# D7.3: New LOTUS products and their potential use in value adding applications

Author list

| Author | Affiliation |
|---|---|
| Henrik Madsen | DHI, Denmark |
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Acronyms

**DEM** Digital elevation model

**LRM** Low resolution mode

**RMSE** Root mean square error

**SAR** Synthetic aperture radar

**SLA** Sea Level Anomaly

**SRTM** Shuttle Radar Topography Mission

**Virtual station** Crossing between the satellite ground track and a river

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# 2 Executive summary

This report has been prepared as part of the project 'Preparing Land and Ocean Take Up from Sentinel-3 (LOTUS)' Work Package 7 'Dissemination and exploitation', Deliverable 7.3. The report provides a summary and assessment of the developments of value adding services and products in the LOTUS project as well as recommendations for further development. The following value adding services have been developed and assessed as part of the LOTUS project:

Value adding services for ocean:

- Wave and wind design data
- Characterization of coastal scale hydrodynamics
- Data assimilation in coastal-ocean models

Value adding services for land

- River model calibration
- Data assimilation in hydrological-hydrodynamic models

In general, high-resolution SAR altimetry data has shown important value for both ocean and land applications. Especially, the combination of SAR data with numerical modelling has large potential for improving the estimation and forecasting of ocean and land systems. However, further research is required before more firm and general conclusions can be drawn regarding the value of SAR data for some of the applications considered. The value of altimetry data is expected to increase with enhanced spatio-temporal resolution from the combination of multiple satellite missions.

# 3 Introduction

The LOTUS project has developed a number of new Level-2 products derived from Cryosat-2 SAR-mode data of relevance for ocean and land applications. The Deliverable 7.2 report provides an overview and summary description of the different products together with an assessment and recommendation of each product. This document provides a summary and assessment of the LOTUS developments of value adding services based on the new Level-2 products together with recommendations for further developments.

# 4 Value adding applications for ocean

## 4.1 Wave and wind design data

Detailed descriptions of methodologies developed and results obtained can be found in the Deliverable 5.1 report 'Improved wave and wind design data'.

### 4.1.1 Level-2 product used

Processed Level-2 altimeter data for the North East Atlantic from CryoSat-2 provided by CLS were used, including 1 and 20Hz resolution data. For comparison, low-resolution mode (LRM) altimeter data from Jason-2 provided by DHI were applied.

### 4.1.2 Value adding service

Two examples of value-adding services and products have been developed and evaluated. They include

- Fast assessment of wave and wind conditions (a stand-alone product)
- Spatial validation of wave and wind model data (a derivative product)

The purpose of providing fast assessments of wave and wind conditions is mainly to support early stages of development and design estimates, in particular for remote coastal areas with limited other sources of information. This may supplement other initial assessments e.g. for planning and design of offshore wind farms, oil/gas platforms or marine infrastructure projects. A fast assessment of wave and wind conditions based on SAR data alone may e.g. include time series, histograms and overall statistics (see examples in Figure 1).

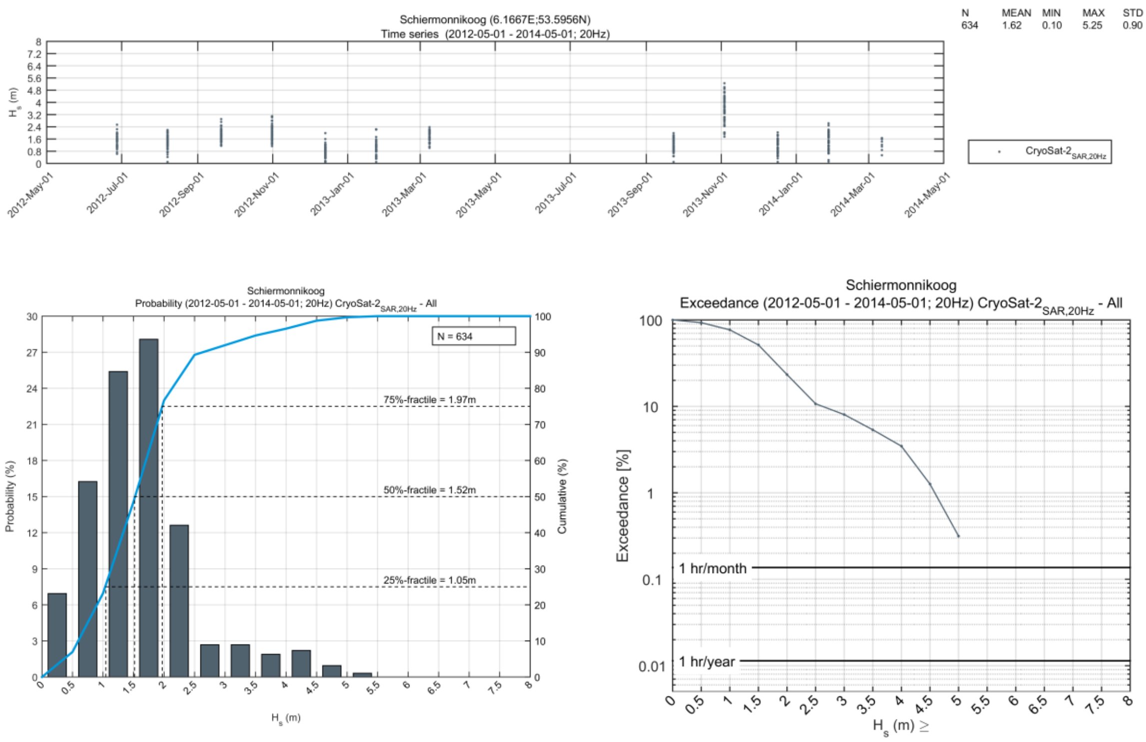


Figure 1: Time series (top), histogram (bottom left) and exceedance distribution (bottom right) of CryoSat-2 SAR derived significant wave height at Schiermonnikoog (10km off the Dutch coast).

The purpose of validating numerical models is mainly to increase the confidence in model data (reducing the uncertainty) and to indicate options for improved model calibration (and hence improved accuracy). In model validation, modelled and altimeter-derived data are compared using different statistical measures. Examples of comparison of modelled and altimeter-derived significant wave height and wind speed data are shown in Figure 2 - Figure 3.

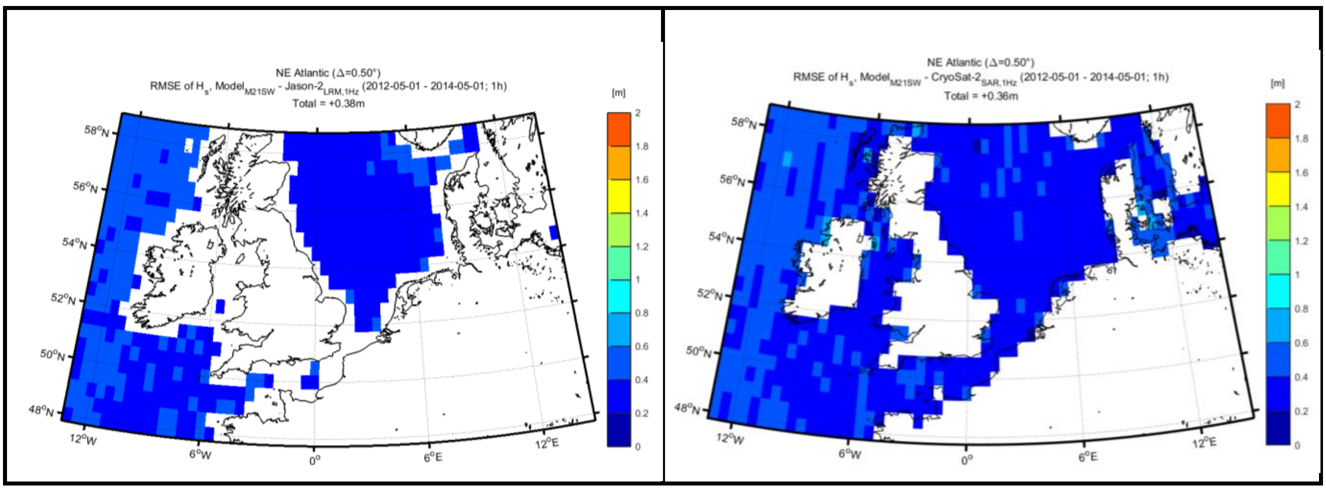


Figure 2: RMSE of significant wave height between model and altimeter data. Left: Jason-2 (LRM, 1Hz), Right: CryoSat-2 (SAR, 1Hz).

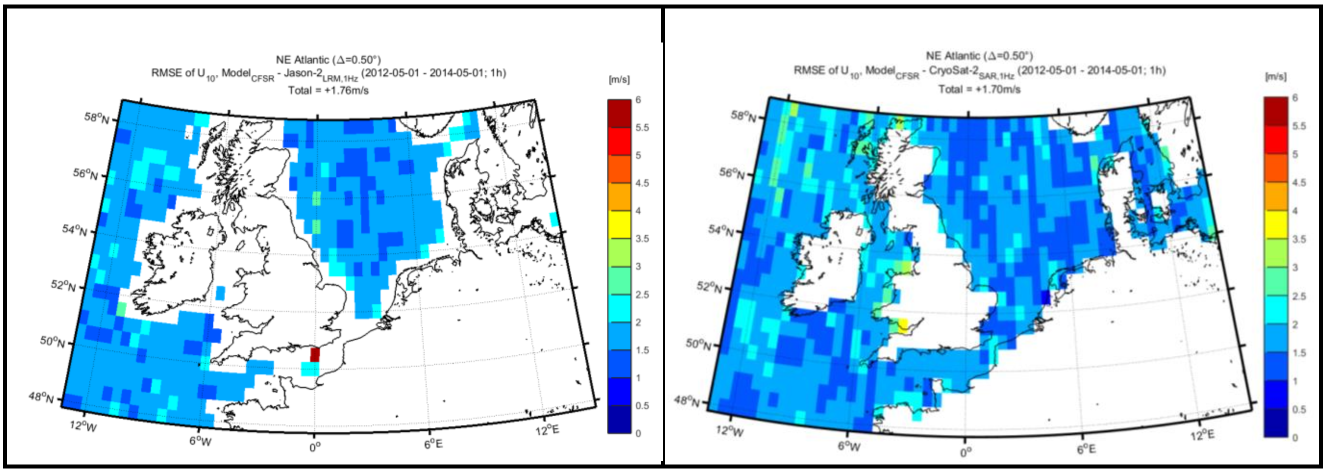


Figure 3: RMSE of wind speed between model and altimeter data. Left: Jason-2 (LRM, 1Hz), Right: CryoSat-2 (SAR, 1Hz).

### 4.1.3 Assessment and recommendation

There is generally a good agreement between the model and the SAR 1Hz data. The 20Hz SAR data show similar performance to the 1Hz SAR data offshore, but somewhat larger deviations in the nearshore areas. Thus, SAR data is a valuable source of data for model validation nearshore, supplementing other altimeter missions of LRM data offshore and in-situ measurements. At this stage, the SAR 1Hz data set may be more appropriate for model validation nearshore compared to the 20Hz data.

The overall conclusion from the evaluation is that CryoSat-2 SAR data are of sufficient quality to support and improve modelling results, especially in areas with low data coverage. The data and value adding services will contribute to future metocean databases and design methods e.g. for offshore wind.

Additional work on the SAR data could e.g. include processing/smoothing of the (along-track) data for more robust verification as well as inclusion of SAR wave spectra. Both of which could possibly also be useful for data quality screening (assessing outliers in SAR data).

## 4.2 Characterization of coastal scale hydrodynamics

Detailed descriptions of methodologies developed and results obtained can be found in the Deliverable 5.2 report ‘Characterization of coastal scale processes’.

### 4.2.1 Level-2 product used

Processed Level-2 altimeter data from the SAR mode of CryoSat-2 for the North East Atlantic and North Adriatic Sea provided by CLS were used. In addition, low-resolution mode Sea Level Anomalies (SLA) from Altika and Jason-2 were included in the analysis.

### 4.2.2 Value adding service

The availability of accurate sea surface elevation and wave height observations at 350m resolution from CryoSat-2 SAR mode is close to the spatial scale of wave groups and hence can be used for the estimation of conditions causing surf beat. Combination with the SAR derived wind product as well as in-situ and numerical model estimates of wind velocity and wave spectra will allow addressing the aliasing of the signal and the wave direction and hence the periods and amplitudes associated with surf beat and potential local seiching in inlets or harbours. In addition, detailed analysis of transient water level response to wind forcing in shallow seas, coastal jets and basin scale seiching can be addressed using a combination of SAR data and numerical modelling.

To evaluate the potential of value adding services for addressing coastal scale processes two case studies have been analysed:

1. North Adriatic Sea where combined storm surges and high tides imply a risk for the city of Venice and coastal areas. Therefore, relevant value adding services may include forecast of flooding situations and forecast of the condition along the barrier island coast, which today also comprise the MOSES storm surge barrier project.
2. Hanstholm Harbour, an exposed North Sea port in Denmark, where a major issue is safe navigation and operation under harsh conditions. A value adding service, enabling better knowledge of wave and current conditions, especially during approach and berthing, may potentially improve safe navigation and provide a more efficient planning of operations. Such a service comprises high-resolution SAR wave and sea surface data, which are fed into numerical wave and flow models of the harbour, including wave disturbance in the port (see Figure 4).

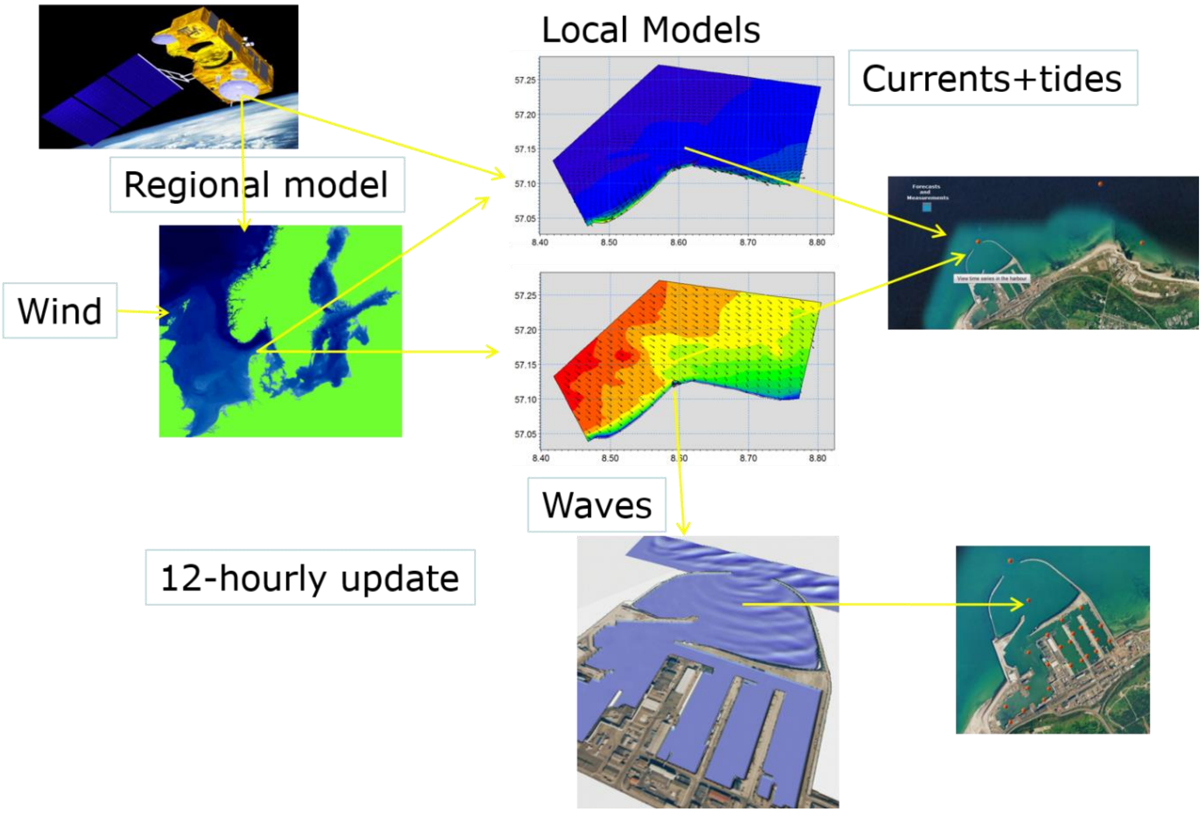


Figure 4: Concept of a local value adding service for navigation support to Hanstholm Harbour. The system consist of SAR observations in high resolution, combined with numerical wave and tidal models, including both regional and local high-resolution models.

### 4.2.3 Assessment and recommendation

The general conclusion from the two case studies is that high-resolution SAR data, both for sea surface elevations and for significant wave heights, provide important information for coastal processes. However, the temporal resolution of the SAR data does not, in general, allow resolving coastal processes, which in most places occur on a timescale of hours. Therefore, the fusion of satellite-based observations with numerical models is a way to utilize the synergies between the two. The satellite-based observations provide valuable ground truth at high spatial resolution, while the numerical models are continuous in space and time and provide a supporting framework for the observations and a physically-based interpolation between the observations.

## 4.3 Data assimilation in coastal-ocean models

Detailed descriptions of methodologies developed and results obtained can be found in the Deliverable 5.3 report ‘End-to-end demonstration of improved surface current design data’.

### 4.3.1 Level-2 product used

Processed Level-2 altimeter data of Sea Level Anomaly (SLA) from the SAR mode of CryoSat-2 for the North East Atlantic and North Adriatic Sea provided by CLS were used. In addition, low-resolution mode SLA from Altika and Jason-2 were included in the analysis.

### 4.3.2 Value adding service

The purpose of assimilation of SAR altimetry data in coastal-ocean models is to improve coastal-ocean design data as well as prediction skills of operational forecasting systems. Data assimilation capabilities were developed in DHI’s flexible mesh coastal-ocean models MIKE 21/3 FM for assimilation of SLA derived from SAR altimetry data. A general data assimilation methodology based on the ensemble Kalman filter was developed that facilitates assimilation of both repeat-orbit and drifting-orbit (CryoSat-2) altimetry data as well as in-situ data from tidal gauges.

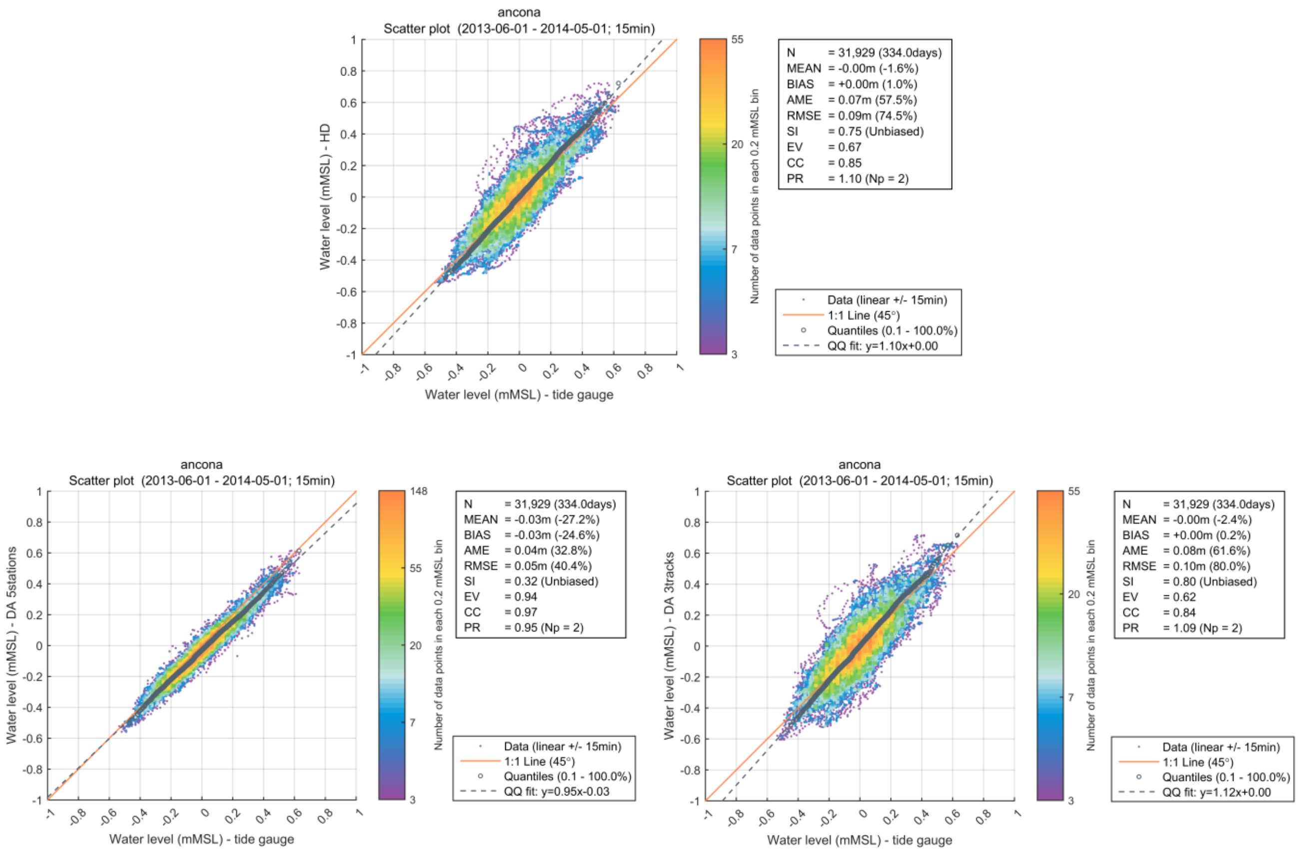


Figure 5: Comparison of modelled and measured water level at Ancona without data assimilation (top), with assimilation of tidal gauge data (bottom left) and altimeter SLA data (bottom right).

Assimilation of altimeter SLA data was evaluated using a 2D MIKE 21 FM model setup of the Adriatic Sea. Altimeter SLA data from CryoSat-2, Altika and Jason-2 for the North Adriatic Sea were applied as well as water level data from tidal gauges in the Adriatic Sea. Some results from the data assimilation experiments are shown in Figure 5. The figure compares modelled and measured water level at a tidal gauge validation station (i.e. a station that was not included in the data assimilation) for, respectively, a simulation without data assimilation, a data assimilation run using water level measurements from 5 tidal gauges, and a data assimilation run using altimeter SLA data.

### 4.3.3 Assessment and recommendation

Comparison of the altimeter and MIKE 21 FM modelled SLA data showed in general good agreement for the NE Atlantic and the North Adriatic Sea, and hence the altimeter data were considered appropriate for data assimilation.

The data assimilation experiments showed that assimilation of tidal gauge data provides large improvements in water level with RMSE reductions in the order of 50%. Assimilation of altimetry SLA data alone, however, provides less satisfactory results with even small increases in RMSE compared to the model simulation without data assimilation. The reason for this could be due to the relative coarse frequency of satellite passes in the model area (on average there is less than one minute of data a day with an average passing frequency of 1.5 days). In addition, the performance may be hampered by assimilating erroneous altimeter SLA data, hence requiring a more thorough quality control of the altimeter data before they are used for assimilation.

Further analysis is required before more firm conclusions can be drawn regarding the value of assimilation of SAR-derived SLA data in coastal-ocean models. In particular, more comprehensive testing of different modifications and enhancements of the data assimilation set-up is required.

# 5 Value adding applications for land

## 5.1 River model calibration

Detailed descriptions of methodologies developed and results obtained can be found in the Deliverable 6.5 report 'Demonstration of water resources management services for the Brahmaputra basin'.

### 5.1.1 Level-2 product used

Processed CryoSat-2 Level-2 data for the Brahmaputra River basin were provided by DTU Space. The basis for the data is the ESA baseline-b L1b 20Hz product. This product was retracked by Villadsen et al. (2015) using a primary peak threshold retracker.

In addition, Envisat derived water level data from 13 virtual stations along the Brahmaputra River were applied. These data originates from the ESA River&Lake project (Berry, 2009).

### 5.1.2 Value adding service

A method was developed for calibration of river cross sections that combines data from CryoSat-2 and the Envisat mission. Due to the drifting orbit, CryoSat-2 data can be used to estimate the average longitudinal water level profile for the entire river. The Envisat mission with its 35-day repeat orbit provides virtual station time series, which can be used to adjust cross section geometries along the river.

Results of application of the procedure developed are shown in Figure 6 - Figure 7. In this example cross sections with a simple triangular shape were placed ca. every 50 km along the entire Brahmaputra River (more densely spaced in regions with abrupt changes in bed slope) and then calibrated using the elevations extracted from the SRTM DEM as a starting point for the calibration.

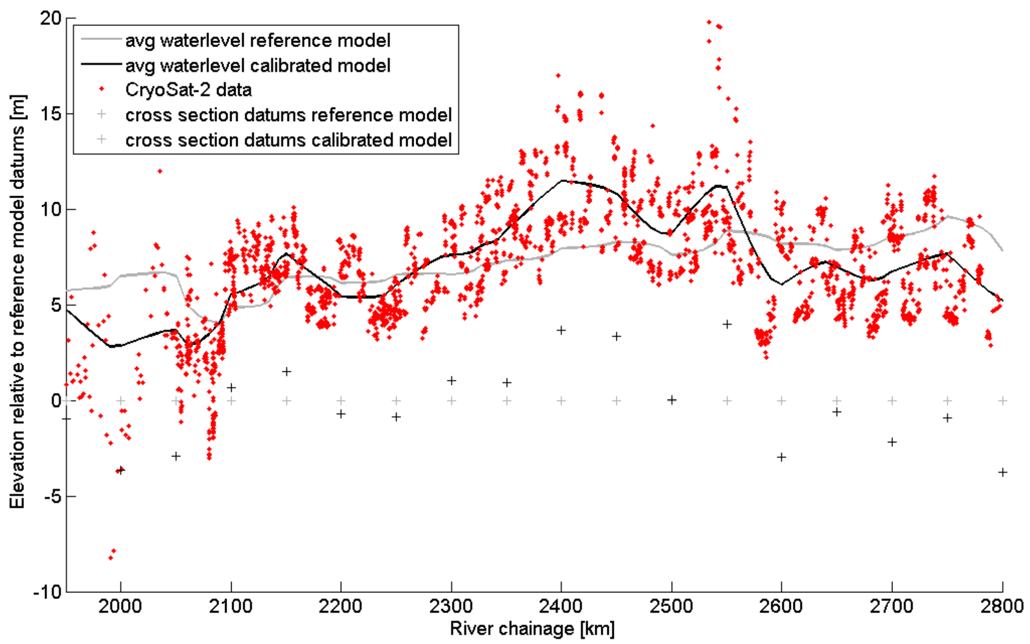


Figure 6: Result of water level calibration for the Assam valley using CryoSat-2 data for the period 2010 to 2013. All levels are shown as elevations relative to the reference model's cross section datums based on the SRTM DEM.

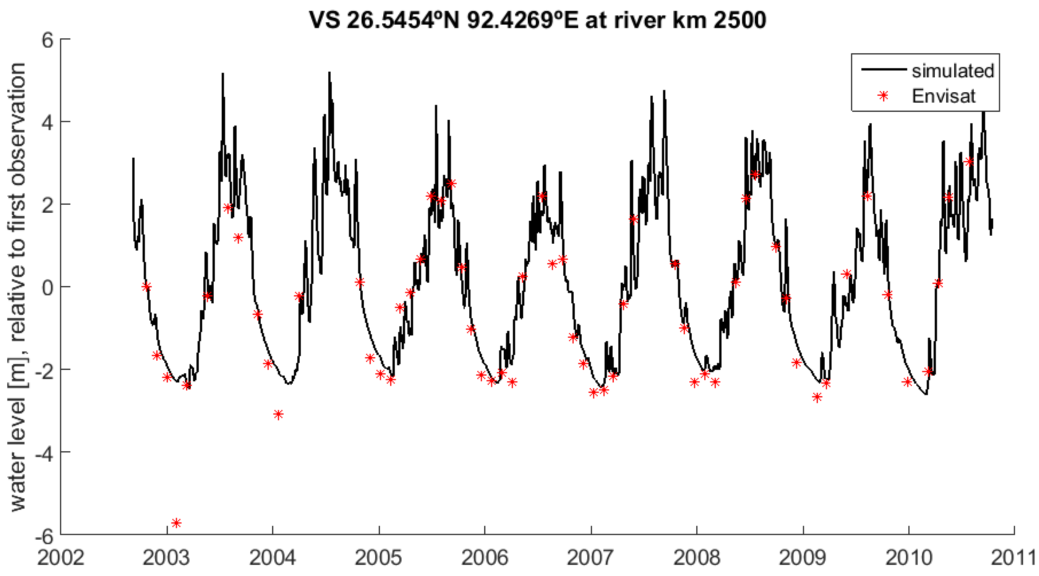


Figure 7: Water levels for one virtual station after calibration of cross section geometry. All levels are relative to the water levels at the time of the first Envisat observation.

### 5.1.3 Assessment and recommendation

Using CryoSat-2 observations for calibration of cross section datums resulted in better average simulated water levels compared to the simulation using the datums derived from the SRTM DEM. The calibration resulted in datum adjustments of up to 4 meters. The subsequent calibration of cross section shapes using Envisat data showed an improvement in the simulation of water level amplitudes.

In conclusion, the cross section calibration method developed offers a way to calibrate water levels in a hydrodynamic river model without precise knowledge of topography and bathymetry. Synthetic cross sections allow the use of practically any shape, however, for the sake of reducing the number of calibration parameters a simple triangular shape would probably be sufficient in most cases.

## 5.2 Data assimilation in hydrological-hydrodynamic models

Detailed descriptions of methodologies developed and results obtained can be found in the Deliverable 6.4 report 'Hydrological-hydrodynamic modelling and data assimilation system' and Deliverable 6.5 report 'Demonstration of water resources management services for the Brahmaputra basin'.

### 5.2.1 Level-2 product used

Processed CryoSat-2 Level-2 data for the Brahmaputra River basin were provided by DTU Space. The basis for the data is the ESA baseline-b L1b 20Hz product. This product was retracked by Villadsen et al. (2015) using a primary peak threshold retracker.

### 5.2.2 Value adding service

A catchment-scale hydrological-hydrodynamic modelling and data assimilation approach has been developed for assimilation of river water level measurements obtained from satellite altimetry data. The purpose of assimilation of satellite altimetry data is to improve hydrological-hydrodynamic model predictions as a basis for establishing more skilful operational forecasting systems in cases where no or only limited in-situ data are available.

The approach developed is based on the MIKE 11 hydrological-hydrodynamic modelling system and the general-purpose DHI Data Assimilation library. The data assimilation implementation has been tailored to assimilation of drifting-orbit altimetry data such as Cryosat-2 and allows also assimilation of repeat-orbit satellite altimetry and in-situ water level data.

Different data assimilation experiments were performed using the Brahmaputra case study to evaluate the value of assimilation of CryoSat-2 data. An example of output from one of the experiments is shown in Figure 8.

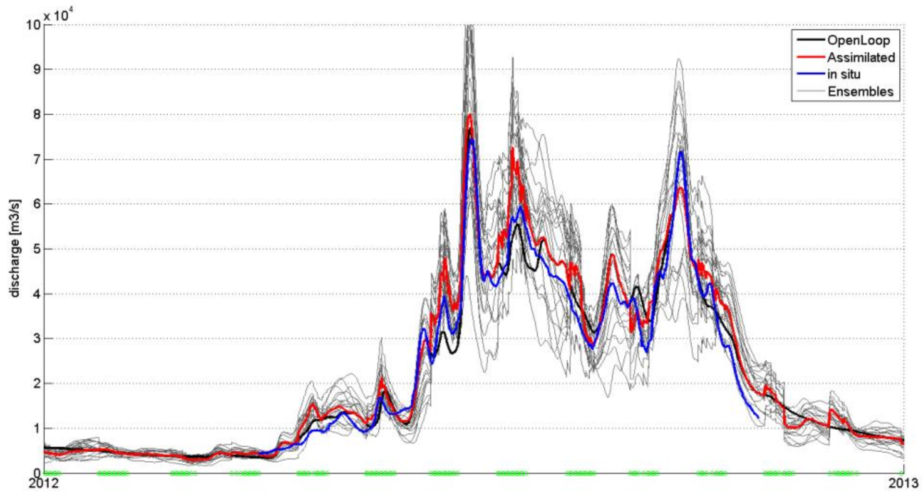


Figure 8: Discharge at Bahadurabad (downstream Brahmaputra station). Ensemble members in grey (representing model prediction uncertainty), open-loop run (without data assimilation) in black, assimilated run in red, and in-situ data in blue. Green dots indicate timing of CryoSat-2 observations.

### 5.2.3 Assessment and recommendation

The data assimilation results showed only marginal improvements in model performance. One of the most important reasons for this may be the assumption of uniform observation error for all CryoSat-2 water level data. The observation error is expected to be non-uniform in space and time due to various corrections applied in the processing of water heights (atmospheric correction, geoid, roll bias). Other issues related to the filtering and projection of the CryoSat-2 data could be improved to increase the accuracy of the data. In addition, different modifications and enhancements of the data assimilation set-up remain to be tested.

The overall conclusion from the data assimilation experiments is that further analysis is required before more firm conclusions can be drawn regarding the value of assimilation of CryoSat-2 data in hydrological-hydrodynamic models. The CryoSat-2 data and inland water altimetry data in general may become a key data source for water managers. The impact of the altimetry data will increase with enhanced spatio-temporal resolution available from the combination of multiple missions and with a better understanding of the error statistics of the data. The modelling and data assimilation approach developed is scalable and can be extended to other basins and to continental/global coverage for establishing operational hydrological-hydrodynamic forecast systems.

# References

Berry, P., 2009. River and Lake Product Handbook v3.5.

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