ESA Climate Change Initiative
River Discharge Precursor
(RD_cci+)

D.1. User Requirements Document.

Contract number: 4000139952/22/I-NB

Reference: CCI-DISCHARGE-0003-URD

Issue 1.1 – 23/05/2023

11 rue Hermès, Parc Technologique du Canal — 31520 Ramonville Saint-Agne, France
Tel +33 (0)5 61 39 47 00 Fax +33(0)5 61 75 10 14
www.cls.fr

CHRONOLOGY ISSUES

Issue	Date	Object	Written by
1.0	21 April 2023	Initial Version	Sylvain Biancamaria
1.1	23 May 2023	Comments from ESA taken into account	Sylvain Biancamaria

Checked by	S. Biancamaria - LEGOS	Sylvain Biancamaria
Approved by	Alice Andral - CLS	Aandral
Authorized by	Clément Albergel - ESA	Clement Albergel

DISTRIBUTION

Company	Names	Email
ESA	Clément Albergel	clement.albergel@esa.int
ESA	Jérôme Benveniste	Jerome.Benveniste@esa.int
CLS	Alice Andral	aandral@groupcls.com
CLS	Yann Bernard	ybernard@groupcls.com
CLS	Maxime Vayre	mvayre@groupcls.com
CLS	Daya Ceccone	dceccone@groupcls.com
CLS	Nicolas Taburet	ntaburet@groupcls.com
CNRM	Simon Munier	simon.munier@meteo.fr
EOLA	Elena Zakharova	zavocado@gmail.com
Hydro Matters	Malik Boussaroque	malik.boussaroque@hydro-matters.fr
Hydro Matters	Laetitia Gal	laetitia.gal@hydro-matters.fr
Hydro Matters	Adrien Paris	adrien.paris@hydro-matters.fr

IRPI	Silvia Barbetta	silvia.barbetta@irpi.cnr.it
IRPI	Stefania Camici	stefania.camici@irpi.cnr.it
IRPI	Paolo Filippucci	paolo.filippucci@irpi.cnr.it
IRPI	Angelica Tarpanelli	angelica.tarpanelli@irpi.cnr.it
LEGOS	Sylvain Biancamaria	sylvain.biancamaria@legos.obs-mip.fr
LEGOS	Julien Lefebve	julien.lefebve@legos.obs-mip.fr
LEGOS	Fabrice Papa	fabrice.papa@ird.fr
Magellium	Gilles Larnicol	gilles.larnicol@magellium.fr
Magellium	Vanessa Pedinotti	vanessa.pedinotti@magellium.fr

LIST OF CONTENTS/SOMMAIRE

LIST OF TABLES AND FIGURES

REFERENCE DOCUMENTS

Global Climate Observing System Programme (GCOS), 2022. The 2022 GCOS ECVs Requirements. GCOS publication n° 245 (WMO).

1 Introduction

More than half of the ECVs listed by GCOS (2022) can benefit from satellites EO (see https://climate.esa.int/en/esa-climate/esa-cci/Objective/). This is why the European Space Agency (ESA) has launched, developed and sustained for over a decade the Climate Change Initiative (CCI), to realize the full potential of the long-term global EO archives. As of early 2023, CCI projects correspond to 27 ECVs, but some ECVs are still to be developed, such as river discharge. To be more specific, river discharge is defined by the World Meteorological organization (WMO) International Glossary of Hydrology (WMO, 2012) as the “Volume of water flowing through a river (or channel) cross-section per unit time” (in m^3/s in the international system of units). If “only” 0.0002% of water on earth is stored in the river network (Gleick, 1996), it corresponds to the main water exchange from land to the ocean with 36,000 km^3/y (Milliman and Farnsworth, 2013).

Climate change is of course affecting the water cycle (Trenberth, 2011) and long-time series of river discharges are needed to better assess its impact on continents and for adaptation of human societies. For multiple reasons (difficulties to access remote gauge locations, decreasing number of gauges worldwide, withholding gauge time series by national or regional agencies, economic issue to maintain or/and expand gauge networks…), the internationally available in situ gauge networks are very heterogeneous both in space and time, as shown on figure 1 from the Global Runoff Data Centre (GRDC). The availability of in situ time series is declining since the middle of the 20th century (Milliman and Farnsworth, 2013). Many in situ gauge measurements are also not shared publicly, as they are considered to be sensitive. This is especially true for transboundary river basins. Figure 1 also evidences that most climatic gauges (i.e., those with time series long enough and recently updated to infer climate change impacts) are mainly located in the northern hemisphere (mainly North America and western Europe), and some part of Southern hemisphere (mainly Australia, Brazil, New Zealand, and South Africa).

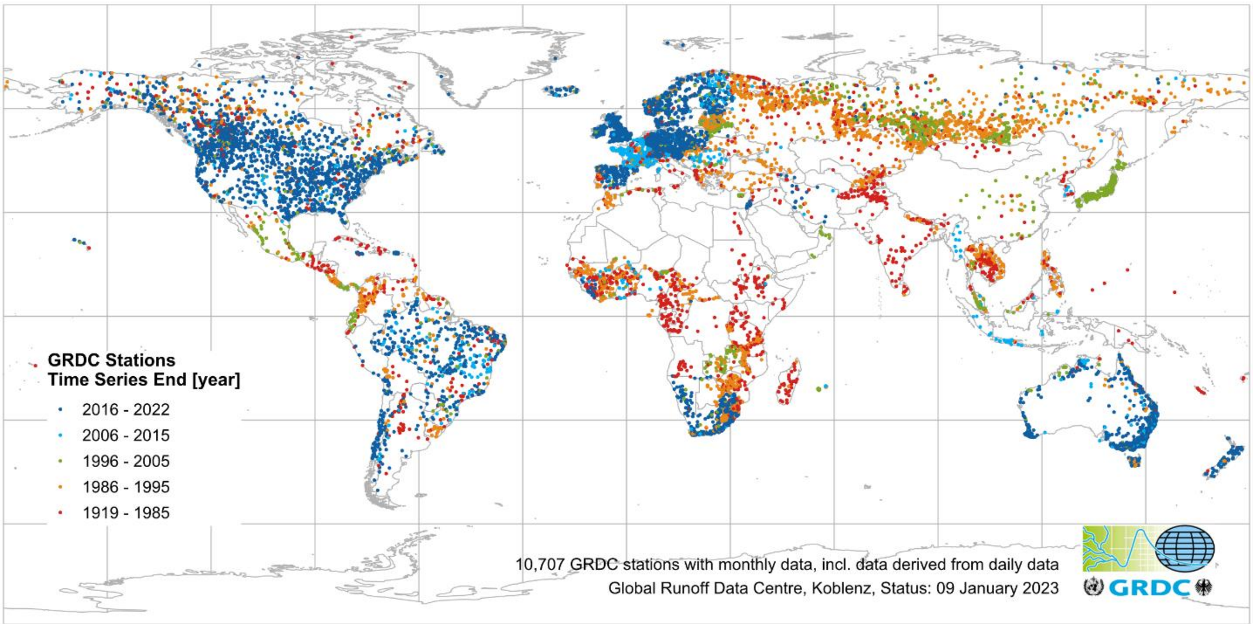

Figure 1. End time of in situ daily/monthly discharge time series available in the Global Runoff Data Centre (GRDC) database (copyright GRDC, www.bafg.de/GRDC)

In this context, and with the achievement of operational services with Earth Observation (EO) satellites, the use of global information given by EO satellites can definitely be used to preserve and improve our capacity to observe and infer climate change impacts on continental freshwater.

Until today, there is no EO sensor capable of directly measuring river discharge from space. Instead, discharge can be estimated indirectly using satellite observation of other river hydrological variables. With several missions launched since the 90's, satellite radar nadir altimeters observe water surface elevation (not to be confused with water depth) along the satellite ground track. These measurements are provided at the intersection of the satellite ground track with the water bodies. The relationship between satellite water surface elevation and in situ or modelled discharge over a common period, called rating curve, can be computed to derive discharge from satellite altimetry observations after the end of the in situ or modelled time series, or before their beginning. This approach is similar to the methodology used to derive discharge time series from gauge readings. Despite these satellite missions do not all have the same orbit tracks and have different sensors characteristics, this wealth of data should allow long-term observations of water level variations for rivers. Moreover, multispectral sensors, specifically in the near infrared (NIR) band, are also able to detect the variability of the river dynamics. The ratio between the reflectance of a dry pixel and a wet pixel is expected to represent the river flow variation. The large advantage of the multispectral sensors is the sub-daily temporal resolution, even if for the optical nature of the sensors they cannot penetrate clouds and therefore they are less reliable during flood events.

In situ data remain crucial to calibrate and validate indirect EO-based discharge, which could not be computed without in situ discharge. It is obvious that EO cannot replace in situ measurements. Once these methods for indirect EO-based discharge estimates have been calibrated/validated, they can favourably complement in situ networks at remote or inaccessible locations, or when the in-situ time series present gaps, discontinuities or delay for being made available.

The purpose of this document is to define the requirements from climate users on an ECV river discharge product and the ones that can be considered in a satellite-based CCI river discharge precursor project. Section 2 presents requirements on river discharge ECV from global observing systems and research programmes. Section 3 corresponds to requirements derived from key climate users interviewed by the CCI discharge project team. Section 4 presents a summary of users' requirements on a CCI discharge product. Finally, section 5 is a discussion on the requirements that are relevant and should be considered by the ESA-funded CCI River Discharge precursor project.

2 Requirements on river discharge ECV from global observing systems and research programmes

2.1 GCOS

This section has been derived from the latest GCOS Implementation plan (2022) and feedbacks from Antonio Bombelli (GCOS / World Climate Research Programme [WCRP] - Terrestrial Observation Panel for Climate [TOPC]) feedbacks.

The Global Climate Observing System (GCOS) is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP), and the International Science Council (ISC). GCOS was established in 1992 to "ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users" (from https://gcos.wmo.int/en/about/gcos-story).

GCOS defines an ECV as a "physical, chemical or biological variable (or group of linked variables) that critically contributes to the characterization of Earth's climate" (GCOS, 2022). These ECVs are subdivided by GCOS into ECV products, which are "measurable parameter[s] needed to characterize the ECV". For GCOS, long-term time series of hydrological observations are needed to better understand changes and trends for these different variables, link these changes to changes in the climate system, and contribute to close the global water budget.

In the 2022 GCOS list, there is a total of 55 ECVs (17 over lands). Among these, the river discharge ECV is divided into two ECV products: river discharge and water level. More specifically, Table 1 presents GCOS requirements on the river discharge ECV product.

According to GCOS (2022), discharge time sampling depends on the use: monthly sampling for climate related modelling of terrestrial, oceanographic and atmospheric systems; daily sampling to determine general discharge patterns at regional and global scales; hourly sampling to monitor single events and for assessment of extremes.

Concerning spatial sampling, it is needed to “capture the freshwater influx from major rivers to the oceans” at global scale (requiring a minimum of 600 gauging stations). If a subset of basins is selected, it should be a balanced coverage of different regions in the world, to have data representative of the global situation.

GCOS (2022) requires discharge measurement uncertainty in between 5% and 15%.

Antonio Bombelli highlighted that “connection between the satellite community with the in-situ one is really important. In situ networks should be highly involved in ESA-CCI projects”. This concern has also been raised by other interviewees, as stated in following sections.

Table 1. Requirements on river discharge ECV from GCOS (2022)

Name	**River Discharge**				
Definition	River Discharge is defined as the volume of water passing a measuring point or gauging station in a river in a given time.				
Unit	$m^3 s^{-1}$				
Note	For station calibration both, the flow velocity and the cross-sectional area has to be measured a few times a year. River Discharge measurements have essential direct applications for water management and related services, including flood protection. They are needed in the longer term to help identify and adapt to some of the most significant potential effects of climate change. The flow of freshwater from rivers into the oceans also needs to be monitored because it reduces ocean salinity, and changes in flow may thereby influence the thermohaline circulation. For climate applications a minimum number of 600 gauging stations globally would be needed to capture the freshwater influx from major rivers to the oceans (which in turn has an impact on ocean temperature and salinity which in turn has impacts on ocean currents and weather systems). A minimum of 4000 gauging stations would be required, in addition to global and regional hydrological data, for deriving changes in rainfall distribution and intensity, and determine climate signals in least anthropogenic impacted basins.				
Requirements					
Item needed	**Unit**	**Metric**	**[1]**	**Value**	**Notes**
Horizontal Resolution			G	-	N/A. In situ observation by a point measurement on gauge.
			B	-	
			T	-	
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	h		G	1	Hourly. Required to monitor single events and for assessment of extreme events.
			B	24	Daily. Suitable to determine general discharge patterns at regional and global scales
			T	720	Monthly. Suitable to support climate related modelling of terrestrial, oceanographic and atmospheric systems
Timeliness	month		G	1 (day)	Daily. For high resolution studies and for preparedness, mitigation during short term events
			B	1	Monthly. Regional forecasting and modelling
			T	12	Yearly. For climatology the provision of monthly data within one year after data collection is necessary
Required Measurement Uncertainty (2-sigma)	%		G	5	Improved measurement techniques and sufficient resources
			B	10	
			T	15	Discharge measurements are affected by a number of changing conditions and uncertainties due to complex calibration needs such as river cross section flow velocities, changing channel conditions, siltation, scour, weed growth, ice conditions.
Stability	$m\ y^{-1}$ / decade	Maximum drift over reference period	G	0.01	For high resolution climatology, necessary to validate discharge variability and extremes.
			B	0.05	
			T	0.1	For climatology
Standards and References	WMO Technical Regulations of Hydrology (WMO-No.49) and Guide to hydrological practices (WMO- No.168) ISO 1100-1 (1996) Measurement of liquid flow in open channels-Part I: Establishment and operation of a gauging station ISO 748 (1997) Measurement of liquid flow in open channels-Velocity area methods WMO (WMO-519) Manual on stream gauging Volume I-Fieldwork and Volume II-Computation of discharge ISO Technical Committee 113 is dealing with all standards related to Hydrometry ISO/TS 24154 (2005) The principles of operation, construction, maintenance and application of acoustic Doppler current profilers (ADCP)				

2.2 GRDC

This section presents requirements on discharge from the GRDC database, based on Ulrich Looser (BfG, Germany, head of the GRDC) feedbacks.

As the GRDC gathers in situ discharge time series from multiple providers and is the main global discharge database, it has a unique view on needs to use discharge for climate studies (at least more than 120 science articles using GRDC data have been published in 2022, see https://www.bafg.de/GRDC/EN/01_GRDC/14_clnts/2022.html). There are some links between GRDC and GCOS, as GRDC is involved in the GCOS–TOPC and Ulrich Looser is the GCOS river discharge ECV Steward.

Figure 2 presents GRDC database download statistics from July 2020 to March 2023. The most downloaded data concern Asia, Europe & Mediterranean region, and Africa. Most users are from the academic or research sectors (almost 90% of the users). Besides, 30% of the users' research activities deals with climate studies.

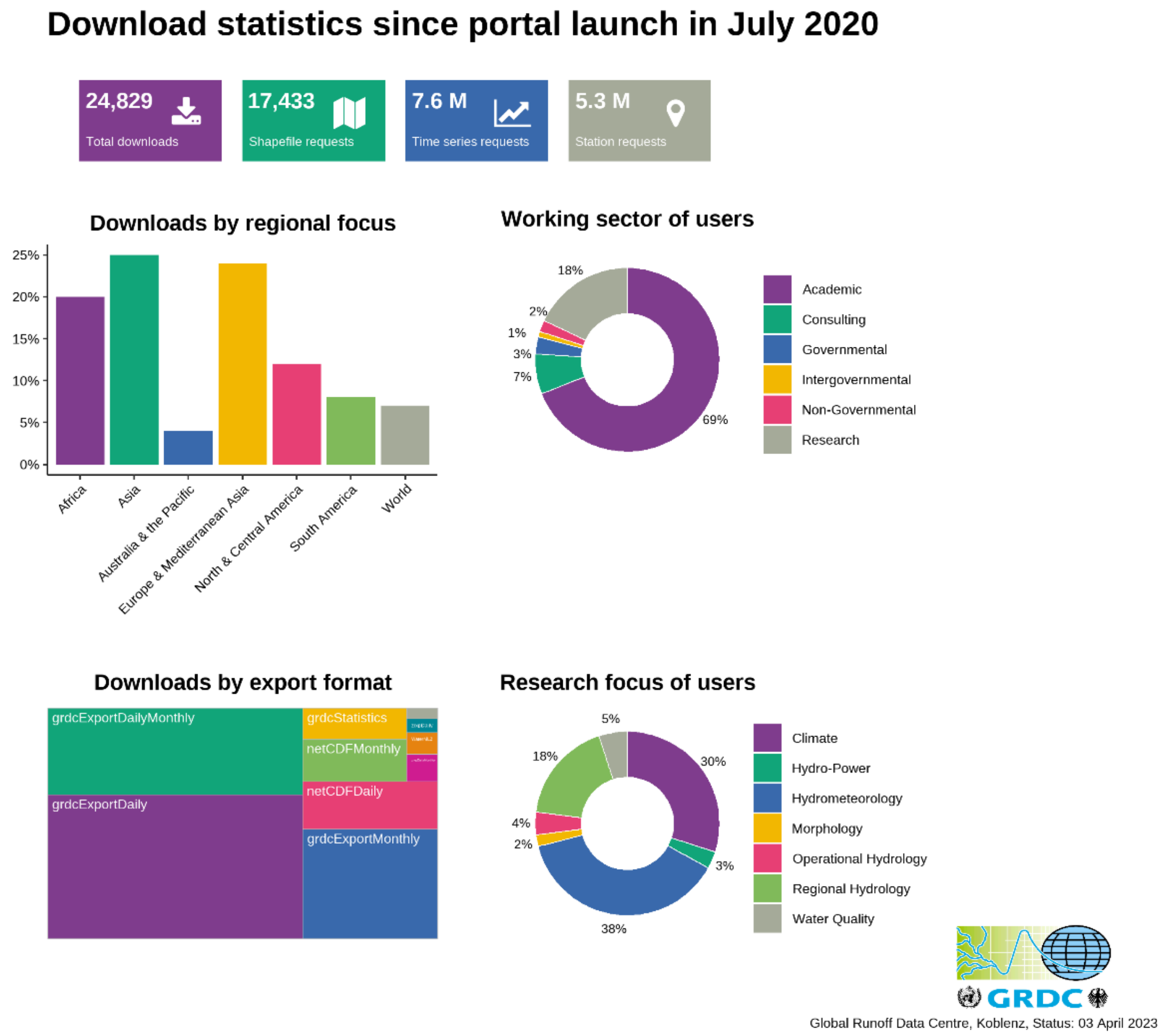

Figure 2. Download statistics concerning the GRDC database from July 2020 to March 2023 (provided by GRDC)

GCOS–TOPC users from this community want long discharge time series, even if it comes from different sensors. In the GRDC database, the mean time series span in between 50 and 60 years, and the longest time series is 200 years long. Yet, mainly in some part of Africa and Asia, time series could be shorter and mostly with monthly average data only. The daily average time series (usually computed from data with higher time resolution) seems to best fit users' needs (except for extreme events studies), but monthly average time series is better than nothing (for example in some part of Africa, the Russian Federation…).

The GRDC database is global and covers both exorheic and endorheic basins (see Figure 1). There are also some specific data products, like the "Freshwater Fluxes to in the World's Oceans" or the "Long-term statistics and Annual Characteristics".

Concerning discharge uncertainties, it is not possible to know uncertainties for all time series. It should be at best 10%, as it seems to be difficult to have more precise data, especially it should be higher for oldest time series. GRDC does not do quality check, but do a consistency check, convert discharge units to m3/s and times to UTC if needed.

Metadata provided by the GRDC are: gauge coordinates (longitude/latitude), drainage area, gauge elevation, gauge name/ID, drainage area, river name (and for small rivers provides also river mainstream name to which this station drains), and which country is operating the gauge. Some users are also interested by the land use/landcover in the gauge drainage area, but this information is changing in time and is not provided by GRDC.

Concerning climate studies, GRDC does only basic statistics for each gauge, but leaves interpretation of data to the user community. Users have their own methodology and GRDC does not have the resources to do this type of study.

2.3 GEWEX

These feedbacks from GEWEX on river discharge product have been provided by Jan Polcher (LMD-IPSL, France, co-chair of the GEWEX Scientific Steering Group).

The Global Energy and Water Exchange (GEWEX) is a core project from the WCRP, aiming at "understanding Earth's water cycle and energy fluxes at and below the surface and in the atmosphere" (https://www.gewex.org/about/). It coordinates science activities related to the global water cycle and interactions between the land and the atmosphere. River discharge and its observation could fit within three of its four panels: the GEWEX Data and Analysis Panel (GDAP), the Global Land-Atmosphere System Studies Panel (GLASS) and the GEWEX Hydroclimatology Panel (GHP). Expanding river discharge estimation have some interests for climate (especially detection/attribution studies, see section 3.1 on this topic) and water budget closure studies.

Concerning science activities done within GEWEX, more information on river discharge could improve current capability for the following type of basins:

- Those for which evapotranspiration is poorly known and needs to be estimated with a water budget closure approach,
- those that are highly anthropized, with an important contribution from surface water to the basin water mass balance.

Monthly discharge is sufficient to study big river basins, hourly data is needed only for smaller basins (that might be difficult to observe with satellite data). The target should be to assimilate river discharge products into global models, to quantify global freshwater inputs to the oceans (e.g., Wang and Polcher, 2019).

Even if providing an estimate of the needed uncertainty on discharge for this type of studies is difficult, having similar uncertainty than in situ data should be a goal. At basin scale, uncertainty on river discharge should be smaller than uncertainty on precipitation, which would allow a coherent estimation of evapotranspiration.

3 Requirements from key climate users

3.1 Requirements from hydrology modelers

This section has been derived from Jean-Christophe Calvet (CNRM, France, member of the CCI CMUG project), Agnès Ducharne (METIS, France), Hervé Douville (CNRM, France), Hannes Müller Schmied (Institute of Physical Geography – Goethe University, Germany), Jan Polcher (LMD-IPSL, France), and ECMWF Environmental Forecasts and Coupled Assimilation Teams (from Christel Prudhomme and Patricia de Rosnay) feedbacks.

For hydrology models, river discharge observations are used to calibrate and/or validate river routing models (RRM) from land surface models (LSM) (e.g., Gelati et al., 2018) or from Global Hydrological Models (GHM), for forecast verification, or to be assimilated into models (to correct initial conditions to forecast discharge or to correct discharge for reanalysis, e.g. Harrigan et al., 2020). Indirectly, river discharge observations could be used to validate some atmospheric forcing or new physical processes added to the LSM or RRM (e.g., Szczypta et al., 2012; Gelati et al., 2018). For climate studies, modelled and in situ discharge are used to detect trends over long period (since the 50's). Impact assessments are then done to detect the influence of climate or anthropogenic factors on these trends (e.g., Vicente-Serrano et al., 2019; Sterling et al., 2013; Gudmundsson et al., 2021). Future projections are uncertain, but models could be better constrained when historical river discharge observations/reconstructions are available. Multiple global river discharge reconstructions from different models are now available, with some spread in their estimation. Having access to more discharge products would help to select the most adapted model reconstruction.

Currently, LSM+RRM and GHM models are validated using in situ discharge database, like the GRDC (figure 1) or the Global Streamflow Indices and Metadata Archive (GSIM; Do et al., 2018) global databases, or the African Database of Hydrometric Indices (ADHI; Tramblay et al., 2021). Yet, as previously stated, these databases are sparse in space and time, especially since the 80's in some part of Africa and Asia (among others). There is therefore a need to complement historical time series for the last decades.

For these two types of studies (cal/val of models and impact assessment studies), drainage area where discharge is available should be equal to few LSM pixel size or more, so around ~10,000 km². ECMWF would even like discharge data for basins from 500 km² to the largest possible. For cal/val studies, any discharge time series with drainage area above these values (between 500 km²/10,000 km²) would be valuable. For impact assessment studies, mesoscale basins are required (drainage area ~ 10,000 km²), otherwise river discharge variability is driven by too many factors and impact assessment is not feasible. Besides, discharge should cover a large range of basins: e.g., different hydro-climatic contexts, topography, land use, and drainage area. Being able to provide discharge information at ungauged locations (as models cannot be validated for these regions) or to complete scarce observations (e.g., complement discontinued in situ discharge time series) would be very valuable. It is even more important for basins with important human population. It should be a mixture of influenced/natural river basins (e.g., upstream/ downstream of reservoirs). Agnès Ducharne also highlighted the need to increase the network of in situ gauges and not just rely on satellite data, as in situ discharge is the most reliable and should not be neglected because of satellite-based discharge.

A monthly time sampling should be enough for these two types of studies, but daily time sampling would be ideal. Long time series are compulsory: the last twenty years is a good starting point but having access to even longer time series (i.e., from the 50's to now) would be ideal. Finer time sampling does not seem to be needed for climate studies, but it is important for other uses. For example, for forecast accuracy assessment and data assimilation, 6 hourly to daily data are needed, according to ECMWF, over at least four years (with several days/weeks in a row of data).

Discharge accuracy/uncertainty is not easy to set, but for trend detection, an accuracy of 5-10% (especially for flood forecast assessment) and not more than 20% seems needed (like in situ data). It is better to have precise monthly time series, rather than daily time series with low accuracy. Of course, uncertainty depends on the discharge value: even for in situ data, discharge during flood or drought period has a higher uncertainty and gauge uncertainty is location dependent (Coxon et al., 2015). Uncertainty estimation is important for assimilating these products into models, it would also help to select which data should be assimilated. A clear description of the uncertainty/error metric also needs to be provided (e.g., 1-sigma error is a good metric, if the error is assumed to be white noise). Some methods exist to consider this uncertainty in climate projections (e.g., Qasmi and Ribes, 2022).

Ancillary data are needed with discharge time series (in addition to the longitude/latitude coordinates of the discharge location): drainage area, information to locate the river where discharge is computed (needed as RRM resolution might be crude and the pixel containing the location might not be the river corresponding to the provided discharge), altitude, mean river width and water elevation (not used for LSM+RRM validation, but could be useful for impact assessment), flood extent (for flood forecast), river bathymetry/channel shape, gauge named/ID if used for calibration (along with the date when the gauge database has been retrieved, as gauge ID might change in time for some global databases, like GRDC). It would be interesting to have the meteorological conditions (e.g. precipitation, air temperature…) associated to the discharge estimation and water temperature (e.g., for nuclear powerplant operations)

ECMWF highlights that rating curves should be updated in time, as they are not stationary (especially in large rivers) over decades.

Some modelers highlighted that having a tool to create an ensemble of perturbed discharge data based on our product and uncertainty estimation would be useful.

3.2 Mountain hydrology

This section corresponds to the interview from Simon Gascoin (CESBIO, France).

Mountain catchments are generally small and less influenced by human activities than downstream areas. They have a higher hydrological predictability than other catchments due to the contribution of winter snow accumulation on the river flow. Climate change is already modifying mountain catchments hydrological regime.

Discharge at the outlet of mountain catchments can be used to assess the accuracy of snow water equivalent estimates. Hourly discharge could be beneficial to characterize the contribution of snow and ice melt. Snow melt and rain-on-snow events can cause abrupt flood with important impacts in downstream areas. The decline of the snowmelt contribution tends to reduce low flows during the summer.

3.3 Other variable from the continental part of the water cycle

This section corresponds to feedbacks from Wouter Dorigo (Technische Universität Wien, Austria, science leader of the CCI Soil Moisture project).

The CCI Soil Moisture project is more interested to water storage changes in the soil, to study depletion of soil water storage, and contribution to groundwater storage dynamics. River discharge is needed to close the water budget at global scale or evaluate irrigation needs. Having a discharge product to complement GRDC database is therefore of interest.

All climatic zones are interesting, even if the project is focusing more on medium to large basins. Having data on small basins could be valuable for few selected cases, like in the Mediterranean region. Monthly time series should be sufficient, with a preference for daily data, with a relative error on discharge around 10%. Additional ancillary information associated to river discharge are: uncertainty, quality flag, information if floodplain is flooded or not, vegetation cover, human infrastructures (like canals or dams).

3.4 Requirements from oceanographers

This section sums up requirements from members of the CCI Sea Surface Salinity (members from Mercator Ocean, France), the CCI Coastal Sea Level (Anny Cazenave, LEGOS, France, science leader) and the CCI Sea Level Budget Closure (Martin Horwath, Technische Universität Dresden, Germany, former science leader; Anny Cazenave; Gilles Larnicol, Magellium, France).

Concerning sea level, an important current field of research concerns the observed coastal sea level trend at river estuaries and deltas. A long river discharge product could be used to explore if these trends could be explained by freshwater input changes, through sea water density changes (e.g., Giffard et al., 2019; Sotillo et al., 2021). Besides, river discharge is used to force the boundary of global and regional ocean models used in ocean reanalysis, that spans over several decades. These ocean CCI projects use discharge and/or land water storage (the sum of groundwaters, soil moisture, liquid surface waters, snow, water intercepted by and in the canopy) estimated from land hydrology models. Validating/correcting these models with ancillary discharge observations or indirect products would be beneficial for these CCI projects.

To address this scientific question, river discharge should be provided at the outlet of exorheic river basins, especially at river estuaries and deltas (the CCI coastal sea level project is even more interested by deltas/estuaries crossed by a Jason track). Estimates of freshwater inputs to the ocean from rivers is needed even from highly anthropized basins. Basins which have known important increase/decrease of discharge (i.e., important trends over decades, important changes in their mean annual discharge or seasonal amplitude…) are important to consider (like the Mississippi or Irrawaddy deltas). More indirectly, for the sea level budget closure, river discharge could be useful for estimating/validating land water storage at global scale or at least at regional scale (and not just for exorheic basins, but also endorheic ones).

Product with monthly time series should be enough for all these uses of discharge products to resolve seasonal to interannual variability. Its time span should cover at least the GRACE period (after 2002) and more preferably the whole altimetry period (since the 90's).

There is no explicit requirement on discharge accuracy, but discharge should be accurate enough to detect if there are significant long-term trends and changes in discharge time series.

This river discharge product would be even more informative, if it could be compared to in situ salinity changes data.

4 Summary of users' requirements on CCI discharge

From these requirements, the followings are the most cited and need to be considered to compute CCI River Discharge products. The traceability of the requirements is given by the following code (provided in brackets at the end of the requirement): G (the source is GCOS, 2022), I (the source is the user interviews done by the project), P (the source is the own experience of the project team).

Users' requirements on river discharge:

Time step: daily average to monthly average time series. (G, I)

Time span: long time series (multiple decades). (I)

Basins: all basins are of interest (even heavily anthropized basins and should include both exorheic and endorheic basins). (I)

Locations: from the basin outlets to smaller (sub-)basins around ~10,000 km^2 or even smaller for mountain basins. For exorheic basins, discharge at the basin outlet is required, to evaluate freshwater inputs to the oceans. It should cover different climatic zones, latitudes and level of anthropization, to be representative of the global situation. (G, I)

Uncertainty: needed for all users (should be around 10% to 20%), but any information on data uncertainty, even with higher error, could be useful. It needs to be provided and should be precise enough to measure trend over decades. A simple quality flag could be also useful for a quick selection of the most accurate time series. At basin scale, uncertainty on river discharge should be smaller than uncertainty on precipitation, to allow an estimation of evapotranspiration. (G, I)

Ancillary data: gauge coordinates (longitude/latitude), drainage area, river name/information to locate without any ambiguity river on which discharge is computed (for small rivers, add river mainstream name to which the station drains), altitude, mean river width and water elevation. (I)

5 Requirements considered within the CCI River Discharge precursor project

EO data that will be used in this CCI River Discharge precursor project to estimate discharge correspond to nadir radar altimeters and multispectral images. Over twenty years, multiple missions, from different space agencies, with different types of sensors, and orbits, have to be considered. For example, Figure 3 presents time span and repeat period of different altimetry missions that will be considered in this precursor project. If spectral images from Landsat-7/8/9, Terra/MODIS, Aqua/MODIS, Envisat/MERIS, Sentinel-2/MSI, and Sentinel-3/OLCI sensors have a better time resolution and spatial coverage than altimeters data, their time sampling is affected by images with too much cloud cover. For more discussion on issues regarding nadir altimeters or multispectral images and their uses to estimate discharge, see, for example, Biancamaria et al. (2017), Crétaux et al. (2017), and Tarpanelli et al. (2021).

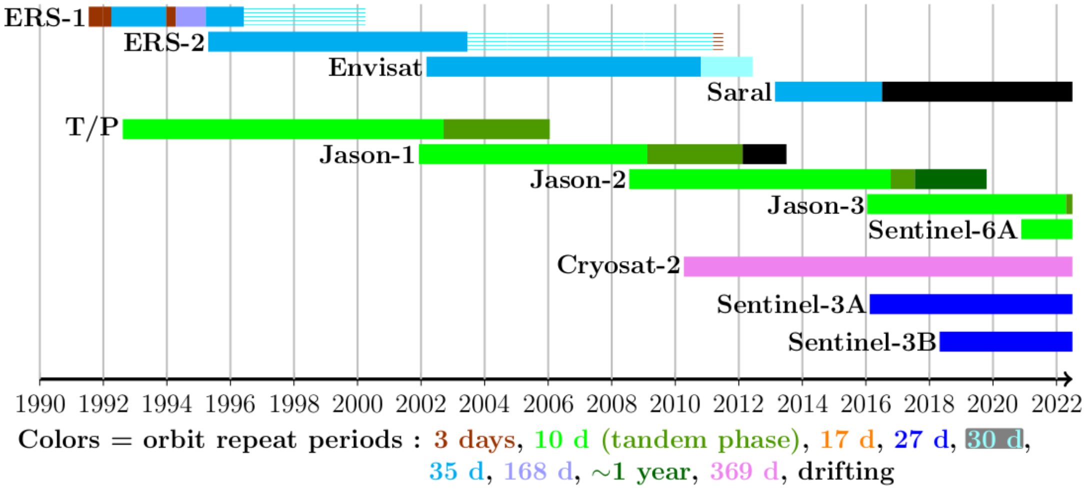

Figure 3. Timeline of the altimetry missions considered in this precursor project. Colours correspond to missions' orbits repeat periods. After June 1996, ERS-1 is in back-up mode and no measurements are recorded and from Mid-2003, altimeter onboard ERS-2 stopped working. That's why the boxplot patterns for these two missions after these dates are changed to show the absence of measurements

For these reasons, not all users' requirements can be fulfilled with an EO-based discharge product. For example, because of their small size and the important slopes, historical altimetry missions usually do not provide useful measurements on mountain rivers (e.g., Biancamaria et al., 2017) and therefore discharge could not be derived for mountain watersheds (so the needs from section 3.2. cannot be considered). Computing daily average discharge (which requires actual sampling much below 1 day) is not realistic, given time sampling of each EO data considered (even from multispectral images). Hourly data for small basins is clearly out of reach, it is therefore not realistic to provide discharge product for locations where drainage area is below few 10,000 km^2.

Nadir altimeters can provide observations only below their ground track. Therefore, even if the project will do its best to complement in situ network to estimate discharge near the outlet of exorheic basins, it will be dependent of the satellite ground tracks locations. It will also be dependent of available in situ discharge data, which are provided only on non-tidal river reaches, which could be located hundreds of kilometres upstream their deltas or estuaries.

As shown on Figure 3, altimetry data are not available before the 90's and have been developed to observe the oceans. They are only used opportunistically on for continental waters. That's why, in this project, only the 2002-2022 time span will be considered to derive river discharge (with a goal to extend to 1995-2022 in a future CCI project).

Furthermore, as a CCI precursor project, the approach will not be global, but at least 15 river basins will be considered.

Given these limitations of satellite data used, only the requirements provided below will be considered to derive CCI River Discharge precursor products requirements (broken down into Threshold, i.e. minimum requirement to be met, and Goal, i.e. ideal requirement). Like for section 4, the traceability of the requirements is given by the following code: G (the source is GCOS, 2022), I (the source is the user interviews done by the project), P (the source is the own experience of the project team), W (the source is WMO, 2012).

Requirements for the CCI River Discharge precursor project:

Geophysical measurement: river discharge (i.e., volume of water flowing through a river cross-section per unit time; WMO, 2012) in m^3/s. (G, P, W)

Time step threshold: products will be delivered at EO observation sampling dates (in UTC time) (P)

Time step goal: monthly average time series product will be delivered and daily (but not daily average) time series product. (G, I)

Time span threshold: 20 years' time series (from 2002-2022). (I, P)

Time span goal: time series from 1995-2022. (I, P)

River basin coverage threshold: at least 15 river basins, covering different climatic zones, latitudes and level of anthropization, and should include both exorheic and endorheic basins. It should be representative of the global situation, excluding mountain basins. (G, P)

River basin coverage goal: observing all basins at global scale with drainage area above multiple 10,000 km^2. (G, I)

Locations threshold: multiple locations shall be provided per basins. For each basin, the estimation of discharge near the outlet on river reach not affected by tides (which could be multiple hundreds of km upstream) will be considered. Within all locations from all basins, locations shall cover different drainage area, from multiple 10,000 km^2 to near the Amazon outlet. Mountain (sub-)basins shall be excluded. (G, I, P)

Uncertainty threshold: It shall be provided based on comparison with in situ measurements, if available and shall at least be mission dependent. (I, P)

Uncertainty goal: having uncertainty around 15% on monthly average discharge product. (G, I)
Note: It is not easy to provide a specific number concerning the required uncertainty. But it is important to note that uncertainty on discharge may also impact uncertainties of other variables in the hydrological cycle and could impact how it is used for different applications.

Ancillary data threshold: gauge coordinates (longitude/latitude), drainage area, river name/information to locate river on which discharge is computed. (I)

Ancillary data goal: gauge coordinates (longitude/latitude), drainage area, river name/information to locate river on which discharge is computed, altitude, mean river width and water elevation. (I)

The products that will be computed by the CCI River Discharge precursor project will be, as much as possible, compliant with the above requirements. The planned products should be: river discharge time series from nadir radar altimeters and ancillary data at satellite observation times, river discharge time series from multispectral images and ancillary data at satellite observation times and discharge time series from a combination of multispectral images, nadir altimetry and ancillary data at multi-satellite observation times. Monthly average product could also be computed for all or some of these products. Long time series over 20 years will be provided at some selected sites with the studied basins (see CCI-Discharge-004-RP_WP2.docx document produced by the CCI River Discharge precursor project).

6 References

Biancamaria S., F. Frappart, A.-S. Leleu, V. Marieu, D. Blumstein, J.-D. Desjonqueres, F. Boy, A. Sottolichio, and A. Valle-Levinson (2017). Satellite radar altimetry water elevations performance over a 200 m wide river: evaluation over the Garonne River. Advances in Space Research, 59, 128-146, doi:10.1016/j.asr.2016.10.008.

Coxon G., J. Freer, I. K. Westerberg, T. Wagener, R. Woods, and P. J. Smith (2015). A novel framework for discharge uncertainty quantification applied to 500 UK gauging stations, Water Resources Research, 51, 5531-5546, doi:10.1002/2014WR016532.

Crétaux J.-F., K. Nielsen, F. Frappart, F. Papa, S. Calmant, and J. Benveniste (2017). Hydrological applications of satellite altimetry: rivers, lakes, man-made reservoirs, inundated areas in Satellite Altimetry Over Oceans and Land Surfaces, Earth Observation of Global Changes (éd. Stammer, D. & A. Cazenave) 459-504 (CRC Press, Boca Raton, USA). isbn:978-1-4987-4345-7.

Do H. X., Gudmundsson L., Leonard M., and Westra S. (2018). The Global Streamflow Indices and Metadata Archive (GSIM) – Part 1: The production of a daily streamflow archive and metadata. Earth System Science Data, 10, 765-785, https://doi.org/10.5194/essd-10-765-2018.

GCOS (2022). The 2022 GCOS ECVs Requirements. GCOS publication n°245 (WMO). Available at: https://library.wmo.int/index.php?lvl=notice_display&id=22135#.Y-Tiv3bMKbg (last accessed 20 March 2023).

Gelati E., B. Decharme, J.-C. Calvet, M. Minvielle, J. Polcher, D. Fairbairn, and G. P. Weedon (2018). Hydrological assessment of atmospheric forcing uncertainty in the Euro-Mediterranean area using a land surface model. Hydrology and Earth System Sciences, 22, 2091–2115, https://doi.org/10.5194/hess-22-2091-2018

Giffard P., W. Llovel, J. Jouanno, G. Morvan, and B. Decharme (2019). Contribution of the Amazon River Discharge to Regional Sea Level in the Tropical Atlantic Ocean. Water, 11(11), 2348, doi:10.3390/w11112348.

Gleick P. (1996). Water resources in Encyclopedia of Climate and Weather (ed. Schneider, S. H.) 817-823 (Oxford University Press, New York, USA).

Gudmundsson L., Boulange J., Do H. X., Gosling S. N., Grillakis M. G., Koutroulis A. G., Leonard M., Liu J., Müller Schmied H., Papadimitriou L., Pokhrel Y., Seneviratne S. I., Satoh Y., Thiery W., Westra S., Zhang X., and Zhao F. (2021). Globally observed trends in mean and extreme river flow attributed to climate change. Science, 371(6534), 1159-1162, doi:10.1126/science.aba3996.

Harrigan S., E. Zsoter, L. Alfieri, C. Prudhomme, P. Salamon, F. Wetterhall, C. Barnard, H. Cloke, and F. Pappenberger (2020). GloFAS-ERA5 operational global river discharge reanalysis 1979–present. Earth System Science Data, 12, 3, 2043-2060, https://doi.org/10.5194/essd-12-2043-2020.

Qasmi S. and A. Ribes (2022). Reducing uncertainty in local temperature projections. Science Advances, 8, eabo6872, doi:10.1126/sciadv.abo6872.

Milliman J. and K. Farnsworth (2013). River discharge to the coastal ocean - A global synthesis. ISBN:978-0-521-87987-3 (Cambridge University Press, Cambridge, United Kingdom).

Sotillo M.G., Campuzano F., Guihou K., Lorente P., Olmedo E., Matulka A., Santos F., Amo-Baladrón M.A., and Novellino A. (2021). River Freshwater Contribution in Operational Ocean Models along the European Atlantic Façade: Impact of a New River Discharge Forcing Data on the CMEMS IBI Regional Model Solution. Journal of Marine Science and Engineering. 9(4), 401. https://doi.org/10.3390/jmse9040401.

Sterling S., A. Ducharne, and J. Polcher (2013). The impact of global land-cover change on the terrestrial water cycle. Nature Climate Change, 3, 385-390, doi:10.1038/nclimate1690.

Szczypta C., B. Decharme, D. Carrer, J.-C. Calvet, S. Lafont, S. Somot, S. Faroux, and E. Martin (2012). Impact of precipitation and land biophysical variables on the simulated discharge of European and Mediterranean rivers. Hydrology and Earth System Sciences, 16, 3351-3370, doi:10.5194/hess-16-3351-2012.

Tarpanelli A., S. Camici, K. Nielsen, L. Brocca, T. Moramarco, and J. Benveniste (2021). Potentials and limitations of Sentinel-3 for river discharge assessment. Advances in Space Research, 68(2), 593-606, doi:10.1016/j.asr.2019.08.005

Tramblay, Y., Rouché, N., Paturel, J.-E., Mahé, G., Boyer, J.-F., Amoussou, E., Bodian, A., Dacosta, H., Dakhlaoui, H., Dezetter, A., Hughes, D., Hanich, L., Peugeot, C., Tshimanga, R., and Lachassagne, P. (2021). ADHI: the African Database of Hydrometric Indices (1950–2018). Earth System Science Data, 13, 1547-1560, https://doi.org/10.5194/essd-13-1547-2021.Trenberth K. (2011). Changes in precipitation with climate change. Climate Research, 47, 123-138, doi:10.3354/cr00953.

Vicente-Serrano, S. M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., et al. (2019). Climate, irrigation, and land cover change explain streamflow trends in countries bordering the Northeast Atlantic. Geophysical Research Letters, 46, 10821-10833. https://doi.org/10.1029/2019GL084084.

Wang F. and J. Polcher (2019). Assessing the freshwater flux from the continents to the Mediterranean Sea. Scientific Reports, 9, 8024, https://doi.org/10.1038/s41598-019-44293-1.

WMO (2012). International Glossary of Hydrology. WMO publication n°385, ISBN:978-92-63-03385-8