
- Given that groundwater levels change as a result of groundwater recharges and anthropogenic removals, it is recommended to put in place monthly monitoring systems. At a minimum ground water levels must be collected twice a year during the wet and dry seasons.

Countries are requested to report on the changes in groundwater level in major aquifers, every 5 years. The data from these 5-year periods will be averaged to smooth short-term variability. To generate percentage change of groundwater levels over time, a common 5-year reference baseline for all aquifers must be established. This baseline period will be used to calculate the percentage change of groundwater quantity for any subsequent 5-year period with respect to the reference period, the following formula is used:

Where:

$$Equation\ 6\text{: Percentage Change in groundwater level }=\frac{(\beta-\gamma)}{\beta}\times 100$$

Where
β = historical 5-year reference groundwater level (to be determined by countries based on their data)
γ = the average groundwater level over the 5 year period of interest

Additional considerations on the Level 1 sub-indicators

Types of water-related ecosystems included in SDG 6.6.1 indicator.

As described above, Level 1 sub-indicators focus on 5 types of water-related ecosystems: 1) rivers and estuaries, 2) lakes, 3) reservoirs, 4) inland vegetated wetlands, and 5) mangroves. For the purposes of reporting, open water bodies (rivers and estuaries, lakes and reservoirs) are separated from vegetated wetlands, which require a totally different methodology to map their spatial extent. Once the spatial extent of open water bodies has been determined, they are then further categorized into natural (lakes, rivers and estuaries) and artificial open water (quarries, reservoirs etc.). Artificial water bodies are included as a standalone category as they can contain a significant amount of a country's freshwater even if they are not a natural ecosystem.

With regard to the extent of in-land vegetated wetlands, saltwater wetlands are not included in this category (they are handled under SDG 14). This means that submerged coastal wetlands like seagrasses or coral reefs are not included in any of the SDG 6.6.1 sub-indicators, while salt-tolerant coastal wetlands that grow in the intertidal areas such as mangroves are included.

Quality of global EO datasets.

All global datasets used to derive level 1 sub-indicators are provided with a quality assessment (i.e. overall accuracy estimation) which is summarized in the "*Monitoring Methodology Indicator 6.6.1, Measuring change in the extent of water-related ecosystems over time"* and in the on-line documentation available on the *Freshwater Ecosystems Explorer* of the SDG 6.6.1a data portal (www.sdg661.app).

These Level 1 global datasets are the results of automated EO data processing applied to all land surfaces, with some regional stratification to account for regional specificities (e.g., different climatologies0, different types of water-related ecosystems). Even in the case of global datasets with high overall accuracy, one should not expect to obtain the same level of accuracy everywhere for local or even national use, hence the importance for countries to validate national extracts of global datasets if they use them in their national reporting on SDG 6.6.1.

Country validation of global EO datasets.

The level 1 sub-indicators (spatial extent of water-related ecosystems and water quality in lakes and reservoirs) are currently entirely based on Earth Observations. National extracts of global EO datasets are shared with countries for their national level validation, where they have the following options:

- **Accept:** country verifies data, validates its use, and data is reported to the United Nations Statistical Division (UNSD).
- **Reject:** country denies the use of data provided, and does not provide replacement data. No data is reported to UNSD.
- **Modification:** country modifies the data provided, or use their own EO-based national data, and re-submits it for reporting to UNSD.
- **Provide own data**: country denies the use of data provided, instead of providing their own data for reporting to UNSD.

The last two options provide opportunities for countries to also use their own data (EO and/or non EO data) and perform their own estimation of the extent of water-related ecosystems, for example using freely available EO platforms and tools (see section below). Therefore, EO can be used not only to produce the global datasets but also as a source of information for countries when validating the national extracts from the global datasets, or to produce their own national datasets.

The Level 1 global datasets are shared openly and freely with countries for their national validation, as and when they become available. Some of these global datasets are noy yet complete enough to fully support national reporting on the changes in water-related ecosystems (e.g. changes in inland vegetated wetlands) or have some spatial or temporal gaps (e.g. only large lakes are monitored by the CGLS LWQ, limited observations in areas with permanent cloud cover when using satellite optical measurements).

As for national validation, many countries still lack the necessary tools and training to validate national extracts of these global datasets. Although theoretically the global data should be generated annually, countries are required to aggregate the data over the target period (typically a 5-year period), using averages of the annual data. If the data are not made available to countries on an annual basis then these 5-year averages will not be computed satisfactorily. Once the 5-year averages are computed, they should be validated by countries before being used to report on percentage changes.

Methodological change

The 6.6.1 methodology has evolved over time since its upgrade to Tier I[2] in 2018. The most recent revision was done in July 2022. One of the major differences in earlier methodology was that countries reported on the extent of all open water bodies, i.e., grouping artificial and natural water bodies together. This could be potentially misleading and has therefore been revised in the latest version in July 2022, stipulating that they must be reported on as separate categories. The Level 1 global datasets were updated accordingly, resulting in a new EO global dataset on reservoirs (extracted from the JRC Global Surface Water).

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[2] As of the 8th meeting of the IAEG-SDG in November 2018

SDG Indicator Metadata 6.6.1b. (Ramsar Convention)

A brief description of the Ramsar monitoring and reporting methodology for SDG indicator 6.6.1 (centered on wetland inventories according to the Ramsar Convention) is provided in the *SDG Indicator Metadata 6.6.1b* (latest update in March 2022), while the full monitoring guidelines for national wetland inventories are described in the "*Ramsar Handbook on Wetland Inventory"* and in the new *Ramsar Toolkit for National Wetlands Inventories*.

The Ramsar Convention on Wetlands is the Intergovernmental treaty that provides the international framework for the Conservation and wise use of wetlands and their resources.

The Ramsar monitoring and reporting guidelines for SDG Indicator 6.6.1 follows strictly the **Ramsar definition of wetlands** which is: "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres*", and the **Ramsar Classification System for Wetland Types**, which was adopted at Ramsar COP 4 in 1990 and later amended at COP 6 in 1996 and COP 7 in 1999.

In the Ramsar classification of wetlands (which is the internationally agreed wetland classification under the Ramsar Convention), the wetland types are grouped in three major categories: 1) marine/coastal wetlands, 2) inland wetlands, and 3) human-made wetlands, as follows:

Marine/Coastal Wetlands

A -- **Permanent shallow marine waters** in most cases less than six metres deep at low tide; includes sea bays and straits.
B -- **Marine subtidal aquatic beds**; includes kelp beds, sea-grass beds, tropical marine meadows.
C -- **Coral reefs**.
D -- **Rocky marine shores**; includes rocky offshore islands, sea cliffs.
E -- **Sand, shingle or pebble shores**; includes sand bars, spits and sandy islets; includes dune systems and humid dune slacks.
F -- **Estuarine waters**; permanent water of estuaries and estuarine systems of deltas.
G -- **Intertidal mud, sand or salt flats**.
H -- **Intertidal marshes**; includes salt marshes, salt meadows, saltings, raised salt marshes; includes tidal brackish and freshwater marshes.
I -- **Intertidal forested wetlands**; includes mangrove swamps, nipah swamps and tidal freshwater swamp forests.
J -- **Coastal brackish/saline lagoons**; brackish to saline lagoons with at least one relatively narrow connection to the sea.
K -- **Coastal freshwater lagoons**; includes freshwater delta lagoons.
Zk(a) – **Karst and other subterranean hydrological systems**, marine/coastal

Inland Wetlands

L -- **Permanent inland deltas**.
M -- **Permanent rivers/streams/creeks**; includes waterfalls.
N -- **Seasonal/intermittent/irregular rivers/streams/creeks**.
O -- **Permanent freshwater lakes** (over 8 ha); includes large oxbow lakes.
P -- **Seasonal/intermittent freshwater lakes** (over 8 ha); includes floodplain lakes.
Q -- **Permanent saline/brackish/alkaline lakes**.
R -- **Seasonal/intermittent saline/brackish/alkaline lakes and flats**.
Sp -- **Permanent saline/brackish/alkaline marshes/pools**.
Ss -- **Seasonal/intermittent saline/brackish/alkaline marshes/pools**.
Tp -- **Permanent freshwater marshes/pools**; ponds (below 8 ha), marshes and swamps on inorganic soils; with emergent vegetation water-logged for at least most of the growing season.
Ts -- **Seasonal/intermittent freshwater marshes/pools on inorganic soils**; includes sloughs, potholes, seasonally flooded meadows, sedge marshes.
U -- **Non-forested peatlands**; includes shrub or open bogs, swamps, fens.
Va -- **Alpine wetlands**; includes alpine meadows, temporary waters from snowmelt.
Vt -- **Tundra wetlands**; includes tundra pools, temporary waters from snowmelt.
W -- **Shrub-dominated wetlands**; includes shrub swamps, shrub-dominated freshwater marshes, shrub carr, alder thicket on inorganic soils.
Xf -- **Freshwater, tree-dominated wetlands**; includes freshwater swamp forests, seasonally flooded forests, wooded swamps on inorganic soils.
Xp -- **Forested peatlands**; peat swamp forests.

Y -- **Freshwater springs;** oases.
Zg -- **Geothermal wetlands.**
Zk(b) – **Karst and other subterranean hydrological systems**, inland.

Human-made wetlands

1 -- **Aquaculture** (e.g. fish/shrimp) **ponds.**
2 -- **Ponds**; includes farm ponds, stock ponds, small tanks (generally below 8 ha).
3 -- **Irrigated land**; includes irrigation channels and rice fields.
4 --**Seasonally flooded agricultural land** (including intensively managed or grazed wet meadow or pasture).
5 -- **Salt exploitation sites**; salt pans, salines, etc.
6 -- **Water storage areas**; reservoirs/barrages/dams/impoundments (generally over 8 ha).
7 -- **Excavations**; gravel/brick/clay pits; borrow pits, mining pools.
8 -- **Wastewater treatment areas**; sewage farms, settling ponds, oxidation basins, etc.
9 --**Canals and drainage channels, ditches.**
Zk(c) – **Karst and other subterranean hydrological systems**, human-made

In the context of SDG indicator 6.6.1, countries are requested to report, as a minimum, the total area of wetlands that fall under two of these wetland categories:

- *Sub-indicator 1:* Total spatial extent and change of "**inland wetlands**".
- *Sub-indicator 2:* Total spatial extent and change of "**human-made wetlands**".

No report on "marine/coastal wetlands" is requested by Ramsar under SDG indicator 6.6.1.

The SDG 6.6.1 monitoring and reporting requested by Ramsar is fully aligned with the national reports that Ramsar Parties (which means countries) have to produce for each Conference of the Parties (COP). The Ramsar reporting is done at intervals of 3 years, which is the cycle of country reporting under the Convention (Ramsar COPs take place every 3 years).

The obligation for countries to provide National Reports to Ramsar on the national extent of wetlands for each of the 3 wetland categories (marine/coastal, inland and human made) was agreed at the 52nd meeting of the Ramsar Standing Committee in 2016, and was included in the National Reports to be provided by the Ramsar Contracting Parties, starting at COP 13 in 2018, with the consequence that the Ramsar Convention contributes to the monitoring and reporting of SDG Indicator 6.6.1 with data from the Ramsar National Reports on extent of wetlands, which are based on the Ramsar classification of wetland types.

As a consequence, **the year 2017 has been selected as the reference baseline year for the Ramsar reporting on wetland extent in the context of SDG 6.6.1 (which was requested to be provided by Countries for the Ramsar COP 13 in 2018)**. Based on their national wetland inventories (which can be complete or partial), countries are requested to provide 2017 baseline figures in square kilometers for the extent of wetlands (according to the Ramsar definition), providing the total area of wetlands for each of the three major categories of wetlands, noting that the extent of marine/coastal wetlands is only used in the Ramsar National Reports on wetland inventories but not in the SDG 6.6.1 reporting.

SDG 6.6.1 reporting under Ramsar is requested on a 3-year interval, following the cycle of the Ramsar COPs, which means that the next reporting will take place at COP 14 in 2022 (one year delay due to covid). Countries are requested to provide the % of changes in the extent of wetlands over the last 3 years, for each of the 2 wetland categories (inland and human made) that are relevant for SDG indicator 6.6.1.

Earth Observation is seen by Ramsar as a major source of information for the production of national wetland inventories. The Scientific and Technical Review Panel (STRP) of the Ramsar Convention has produced in 2018 a Ramsar Technical Report on "*Best practice guidelines for the use of Earth Observation for wetland inventory, assessment and monitoring*".

Under the Convention, multiple guidelines have been produced to assist countries in completing their national wetland inventories (NWIs). The new *Ramsar Toolkit for National Wetlands Inventories*, issued in 2020, provides practical guidance and examples on how to implement National wetland inventories, with a step-by-step process, which includes the use of Earth Observation techniques.

Differences in UNEP and Ramsar approaches

Although the two custodian agencies have made some efforts to align their monitoring and reporting guidelines on SDG 6.6.1, it is recognized that UNEP and Ramsar have some significant differences in their approaches. For example, mangrove swamps are included in the Ramsar category of "marine and coastal wetlands" and hence not reported by Ramsar Parties under SDG 6.6.1, or Ramsar does not make a distinction between surface waters and vegetated wetlands, which are both included in the "inland wetlands" category of Ramsar wetland types.

These differences are essentially related to aggregation issues, which can easily be handled, provided that the wetland inventories (according to Ramsar) are produced with the adequate disaggregation level in terms of wetland habitat classification.

Satellite Observations

EO Contribution

For simplicity and ease of communication, the analysis of the EO contribution to the SDG Indicator 6.6.1 addresses water-related ecosystems following the distinction made by the UNEP guidelines (SDG Indicator Metadata 6.6.1a) on ecosystem types (rivers and estuaries, lakes and reservoirs, inland vegetated wetlands, mangroves and aquifers) and on extent components (spatial extent, change over time, quality/conditions, volumes/flows). The Ramsar monitoring and reporting guidelines (SDG Indicator Metadata 6.6.1b) are discussed in the sub-section on wetlands.

6 aspects of water-related ecosystems are discussed in this section:

- Open water bodies (which includes rivers and estuaries, lakes and reservoirs),
- Inland vegetated wetlands,
- Mangroves,
- Water quality of lakes and artificial water bodies,
- Quantity of water in rivers and estuaries (river discharge),
- Quantity of groundwater within aquifers (groundwater levels).

The UNEP guidelines recognize the value of Earth Observation as an important data source for measuring a number of sub-indicators (level 1), while in-situ data are seen as the main source for the other sub-indicators (level 2). This section shows that there are opportunities to exploit EO data even further in level 1 sub-indicators, and to explore its use with in-situ data for the level 2 sub-indicators, where EO is currently not mentioned as a data source.

In terms of exploring EO opportunities in more detail, the following sub-sections give an overview of current EO possibilities for mapping the different components of each sub-indicator. For the sub-indicators on the spatial extent of water-related ecosystems, these are the spatial extent of open water bodies (with a separate treatment of natural and artificial water bodies), inland vegetated wetlands and mangroves. As each sub-indicator requires different EO-based approaches and methodologies, they are discussed in separate sub-sections.

1. Open water bodies (rivers, estuaries, lakes and reservoirs)

The spatial extent and change of natural open water bodies (lakes, rivers and estuaries) and artificial water bodies (reservoirs) can all be monitored using satellite data, but with varying degrees of accuracy and coverage depending on the type of remote sensing approach take (e.g., whether using optical or radar imagery, or preferably with combined approaches) and depending on the specific region of interest (differences in satellite data coverage, differences in terrain, differences in climate/vegetation conditions). Open water bodies can, in general, be better monitored with both optical and radar imagery.

The Global Surface Water (GSW) dataset from the European Commission's JRC used the entire archive of Landsat imagery spanning 40 years to show the global spatio-temporal variations in surface water at 30m spatial resolution including its intra and inter-annual variation. However, challenges occur due to data gaps within cloudy regions such as the humid tropics where cloud-free observations can hardly be obtained and when radar systems such as Sentinel 1 or ALOS-2 are needed.

A new feature of the GSW dataset is the separation between artificial and natural water bodies. This is a non-trivial task that requires ancillary data such as boundaries of reservoirs, dam locations and other elements of water infrastructure from water basin authorities, the location and extent of disused quarries and mines to delineate flooded cavities as well as other built-up features such as piers and jetties which can be used to identify an artificial water body. In some cases, artificial water bodies can be identified by their temporal dynamics, as managed water levels in reservoirs are relatively stable compared to those in natural water bodies such as lakes which fluctuate with the hydrological cycle.

Open water bodies (natural and artificial)

Main satellite data sources (openly and freely available):

- Moderate resolution (10 to 100m) multi-spectral optical data (e.g. Landsat 5-9, Sentinel 2A and 2B)
- Moderate resolution (10 to 100m) C-Band SAR data (e.g. Sentinel 1A and 1B)
- Moderate resolution (10 to 100m) L-Band SAR data (e.g. ALOS-2 PALSAR-2)
- Low resolution (100 to 500m) multi-spectral optical data (e.g. MODIS, VIIRS, Sentinel 3)
- Radar Altimetry missions (e.g., Sentinel 3 SRAL, Jason, Sentinel 6A, Cryosat, HY-2A/2B)
- Laser Altimetry missions (e.g., ICESat-2)

Challenges identified in current EO approaches (based on 30m optical sensors):

- Areas of persistent cloud cover (e.g., tropical cloudy regions) inhibit the observation of surface waters with optical sensors.
- Smaller rivers and water bodies includimg larger braided rivers are not captured with 30m optical sensors (such as Landsat) as they are too narrow to detect.
- Forest canopy can prevent observations of rivers in dense forests (rivers below forest canopy).
- Distinction between permanent and seasonal surface waters strongly depends on the availability of reliable monthly observations (also during the rainy seasons).
- The open water body dataset can include land vegetated areas that are temporarily inundated such as vegetated wetlands and paddy fields.
- Artificial vs natural water surface distinction is difficult but can be achieved within acceptable accuracies by using ancillary datasets (e.g., Global Reservoir and Dam database) combined with AI classification methods.
- Reservoirs smaller than 3 hectares and reservoir branches of width smaller than 30 meters can’t be captured with 30m optical sensors.
- GSW is about archives retreatment which is its main limitation. There is an opportunity to consider whether it is possible to easily update the database annually.
- The currently available datasets don’t provide information on the changes in volumes (water storage) in lakes and reservoirs.
- Lake and reservoir surface water classification is difficult with large amounts of vegetation in or floating vegetation on the water surface, or with (very) large sediment loads.
- Frozen water surfaces (ice) and coverage with snow (on the ice), especially relevant for higher latitudes.
- Steep mountainous terrain, which can obscure (parts of) water features, depending on sensor angle, and/or hinder detection because of (persistent) shadows.

Areas of improvements:

- Monthly or even weekly presence of surface waters can be achieved in many places of the world with current moderate resolution sensors (e.g., Landsat, Sentinel 1, Sentinel 2) but this requires solid multi-sensor approaches that fully exploit all optical and SAR data streams in order to address limitations of single sensor approaches and better capture temporal dynamics.
- The above can be further enhanced by also using low resolution sensors (e.g. MODIS, VIIRS, Sentinel 3), combined with downscaling and/or data fusion approaches.
- Use of L-band data to detect open surface waters beyond the canopy (e.g., in tropical cloudy regions) should be explored.
- Recent advances in integrating Water Surface Elevation (WSE) from radar altimetry (e.g., S3 SRAL, Jason, Cryosat, ICESat-2) to infer changes in lake volumes and provide information on the changes in lake/reservoir water storage should be exploited. Also the use of geo-statistical approaches using surrounding elevation and topology to estimate the area-volume relationship may be explored. Further consolidations are needed before changes in lake/reservoir water storage can be included in the UNEP methodological guidelines.

2. Inland vegetated wetlands

Earth Observation can be used to monitor vegetated wetlands with high accuracy, by combining information from optical and radar instruments.

While optical imagery allows surface water dynamics to be observed and separated from vegetated wetlands (cloud permitting), radar can enhance the separation by penetrating the vegetation canopy to the underlying standing water, especially using longer SAR wavelengths, primarily L-band (e.g. JERS-1, ALOS and ALOS-2), as well as by P-band (BIOMASS). Therefore, areas of inundated vegetation can be better separated from both open water and vegetation, confusion between them is reduced and vegetated wetlands can be reported separately.

Other radar-based parameters that can aid vegetated wetland identification are the moisture content of soils which can indicate the presence of wetlands even if there is no surface water. Multi-spectral optical imagery is sensitive to vegetation cover and, through the detection of water absorption in the NIR and SWIR spectral regions, can also help discriminating wetland vegetation from other types of vegetation.

Given the diversity of wetland ecosystems, the most appropriate approach is to combine information from optical and radar systems to address the multiple challenges of wetland monitoring. Information from both sensor systems is often combined with elevation data to extract the extent of vegetated wetlands more accurately as vegetated wetlands are most prevalent in flat and low-lying areas.

Thermal imagery is a less explored source for wetland mapping, yet an interesting additional information as Land Surface Temperature (LST) is closely related to the surface energy balance and the wetness status. Evapotranspiration (ET) is the primary energy loss mechanism for wetlands and due to the higher moisture content, ET tends to be higher and hence temperature lower in wetlands than in their surroundings.

Vegetated wetlands such as saltmarshes or peatlands have not been mapped as systematically as other wetland types such as mangroves, although there are ongoing efforts, for example by the Global Peatlands Initiative to produce a rapid global assessment of peatland extent and carbon content using remote sensing, starting with their four partner countries: Indonesia, Peru, Democratic Republic of Congo and the Republic of Congo. Peatlands, saltmarshes, mangroves, and other vegetated wetlands are to be valued not only for the biodiversity they host but also as carbon sinks and storage of global significance. There is therefore an urgent need to identify them quickly and map their extent and condition.

As wetlands are highly dynamic ecosystems and tend to be subject of high annual variations, multi-year data (from 3 to 5 years) must be collected to eliminate potential annual biases and create robust estimates of wetland areas, in particular the detection of ephemeral wetlands.

Inland Vegetated Wetlands

Main satellite data sources (openly and freely available):

- Moderate resolution (10 to 100m) multi-spectral optical data
  (e.g. Landsat 5-9, Sentinel 2A and 2B)
- Moderate resolution (10 to 100m) C-Band SAR data
  (e.g. Sentinel 1A and 2B)
- Moderate resolution (10 to 100m) L-Band SAR data
  (e.g. PALSAR ALOS)
- Low resolution (100 to 500m) multi-spectral optical data
  (e.g. MODIS, VIIRS, Sentinel 3)
- Soil Moisture Sensors
  (e.g. SMOS, SMAP)

Challenges identified in current EO approaches:

- Despite international efforts to develop robust and automated approaches for wetland inventories, there are still no global maps of wetlands (and consequently of inland vegetated wetlands) and of their changes with acceptable accuracies for use in national statistics.
- Areas of persistent cloud cover (e.g., tropical cloudy regions) inhibit the observation of inland vegetated wetlands with only optical sensors.
- A major source of commission error in automated wetland mapping is the detection of high-intensity irrigated agriculture, which can be classified as wetlands because it resembles many of the spectral features inherent in wetlands (i.e., high soil moisture and presence of vegetation even in the dry season). Global wetland mapping should therefore be associated with the detection of irrigated croplands.
- Smaller wetlands can not be captured with 30m optical sensors as they are too narrow to detect, hence the need to move to higher spatial resolution (e.g., 10/20m of Sentinel 2).
- Forest canopy can prevent observations of forested wetlands unless longer SAR wavelengths (such as P- and L-band SAR) are used.
- EO solutions for the discrimination between inland and coastal wetlands are still to be consolidated.
- Small islands and potentially even entire small island states can fall outside the acquisition plans of EO satellites with the consequence that these islands can be excluded from global wetland mapping.

Areas of improvements:

- Good progress in EO solutions for large-scale wetland mapping but satellite data needs still need to be well consolidated.
- Multi-sensor approaches are needed to overcome the limitations of single-sensor approaches and better capture the temporal dynamics of wetlands.
- Use of L-band SAR time-series data to detect water below the canopy (e.g., forested wetlands) and to monitor inundation dynamics is a necessity.
- Use of C-band and/or L-band SAR time-series data to detect and identify irrigated rice cultivation.
- Integration of different moderate resolution data streams (i.e., multispectral optical, C-band SAR and L-band SAR) is needed to provide robust solutions for large-scale wetland mapping.
- The accuracy of the EO-based wetlands maps can be improved with the integration of national wetland inventories and ground truthing, especially through the use of machine learning solutions. Countries are strongly encouraged to share their geo-referenced wetland data to be used in wetland classification as training data for ML/DL models.

- Wetland ecosystems such as saltmarshes and peatlands should be systematically mapped (transferability/generalization studies on-going).
- Use of Thermal Infrared (TIR) sensors in wetland mapping should be explored, since LST is closely related to surface energy balance and wetness status (higher evapotranspiration).
- Development of Deep Learning (DL) models is encouraged to more explicitly reflect temporal and spatial aspects of wetland predictions and account for the high diversity of wetland ecosystems.
- Development of remote sensing techniques to estimate Wetland Carbon Sequestration and Storage (Carbon sinks in wetlands).

3. Mangroves

Today, mangroves as well as their changes have been mapped consistently for the pan-tropical region by the Global Mangrove Watch (GMW), in collaboration with the Japan Aerospace Exploration Agency (JAXA).

While cloud cover limits the use of optical satellite data in tropical and sub-tropical regions, Synthetic Aperture Radar (SAR) sensors are particularly well suited for mangrove monitoring as SAR data can be acquired regardless of clouds, smoke and haze. L-band SAR is particularly suitable as it is sensitive to both vegetation structure and water presence, and its longer wavelength allows the microwave signals to better penetrate the forests. With JAXA's JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2 missions a consistent L-band SAR data record spanning over two decades is available and provides a unique opportunity to map the extent and changes of the global mangrove cover. The Global Mangrove Watch was initiated as part of the JAXA ALOS Kyoto & Carbon (K&C) Initiative in 2011, and is led by Aberystwyth University, solo Earth Observation, Wetlands International (WI), and The Nature Conservancy (TNC) in collaboration with the International Water Management Institute (IWMI) and the UNEP World Conservation Monitoring Centre (WCMC).

The GMW has generated a global baseline map of mangroves for 2010 using ALOS PALSAR and Landsat (optical) data, and changes from this baseline for eleven epochs between 1996 and 2020 derived from JERS-1, ALOS and ALOS-2. Annual maps are planned from 2021 and onwards.

The GMW maps also constitute the official mangrove datasets used by UNEP for reporting on Sustainable Development Goal 6.6.1, and is also used by Ramsar STRP in its flagship publication "*Global Wetland Outlook*" and the "State of the World Mangroves" report by the Global Mangrove Alliance.

The GMW maps are globally produced data, and as such, should not be expected to achieve the same level of accuracy as a local scale maps. However, GMV maps can be improved locally (or nationally) by adding improved information (in-situ data and aerial or drone data) for training and re-classification. Different factors can affect the overall classification accuracy, including satellite data availability, mangrove species composition and level of mangrove degradation.

The Global Mangrove Watch has recently joined forces with other international EO experts in mangrove mapping (e.g. NASA Mangrove Science Team) to develop the Global Mangrove Watch Platform (globalmangrovewatch.org) as the evidence base informing the Global Mangrove Alliance.

Mangroves

Main satellite data sources (openly and freely available):

- Moderate resolution (10 to 100m) L-Band SAR data
  (e.g. JERS-1, ALOS and ALOS-2 global mosaics)
- Moderate resolution (10 to 100m) multi-spectral optical data
  (e.g. Landsat 5-9, Sentinel 2A and 2B)
- Moderate resolution (10 to 100m) C-Band SAR data
  (e.g. Sentinel 1A and 1B)

Challenges identified in current EO approaches:

- While the original pixel spacing of the satellite data used for the mapping is 25-30 metres, a minimum mapping unit of 1 hectare is recommended due to high classification uncertainties when working at pixel level.
- The classification errors (in particular omission errors) typically increase in regions of mangrove disturbance and fragmentation, as well as along riverine or coastal reef mangroves that form narrow shoreline fringes.
- The mangrove seaward border is more accurately defined than the landward side where distinction between mangrove and certain wetland or terrestrial vegetation species can be unclear.

Areas of improvements:

- Multi-sensor approaches are needed to address limitation of single sensor approaches and better capture temporal dynamics. For example to monitor changes in mangrove extent, further improvement is expected from the integration of dense C-band SAR datasets (Sentinel 1) with PALSAR and Landsat 8 / Sentinel 2 data.
- 10m required for fragmented mangroves and along narrow rivers.

4. Water quality of lakes and artificial water bodies:

The Water Quality sub-indicators on Trophic State Index and Turbidity in lakes and artificial water bodies require observation data respectively on Chlorophyll a (Chl) and Total Suspended Solids (TSS). Both parameters can be derived from optical EO sensors using empirical algorithms that describe the relationship between spectral reflectance and water quality. As these parameters fundamentally alter the “colour” of the water body in terms of photosynthetic content, Chlorophyll a and Total Suspended Solids can be provided, with different accuracies, by both multi-spectral optical sensors at high resolution (e.g., Landsat, Sentinel 2) and ocean colour scanners at medium resolutions (e.g., Terra/Acqua MODIS, VIIRS, Sentinel 3 OLCI).

Multi-spectral land optical sensors such as the Landsat 8 Operational Land Imager (OLI) and Sentinel-2 Multispectral Instrument (MSI) have the capacity to map water quality of small water bodies (~1ha) given that a spatial resolution of up to 10m can be achieved with the MSI. However, in situ water samples are necessary at a commensurate spatial resolution to drive the empirical model.

Ocean colour sensors such as Sentinel-3 OLCI, Envisat MERIS (decommissioned), NOAA/NASA VIIRS and NASA Terra/Aqua MODIS are coarser resolution sensors (≥250m), meaning that small lakes or other water bodies are either undetectable or averaged out over large areas. However, in situ sampling of the water bodies can afford to be less dense compared to multi-spectral moderate resolution optical sensors (i.e., Landsat and Sentinel 2). As coarse resolution sensors have a wider swath width, they tend to have a high revisit time and therefore offer the possibility of more frequent observations than higher resolution sensors.

Satellite sensors do offer other water parameters which can help in an assessment of water quality such as water temperature.

Water Quality in lakes and reservoirs

Main satellite data sources (openly and freely available):

- Coarse resolution (>100m) Ocean Colour Radiometry (OC) sensors
  (e.g. Terra/Acqua MODIS, VIIRS, Sentinel 3 OLCI)
- Moderate resolution (10 to 100m) multi-spectral optical data
  (e.g. Landsat 5-9, Sentinel 2A and 2B)

Challenges identified in current EO approaches:

- In situ water samples are needed in order to calibrate empirical WQ retrieval models (algorithm genericity).
- OC sensors have a coarse spatial resolution that does not allow to retrieve water quality parameters in small or narrow water bodies.
- Higher resolution multi-spectral optical sensors (e.g., Landsat OLI and Sentinel 2 MSI) are primarily land mapping sensors and are less suitable for water quality retrieval due to their spectral resolution and radiometric sensitivity; especially in oligotrophic waters. .Nevertheless, they provide valuable information, e.g.. for turbidity and especially in combination, both sensor types are used for water quality assessments.
- Cloud and ice coverage prevent the retrieval of water quality parameters. A good flagging (masking) of invlaid pixels is mandatory for good quality. The detection of thin clouds and melting (dark) ice has a higher uncertainty.
- Certain constellations of viewing and sun geometry and wind conditions cause direct reflection of sunlight on the water surfaces. Sun glint needs be flagged in case a correction is not possible

Areas of improvements:

- Multi-sensor approaches are needed to address limitation of single sensor approaches (Ocean colour sensors are too coarse for smaller water bodies) and better capture temporal dynamics; need to integrate multi-spectral sensor data (L8/S2) into current OC-based WQ data processing;
- OC sensors provide good data basis for Eutrophic/Turbidity state at 250/300m resolution but too coarse for smaller water bodies and rivers. Need to integrate multi-spectral sensor data (L8/S2) into current OC-based WQ data processing.
- Use of thermal Infrared for determining Lakes and rivers surface Temperature to be explored as an additional proxy of water quality.
- Further water parameters can be provided, such as chlorophyll concentration, cyanobacteria occurrence, floating vegetation, secchi (visibility) depth.

5. Quantity of water in rivers and estuaries (river discharge):

The river discharge sub-indicator is primarily measured in-situ, with techniques including gauging stations and discharge meters. The availability of in-situ observations is spatially heterogeneous and scarce in large parts of the world. Furthermore, large scale monitoring networks are expensive and, in many cases, impractical, particularly for large scale or subsurface processes such as groundwater dynamics. River flow and ground water cannot be directly observed from space, but they can be simulated by combining Earth Observations and numerical simulations. These models typically use a relatively simple rainfall-runoff model calibrated against point flow or water level data. The main inputs are rainfall and topography, both of which are available from EO sources. Additionally, satellite altimetry can be used to estimate the surface water elevation of open water bodies, along with changes of these over time. These water level observations can further assist in the estimation of 2 different aspects of changes in water quantity: change in water volumes (see section 2 on water storage) and river discharge..

Traditional radar altimeters have had footprints which have been too large to reliably estimate Water Surface Elevation (WSE) parameters over smaller water bodies, due to interference from land. However, new lasers-based systems, like ICESat-2, provides altimetry data with much smaller footprints which makes it possible to map changes in water volume over time in smaller water bodies, and through this determine water availability and long term drought indicators.

River discharge

Main satellite data sources (openly and freely available):

- Radar Altimetry missions
  (e.g., Sentinel 3 SRAL, Jason, Sentinel 6A, Cryosat, HY-2A/2B)
- Laser Altimetry missions
  (e.g., ICESat-2)
- Moderate resolution (10 to 100m) multi-spectral optical data
  (e.g. Landsat 5-9, Sentinel 2A and 2B)
- Moderate resolution (10 to 100m) C-Band SAR data
  (e.g. Sentinel 1A and 2B)

Challenges identified in current EO approaches:

- Traditional radar altimeters have footprints which can be too large to reliably estimate Water Surface Elevation (WSE) parameters over small rivers, due to interference from land.
- Satellites have limited spatial and temporal coverage – Sentinel-3 tracks are 52 km apart with a return period of 27 days, which means some targets may not be covered and important temporal fluctuations may be missed.
- Altimeters measure water surface elevation relative to a reference elevation, most often the geoid, while rainfall-runoff models simulate discharge. Models must be adapted to bridge this discrepancy.

Areas of improvements:

- Advances in the integration of Water Surface Elevation (WSE) from radar altimetry missions to infer changes in river flow discharges (through use of modelling);.
- New lasers based system (e.g. ICESat2) provide smaller footprint to estimate elevation parameters over smaller water bodies;
- Use of InSAR technology combined with gravitational measurements from gravity missions to infer information on changes in Aquifer content is a research field to be explored.
- Multi-mission and/or modelling approach to mitigate limited space-borne altimetry coverage.

6. Quantity of groundwater within aquifers:

The data sources for the ground water sub-indicator are primarily in-situ data using boreholes. However experimental EO methods are in development that can support countries in future reporting.

The Gravity Recovery and Climate Experiment (GRACE) and GRACE-FO (follow-on) missions monitor changes in the Earth's global surface mass, including those caused by motion in underground water and mass in groundwater storage. This could provide a means to measure relative changes to groundwater within aquifers but such EO methods are not yet ready for operational reporting and require further research. Gravity measurements, combined with SAR interferometry (through the computation of surface displacements due to changes in groundwater levels), can be assimilated in groundwater storage models (e.g., ground water extraction and recharge models) to estimate changes in groundwater levels.

Groundwater levels in acquifers

Main satellite data sources (openly and freely available):

- Gravity missions
  (e.g.,GRACE, GRACE-FO)
- Moderate resolution (10 to 100m) C-Band SAR data
  (e.g. Sentinel 1A and 2B)

Challenges identified in current EO approaches:

- The use of EO to estimate changes in groundwater storage is still in the research domain. There is good potential to infer changes in groundwater storage from gravity changes observed by GRACE and GRACE-FO missions but futher research is needed on the subject.
- The dynamics observed by GRACE include all inland water stores, and the groundwater signal cannot be extracted from the observations alone.
- GRACE and GRACE-FO data are coarse spatio-temporally, making these analysis most relevant at regional or global scale.

Areas of improvements:

- InSAR technology combined with gravitational measurements from gravimetry missions to be considered as a long-term monitoring system to infer information on changes in Aquifer content.
- Combination with numerical models and altimetry to isolate ground storage signal.

Satellite data requirements

Table 1 summarises the satellite data needs for each of the SDG sub-indicators (including potential new sub-indicators), with reference to CEOS mission classes provided in Table 2.

SDG sub-indicators	Spatial Resolution	Measurement Type	Observation Frequency	Sampling Type	Comments	Mission Classes
Rivers and estuaries **(spatial extent)**	10-30m	Optical and Radar	monthly	Global	30m Global Surface Water Explorer (GSWE) used as default global dataset (Landsat 5-8, Sentinel 1)	**2,3,(4)**
Lakes and Reservoirs **(spatial extent and volume changes)**	10-30m	Optical and Radar (+ Altimetry)	monthly	Global	30m Global Surface Water Explorer (GSWE) used as default global dataset (Landsat 5-8, Sentinel 1)	**2,3,(6)**
Wetlands **(spatial extent)**	10-100m	Optical and Radar Soil moisture	multi-annual	Global	DHI global wetland map (2016-2018) used as default global dataset (Sentinel 1, Sentinel 2, Landsat 8)	**2,3,(4),(5)**
Mangroves **(spatial extent)**	10-100m	SAR and Optical	annual	Global	Global Mangrove Watch (GMW) uses as default global dataset (JERS-1, ALOS PALSAR, ALOS-2 PALSAR-2, Landsat 5-7)	**2,(3),4**
Water Quality (in lakes and reservoirs)	10-500 m	Optical (OC and Multi-spectral)	Monthly	globally distributed selected Lakes	Copernicus Global Land Services (CGLS) Lake Water Quality used as default global dataset (ENVISAT MERIS, S3 OLCI)	**1,(2)**

Table 1: Satellite data needs for the SDG 6.6.1 indicators

Class	Mission	Instrument	Agency	Launch	Revisit	Swath	Resolution
	Optical - Coarse Resolution (>100m)						
1	Terra	MODIS	NASA	Dec 1999	1 day	2330 km	250, 500, 1000m
	Aqua	MODIS	NASA	May 2002	1 day	2330 km	250, 500, 1000m
	Suomi-NPP	VIIRS	NASA	Oct 2011	1 day	3000 km	375, 750m
	Sentinel-3A	OLCI	ESA	Feb 2016	1-2 days	1270 km	300m (OLCI), SLSTR: 500m (VNIR/SWIR)+1000m (TIR)
	Sentinel-3B	OLCI	ESA	Apr 2018	1-2 days	1270 km	300m (OLCI), SLSTR: 500m (VNIR/SWIR)+1000m (TIR)
	Proba-V	VGT-P	ESA/BELSPO	May 2013	1 day	2285 km	100, 300, 1000m (1km free, 100+300 free >1 month)
	Optical - Moderate Resolution (10 to 100m)						
2	Landsat-7	ETM+	NASA/USGS	Apr 1999	16 days	183 km	15m (PAN), 30m (VIS/SWIR), 60m (TIR)
	Landsat-8	OLI + TIRS	NASA/USGS	Feb 2013	16 days	183 km	15m (PAN), 30m (VIS/SWIR), 100m (TIR)
	Landsat-9	OLI + TIRS	NASA/USGS	Sept 2021	16 days	183 km	15m (PAN), 30m (VIS/SWIR), 100m (TIR)
	Sentinel-2A	MSI	ESA	Jun 2015	10 days	290 km	10m (VNIR), 20m (SWIR)
	Sentinel-2B	MSI	ESA	Mar 2017	10 days	290 km	10m (VNIR), 20m (SWIR)
	CBERS-4	WFI-2, PAN, MUXCam, IRS	INPE/CAST	Dec 2014	5-26 days	120 to 866 km	5m (PAN), 10m, 20m, 64m (VIS/NIR), 40m (SWIR), 80m (TIR)
	HJ-1A	HSI	CRESDA/CAST	Sep 2008	31 days	50 km	100m
	Meteor-M N1	KMSS	ROSKOSMOS	Sep 2009	4 days	900 km	60 m, 120 m
	C-Band SAR						
3	Sentinel-1A	SAR	ESA	Apr 2014	12 days	80, 250, 400 km	9, 20 (IWS), 50 m
	Sentinel-1B	SAR	ESA	Apr 2016	12 days	80, 250, 400 km	9, 20 (IWS), 50 m
	Sentinel-1C	SAR	ESA	Planned 2023	12 days	80, 250, 400 km	9, 20 (IWS), 50 m
	L-Band SAR						
4	ALOS-2	PALSAR-2	JAXA	May 2014	14 days	25 to 490 km	10 to 100 m (only annual mosaics free)
	ALOS-4	PALSAR-3	JAXA	Planned 2023	14 days	25 to 490 km	10 to 100 m
	NISAR	SAR	NASA, ISRO	Planned 2023	12 days	240 km	10m
	Soil Moisture						
5	SMOS	MIRAS (L-Band MW)	ESA	Nov 2009	1-2 days	1050 km	15 km
	SMAP	SMAP (L-Band MW)	NASA	Jan 2015	1-2 days	1000 km	10 km (active) to 40 km (passive)
	Radar Altimetry						
6	Sentinel-3A	SRAL	ESA/EUMETSAT/EC	Feb 2016	27 days	Profiling	3 cm
	Sentinel-3B	SRAL	ESA/EUMETSAT/EC	Apr 2018	27 days	Profiling	3 cm
	Jason-3	Poseidon Altimeter	EUMETSAT/NOAA/CNES/NASA	Jan 2016	10 days	300 km	3.4 cm
	Sentinel-6A Michael Freilich	Poseidon Altimeter	EUMETSAT/EC/ESA/NASA/NOAA	Nov 2020	10 days	300 km	3.2 cm
	Sentinel-6B Michael Freilich	Poseidon Altimeter	EUMETSAT/EC/ESA/NASA/NOAA	Planned 2025	10 days	300 km	3.2 cm
	HY-2A	ALT	NSOAS/CAST	Aug 2011	14 days	16 km	4 cm
	HY-2B	ALT	NSOAS/CAST	Oct 2018	14 days	16 km	4 cm

Table 2: CEOS satellite mission classes

EO Data Access

- Sentinel data can be accessed for download through the Conventional Data Hubs (https://www.copernicus.eu/en/access-data) that include the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/) and the EUMETSAT data services (https://data.eumetsat.int/). Sentinel data are also accessible for on-line data processing through the cloud-based Information Access Services (DIAS) platforms (https://www.copernicus.eu/en/access-data/dias).
- Landsat, MODIS and VIIRS data are available via the EarthExplorer (https://earthexplorer.usgs.gov/).

	● The MERIS data archive is available from the MERIS online dissemination service (https://meris-ds.eo.esa.int/oads/access/) ● JERS-12, ALOS, and ALOS-2 global mosaic data can be accessed through the Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Center (EORC) (https://www.eorc.jaxa.jp/ALOS/en/dataset/dataset_index.htm). ● Altimetry observations from Jason is available via USDA Global Reservoir and Lake Monitor (G-REALM) https://ipad.fas.usda.gov/cropexplorer/global_reservoir/ . ● Altimetry observations from Topex/Poseidon, Jason-3, Envisat, Sentinel3 are also available at Hydroweb: http://hydroweb.theia-land.fr/ (see Hydroweb description below) ● Commercial satellite data can be purchased through data providers and their reseller network. ● As an alternative to downloading data, it is possible to find relevant data in various cloud computing frameworks, such as the Amazon Web Services (http://registry.opendata.aws) and Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog). Tools and services can be installed on AWS or the Google Cloud to connect to these data, or tools such as Google Earth Engine can be used for analysis purposes. These options remove the requirement to download data, which is a growing issue for large global datasets.
Analysis Ready Data	CEOS has published ARD Standards for land applications (https://ceos.org/ard/), including links to ARD data access sites, which may enable countries to convert their national datasets to ARD standard.
EO-based global datasets	There is a range of global data products which could be used within the indicator monitoring and reporting: ***Natural open water bodies (lakes, rivers and estuaries)*** ● **The Global Surface Water Explorer (GSWE)** is developed and maintained by the European Commission's Joint Research Centre (JRC). It uses only Landsat imagery to provide the spatial extent of the world's surface water resources including their temporal dynamics over the last 38 years. See https://global-surface-water.appspot.com/ ● **Global Water Watch (GWW)** developed with Deltares, the World Resources Institute (WRI) and World Wide Fund (WWF) is a data platform of free, globally accessible near-real-time information on water. It provides information on thousands of global reservoirs and major river systems, helping decision-makers respond to monitor the status of water resources in near real-time, act on extreme weather events and manage growing risks of climate change. The current state is that the water surface of lakes and reservoirs world-wide is monitored and updated regularly. The expectation is that by the end of 2022, the surface area time series will be available with weekly updates from satellite imagery of Sentinel-2 and Landsat missions. By June 2023, it is expected that also estimates of storage (in m3) will be available through hypsometric relationships derived with ICESat-2 and several stici elevation dataset. *See https://www.globalwaterwatch.io* ***Artificial open water bodies (reservoirs)*** ● **The Global Dam Watch** is a partnership of leading academic institutions and NGOs that curate and make freely available global data on dams and reservoirs. Therefore, it can be used by countries to link the presence of dams to water bodies obtained from the GSWE and the river network from other resources. Only one of the three datasets on GDW is EO-derived - GOODD[2], a map of 38,660 dams visible in Google Earth imagery. The others - the Global Reservoir and Dam Database (GRanD) maps the location and attribute data of 7,320 dams greater than 15m in height or with a reservoir of more than 0.1km3. Future Hydropower Reservoirs and Dams (FHReD) maps 3,700 dams that are under construction or in advanced planning stages. *See http://globaldamwatch.org/*

Vegetated wetlands

- **The Global Mangrove Watch (GMW)**, initiated under JAXA's Kyoto & Carbon initiative, provides geospatial information about mangrove extent and changes on an annual basis, currently available for eleven annual epochs between 1996 and 2020. The Global Mangrove Watch Platform provides an interactive tool to interact with the data and e.g. calculate national statistics. The GMW datasets are publicly available under a Creative Commons (CC BY 4.0) license and available for free download from JAXA Earth Observation Research Center (GeoTiff format) and UNEP-WCMC (shape file format). The GMW dataset constitutes the default mangrove data layer used by UNEP for SDG 6.6.1 reporting, and is used as the mangrove layers on the WRI Global Forest Watch and Resources Watch portals, and the UNEP-WCMC Ocean Data Viewer and Ocean+ Habitats portals.

  See https://www.globalmangrovewatch.org/

- **The Global Wetlands Map** is developed under the framework of the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP) and provides access to information and data on the distribution of tropical wetlands, peatlands and carbon stocks. The data is based on satellite images using MODIS data and covers the tropical and subtropical regions up to 30 degrees North and 70 degrees South. The data products are available for the baseline year 2011 and can be accessed from the global wetland map website.

  See https://www.cifor.org/global-wetlands/

Water quality of lakes

- **The Copernicus Global Land Services** is now providing operational WQ products at 100m, 300m and 1km for lakes globally. Historic data are available from May 2002 to March 2012, based on MERIS imagery, and present data from Sentinel-3 OLCI from May 2016 onwards. The data product is composed of three core datasets:
  - Turbidity or water clarity
  - Trophic state index or eutrophication status
  - Lake surface reflectances or water colour

  See *https://land.copernicus.eu/global/products/lwq*

- **The CCI Lakes data set** provides several lake related variables for 2000 globally distributed lakes in 1km spatial resolution. Variables are among others Lake Water Temperature, chlorophyll concentration, turbidtiy, lake ice coverage, lake water level, lake water extent. The data set is optimized for climage change analyses and provides harmonised time series of the parameter.

  See https://climate.esa.int/en/projects/lakes/

  data: https://catalogue.ceda.ac.uk/uuid/a07deacaffb8453e93d57ee214676304

Water levels

- Altimetry derived time series water levels from large rivers and lakes are available from a number of different sources e.g. Hydroweb THEIA and Database for Hydrological Time Series of Inland Waters (DAHITI) (). Time series are typically constructed from the combined use of various altimetry missions including: ERS-1 & 2, Topes/Poseidon, Envisat, S3 SRAL and Jason.

  See http://hydroweb.theia-land.fr/ and https://dahiti.dgfi.tum.de/

- Since 2 years, NASA's ICESat-2 mission delivers surface elevation estimates over land, oceans and inland water bodies. Literature already shows that this can be used to monitor the water level in both small and large inland water bodies.

Platforms and Tools

- **The Freshwater Ecosystems Explorer** has been co-developed by UN Environment, Google and the JRC to enable countries to view and download time series data as well as statistical data between 1984 and 2018 on the spatial extent of water-related ecosystems and their temporal dynamics. Data can be disaggregated by sub-national, national and hydro basin boundaries.

  See https://www.sdg661.app/home

	● **GlobWetland Africa** is an open and free software toolbox, developed by ESA in partnership with the Ramsar Convention, which enables end-to-end processing workflows for wetland delineation, wetland habitat mapping, monitoring of inundation regimes, extraction of water quality and modelling of river basin hydrology. For water quality, the toolbox draws upon functions already built into the SNAP/BEAM toolset. However, it builds on water quality functionality through added workflows (monitoring of aquatic eutrophication and physical disturbance). Output indicators: Time series of chlorophyll concentration (mg/m³), turbidity, suspended sediment concentration (g/m³), indicators for floating vegetation. *See http://globwetland-africa.org* ● **ESA SNAP/BEAM and Sentinel-3 toolboxes** can be used for pre-processing optical data for use in water quality algorithms. SNAP is the SeNtinel's Application Platform. It is a generic, open-source platform for ESA Toolboxes ideal for the exploitation of Earth Observation data. SNAP tools allow the user to pre-process the EO data before WQ parameter retrieval.SNAP and the SNAP toolboxes can be used to process MERIS, OLCI, Sentinel-2 L2 product data for use in water quality algorithms, e.g. in atmospheric correction over water or apply band ratios for water occurrence.. *See https://step.esa.int/* ● **Hydrology Thematic Exploitation Platform (TEP)** - the TEP for Hydrology is a tool where the members of the community can rapidly and easily access to a large number of Earth Observation data, integrate their own data and tools (in-situ data, socioeconomic data, analysis tools...) and process their processors (service prototypes, hydrological models, meteorological models) within a user-friendly environment. Thematic applications include Water Observation and Information System (WOIS – open-source tool for water-related satellite data processing), flood monitoring service, hydrological modelling service, water level service and small water body mapping service. *See https://hydrology-tep.eu/*
International Initiatives	● **The GEO Wetlands** initiative aims to realise the possibility of a Global Wetlands Observation System (GWOS) on behalf of the Ramsar Convention. Being a GEO Initiative it adopts the basic principles of openness and data sharing. This will be achieved through a wetland community geo-portal. GEO-Wetlands is already building a community of wetland observation practitioners, spanning a range of actors and has pilot projects, e.g. Global Mangrove Watch, with a view to building the GWOS. *See https://geowetlands.org* ● **The GEO AquaWatch**, the GEO Water Quality Initiative, aims to develop and build the global capacity and utility of Earth Observation-derived water quality data, products and information to support water resources management and decision making. AquaWatch is aiming to produce a global monitoring system for water quality by 2025 called the Water Quality Information Service which will be a direct contribution to indicator 6.3.2 (water quality), 6.1.1 and 6.1.12 (sanitation). *See https://www.geoaquawatch.org/* ● **The Global Peatlands Initiative** aims to improve the conservation, restoration and sustainable management of peatlands. It is a partnership led by UN Environment. Although primarily focused on the reduction of carbon emissions from peatland degradation, it also addresses peatlands as an important ecosystem and is of direct relevance for indicator 6.6.1. Mapping the extent of peatlands using EO in priority countries is a key aim of the initiative. *See https://www.globalpeatlands.org* ● **The World Water Quality Alliance (WWQA)** represents a voluntary and flexible global multi-stakeholders network that advocates the central role of freshwater quality in achieving prosperity and sustainability; it explores and communicates water quality risks in global regional, national and local contexts and points towards solutions for maintaining and restoring ecosystem and human health and well-being with an aim to serve countries throughout the lifetime of the 2030 Agenda for Sustainable Development and beyond. See https://communities.unep.org/display/WWQA/World+Water+Quality+Alliance

EO Methodology

Step-to-Step guide for EO integration into SDG framework

The preceding sections have documented the background to the indicator methodology and suggested global EO datasets, tools and platforms which can be used to access data and resource related to the 6.6.1 sub-indicators. While global EO approaches are important, particularly for the Level 1 sub-indicators, there are also opportunities for countries to compute the indicators themselves from EO data.

This section contains an end-to-end description of the EO Processing Chain for those countries who would like to do produce the indicators (or sub-indicators) themselves. Each sub-section replicates the same structure, consisting of the steps required to obtain, process and validate the EO data and derived indicators. The mapping of water-related ecosystems is a domain of ongoing research which will eventually provide operational methodologies. Therefore, not all methods of computing the sub-indicators from EO data have been comprehensively described here, only those which are mature enough for countries to implement by themselves.

Spatial extent of water-related ecosystems

STEP 1: Get data

As a first step users need to verify whether the public domain datasets are representative of the reporting period as well as consider the need and availability of more precise datasets. If the public domain datasets are considered inadequate users have the option to acquire new EO imagery and water-related data to generate updated information on the spatial extent, quantity and quality. Typically, the extent and location of artificial water bodies will be obtained through a government department or ministry while users who wish to use EO imagery alone to identify artificial from natural water bodies will need to bring their own EO data and machine learning methods, e.g. for mapping dams. This might require access to commercial optical imagery at very high resolution to identify dams and other water management related infrastructure. Openly available medium resolution imagery (e.g. Sentinel and Landsat) might be perfectly adequate for mapping water body extent and quality, depending on their size and distribution. Sentinels 1 and 2 and Landsat, can also be used to map vegetated wetlands and which have a free and open data policy.

STEP 2: Process data

To derive the extent of water-related ecosystems (and vegetated wetlands in particular), a multitemporal approach is recommended making use of both optical and radar observations over a period of 2 to 5 years. The length of the period depends on the regional conditions (i.e. availability of soil moisture). Whereas in some regions a short period might be sufficient to track the dynamics of water-related ecosystems, arid regions might require a longer time period to fully track these dynamics. The more observations are included in the analysis, the higher will be the precision of the resulting product on the wetland extent.

The basic idea of the proposed approach is to derive information about the presence of water and wet soils (wetness) within the particular time period to report the Water and Wetness Presence/Probability Index (WWPI). This information together with local expert knowledge can be used to extract the extent of water-related ecosystems.

Information about surface water and the wetness of soils are ideally derived from the optical and radar datasets and fused in the end to give a map of the WWPI. The optical approach is based on Sentinel-2 Multi-Spectral Imager (MSI) data for which a selection of spectral indices is calculated. A combination of these indices and the Topographic Wetness Index yields the water and wetness probabilities. Subsequently, split-based dynamic image thresholding is applied to derive water and wetness extents for each Sentinel-2 scene (or multi-temporal composites). Finally, these extents are aggregated to get water and wetness frequencies (Ludwig et al., 2019).

The radar-based algorithm builds on geophysical parameters, surface soil moisture dynamics and water bodies, mainly derived from Sentinel-1 backscatter time series to identify permanent/temporary wet and flooded areas. In addition, it is possible to identify flooded vegetation according to the double-bounce scattering principle in densely vegetated wetlands. The non-flood prone areas are masked using the Height Above Nearest Drainage (HAND) index which is generated using the digital elevation model and flow direction within the drainage network.

After the separate processing of the optical and radar imagery, the data are fused into a combined water and wetness product. A rule-based classification can be applied to finally derive the wetland extent based on local expert knowledge and in situ information to help fine-tune the algorithm for the regional context (environmental conditions).

The above-described approach allows to distinguish between vegetated wetlands and open surface waters since both types of ecosystems are separately derived. Moreover, information on open surface waters could also be taken from the Global Surface Water Explorer. Additional datasets may be of use for supplementing this data, including Global Mangrove Watch.

As a next step, open surface waters need to be further disaggregated into (1) lakes, (2) rivers and estuaries, and (3) artificial water bodies. For artificial water bodies, a combination of approaches can be used. This includes overlaying the wetland extent dataset with national datasets for artificial water bodies (if they exist). Examining significant changes from one year to the next can also give an indication of the presence of artificial water bodies. This uses the premise that open water locations where spatial extent has increased or decreased significantly from one year to another indicate an artificial waterbody has been formed. This should then be further refined by examining if the shift in spatial extent remains constant over a year, to distinguish from waterbodies changing in spatial extent due to seasonal fluctuations.

STEP 3: Validate data

The mapping of wetlands from remote sensing is challenging in that there is a frequent confusion between flooded areas (or surface waters) and wetlands, despite their major ecological difference: some wetlands are only rarely and partly flooded, whereas many non-wetland habitats (e.g. agricultural or forest) can occasionally be flooded (Perennou et al., 2018). This means that validation requires local knowledge of wetland dynamics to interpret the classification of wetland correctly. In addition, validation procedures are slightly different between open water bodies and vegetated wetlands.

After the production of the vegetated wetlands map, it is necessary to validate them independently to assess their quality and correctness. A sampling approach should be employed whereby sample points for the validation should be selected strategically, with a good spread of points geographically and equally between vegetated and non-vegetated wetland. The amount of points is dependent on the resources available and the time needed for interpretation but should reach a statistical minimum, i.e. there should be enough points to produce a statistically robust sample.

Once a set of sample points has been selected, the validation procedure should use a consistent approach, standard procedures and the same interpreters across vegetated wetlands layer. There are open-source tools which can be used to support the validation procedure, e.g. LACO-Wiki[3], an established, open, free, online validation package, which gives access to Google and Bing imagery, Copernicus web services and other datasets available through a Web Map Service (WMS). This allows the user to distribute the processing across different WMS. It is user-friendly and straightforward to set up and save validation sessions which can be resumed when required. The validation approach taken will depend on whether the open water bodes and vegetated wetlands are in the same dataset or in two separate datasets to validate.

If the water bodies and vegetated wetland classes are in a single dataset then a blind, plausibility or enhanced plausibility approach against the full dataset nomenclature can be used. The detailed results can then be summarised and reported as required by the indicator. The different validation possibilities open to the interpreter are explained below:

Blind: the interpreter is not aware of the class recorded in the product being validated and will do a blind interpretation
Plausibility: the interpreter is aware of the class recorded in the product being validated, but has to determine whether it is correct or not without giving a plausible alternative
Enhanced plausibility: the interpreter is aware of the class recorded in the product being validated, if a code is partially valid, e.g. grassland vs. flooded grassland, the object can be flagged as correct

If the water bodies and vegetated wetland classes are not in a single dataset then the water could be validated with blind or plausibility yes/no and the wetland can be validated with an enhanced plausibility approach.

The list of tasks needed to run a validation session in LACO-Wiki is listed below:

Task 1: Technical review: Review the technical specifications of the vegetated wetland product against the user requirements for the indicator – are they compliant? Visually check the wetland product against Bing

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[3] https://laco-wiki.net

and Google imagery and Open Street Map (OSM). Note any deviations and evaluate for discussion and/or correction. Design a sampling scheme to distribute a total number of sample points across the national extract of the global product based on the area mapped and the number of thematic classes present (in the case of vegetated wetlands).

Task 2: Data preparation/validation session set up. Prepare the product datasets and plan the validation activity in detail. Reformat, clean and re-project the products to be suitable for importing into LACO-Wiki. Load the product into LACO-Wiki and check that the meta data present in the system is correct for the data set, i.e. spatial resolution, time of image acquisition etc. Set up an appropriate legend based on the nomenclature used for vegetated wetland (if any). For the wetland product prepare a sample set and a validation session.

Task 3: Validation point collection. For the wetland product, the interpreter steps through the individual sample points and performs an interpretation of the area represented by the sample vector object surrounding the sample point to determine if it is vegetated wetland or not. At each sample point/vector object, the interpreter assesses the correctness of the classification, if necessary, selects the most detailed alternative thematic class that can be identified from the available reference data before moving on to the next sample point. This process is then repeated for each sample point in each validation session.

Task 4: Reporting. The detailed analysis of the validation data should be undertaken by the indicator custodian, e.g. to produce a contingency matrix of errors of omission versus commission. However, depending on the approach taken, i.e. blind, plausibility or enhanced plausibility, there will be different results as these approaches make certain assumptions and record different levels of information. For example, in the binary maps (water/no water, vegetated wetlands/no vegetated wetlands), LACO-Wiki will produce a contingency matrix of errors of omission versus commission. In the case of classified types of vegetated wetlands, there will be per class accuracies and overall users' and producers' accuracy which allow the user of the global datasets to understand how well they perform in mapping different wetland classes in the national context. Regardless of the approach taken and to inform future validation efforts, progress and summary report should be prepared, including a description of the validation process, details of the application of the process, summary accuracy analysis (confusion matrix outputs from LACO-Wiki), issues arising and lessons learnt.

Water quality of lakes and artificial water bodies

STEP 1: Obtain data

Sentinel-3 OLCI, Sentinel-2 and Landsat 8/9 and Envisat MERIS (ideally full resolution –FR)
MODIS Calibrated Radiances: Surface reflectance must be determined for the solar reflective bands (bands 1-19, 26) through knowledge of the solar irradiance (e.g., determined from MODIS solar-diffuser data, and from the target-illumination geometry).
VIIRS Spectral Reflectance and WG parameters are ravailable from NOAA from October 2011to present at 375 m.
User-supplied *in-situ* data

STEP 2: Process data

When MODIS, VIIRS, Landsat, Sentinel-2 or Sentinel-3 OLCI images become available, the images are processed to water quality indicators. The methodology for this Sub-Indicator requires that water leaving reflectances are generated (atmospheric correction applied) and processed into two datasets of chlorophyll a (Chl) and total suspended solids (TSS) within lakes globally. This is a complex process but there are toolboxes available to national users to enable the extraction of these water quality parameters from EO data. Masking of invalid pixels (e.g. clouds, cloud shadow, ice coverage, mixed land-water pixels) is essential to retrieve good quality data sets.

Approximate workflow (based on SNAP/BEAM)

- create a batch file (workflow manager) in SNAP (export as an xml file) for all steps
- In the case of water quality, the data (pre-) processing is also done in SNAP, e.g. atmospheric correction
- Within SNAP, different water quality algorithms can be used:
    - The FUB algorithm (Schroeder et al., 2007), named after the Free University of Berlin, is a bundle of dedicated NN algorithms for chl-a, total suspended matter (TSM) and coloured dissolved organic matter (CDOM) retrieval from MERIS L1B data

    - The Maximum Peak Height algorithm (MPH; Matthews et al., 2012), uses Rayleigh corrected MERIS bands 6–10 and 14 for the retrieval of the red-NIR reflectance peak height and position, which allow for the identification of cyanobacteria- and eukaryote-dominated pixels, water surface covering by cyanobacteria scum or floating vegetation, and chl-a quantification
    - C2RCC (Doerffer et al. 2007, Brockmann et al.2016) applies several neural networks for atmospheric correction and inwater retrieval. It relies on a large database of simulated water leaving reflectances, and related top-of atmosphere radiances. Neural networks are trained in order to perform the inversion of spectrum for the atmospheric correction as well as the retrieval of inherent optical properties of the water body. It is available for several sensors, e.g. ENVIDAT MERIS, Sentinel-3 OLCI, Sentinel-2 MSI, Landsat OLI.
- further algorithm atmospheric correction and water retrieval are openly available, e.g. polymer (hygeos,https://www.hygeos.com/polymer) or ACOLITE (https://odnature.naturalsciences.be/remsem/software-and-data/acolite).
- WQ parameters (chl-a and TSS) can be further refined, in absolute terms depending on availability and quality of field measurements:
    - CHL – Chlorophyll *a*, μg l^{-1}(CHL-α concentration is provided as a proxy for phytoplankton abundance and algal biomass)
    - TSM – Total Suspended Sediments, mg l^{-1}, (particulate matter)

STEP 3: Validate data

Water quality validation requires reference data from *in situ* water sampling sites. Reference data should be obtained by countries through local water quality monitoring authorities or university research stations before attempting to validate the EO-derived product.

Validation of water quality products is usually based on two types of analysis, matchups and time series. Match-up analysis process the pixels for a certain measurement date. It is specified by the position of the reference measurement and a certain time constraint, e.g. same day or +/- 3 hours, between measurement and overflight. The input for a match-up extraction is a table of in-situ data with location, date, time, measurement values. The output of the match-up extraction is a table with all in-situ information plus all EO data products. Match-up extraction is used for the generation of regression plots and statistics to compare reference measurements and satellite-derived parameters. Time series extraction processes for each station (location) of an input (reference) data set the respective pixels of all overflights covering this position, or all monthly means for the generated products. Thus, one station will generate many extractions. Time series extraction is used for the generation of time series plots, which can either show only the satellite-derived parameters (consistency check) or together with the in-situ data to show the agreement between both measurement methods. Once matchups or time series extractions have been performed, a filtering on the resulting pixels is applied. This filtering allows for the removing of non-valid pixels, e.g. cloud or land (or land influenced) pixels, or outliers (outside of the algorithm training range for example).

Quantity of water (discharge) in rivers and estuaries

STEP 1: Obtain data

There are two main EO based approaches to streamflow (discharge) measurement by EO – hydrological modelling and indirect estimation based on physical flow laws. Depending on the method used, different datasets will have to be obtained.

The hydrological models vary greatly in terms of model complexity, from simple rainfall-runoff models to advanced models taking into account multiple aspects of the hydrological cycle (e.g. abstraction losses, deep aquifer storage). Calibration and parameterisation of the advanced models is difficult in many river basins due to the lack of sufficient observations. It also requires the expertise of a highly-skilled modeller. Therefore, for global applicability, the simpler models are preferred. The basic data requirement of any hydrological model is a digital elevation model (DEM) which is used to derive the stream network and water routing. The Shuttle Radar Topography Mission (STRM) DEM is free to access and has been frequently used for this purpose. Another required data set is the rainfall estimate. Famine Early Warning System Rainfall Estimate (FEWS-RFE) and Tropical Rainfall Measuring Mission (TRMM) are two satellite-based rainfall estimate products suitable for use in hydrological models. The final requirement of the simple models is an estimate of temperature or potential evapotranspiration which is derived based on meteorological datasets, such as ERA-5 available from the Copernicus Data Store. More advanced hydrological models might require more inputs, some of which can be satisfied by satellite observations. For example, actual evapotranspiration could be derived using thermal and optical data from Sentinel-3 satellite, soil moisture could be derived from Sentinel-1 observations, large changes in aquifer storage could be estimated using the GRACE or GOCE satellites and water levels can be estimated from altimeters flying on CryoSat2 or Sentinel-3 satellites.

The indirect approaches require three main inputs observed over a longer period of time: river width, water surface height and slope. River width can be calculated from water extent derived from optical observations (e.g. from Sentinel-2 or Landsat satellites) or SAR observations (e.g. from Sentinel-1 satellites). Water surface height and slope can be estimated based on altimeter measurements, e.g. from CryoSat2 or Sentinel-3 satellites.

Both approaches require some discharge measurements in order to calibrate the models. Those measurements could be historical or (especially in case of indirect approach) obtained from a river section with similar hydrological and geomorphological properties.

STEP 2: Process data

Hydrological modelling
The focus here is on simple hydrological models since complex models have very demanding data requirements and need to be set-up by an experienced hydrologist or modeller. An example of a simple but effective model is the Budyko Hydrological Model available in the GlobWetand Africa toolbox. It couples a simple rainfall-runoff model and a routing scheme and can be set-up and executed within the toolbox by following step-by-step instructions.

The first step in setting up the model is to delineate water streams and their flow directions and contributing areas based on a DEM. Based on this the watersheds (sub-basins) and stream reaches and their geometries (length, slope, etc.) can be defined. In the next step, the precipitation and meteorological data is retrieved and processed to derive mean precipitation and mean minimum and maximum air temperatures at daily timesteps within each sub-basin area. Once the input data is pre-processed the model needs to be calibrated based on historical discharge measurements. The calibration routine tests different model parameterisations and compares the model output with the observed discharge in order to select the best fitting parameters. Once the calibration is completed the model is ready for use and can be driven by recent precipitation and meteorological datasets.

Indirect estimation
Indirect discharge estimation typically apply basic flow laws and the principle of mass conservation to work out the river’s discharge. The approach assume that water mass within a river channel is conserved, and this assumption only holds over short river reaches and a stable cross-section.

The indirect discharge estimation is obtained by the following steps:

1. Download the altimetry data from a given area of interest.
2. Extract valid altimetry levels. Water masks with sufficiently high resolution are required to extract altimetry levels which is not contaminated from other surfaces. Both Sentinel and/or Landsat imagery has proved useful to derive accurate river masks for extracting valid altimetry observations.
3. Obvious outliers are removed by comparing the water level (h) with SRTM elevation (e) i.e. data points are discarded if $|h–e| > 20$ m.
4. Convert altimetry levels to discharge. Various methods can be used which is adapted to different data-availability scenarios: [a] with an in situ rating curve available*, [b] secondly with one simultaneous field measurement of cross-section and discharge, and [c] finally with only historical discharge data available.

*An interesting emerging technology is to use drones to measure water surface elevation, land surface elevation and water surface velocity. By combining the three parameters reliable uniform flow rating curve can be established for specific RA virtual stations. Rating curves which can then be used to translate water surface elevation data from satellite radar altimetry into river discharge.

STEP 3: Validate data

Validation requires discharge observations from in-situ measurements. This requires installation of river gauging stations or other sensors from which the water flow can be estimated. Commonly used metrics to summarize errors in water levels are mean error and Root Mean Square Error (RMSE). The mean error tends to zero for a single dimension when bias is absent. Bias refers to a systematic pattern of error – when bias is absent, error is said to be random. RMSE is computed as the square root of the mean of the squared errors:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \quad \Delta x_i^2} \ ,$$

where n is the number of samples and x is the map estimate for sample i. RMSE is a measure of the magnitude of error which does incorporate bias. The RMSE provides a measure of accuracy in the units of the variable in question and it is therefore useful for evaluating accuracies in continuous fields including discharge.

A previous study in the Zambezi region using retracked ENVISAT altimetry data has demonstrated the potential for obtaining stage measurements for rivers down to 80 m wide with an RMSE relative to in situ levels of 0.32 to 0.72 m at different locations (Michailovskyet al. 2012). It is reasonable to expect similar or better accuracies using the new generation of sensors (i.e. Sentinel-3, Jason-CS/Sentinel-6 and SWOT) due to improved sensor design compared to ENVISAT.

Recommendations for implementation

Activities

- Lessons learned from the SDG 6.6.1 methodology development shows that a coordinated response from Space Agencies greatly facilitates the integration of EO in the 6.6.1 monitoring guidelines.
- Multi-sensor approaches are needed for most of the sub-indicators and associated variables. This requires the development of solid multi-sensor but also multi-scale development that fully exploits the high temporal revisiting of coarse resolution sensors with the finer spatial details of high resolution imagery.
- The need for an accurate global wetland inventory with global EO datasets on vegetated wetlands – beyond the existing mangrove dataset – needs to be addressed as a first priority.
- The significant potential for monitoring of seasonal inundation dynamics in forested wetlands by L-band SAR should be explored by CEOS agencies. Missions such as ALOS-2, ALOS-4, SAOCOM-1 and NISAR all feature systematic observation strategies that would facilitate operational monitoring of inland forested wetlands.
- Although UNEP methodology gives preference to Level 1 global datasets, two different pathways needs to be followed: (1) providing global EO datasets as default data for countries who are lacking data, capacity and resources, while (2) ensuring that countries have access to Earth observation data tools and knowledge if they wish to conduct their own national monitoring.
- The UNEP methodology envisages that Level 1 sub-indicators derived from global EO datasets (e.g., spatial extent of water-related ecosystems and water quality of lakes and reservoirs), would be generated annually, and then summarised as 5-year averages for some of the sub-indicators. UNEP approach to baseline and reporting could be improved and better aligned with the Ramsar reporting cycles (3 years reporting aligned with the COPs).
- The provision of uncertainty measures is as important as the measurements themselves and should be communicated to the countries (e.g., through the insertion of quality flags in each product). The default global datasets don't include in most parts any uncertainty information. give a quality flag on each product
- Global, ready-to-use and publicly available Water Surface Elevation (WSE) time series (e.g., Copernicus GLS Water Level, HydroWeb, DAHITI, HydroSAT) should be improved with full catchment-scale coverage (through denser Virtual Stations networks) and shorter time-lag between data acquisition and availability. This could imply increasing the temporal resolution of WSE measurements by exploiting the full suite of altimetry satellite missions (which implies a subtantial work of inter-calibration of altimetry missions)

	● The Sentinel-3 dataset is available on public processing platforms for WSE extraction over inland water. In order to benefit from the full high spatio-temporal coverage of Sentinel-3, dedicated processing workflows and evaluation tools for WSE extraction over inland water targets are needed (e.g. in SNAP). ● Global data sets should provide the tools for subsetting the data sets for time and area of interest.
Timeframe	**Current indicator timeframe considerations:** The methodology envisages that level 1 indicator data, i.e. global datasets of the spatial extent of water-related ecosystems and water quality, would be generated annually, then summarised as five-yearly averages. Countries would then be required to validate these 5-year averages and report accordingly. The change in national spatial extent is calculated using 5-year averages to account for seasonal and climatic fluctuations. For sub-indicator 1, a historical baseline of 2001-2005 is recommended to compare subsequent 5-year averages of change, therefore there almost three 5-year periods elapsed since the baseline: – 2006-2010 – 2011-2015 – 2016-2020 A historical baseline has not been defined for the other sub-indicators, therefore it would be good to clarify for countries what the historical 5 year reference period should be and is it is up to countries to determine their own baseline, how reporting can be consistent at a global level. **EO timeframe considerations:** Technology is mature and EO services already established and in use.
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EO technical sites	● UNEP Freshwater Ecosystems Explorer https://www.sdg661.app/ ● Joint Research Centre (JRC) Global Surface Water Explorer https://global-surface-water.appspot.com ● Global Mangrove Watch (GMW) Portal: https://www.globalmangrovewatch.org/ ● Copernicus Global Land Service (CGLS) Lake Water Quality products https://land.copernicus.eu/global/products/lwq ● Copernicus Global Land Service (CGLS): Water Level https://land.copernicus.eu/global/products/wl ● UNEP-WCMC Ocean Data Viewer: https://data.unep-wcmc.org/