ESA Climate Change Initiative
River Discharge Precursor
(RD_cci+)

RD_cci+ Product User Guide (PUG)

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[**RD-1**] D.1. User Requirements Document for CCI River Discharge precursor project (CCI-Discharge-0003-URD, Issue 1.1), https://climate.esa.int/media/documents/D1_CCI-Discharge-0003-URD.pdf

[**RD-2**] D.2. Selection of river basins. CCI River Discharge precursor project Document (CCI-Discharge-0004-RP_WP2, Issue 1.1), https://climate.esa.int/media/documents/D2_CCI-Discharge-0004-RP_WP2_v1-1.pdf

[**RD-3**] D.3. Water Surface Elevation (WSE) Algorithm Theoretical Basis Document (ATBD) (CCI-Discharge-0005-ATBD-WSE, Issue 1.2), https://climate.esa.int/media/documents/CCI-Discharge-0009-ATBD-WSE_v1-2.pdf

[**RD-4**] D.3. River Discharge (Q) from Altimeters and Ancillary data, multispectral images and data combination - Algorithm Theoretical Basis Document (ATBD) (CCI-Discharge-0012-ATBD, Issue 1.1), https://climate.esa.int/media/documents/CCI-Discharge-0012-ATBD-Discharge.pdf

[**RD-5**] The ESA River Discharge CCI+ precursor project website, https://climate.esa.int/en/projects/river-discharge/about-the-river-discharge-project/

[**RD-6**] ESA Climate Office (2021). CCI Data Standards. Ref. CCI-PRGM-EOPS-TN-13-0009, issue 2.3, available at https://climate.esa.int/documents/1284/CCI_DataStandards_v2-3.pdf

[**RD-7**] D.4. Release Note on Water Level Climate Research Data Package (CCI-Discharge-0006-WSE-CRDP-ReleaseNote, Issue 1.1, https://dap.ceda.ac.uk/neodc/esacci/river_discharge/docs/WL/v1.1/CCI-Discharge-0006-WSE-CRDP-ReleaseNote_v1.1.pdf)

[**RD-8**] D.5. Release Note on Altimetry-Based River Discharge Climate Research Data Package (CCI-Discharge-0013-Qalti-CRDP-ReleaseNote, Issue 1.0)

LIST OF ACRONYMS

ATBD	Algorithm Theoretical Basis Document
AlTiS	Altimetry Time Series software
CCI	Climate Change Initiative
CDF	Cumulative Distribution Function
CDR	Climate Data Record
CF	Climate and Forecast
CM	Difference between a Calibration (C) and a Measurement (M) pixels
CRDP	Climate Research Data Package
CSV	Comma-Separated Values
CTOH	Centre for Topographic Studies of the Oceans
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable(s)
Envisat	Environmental Satellite
EO	Earth Observation
ERA5	ECMWF Reanalysis v5
ERS-2	European Remote Sensing satellite 2
ESA	European Space Agency
FDC	Flow Duration Curve
GCOS	Global Climate Observing System
GDR	Geophysical Data Records
GRDC	Global Runoff Data Centre
J1	Jason-1
J2	Jason-2
J3	Jason-3
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LRM	Low Resolution Mode
MCMC	Markov Chain Monte Carlo
MH	Metropolis-Hasting sampler
MODIS	Moderate resolution imaging spectroradiometer
NetCDF	Network Common Data Form
NIR	Near-InfraRed
NUTS	No-U-Turn Sampler
OCOG	Offset Centre of Gravity
PUG	Product User Guide
RC	Rating Curve
RD	River Discharge
RDC	Recession Duration Curve
RD-alti	River Discharge from altimeters and ancillary data
RD-multispec	River Discharge from multispectral images and ancillary data
RD-merged	Satellite-based River Discharge – merging approach
RD-mergedL2	RD-merged – merging approach using Level 2 products (WSE/CM)
RD-mergedL3	RD-merged – merging approach using Level 3 products (RD-alti/RD-multispec)
S3A	Sentinel-3A
S3B	Sentinel-3B
S6	Sentinel-6 Michael Freilich
Saral	Satellite with ARgos and ALtika
SWOT	Surface Water and Ocean Topography
TP	Topex-Poseidon
UTC	Coordinated Universal Time
VS	Virtual Station
WL	Water Level
WMO	World Meteorological Organization
WP	Work Package
WSE	Water Surface Elevation

1 Introduction

This document provides all the information needed by the users to successfully employ the CCI River Discharge CRDPs in their work. The PUG may reuse information that was originally provided in the ATBDs and release notes for each product.

Section 2 is dedicated to the general background of the project and its objectives. Section 3 focuses on the description of the products and the methodologies used to compute them with a part on the limitations and weaknesses associated to these products. Section 4 provides a detailed description of the data format, with guidance for their reading and display. For readers information, Calibration/Validation periods defined for in situ data used to compute satellite-data/discharge relationship for each station are provided in [RD-4, Annex]. In all sections, references to specific CCI documents are provided for readers needing more details.

2 General Background

Satellites are essential tools for observing Earth's surface and monitoring its changes. The Global Climate Observing System (GCOS) has identified numerous Essential Climate Variables (ECVs), more than half of which can benefit from Earth Observation (EO) data collected by satellites (GCOS, 2022). The European Space Agency (ESA) has recognized the significance of utilizing satellite EO data for climate monitoring and has thus initiated the Climate Change Initiative (CCI) over a decade ago. The primary objective of CCI is to leverage long-term global EO archives to realize the full potential of satellite observations in understanding and addressing climate change (ESA Climate Change Initiative).

As of early 2023, the CCI projects have focused on 27 ECVs, including some like river discharge, which are still in the development phase (ESA Climate Change Initiative). River discharge, defined by the World Meteorological Organization (WMO) as the volume of water flowing through a river or channel per unit of time, is crucial for understanding the dynamics of the water cycle (WMO, 2012). It plays a pivotal role in transporting water from land to oceans, with approximately 0.0002% of Earth's total water stored in river networks, amounting to around 36,000 km^3 per year (Gleick, 1996; Milliman and Farnsworth, 2013).

Climate change significantly impacts the water cycle, necessitating long-term monitoring of river discharges to assess its effects on continents and facilitate adaptation strategies (Trenberth, 2011). However, obtaining consistent and reliable long-term river discharge data is challenging due to various factors. These include difficulties in accessing remote gauge locations, a decreasing number of gauges worldwide, limitations imposed by national or regional agencies on gauge time series sharing, and economic constraints hindering the maintenance or expansion of gauge networks (Global Runoff Data Centre [GRDC]; Milliman and Farnsworth, 2013).

The decline in the availability of in-situ gauge measurements has been observed since the mid-20th century, exacerbating the challenges associated with monitoring river discharge (Milliman and Farnsworth, 2013). Furthermore, many in-situ gauge measurements, especially in transboundary river basins, are not shared publicly due to sensitivity concerns.

In this context, EO satellites offer a promising solution to preserve and enhance our capacity to observe and understand climate change's impact on continental freshwater resources. The CCI River Discharge precursor project aims to capitalize on EO data, including nadir radar altimeters and multispectral images, spanning over two decades [RD-5]. However, utilizing EO data poses challenges, as highlighted in previous studies (Biancamaria et al., 2017; Crétaux et al., 2023; Tarpanelli et al., 2021).

For instance, while multispectral images provide superior temporal resolution and spatial coverage compared to altimetry data, their effectiveness is impeded by cloud cover, particularly in mountainous regions. Concerning nadir altimeter, they have two main limitations: their coarse spatial sampling (i.e. measurements are done only along the satellite ground tracks) and temporal sampling (from 10 days to 35 days, depending on the mission).

Despite these challenges, the CCI precursor project endeavors to meet the stringent requirements of various scientific communities [RD-1]. For example, oceanographers require discharge data to understand freshwater inputs into oceans, necessitating precise measurements over extended periods. Similarly, hydrologists utilize discharge data to model river flows, assess water availability, and manage water resources effectively. Their requirements [RD-1] include geophysical measurements of river discharge, monthly average time series products, and a time span extending from 2002 to 2022, with a goal to cover the 1995-2022 time span. 18 rivers basins have been selected to be representative of diverse climatic zones and anthropization levels, albeit excluding mountain basins due to data limitations, as well as 54 stations to consider the requirements to each scientific community (Figure 1) [RD-2].

Through meticulous data integration and adherence to predefined requirements tailored to each scientific community [RD-1], the CCI River Discharge precursor project aims to deliver robust discharge products [RD-3, RD-4] meeting the diverse needs of the oceanographic, water cycle, hydrology, and related communities [RD-1].

In summary, the main goal of the CCI River Discharge precursor project is to integrate multispectral and altimetry satellite data to compute long-term river discharge time series [RD-5]. By addressing user requirements defined in [RD-1], the project seeks to advance our understanding of hydrological processes and climate change.

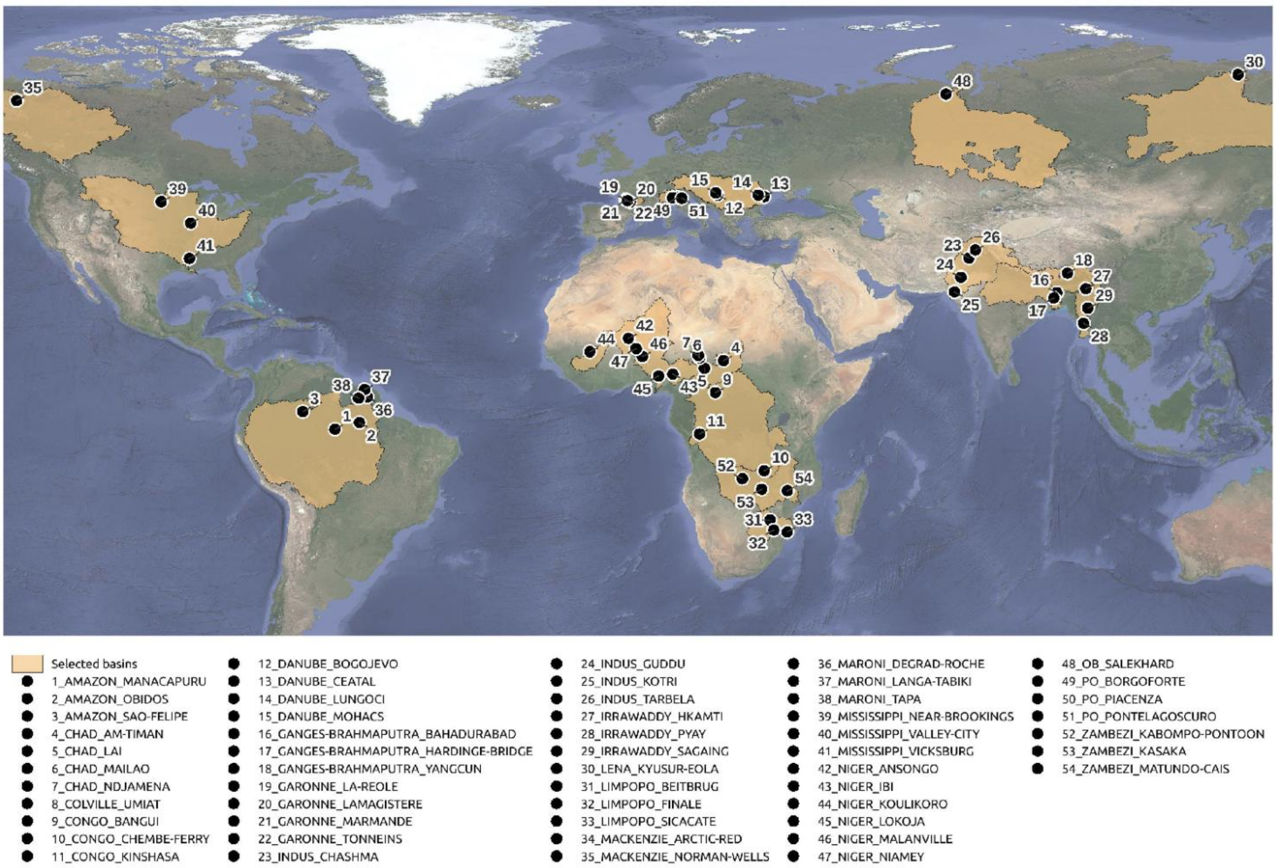

Figure 1: Selected basins (yellow) and selected locations (black points) near which nadir radar altimeter WSE time series and satellite-based river discharge have been computed

3 Products descriptions

To assess the potential for deriving long-term discharge ECV time series from remote sensing observations and ancillary data, 6 types of products have been provided at selected locations [RD-3, RD-4]:

- WSE timeseries for both single altimetry mission and merged altimetry missions
- RD-alti timeseries
- RD-multispec timeseries
- RD-merged timeseries both at the Level2 (RD-mergedL2) and at the Level 3 (RD-mergedL3)

The table below summarizes the availability of each product provided during this precursor CCI project for each station.

BASINS	STATIONS	PRODUCTS						
		WSE			Altimetry-based RD	Multispectral-based RD	Satellite-based RD (merging product)	
		Single mission	*Basic merging*	*Stochastic merging*	*RD-alti*	*RD-multispec*	*RD-mergedL2*	*RD-mergedL3*
AMAZON	OBIDOS	X	X		X	X	X	X
	SAO-FELIPE	X	X		X	X	X	X
	MANACAPURU	X	X		X	X	X	X
CHAD	NDJAMENA	X				X		
	AM-TIMAN	X	X		X	X		X
	LAI	X	X		X	X		X
	MAILAO	X	X		X	X		X
COLVILLE	UMIAT	X	X		X	X	X	X
CONGO	CHEMBE-FERRY	X	X	X	X	X		X
	BANGUI	X	X	X	X	X	X	X
	KINSHASA	X	X	X	X	X	X	X
	Densified space sampling			X				
DANUBE	BOGOJEVO	X	X		X	X		X
	MOHACS	X	X		X	X		X
	LUNGOCI	X	X		X	X		X
	CEATAL	X	X		X	X		X
GANGES-BRAHMAPUTRA	YANGCUN	X	X		X	X		X
	HARDINGE-BRIDGE	X	X		X	X		X
	BAHADURABAD	X	X		X	X		X
GARONNE	LAMAGISTERE	X	X		X	X	X	X
	TONNEINS	X	X		X	X	X	X
	MARMANDE	X	X		X	X	X	X
	LA-REOLE	X	X		X	X	X	X
INDUS	KOTRI	X	X		X			X
	CHASMA	X	X					
	TARBELA	X	X					
	GUDDU	X	X					
IRRAWADDY	HKAMTI	X	X		X	X		X
	SAGAING	X	X		X	X		X

	PYAY	X	X		X	X		X
LENA	KYUSUR	X	X		X	X	X	X
LIMPOPO	FINALE	X	X		X	X	X	X
	BEITBRUG	X	X		X	X	X	X
	SICACATE	X	X		X	X		X
MACKENZIE	ARCTIC-RED	X	X		X	X	X	X
	NORMAN-WELLS	X	X		X	X	X	X
MARONI	LANGA-TABIKI	X	X		X	X	X	X
	DEGRAD-ROCHE	X	X		X	X		X
	TAPA	X	X		X	X	X	X
MISSISSIPPI	NEAR-BROOKINGS	X	X		X	X	X	X
	VALLEY-CITY	X	X		X	X	X	X
	VICKSBURG	X	X		X	X	X	X
NIGER	KOULIKORO	X	X	X	X	X		X
	NIAMEY	X	X	X	X	X	X	X
	LOKOJA	X	X	X	X	X		X
	MALANVILLE	X	X	X	X	X		X
	ANSONGO	X	X	X	X	X		X
	IBI	X	X	X	X	X		X
	Densified space sampling			X				
OB	SALECKHARD	X	X		X	X	X	X
PO	PONTELAGOSCURO	X	X		X	X	X	X
	BORGOFORTE	X	X		X	X	X	X
	PIACENZA	X	X		X	X	X	X
ZAMBEZI	KASAKA	X	X		X	X		X
	KABOMPO-PONTOON	X	X		X	X		X
	MATUNDO-CAIS	X	X		X	X		X

Table 1: Summarize the computation of time series for each station and product based on the methodology employed.

3.1 Water Surface Elevation from altimetry

3.1.1 Data definition

Long time series Water Surface Elevation (WSE), which could also be referred to as Water Level (WL) in the literature or CCI products, are measured from different satellite nadir altimeter missions since 1992 [RD-3]. This data provides valuable information about river water levels dynamics, which is crucial for understanding hydrological processes, managing water resources, and assessing environmental impacts. It is also an ECV defined by GCOS and is a good proxy of river discharge, through the so-called rating curve approach (see [RD-4] for more details).

WSE is defined as the distance between the river water surface and a reference surface (ellipsoid or geoid) [RD-3]. The chosen reference surface for the CCI River Discharge project is the WGS84 ellipsoid. The geoid is more meaningful from a hydraulic point of view. However, as WSE is not used to compute river slopes in this project and as many global to national geoids are available (and multiple versions of a specific geoid might exist), it is better suited to use a mathematically defined surface, i.e. an ellipsoid.

This precursor project used some WSE time series near locations identified in [RD-2] that are available on the Hydroweb database (https://hydroweb.next.theia-land.fr). This database contains mainly time series from S3A/B, J3 and S6 missions' Virtual Stations (VS). However, it has been needed to extensively extend this database for past missions and VS with current missions not available on Hydroweb [RD-3].

The corresponding DOI number for this WSE from altimetry product is:
https://dx.doi.org/10.5285/c5e585820d1240e89eea85ff2c9b4569.

3.1.2 Data characteristics

The timeline and repeat cycle of all nadir radar altimeter missions used are provided in Figure 2. This figure gathers, through the same color code, missions that were on the same orbit tracks. This means they observe the same locations with the same repetitiveness. If the TP/J1/J2/J3/S6A observe the same VS every 10 days from 1992 to now, with some time overlaps between consecutive missions, this is not the case for other orbits. The ERS-2/Envisat/Saral 35-days orbit tracks are not sampled since 2016, when Saral satellite began to drift and not being anymore on a repeat orbit. Another issue is the absence of time overlap between Envisat on its nominal orbit and Saral launch, leading to a few years of observation gap. S3A and S3B missions are on another orbit, with a better time sampling (27 days), but have been launched quite recently (2016 and 2018, respectively). To sum up nadir radar altimeter missions used are the following: ERS-2, Envisat, Saral, Topex-Poseidon, Jason-1, Jason-2, Jason-3, Sentinel-3A/B, and Sentinel-6 [RD-3, RD-7]. Use of Cryosat-2 has been investigated to complete and correct bias in WL time series between Envisat and Saral, but because of river slopes and crude time sampling of the mission, it has been decided not to use Cryosat-2 data in this precursor project [RD-7].

The satellite orbit defines both the spatial and temporal sampling of the nadir altimeter mission. They change in opposite directions: the greater the number of tracks in an orbit, the finer its spatial sampling is, but the greater its repeat period (i.e. the time taken for the satellite to fly over the same point again), the coarser its temporal sampling is. Therefore, Jason series allows a better time sampling than other orbits (i.e. 10 days), but the counter part is the scarcity of its spatial sampling (nadir altimeter observing only within the footprint of the instrument at the nadir of the satellite and Jason series intertrack distance at the equator is equal to 315 km). It means that for some selected locations, only observations from altimeters on Envisat orbit could be used, leading to observation gaps (at least between Envisat change of orbit and launch of Saral) and a coarser time sampling of 35 days. Furthermore, due to some technical limitations, satellite ground tracks are controlled to within ± 1 km around their nominal positions for most altimeter missions (for more details, see product handbook for each mission).

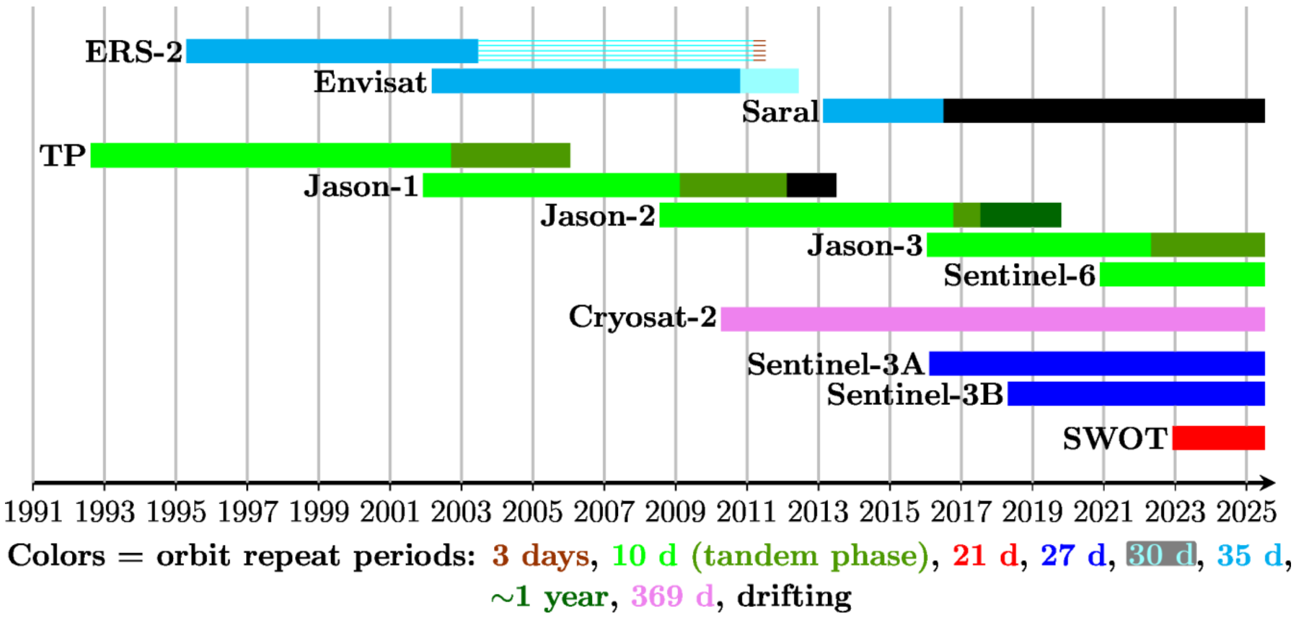

Figure 2. Timeline of the altimetry missions considered in this precursor project. Colors correspond to missions' orbits repeat periods. After mid-2003, altimeter onboard ERS-2 stopped working, that's why its boxplot pattern after this date is changed to show the absence of measurements.

It should also be noted that the oldest missions are the least accurate. The most important issue arises for J1, which was finer tuned to observe the ocean than TP, resulting in less data acquisition over continental water bodies.

The intersection of the satellite ground track with a targeted water body (e.g. a river reach) is usually referred to as "virtual station" (VS) in scientific literature. Its definition is therefore intrinsically linked with the orbit of the radar nadir altimeter mission considered. The VSs from all available missions tracks near the selected locations in [RD-2] have been processed to compute WSE time series.

3.1.3 Time series per mission

The methodology employed for deriving Water Surface Elevation (WSE) time series from individual radar nadir altimeter missions over rivers is quite standard now (see for example Cretaux et al. 2017, 2023). It requires various corrections and selection processes to ensure the accuracy and reliability of the generated data. These corrections encompass ionospheric correction, dry and wet atmospheric corrections, solid Earth correction, and pole tides correction. These corrections are directly provided by the space agencies in the Geophysical Data Records (GDR) products. Notably, for missions such as TP, where atmospheric corrections are absent at multiple locations, a substitute approach is adopted. Leveraging climatology derived from corrections made during the Jason-1 to Jason-3 period, this ensures continuity and consistency in the derived WSE time series.

Nadir altimeter measurements basically provide a "waveform" that is used to compute the range, i.e. the distance between the satellite center of mass and the surface of the river. CCI River Discharge WSE have been computed using ranges estimated from the waveforms using the so-called "Ice-1" or "OCOG" retracker (Wingham et al., 1986; Bamber, 1994) [RD-3]. These retracked ranges are directly available in the GDR files. This retracker is commonly used to retrieve WSE over rivers, as stated, for example, in Cretaux et al. (2017).

In cases where data is not readily available within the Hydroweb database, an intricate manual selection process is initiated, utilizing specialized software tools, such as AlTiS developed at LEGOS/CTOH (https://gitlab.com/ctoh/altis). This manual selection involves several steps: including the delineation of a polygon at the intersection of the satellite ground track and the observed river reach, visualization and analysis of WSE for all cycles and measurements within this polygon, removal of outliers based on predefined criteria, computation of the median of selected WSE for each cycle, and subsequent exportation of the WSE time series (Santos da Silva et al., 2010) [RD-3].

Furthermore, the differences between the CCI Lake WSE and precursor CCI River Discharge WSE processing are the following: river WSE are referenced to an ellipsoid (contrarily to CCI Lake WSE referenced to a geoid) and located on a river reach, the geoid slope correction, crucial for lakes, is not applied for rivers WSE, bias between missions (see [RD-4] for more details) is computed differently as there are usually less time series overlaps.

Additionally, it is emphasized that no slope values are utilized to correct ± 1 km satellite drifts between each revisit time, because of the lack of a globally accurate river slope product. The potential consideration of such corrections, contingent upon the availability of validated SWOT river slope products, is not yet available globally and will probably be analyzed in future phase of the project [RD-3].

Lastly, dates in the time series are provided as UTC time to ensure standardization and facilitate compatibility across different datasets and analyses.

3.1.3.1 Merge time series

As there is not a single nadir altimeter mission covering the whole period of interest (2002-2022, see Figure 2), the precursor project computed merged multi-mission WSE time series. These merged time series are used to compute a discharge product (RD-alti), but it is also provided as a specific product, as users are also interested in getting merged WSE time series [RD-1]. Two methodologies have been developed aims to address this need and are briefly described below (see [RD-3] for more details).

3.1.3.1.1 Basic merging methodology

The proposed approach involves computing a merged WSE at a specific Virtual Station (VS). This VS is intrinsically tied to a specific mission and its ground tracks. The selection of the reference VS prioritizes missions with the longest duration, highest time sampling, and recent launch dates to ensure accuracy. Jason-3 is suggested as the preferred reference mission due to its extended time span and high repeat period.

- **Merging Time Series on the Same Ground Track**: Biases between consecutive missions on the same ground track are computed and corrected. This involves calculating the mean bias over the common period between consecutive time series and adjusting the WSE accordingly. When multiple observations are available for a single day, priority is given to the most recent data.
- **Merging Time Series from Different Tracks**: After merging time series from missions on the same track, the WSE time series from different surrounding VSs need to be merged. A reference VS is identified, and a linear relationship between WSE time series from different VSs and the reference VS is computed, to consider bathymetry differences between VSs. A time lag is also applied, if needed, to consider the flow propagation time.
- **Correction of Biases for Non-Overlapping Time Series**: a WSE climatology is computed for both time series and the bias is computed between these climatologies. Extreme events or short high flow periods are addressed by removing the highest data points before computing the bias.
- **Monthly Discharge Time Series**: While monthly discharge time series are a goal, no similar requirement exists for WSE products. As a result, monthly WSE time series are not computed.

This methodology ensures the creation of a comprehensive and accurate merged WSE dataset with one measurement per day. It leverages data from multiple missions and employs various correction techniques to enhance accuracy, particularly for river discharge computations.

3.1.3.1.2 Stochastic method to merge WSE timeseries

As a complement to the WSE time series merging method presented in previous section3.1.3.1.1, an alternative fusion approach based on a stochastic model is proposed. Its methodology is described below (see [RD-3] for further details), to clarify the requirements and benefits associated with the use of these merged WSEs.

This approach relies on a space-time model that enables the generation of merged time series along a river, provided that a sufficient amount of data is available to characterize it. Within the CCI project framework, virtual stations are defined at two levels: (i) those identified during Phase 1, and (ii) those located at the intersections between Jason-3 ground tracks and rivers in the studied basins.

The spatio-temporal model used is based on the work of Nielsen et al. (2022) and relies on several assumptions. Firstly, it is assumed that timeseries follow a first-order autoregressive process. This allows a first-order simulation of a seasonal behaviour (see [RD-3] for more details). Additionally, water surface elevations are spatially constrained using a space model (defined in Nielsen *et al.* 2022) to which we have added an elevation profile provided by the SWOT RiverSP Nodes dataset (Altenau et al., 2021). By combining these two constraints and applying the Maximum Likelihood formalism, a time series can be estimated (see [RD-3] or Nielsen et al., 2022).

This methodology allows for the generation of time series along a river by incorporating elevation measurements from various missions, up to several hundred kilometers from the virtual station. The temporal resolution of these timeseries is 5 days.

3.1.3.2 Uncertainties

Altimetry-based WSE uncertainties are quite difficult to estimate a priori and depend on any factors (sensor characteristics, orbit track orientation with reference to the river, complexity of the observation, previous measurements or data stored onboard…). We compared altimetry-based WSE to in situ WSE at some locations where such in situ data are available, to estimate a global WSE uncertainty per altimeter mission. We assumed that in situ WSE uncertainties are at least one order magnitude lower than altimetry-based WSE, therefore in situ WSE are considered as “perfect”.

Given the potential for significant differences in uncertainty between Arctic rivers and other rivers, separate standard deviations for WSE per mission were computed. One standard deviation was calculated for the Arctic basin, while another one was computed for other regions.

For each of the 28 locations where in situ WSE data were available (5 locations for arctic region and 23 for lower latitudes), a comparison was made between the anomalies of these in situ WSE and the anomalies of WSE derived from altimetry merged time series over a common period. The closest dates were used as common dates if the lag time between the datasets did not exceed 24 hours. It should be noted that the absolute difference between in situ and altimetry WSE cannot be computed because in situ measurements are not made at the exact location of the VS. This also means that the difference between in situ and altimetry WSE could be due to difference in river bathymetry at the in situ and at the VS.

Following this comparison, the standard deviation of these errors was calculated for each mission (Eq.1). The decision to compute the standard deviation across all locations, rather than calculating the mean standard deviation for each location, aimed to address the challenge of assigning equal weight to each location regardless of the number of common dates per station.

$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n-1}}$$ Eq. 1

Where, σ_m is the standard deviation for the satellite mission m; x_i represents each individual difference between in-situ water high anomaly and altimetry-based WSE anomaly; μ is the mean of the differences; n is the total number of observations (dates and stations).

The following table summarizes the standard deviation for each satellite mission for Arctic rivers and other rivers (lower latitudes) where data are available over the same period. Therefore, values for T/P, Jason-1, and Sentinel-6 have not been provided for Arctic rivers due to the absence of WSE data from these missions over the considered rivers. These standard deviations were calculated mostly based on a small number of points (fewer than 200 dates on average) and should therefore be considered with caution, moreover the comparison has been made between Virtual Station (VS) and insitu station not located at the same position. However, they provide an initial indication of the errors related to altimetry.

Satellites	*TP*	*ers2*	*Envisat*	*J1*	*J2*	*J3*	*Saral*	*S3A*	*S3B*	*S6*
Arctic	-	0.50 (26)	1.13 (681)	-	0.86 (605)	1.02 (550)	1.12 (110)	1.02 (515)	0.87 (274)	-
Other	1.01 (1094)	0.91 (131)	0.83 (663)	0.91 (740)	0.65 (2550)	0.62 (2534)	0.71 (190)	1.02 (253)	0.32 (124)	0.51 (752)

Table 2: Summary of the standard deviation of WSE anomaly difference to in situ WSE anomaly for each satellite mission, categorized into two groups: Arctic rivers and rivers from other regions. The number of dates used to calculate the statistics is indicated in parentheses and green.

For the merging stochastic method, the WSEs estimated using the stochastic method are water surface elevations defined by normal probability density functions (PDFs), meaning they are described by a mean and a standard deviation that represent the probabilistic dispersion of the estimated parameters.

Measurement uncertainties for each satellite are estimated during the fusion process and are also statistical in nature. It allows to deal with several altimetry mission with different WSE retracking uncertainties.

3.1.4 Data limitation

The main limitation is the heterogeneity of time sampling in time within each time series. This is due to the fact there is no satellite altimeter mission that lasts 20 years. As time series from multiple missions are merged, which could have different orbit characteristics, some merged time series could have a 35 days' time sampling during the Envisat period and then ten days' time sampling if some data from Jason-2 or its successor can be used. There are some important time gaps in time series, due to the non-overlapping period between Envisat and Saral, or the issue of data loss for the missions in "closed loop tracking mode" (see RD-3). This last issue is particularly important at Finale and Beitburg locations in the Limpopo basin, for which there is no data before 2017.

There are also some sensor characteristics changes between the oldest and the newest missions, which explains why the accuracy can change in time. The "Low Resolution Mode" (LRM) missions (ERS-2, Envisat, Saral, Topex-Poseidon, Jason-1, Jason-2, and Jason-3) have large footprints (8km, 18km and

30km diameter for Saral, Envisat and Jason series, respectively), which means that radar altimeter waveforms can record information from any water bodies (and even other targets) in the footprint. Therefore, waveforms can have multiple peaks, and only one corresponds to the targeted water body. This means that the OCOG retracked range and the corresponding WSE might not correspond to the river WSE. Such cases can be easily removed when the retracked data is some order of magnitude higher than the expected river WSE. But in some cases, it is not possible to filter them out. It explains why some time series are noisy and some WSE are erroneous. It usually concerns only few measurements, but, in some cases, it could concern the whole time series, like at Chembe-Ferry on the Congo basin.

Some sensors could also have some limitations that could result in higher WSE uncertainties than other missions. For example, there is the specific case of Envisat that could have a tracking window with adaptive size (64m, 256m, 1024m), but with same number of bins. For the largest tracking windows, bins will be wider and therefore WSE will be more uncertain. Jason series altimeters (i.e. Poseidon series) could saturate and lead to important uncertainties on WSE. Nevertheless, it appears that the oldest altimeter missions (e.g. ERS-2, ENVISAT and Topex/Poseidon) have the largest errors and data loss.

For the merged time series from the basic merging methodology, even if the intermission bias issue has been addressed, there could still be some residual bias between different mission time periods.

For the merged time series from the stochastic approach, the intermissions bias is statistically considered in the process as well as the uncertainties concerning the retracking performance of the various altimetry missions. The main issue come from the temporal sampling of the observations. If a river section—due, for example, to its orientation—is observed by only a few missions, the model's degrees of freedom will be insufficient to converge toward a solution.

3.2 Altimeters-based River Discharge (RD-alti)

3.2.1 Data definition

Altimetry-based River Discharge refers to the measurement and estimation of river discharge using data obtained from altimetry satellites. These data can serve as an alternative means of estimating river discharge when in-situ river discharge (Q) is not available [RD-4]. This data is instrumental in understanding river dynamics, monitoring hydrological processes, managing water resources, and assessing environmental impacts [RD-1].

The measurement is based on the relationship between water surface elevation (WSE) and river discharge, established through a power-law physical approach, implemented via a rating curve. This rating curve is a mathematical relationship derived from field measurements, defining the relationship between river stage (or WSE) and discharge. It enables the conversion of observed water levels into corresponding discharge values, enhancing the accuracy and reliability of discharge estimations [RD-4].

This product aims to use long time series of WSE and in-situ discharge ensuring comprehensive coverage for accurate river discharge assessments.

The corresponding DOI for this altimetry-based river discharge product is: https://dx.doi.org/10.5285/44c930e1388f40728884fbdf7e28c109 .

3.2.2 Data characteristics

Just as in-situ water heigh measurements can be used to gauge river discharge, altimetry-derived water surface elevation (WSE) can serve as an alternative means of estimating river discharge when discharge time series data (Q) is not available. Several methodologies have been documented for deriving discharge time series from altimetry observations and supplementary data.

3.2.2.1 Methodology used

Two approaches have been used [see RD-4 for more details], depending on the available temporal overlap between discharge and altimetry water surface elevation (WSE) time series:

Method 1 – temporal overlap data: The preferred approach relies on the altimetry water surface elevation time series and in situ or simulated discharge time series to create a rating curve (RC) characterized by a power relationship between these two variables following a Bayesian approach (Rantz, 1982). This method has already been applied to major river basins, including the Amazon, the Niger, the Ganges-Brahmaputra, the Mekong, and the Ob, by the institutions and organizations involved in this project (Paris et al., 2022; Bogning et al., 2021; Zakharova et al., 2020). However, this method necessitates a significant overlap period between discharge data and radar altimetry measurements (e.g., Kouraev et al., 2004; Biancamaria et al., 2011; Papa et al., 2012), or it requires the assumption that the rating curve remains valid and consistent when discharge data is only available prior to the altimetry observation period (Tourian et al., 2013, 2017; Frappart et al., 2015; Bogning et al., 2018).

The rating curve is conducted over the calibration period defined as the last 2/3 of the period extending from the first to the last date of overlap (closest value, less than 24 hours) between altimetric data and in-situ discharge data (see Appendix 1). To ensure the robustness of this method, we have established that it can only be applied if the number of overlap points exceeds 15 otherwise, the Method 2 (described below) has been applied.

Three cases have been identified to create rating curves:

- <u>Case 1:</u> General cases where we can directly compute the rating curve between the available WSE and Q.
- <u>Case 2:</u> In cases where ice cover appears intermittently over certain years and months due to local climate conditions, an alternative method involves excluding these frozen dates from the rating curve dataset. This can be achieved by using the monthly mean temperature to filter out these specific data points. For instance, at the Near-Brookings station, observations reveal the presence of a frozen river during some years between December and March, creating outliers in the rating curve (refer to the figure below). By examining the temperatures recorded during these months, based on the ECMWF fifth reanalysis for the global climate and weather (ERA5 database), we can discard data points where the monthly temperature falls below 0°C. Implementing this approach allows us to generate an alternative rating curve devoid of these outlier points.
- <u>Case 3:</u> In several specific cases especially in arctic, the relation between water surface elevation and discharge may be not uniform. This occurs, for example, near nodes of rivers confluence or during ice cover and ice breakup periods. For these cases the set of the rating curves, specific for a particular condition could be developed. A prior knowledge about these particular conditions and range of applicability of each rating curve is compulsory. The modification of flow hydraulics due to the river ice can be mapped using remote sensing techniques and even altimetry observations simultaneous with the water surface elevation retrievals (Zakharova et al., 2021). For the Arctic rivers an application of the set of the rating curves, specific for recession, ice period and for flood rise demonstrated better accuracy in several previous studies (Zakharova et al., 2020). The rating curves for recession and flood rise are approximated by the classical power equation, while for the ice period a polynomial equation of low degree may produce better accuracy. For the Ob River for example, an automated method of ice setup and breakup detection based on altimetry measurements were tested and the WSE timeseries subset for 2008-2019 ice periods based on this ice product is isolated and used for calibration/validation of ice rating curve. For other years, the Landsat and MODIS images are used for ice on/off detection. Optical

imagery is used for other Arctic test sites as well. The spring flood rise subset is extracted directly from the WSE timeseries. For four Arctic test sites located on the Colville, Mackenzie and Lena Rivers two rating curves (flood recession and merged winter - flood rise RCs) were built using modified Bayesian method, while for the Ob River the flood rise was fitted with its own RC. The modification of Bayesian method consisted in probabilistic estimate of only two RC parameters ("a" and "z0"), while b parameter was fixed at each approximation step allowing expert correction of the RC shape for winter and flood rise periods.

Method 2 – no temporal overlap data: The second approach was employed when there is no temporal overlap between in-situ or simulated discharge and water surface elevation data (or not enough – less than 15 overlap dates), it assumes that the validity and stability of the rating curve persist across the various time periods covered by the two datasets. Both time periods should be sufficiently long to encompass a wide range of events. With this assumption, Tourian et al. (2013, 2017) introduced a method for calculating the rating curve, not based on the time series of discharge and water surface elevation, but on the distribution of their quantiles. This method has been adopted by a limited number of recent studies (e.g., Belloni et al., 2021). However, it's important to note that this methodology naturally introduces higher errors when compared to the preferred approach. For this reason, this methodology will be validated over some stations with various hydrological dynamics and satisfying previous methods (overlap period exists between WSE and Q).

For both methodologies, the Bayesian approach has been used to compute the rating curve, except for specific cases of arctic basin as explained before. This method is a robust statistical approach used for constructing a rating curve, frequently applied in the field of hydrology when the goal is to estimate unknown parameters from observed data, while taking into consideration the associated uncertainty in these estimates (Gelman et al., 2013). This method is grounded in the computation of posterior probabilities for the model parameters, employing Bayes' theorem (Eq.2):

$$P(\theta/D) = P(D)\cdot P(D/\theta)\cdot P(\theta) \quad \text{Eq. 2}$$

Here, *P(θ/D)* denotes the posterior probability of the model's parameters θ, which is the value we are attempting to estimate. *P(D/θ)* signifies the likelihood of the data D given a specific set of parameters θ, typically based on the chosen probabilistic model. *P(θ)* represents the prior probability of the parameters, derived from our prior knowledge or assumptions, while *P(D)* is the marginal probability of the data, serving as a normalization factor.

According to this, the estimation of the rating curve using the Bayesian method involves several steps:

- The initial step entails defining a probabilistic model that describes the relationship between observed data and the parameters we aim to estimate. In many hydrological applications, the relationship between discharge data (Q) and water surface elevation data (WSE) is often expressed as a power function (Eq.3):

  $$Q = a\cdot(WSE-z0)^{b} \quad \text{Eq. 3}$$

  Here, *a, z0* and *b* are the parameters of the rating curve. *a,* is a scaling coefficient governing the magnitude of the Q-WSE relationship, *b,* characterizes the nature of this relationship, and *z0*, represents the height of the free surface above the reference point, corresponding to the river bottom's altitude.
  The power relationship is especially pertinent due to its consistency with numerous hydrodynamic phenomena. The exponent b within the equation allows for the representation of distinctive flow characteristics, including factors like roughness and channel geometry. Moreover, it offers adaptability in modelling to accommodate variations in flow characteristics, whether they are

turbulent or laminar. This relationship, despite its mathematical simplicity, facilitates the fine-tuning of model adjustments in accordance with observed data (Chow, 1959).

- The second step involves the use of prior normal distributions, reflecting our prior knowledge about these parameters. These distributions can either be informative or uninformative, depending on our level of knowledge.
  The limits and ranges for a, z0 and b can vary depending on the specific context of the study, the dataset used, and the characteristics of the river or channel being analysed.
  Coefficient "a":
  "a" is an adjustment parameter for the rating curve representing the scaling factor for discharge. Its value can significantly fluctuate based on various factors such as the characteristics of the river or channel, hydraulic conditions, and other influencing factors. Consequently, "a" must be non-negative and constrained within a sensible range specific to the system under study.
  Following the Manning equation, "a" must be equal to $W/n*S^{1/2}$ (Chow et al., 1988) where W is the river's width (m), n the Manning's roughness coefficient and S the slope (m/m). Given the considerable variability in river width and slope across different stations, a feasible range for this coefficient can be considered as:

$$a \in [0; 3000]$$

  Coefficient "b":
  "b" is also an adjustment parameter representing the exponent of the rating curve and indicating the hydraulic condition of the study site. Like "a," this value must comply with physical constraints and cannot be negative.
  Following the Manning equation, "b" must be equal to 5/3 for reference hydraulic condition (Rantz, 1982). To accommodate the variability in system characteristics across sites, the following range values can be considered for this coefficient:

$$b \in [0; 5]$$

  Coefficient "z0":
  "z0" represents an offset or the elevation at which discharge begins. It should be within the range of elevations relevant to your study. For this *reason, the value* cannot exceed the minimum value of water surface elevation (WSE) and the range value need to consider of the variability in term of water depth over the sites. A feasible range for this coefficient can be considered as:

$$z0 \in [\min(WSE)-50; \min(WSE)]$$

- The final step involves parameter estimation. The posterior distribution of the parameters yields probabilistic estimates of the rating curve parameters in the form of mean values (optimal values) and credibility intervals (95th percentiles). This accounts for the uncertainty associated with these parameters and is achieved through Markov Chain Monte Carlo (MCMC) sampling from the posterior distribution (Robert and Casella, 2004). Two commonly employed MCMC algorithms are "NUTS" (No-U-Turn Sampler) and "Metropolis-Hastings". The Metropolis-Hasting sampler "MH" algorithm, which is relatively simple and efficient where a balance between exploration and exploitation is desired. This algorithm can be adapted to sample from discrete state spaces (Geyer, 2011).

3.2.2.2 Uncertainties

Uncertainty propagation through mathematical models plays a crucial role in estimating the reliability of derived results in various scientific fields. In the context of hydrology and discharge estimations, the propagation of uncertainties in parameter estimation, such as those in the parameters of the discharge equation, becomes essential for assessing the reliability of the calculated discharge values. Utilizing a Gaussian error propagation method provides a systematic approach to quantify the uncertainties associated with parameters a, WSE, b, and z0 from the power law function to express the relation between Q and WSE.

This method involves employing statistical principles to propagate uncertainties through the mathematical relationships between the parameters and the discharge equation. By considering the Gaussian distribution of errors in these parameters, this approach enables a more comprehensive evaluation of the overall uncertainty in discharge estimations (e.g., McMahon and Peel, 2019, Tourian et al., 2017).

Given the mean values and standard deviations (σ) for each parameter, the uncertainty in discharge (δ(Q)) due to uncertainties in these parameters can be computed as follows (Eq.4):

$$\partial(Q)=\sqrt{\left(\frac{\partial Q}{\partial a}\cdot\partial a\right)^2+\left(\frac{\partial Q}{\partial WSE}\cdot\partial WSE\right)^2+\left(\frac{\partial Q}{\partial b}\cdot\partial b\right)^2+\left(\frac{\partial Q}{\partial z0}\cdot\partial z0\right)^2}$$

Eq. 4

$$\partial(Q)=\sqrt{((WSE-z0)^b\cdot\sigma a)^2+(a\cdot b\cdot(WSE-z0)^{b-1}\cdot\sigma WSE)^2+(a\cdot(WSE-z0)^b\cdot\ln(WSE-z0)\cdot\sigma b)^2+(-a\cdot b\cdot(WSE-z0)^{b-1}\cdot\sigma z0)^2}$$

Where, σa, σb, σz0 and σWSE correspond to the standard deviations of parameters a, b, z0 and WSE respectively. The standard deviations for a, b, and z0 will be determined using the Bayesian approach through the MCMC algorithms. Due to modification in RC fitting method, the uncertainties in b parameter were not evaluated for the Arctic sites. The term σb for the Arctic was set up to the global mean equal 0.1.

This formula uses the standard deviations as measures of uncertainty in each parameter and calculates the overall uncertainty in discharge considering the propagation of these uncertainties through the power law equation relating discharge and the parameters a, b, z0 and WSE.

It is important to notice in one hand, that this equation assume that the uncertainties in the parameters (a, b, z0) and WSE are independent, and in another hand, that the propagation of uncertainties provides an estimate based on the assumption of linearization around the mean values of the parameters.

3.2.3 Data limitation

Creating accurate streamflow time series based on altimetry data is a complex endeavor due to several inherent challenges. Firstly, the reliability on rating curves, which establish the empirical relationship between WSE and discharge, poses a significant limitation. These curves, established based on a specific period or over two different periods for each variable, can be irrelevant due to changes in hydraulic dynamics within the river system over time. Factors such as dam construction, river morphology alterations through natural processes or human intervention, and land use changes can all impact the river's flow characteristics. Consequently, the established rating curves may no longer accurately represent the true relationship between WSE and discharge, leading to potential inaccuracies in streamflow estimations.

Secondly, the spatial disparity between virtual stations and in-situ discharge stations introduces additional challenges. Ideally, an in-situ station and the associated virtual station should be close to each other to facilitate the computation of reliable rating curves. However, achieving this proximity can be logistically challenging, particularly mostly due to the disparity in space and time of the altimetry and discharge data. The distance between the altimetry track and the discharge station can introduce errors in flow estimation, especially when hydraulic conditions vary significantly between the two locations (e.g. Mohacs station over the Danube basin or Ibi station over the Niger basin both with a distance between SV and in-situ discharge data of more than 200 km). Moreover, errors may arise from variations in slope between these two stations, further complicating the accuracy of streamflow estimations.

Furthermore, the general limitations of altimetry data also play a crucial role in the accuracy of river discharge estimations. Altimetry data may be affected by various factors, as described in the previous section on altimeter data limitations (section 3.1.2). These uncertainties propagate into altimetry-based streamflow estimations, potentially compromising the overall accuracy of the derived time series.

Addressing these challenges requires a comprehensive approach that integrates regular updates of rating curves to reflect changes in hydraulic dynamics, strategic placement of monitoring stations to minimize spatial disparities, and the utilization of advanced remote sensing technologies to mitigate the limitations of altimetry data. Additionally, ongoing monitoring, validation, and calibration efforts are essential to improve the reliability of altimetry-based RD estimations and ensure accurate representation of river discharge dynamics over time.

3.3 Multispectral images-based River Discharge (RD-multispec)

3.3.1 Data definition

Multispectral-based RD refers to estimating river discharge by exploring the spectral behaviour of pixels with the presence and absence of water in the near-infrared (NIR) band of the electromagnetic spectrum. Specifically, adhering the spectral variability of the different land uses (viz., soil, water, vegetation) along the river and near river environment, numerous spectral indices are developed that can be used to estimate river discharge. To develop those spectral indices, the multispectral images are processed to retrieve the signals (hereafter, denoted as CM and based on the different behaviour in the NIR region between a Calibration (*C*) and a Measurement (*M*) pixels) and further utilized for discharge estimation along the sparsely gauged rivers.

The corresponding DOI for this multispectral images-based river discharge product is:
https://dx.doi.org/10.5285/a8422dd3766c447d8b5fa80920649f31

3.3.2 Data characteristics

Like the in-situ observations of the river hydraulic variables, the temporal dynamics of CM signals can be used as the proxy variables to study the discharge dynamics along the river. To derive the long-term time series of river discharge, all the available multi-spectral images from the available sensors (i.e., Aqua and Terra MODIS, Landsat Series, Sentinel 2 and 3 Series) are merged for the analysis. The detailed formulation of the algorithms by considering these pixels can be found in the ATBD report [RD-4]. To formulate the river discharge algorithm, we need to calibrate the CM signals against the contemporary in situ river discharge for any typical river sites. However, along the selected river sites, the in-situ observations are often unavailable during the period in which satellite data are available (2006-2005 for Landsat 5, 2021-2022 for Landsat-9; 2016-2022 for the remnants). Therefore, two different analyses were carried out depending on the availability of the in-situ data: 1) calibrated approach (when coincident observation of in situ Q and CM signals are available) and 2) uncalibrated approach (when only in situ observation non-contemporary to satellite data are available). Among the selected 54 gauging sites, only 22 sites have the facility to test the calibrated approach as presented in Figure 3. The detailed framework of calibrated and uncalibrated approaches is explained in the ATDB [RD-4].

Figure 3: Observed data availability for the 54 stations. In blue, the selected calibration period, In red the stations in which the observed data overlap with the calibration period.

3.3.2.1 Calibrated Approach

With the coincident data availability of CM and Q, the calibrated approaches are categorized into two types of formulation: 1) Empirical Formulation and 2) Probabilistic Formulation. Notably, the calibrated procedure is performed following the pre-fixed calibration and validation period.

- In the case of empirical formulation (**cal-BestFIT**), four potential distributions (linear, quadratic, power, and exponential) are selected as potential laws between Q and CM data. CM and Q time series are, therefore, trained with the aforementioned formulations. To check the best-fit solution from the selected distribution, a model evaluation criterion has been set considering Akaike Information Criteria (AIC; Eq.5a), Bayesian Information Criteria (BIC, Eq.5b), and Pearson correlation coefficient (*r*). The best fit of any site has been obtained by lower values of AIC and BIC with a higher value of *r*; thus, a composite index (CI; Eq.5c) is formulated to evaluate the overall model scores to determine the best-fit model for the selected site.

$$AIC = 2k - 2\ln L \quad \text{Eq.5a}$$

$$BIC = k * \ln n - 2\ln L' \quad \text{Eq.5b}$$

$$CI = r + (1\text{-}AIC) + (1\text{-}BIC) \quad \text{Eq.5c}$$

  where k equals to the number of parameters used in the model; n equals to the sample size, and L' is the maximum value of the likelihood function for the model.

- In the case of probabilistic formulation (**cal-Copula**), the widely used Copula function is selected for the analysis. Here, the framework proposed by Sahoo et al. (2020) is being adopted. First, the CM and corresponding Q values are considered as pairs to compute Kendall's tau (τ) and the dependence parameter (θ). Second, the five Archimedean family copulas are being formulated, and the best copula fit is obtained by performing Kolmogorov-Smirov (KS) statistic test. In all the 22 analyzed sites, the Frank copula is found to be the best-fit copula for the analysis, and subsequently, the formulation is performed to derive the discharge. For more information about the copula approach, the reader is referred to Sahoo et al (2020).

3.3.2.2 Uncalibrated procedure

In the absence of coincident observations of Q and CM time series, the uncalibrated procedure (**uncal-CDF**) uses the same framework proposed by Tourian et al. (2013). Here, the available discharge and retrieved CM signal time series are sorted independently in descending order. Subsequently, the corresponding exceeding probability of each value in the time series is computed for both Q and CM time series individually by considering their percentage of the observation periods. Despite the Flow Duration Curves are obtained with the same method, it is better to not merge too much information. For this reason, the paper by Tourian et al. (2013) is referenced, and the method for Reflectance indices is termed "CDF matching. For each site, the basic assumption is made that the in-situ Q and CM signals have the same exceedance probability. Developing the joint probability distribution between these two curves can be a suitable solution to estimate river discharge from the CM signals when the in-situ observation is not available. Following the aforementioned steps, the uncalibrated procedure has been designed for each site to derive the long-term discharge time series from the CM signals (see Tarpanelli and Domeneghetti; 2021 for more details).

The final product includes a single time series for each site calculated in a different way based on the availability (cal) of in-situ data or not (uncal). In case of calibrated data, the best performing method between BestFit and Copula is selected.

3.3.3 Data limitation

For deriving the long-term discharge time series from CM signals, the major limitation is the cloud cover, as the signals are retrieved from the optical images. As the optical images are frequently contaminated with clouds, the signals received from the images with unmasked clouds, unmasked cloud shadows, and unmasked ice can add a source of noise to the analysis. Moreover, the majority of the flood events occurred during the cloudy period; therefore, capturing this dynamic using the CM signals is still a challenging task with the unavailability of images during this period. Using the coarser resolution pixels (e.g., 250 m resolution of MODIS), the retrieval of CM signals along narrow or small rivers is prone to noise due to the interference of adjacent pixels. Additionally, the selection of W pixel along the narrow river stretch is still a challenging task for which there is limited application of uncalibrated approach along the small rivers. Retrieval of CM signals along the braided rivers can also be affected by the menders while the river changes its courses over a certain period due to the change in flow dynamics.

The merging procedure to generate the long-term CM signals is based on the contemporary availability of data from different sensors. Without having the contemporary data, one can successfully obtain the merged time series, but those signals may not be a suitable choice for capturing the flow dynamics. Thus, for the implementation of the merging procedure, contemporary observations are needed.

For generating long-term discharge time series using the CM signals, the calibrated procedure is based on the coincident observations of in situ Q and CM. The absence of CM signals during flood events due to the presence of cloud cover in the images may affect the model parameterization to capture the high flow dynamics both in cal-BestFIT and cal-Copula solutions. Although the uncal-CDF procedure is independent of the coincident observations of in situ Q and CM, the availability of the in-situ Q data period is still a key concern. For instance, the hydrograph generated from a short event may not represent the long-term period. Consequently, the derived Flow Duration Curve (FDC) and Recession Duration Curve (RDC) may not yield accurate results when determining the joint distribution. This can introduce significant uncertainties in deriving long-term discharge time series. Additionally, in both calibrated and uncalibrated procedures, there is a risk of losing flood information due to the absence of CM signals caused by frequent cloud cover.

3.4 Satellite-based River Discharge (RD-merged)

3.4.1 Data definition

The RD-merged product has been computed at different locations by the combination of satellite sensors of altimeters and multispectral. Two levels of combination are implemented based on the original products: Level-2, in which the data has been derived merging multi-mission multispectral time series and radar altimeters water level product following the RIDESAT method and Level-3, in which the river discharge products obtained from altimeters and multispectral are used.

The corresponding DOI for this satellite-based river discharge (RD-merged) is: https://dx.doi.org/10.5285/d32244e674dd438ca4d321560daad755

3.4.2 Data characteristics

The traditional process to estimate river discharge that uses data from altimetry is here advanced with the contribution of multispectral images to overcome the altimeter limits related to the temporal frequency. The merging procedure is carried out through two different methods based on the Level of data: RD-mergedL2 and RD-mergedL3 approach. In the following the description of the methods and the associated products is provided.

3.4.2.1 RD-merged Level 2

The RD-mergedL2 is derived by two approaches. The best performing approach has been selected in the final product. The two methods are RIDESAT approach and Copula-based merging approach

RIDESAT approach

River discharge, traditionally defined as the product of flow area and velocity, is derived from altimetry and multispectral sensors considering that the flow area is calculated based on the water level measured by the altimeter, while flow velocity, typically measured by in-situ instruments, is estimated using reflectance data from the Near Infrared signal of the multispectral sensor (Tarpanelli et al., 2015). In the study by Tarpanelli et al. (2013), seven years of daily MODIS images along four stations on the Po River showed that the C/M reflectance ratio varied with discharge, particularly correlating with flow velocity. In a later study (Tarpanelli et al., 2015), this relationship was used to estimate flow velocity at another Po River site, combining it with water level data from altimetry.

Following the base hydraulic definition and considering the reflectance indices as proxy of flow velocity, the RIDESAT formulation can be summarized as follow (Eq.6):

$$q = c\frac{\delta Q}{A_d} = c\frac{v\delta A}{A_d} = \frac{K}{A_d}\left(\frac{C}{M}\right)^f (H - H_{min})^b \quad \text{Eq. 6}$$

in which q is the river discharge Q, divided for the basin area A_d, H and H_{min} are the water level at a certain point and the minimum observable from altimetry, C/M are the reflectance indices obtained by the multi-spectral analysis and K, f and b are parameters estimated by the maximization of the Nash-Sutcliffe efficiency, NS, between the simulated discharge and the ground observed discharge.

More details are available in the ATBD document [RD-4].

Copula-based merging approach

To estimate river discharge from the multi-mission, the copula approach could be used to merge both the multi-spectral (CM approach) and altimeter-based approach. Following the same theory, Copula method has been applied between the coincident observations of CM from multi-spectral and WSE from altimeters for 18 sites out of 54. Due to the complex behavior of river flow along with the geomorphology in the arctic regions, the gauging stations present in those areas are also omitted for this merging analysis.

The bestfit-copula was determined by evaluating the minimum values of both KS and S_m. Subsequently, the WSE time series were derived from the CM time series using the bestfit-copula function at the selected gauging sites. The CM-derived and altimeter-derived WSE time series were merged by providing the max weightage to the altimeter-derived WSE while getting any coincident observations. Adopting the rating-curve coefficients derived by altimetry analysis for the selected gauging sites, the RD time series was derived, which has been constructed by merging the information obtained from both multi-spectral images and altimeters.

More details are available in the ATBD document [RD-4].

3.4.2.2 RD-merged Level 3

A weighted merging process was developed for the Level 3 products. Here, the river discharges calculated in the previous steps (from altimetry and from multispectral sensors) are combined to improve the actual simulated value (through the weighted average) and the frequency (at the altimetry time series is added the dense multispectral time series). The combination represents an added value to the final product.

The temporal distance from the observation date and the accuracy of each river discharge product are both considered to achieve optimal merging results. As the first step, all dates with simultaneous

altimetry- and multispectral- derived river discharge are identified. These dates are then filtered to retain only those where the discharge patterns from both sources are concurrent and with the same sign (both increasing or decreasing). The resulting data are used as reference points to rescale one data source to the other.
The merged product considers a weighted average calculated based on the temporal distance from the last acquisition (high weight for a recent measurement and low weight for a measurement distant in time). Further details are included in the ATBD document [RD-4].

3.4.3 Data limitation

Despite the procedure developed to combine data from the two sensors proving capable of representing in situ discharge with sufficient accuracy, there are still intrinsic limitations that need to be considered.

- For the Level-2 product generated by the procedure calibrated with RIDESAT, the added value of the combination is compromised by the fact that only coincident observations are considered. This condition makes the procedure quite challenging to apply in order to obtain a dense and temporally homogeneous time series. In fact, coincident measurements between different sensors are rather rare, and the solution is to densify the altimetric series as much as possible to increase the chances of combining it with multispectral sensor data.
- The merging procedure is completely dependent on the relationship between CM indices and WSE on coincident passing days. The accuracy of both the measurements has an important role in building the function, therefore erroneous WSE or CM indices may affect the merging model accuracy.
- Similar to the point 2, for the Level-3 product the accuracy of the discharge value derived by CM indices or WSE is fundamental for the final value of the discharge. The positive aspect of the procedure is the fact that the discrepant measurements (with opposite trend) are partially compensated considering the weighted average.

4 RD dataset

4.1 Main characteristics

The CDR (Climate Data Record) River Discharge dataset is a merged product composed of the thematic product described in the previous section and summarized in the Figure 4. There are three CRDPs (Climate Research Data Packages) provided within the CCI River Discharge precursor project:

- WSE CRDP (https://dx.doi.org/10.5285/c5e585820d1240e89eea85ff2c9b4569)
- RD-alti CRDP (https://dx.doi.org/10.5285/44c930e1388f40728884fbdf7e28c109)
- RD-multispec CRDP (https://dx.doi.org/10.5285/a8422dd3766c447d8b5fa80920649f31)
- RD-merged CRDP (https://dx.doi.org/10.5285/d32244e674dd438ca4d321560daad755)

All products are provided with two different formats. The first one corresponds one NetCDF4 file per station following the CCI data standard [RD-6]. The second one corresponds to one CSV file per station. Next sections describe in detail the CRDP directory structure, and the CSV and NetCDF file formats computed for all CRDPs. If more information is needed, users can read [RD-7] and [RD-8], the release notes for WSE and RD-alti CRDPs, respectively.

Products generated in this precursor CCI+ project are derived from data acquired by multiple sensors and satellites (for details see [RD-3] and [RD-4]). Therefore, they have different temporal and spatial resolutions, but also different accuracies.

Both single mission WSE time series and merged WSE time series are provided for VS near locations defined in the [RD-2] at the satellite observation times. However, in the merged time series, only one measurement per day is kept if multiple observations are available for a given day (the earliest one being retained [RD-7]).

Altimetry-based RD time series are provided at the in-situ discharge station locations defined in [RD-2]. In situ data are used over the calibration period [RD-4], when there is time overlap with altimetry data, to compute the rating curve, using merged WSE time series.

The multispectral images-based RD time series are also provided in all the stations defined in [RD-2]. As discussed in 3.3.2, three different river discharge products are provided, according to the availability of observed data that overlaps with the multispectral indices: in case of observed data availability, the RD obtained through the copula and best-fit approach are calculated, together with the RD from the uncalibrated CDF matching. In case no overlapping observed data are available, just the RD from the uncalibrated CDF matching is provided.

Valid uncertainty estimates are provided only for RD-alti and correspond to a first estimate of a partial end-to-end uncertainty budget (see [RD-4]).

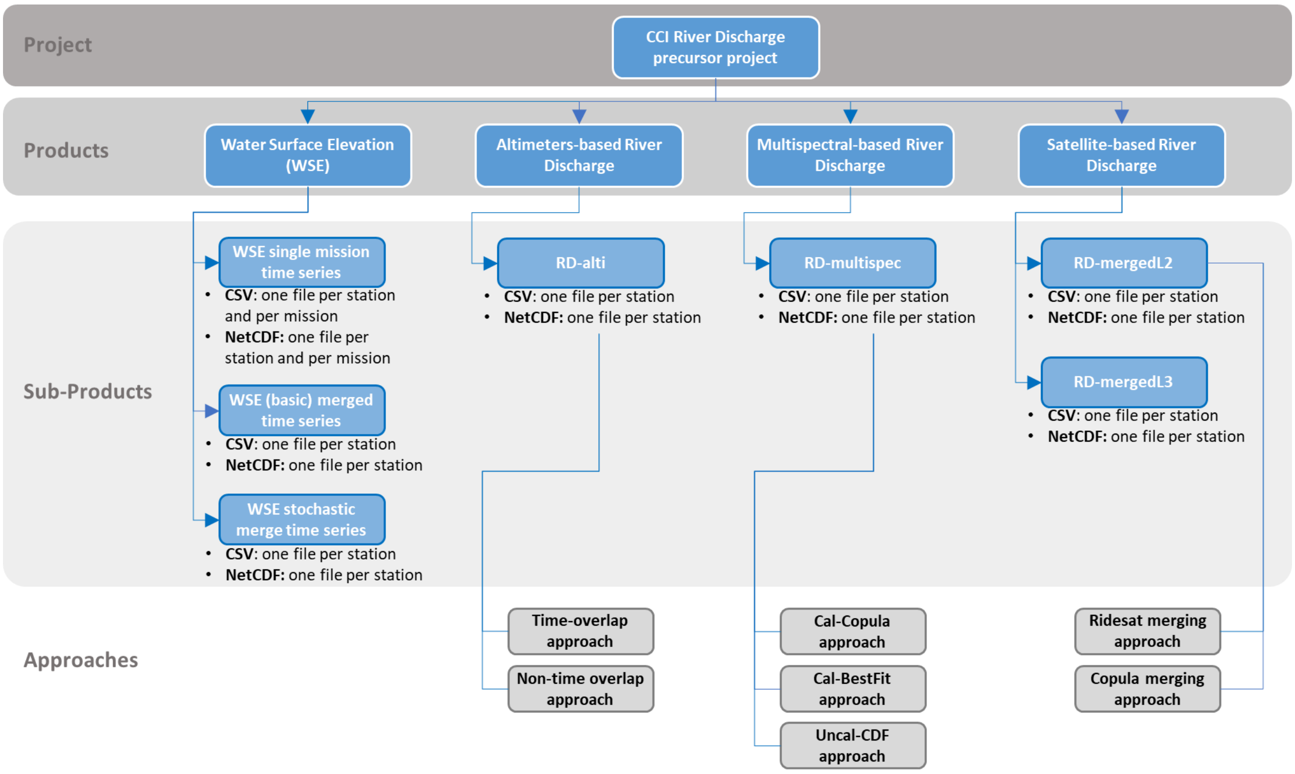

Figure 4. Organigram of the products, sub-products and approaches of the CCI+ River Discharge Precursor Project.

4.2 CRDPs directory structure

4.2.1 WSE CRDP directory structure

Concerning WSE CRDP directory structure, the highest-level directory corresponds to the current CRDP version number. Then, there are two subdirectories, corresponding to the file formats. They are labelled "CSV" and "NetCDF". They contain only files with format corresponding to their name subdirectory. Subdirectories structure for these two directories is the same. Single mission time series are provided in one directory called "single_mission_timeseries". Merged time series are provided in directories "merged_timeseries" and "stochastic_merge_timeseries", which correspond to time series from the basic method and the stochastic method, respectively. In the first two directories ("single_mission_timeseries" and "merged_timeseries"), there are 18 directories, one per selected basin in [RD-2], labelled with the name of the basin in capital letters. The "stochastic_merge_timeseries" directory only contain two folders associated with the processed basins (Congo and Niger). Then, in each "basin" directory, there is one directory per location defined in [RD-2] for this basin. These "location" directories are labelled with the name of the location in capital letters (see Appendix B for the name of these locations). Altimetry time series files for all VS associated to these locations are located within these "location" directories (rather in CSV format or in netCDF format, depending on the level 2 directory name). For merged time series, there is one file in each location directory. A diagram of the CRDP directory structure is shown in Figure 5.

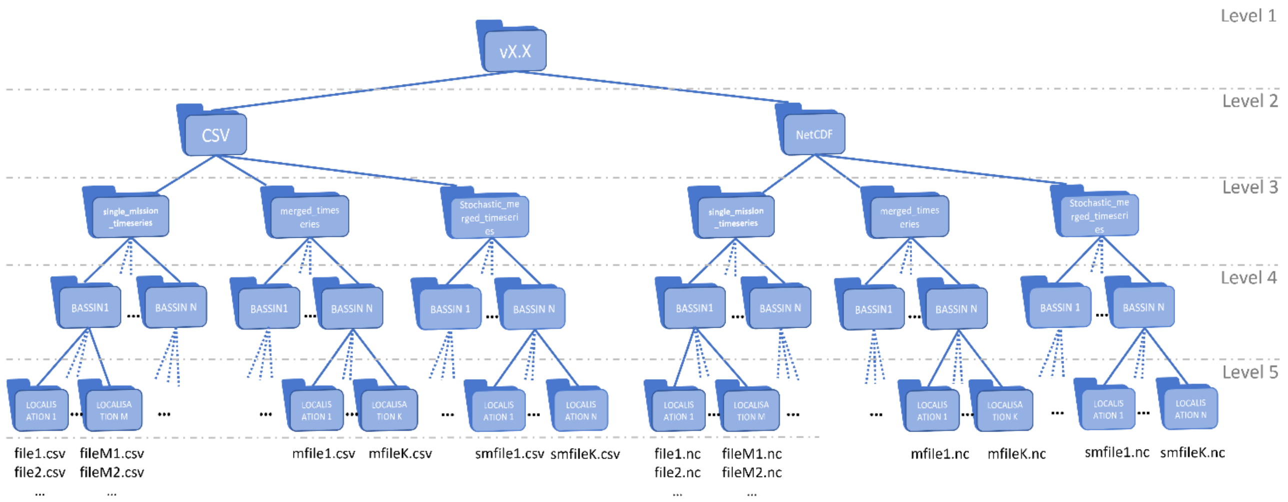

Figure 5. WSE CRDP directory structure

4.2.2 RD-alti and RD-multispec CRDPs directory structures

RD-alti CRDP and RD-multispec CRDP have a similar directory structure. Like WSE CRDP, the highest-level directory for these two CRDPs corresponds to the current CRDP version number. Then, there are two subdirectories, corresponding to the file formats. They are labelled "CSV" and "NetCDF" and contain only file format corresponding to their name subdirectory. River discharge time series files for all locations are provided in these two subdirectories, with just one file per location. A diagram of the RD-alti CRDP and RD-multispec CRDP directory structure is shown in Figure 6.

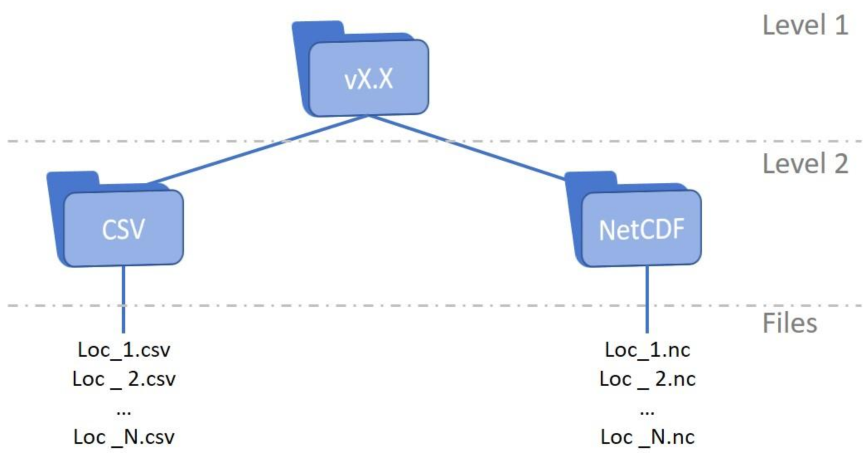

Figure 6. RD-alti CRDP and RD-multispec CRDP directory structure

4.2.3 RD-merged CRDP directory structure

RD-merged CRDP directory structure has two levels. Level 2 and level 3. Level 2 corresponds to the merged approach with level 2 products (WSE for RD-alti and CM for RD-multispec) used to compute river discharge (RD-mergedL2). Level 3 corresponds to the merged approach with Level 3 products (RD-alti and RD-multispec) used to compute river discharge (RD-mergedL3). Finally, RD-merge time series files for the computed locations are provided in these two subdirectories. A diagram of the CRDP directory structure is shown in Figure 7.

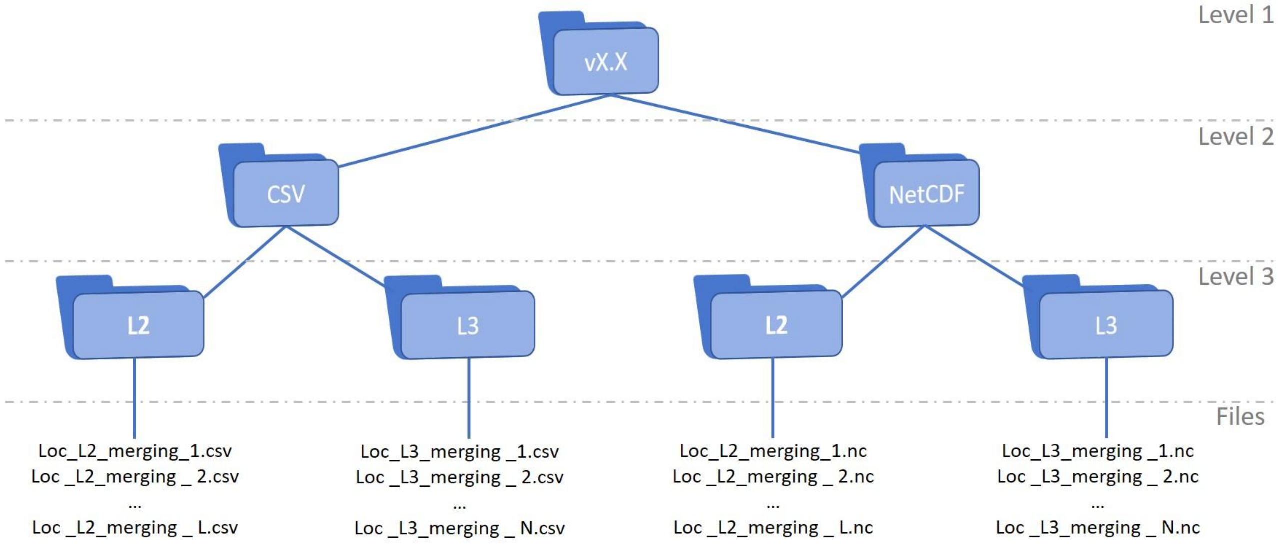

Figure 7. RD-merged CRDP directory structure

4.3 NetCDF files

The first type of file format in CCI River Discharge CRDPs corresponds to NetCDF4 files, compliant with most of the CCI Data Standards [RD-6]. There is one NetCDF file per time series. Sections below describe first the file naming convention used and the formatting.

4.3.1 File naming

NetCDF file names in the CCI+ River Discharge precursor project, are compliant with the CCI data standards [see RD-6 for more details] and follow the pattern:

ESACCI-RD-<Processing Level>-<Data Type>-<Product String>-<Additional Segregator>-<Indicative Dates>-fv<File version>.nc

Where:

<Processing Level> equal to “L3C” for single mission WSE time series or “L3S” for merged WSE time series whereas, is equal to “L4” (i.e. level 4) for RD time series created from the level 3 (L3S) satellite data or from multispectral ratio.

<Data Type> equal to “RD” for River Discharge time series, or equal to “WL” for WSE time series, to follow the CCI data standards [RD-6]

<Product String> equal to “SINGLE_nobiascorrection” (for single mission WSE time series), “MERGED” (for merged WSE time series), “ALTIBASED” for RD-alti, “CMCALBESTFIT” for RD-multi/Cal-BestFit product, “CMCALCOPULA” for RD-multi/Cal-Copula product, or “CMRATIO” for RD-multi/uncal_CDF product.

<Additional Segregator> equal to "BASIN_RIVER_STATION_MISSIONNAME_TRACKNUMBER_LATID" for WSE time series and equal to "BASIN_RIVER_STATION" for RD time series.

With: BASIN = Basin name in capital letters

RIVER = River name in capital letters

STATION = Location name defined in [RD-2, RD-7] in capital letters

MISSIONNAME = VS mission name, in lower case. It corresponds to the mission's name of the time series in the file among the following values: ers2, envisat, saral, topex, jason1, jason2, jason3, sentinel3a, sentinel3b, and sentinel6. For merged time series, it corresponds to the mission's name of the reference VS (see [RD-3]), preceded with the word "merged"

TRACKNUMBER = Mission orbit track number associated to the VS, coded on 4 digits

LATID = It is an ID defining the mean latitude of the VS. It begins with "N" if the mean latitude of the VS is in the Northern Hemisphere or with "S" if it is in the South Hemisphere. Then, it is followed by the mean latitude value with two decimals and without any point for decimal separator, coded on four digits (for example, if the mean latitude of the VS is 44.24 ° N, then LATID = N4424)

<IndicativeDates> corresponds to the first date and the last date in the time series, separated with "_". Dates are provided in the form YYYYMMDD, where YYYY is the four digits year, MM is the two digits month, and DD is the two digits day of the month.

<File version> is the file version.

4.3.2 Format

The River Discharge dataset is stored in the NetCDF4 classic format (Network Command Data Form) using the CF (Climate and Forecast) metadata convention (v1.8) and CCI Data Standards (v2.1), as requested in [RD-6].

The following sections describe the content of NetCDF files for each CRDP.

4.3.2.1 Global attribute

The 41 global attributes correspond to the ones required in [RD-6]. They are self-explanatory and only the main ones are described in the Table 3.

Attribute Name	Attribute description
Source	sources of the data used to compute the time series. It is set to the name of the space agencies that conceived the satellite altimetry mission.
time_coverage_resolution	time resolution of the dataset. As measurement varies in time, depending of the satellite mission(s) available, it is set to "satellite_orbit_frequency"
spatial_resolution	spatial resolution of the dataset. As measurements are provided at some specific location and not on a grid, it is set to "Point-based measurement at the satellite nadir" for WSE time series, "Point-based measurement of the in-situ discharge data" for RD-alti time series, or "Point-based from pixel reflectance index over an area ranging from 0.04degx0.04deg to 0.15degx0.15deg" for all RD-multispec products.
platform and sensor	name of the satellites/platforms and the associated sensor, respectively, of which data has been used to produce the time series.

Table 3. Global attributes

In addition to these attributes, there are also a few global attributes specific to this CRDP and depending on the dataset (WSE or RD time series).

Attribute Name	Attribute description
basin_name	the name (in upper case) of the basin river (see Table 1)
river_name	the name (in upper case) of the river
Location	the name (in upper case) of the station (see Table 1)
reference_virtual_station	the name/ID given by this CCI project to the VS - only for the WSE dataset (see line "#ID" in Table 7 for more details)
Methodology	methodology used to compute the rating curve (see [RD-4] for more details) - only for RD dataset
Doi	the Digital Object Identifier (DOI) associated to this CRDP and should be used when citing this CRDP

Table 4. Additional Global attributes

4.3.2.2 Dimensions

Following the CCI data standards, the products have three dimensions: time, latitude and longitude. All the variables included share the same dimensions.

4.3.2.3 Variables

The attributes of the variables in the NetCDF files follow the CCI data standards guidelines [RD-6] and consequently, the CF recommendations. All variables have only one dimension, named *time*, which has unlimited dimension and corresponds to time dimension of the time series. This *time* dimension differs between products. Only the variable "plateform", corresponding to the platform name (character array), has another dimension, labeled *strlen* to follow CF Metadata Conventions (see [RD-6]). This *strlen* dimension corresponds to the longest platform name.

Table 5 and 6 present the variables in the NetCDF files for WSE and RD datasets, respectively.

Variable Name	Variable description
time(time)	corresponds to satellite measurement times in the time series for the VS. It is provided as seconds from 1970-01-01.
lat(time) and lon(time)	correspond to WGS84 latitude and longitude, respectively, of each VS for WSE time series, or locations defined in [RD-2] for RD-alti and RD-multispec products. No data (or fill value) are set to 9.969209968386869e+36.
water_surface_height_above_reference_datum(time)	key variable and corresponds to the WL (in m) time series at the VS. No data (or fill value) are set to 9.969209968386869e+36
water_surface_height_uncertainty(time)	for each measurement time, it is the median absolute deviation (in m) of the selected along-track measurements at the measurement time to compute *water_surface_height_above_reference_datum* (see [RD-3]). No data (or fill value) are set to 9.969209968386869e+36.
orbit_track_number(time)	corresponds to the satellite orbit track number for the platform that did the measurement. No data (or fill value) are set to -2147483647.
mission_cycle_number(time)	corresponds to the satellite orbit cycle number for the platform that did the measurement. No data (or fill value) are set to -2147483647.
platform(time, strlen)	is only defined for merged WSE time series and corresponds to the name of the platform that made the measurement for each time step. The platform names are the ones defined in the CCI ontology table (see [RD-6]). No data (or fill value) are set to '\x00'.

Table 5. List of global variables in the NetCDF file for the WSE dataset

Variable Name	Variable description
time(time)	corresponds to satellite measurement times in the time series for the VS. It is provided as seconds from 1970-01-01.
lat(time) and lon(time)	correspond to WGS84 latitude and longitude, respectively, of the location where discharge is provided
float_water_volume_transport_in_river_channel(time)	key variable and corresponds to the satellite-based RD (in m3/s) time series at the location (i.e. in-situ station). No data (or fill value) are set to NaNf.
float_water_volume_transport_in_river_channel_uncertainty(time)	for each measurement time, it is the uncertainty associated to the satellite-based RD (in m3/s) using methodology defined in [RD-4]. No data (or fill value) are set to NaNf.
platform(time, strlen)	corresponds to the name of the satellite mission/platform that made the measurement used to derived discharge for each time step. No data (or fill value) are set to '\x00'.

Table 6. List of global variables in the NetCDF file for the RD datasets

4.4 CSV files

The second type of file format in CCI River Discharge CRDPs corresponds to CSV files. They are generated in addition to the NetCDF files, and they contain the same time series and metadata. There is one CSV file per time series. Sections below describe first the file naming convention and the formatting.

4.4.1 File naming for WSE CRDP

The same naming convention than the Hydroweb time series is used and expanded for the WSE time series. It follows the following pattern:

R_BASIN_RIVER_KMXXXX_MISSIONNAME-TRACKNUMBER_LATID.csv

with: BASIN = Basin name in capital letters

RIVER = River name in capital letters

XXXX = Distance from river mouth (curvilinear abscissa). If not known, it is set to “XXXX”.

MISSIONNAME = VS mission name. It is in lower case and corresponds to the mission’s name of the time series in the file among the following values: ers2, envisat, saral, topex, jason1, jason2, jason3, sentinel3a, sentinel3b, and sentinel6. For merged time series, it corresponds to the mission’s name of the reference VS, preceded with the word “merged”

TRACKNUMBER = Mission orbit track number associated to the VS, coded on 4 digits

LATID = It is an ID defining the mean latitude of the VS. It begins with “N” if the mean latitude of the VS is in the Northern Hemisphere or with “S” if it is in the South Hemisphere. Then, it is followed by the mean latitude value with two decimals and without any point for decimal separator, coded on four digits (for example, if the mean latitude of the VS is 44.24°N, then LATID = N4424)

4.4.2 File naming for RD-alti and RD-multispec products

File naming used for RD-alti and RD-multispec products is derived from the GRDC one, slightly expanded and follows the pattern:

BASIN_STATION_Q_Day.Cmd.csv

with: BASIN = Basin name in capital letters

RIVER = River name in capital letters

4.4.3 File naming for RD-merged

File naming used for RD-merged is similar to RD-alti and RD-multispec, with information concerning follows the pattern:

BASIN_STATION_Q_Day.METHOD.csv

with: BASIN = Basin name in capital letters

RIVER = River name in capital letters

METHOD = Method used to compute RD-merge products. It is equal to "L2_merging" for RD-merge approach using Level 2 products and equal to "L3_merging" for RD-merge approach using Level 3 products.

4.4.4 Format

The WSE time series file format for this precursor project is the same one as the Hydroweb expert river data format. The RD time series file format is inspired by the GRDC discharge data format and is the same one for RD-alti and RD-multi. These data formats have been chosen as they are quite well known and used in the satellite hydrology science community.

4.4.4.1 Header

Every file starts with a fixed header, containing information on the contents of the file. The lines of the header are preceded by the hash character (i.e. #). This character may only be used in the header of the file. Header data is not required but will always be exported to make the data files more intelligible for humans.

The Tables 7 and 8 present the header information in the CSV files for WSE and RD CRDP, respectively.

Lines 1 to 7 correspond to hydrological metadata:	
#BASIN:	Basin Name
#RIVER:	River name
#ID:	VS ID (unique identifier), it is of the form mission-tracknumber_LXXXX, where mission is the mission name, tracknumber is the mission orbit track number associated to this VS, L is equal to N if the mean latitude of the VS is in the Northern Hemisphere or S if it is in the South Hemisphere, XXXX is the mean latitude value with two decimals and without any point for decimal separator on four digits (i.e.if the latitude is in between 10°S and 10°N, the first digit is zero, 0). For merged time series, the mission's name corresponds to the one from the reference VS, preceded with "merged". Tracknumber corresponds to the reference VS mission orbit track number. For the stochastic merged timeseries, the naming convention is the same as for merged time series, excepted that the mission name is preceded by "stomerged".
#TRIBUTARY OF::	Upstream river name (equals to "NA" if unavailable)
#APPROX. WIDTH OF REACH (m)::	River width estimation (equals to "NA" if unavailable)
#SURFACE OF UPSTREAM WATERSHED (km2):	Estimated upstream watershed surface (equals to "NA" if unavailable)
#RATING CURVE PARAMETERS A,b,Zo such that Q(m3/s) = A[H(m)-Zo]^b::	as only WL time series are provided, they are equals to "NA NA NA"
Lines 8 to 18 correspond to geographical metadata:	
#REFERENCE ELLIPSOID::	Ellipsoid of reference

#REFERENCE LONGITUDE::	VS longitude
#REFERENCE LATITUDE::	VS latitude
#REFERENCE DISTANCE (km)::	Distance from river mouth (curvilinear abscissa; equals to "NA" if unavailable)
#GEOID MODEL::	Reference geoid (geoid model version), set to NA as WL are referenced to WGS84 ellipsoid
#GEOID ONDULATION AT REF POSITION(M.mm)::	Geoid value at the VS location, set to NA
#MISSION(S)-TRACK(S)::	List of the used mission(s)-track(s) to build the timeseries. For merged time series, it is set to VS ID without the "_LXXXX" part.
#STATUS:	It could be "Operational (daily processed)" or "RESEARCH" (set to "RESEARCH" in this CRDP)
#VALIDATION CRITERIA::	"EXPERT", or "AUTOMATIC" (i.e. VS validated from hydrological expert, or automatically from statistical criteria)
#MEAN ALTITUDE (M.mm)::	Mean WSE
#MEAN SLOPE (mm/km)::	Mean slope over the river reach (equals to "NA" if unavailable)
Lines 19 to 28 correspond to product metadata:	
#NUMBER OF MEASUREMENTS IN DATASET::	Measurements number
#FIRST DATE IN DATASET::	First date in the timeseries
#LAST DATE IN DATASET::	Last date in the timeseries
#DISTANCE MIN IN DATASET (km)::	Minimal distance from river mouth (equals to "NA" if unavailable)
#DISTANCE MAX IN DATASET (km)::	Maximal distance from river mouth (equals to "NA" if unavailable)
#PRODUCTION DATE::	Production date
#PRODUCT VERSION::	Product version
#PRODUCT CITATION::	Product citation (equal to "ESA CCI+ River Discharge precursor project, DOI:10.5285/c5e585820d1240e89eea85ff2c9b4569")
#SOURCES::	Product sources (empty value for the moment)
#PRODUCT CONTENT::	Description of the data content (empty value for the moment)
Lines 29 to 45 describes each column of the file:	
#COL 1:	DATE(YYYY-MM-DD)
#COL 2:	TIME(HH:MM:SS)
#COL 3:	ORTHOMETRIC HEIGHT (M) OF WATER SURFACE AT REFERENCE POSITION
#COL 4:	ASSOCIATED UNCERTAINTY(M)
#FIELD SEPARATOR (":")	
#COL 5:	LONGITUDE OF ALTIMETRY MEASUREMENT (deg)
#COL 6:	LATITUDE OF ALTIMETRY MEASUREMENT (deg)
#COL 7:	ELLIPSOIDAL HEIGHT OF ALTIMETRY MEASUREMENT (M)
#COL 8:	GEOIDAL ONDULATION (M) at location [5,6]
#COL 9:	DISTANCE OF ALTIMETRY MEASUREMENT TO REFERENCE POSITION (KM)
#COL 10:	SATELLITE (for merged time series, it corresponds to the one from the reference VS, preceded with "merged" or "stomerged" depending of the merging method used)
#COL 11:	ORBIT / MISSION
#COL 12:	GROUND-TRACK NUMBER

#COL 13:	CYCLE NUMBER
#COL 14:	RETRACKING ALGORITHM
#COL 15:	GDR VERSION

Note: the field separator between columns 4 and 5 is introduced by Hydroweb team to separate data that are provided in the "basic" files (only the four first columns) and the "expert" files (all columns).

- The last header line separates the header to the data and corresponds to:

###

Table 7. List of variables in the CSV header file for the WSE dataset

Lines 1 to 11 correspond to hydrological metadata:	
# Title: # Format: # Field delimiter: # missing values # file generation date: # # Basin: # River: # Station: # Country:	Title of the data with project name and type of data ---------------- Data's format (CSV) Field delimiter (;) Value for no data (nan) Date of data generation (%Y-%m-%d) Basin Name in capital letters. Spaces have been replaced by "-" River Name in capital letters. Spaces have been replaced by "-" Station Name in capital letters. Spaces have been replaced by "-" Country Name in capital letters. Spaces have been replaced by "-"
Lines 12 to 16 correspond to geographical metadata:	
# Latitude (DD):	Latitude in decimal degrees [-90,90] with 4 decimals – corresponding to the insitu discharge station [see Appendix A and Appendix B]. If multiple sources, longitude and latitude from GRDC is privileged.
# Longitude (DD):	Longitude in decimal degrees [-180,180] with 4 decimals - corresponding to the insitu discharge station [see Appendix A and Appendix B]. If multiple sources, longitude and latitude from GRDC is privileged.
# Catchment area (km²):	Catchment area in km². Equals to "nan" if unavailable
# Altitude (m ASL):	The altitude of the station is expressed in meters above sea level. Equals to "nan" if unavailable
# Next downstream station:	Next downstream station. Equals to "nan" if unavailable
Lines 17 to 29 correspond to product metadata:	
# Institution: # Owner and License: # doi: # # # Data Set Content: # # Unit of measure: # Time series: # Last update: # Methodology:	Institutions responsible for producing the data. Owner of the data and associated license. Doi of the dataset (same for all altimetry-based RD time series) ** Type of data in this file - RIVER DISCHARGE (RD) ------------------- Unit of measure - m³/s First and last date of available data. Both are notified in this format: %Y-%m-%d and separate by a "-" as %Y-%m-%d - %Y-%m-%d Date of the last update in %Y-%m-%d Methodology used to compute the rating curve. The first part describes the approach used to compute the RC and the second part, separated by "_", describes the algorithm used. To avoid any issue for the reader the spaces have been replaced by "-". For RD-alti, two approaches ("Overlap-approach", where there is time overlap between in situ and altimeter data, or "Quantile-approach" where there is no or not enough

	time overlap) and two algorithms ("Bayesian-algorithm", or "Multiple-algorithms" used for Arctic rivers experiencing frozen periods) are available. For RD-multi, it could be "Calibrated CM approach - best fit regression" for RD-multi/Cal-BestFit product, "Calibrated CM approach - copula regression" for RD-multi/Cal-Copula product, or "Uncalibrated CM approach - CDF regression" for RD-multi/uncal_CDF product. For RD-mergeL2 and RD-mergeL3, the same methodology has been used for each station.
# Insitu discharge:	Insitu discharge database used to compute the RC. If multiple sources have been used to compute the RC, they are separated by "/". 9 sources haves been identified: - Global Runoff Data Centre (GRDC) - 56068 Koblenz – Germany - Global River Discharge (RivDIS) data set - U.S. Geological Survey (USGS) - Amazon basin water ressources observation service (SO-HYBAM) - Service Central d'Hydrometeorologie et d'Appui a la Prevision des Inondations (SCHAPI) HydroPortail - Arctic Great Rivers Observatory (ArcticGRO) - Environment and Climate Change Canada Historical Hydrometric Data web site (HYDAT) - Simulation from MGB hydrological model - Research Group (IPH - UFRGS) - Porto Alegre - Agenzia Interregionale del Fiume Po (AIPo)
# Calibration period:	Calibration period. Period uses to compute the RC with first date (%Y-%m-%d) and last date (%Y-%m-%d) separated by "-" as %Y-%m-%d - %Y-%m-%d
Lines 30 to 39 describes each column of the file and information on data lines	
# Table Header: # Date # Time # Value # Uncertainty # Satellite # # # Data lines: # DATA	 - Date's format - YYYY-MM-DD - Time's format - hh:mm:ss - original (provided) data – here discharge data in m³/s - Value's uncertainty (same unit than "Value") - Altimetry mission source (envisat, topex, ers2, saral, jason1, jason2, jason3, sentinel3a, sentinel3b, sentinel6) ** Number of data – integer value

Table 8. List of variables in the CSV header file for the RD datasets

4.4.4.2 Data

The data are provided in the CSV file just after the header. Each line corresponds to a different measurement time. Columns are separated by a space character for WSE data and by a semicolon character for the RD data.

Measurement data are provided within columns. The content of each column is described in the header (see previous section).

5 Guidance for reading and visualizing

The CCI River Discharge data are stored both in CSV and NetCDF formats. The same content is provided in these two types of formats.

Unidata web site (https://www.unidata.ucar.edu/software/netcdf/software.html) proposes a wide range of software for manipulating and displaying NetCDF data. They can be used to explore and process CCI River Discharge NetCDF products.

Concerning CSV products, they could be opened with any text editor. Typically, spreadsheet programs can open them and plot time series. Alternatively, scientific software or programming languages (like Matlab, R or python) can easily load, process and/or plot data stored in this format.

Furthermore, the CSV file format used for the RD and WSE time series follows the standard formats commonly used by many scientists. The CSV file format for the WSE corresponds to the expert Hydroweb CSV files, while the CSV file format for the RD is inspired by the file format of the GRDC.

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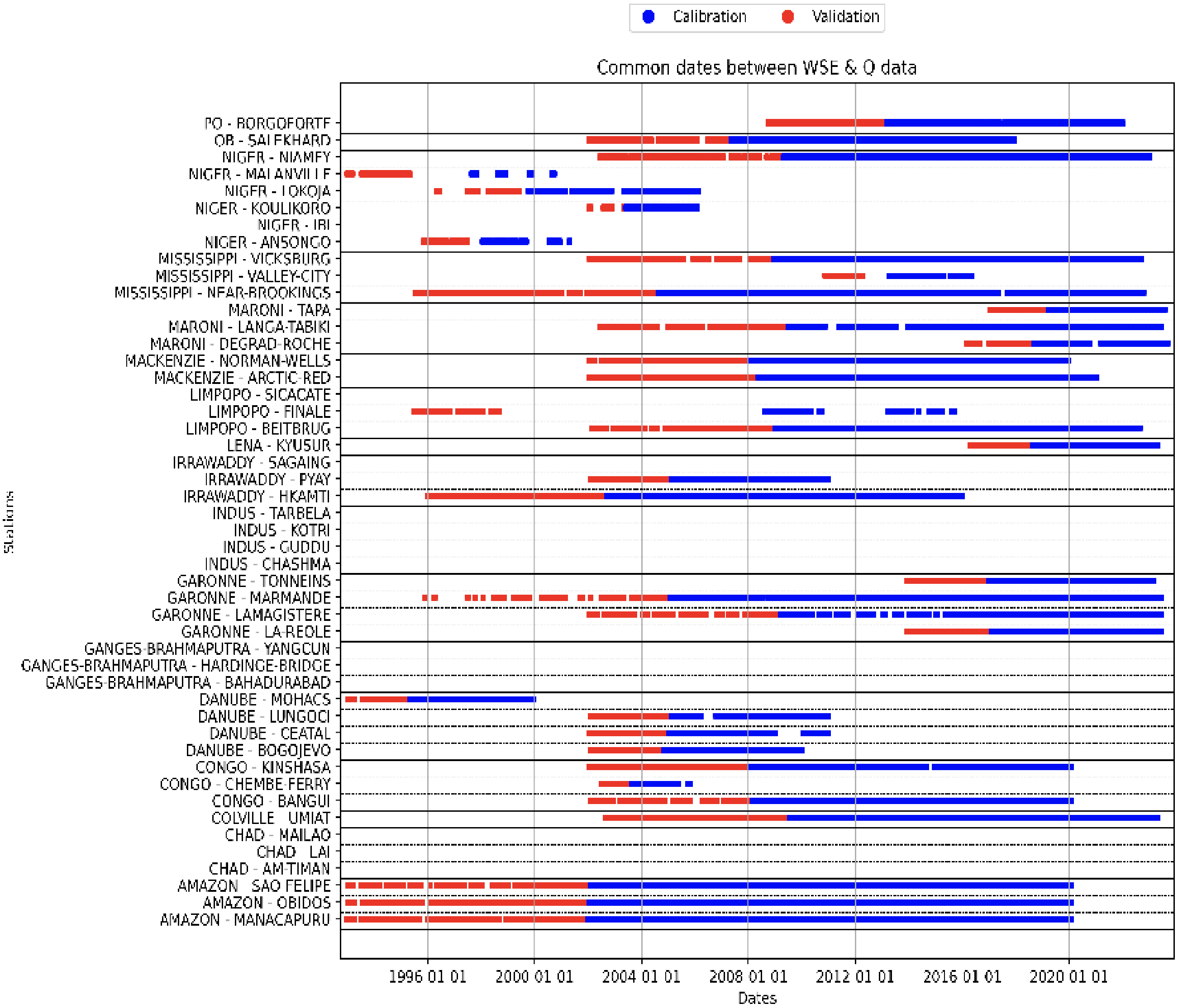
Appendix A - Cal/val periods for each in situ station

Table A1. Calibration/Validation periods according to data availability for each station



Appendix B - Name and coordinates of each in situ station used for cal/val

Table A2. Location (with longitude and latitude) for each selected station [RD-2].

id	Basins	Station	lon	lat	source
1	AMAZON	MANACAPURU	-60.6094	-3.3106	GRDC
2	AMAZON	OBIDOS	-55.5131	-1.9192	GRDC
3	AMAZON	SAO-FELIPE	-67.3128	0.3717	GRDC
4	CHAD	AM-TIMAN	20.28	11.03	RivDIS
5	CHAD	LAI	16.3	9.4	GRDC
6	CHAD	MAILAO	15.28	11.58	GRDC
7	CHAD	NDJAMENA	15.03	12.12	GRDC
8	COLVILLE	UMIAT	-152.1227	69.3605	USGS
9	CONGO	BANGUI	18.5833	4.3667	So-hybam
10	CONGO	CHEMBE-FERRY	28.75	-11.9666	GRDC
11	CONGO	KINSHASA	15.3008	-4.2823	So-hybam
12	DANUBE	BOGOJEVO	19.08	45.53	GRDC
13	DANUBE	CEATAL	28.7167	45.2167	GRDC
14	DANUBE	LUNGOCI	27.5122	45.5559	GRDC
15	DANUBE	MOHACS	18.67	46	GRDC
16	GANGES-BRAHMAPUTRA	BAHADURABAD	89.67	25.18	GRDC
17	GANGES-BRAHMAPUTRA	HARDINGE-BRIDGE	89.03	24.08	GRDC
18	GANGES-BRAHMAPUTRA	YANGCUN	91.88	29.28	GRDC
19	GARONNE	LAMAGISTERE	0.831	44.121	schapi
20	GARONNE	LA-REOLE	-0.036	44.5776	schapi
21	GARONNE	MARMANDE	0.156	44.5	schapi
22	GARONNE	TONNEINS	0.301	44.389	schapi
23	INDUS	CHASHMA	71.38	32.43	nan
24	INDUS	GUDDU	69.713	28.419	nan
25	INDUS	KOTRI	68.317	25.442	nan
26	INDUS	TARBELA	72.698	34.09	nan
27	IRRAWADDY	HKAMTI	95.7	26	GRDC
28	IRRAWADDY	PYAY	95.22	18.8	GRDC
29	IRRAWADDY	SAGAING	96.1	21.98	GRDC
30	LENA	KYUSUR	127.39	70.68	ArcticGRO
31	LIMPOPO	BEITBRUG	29.9903	-22.2261	GRDC
32	LIMPOPO	FINALE	30.7414	-24.3311	GRDC
33	LIMPOPO	SICACATE	33.5431	-24.7444	GRDC
34	MACKENZIE	ARCTIC-RED	-133.745	67.458	HYDAT
35	MACKENZIE	NORMAN-WELLS	-126.85	65.27	HYDAT
36	MARONI	DEGRAD-ROCHE	-53.87	3.42	GRDC /schapi
37	MARONI	LANGA-TABIKI	-54.43	4.98	GRDC /schapi
38	MARONI	TAPA	-55.697	3.18	MGB
39	MISSISSIPPI	NEAR-BROOKINGS	-96.7489	44.18	GRDC

40	MISSISSIPPI	VALLEY-CITY	-90.6454	39.7034	GRDC
41	MISSISSIPPI	VICKSBURG	-90.9058	32.315	GRDC
42	NIGER	ANSONGO	0.5	15.6667	GRDC
43	NIGER	IBI	9.7333	8.2	GRDC
44	NIGER	KOULIKORO	-7.55	12.8667	GRDC
45	NIGER	LOKOJA	6.7667	7.8	GRDC
46	NIGER	MALANVILLE	3.4	11.88	GRDC
47	NIGER	NIAMEY	2.09	13.52	GRDC
48	OB	SALEKHARD	66.6	66.63	GRDC
49	PO	BORGOFORTE	10.7554	45.0449	AIPo
50	PO	PIACENZA	9.6667	45.0167	GRDC /AIPo
51	PO	PONTELAGOSCURO	11.6	44.8833	GRDC /AIPo
52	ZAMBEZI	KABOMPO-PONTOON	24.2166	-13.6	GRDC
53	ZAMBEZI	KASAKA	28.2166	-15.8166	GRDC
54	ZAMBEZI	MATUNDO-CAIS	33.5917	-16.15	GRDC