HYDROCOASTAL

SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level

Impact Assessment Report Inland water Case Studies

Deliverable D3.2

Sentinel-3 and CryoSat-2 SAR/SARin Radar Altimetry for Coastal Zone and Inland Water

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1. Introduction

1.1. The HYDROCOASTAL Project

The objectives of the HYDROCOASTAL project, funded by the European Space Agency under the EO Science for Society programme, were to enhance the understanding of interactions between the inland water and coastal zone, between the coastal zone and the open ocean, and the small scale processes that govern these interactions. The project also aimed to improve the capability to characterize the variation at different time scales of inland water storage, exchanges with the ocean and the impact on regional sea-level changes.

To achieve these aims, the HYDROCOASTAL project team has developed and implemented new SAR altimeter processing algorithms for the coastal zone and inland waters, and with these processed Sentinel 3A, 3B and Cryosat-2 data to generate an initial 2-year Test Data Set for selected regions. The performance of these new algorithms was evaluated by statistical analyses and comparison against in situ data. From this analysis, the best performing algorithms were identified and a processing scheme implemented to generate a global scale coastal zone and inland water altimeter data set (described below).

In the final stage of the project, a series of case studies were implemented to assess these products in terms of their scientific impact on coastal and inland water studies. From these results, and other experience gathered during the project, a Scientific Road Map has been developed which contains a series of recommendations terms of priorities for further development of processing algorithms, recommendations for further SAR and SARin altimeter missions, priorities for further scientific research in the coastal zone and inland waters, to maximise the use and benefit of data from SAR and SARin altimeter missions.

1.2. HYDROCOASTAL final product

The HYDROCOASTAL final product was produced using innovative retracking algorithms for the coastal zone (UBonn Statistical STARS type: Buchhaupt et al, 2018, Roscher et al, 2107) and inland waters (DTU: Multiple Waveform Persistent Peak, MWaPP: Villadsen et al, 2016), which were selected as the best performing algorithms tested earlier in the project. The results of the evaluation of the performance of the algorithms are reported in the HYDROCOASTAL Product Validation Report (RD-08). The algorithms are fully described in the HYDROCOASTAL ATBD (RD-06).

To provide continuity between river and coastal water levels, the DTU MWaPP algorithm was applied to all regions, coastal and inland waters. The U Bonn STARS type retracker was applied only to Coastal Zone data. The product is provided at 3 levels:

- **L2E: Level 2 Extended Product**. Along track L2 product for all regions.
- **L3: Inland Waters, Water Level Time Series**. For all inland water regions.
- **L4: Inland Waters, River Discharge Time Series**. For selected inland water regions.

The source data are Sentinel 3A and Sentinel 3B SRAL L1a data, for all the operational mission to 30/09/2022 (S3A from 01/04/2016 to 30/09/2022, S3B from 11/05/2018 to 30/09/2022; South Australia starting from 01/01/2017) and Cryosat-2 SAR mode FBR data, for all the operational mission available in Baseline D (from 06/09/2010 to 21/08/2021). The format of the HYDROCOASTAL products is described in RD-07

The processor to L2 was implemented by isardSAT on a parallel processor virtual machine, with 64 threads, through a GBOX algorithm development and execution environment provided by EarthConsole (https://earthconsole.eu), funded by ESA Network of Resources sponsorship. In addition, the ESA Altimetry Virtual Lab on EarthConsole (https://earthconsole.eu/altimetry-virtual-lab/) SARvatore for Sentinel-3 service has been extensively used during the project for producing additional data sets with specific processing requirements, for comparison against the HYDROCOASTAL product. The Team is pleased to acknowledge the importance of this service for the altimetry community.

1.3. Impact Assessment Case Studies and the Scope of this Document

An important part of the HYDROCOASTAL project was a series of Impact Assessment Case Studies, the objective of which was to evaluate and report on the potential benefits offered by the new coastal zone and inland water processors, used toas implemented to generate the HYDROCOASTAL Final Product.

In total 13 Impact Assessment Case Studies were carried out, to investigate the capabilities of the HYDROCOASTAL product in a range of different inland water and coastal environments, and to investigate the potential improvements and benefits of possible further developments in SAR and SARin altimeter processing approaches.

This report summarises the key points of the four inland water case studies, highlights the major findings and summarises key recommendations.

1.4. Applicable Documents

AD-01: Sentinel-3 and CryoSat-2 SAR/SARin Radar Altimetry for Coastal Zone and Inland Water-Statement of Work, V1.0 10/01/2019 Ref: EOP-SD-SOW-2018-089.

1.5. Reference Documents

RD-01 HYDROCOASTAL Technical Proposal. V1.1 28/11/2019, SatOC and HYDROCOASTAL team.

RD-02 HYDROCOASTAL Implementation Proposal. V1.1 28/11/2019, SatOC and HYDROCOASTAL team.

RD-03 HYDROCOASTAL Management Proposal. V1.3 26/11/2019, SatOC and HYDROCOASTAL team

RD-04 HYDROCOASTAL Financial Proposal. V1.2 28/11/2019, SatOC and HYDROCOASTAL team

RD-05 HYDROCOASTAL Contractual Proposal. V 1.2 26/11/2019, SatOC and HYDROCOASTAL team

RD-06 HYDROCOASTAL Algorithm Theoretical Basis Document. V2.1, 23/06/2023. HYDROCOASTAL_ESA_ATBD_D1.3 HYDROCOASTAL Team

RD-07 HYDROCOASTAL Product Specification Document, V2.0, 20/06/23, HYDROCOASTAL_ESA_PSD_D2.3, HYDROCOASTAL Team

RD-08 HYDROCOASTAL Product Validation Report, V2.0, 25/07/22, HYDROCOASTAL_ESA_PVR_D2.5, HYDROCOASTAL Team

RD-09 Case-Study of the River Rhine and Lake Constance, Luciana Fenoglio, Hakan Uyanik, Jiming Chen, University Bonn.
RD-10 River discharge validation, Angelica Tarpanelli, Paolo Filippucci, Stefano Vignudelli and Francesco De Biasio.
RD-11 Lake Size and riverbank configuration study. Case of Republic of Ireland, Elena Zakharova, Peter Thorne, Simon Noone.
RD-12 A hydraulic model of the Amur River informed with ICESat-2 elevation, Peter Bauer-Gottwein

1.6. Document Organisation

After the introductory section 1, the next sections provide summaries of each of the inland water case studies, and conclusions and recommendations are given in the final section.

2. Case Study 1: The Rhine River and Lake Constance (UBonn)

2.1. Overview of Case Study

The main objective with this case study (RD-09) is to assess the HYDROCOASTAL water level product in German rivers and lakes and to highlight the benefits and the scientific value of an improved inland altimetry product to estimate river runoff and water storage change in lakes and reservoirs. The River Rhine and Lake Constance have been considered (Fig. 2.1). The River Rhine originates in the Swiss Alps and flows over a distance of 1233 km into the North Sea. Its catchment area spans nine countries. Some of the water is temporarily stored in alpine reservoirs and flows through large lakes at the edge of the Alps, such as Lake Constance and the lakes along the Jura mountains.

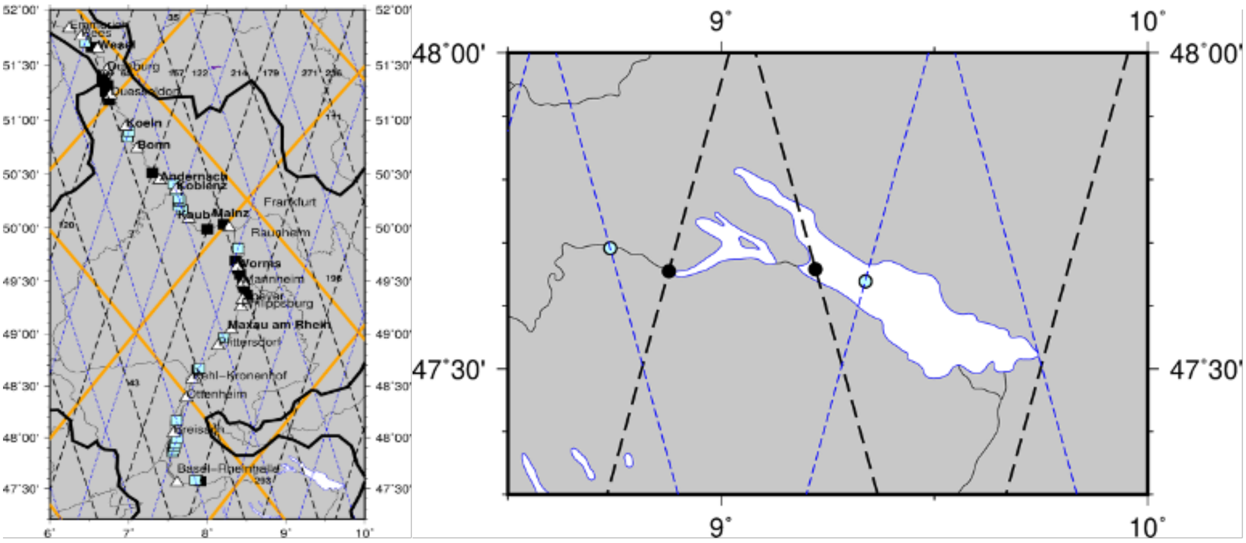

Figure 2.1. Inland Water case study on the River Rhine with Sentinel-3A/3B/6A ground tracks (black, blue, orange) and locations of fiducial reference data from operational tide gauges of the BfG network (left). Lake of Constance (right).

The HYDROCOASTAL water level product was compared in the Rhine River and in the Lake of Constance to a range of other Unfocused SAR (UFSAR) and Fully Focused SAR (FFSAR) processors. The UFSAR include the official ESA products, SAR Versatile Altimetric TOolkit for Research and Exploitation (SARvatore) for Sentinel-3 with the SAMOSA+ retracker, that is available through the EarthConsole platform (Dinardo et al., 2016). Alternative processing is made with in-house FFSAR processor with Omega-kappa (ωk) algorithm and SAMOSA+ retracker.

A land-sea processor for Sentinel-3 was coded in Matlab to assess the performance of the HydroCoastal product against in-situ Real Gauges (RG). Its main functionality is to:

- read HYDROCOASTAL data.
- reconstruct time series at each Virtual Gauge (VG), at the intersection of track and river.
- evaluate the altimetric products time-series against the RG.

The metric to evaluate the agreement between gauge and altimetry includes the standard deviation differences (STDD) and correlation. For a river, for each VG one single time-series with one value per cycle is constructed. For a lake a binned method is applied along each track, segmenting the track into bins, and computing the STDD for each bin to find the location with the smallest STDD and thus the highest accuracy.

Additionally, river discharge from space observations was estimated using simple equation including the Manning's roughness coefficient and the parameters water depth, river slope, river width. The key first-order hydraulic parameters, i.e. channel bathymetry and Manning's roughness coefficient are not measurable from space. The depth of the water, that's the water level above the river bottom, is here derived from SAR nadir altimetry over 2016-2023 using a Digital Terrain Model (DTM). The river slope is derived from satellite altimetry as the difference in water height above the geoid at two virtual gauges located on the same ground track in the same altimeter cycle. The river width is obtained from satellite imagery. The fluvial characteristics of the Rhine river is first investigated. The river width changes less during the year, while changes in heights and slope are more relevant. Mean discharge is computed from 17 in-situ stations of the GRDC database.

Manning coefficient and the exponents of the equation are derived in a least square adjustment at virtual gauges where slope can be computed from altimetry and where 15-min river discharge is available from in-situ nearly stations. The derived discharge is externally validated against in-situ daily GRDC data, against model discharge of the Sobek hydrodynamic model and against discharge from an empirical model GR4J, a catchment water balance model that relates monthly runoff to rainfall and evapotranspiration (https://webgr.inrae.fr/en/models/daily-hydrological-model-gr4j/description-of-the-gr4j-model/). The validation is done on a multi-criteria basis, including standard statistical scores such as the correlation coefficient, bias, root mean square error, and Nash-Sutcliffe efficiency.

2.2. Main Scientific Findings

The agreement between gauge and altimetric time-series depends on the method used to build the altimetric time-series and on the geophysical characteristics of the region. The orientation of tracks is relevant.

Typical values for accuracy (STDD) found in literature are in the range 10-50 cm. With the HydroCoastal product, this study finds median values of 30 cm in the river Rhine for the 42 virtual gauges of Sentinel-3A and Sentinel-3B with distance smaller than 30 km from the nearest in-situ river gauge. There is a clear consistency between the standard and the Hydrocoastal products. See in Fig. 2.2 the Boxplot with the four UFSAR products developed by the Hydrocoastal project and the three external products, the two 20 Hz standard Copernicus and the dedicated 80 Hz SARVatore from Earth Console with Samosa+ retracker. In UFSAR the best results are from this last. The results of the Fully Focused processing at 80 Hz and retracted with SAMOSA+ are good and comparable to UFSAR SARVatore 80 Hz, the accuracy is only slightly improved. One of the smallest STDD of the 42 VGs is obtained at VG with nearest RG in Mainz, STDD is 9 cm from UFSAR Samosa+ and 8 cm from FFSAR Samosa+, see time-series in Fig. 2.3.

Among the Level 2 Hydrocoastal products, the DTU 20 Hz products has the smallest STDD with median of 36 cm against the 25 cm of Earth Console 80 Hz SARVatore (Table 2.1). The DTU Level 3 products have smaller mean of STDD than from Level 2 but fewer VGs are found.

Table 2.1 River Rhine. Statistics of comparison of altimetric time-series derived from L2 DTU with in-situ data over the 42 VGs.

STDD with in-situ (m)	L2toL3 20Hz-DTU ECMWF	L2toL3 20Hz-ESA ECMWF	L2toL3 20Hz-DTU UPorto	L2toL3 20Hz-ESA UPorto	80 Hz UFSAR SARVatore SAMOSA+
Median	0.355	0.425	0.371	0.424	**0.267**
Mean	0.807	0.583	0.815	0.583	**0.479**

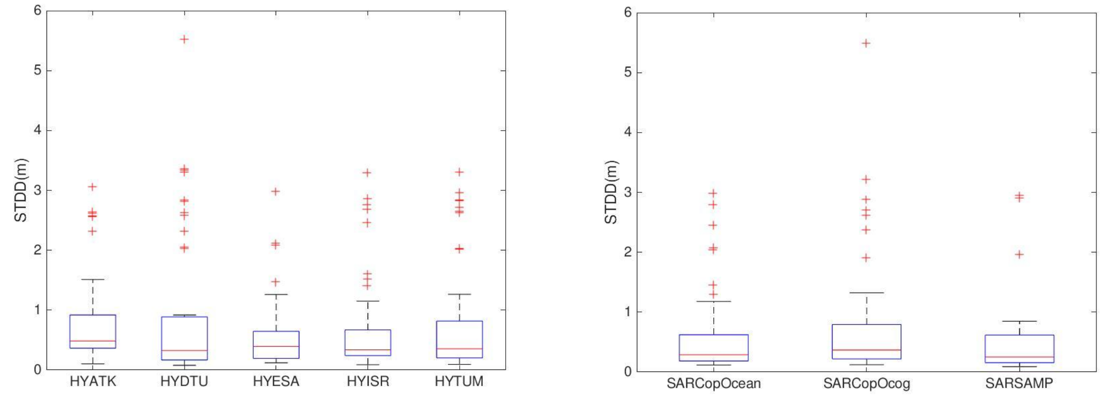

Figure 2.2 Boxplot of STDD at the 42 VGs for unfocused SAR Hydrocoastal (left) and for standard and dedicated products (right). The best accuracy is from SARvatore SAMP

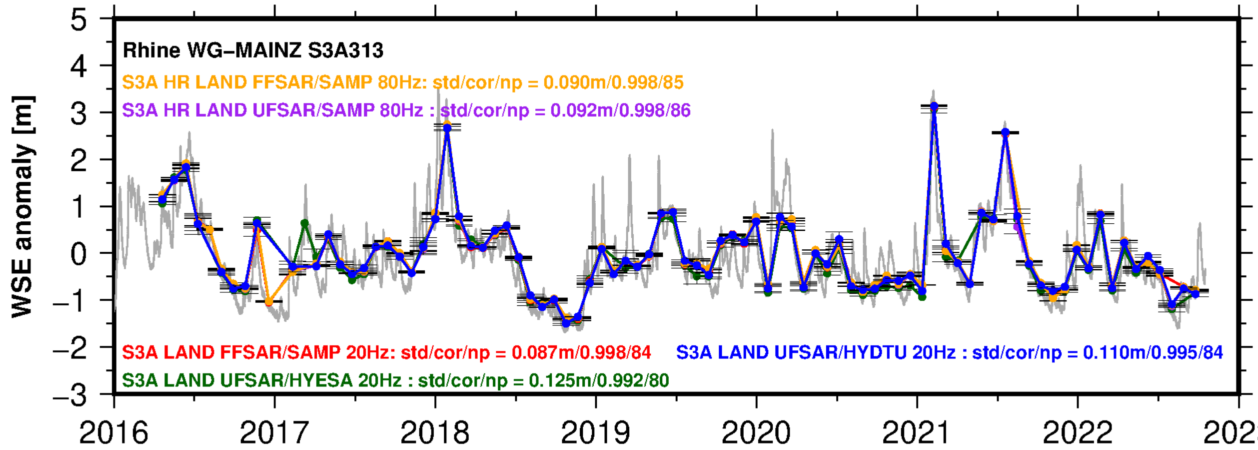

Figure 2.3 Altimetric time-series in Mainz for Sentinel-3A UFSAR 20 Hz DTU (blue) and ESA (green), UFSAR SARvatore SAMOSA+ (violet) and FFSAR/SAMP 80 Hz (orange)

Lake Constance is included in Level 2 Hydrocoastal products, STDD of DTU 20 Hz and in-situ have means of 8 cm and up to 40 cm for the bins along two tracks and similar values from FFSAR processing (Fig. 2.3). We conclude that accuracy is highly variable in time and space.

This case-study of inland water rivers and lakes shows that altimeter data exploitation is possible very near to land. Contamination by land can however not be eliminated neither in USAR nor in FF-SAR, the reason for contamination can be other than land effect and should be investigated. In rivers the accuracy compared to the tide gauge is high (up to 10 cm). In lakes the accuracy can reach 6 cm, but varies along-track due to other effects, could be wind, to be investigated. Some interesting findings that we mention hereinafter.

- Binned method is the preferable in the construction of the time-series.
- Use of 80 Hz instead than 20 Hz is preferable in rivers.

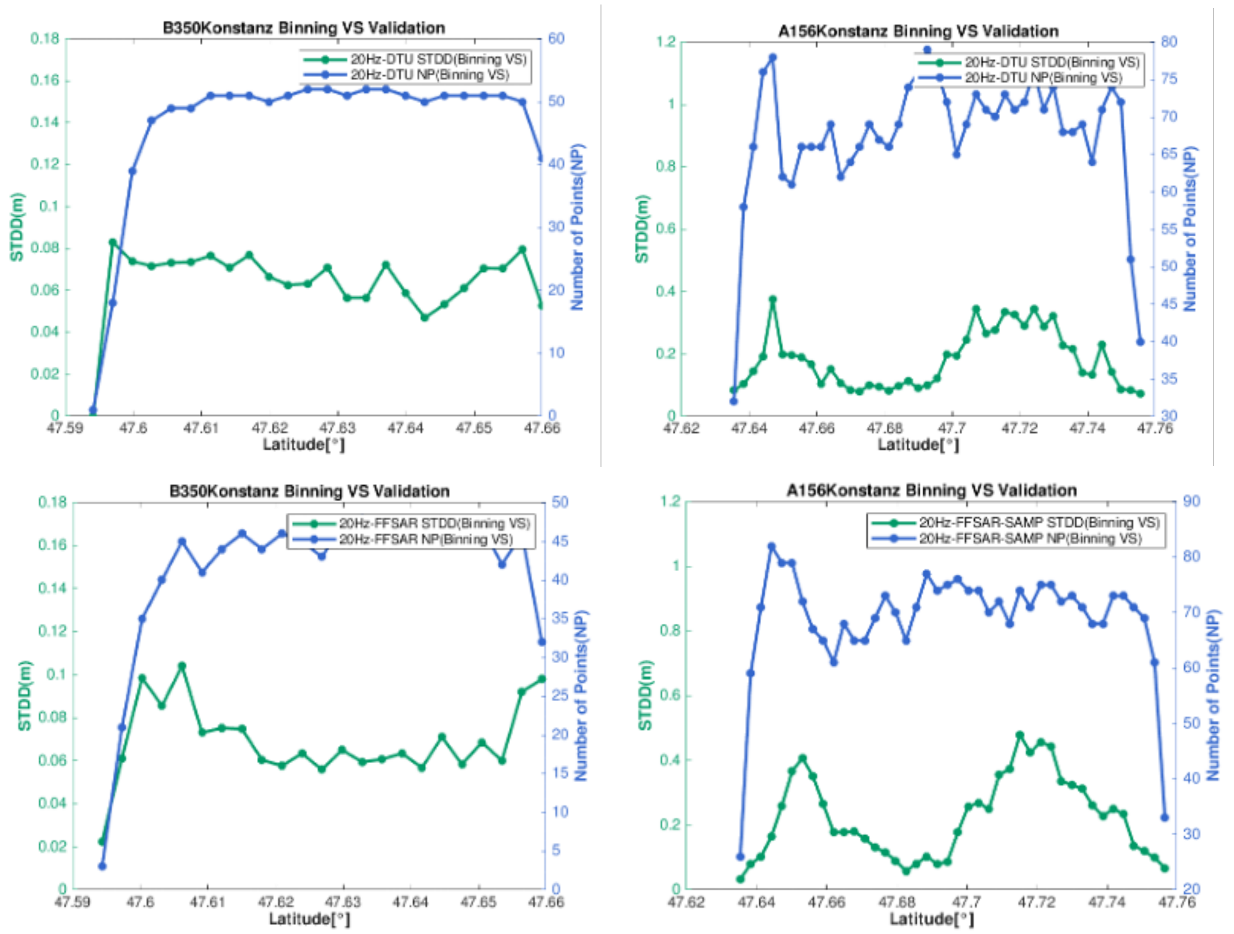

Figure 2.4 Lake of Constance. Accuracy as STDD of altimetric and gauge water height (green) and number of points per bin (blue) from the DTU products (top) and from in-house FF-SAR (bottom). Ground tracks SA156 and SB350 in Fig. 2.1.

The river discharge is derived from space observations using the simple equation below that includes the Manning's roughness coefficient and the parameters water depth, river slope, river width. The observations are slope and the water level from altimetry and the discharge at in-situ stations. Width and depth of water are auxiliary parameters. Firstly channel conductance and the three exponents' values suggested in Bjerklie (2005, Table 3) are used here (case 1). Secondly, we keep the exponents values fixed and estimate the conductance (case 2). Thirdly, the four parameters are derived in a least square adjustment. The slope is from altimetry and 15-min river discharge is from in-situ nearly stations. Case 3 gives the better results in terms of NS coefficient (0.93 in Worms). The third method is then applied to all the VGs where the slope can be used shows stable values for the estimated exponents and larges change for the conductance, k.

$$Q = k_2 W Y^{1.67} S^{0.33}$$

$$Y = f(H_{alti}) = H_{alti} - H_0$$

(Eq. 1-2-3)

$$S_{alti} = \frac{H_{altiWorms} - H_{altiMainz}}{L_{river}}$$

Figure 2.5 Shows the estimated discharge from the different methods.

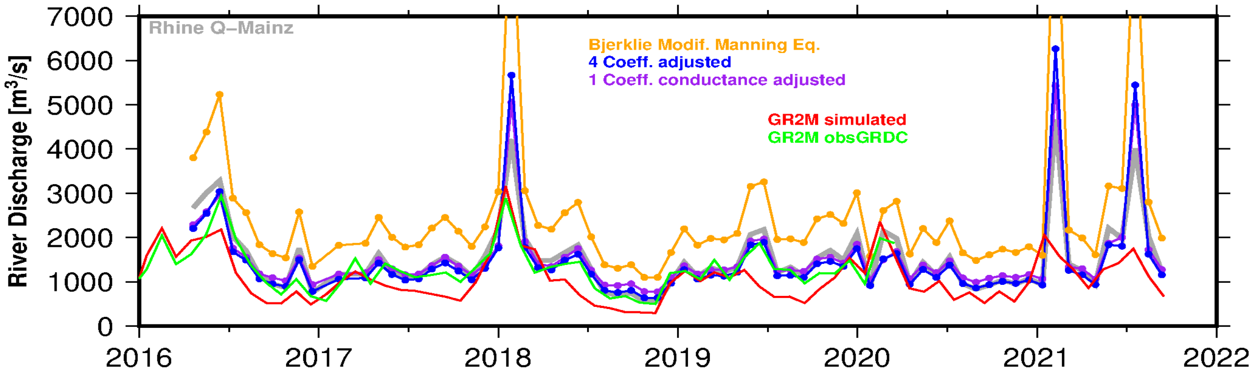

Figure 2.5 River discharge derived in Mainz from the three approaches and from the GR2M model

2.3. Main Recommendations and suggestions for new studies

To summarise, the in depth altimeter data analyses outlined a number of topics to be addressed, including specific research investigations that deserve further consideration, with future projects to be implemented. Hereinafter we provide key recommendations:

1. As the river slope is a key parameter, to derive river discharge, we suggest to improve and refine estimation of river slope variability from altimetry
2. As demonstrated within the HYDROCOASTAL project, the methodology to reconstruct the water level time series has an influence on the validation results. Therefore we suggest examining this further.
3. Based on this impact assessment, FFSAR data as well as 80 Hz data, have provided promising results. Especially for rivers the improved resolution compared to the standard 20Hz data is essential. We therefore recommend to conduct further investigations with FFSAR and 80Hz UFSAR over different surfaces, sea, river, bays, lakes.
4. Based on our findings we suggest using more complex hydrological models using daily inputs for discharge estimation.

3. Case Study 2: River discharge validation & River Po outlet (CNR/IRPI)

3.1. Overview of Case Study

The case study (RD-10) consists of three parts. The first part is a validation of the river discharge HYDROCOASTAL product. The second part consists of a qualitative assessment of the 2022 drought event in the Po River and the third study investigates the L2 HYDROCOASTAL product to understand the river ocean interaction from the ocean side in case of flood and drought events in the period 2018-2022.

The river discharge is estimated from Near InfraRed sensor data, from satellite altimetry, and by merging the two products based on the procedure described in the D1.3 Algorithm Theoretical Basis Document, this is also referred to as the RIDESAT algorithm. In the HYDROCOASTAL project river discharge was estimated for selected globally distributed rivers. To evaluate the river discharge the following statistical summary measures were calculated: Mean, Standard Deviation (SD), Pearson correlation (R), Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE), Nash-Sutcliffe Efficiency (NSE), Klinge Gupta Efficiency (KGE).

Regarding the flood and drought analysis of the Po River, it is tested how well the HYDROCOASTAL L3 and L4 product can be used to measure extreme events. This analysis aimed to evaluate two aspects:

i) if the satellite altimetry was able to monitor the decreasing of the water levels along the main water course and
ii) if it was possible to observe the intrusion of the salt water in the downstream part of the Po River.

This study report also describes a preliminary investigation of floods and drought events on the northern Adriatic Sea in front of the Po River delta. For this investigation, the HYDROCOASTAL L2 products was used along four Sentinel-3 tracks in the northern Adriatic Sea.

3.2. Main Scientific Findings

Po, Mississippi, Rhine, and Ob Rivers

In general, the altimetry-derived discharge time series better represents the ground observation with respect to the reflectance indices-derived discharge. However, the number of observations with the Near InfraRed (NIR) images is significantly higher than the altimetry data. It is here demonstrated that the RIDESAT algorithm, where both altimetry and reflectance indices are combined, is able to improve the estimated river discharge.

Table 3.1: Performances between observed and simulated river discharge obtained by RIDESAT algorithm.

	Mean error	*Dev standard error*	*R*	*RMSE/ 100*	*RRMSE*	*NSE*	*KGE*	*mean T*
Piacenza	-4.33	331.39	0.83	3.27	0.40	0.56	0.67	**36.00**

Cremona	6.66	164.46	0.89	1.63	0.17	0.92	0.89	**30.76**
Borgoforte	19.54	266.09	0.95	2.65	0.20	0.93	0.95	**25.36**
Sermide	12.43	304.78	0.89	3.03	0.24	0.84	0.88	**19.58**
Pontelagoscuro	21.40	250.52	0.95	2.50	0.19	0.92	0.95	**20.97**
Thebes	127.82	1443.80	0.98	14.31	0.11	0.92	0.97	**24.50**
Chester	105.74	2310.24	0.90	22.88	0.19	0.78	0.88	**23.47**
Memphis	257.57	3050.41	0.93	30.02	0.10	0.92	0.93	**37.24**
Worms	-4.96	420.87	0.59	4.16	0.29	0.56	0.54	**22.90**
Kaub	-0.08	200.89	0.90	1.99	0.13	0.85	0.89	**20.93**
Mainz	14.66	378.65	0.94	3.75	0.24	0.76	0.88	**29.42**
Salekhard	84.76	4537.80	0.66	45.06	0.31	0.83	0.65	**18.35**
Median	**17.10**	**355.02**	**0.90**	**3.51**	**0.19**	**0.85**	**0.88**	**23.98**
mean	**53.43**	**1138.32**	**0.87**	**11.27**	**0.21**	**0.82**	**0.84**	**25.79**

River discharge for Ganges, Niger, White Nile, Ebro Rivers

These rivers represent the ones selected for the second phase. Gauge data for validation was only available for the Ebro river, for the other rivers (Ganges, Niger, and White Nile), the calibration of the parameters of the RIDESAT algorithm were obtained through the use of modelled discharge by Glofas[1] dataset. Also for these rivers the RIDESAT approach provided the best results. For the White Nile it was not possible to derive river discharge, since the Glofas data is of a poor quality. It was however demonstrated that the altimetry based water levels and the reflectance indices show the same variations, indicating that these data sources capture an actual signal.

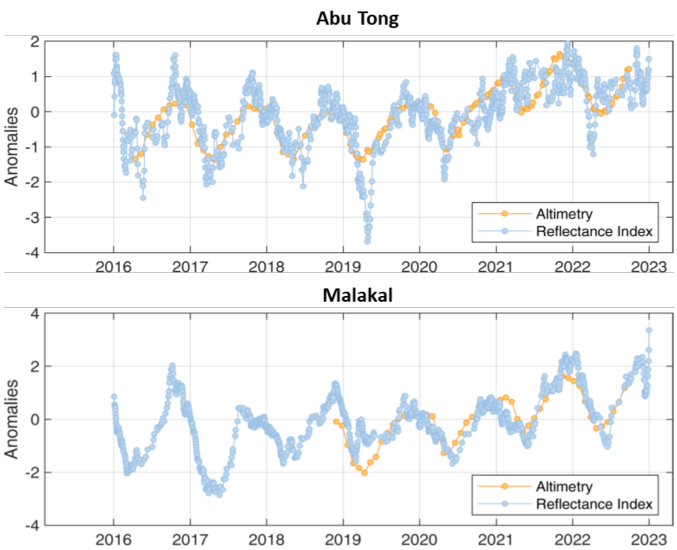

Figure 3.1: comparison between the water level from altimetry time series and the reflectance indices for the two stations along the White Nile. Both the time series are dimensionless to show the comparison

[1] GLOFAS – Global Flood Awareness System - www.globalfloods.eu

The 2022 summer drought event over the Po River

Concerning the case study along the Po River, the study indicated that all the time series of the water level and river discharge show a significant decrease in the value during the summer 2022. In addition, the analysis of the data at the virtual stations in the downstream part of the Po River along with the L2 data along the tracks of the plume closer to the mouth of the river demonstrated the interaction between sea and river.

In particular, the temporal series of the river clearly show the intrusion of the sea for some km along the river (more than 40 km as stated in the news) that caused substantial damages to the agriculture and drinking water aquifers. It is obvious that a multi-mission time series with data every 2-3 days is preferable for carrying out the analysis and evaluate in detail the beginning of the drought event and its evolution.

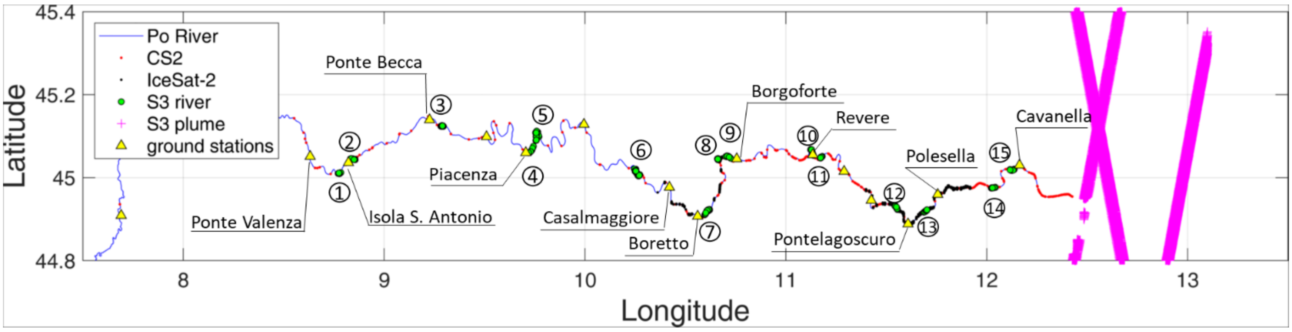

Figure 3.2: Po River - location of the ground stations and the satellite products (IceSat-2; Cryosat-2: CS2; Sentinel-3: S3)

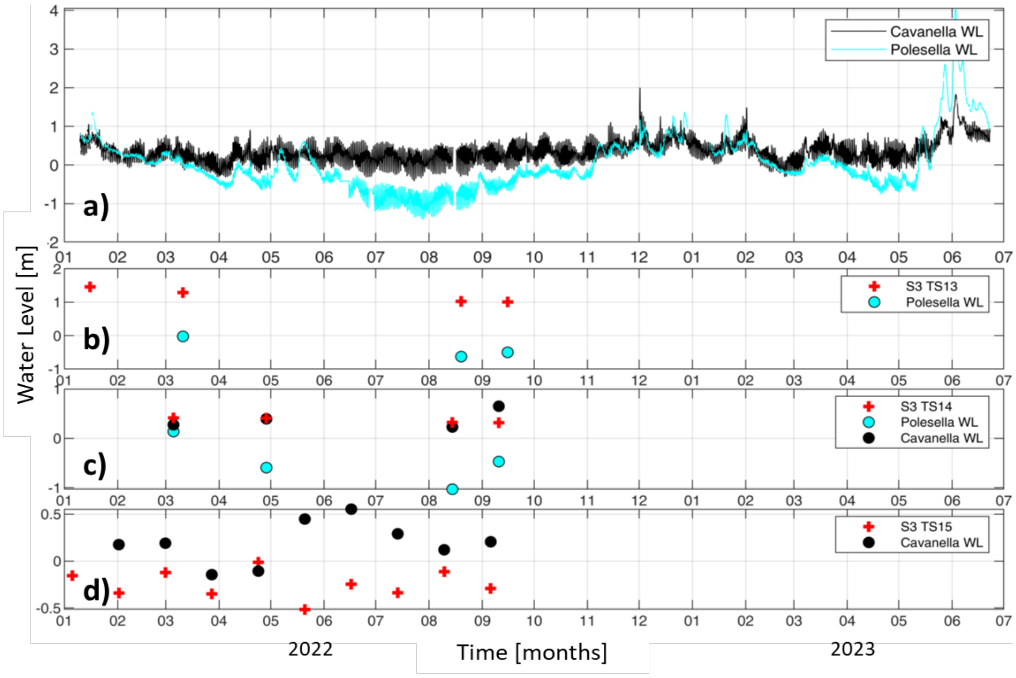

Figure 3.3: Po River - Temporal series of the two ground stations of Polesella and Cavanella along the Po River (a) and their comparison with the satellite time series at the virtual stations 13 (b), 14 (c) and 15 (d).

River and ocean interaction in case of flood and drought events.
This investigation qualitatively shows that extreme hydrological events can be captured also at open sea in this Area of Interest (AOI). The main findings are:

- During flooding events the signature is well reproduced near the river mouth, with formation of water level bulges in correspondence with the river plume.
- Flood events are generally accompanied by higher overall sea level profiles than during normal to drought periods.
- Drought events are characterised by lower overall Sea Level Anomaly (SLA) levels in the AOI.

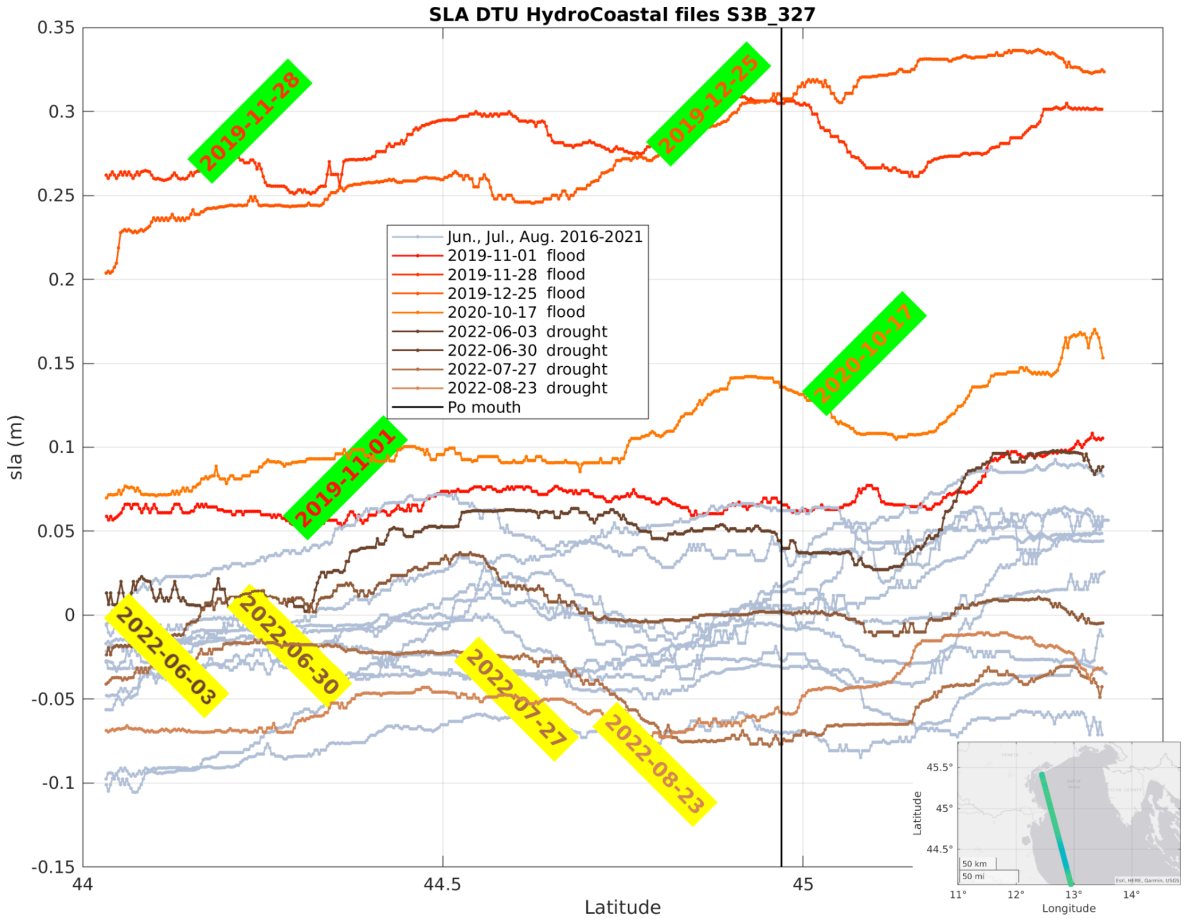

Figure 3.4: Sea level anomaly profiles along the track 327 of Sentinel-3B. Warm colours (green labels) show the SLA profiles during the flood events. Brown colours (yellow labels) mark the SLA profiles during drought events. The grey colour identifies the SLA profiles of the satellite passes in the summer periods of the years 2019-2021.

3.3. Main Recommendations

On the basis of the analysis made in this case study, we suggest the following recommendations:

- Improving revisiting of the radar altimeter as the flooding has some evolution in time (e.g. with constellations of small satellites).
- Improving the number of tracks of the radar altimeter to improve the monitoring of the reservoirs.
- Ensuring the continuity of the product from river to sea (same retracker and same corrections).
- Developing an improved Mean Sea Surface (MSS) to be used in the coastal zone that has to be coherent with the geoid at the land-sea boundary.
- Exploiting the satellite imagery to map the plume at sea (before, during and after the event).
- Using existing ocean current measurements available in the North Adriatic Sea to better characterise the ocean circulation and its variability especially during flooding and drought events.
- Developing a sand-box model to simulate the impact of the flooding and drought extreme events with the aim of providing scenarios to local stakeholders from the integration of river discharge and coastal circulation and facilitate the interpretation of the radar altimetry product.

4. Case Study 3: Lake Size and riverbank configuration study, Republic of Ireland (NUIM)

4.1. Overview of Case Study

In this case study (RD-11) the potential of on-going satellite altimetry missions to contribute to the monitoring of the Irish surface waters of various typologies is investigated. The region represents a substantial challenge for altimetry due to complex lakeshore configuration, small river watersheds and narrow river channels located within a hilly environment. A comparison of HYDROCOASTAL water level (WL) products with other WL satellite products produced from on-going satellite altimetry missions (Jason-2, 3 and Cryosat-2) as well as from different altimetry signal processing algorithms (ESA Sentinel-3 baselines 3 and 4 and Earth Console ESA Altimetry Virtual Lab SARvatore) was performed. The different altimetry products are presented in Table 4.1 below.

Table 4.1 Altimetry Products used in NUIM study.

Mission/product	Period	Repeat cycle, days	Altimeter type	Spatial resolution, m	Retracker used
Jason-2 L2 GDR	2008-2016	10	Pulse limited	315	Ice1
Jason-3 L2 GDR	2016-2020	10	Pulse limited	315	Ice1
Cryosat-2 L2 GDR	2010-2020	369	SAR	~300	NPPT*
Sentinel-3A L2 LAN	2016-2020	27	SAR	300	SAMOSA
Sentinel-3B L2 LAN	2019-2020	27	SAR	300	SAMOSA
Sentinel-3A L2 AVL	2016-2020	27	SAR	80	SAMOSA+
Sentinel-3B L2 AVL	2019-2020	27	SAR	80	SAMOSA+
Sentinel-3A L2 HC	2016-2020	27	SAR	300	DTU MWaPP
Sentinel-3B L2 HC	2019-2020	27	SAR	300	DTU MWapp
Sentinel-3A/3B L3 GlobHC	2019-2020	27	SAR	300	DTU MWaPP

* Narrow Primary Peak Threshold retracker (Villadsen et al., 2016)

A standard validation approach consists of comparison of WL retrievals with WL observations on gauging stations (GS). The validation was undertaken only for virtual stations located on the same waterbody/watercourse within 10 km from a gauging station. The validation was performed in the period 2019-2020 with the summary statistics; correlation coefficient (Rcorr) and Root Mean Square Error (RMSE).

Besides lake and river levels, water level time series from peatlands was also investigated and provided promising results (Figure 4.1).

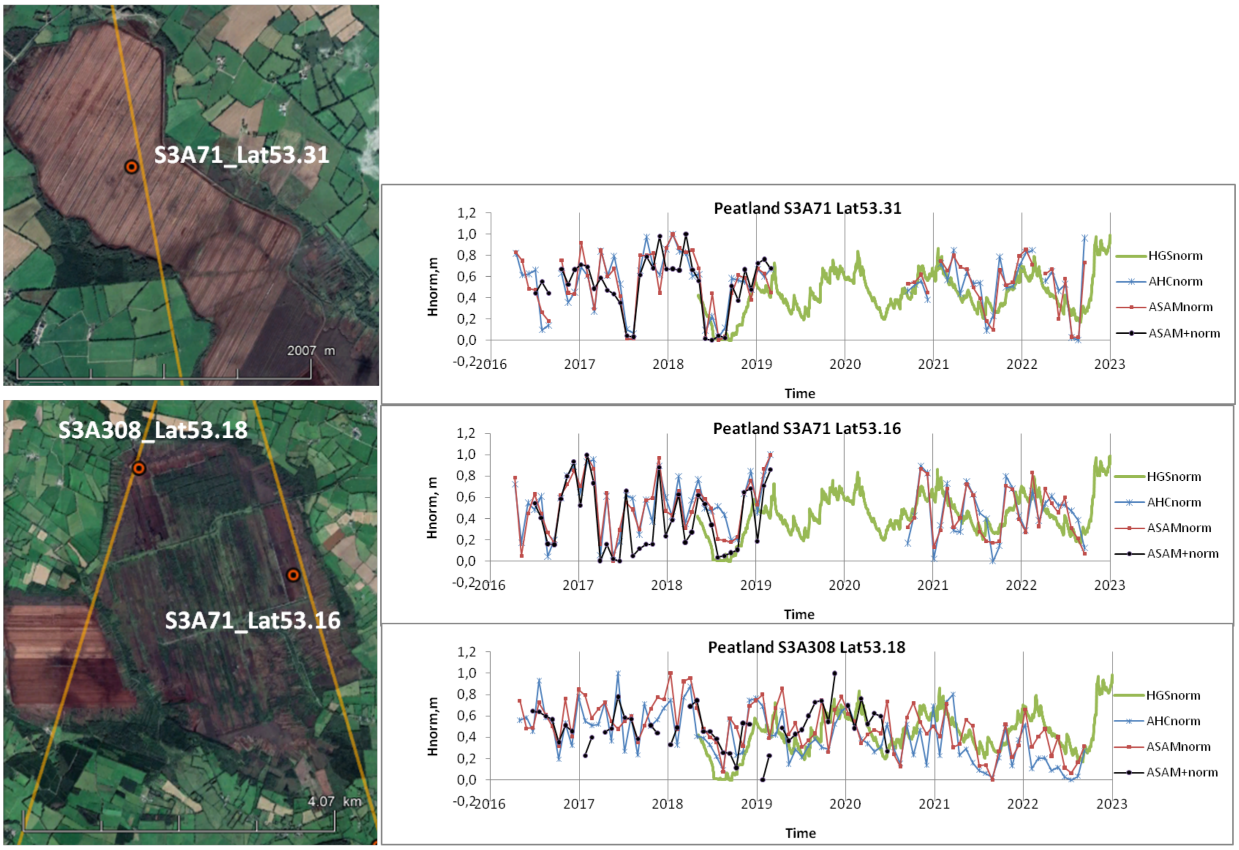

Figure 4.1 Two Sentinel-3A peatland crossovers (a) and variability of the satellite water level retrieved with different L1B processing and retrackers and in situ water level at Scragh Bog (HGS) (b). Water level values are normalised between series' maximum and minimum observed. The acronyms in the legend represent AHC: HYDROCOASTAL L3 water level time series (Sentinel-3A), ASAM: Water level time series based on the SAMOSA2 retracker (Sentinel-3A), and ASAM+: Water level time series based on the SAMOSA+ retracker (Sentinel-3A).

4.2. Main Scientific Findings

1. The HYDROCOASTAL L2 product over small lakes (area between 20 and 115 km^2) and rivers (width < 100 m) of Ireland did not show an improvement in accuracy of water level retrievals from altimetry measurements compared to the official ESA LAND and SARvatore 80Hz L2 products. However, the HYDROCOASTAL L3 product evaluated for three large Irish lakes (area of 50 - 115 km^2) demonstrated significant improvement in accuracy (0.05-0.09 m RMSE) compared L3 products generated from the L2 products listed in Table 4.1. This implies the importance of having a robust method to reconstruct the water level time series as done via the "R"-package "tsHydro" (https://github.com/cavios/tshydro) in the HYDROCOASTAL project.
2. Water Level Time Series data obtained from the HYDROCOASTAL L2 product demonstrated better performance for reproducing water level seasonal and interannual variability over Irish lakes, including small lakes with area from 0.2 km^2 for which we could not evaluate the water level accuracy due to absence of ground stations.
3. HYDROCOASTAL WLTS over lakes and peatlands are coherent with WLTS obtained from the ESA official product with respect to number of gaps. They are slightly better over the rivers, i.e. have fewer gaps.

4. None of the explored factors, such as river and floodplain width and satellite-river cross-angle systematically affected the accuracy of the WLTS retrievals over small rivers, which exhibits little variation from VS series to series. The RMSE medians of different VSs stay within 0.40 - 0.55 m.
5. We evaluated that about 637 km2 of lake area can be monitored by current altimetry missions: Sentinel-3A and 3B and by Sentinel-6 (a successor of the Jason-2 and 3). Additionally to 21 large and medium-size lakes surveyed by ground stations, at 27 small lakes accounting for an additional 47 km2 of water area, the water level seasonal and interannual variability can potentially be monitored for climate change purposes. For operational monitoring of small lakes the temporal frequency of the current missions is insufficient. Moreover, several big Irish lakes stay unmonitored by current satellite altimetry missions.

4.3. Main Recommendations

SAR altimetry, independently of retracker and processing of low level altimetry products, has demonstrated its potential for monitoring small water bodies and water courses of less than 1 km^2 in area and 50 m in width, respectively, located within flat landscapes with slope < 2.5 m/km. These water objects are usually numerous, largely used by local communities but rarely included in the ground monitoring networks.

1. The method used for construction of L3 HYDROCOASTAL product over several large Irish lakes (TsHydro) provided WLTS with better accuracy than the method based on a simple statistical filtering approach. We would recommend adapting and testing this method over smaller water objects.

2. However, the water mask products currently used for elaboration of water level time series (i.e. SWORD) do not contain water objects of such small size. We would recommend a development of specific water mask products based on high resolution optical/SAR images or altimetry-based methods for geographical selection of altimetric measurement over small inland water bodies and courses.

3. SAR altimetry may be a potential contributor to measure the water changes in peatlands and may therefore provide important information to climate modelers as the ground observations of water regime in these inland water objects are scarce. However, little is known about altimetry signal behaviour over peatland surfaces, which, similar to freshwater ice, may have during dry season two reflecting layers: top of porous peat and water table. A dedicated study will be useful.

4. Over small inland water objects SAR altimetry demonstrated good performance in flat landscapes. In hilly areas the cross-track orbit oscillation was critical for construction of meaningful water level time series. A reduction of the satellite orbit cross-track oscillation is important for monitoring small bodies and streams in more complex topography.

5. The current configuration of orbits of altimetry missions (Sentinel-3A, 3B and Sentinel-6) means that many important middle-size Irish lakes are not covered by observations. A densification of orbits of SAR altimeters will allow to enhance the space monitoring of water resources on regional and country scales.

5. Case Study 4: A hydraulic model of the Amur River informed with ICESat-2 elevation (DTU)

5.1. Overview of Case Study

This case study (RD-12) presents a hydraulic modelling workflow for continental-scale rivers, here demonstrated for the Amur River. Availability and quality of river cross-section geometry datasets is a common problem for hydraulic model development at this scale, especially in remote and poorly instrumented rivers, and this study demonstrates that ICESat-2 elevation datasets provide important new information in this context. ICESat-2 elevation datasets allow for the retrieval of reliable effective river cross section geometry and thus enable water surface elevation predictions along entire river courses at continental scale. The workflows developed are applicable at global scale and provide a consistent methodology for the simulation of water surface elevation in global rivers that can be combined with the global inland water record available from satellite altimetry.

To validate the hydraulic model and demonstrate its value for water level prediction, simulated water levels were compared with in-situ station datasets from 12 stations (7 in Russia and 5 in China, see Figure 3.5) and dozens of satellite altimetry water level time series at virtual stations (VS, Figure 3.5). Two products are used for comparison with the simulated water levels 1) 116 virtual station time series from the Hydroweb database (Crétaux et al., 2011, https://hydroweb.theia-land.fr/), and 2) 156 water level time series based on the Hydrocoastal dataset for the Amur River.

5.2. Main Scientific Findings

Using the ICESat-2-derived river cross sections and the parameterization of Manning's roughness coefficient, the hydraulic model was run for the period 2001-2021, using the runoff and tributary flow forcings provided by the rainfall-runoff models and the reservoir/river routing routine. Simulated WSE and discharge is thus available for a 20-year simulation period at any location of interest on the river network.

The Hydrocoastal L3 and Hydroweb VS datasets are equally valuable for the validation of the hydraulic model derived from ICESat-2 elevations. The VS density is somewhat higher in the Hydrocoastal L3 dataset (156) compared to the Hydroweb dataset (116). However, model bias and RMSE are slightly larger in the Hydrocoastal L3 dataset, which could indicate that marginal/low quality VS records are included in the Hydrocoastal L3 dataset, which have been removed from the Hydroweb dataset.

Additionally, simulated rating relationships show two distinct branches, which correspond to the frozen and unfrozen periods of the Amur River with different Manning numbers.

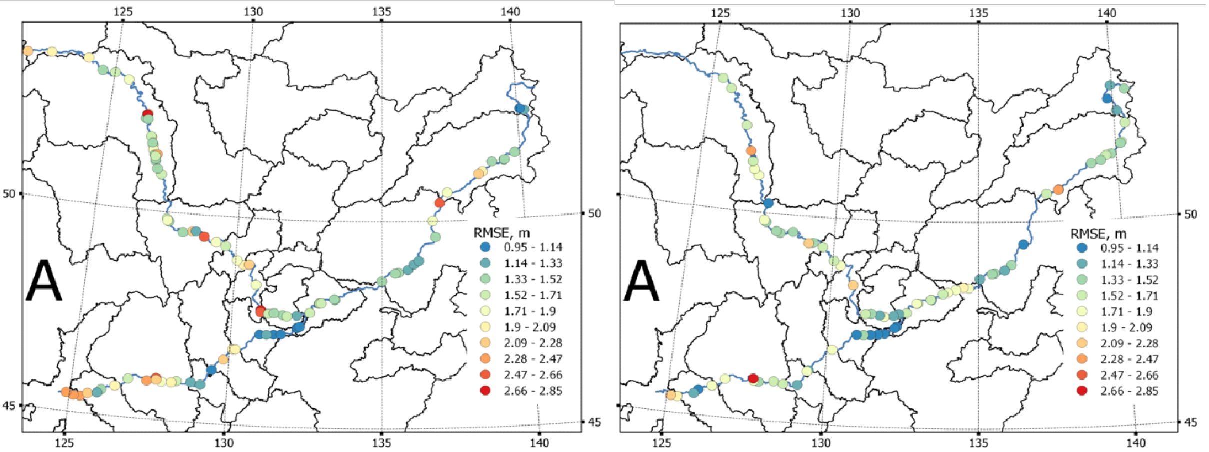

Figure 5.1: Overview of the spatial distribution of WSE RMSE at the different Hydroweb (right) and Hydrocoastal L3 (left) virtual stations.

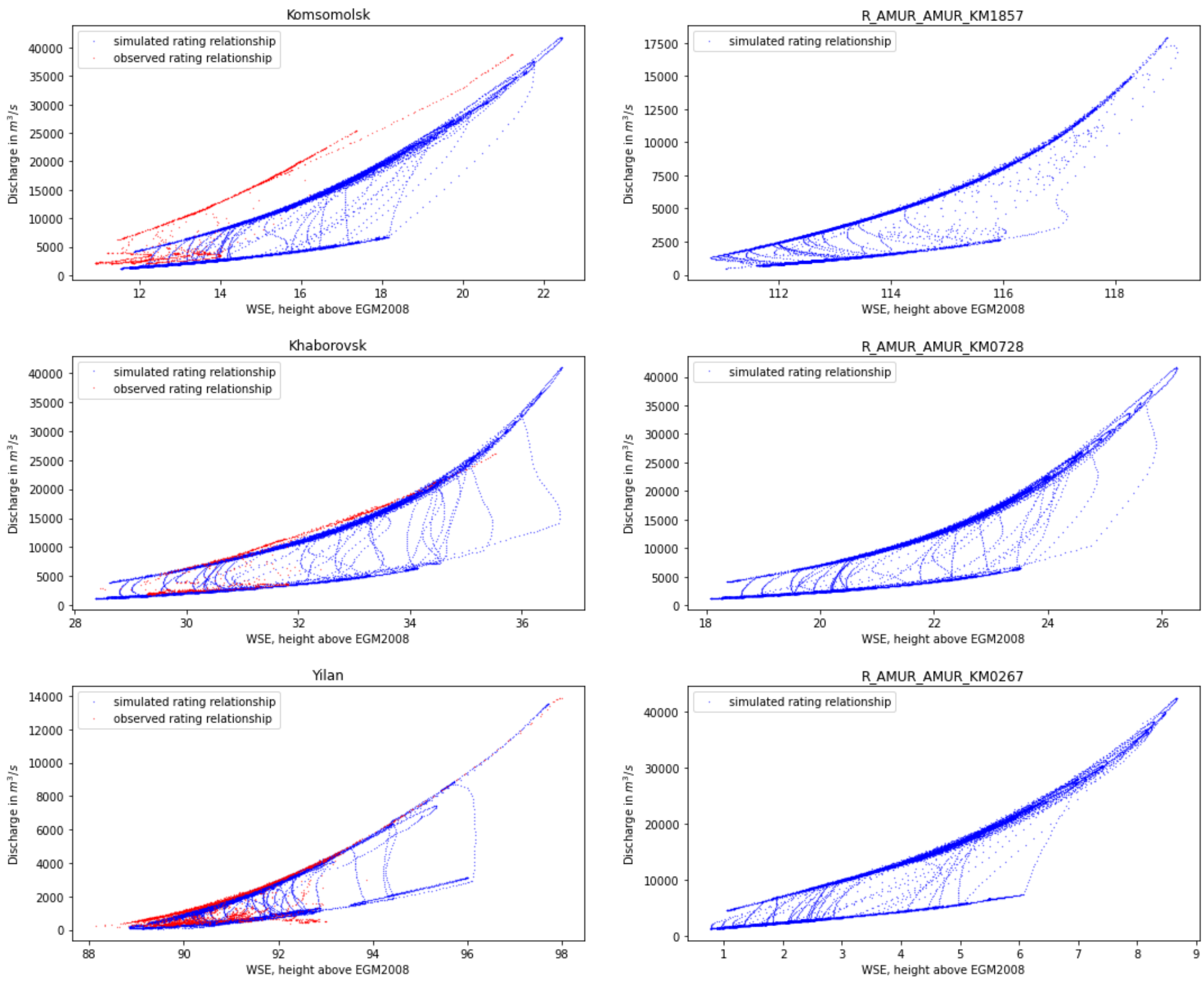

Figure 5.2: Simulated and observed rating relationships at selected in-situ stations (left) and virtual stations (right) on the Amur River

5.3. Main Recommendations

This case study demonstrates a hydraulic modelling workflow, developed here for the Amur, is suitable for global-scale application and provides building blocks for operational, global-scale river water level prediction systems. The model is based on a combination of rainfall-runoff models, ICESat-2 elevation datasets, and satellite-based WSE observations, such as the Hydrocoastal and Hydroweb datasets.

For the Hydrocoastal product to become a competitive alternative to Hydroweb and other existing databases, it is crucial to

1. Ensure periodic near real-time updating of the VS time series.
2. Build an easily accessible GIS-based user interface where users can download geographic and temporal subsets of the dataset in commonly used and easily understandable data formats.
3. Implement automatized quality assurance routines for VS time series to make sure that only time series with sufficient quality (i.e. sufficient accuracy and temporal coverage) are distributed to users.

Regarding the model

1. in view of potential global application of this modelling workflow, we would like to focus on a calibration-free cross section delineation workflow in this study and demonstrate that such a workflow can deliver WSE predictions with satisfactory accuracy.

6. Summary and Conclusions

6.1. Overview of inland water Case Studies

Four Case studies are reported in this document:

1. UBonn has evaluated the quality of the HYDROCOASTAL product against official and other specialized products and gauge data. The evaluation was conducted over the Rhine River and Lake of Constance.
2. CNR-IRPI validated the HYDROCOASTAL discharge product which is primarily based on the approaches from the ESA RIDESAT project. Additionally, the interaction between the Po river outlet and coastal zone was investigated in relation to flood and drought events in 2022. Additionally the influence of river floods and drought was studied from the ocean side.
3. NUIM validated the HYDROCOASTAL products over lakes and rivers in Ireland. Additionally the use of altimetry provided promising results over peatlands.
4. DTU developed a hydraulic model informed with river cross section profiles based on ICESat-2. The model can simulate water level and discharge at any location along the river.

6.2. Major Scientific Findings of Processing Case Studies

Rhine River (UBonn)

- In UFSAR the best results are found using the SAMOSA+ retracker.
- The "binned method" is preferable for the construction of the time-series in lakes.

River discharge / Po river and coastal zone interaction (CNR-IRPI)

- Based on the validation of HYDROCOASTAL river discharge, the approach developed in the ESA RIDESAT project provided the best results.
- In case of drought and flood event a clear signal in the river and coastal zone was detected indicating a substantial exchange of water between these environments.

Ireland lakes, rivers, and peatlands (NUIM)

- HYDROCOASTAL L3 product elaborated for three large Irish lakes (area of 50 - 115 km^2) demonstrated significant improvement in accuracy (0.05-0.09 m RMSE), that implies an importance of rigorous satellite measurements selection and filtering during construction of WLTS.
- Promising results are obtained over peatlands, which demonstrates a new application of satellite altimetry.

Hydraulic model, Amur river (DTU)

- River cross sections from ICESat can be used to inform a hydraulic model.
- HYDROCOASTAL L3 water level time series are of similar quality to the Hydroweb product. The HYDROCOASTAL product provides 50% more time series of which some are of a lower quality when evaluated against the modelled water level.

6.3. Impact Assessment from Processing Case Studies - Summary

A main objective of the Impact Assessment Reports is to summarise the results of the case studies in terms of the impact on scientific and operational applications that the HYDROCOASTAL Final Products can provide.

The Inland water Case studies have all applied the HYDROCOASTAL L2 and L3 product but also used other altimetry products e.g. official products from Sentinel-3 and other missions or especially processed products from the EarthConsole or inhouse product. In the following we summarise the impact of the HYDROCOASTAL products in relation to other altimetry products but also the new scientific applications which are a result of the HYROCOASTAL data and the project in general.

In the projects several inland water relevant retracts were evaluated but the DTU MWaPP retracker was selected for the production of the final global products. The performance is in general good, and it is the only retracker that was used for both inland water and the coastal zone. Being able to apply the same retracker in this transition zone is important for consistency to avoid an elevation bias.

When compared to other altimetry products and gauge data the quality of the MWaPP retracker was in the high to medium performance range depending on the specific study (as demonstrated by NUIM and CNR IRPI). The UBonn case study showed that the use of FFSAR may provide improved results, but simply increasing the resolution of unfocused SAR to 80Hz could also lead to improved results.

Another result that was gained from the project is the role of generating time series and critical data and result filtering. UBonn demonstrated that for lakes one simple virtual station time series may not be ideal, whereas a better solution is to generate several time series along the tracks representing the virtual station. NUIM demonstrated that the HYDROCOASTAL approach to generate time series improved the RMSE by several cms compared to the simpler approach also used in the case study. In the case study regarding the Amur river, DTU showed that the HYDROCOASTAL L3 product is of similar quality as the HydroWeb products. The HYDROCOASTAL product provided approximately 50% more virtual stations but some were of reduced quality, indicating that a more critical quality assurance is necessary.

River discharge was produced on the basis of the L3 water level time series via rating curve approach and the RIDESAT algorithm (CNR-IRPI). Rating curves were produced based on altimetry and reflectance indices obtained from imagery. From the study by CNR-IRPI it was demonstrated that the RIDESAT algorithm outperformed the other methods. This study further highlighted the necessity of an increased temporal resolution of altimetry to improve discharge and the issues of spectral data loss in tropical and arctic areas due to cloud cover.

The HYDROCOASTAL project has fostered several new scientific applications of altimetry. NUIM demonstrated with promising results that altimetry (here the HYDROCOASTAL product) can be used to monitor water level change in peatlands. CNR-IRPI showed that the HYDROCOASTAL products (L3 and L4) were able to map the extreme 2022 drought event of the Po River. The study further showed that the intrusion of seawater could be detected in the downstream part of the river. Additionally, the HYDROCOASTAL L2 (MWaPP) sea levels could detect both floods and droughts near the mouth of the Po River. DTU developed a hydrodynamic model which is informed by ICESat-2 based river cross sections. The benefit of such a model is that it will allow the prediction of water level and discharge along the river reached included in the model.

In summary the HYDROCOASTAL project has fostered many new products and scientific results that will be a stepping stone for several new products and studies.

6.4. Main Recommendations from Inland water Case Studies

Based on the work done in the project the following recommendations are formalized

- For smaller targets it would be beneficial to increase the resolution to 80Hz for unfocused SAR and to apply the FFSAR technique to increase the along-track resolution (UBonn).
- A reduction of cross-track orbit variability is important for small targets located in areas of more complex topography (NUIM).
- Ensure consistency of the river and sea level by having a common retracker such as the MWaPP retracker. In addition, a consistent reference surface in this zone is equally important (CNR-IRPI).
- Developing a sand-box model to simulate the impact of the flooding and drought extreme events with the aim of providing scenarios to local stakeholders from the integration of river discharge and coastal circulation and facilitate the interpretation of the radar altimetry product (CNR-IRPI)
- To improve discharge estimation and the study of extreme events it is critical to improve the temporal resolutions of altimetry (e.g. with constellations of small satellites) (CNR-IRPI).
- Investigate combination of multi-mission 1D and 2D altimetry to improve temporal and spatial coverage (UBonn)
- Expand the use of satellite altimetry, one example could be over peatlands, which are important sources of carbon dioxide (NUIM).
- Satellite missions with a high across track resolutions (as CryoSat-2) is important for hydrology to better map the river profile and to ensure that more lakes are mapped, which is the case for Sentinel-3 (as demonstrated with the Irish lakes).
- The methodology to generate time series from L2 water levels may influence the results and should be further investigated (UBonn, NUIM, DTU)
- To ensure the value of products such as HYDROCOASTAL, a strategy for continuation and easy access via a web interface is important (DTU).
- A strict quality assessment is important before public release (DTU).
- In view of a potential global application of the hydrodynamic workflow a focus on a calibration-free cross section delineation workflow is important (DTU).

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Acronyms

AD	Applicable Document
AOI	Area Of Interest
AVL	Altimeter Virtual Laboratory
CNR-IRPI	Consiglio Nazionale delle Ricerche – Istituto di Ricerca per la Protezione Idrogeologica
CS2	CryoSat-2
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
ECMWF	European Centre for Medium Range Weather Forecasting
ESA	European Space Agency
EO	Earth Observation
FFSAR	Fully Focused SAR
GDR	Geophysical Data Record
GlobHC	Global Hydrocoastal Product
GS	Guaging Stations
HC	HydroCoastal
L2 LAN	Level 2 Land Product
MSS	Mean Sea Surface
MWaPP	Multiple Waveform Persistent Peak. DTU developed SAR altimeter retracker for inland water.
NIR	Near InfraRed
NPPT	Narrow Primary Peak Retracker
NRMSE	Normalised Root Mean Square Error
NSE	Nash-Sutcliffe Efficiency
NUIM	National University of Ireland Maynooth
R	Pearson Correlation
Rcorr	Correlation Coefficient
RD	Reference Document
RG	Real Gauge
RIDESAT	ESA Project onriver flow monitoring and discharge estimation (http://hydrology.irpi.cnr.it/projects/ridesat/)
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SARin	Synthetic Aperture Radar – Interferometric operation.
SAMOSA	SAR altimeter retracker
SAMOSA+	Development of SAMOSA retracker for the coastal zone
SAMP	Samosa plus
SARVatore	SAR Versatile Altimetric TOolkit for Research and Exploitation
SD	Standard Deviation
SLA	Sea Level Anomaly

STDD	Standard Deviation of Differences
SWOT	Surface Water and Ocean Topography – A satellite altimeter operated by NASA and CNES, launched in December 2022.
S3	Sentinel-3
S3A	Sentinel-3A
S3B	Sentinel-3B
SWORD	River data base developed for the SWOT Satellite mission (http://gaia.geosci.unc.edu/SWORD/)
TSHydro	Software package (written in “R”) developed by DTU to estimate water level time series from altimeter data.
UFSAR	Unfocused SAR
UBonn	University of Bonn
UPorto	University of Porto
VG	Virtual Gauge
VS	Virtual Station
WL	Water Level
WLTS	Water Level Time Series
WSE	Water Surface Elevation