HYDROCOASTAL

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

Lake Size and river bank configuration study. Case of Republic of Ireland

Deliverable D3.2

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

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1. INTRODUCTION

In Ireland, lakes play an important role in the economy. Lake waters are used for water supply of the big cities (Dublin, Galway, etc.), for energy production, for flood control, and for fisheries and recreation. In the North, several big regulated lakes lay on the Ireland/UK border and are subject to transboundary regulations. The last 40 years have been unusual for Ireland climate due to the absence of persistent drought events, which have occurred frequently over the last two centuries. However, the changing global climate results in increasing frequency of extreme hydro-meteorological events (including droughts) and the year 2018 demonstrated the vulnerability of the national water resources to drought. In summer 2018 the domestic water use in Dublin and many other areas was subjected to restrictions. In these conditions, the shrinkage of the in-situ hydrological observational network observed since 2006 may leave critical gaps reducing adaptation potential.

In this case study 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.

2. DATA

For Sentinel-3 and Jason-2,3 water level time series were retrieved over lakes, ponds, rivers and peatlands. About 80 Landsat based water masks were manually created at cross-sections of satellite tracks and water bodies and water courses. Obtained water level time series (WLTS) were examined for: 1) their accuracy (standard validation protocol against in situ observations in areas close to gauging stations); and 2) for their ability to reproduce the water regime (seasonality and interannual changes) for gauged and ungauged river reaches, lakes and peatlands.

Missions and products used for production of WLTS from L2 altimetry products are shown in Table 1. Nine WL datasets were assessed:

1) combined Jason-2/Jason-2 (**J23**);

2 and 3) Sentinel-3A and 3B WLTS based on GDR LAN product retrived from Ocean or SAMOSA2 retracker (**ASAM** and **BSAM**, respectively) ;

4 and 5) Sentinel-3A and 3B WLTS based on SARvatore processor (**ASAM+** and **BSAM+**); parameterisation of SARvatore processing is shown in Table 2.

6) combined Cryosat-2 and Sentinel-3A_LAN and Sentinel-3B_LAN WLTS for 19 big lakes

(**CS2**) created by DTU Space and based on official ESA L2 products;

7 and 8) Sentinel-3A and Sentinel-3B WLTS based on HYDROCOASTAL L2 product (**AHC** and **BHC**, respectively);

9) combined Sentinel-3A/3B HYDROCOASTAL L3 WLTS derived from HYDROCOASTAL L2 product and global SWORD water masks (**GlobHC**).

Table 1. Altimeter missions used and their characteristics

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
Sentinel-3B L2 HC	2019-2020	27	SAR	300	DTU
Sentinel-3A/3B L3 GlobHC	2019-2020	27	SAR	300	DTU

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

Table 2. Configuration parameters used in SARvatore processor.

Parameter	Value	Parameter	Value
L1B		L2	
Data posting rate	80 Hz	Processing for specific surface	No
Hamming Weighting Window	yes	PTR width alphap parameter	LUT
Exact Beam-Forming	Approximated	SAMOSA model	SAMOSA+
FFT Zero-Padding	yes	Single- Multi-look Model	Multi-look
Radar Receiving Window size	128x2		
Stack subset	180		

3. VALIDATION RESULTS

3.1. ACCURACY OF THE LAKE AND RIVER WATER LEVEL PRODUCTS

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 distance from a gauging station. To ensure consistency of results the validation was performed for the common period of observations framed by Sentinel-3B and SARvatore WLTS, i.e. 2019-2020. Two main statistics are used : correlation coefficient (Rcorr) and Root Means Square Error (RMSE). Results of the validation are presented in Figure 1.

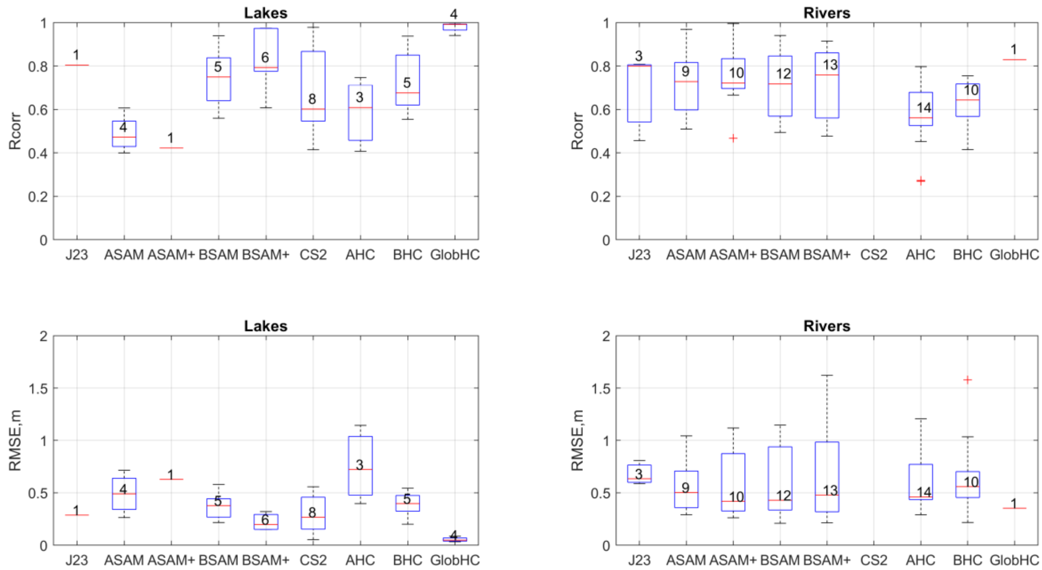


Figure1. Correlation coefficient (Rcorr) and RMSE between in situ observations and satellite WLTS retrieved from different missions and different products. The number of VS available for assessment is provided within boxes.

Based on these evaluation criteria for **lakes** the WLTS can be ranked in following order:

Lakes :
GlobHC > BSAM+ > BSAM > CS2 > **BHC** > ASAM > **AHC** *(by RMSE).*

However, the assessment for the Jason (J23) and Sentinel-3A (ASAM+) WLTS over lakes should be taken with caution as they are based only on one water body. Other comparisons have substantially more comparators available and may be more robust as a result.

For **rivers** the WLTS derived from HYDROCOASTAL L2 product expressed lower correlation with the in situ WL measurements than WLTS derived from ESA L2 LAN and SARvatore L2 products. Nevertheless, the accuracy of the HYDROCOASTAL WLTS was comparable with that of other WL datasets used. The datasets ranking based on medians of RMSE is as follows:

Rivers:
ASAM+ > BSAM > BSAM+ > **AHC >** ASAM > **BHC** > J23.

The assessment of **GlobHC** dataset is based only on one WLTS, and thus is not considered rigorous and was not included in the ranking.

3.2. ASSESSMENT OF REPRESENTATIVENESS OF WATER LEVEL PRODUCTS OVER LAKES, RIVERS AND PEATLANDS

The ability of different altimetry WL datasets to reproduce the water regime, i.e. seasonality and interannual water level changes, was evaluated for a larger set of virtual stations and included for gauged and ungauged river reaches, lakes and peatlands. In the temperate maritime climate conditions of Ireland the amount of liquid precipitation is assumed to be a principle factor affecting lake and river water regime. Based upon this assumption the correlation between altimetric WLTS and amount of precipitation recorded for the nearest meteorological station was calculated. The criterion <10 km distance between VS and meteorological station was also applied for selection of hydrological-meteorological stations pairs (Figure 2a). WLTS expressed significant correlation with precipitation (p-value <0.05) were considered meaningful. The following ranking of a dataset's ability to adequately represent seasonal and interannual variability of water regime impacts is observed:

Lakes :
GlobHC ≈ BHC > BSAM+ > BSAM > CS2/AOCOG > **AHC** > ASAM ≈ ASAM+ ≈ J23

Rivers :
BHC > BSAM > BSAM+ > ASAM+> ASAM > **AHC >** J23

Peatlands :
BSAM ≈ BSAM+ > ASAM+ ≈ ASAM > **AHC** > J23

The WL datasets with only one virtual station were not included in the assessment for each type.

3.3. ASSESEMENT OF DATA LOSS RATE

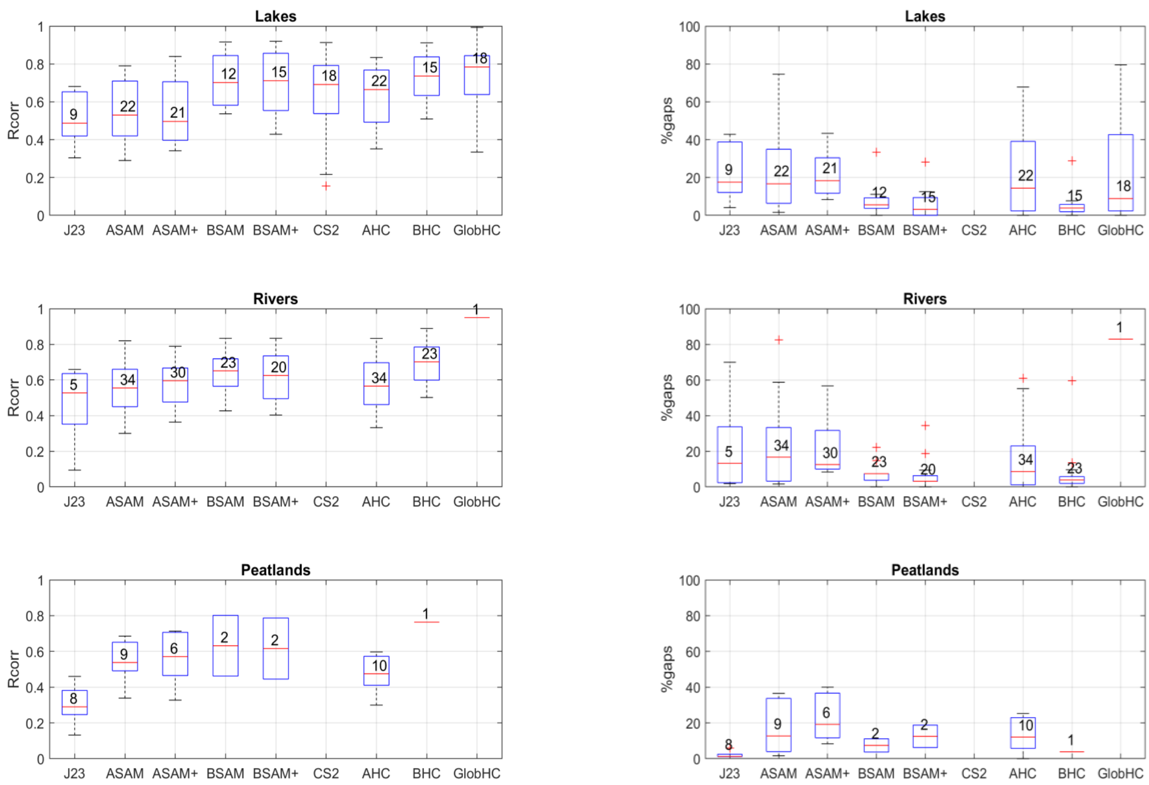
One of the criterion of the quality of observations is a low number of records' gaps. The ratio of satellite overpasses, which did not produce valid water level retrievals to the total number of satellite overpasses for considered period of observations (Table1), named data loss rate (DLR), was used as an additional criterion for WLTS quality assessment (Figure 2b). The data loss rate was calculated for all meaningful Jason-2,3 and Sentinel-3A and 3B time series, i.e. time series expressed the significant correlation with precipitation. According to this criterion the datasets can be ranked as follow:

Lakes:
BHC > BSAM+ > BSAM > **GlobHC** > **AHC** > ASAM≈ASAM+ > J23

Rivers:
BSAM+ ≈ **BHC** > **AHC** > J23 ≈ ASAM+ > ASAM

Peatlands:
J23 > BSAM > BSAM+ > **AHC** > ASAM > ASAM+

Here, again, the WL datasets with only one virtual station were not included in the assessment.



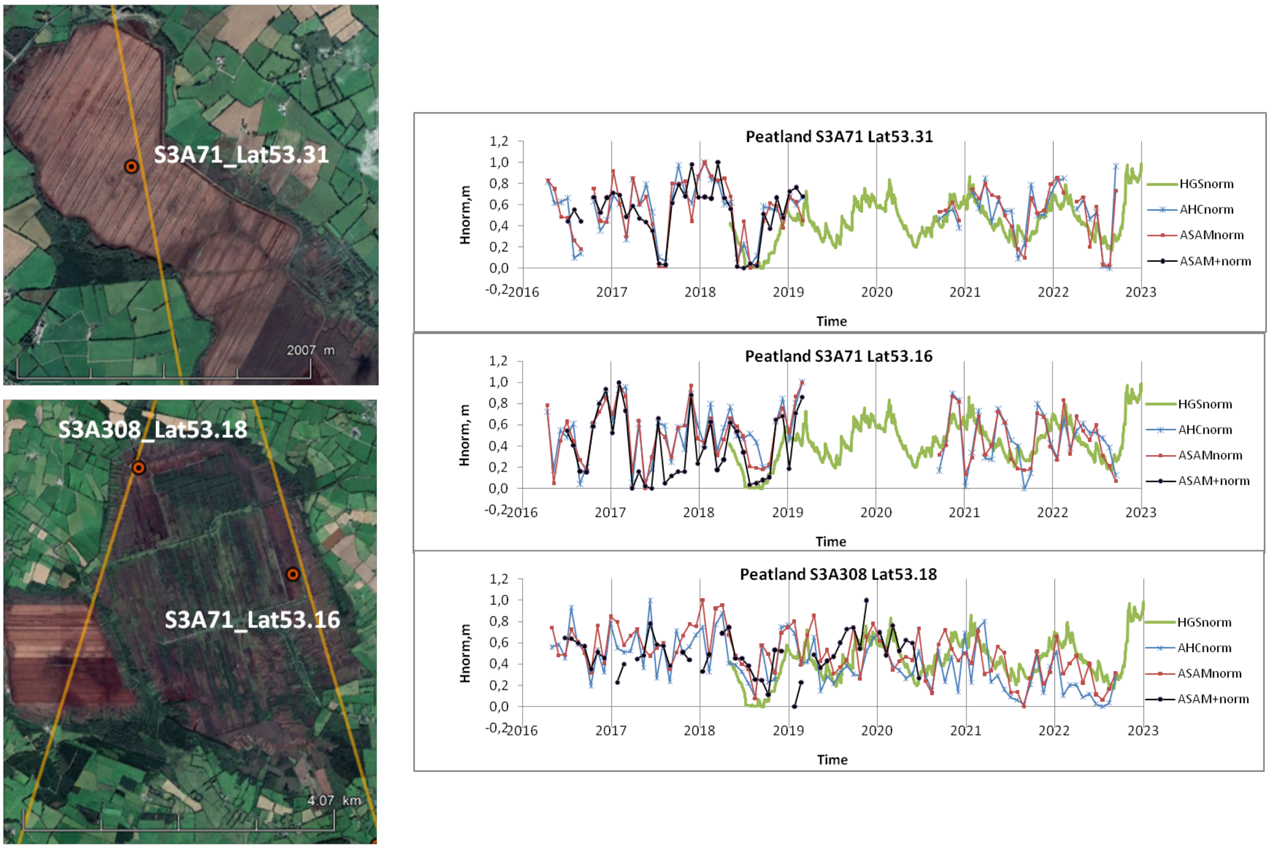
a) b)

Figure 2. Correlation coefficient (Rcorr) between precipitation and satellite WL datasets (a) and percentage of gaps in WLTS (b). The number of VS used is provided within boxes.

4. NEW APPLICATION FOR INLAND WATER ALTIMETRY

Results showing altimetry potential to measure changes in peatlands which may be related to peatland water table movements are intriguing. Peatlands represent potentially millenial scale carbon storage. Efficacy of storage depends upon the health of the peatland which is directly related to the stability of the water regime in the peatlands. If altimetry can systematically monitor remotely the health of peat bogs then this has significant potential to improve our monitoring of LULUCF (Land Use, Land-use Change and Forestry) net emissions changes. Specifically, altimetry may be a useful tool in verifying the efficacy of peat and restoration efforts in disturbed peatland environments which ESA members may use in national inventories as we drive towards net zero GHG emissions. In Ireland the water regime is monitored since 2018 only in one small Scragh Bog (of 2 km x 0.2 km size) located in the central part of the island and belonging to the Shannon River watershed. According to *in situ* records, the water regime in bog has distinct seasonal variability with the seasonal water level magnitude of 0.6 m. Despite of the accuracy often comparable with the seasonal magnitude of water table in bogs, the Sentinel-3 peatland WLTS showed a clear seasonality and sensitivity to the extreme climate events. Figure 3 demonstrates configuration of Sentinel 3A virtual stations over two peatlands located in 20 and 35 km from the Scragh Bog as well as comparison of HYDROCOASTAL, SAM and SAM+ water level changes over these peatlands. The 1.5 year gap in satellite observations at the track S3A_71 is related to onboard DEM change issue. Even if the direct validation of the peatland WLTS was not possible, one can see a good coherence of satellite and *in situ* WL variability at the VS S3A71_Lat53.31 during 2021-2022. Many intermediate peaks in the satellite WLTS which differ in their height also agree well with the peaks in the *in situ* observations. The extreme drought that hit Ireland in summer 2018 is well distinguished in all satellite time series over the peatlands.

Over peatlands the meaningful WLTS (i.e. WLTS demonstrated significant correlation with atmospheric precipitation) were obtained only in landscapes with flat relief. In hilly areas a noise in WLTS due to steep cross-track topography hides the seasonal signal. In this context, a reduction of cross-track variability of mission's orbit could be beneficial.



a) b)

Figure 3. 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.

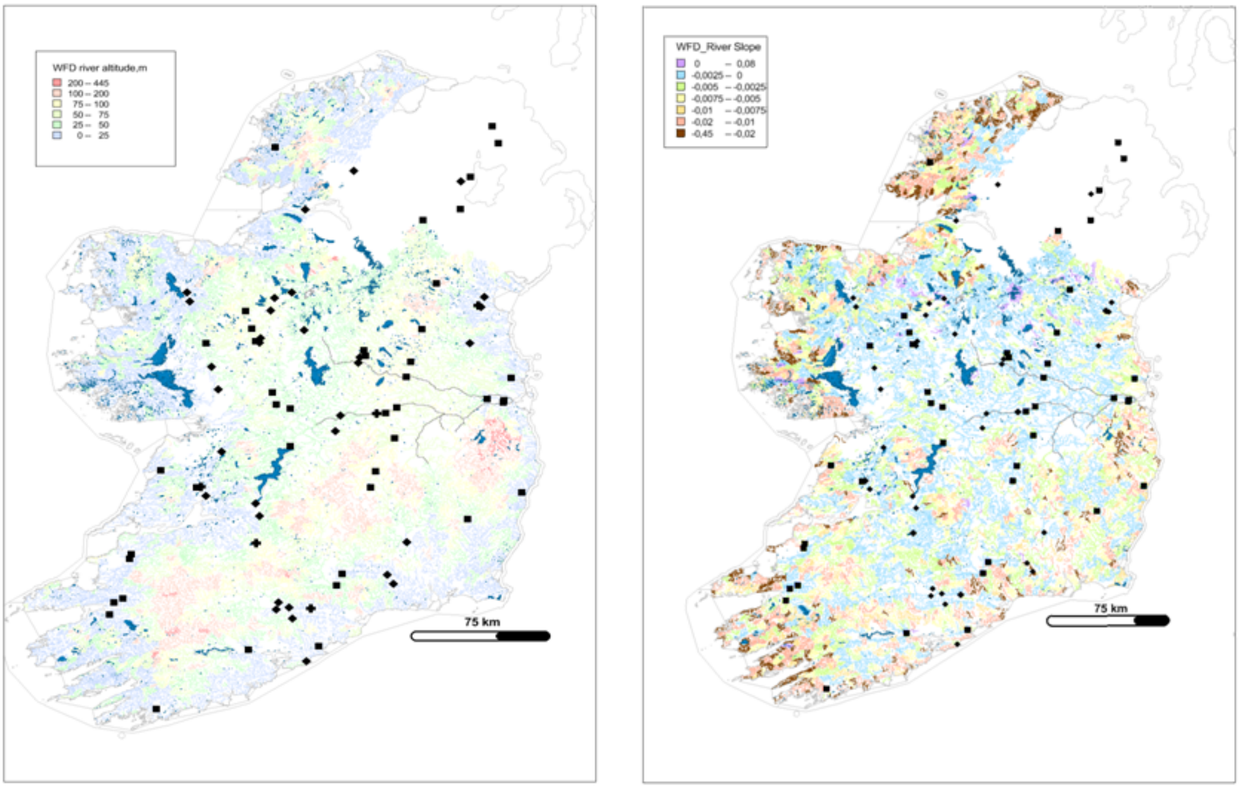
5. EFFECT OF ENVIRONEMENTAL FACTORS ON ACCURACY OF THE WLTS FOR IRELAND

5.1. TOPOGRAPHIC EFFECTS

To assess the effect of the environmental factors on the water level retrievals, the location of the **river** VS with meaningful WLTS was plotted on an topographic map (Figure 4a) and on a map showing the river slope (Figure 4b). We noted that in hilly areas with elevation >200 m a.m.s.l, there were no VS with meaningful WL retrievals. As the river slope is a product of the terrain topography, the adequate WL retrievals were obtained for river segments with gentle slope, mostly below 2.5 m/km (in rare cases below 5 m/km). Considering almost 2 km cross-track oscillation of the Sentinel-3 orbits, the WL local variability due to topography in steeper river segments becomes critical and for small rivers may hide the seasonal WL signal. For small rivers with slope higher than 2.5 m/km and seasonal water level magnitude of 2-3 m an application of slope correction during WLTS construction could be beneficial as well.

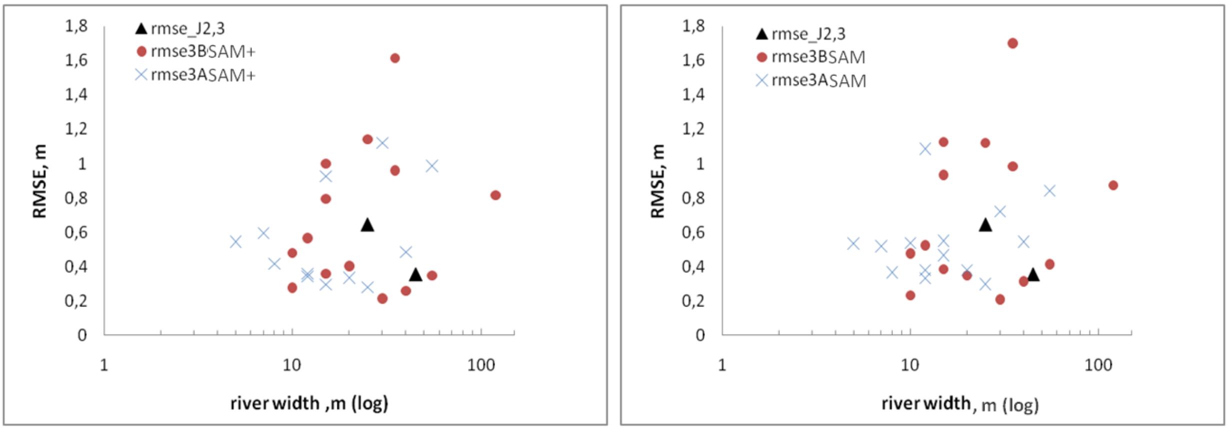
5.2. EFFECT OF CONFIGURATION OF VIRTUAL STATIONS

Orientation of the altimeter ground track to the river channel orientation can potentially affect the estimation of the water level from satellite measurements. For this case study for virtual stations where traditional validation was made (i.e. RMSE was evaluated) the angle between satellite track and river channel as well as the width of the channel and adjacent floodplain at the cross-section were evaluated. Figure 5 demonstrates that **for small rivers** there is no distinct effect of the river width on the accuracy of the water level retrievals. Similar, the high dispersion of the points was observed on the "RMSE - angle" scatter plots (Figure 6). Additional criteria such as channel width, floodplain width at track-channel cross-section and VS distance to gauging stations used for RMSE calculation were examined. None of the parameters expressed clear effect on the WLTS accuracy. One can expect that at parallel orientation of the satellite track and river channel (0° angle) the accuracy may decrease as a part of the measurements comes from the land due to ± 1 km cross-track satellite orbit oscillation. However, among three VSs with parallel track orientation, one (for SAM+ dataset) and two (for SAM dataset) WLTS demonstrated RMSE comparable with the median values obtained for Irish small rivers, i.e. 0.40-0.55 m (see Figure 1).



a) b)

Figure 4. Mean elevation of river reaches (a) and rive slope (b) and location of river virtual stations with meaningful retrievals of WL (J2,3 - crosses, S3A-sqaures, S3B- lozenges).



a) b)

Figure 5. Relation between river width and RMSE estimated for WL derived from Jason-2 and 3 and Sentinel-3 a) enhanced SARvatore processing with SAMOSA+ retracker (SAM+) and b) standard GRD ESA L2 LAN product with SAMOSA retracker (SAM).

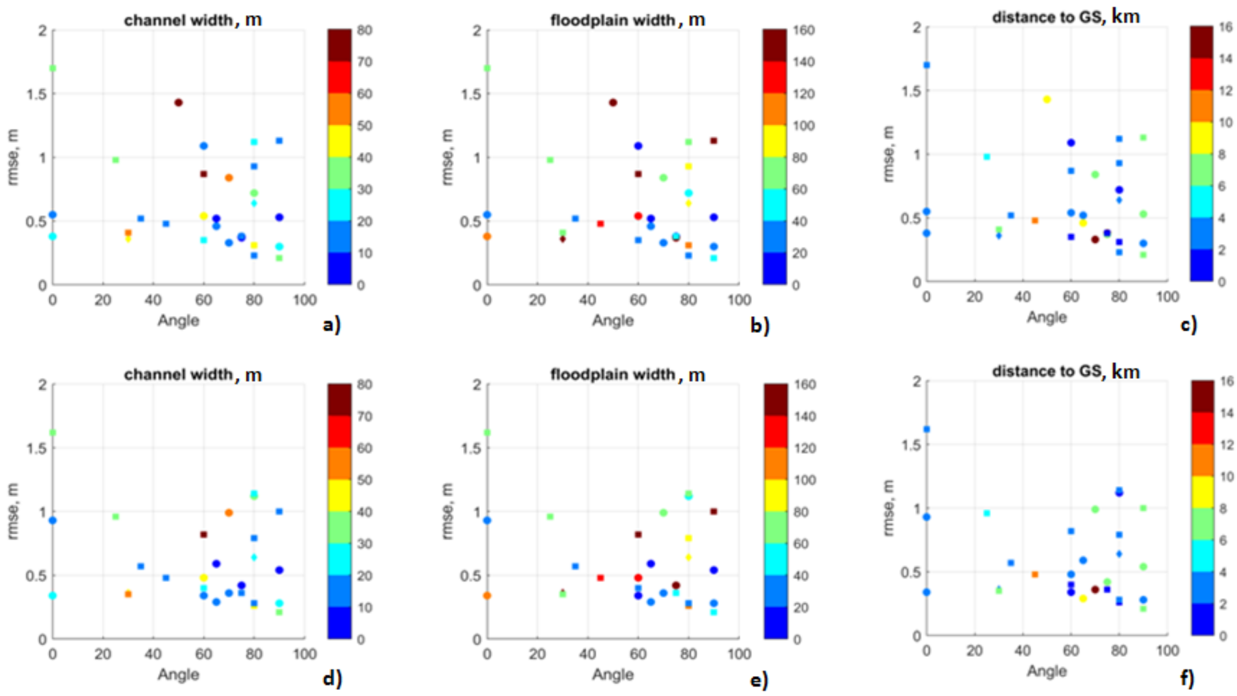


Figure 6. Relation between river channel-satellite cross-section angle (in degree) and RMSE estimated for WL derived from Jason-2 and 3 (lozenges) and Sentinel-3A (circles) and Sentinel-3B(squares) from standard GRD ESA L2 LAN product with SAMOSA retracker (a, b, c) and from enhanced SARvatore processing with SAMOSA+ retracker (d, e, f). The markers are coloured according to channel and floodplain width (in m) and distance between virtual and gauging stations (in km).

6. CONCLUSION

1. HYDROCOASTAL L2 product over small lakes (area between 20 and 115 km2) and rivers (width < 100 m) of the Ireland did not expresse an improvment **in accuracy** of water level retrievals from altimtery measurements compared to official ESA LAN and SARvatore 80Hz L2 products. However, HYDROCOASTAL L3 product elaborated for three large Irish lakes (area of 50 - 115 km^2) demonstrated significant improvment in accuracy (0.05-0.09 m of RMSE), that implies an importance of rigorous satellite measurements selection and filtering during construction of WLTS.

2. WLTS obtained from 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 the we could not evaluate the WL accuracy due to absence of ground stations.

3. HYDROCOASTAL WLTS over lakes and peatlands are cohherent with WLTS obtained from ESA official product with respect to number of gaps. They are slightely better over the rivers, i.e. have less number of 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 km^2 of lake area can be monitored by current altimetry missions : Sentinel-3A and 3B and by Sentinel-6 (a sucssessor 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 km^2 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 uncovered by current satellite altimetry missions.

7. RECOMMENDATIONS.

SAR altimetry, independently on retracker and processing of low level altimetry products, 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 big Irish lakes (TsHydro) provided WLTS with better accuracy than the method based on simple statistical filtering approach. We would recommend to adapt and test 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. Demonstrated by SAR altimetry potential to measure water changes in peatlands may be important for climate modelers as the ground observations of water regime in these inland water objects are scarce. However, little known about altimetry signal behavior 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 helpful.

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. At current configuration of orbits of altimetry missions (Sentinel-3A, 3B and Sentinel-6) 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.

8. REFERENCES

Villadsen, H., Andersen, O.B., Stenseng, L., Nielsen, K. and Knudsen, P., 2015. CryoSat-2 altimetry for river level monitoring—Evaluation in the Ganges–Brahmaputra River basin. Remote Sensing of Environment, 168, pp.80-89.