Review by anonymous referee #1

GENERAL COMMENTS:

Reviewer's comment	*The paper is interesting because it shows a practical use of Cryosat-2 data for a hydrodynamic modelling. So far, a few studies are available on this issue in the scientific literature. Therefore, I found the paper highly timely and appealing.* *The manuscript is well written and easy to follow, even if some aspects should be better clarified. The main issues concern: 1) the specification of the paper purpose, 2) the description of the hydrodynamic model and 3) the procedure of optimization of the cross-section geometry. Moreover, I have doubts concerning the study area characteristics. The evaluation of the Cryosat-2 data performances cannot be exhaustively tackled if no data are available for the validation.*
Authors' response	We thank the reviewer for constructive feedback on this article. We believe incorporating the reviewer's comments has improved the article.
changes	-

SPECIFIC COMMENTS:

Introduction:

Reviewer's comment	*1) The purpose of the study is not well specified. I suggest the authors to add in the introduction a couple of sentences on this aspect also to introduce the model and the datasets used: why do they use 1D model for this complex river? Why software MIKE 11? Why Cryosat-2 and Envisat?*
Authors' response	The choice of CryoSat-2 is due to its unique drifting orbit which provides water level profiles with high spatial resolution. In combination with (any, not necessarily Envisat) repeat orbit altimetry data providing water level time series at virtual stations these data can be used to calibrate the water level dynamics (which hopefully also becomes more clear in section 3.4). So, the purpose of the paper is to find out what CryoSat-2 can do for river modelling. The 1D model was used because, for the study area, we lack (access to) precise DEMs or bathymetry data. Hence, a 1D model with synthetic cross sections was used – the focus of the study is to simulate water levels (and discharge) in the river, however not flood extent. Furthermore, at the large scale of the model (1000 km plus of river) anything else than a 1D model will become computationally heavy in calibration (or potential use of model ensembles in uncertainty analysis or data assimilation).
changes	p. 1, line 29 – p. 2, line 3: extended motivation in introduction p. 3, line 31 – p. 4, line 10: new section 1.3 on Hydrodynamic river models (mainly as response to comment 2 of anonymous referee #2)

Reviewer's comment	*2) I believe that the background should be addressed following the purpose of the paper. The literature review described in the introduction is quite extensive, but it should be more focused on the use of radar altimetry for the calibration of the hydrodynamic models or the cross-sections geometry, mentioning similar studies (see references).* *For example:* *Domeneghetti et al. (2014; 2015) compared the performances and analyzed the uncertainty of ERS-2 and ENVISAT radar altimetry in the calibration of the manning coefficient of the Hec-RAS model along a river reach of the Po river in Italy.* *Yan et al. (2014) calibrated the manning roughness coefficient and the depth of the cross sections for the LISFLOOD-FP model in the Danube River with the use of water surface level derived by Envisat radar altimetry.* *Biancamaria et al. (2009) compared the water levels derived by 22 TOPEX/POSEIDON VSs with the ones simulated by large scales coupled hydrological-hydraulic model of the Ob river in Siberia calibrating the river depth and Manning' roughness coefficient.*
Authors' response	Thanks for the list of interesting and relevant references.
changes	p. 3, line 6 – line 13: extended literature review

Reviewer's comment	*3) I suggest citing Tourian et al. (2016) for the merging of satellite altimetry. They analyzed different time series from Envisat, Saral/Altika, Topex/Poseidon and Cryosat-2 in the Po, Congo, Mississippi and Danube rivers.*
Authors' response	Indeed, a relevant reference
changes	p. 2, line 19 – 23: included the reference and some discussion of it

Study area:

Reviewer's comment	*1) Why do the authors focus on Brahmaputra River? Cryosat-2 data are available for rivers where the in-situ data could be easily obtained. The risk to use a poorly gauged river (or as in this case a river where the data are not publicly available) is to be not able to validate the procedure in a proper manner.*
Authors' response	Yes, that is correct, the data over the Brahmaputra River is hard to validate. The alternative would have been to use another, better gauged river. The choice of suitable rivers however is not very large, because it needs to be of sufficient width, preferably flowing in west-east direction and (fairly) unregulated. One common example is the Amazon River. In this case however the river is being monitored on the ground, hence the information gained from satellite altimetry is less crucial. Furthermore, the Amazon River (in large parts) is exceptionally wide, and not representative of other rivers (if one considers the transferability of this work). In this trade-off it was decided to go for a study region where in-situ data actually is scarce, making application of remote sensing data crucial. Also, for the Amazon River, there are already plenty of altimetry studies available.
changes	p. 4, line 20 – 23: extended section 2 Study area

Reviewer's comment	*2) I have doubts on the use of "calibration" term in the text: "discharge calibration" or "water level calibration". The calibration is referred to the parameters of the model in order to reproduce the measured discharge or water level. I guess that, in this case, the authors calibrate the parameters of the hydrodynamic model and, then, compare the simulated discharge with the observed one. Therefore, I suggest to pay attention.*
Authors' response	We assume that the confusion is about whether naming the calibration after the target (discharge or water level) or the calibration parameter (for example cross section datum). We hope that the changes described below, together with the extended Figure 3, makes things more clear.

changes	p. 1, line 18 and line 17 – 18: clarified the terms in the abstract p. 4, line 31 – p. 5, line 5: Changed term "water level calibration" to the throughout the manuscript used "cross section calibration", and explained what happened during the (discharge) calibration of the hydrodynamic model p. 9, line 24 – 27: As above. Also added "fitting water levels to observed water levels from altimetry" to make the calibration target clear. Furthermore, the captions of Figure 7, Figure 8 and Table 1 were changed ("cross section calibration" instead of "water level calibration")

Data and Methods:

Reviewer's comment	*1) This section is quite unbalanced. The description of the satellite data, especially for the water mask, is too long with respect to the hydrodynamic model.*
Authors' response	This was also pointed out by the other reviewer (and confirmed by the editor): the description of the hydrodynamic model is too short, it was extended. For details see below (comments 3a to 4)
changes	See below

Reviewer's comment	*2) From Fig.2 the model river line seems very different from the natural water course. The authors should clearly describe how it was derived.*
Authors' response	This disagreement between river mask (~natural water course) and 1D model river line comes from the fact that the river line is derived from the SRTM DEM by DEM hydroprocessing performed in ArcGIS. Such a course will deviate from the natural water course for Brahmaputra River in the Assam valley mainly because of i) inaccuracies in the SRTM and the relatively flat river valley and ii) changes in the river's course over the years since the acquisition of the SRTM data in 2000. (The hydrodynamic model however will be insensitive to changes in the river's course, as long as the total length of the stretch remains approximately the same) (see also response to comment 3a below and to comment 4 by anonymous referee #2)
changes	p. 8, line 5 – 8: added two sentences on this to section 3.3.1 Hydrodynamic model

Reviewer's comment	*3) About the hydrodynamic model, more details and clarifications are necessary.* *3.a) First, the authors state that Bahadurabad is along the Brahmaputra river, but in Figure 1 it seems outside the contour of the basin. If we suppose that the gauged site is available inside the basin near the outlet (and hence, the contour is wrong), it could be sufficient for calibrating the rainfall-runoff model. Why do the authors extent the rainfallrunoff model to the Gange Basin? Moreover, how do they transfer the parameters for the 11 subcatchments to the remaining ones? Please specify.*

Authors' response	Bahadurabad station is assumed to be placed at the outlet of the model. It is correct that the outline of the model displayed in Figure 1, which is the basis for the rainfall-runoff model subcatchments, does not agree when the location of the river line is considered in this part of the model. The reason for this is inaccuracies in the SRTM DEM that was used for the subcatchment delineation. Near Bahadurabad station, where the river valley is very flat this lead to the subcatchments ending approximately 10 to 20 km west of where they actually would be expected to end – when one looks at the actual location of the river. However, in the model (remember also that the NAM rainfall-runoff model is a lumped model), the subcatchments are correctly attributed to/draining into the river of the hydrodynamic model. The Brahmaputra basin model used here is part of a larger model covering both the Ganges and Brahmaputra basins. This model originates from a consultancy project of DHI and ICIMOD. However, no part of the Ganges basin model is used for the work described in the article. So, the model was not really extended to the Ganges basin as the reviewer might have understood, but rather that the available information from the Ganges basin (i.e. the rainfall-runoff model parameters) was used for the Brahmaputra basin. Parameters were transferred between subcatchments using simple heuristics. Because of the unfortunate situation that only 11 (out of 86 in total) subcatchments could be calibrated against in-situ discharge at their outlets, the other subcatchments had to be given parameters that were derived from those 11. Parameters in the NAM model have some physical meaning, so differences in topography for example can guide in how to transfer parameters from one catchment to another. Furthermore, total runoff from all the aggregated Brahmaputra catchments could be checked against the discharge at Bahadurabad station – the total water balance bias between simulated and observed discharge at that station is only 2%, as mentioned at the end of section 4.2.
changes	As part of the expansion of the model explanation, further subsections were added (now: 3.3.1 Hydrodynamic model, 3.3.2 Rainfall-runoff forcing of the hydrodynamic model, 3.3.3 Boundary and initial conditions) and the heading of section 3.3 was changed to "Hydrologic-hydrodynamic model" p. 8, line 5 – 9: added some explanations on the inaccuracies of the SRTM DEM causing slight disagreements between river's course, gauging station location, and basin outline p. 8, line 16 – 17: added some words on the origin/initial setup of the Brahmaputra model p. 8, line 30 – 33: added some words explaining the NAM parameter transfer p. 9, line 1 – 2: removed reference to Hardinge Bridge station for discharge calibration, as it is part of the Ganges River which is not part of this study. This might also have caused some confusion to the reviewer. p. 12, line 30 – 32: added some words on the (good) calibration results and how they indicate that the NAM parameter transfer can be considered successful

Reviewer's comment	*3.b) About the hydrodynamic model, the procedure of calibration of the cross section geometry is not clear. If Cryosat-2 and Envisat do not refer to the same cross-section (VS), it should be specified how step 1 and step 2 should be applied. Indeed, some details are given in Table 1, but I believe that a deeper description should be added in the text.*
Authors' response	Yes, the different number of cross sections is confusing. The data from Envisat does not cover exactly the same river section as the CryoSat-2 data used, hence not all the same cross sections are calibrated. With Envisat, cross sections from river km 2050 to 3050 could be calibrated, whilst with CryoSat-2 data cross section between rive km 1950 and 2800. Hence, only the overlap from river km 2050 to 2800 can be considered fully calibrated. In other words, the 22 cross sections in this overlap are calibrated in both step 1 and step 2.
changes	Table 1: added river km to the calibration parameters p. 13, line 18 – 21: added explanation on the overlap (furthermore, we hope that the changed Figure 3 helps explaining the calibration process better – see the comment below)

Reviewer's comment	*Moreover, after the second calibration step, in Fig.3 the flow chart indicates that the procedure is iterative. I do not understand at what level the iteration happens. I think that in order to obtain a calibration the objective function should be unique and minimize the RMSE for both the steps in parallel. I think this is a very important part of the procedure, therefore I suggest to add details and clarifications. Indeed, page 10 Lines 28-30 should be moved in this section.*
Authors' response	Yes, the authors agree that Figure 3 can be improved. We however are not sure how to go about minimizing the RMSE for both steps in parallel, as suggested by the reviewer. The two different objectives from step 1 and step 2 could be merged into one optimization. This however would also increase the complexity of the problem, as both sets of decision variables would have to be considered. This probably will increase the computational demand of the already demanding optimization problem. Hence, because the sensitivity of the water level amplitudes to small changes in the cross section datums is very low, this iterative approach is considered sufficient. Given the low sensitivity of, in other words, the objective of step 2 to changes resulting from step 1, the iteration usually can be ended after a run of step 1.
changes	p. 13, line 16 – 18 (which was p. 10, line 28 – 30 in the original document) moved and slightly extended as suggested by reviewer to p. 10, line 25 – 31 Figure 3: changed. Extended, to add more clarity (also concerning the discharge and runoff calibration)

Reviewer's comment	*3.c) In the hydraulic model, no mention is given to the roughness manning coefficient. Even if it was not specified in the text, I think the authors used a unique coefficient value for the entire river. Please add some details.*
Authors' response	The Manning coefficient was calibrated to one unique value along the entire river.
changes	p. 8, line 11 – 13: added explanation on Manning's number calibration to section 3.3.1 Hydrodynamic model (for results, see response to comment 2 in the Results section)

Reviewer's comment	*3.d) How do you set the initial condition of the model? What about the boundary condition at the downstream site? Please specify.*
Authors' response	The initial conditions of the hydrodynamic model are taken from a hotstart of the model. More important however is the hotstart of the hydrologic part of the mode, i.e. the NAM rainfall-runoff models, because those models have states with much "longer memory". The hotstart of the NAM rainfall-runoff models was created by running the initial calibration period of the model, 2002 to 2007, 30 times, reusing the final state of the respective prior run as a hotstart. After 30 iterations, or 180 years, all states with long memory (mainly groundwater and snow storage) have reached equilibrium. This then is used as the hotstart. A time series of water levels at the downstream boundary of the model (which lies ~180 km downstream of Bahadurabad station) could be obtained for the years 2001 to 2009 – outside that range a climatology of these values was used. In any case, discharge and water level at Bahadurabad station (so the downstream end of the area of interest) is insensitive to this downstream boundary condition.
changes	p. 9, line 3 – 11: added section 3.3.3 Boundary and initial conditions of the model

Reviewer's comment	*4) Which is the length of the river simulated with the hydraulic model?*
Authors' response	The total length of the Brahmaputra River modelled (tributaries excluded) is approximately 3090 km.
changes	p. 7, line 27 – 28: added this to section 3.3.1 Hydrodynamic model

Results:

Reviewer's comment	*1) Why do you choose 20 m for defining the outliers of the Cryosat-2 values?*
Authors' response	This is a value that was chosen after inspecting the differences between SRTM and CryoSat-2 elevations along the river. In general, CryoSat-2 observations group nicely around the SRTM values, and only very few clear outliers do exist – these will be removed with the chosen threshold of 20 metres deviation.
changes	p. 11, line 3 – 8: added explanations on outlier definition. Furthermore, an error with the number of outlier filtered measurements was corrected.

Reviewer's comment	*2) The authors state that the manning's number is calibrated. Which is the value? Is it plausible for this river?*
Authors' response	The resulting value is a Manning's n value of 0.029 in SI units, which is considered plausible (compare for example http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm) (same as comment 6 by anonymous referee #2)
changes	p. 12, line 10 – 11: added the above

Reviewer's comment	*3) In the text, it is mentioned that the investigated river reach is the Assam Valley. Figure 7 shows the water levels for a river reach from 1950 km to 2800 km. Figure 8 shows the VS at 2839.019. Could the authors add the length of the analyzed river (not well specified) and update Figure 7 for the actual length?*
Authors' response	The authors understand that the figures should show the relevant stretch (the overlap between river km 2050 and 2800, see reply to comment 3b).We hope that also the changes made in response to comment 3b) above help clarifying this.
changes	Figure 7: changed to show river only between river km 2050 and 2800, i.e. the stretch covered by both Envisat and CryoSat-2 data Figure 8: changed to VS at river km 2750

Conclusions:

Reviewer's comment	*1) The authors state that "SRTM products do not provide sufficient information to create a hydrodynamic model reproducing accurate water levels or inundations areas". I believe the river is not enough gauged to evaluate the performance of SRTM. In a different study area, the authors could evaluate the accuracy of SRTM in comparison with the proposed procedure, but in this case the only conclusion that can be drawn is that SRTM and radar altimetry gave different results.*

Authors' response	The authors agree that this statement may be too simplistic. However, the authors still believe that the SRTM – at least as a raw product – is not precise enough to directly derive a hydrodynamic model accurately reproducing water levels. This can be shown for example by the significant improvements that Jarihani et al. (2015) could achieve when deriving cross sections from SRTM DEM, and then subsequently correcting the SRTM DEM for vegetation and other issues (Table 4 in their article). Their baseline for the comparison is derived from ICESat data, which they could validate against in-situ data to have a RMSD of only 0.23m. But even when the SRTM DEM was vegetation smoothed and hydrologically corrected, its RMSD compared to a cross section from ICESat was above 1.1m. Another example is the work by Md Ali et al. (2015) using a DEM from lidar data with 1m resolution to set up a 1D hydrodynamic model and comparing it to, amongst others, the same hydrodynamic model based on the SRTM DEM. They found the resulting simulated water levels of the SRTM DEM based hydrodynamic model to have a MAD of 0.76m compared to the same levels from the lidar based model. With the proposed procedure, the water levels will be fitted to CryoSat-2 observations. Based on the literature cited the authors assume that fitting the simulated water levels to CryoSat-2 data also means a better fit to real water levels than what can be achieved by setting up the hydrodynamic model based on the SRTM DEM only. Remember also the difficulties of obtaining an estimate of bathymetry from DEMs, whilst the suggested procedure does not require any knowledge of bathymetry. References: Jarihani, A. A., Callow, J. N., McVicar, T. R., Van Niel, T. G. and Larsen, J. R.: Satellite-derived Digital Elevation Model (DEM) selection, preparation and correction for hydrodynamic modelling in large, low-gradient and data-sparse catchments, J. Hydrol., 524, 489–506, doi:10.1016/j.jhydrol.2015.02.049, 2015. Md Ali, A., Solomatine, D. P. and Di Baldassarre, G.: Assessing the impact of different sources of topographic data on 1-D hydraulic modelling of floods, Hydrol. Earth Syst. Sci., 19, 631–643, doi:10.5194/hess-19-631-2015, 2015.
changes	p. 14, line 14 – 22: Reformulated the mentioned statement, and discussing the above references

Reviewer's comment	*2) Could the procedure be transferable to other case studies? Could the authors suggest the minimum width to apply it?*
Authors' response	Yes, the authors expect that this procedure can be transferred to other case studies. A minimum river width however seems to be hard to define, as the ability of satellite altimeters to reliably measure water level in (narrow) rivers depends (besides the actual instrument and processing) not only on the river width, but also on the topography of the river valley – see for example what is discussed in connection with the results shown in Figure 5 and the article by Dehecq et al., 2013 discussed in section 4.1 (p. 11, line 22 – 25)
changes	p. 1, line 25: added the transferability to the abstract p. 15, line 3 – 5: added some words on the transferability to the conclusion

TECHNICAL CORRECTIONS:

Reviewer's comment	*Please, remove capital letter after the colon.*
Authors' response	done
changes	throughout the manuscript

Reviewer's comment	*Page 3, Line 19: "Mike 11 software": a previous citation of the hydraulic model MIKE 11 used for the analysis is necessary. Please specify if it is a hydrological or hydraulic model and add some references.*
Authors' response	

changes	p. 4, line 25 (previously p. 3, line 19): Added reference to MIKE 11 reference manual p. 7, line 30 – p. 8, line 4: added details on the used hydrodynamic model

Reviewer's comment	*Table 1: why 27 cross sections? The Envisat tracks are 13 as reported in the pages 8 Line 15.*
Authors' response	Yes, there exist only 13 virtual stations along the Assam valley. Angles for cross sections lacking neighbouring virtual stations were linearly interpolated between the next cross sections. We hope we made this more clear together with what is mentioned in the reply to comment 3b)
changes	p. 10, line 25 – 26: added a sentence mentioning the above

Review by anonymous referee #2

Reviewer's comment	*This paper describes the application of remotely sensed altimetry data from the CryoSat-2 satellite to large scale hydraulic modelling, using the Brahmaputra Basin as an example. While the paper is generally well written and clear, there are a few issues related to the focus and balance of the paper that will need addressing.* *The remote sensing aspects of the study seem very well described, but the description of the hydraulic modelling is relatively weak. In this respect, the novelty of the work lies in the use of the Cryosat-2 data rather than the hydraulic modelling. In fact given the current research in large scale hydraulic modelling the approach used in the paper is overly simple. Moving beyond the "virtual gauge" is of great research interest and I think this study has real value here, particularly with the fusion of drifting orbit and Envisat virtual stations. The filtering using a dynamic Landsat water mask is also of value and overall I think there is sufficient novelty in the work for publication.* *While there are some issues to address, I do not think further modelling is required. I think most of the issues can be addressed with changes to the core text. There should be better reference to existing large scale hydraulic river modelling and more discussion/openness about the modelling limitations.*
Authors' response	We thank the reviewer for constructive and insightful comments and suggestions. We fully agree with the reviewer that the contribution of this paper is the integration of CryoSat-2 data into a hydrodynamic model (and not for the hydrologic-hydrodynamic modelling as such).
changes	-

Some more specific points that should be addressed:

Reviewer's comment	*(1) The work seems to miss some aspects of recent research that I would assume would be relevant to the work. For example no mention is made of studies that use ICESAT – another dataset that has been used for similar hydraulic model calibration. There is also no reference to the relevant work on channel representation in large scale 1d-2d modelling such as that of Neal et al (2015) (and previous studies).*
Authors' response	We agree that the referencing may be too narrow in places and will include the suggested content in the revision. (the 1d-2d model discussion is included as part of the response to the next comment)
changes	p. 2, line 8 – 11: added general reference to ICESat p. 3, line 1 – 3 and p. 3, line 12 – 13: references to studies using ICESat altimetry to compare to or calibrate models

Reviewer's comment	*(2) Why only use a 1d model when there are plenty examples of this scale of hydraulic model using 1d&2d? Essentially all the floodplain and braided river section details are being lumped into the single triangular cross-section, so I am not sure how valid the representation of the river/floodplain is in the end. It might work as a simple water level response function that can be calibrated (as demonstrated in the paper), but it losses any physically based reality in representing the river and its floodplain, thereby limiting the value to the model for basin/river/floodplain studies. It is possible of course that the hydraulic conditions are such that the detailed representation of the channel is less important, such as found by Trigg et al 2009 on the Amazon. However there is no detail provided to show this is the case, for example what are the Froude numbers for the flow? It has not been demonstrated that the resulting model has value outside of the modelled scenario. I don't think that the model necessarily has to be redone, but I do think its limitations need more discussion.*

Authors' response	Focus here is on accurate prediction of water levels and discharge, this is not a flood model. No predictions about flood extent is possible. The main reason for choosing a 1D model was computational efficiency. It is correct that 1d-2d modelling at this scale is feasible, but probabilistic approaches using large ensembles of model runs would pose significant computational challenges. For example, the cross section calibration presented in the article using a genetic algorithm to find optimal parameters requires many runs (in the range of 10 000) of the model. Moreover, running a meaningful 1d-2d model would require accurate topography/bathymetry, which is unavailable for this braided and highly dynamic river system. The result of the cross section calibration, especially of step 2 where the amplitudes are being fitted, is consistent with the results by Trigg et al. (2009): with the chosen – simplistic – cross section representation we are able to reproduce observed water level dynamics. The authors however assume that the study is transferable to other rivers as well, given the availability of sufficient altimetry data. Even if a triangular cross section with varying angle will not be able to reproduce observed water level dynamics for all rivers, the same calibration procedure could be applied to other descriptions of cross section geometry. For example the same procedure should also work for the power-function cross section shape described by Neal et al. (2015): Instead of using a triangular cross section with the angle as only parameter, one could use the power function cross section shape and use i) only shape parameter s or also ii) both shape parameter s and bankfull depth h_full as calibration parameters. (assuming that the third parameter to describe the cross section in Neal et al.'s approach, bankfull width w_full, can easily be estimated from remote sensing data) Concerning the hydraulic plausibility of the results: The Froude numbers range from ~0.1 to ~0.4, as expectable for the given river section. Also, water depths are mostly in a range between 1 and 10 metres. This means that the hydrodynamic model with the performed cross section calibration behaves somewhat as expected (e.g.: subcritical flow), at least not in physically implausible regions.
changes	(introduced sub-sections 1.1 to 1.3 in the now extended introduction for clarity) p. 3, line 31 – p. 4, line 10: Added section 1.3 to discuss the choice of a 1D over a 2D model p. 13, line 30 – p. 14, line 3: added a few words on the limitations of the chosen synthetic cross section shapes to the discussion, including a reference to the work by Trigg et al. (2009) and Neal et al. (2015) p. 13, line 26 – 30: Added some values on the discussed hydraulic plausibility of the hydrodynamic model

Reviewer's comment	*(3) More discussion is required on the uncertainty in flow produced by the rainfall runoff modelling and how it affects the hydraulic modelling.*
Authors' response	The uncertainty in the subcatchments' rainfall-runoff models indeed is quite big (see Table 4, which was added in the revision). However, when aggregated in the larger hydrodynamic model, these uncertainties cancel each other out, producing a better model fit on the basin level than on the subcatchment level. the average cross correlation coefficient of the residuals of the subcatchments' runoff is only 0.16. Include some details and discussion of the uncertainty of the rainfall-runoff models. Potentially including data from the calibration catchments.
changes	added new Table 4: Performance criteria for simulated discharge in the calibration subcatchments. p. 12, line 25 – 32: added some discussion of the uncertainty on subcatchment vs. basin level

Reviewer's comment	*(4) There is reference to the dynamic nature of river channel with regards to the water mask, but no discussion of the how important this geomorphology might be to the simple triangle river channel model used.*

Authors' response	For this simple 1D model, with its synthetic cross sections, we assume that the change of the river channels does not significantly affect the water level-discharge relationships. Also, Mirza (2003) found rating curves at the Brahmaputra to exhibit fairly constant Q-h relationships over decades, leading to the conclusion that the Brahmaputra River is in "dynamic equilibrium". Reference: Mirza, M. M. Q.: The Choice of Stage-Discharge Relationship for the Ganges and Brahmaputra Rivers in Bangladesh, Nord. Hydrol., 34(4), 321–342, doi:10.2166/nh.2003.019, 2003. (see also response to comment 2 and 3a in Data and Methods by anonymous referee #1)
changes	p. 8, line 5 – 10: added a few words on this, including the above reference

Reviewer's comment	*(5) I am not clear on how the SRTM is actually translated into the triangle river channel. Has the raw SRTM data been processed to remove the vegetation bias? What is actually used for the 1d triangle, the width and depth of the river extracted from the SRTM? If so maybe river width from landsat would be better for the width and estimate of depth from geomorphological relationships (Leopold, and Maddock, 1953) would be better? What size are these calibrated triangles. Do they bear any resemblance to the real river sections?*
Authors' response	What is referred to as "reference" cross sections in the paper was visually extracted from satellite imagery and the SRTM DEM in a consulting project preparing the Ganges-Brahmaputra hydrologic model used in this paper. The real river cross sections (of this multi-channelled river) will of course be very different from these simplistic cross sections. However, this is not so important in a 1D model, as long as the relationship A = A(h) and P = P(h) are realistic, i.e. we need to get the relationship between flow cross sectional area and wetted parameter right.
changes	p. 9, line 14 – 20: added explanations on the "reference" cross sections and their limitations p. 13, line 3 – 4: added reference to the explanation of "reference" cross sections above

Reviewer's comment	*(6) Manning's is mentioned but no values given. Given its direct control on water levels and it should have some link to expected values it should not be omitted. Given the crude nature of the cross-sections and the fact that Manning's will compensate for lots of missing processes in this regard, I am not sure the calibrated Manning's values will bear resemblance to what might be expected for such a river.*
Authors' response	The resulting value is a Manning's n value of 0.029 in SI units, which is considered plausible (compare for example http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm) (same as comment 2 to Result section by anonymous referee #1)
changes	p. 12, line 10 – 11: added the above

Application of CryoSat-2 altimetry data for river analysis and modelling

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Abstract. Availability of in situ river monitoring data, especially of data shared across boundaries, is decreasing, despite growing challenges for water resource management across the entire globe. This is especially valid for the case study of this work, the Brahmaputra basin in South Asia. Commonly, satellite altimeters are used in various ways to provide information about such river basins. Most missions provide virtual station time series of water levels at locations where their repeat orbits cross rivers. CryoSat-2 is equipped with a new type of altimeter, providing estimates of the actual ground location seen in the reflected signal. It also uses a drifting orbit, challenging conventional ways of processing altimetry data to river water levels and their incorporation in hydrologic-hydrodynamic models. However, CryoSat-2 altimetry data provides an unprecedentedly high spatial resolution. This paper suggests a procedure to i) filter CryoSat-2 observations over rivers to extract water level profiles along the river, and ii) use this information in combination with a hydrologic-hydrodynamic model to ~~calibrate~~ fit the simulated water levels at an accuracy that cannot be reached using information from globally available DEMs such as SRTM only. The filtering was done based on dynamic river masks extracted from Landsat imagery, providing high enough spatial and temporal resolution to map the braided river channels and their dynamic morphology. This allowed extraction of river water levels over previously unmonitored narrow stretches of the river. In the Assam Valley section of the Brahmaputra River, CryoSat-2 data and Envisat virtual station data were combined to calibrate ~~water levels~~cross sections ~~simulated by a~~in a 1D hydrodynamic model of the river. The hydrologic-hydrodynamic model setup ~~used here~~and calibration ~~is~~ are almost exclusively based on openly available remote sensing data and other global data sources, ensuring transferability of the developed methods. ~~providing~~ They provide an opportunity to achieve forecasts of both discharge and water levels in a poorly gauged river system.

1 Introduction and background

This study shows how river water level measurements from the drifting-orbit radar altimetry mission CryoSat-2 can be used in combination with hydrodynamic river models. This new type of satellite altimetry data, providing river water level profiles with unprecedented spatial resolution was used~~,~~ in combination with conventional data from Envisat, providing water level time series at virtual stations. The combination of these two datasets allowed accurate calibration of water level

~~calibration~~ dynamics – both absolute water levels as well as water level amplitudes – along a continuous stretch of a 1D hydrodynamic model of the Brahmaputra River. This is obtained without precise knowledge of topography or bathymetry. ~~in a study region with scarce availability of in situ data.~~

1.1 Satellite altimetry over rivers

Satellite altimetry is often used in data scarce river basins such as the Brahmaputra basin. ~~Many~~Numerous studies combining satellite altimetry with hydrologic river models have been carried out using data from repeat orbit satellites such as Envisat, ERS-2, TOPEX/Poseidon or Jason-1 and 2. Those satellites are on repeat orbits with a repeat cycle of 10 to 35 days (see for example Schwatke et al. (2015) for an overview of the main characteristics of current satellite altimetry missions).~~,~~ The laser altimeter mission ICESat, in operation from 2003 to 2009, has an unusually long repeat cycle of 91 days, resulting in a higher across track resolution. Processed ICESat data over inland waters though only became freely available recently (O'Loughlin et al., 2016). ~~which~~ Repeat orbits simplify~~ies~~ application in hydrologic studies, especially for rivers. First, observations occur only at a few locations along a river. This eases filtering of the data, as water masks which are commonly used to distinguish relevant points over the river from non-relevant points over land, only have to be applied to limited areas. Second, repeat orbits result in water level time series at certain points in the river – so-called virtual stations – a format commonly used in hydrology. Both does not apply to CryoSat-2: i~~I~~ts drifting orbit results in water level measurements along the entire river, and the long repeat cycle of 369 days does not allow for direct derivation of water level time series (see the map inset in Figure 1 for a comparison of the Envisat and CryoSat-2 ground tracks). A good example for the focus of the hydrologic community on time series is the choice of Schwatke et al. (2015) to merge satellite altimetry from missions with differing orbits into common virtual stations for their satellite altimetry database DAHITI. Another effort to obtain a densified altimetry dataset is the work by Tourian et al. (2016): They merged multi-mission altimetry data over several rivers, linking the data between different virtual stations statistically and hydraulically, including data from CryoSat-2. The hydraulic link, however, is not a model but a simple time lag. They also found that the inclusion of CryoSat-2 data gives a more accurate representation of the river's water level profile. In ~~this~~ our study, ~~these two issues~~ CryoSat-2 data were handled by filtering ~~CryoSat-2~~its Level 2 altimetry data over a dynamic river mask based on Landsat imagery and using the resulting spatially distributed data to calibrate the water level profile along a continuous stretch of a river model.

1.2 Combining satellite altimetry with river models

Many of the studies using satellite altimetry over rivers have been done for the Amazon River due to its large width and favourable direction of flow – predominantly west to east – in relation to altimetry satellite orbits~~. See~~ (~~(~~for example ~~the work by~~ Yamazaki et al., ~~(~~2012b~~),~~ ~~or~~ and Paiva et al., ~~(~~2013~~)~~). Other examples include other big rivers, such as the Mekong and Ob in the work of Birkinshaw et al. (2014) where daily discharge data were estimated from Envisat and ERS-2 altimetry. A combination of MODIS data of river velocity and Envisat water levels was used by Tarpanelli et al. (2014) to estimate discharge in the Po River. Becker et al. (2014) ~~have~~ used Envisat altimetry data to obtain a comprehensive dataset of water levels over the Congo basin, a poorly gauged river system. The dense sampling pattern of ICESat was used by O'Loughlin et al. (2013) to derive water level slopes along the Congo River. ICESat river water levels were also used to evaluate the output of different hydraulic models (Jarihani et al., 2015 and Neal et al., 2012). Moreover, applications of data from the wide-swath drifting orbit mission Surface Water Ocean Topography (SWOT) have been considered (for example Biancamaria et al., ~~(~~2011a~~)~~ or Yoon et al., ~~(~~2012~~)~~), however only with synthetically generated data: t~~T~~he SWOT mission is expected to be launched in 2020 (NASA, 2016). Calibration of hydrodynamic model parameters has been explored as well: Domeneghetti et al. (2014) calibrated channel roughness for a part of the Po River using multi-year Envisat and ERS-2 altimetry data. Their work relied on the availability of cross section surveys. A method using the 2D hydrodynamic model LISFLOOD-FP based on SRTM topography was suggested by Yan et al. (2014). They used Envisat altimetry to calibrate channel roughness and a parameter estimating channel bed elevation below the SRTM elevations representing the water surface. Similar is the work by Biancamaria et al. (2009). They assumed fixed-width rectangular cross sections and estimated channel roughness and river depth by comparing model results to in situ discharge data and altimetry from Topex/POSEIDON. Cross section parameters were calibrated using ICESat altimetry in the lower Zambezi River (Schumann et al., 2013).

Also the chosen study area for this work, the Brahmaputra basin in South Asia, has already been used to show the value of Envisat altimetry data (Michailovsky et al., 2013). Furthermore, for example the work of Biancamaria et al. (2011b) provided forecasts of water levels in the high-flow season for the Ganges and Brahmaputra River near the Bangladeshi border with the aid of TOPEX/Poseidon satellite altimetry. Based on the ideas from that study, Hossain et al. (2014) developed an operational flood forecasting system for Bangladesh using Jason-2 water level observations from the upstream parts of the Ganges and Brahmaputra River in India. Also basin water storage can be estimated from satellite altimetry, see the work of Papa et al. (2015) where a combination of Envisat altimetry and GRACE time-lapse gravimetry has been used to estimate surface and sub-surface water storage in the Ganges-Brahmaputra basin.

Obviously, using satellite altimetry is particularly attractive over poorly gauged basins where in situ data are scarce. Satellite altimetry for river monitoring has recently become even more important: o~~O~~n the one hand, inland water altimetry is progressing with new satellites and sensors and improved data processing. On the other hand, despite growing challenges in managing our freshwater resources due to climate change, economic growth and population growth, the availability of in situ river level or discharge data is decreasing in recent years. This can be seen amongst others in the amount of data that is archived in the Global Runoff Database (Global Runoff Data Center (GRDC), 2015). Robert Brakenridge et al. (2012) for example discuss that this is not only an issue of lacking in situ gauging stations, but often also a political decision to not share river monitoring data. In both cases, remote sensing data for example in the form of satellite altimetry as used in this work can help water resource management and flood prediction.

1.3 Hydrodynamic river models

If a river model is used to make predictions about water levels, a physically based discharge routing model has to be used. There exist 1D hydrodynamic models based on the Saint-Venant equations for unsteady flow, like the MIKE 11 model used in this study (Havnø et al., 1995). More complex 2D or coupled 1D-2D models also include the river flood plain and interactions between channel and flood plain. The increased complexity of a 2D model compared to a 1D model obviously leads to higher computational demand. Furthermore, a meaningful setup of a 2D model requires more input data. Especially for large models in data scarce regions like the Brahmaputra basin, a compromise between computational efficiency and realistic simulation of water flow has to be made. Even though 2D models nowadays are successfully applied also to basin-scale models (Biancamaria et al., 2009, Biancamaria et al., 2011a and Schumann et al., 2013) their computational demand still puts limits to the number of possible model runs (García-Pintado et al., 2013). For model calibration or data assimilation many model runs are required. Moreover, the setup of a 2D river model requires precise DEMs. Globally available datasets such as the SRTM DEM might not always be accurate enough, even if corrected specifically for their application in a river model (Yamazaki et al., 2012a). In such cases, a less complex 1D model is more robust.

2 Study area

The Brahmaputra basin in South Asia and its main river are being monitored closely by India and China, however almost none of this in situ hydrologic monitoring data are publicly available. The ~~Brahmaputra~~ basin, for example, is considered a “classified basin” by the Indian government (Central Water Commission, 2009). This shows the importance of remote sensing data to aid any hydrologic modelling of the basin, such as flood forecasting in Bangladesh, the downstream neighbour of India. Bangladesh, a low lying country at the Bay of Bengal in the estuary region of the three large rivers Ganges, Brahmaputra and Meghna is often hit by devastating floods. More than 90% of its surface water originates from outside the country, i.e. mainly India, but still little data are shared between Bangladesh and India (Biancamaria et al., 2011b). Because of the absence of trans-boundary data sharing, the region’s dynamic hydrology, and the considerable size of the rivers in the Ganges-Brahmaputra-Meghna system, the area has repeatedly been in focus of river altimetry studies. These are also the main reasons why the Brahmaputra basin has been chosen as a study area, despite making it hard to validate the altimetry data against in situ observations. As already mentioned, the Amazon River is another common study area for this kind of studies, but the river is exceptionally wide, making transferability of the applied methods hard.

Figure 1 shows a map of the hydrologic-hydrodynamic model of the entire Brahmaputra basin, which was set up in the DHI MIKE ~~11~~ HYDRO River software (DHI, 2015). The course of the Brahmaputra River can be roughly divided into two parts: t~~T~~he upstream part in the Tibetan Plateau and through the Himalaya into India, where the river is often flowing in steep valleys in a narrow river bed. River morphology changes in the downstream part as soon as the river leaves the Himalayan Mountains and enters the Assam Valley in India: h~~H~~ere the Brahmaputra River is a wide, braided river with a low gradient and dynamically changing river channels (Sarkar et al., 2012). Finally, the Brahmaputra River merges with the Ganges and Meghna Rivers (outside the area modelled in this study) and flows into the Bay of Bengal.

~~Discharge c~~Calibration of the hydrodynamic model’s channel roughness was performed using discharge data from Bahadurabad station. ~~Water level~~ River cross section calibration, however, proves more challenging as no accurate digital elevation model (DEM), river bathymetry, or other topographic information is available for the study area.~~,~~ ~~and water levels~~ Cross sections have to be calibrated along the entire river, to allow realistic simulation of water levels. For this, a combination of conventional satellite altimetry from Envisat with the new data from CryoSat-2 ~~were~~ was used. Envisat data, like other data from repeat orbit missions, enable derivation of water level time series at so-called virtual stations where the satellite ground track intersects the river. ~~Water level~~Cross section calibration had to be limited to the Assam Valley, as this is the only part of the river where sufficient data from both CryoSat-2 and Envisat exist.

3 Data and methods

3.1 CryoSat-2 satellite altimetry data for rivers

In April 2010, the European Space Agency (ESA) launched CryoSat-2, a Synthetic Aperture Rader (SAR) satellite mainly designed to observe the cryosphere. However, it also proved useful to observe water levels over oceans and inland waters.

The data from CryoSat-2 are unique due to i) the satellite's drifting orbit and ii) its SAR Interferometric Radar Altimeter (SIRAL) sensor, making it possible to use a second antenna and then determine off-nadir positions of the radar reflections (European Space Agency and Mullar Space Science Laboratory, 2012). As will be shown in this work, this opens up for new applications of the data compared to conventional altimeters on a repeat orbit. CryoSat-2 is operating in three modes in different regions of the world determined by a geographical mode mask (European Space Agency 2016): In Low Resolution Mode (LRM) as a conventional altimeter over the interior of ice sheets or regions of low interest to the cryosphere community; in SAR mode with an along-track footprint of only 300m (Wingham et al., 2006) for example over regions where sea ice is of interest; and in SAR Interferometric (SARIn) mode using a second antenna and other additional signal processing steps over areas with challenging terrain. Because of the two antennas used in SARIn mode, the signal's main reflectance location can be determined. This gives an estimate of the exact location of the measurement, instead of the assumption that the measurement is placed directly at nadir as with conventional LRM and SAR altimetry data.

The data used for this study are Level 2 CryoSat-2 altimetry provided by the National Space Institute, Technical University of Denmark (DTU Space). These data were based on the ESA baseline-b Level 1b 20 Hz product, and retracked with an empirical retracker. For details of the processing please refer to Villadsen et al. (2015). Villadsen et al. also describe the application of the data over the Ganges and Brahmaputra rivers. Furthermore, Nielsen et al. (2015) were able to use these data to extract water levels over lakes as small as 9 km^2 at unprecedented accuracy. Some of ~~this~~ these data over lakes can be accessed via the Altimetry for inland Water (AltWater) service at http://altwater.dtu.space/ of DTU Space. For this work, data from CryoSat-2 are used from the beginning of its operation in 2010 until the end of 2013. Most of the Brahmaputra River is covered in SARIn mode, from its origin to the downstream end of the SARIn mask indicated in Figure 1, approximately 100 km upstream of the gauging station Bahadurabad.

3.1.1 Filtering of CryoSat-2 data – river mask

In the case of small inland water bodies, CryoSat-2 data, like any SAR altimeter data, currently do not deliver reliable information on whether it was acquired over water or over land surface. One relevant metadata item of satellite altimetry is the backscatter coefficient (also referred to as Sigma0). This value however, over small and often turbid water surfaces such as rivers does not allow a reliable discrimination between water and land surface points. In an effort of processing multi-mission data over inland waters, Schwatke et al. (2015) found backscatter only useful to deliver information about potential ice cover. This applies to both the Level 1b and Level 2 data. These challenges are also reflected in the processing of altimetry data developed for databases providing global inland water altimetry data that are described below.

Commonly, to filter relevant altimetry observations that represent river or lake surfaces, water masks derived from other remote sensing data are used. Existing global products include the MODIS river mask from the Moderate Resolution Imaging Spectroradiometer on board of the Terra and Aqua satellites. Those multi-spectral instruments can provide a mask with a high temporal resolution, however only at 250 m spatial resolution (Enjolras and Rodriguez, 2009). Often, those masks are also only used as static masks, see for example the MOD44W product (Carroll et al., 2009) used with CryoSat-2 data over the Brahmaputra and Ganges by Villadsen et al. (2015). Also the River&Lake dataset, an ESA project providing water level time series over inland water bodies globally from altimeters on board of ERS-2, Envisat and Jason-2, used a static water mask (Berry and Wheeler, 2009). Another database for satellite altimetry with global coverage, HydroWeb, uses simple rectangular masks at virtual stations where the satellites' repeat orbits intersect with the river (Rosmorduc, 2016), and then applies some outlier filtering based on single transects (Santos da Silva et al., 2010). Such a procedure cannot easily be applied to CryoSat-2 because of its drifting orbit. For the DAHITI database (Schwatke et al., 2015), which combines multi-mission data into common water level time series, a river mask is only applied via a simple latitude threshold (as all satellite tracks run in predominantly north-southerly direction). Then, further outlier criteria are applied to the data, including expected water height thresholds, height error thresholds, and along-track outlier tests. This procedure however also requires manual, individual inspection of river transects to tune the respective parameters.

The Brahmaputra in the Assam Valley has a braided river bed with river channels continuously changing their location and shape. Often, relevant changes can be seen from one year to another. Hence, for this work a high resolution, dynamic river mask was necessary for correct filtering of the CryoSat-2 altimetry data. This river mask was extracted from Landsat 7 and Landsat 8 NDVI imagery. Landsat imagery has been used repeatedly as a more finely resolved alternative to the global water masks discussed above, see for example the use with Envisat data over the Zambezi river by Michailovsky et al. (2012), with Envisat and ERS-2 data over the Mekong and Ob rivers by Birkinshaw et al. (2014), or the work by O'Loughlin et al. (2013) using river widths etc. extracted from Landsat NDVI imagery for a hydraulic characterisation of the Congo River.

32-day composites of Landsat 7 and 8 NDVI imagery, as available online from the EarthEngine (NASA Landsat Program, 2016) have been used to extract binary water masks over the entire Brahmaputra River covered in CryoSat-2's SARIn mode, where all areas with a NDVI value greater than zero were considered land surface, and the remaining parts water surface.

Because of optical imagery being unable to penetrate cloud cover, in this region it is not possible to acquire a complete river mask during each of these 32-day windows. The water mask extraction was done differently for the upstream and downstream portions of the river: u~~U~~pstream of the Assam Valley the Brahmaputra River bed is less dynamic, because the river is usually contained by a steep valley. For this part, available, i.e. cloud cover-free imagery from the years 2012 and 2013 was combined into one river mask. For the more dynamic Assam Valley, one river mask for each year was created from all available imagery for this year, resulting in four river masks for the relevant years 2010 to 2013. Only pixels that were water-covered in all usable 32-day composites of each year were considered water in the resulting mask. This means that the river masks represent an estimate of minimum water extent during each year. Manual inspection of Landsat imagery from different years has shown that most dramatic changes to the river's morphology become visible after each high-flow season, i.e. each year in late autumn. Hence, from the beginning of each calendar year a new river mask was used.

3.1.2 Projecting CryoSat-2 data into model space

In order to filter CryoSat-2 data for use in combination with the 1D hydrodynamic model used in this work, the points of CryoSat-2 observations have to be projected onto the model river line.

This procedure is displayed in Figure 2. CryoSat-2 observations are first filtered over the river mask of the respective year, and then projected onto their nearest neighbouring point on the model river line. The model river line is static over the entire simulation time. This is due to technical challenges in setting up and calibrating a model with a changing river line in MIKE ~~11~~HYDRO River. In addition, the hydrodynamic model's simulation results are relatively insensitive to the exact course of the river line as long as the 1D approximation adequately represents river conveyance. However, the model river line affects where the CryoSat-2 observations are mapped to the model.

3.2 Envisat virtual station data

The Envisat virtual station data to extract the water level amplitudes in the Brahmaputra River were taken from 13 virtual stations along the Assam Valley for the years 2002 to 2010. The data were taken from the River&Lake project database (Berry and Wheeler, 2009).

3.3 Hydrologic-h~~H~~ydrodynamic model

3.3.1 Hydrodynamic model

A model of the Brahmaputra Basin from the origin of the river to Bahadurabad station, close to the river's confluence with the Ganges River was set up in the DHI MIKE ~~11~~ HYDRO River software. The Brahmaputra River was modelled over a length of overall 3090 km. See Figure 1 for an overview. River flow in MIKE HYDRO River (previously referred to as MIKE 11) is modelled using a 1D dynamic wave routing based on the Saint-Venant equations for unsteady flow ~~(MIKE by DHI, 2009)~~ (Havnø et al., 1995). The governing equations are solved using a 6-point implicit finite difference scheme

(Abbott and Ionescu, 1967). The solution is computed on a staggered grid of alternating Q and h points. Simulated discharge is available at Q points only, while simulated water level is available only at h points. Cross sections can be placed anywhere along the river, but in the model they are always placed at h points. If necessary, cross section datums and shapes are linearly interpolated to achieve this. In our setup, the default distance between each Q and h point is 2.5 km The delineation of the river was based on the SRTM DEM. However, it should be noted that a river line based on the relatively coarse SRTM DEM can deviate from the natural river's course (or its centre line), see Figure 2. Inaccuracies in the used DEM also explain the slight disagreements between the river's course, the location of the discharge station and the actual basin outline in the very flat part of the river valley around Bahadurabad station. Discharge routing in the 1D hydrodynamic model however is insensitive to the exact location of the river line. Furthermore, despite considerable changes to the river channel, the general discharge-water level relationship in the Brahmaputra River seems to be fairly stable (Mirza, 2003). The hydrodynamic model was forced by simulated runoff from subcatchments. Applying this forcing, Manning's number was calibrated to a uniform value along the entire river (see also Figure 3) by minimizing RMSE between simulated and observed discharge at Bahadurabad station.

~~3.3.1~~3.3.2 Rainfall-runoff forcing of the hydrodynamic model

Simulated runoff was derived from a larger hydrologic-hydrodynamic model of the Ganges and Brahmaputra Basins developed ~~at the Danish Hydrologic Institute (~~ in a consultancy project of DHI~~)~~ and the International Centre for Integrated Mountain Development (ICIMOD). In this model, the runoff was simulated in 86 subcatchments (33 in the Brahmaputra Basin, indicated in Figure 1, and 53 in the Ganges Basin) using NAM rainfall-runoff models (Nielsen and Hansen, 1973). NAM is a lumped, conceptual rainfall-runoff model and can, as in this work, include snow melt processes. Due to restricted access to in situ data, the hydrologic model was based almost entirely on freely available remote sensing and other global data sources. For subcatchment delineation and elevation zoning of the NAM snow melt module the SRTM DEM was used. Precipitation forcing was derived from TRMM v7 3B42 data (Tropical Rainfall Measurement Mission Project (TRMM), 2011). Temperature and evaporation forcings were derived from the ERA-Interim reanalysis products from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., ~~(~~2011~~)~~ and Berrisford et al., ~~(~~2011~~)~~).

In situ discharge data were available for only 11 of the 86 subcatchments. Most of these are located in the Nepalese Himalaya and are part of the Ganges Basin. Only ~~one~~ two of the available in situ discharge stations ~~is~~ are located in the Brahmaputra Basin. Furthermore, in situ discharge data exist for both main rivers, the Ganges and Brahmaputra River, close to their confluence with each other, at Hardinge Bridge station and Bahadurabad station respectively. The existing subcatchment in situ discharge was used to calibrate the NAM models. Parameters for the 11 subcatchments were calibrated individually and then transferred to the remaining subcatchments, using simple heuristics. Parameters in the NAM model have some physical meaning, so for example differences in topography or land use can guide in how to transfer parameters from one catchment to another. So, even though only the Brahmaputra basin was part of this study, information on NAM parameters gained from the larger Ganges-Brahmaputra model was used. The overall performance evaluation of the model, and a calibration of the Manning's number of the hydrodynamic model was done by evaluating the model output at ~~the two stations Hardinge Bridge and~~ Bahadurabad station at the outlet. The calibration period included the years 2002 to 2007.

3.3.3 Boundary and initial conditions of the model

The hydrodynamic model was initialized from arbitrary initial conditions and warmed up for a sufficiently long period prior to the start of the actual simulation period. More relevant, however, are the initial conditions of the hydrologic model: some of the NAM model storages, such as groundwater and snow storage, have long residence times. Hence, the NAM models have been run for 30 iterations of the calibration period, until model states reached equilibrium. The resulting model states were then used as initial conditions for the simulation period. Furthermore, water level data from Aricha available for the years 2001 to 2009 was used as a downstream boundary condition of the hydrodynamic model. Outside this period, a daily water level climatology derived from the available observations has been used. Due to the location of Aricha approximately 180 km downstream of Bahadurabad station this has a negligible effect on results.

3.4 Cross section calibration

In the absence of in situ or precise local remote sensing data of the Brahmaputra River's cross sections or bathymetry, we used the SRTM DEM to derive the river's course with DEM hydroprocessing routines. The SRTM DEM, in combination with satellite imagery, was also used for a first guess of cross section datums and shapes along the Brahmaputra. These cross sections are a result of the DHI/ICIMOD project. Already here, due to the use of a 1D hydrodynamic model, the multi-channel river was simplified into one channel only. Due to the low spatial resolution of the SRTM DEM (90 metres) and the vertical standard error in the range of a few metres (Rodríguez et al., 2006), this provides a rough estimate of cross section datum. Furthermore, the SRTM DEM does not retrieve the submerged part of the river cross section, ~~thus cannot represent bathymetry~~which has to be estimated or guessed. Hence, a hydrodynamic model with cross sectional data derived from such a DEM cannot be expected to accurately simulate water levels. As CryoSat-2 observations will occur along the entire river, and not only limited to virtual station locations, water levels have to be reproduced accurately by the model along the entire river, if the (or any) altimetry data were to be combined with the model.

The ~~water level~~cross section calibration described in the following, fitting simulated water levels to observed water levels from altimetry, could only be performed for the downstream part of the Brahmaputra River, the Assam Valley. This is due to insufficient altimetry data from CryoSat-2 and Envisat available for the upstream part of the Brahmaputra River. ~~Water level~~ Cross section calibration was performed after ~~discharge~~ calibration of the ~~model~~ Manning's number as described in the previous section.

For the hydrodynamic model, conceptual cross sections in triangular shape were placed at regular 50 km or 12.5 km intervals along the river; with information from the SRTM DEM as a first guess. This generic, simple shape was chosen to ease the calibration process. Cross section parameters (datum and opening angle) were then calibrated using information obtained from both satellite altimeter data sources mentioned above to fit i) the average absolute water level along the river and ii) the water level amplitudes in the river. In combination, the two altimeter missions proved to provide very useful insight into all relevant dynamics of water levels in the river (profiles of average absolute water levels and water level amplitudes) ~~of water levels in the river~~ due to their different orbits.

Figure 3 ~~shows~~ summarises the entire calibration process of the hydrologic-hydrodynamic model. It is assumed that the cross section calibration has negligible influence on (the timing of) discharge. With the used hydrodynamic model this holds true if a reasonable first guess for the cross sections was made.

3.4.1 Step 1: c~~C~~ross section calibration using average water levels

The drifting orbit of CryoSat-2 allows derivation of average water level profiles along the river with high spatial resolution if several years of data are taken into account. These water level profiles are of higher accuracy than what can be extracted from SRTM DEM because of the lower standard error of CryoSat-2 altimetry data. Besides that, the CryoSat-2 data are filtered specifically to include only data of the actual water surface, unlike the SRTM DEM that averages different landcover and terrain types within one 90 m pixel. Also the dynamic river morphology requires use of current water level observations, instead of historic SRTM data which was acquired in 2000. This means that in the first step, as displayed in Figure 4, the cross sections' datums were calibrated to fit the average simulated water level profile along the river to the average water level profile observed by CryoSat-2.

3.4.2 Step 2: c~~C~~ross section calibration using water level amplitudes

In the second step, the Envisat virtual station water level time series were used to calibrate cross section shapes to fit the water level amplitudes at the locations of the 13 virtual stations (see Figure 1) along the Assam Valley. The information used here was the relative water levels, i.e. simulated yearly water level amplitudes were fitted to the observed ones from Envisat. To account for the coarse temporal resolution of Envisat data of 35 days and the resulting risk of losing a peak, simulated data were only extracted at the exact times of Envisat observations to determine the simulated water level amplitudes.

To perform the calibration, the MIKE ~~11~~ HYDRO River model was coupled with a genetic search algorithm implemented in Matlab for numerical optimisation. Table 1 gives an overview over calibration parameters and objective functions used for both steps.

As cross sections were placed every 12.5 km or 50 km, i.e. at finer intervals than virtual station observations were available, cross section angles were interpolated linearly for cross sections without any neighbouring virtual station. The change of the cross section shape in calibration step 2 has a relevant effect not only on the water level amplitudes but, at some points in the model, also on the absolute average water levels. Consequently, step 1 of the water level calibration procedure has to be repeated with the cross section shapes that resulted from step 2. This leads to an iterative process displayed in Figure 3. It usually can be ended after few iterations at step 1, as simulated water level amplitudes are insensitive to moderate changes in the cross section datums.

4 Results and Discussion

4.1 Water level from CryoSat-2 data

The filtering of CryoSat-2 data over the Landsat river masks for 2010 to 2013 resulted in 4806 single observations. A~~n~~ ~~outlier~~ filtering of obvious outliers was performed, excluding CryoSat-2 values which deviate more than 20 metres from the SRTM elevations along the model river line. After outlier filtering, 3868 CryoSat-2 observations remain. Figure 5 displays longitudinal profiles of outliers and outlier-filtered values, as well as mapped outlier-filtered values along the course of the Brahmaputra River. The value of 20 metres was chosen after inspection of the data. It ensures removal of all obvious outliers, maybe due to issues with the closed-loop control of CryoSat-2. ~~2794~~ 2710 of the outlier-filtered measurements lie in the Assam Valley of the Brahmaputra River, which were used for the cross section calibration. The number of data points and outliers are summarized in Table 2.

In the upstream part of the Brahmaputra, from river km 0 to approximately km 2100, there is a considerable amount of outliers. This is the part characterised by a steep or even gorge-like river valley (Jain et al., 2007). All the CryoSat-2 data used here are acquired in SARIn mode which allows determining the true ground location of the observation. However, the applied off-nadir ranging is also connected with uncertainties (Armitage and Davidson, 2014). This could be one reason for the large amount of outliers in this part of the river. Furthermore, these outliers – most of them are clear outliers, with elevations hundreds of metres off – can be related to the steep valley making it impossible for the altimeter's signals to reach the valley bottom, i.e. the river water surface. Note in this context that CryoSat-2's measurement footprint area is 0.5 km^2 (Scagliola, 2013) with an along-track resolution of about 300 metres (European Space Agency and Mullar Space Science Laboratory, 2012) in SARIn mode. Envisat, for example, has a measurement footprint diameter of 2 to 10 km (Chelton et al., 2001) and an along-track resolution of 369 metres (Berry et al., 2008), making it more likely for CryoSat-2, especially over challenging terrain, to lock onto the target of interest. Another issue with steep terrain is that the range window, in which an altimeter actually records potential reflections from the surface, constantly has to be adjusted according to the terrain. CryoSat-2's closed-loop control in SARIn mode means that it often misses to reach valley bottoms in mountainous regions (Dehecq et al., 2013). It can be seen in the graph in Figure 5 that the steepest parts of the river (around river km 500, 900, 1250, and between km 1600 and 2000) contain almost no usable data at all. These steepest parts of the river often coincide with the most narrow parts of the river valley. The Assam Valley however requires almost no outlier filtering at all. Furthermore, it can be seen that CryoSat-2 captures some details in the river bed level that the SRTM data are not showing – see for example the detail around river km 1200 in Figure 5. And the CryoSat-2 data give an idea of the seasonal variability of water levels along the river.

It can be concluded that CryoSat-2 altimetry data can be used over the parts of the Brahmaputra River with moderate topography. In the areas with extreme topography, a large amount of outliers can be found, however still leaving a relevant amount of usable observations. This is important as none of the existing inland water altimetry databases (River&Lake, HydroWeb, DAHITI) provides data over the upstream part of the Brahmaputra River.

The use of a better river mask would likely improve the data yield. Such river masks should have a high temporal resolution (at least seasonal), and a high spatial resolution (well below the widths of the river channels of a few hundred metres). Using SAR imagery should give better results than the optical Landsat imagery used here: SAR imagery penetrates cloud cover, also giving results in the high-flow season of the Brahmaputra River where it was never possible to get consistent optical imagery. Since the start of Sentinel-1A as part of the Copernicus programme in April 2014, a freely available source for high resolution SAR imagery exists (Sentinel-1 Team, 2013) that could largely improve the river masks used for this work.

4.2 Hydrologic-hydrodynamic model calibration of discharge

After the calibration of the rainfall-runoff models the hydrodynamic model was calibrated to in situ observations at its outlet, Bahadurabad station (see Figure 1). This was done by adjusting Manning's number, affecting the timing of the discharge routing. The optimal Manning's number was found to be 0.029 in SI units, which is considered plausible (compare Chow (1959), Table 5-6). Furthermore it was observed, both for the single catchments and the entire Brahmaputra River at Bahadurabad, that the precipitation forcing is likely underestimating the real precipitation. It was necessary to scale the TRMM precipitation data with a factor of 1.4 to obtain a good water balance. An underestimation of precipitation by remote sensing data can be observed sometimes, especially in regions with a large share of small-scale convective rainfall events. Also Michailovsky et al. (2013) observed in their work that the TRMM 3B42 had to be scaled by a factor of 1.25 to give good results in a hydrologic model of the Brahmaputra Basin. Moreover, given the large size of the subcatchments, spatial variation of precipitation due to topography (which is present in the Himalaya, see for example Bookhagen & Burbank, ~~(~~2006~~)~~) cannot be fully accounted for. Figure 6 shows simulated and observed discharge at Bahadurabad station.

Table 3 gives an overview over performance criteria, comparing observed and simulated discharge at Bahadurabad station for the calibration and validation period. For the validation period 2010 to 2013 data were usually only available during the high-flow season April to October. Hence, for comparability Table 3 also lists values for the calibration period taking only April to October into account. The good performance for the calibration period with a Nash-Sutcliffe coefficient (NSE) of 0.93, or 0.89 respectively, is reduced for the validation period to a NSE of 0.81. Also, the low water balance bias of around -2% in the calibration period increases to +11% for the validation period, meaning that the model is overestimating the discharge at Bahadurabad station. It is noticeable that the rainfall-runoff model performance on the subcatchment level is poorer than the performance of the aggregated model at the basin outlet (see Table 4). For subcatchments with available discharge observations the average NSE is 0.47. The poor subcatchment-level performance can maybe be explained by small scale precipitation patterns not properly represented by the TRMM precipitation product. The errors on the subcatchment level are almost uncorrelated to each other: the average Pearson coefficient of cross correlation of the subcatchments' runoff residuals is only 0.16. When these runoffs then are aggregated in the hydrodynamic model the uncertainties from the individual subcatchments cancel each other out to some degree, leading to a much better performance on the basin level than on the subcatchment level. This can also be seen as an indicator that the NAM model parameter transfer was successful.

4.3 Cross section calibration

Figure 7 shows the results of step 1 of the water level calibration. For better visibility, the results are all shown in elevations relative to the reference model's cross section datums instead of absolute elevations. The reference model was run with the first-guess cross sections ~~datums~~ derived from the SRTM DEM described in section 3.4. It can be seen that the average simulated water levels from the reference model do not accurately represent the CryoSat-2 observations. After calibrating the cross section datums – which meant adjusting their datum by up to 4 metres – the simulated average water level follows the CryoSat-2 observations more closely. The calibration reduced the RMSE between average simulated water level and CryoSat-2 observations from 3.1 metres for the reference model to 2.5 metres. The remaining deviation can mainly be explained by the seasonal water level variations in the river.

While studying first results from this calibration step, we realized that between river km 2050 and 2150 the river bed slope is changing multiple times and finer cross section spacing is needed to accurately represent river morphology. Hence, in this part additional cross sections were added reducing the cross section spacing from 50 km to 12.5 km.

For one of the virtual stations, the results of step 2 of the cross section calibration can be seen in Figure 8. The average RMSE between simulated and observed yearly water level amplitudes for all 13 virtual stations was 0.83 metres after the calibration.

~~The change of the cross section shape in this calibration step showed to have a relevant effect not only on the water level amplitudes but, at some points in the model, also on the absolute average water levels. Consequently, step 1 of the water level calibration procedure had to be repeated with the cross section shapes that resulted from step 2.~~It has to be noted that CryoSat-2 data was used approximately from river km 1950 to 2800, whilst Envisat data was available from river km 2050 to 3050. Hence, only the overlapping stretch from river km 2050 to 2800, spanning a total of 22 cross sections in the chosen setup, can be considered fully calibrated.

The cross section calibration procedure developed offers a way to obtain a rather simple 1D hydrodynamic model accurately representing water levels, without precise knowledge of topography or bathymetry. Synthetic cross sections allow the use of practically any shape, however for the sake of reducing the number of fitting parameters in the calibration algorithm a simple triangular shape was chosen. These simple cross section shapes proved to be able to reproduce the observed water level amplitudes. Also, other physical properties of the hydrodynamic model are in a plausible range: For the calibrated stretch of the Brahmaputra River, the average Froude number at the model's individual grid points varies from 0.086 to 0.4149 in the high flow season, and from 0.070 to 0.399 in the low flow season. The average simulated water depth varies from 1.80 to 9.77 metres in the high flow season, and from 1.02 to 6.08 metres in the low flow season. This means that the modelled flow is well in the subcritical range, as expected for the given river section. Still it has to be stressed that properties other than discharge and water level will not be represented realistically. Trigg et al. (2009) had similar success with simplistic cross section geometries: They introduced only marginal errors in water levels from a hydrodynamic model of the Amazon River when switching from surveyed cross sections to rectangular representations. However, for some rivers, it might be impossible to model the observed discharge-water level relationships with such simplistic cross sections. The approach can be adapted for a slightly more complex representation of cross section geometry, as for example suggested by Neal et al. (2015).

5 Conclusion

This is one of the first studies demonstrating how to use Cryosat-2 type radar altimetry data in connection with river models. There have been other suggestions on how to use spatially distributed satellite altimetry in combination with hydrologic~~al~~ models. Often, however, they still rely on the concept of virtual stations; see the review in the introduction section. Other studies fall back on data from in situ gauging stations such as the work by Getirana (2010) using Envisat data to calibrate a model of the Negro River in the Amazon Basin, where data from a network of in situ gauging stations was used to estimate the water level-discharge relationships in a hydrologic model.

The method developed in this study, combining altimetry data from two missions with different orbits with a hydrologic-hydrodynamic model allows the calibration of cross sections in a 1D hydrodynamic river model without precise knowledge of topography or bathymetry. This results in a model accurately simulating water levels, which is an important achievement if poorly gauged river basins are to be modelled. ~~Using globally~~Globally available DEMs such as the SRTM product ~~does not provide sufficient information~~ are used to create~~ a~~ hydrodynamic models, though they do not always provide enough information to ~~reproducing~~ reproduce ~~accurate~~ water levels or inundations areas at high accuracy. Jarihani et al. (2015) used cross sections derived from the SRTM DEM and different hydraulically and vegetation corrected versions of it, and compared to elevations from ICESat and surveyed points. Even correcting the SRTM for vegetation and submerged parts, a relevant error remained. Similar work was done by ~~as could be seen in this study and was for example shown by~~ Md Ali et al. (2015), who compared water levels in a hydrodynamic model based on the SRTM DEM with those from a model based on more accurate lidar data. The resulting simulated water levels showed relevant differences. Similar conclusions can be drawn from this study.

Envisat data – similar to data from other conventional altimeters such as ERS-2, Jason-2 or TOPEX/Poseidon – were used as a virtual station time series to extract water level time series. This kind of water level data are directly accessible from inland water satellite altimetry databases such as River&Lake, HydroWeb, or DAHITI. DAHITI started incorporating CryoSat-2 data in their multi-mission product. Still, CryoSat-2 data as river water levels currently cannot be accessed directly through any of those sources. Hence, for this work a filtering procedure based on dynamic Landsat river masks was developed and applied to the CryoSat-2 data. This procedure took the dynamic nature of the Brahmaputra River's morphology into account and allowed to extract river water levels also over narrow parts of the river in extreme terrains, where existing global databases of inland altimetry do not offer any data. These data cannot be used to directly extract water level time series, but they display longitudinal water level profiles.

The hydrologic-hydrodynamic model of Brahmaputra River Basin that was used in conjunction with the satellite data, has been set up almost exclusively using openly accessible remote sensing and other global data sources. Thus, the methodology developed is ~~applicable to any sufficiently large river system~~transferrable to other case studies. The applicability of the suggested cross section calibration is only limited by the availability of a sufficient amount of (satellite) altimetry observations, which mainly depends on river width and topography. The resulting calibrated model can be used for operational river discharge or water level forecasting, and be further informed by assimilating discharge measurements or water level measurements from various sources such as different altimetry missions.

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References

Abbott, M. B. and Ionescu, F.: On The Numerical Computation Of Nearly Horizontal Flows, J. Hydraul. Res., 5(2), 97–117, doi:10.1080/00221686709500195, 1967.

Armitage, T. W. K. and Davidson, M. W. J.: Using the Interferometric Capabilities of the ESA CryoSat-2 Mission to Improve the Accuracy of Sea Ice Freeboard Retrievals, IEEE Trans. Geosci. Remote Sens., 42(1–2), 529–536, doi:10.1109/TGRS.2013.2242082, 2014.

Becker, M., da Silva, J., Calmant, S., Robinet, V., Linguet, L. and Seyler, F.: Water Level Fluctuations in the Congo Basin Derived from ENVISAT Satellite Altimetry, Remote Sens., 6(10), 9340–9358, doi:10.3390/rs6109340, 2014.

Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S. and Uppala, S.: The ERA-Interim Archive - Version 2.0., 2011.

Berry, P. A. M. and Wheeler, J. L.: JASON2-ENVISAT Exploitation - Development of Algorithms for the Exploitation of JASON2-ENVISAT Altimetry for the Generation of a River and Lake Product. Product Handbook v3.5., 2009.

Berry, P. A. M., Smith, R. G. and Benveniste, J.: ACE2: The New Global Digital Elevation Model, in Gravity, Geoid and Earth Observation, vol. 135, edited by S. P. Mertikas, Springer., 2008.

Biancamaria, S., Bates, P. D., Boone, A. and Mognard, N. M.: Large-scale coupled hydrologic and hydraulic modelling of the Ob river in Siberia, J. Hydrol., 379(1–2), 136–150, doi:10.1016/j.jhydrol.2009.09.054, 2009.

Biancamaria, S., Durand, M., Andreadis, K. M., Bates, P. D., Boone, A., Mognard, N. M., Rodríguez, E., Alsdorf, D. E., Lettenmaier, D. P. and Clark, E. A.: Assimilation of virtual wide swath altimetry to improve Arctic river modeling, Remote Sens. Environ., 115(2), 373–381, doi:10.1016/j.rse.2010.09.008, 2011a.

Biancamaria, S., Hossain, F. and Lettenmaier, D. P.: Forecasting transboundary river water elevations from space, Geophys. Res. Lett., 38, L11401, doi:10.1029/2011GL047290, 2011b.

Birkinshaw, S. J., Moore, P., Kilsby, C. G., O'Donnell, G. M., Hardy, A. J. and Berry, P. A. M.: Daily discharge estimation at ungauged river sites using remote sensing, Hydrol. Process., 28(3), 1043–1054, doi:10.1002/hyp.9647, 2014.

Bookhagen, B. and Burbank, D. W.: Topography, relief, and TRMM-derived rainfall variations along the Himalaya, Geophys. Res. Lett., 33(8), L08405, doi:10.1029/2006GL026037, 2006.

Carroll, M. L., Townshend, J. R., DiMiceli, C. M., Noojipady, P. and Sohlberg, R. A.: A new global raster water mask at 250 m resolution, Int. J. Digit. Earth, 2(4), 291–308, doi:10.1080/17538940902951401, 2009.

Central Water Commission: Integrated Hydrological Data Book (non-classified river basins), New Delhi., 2009.

Chelton, D. B., Ries, J. C., Haines, B. J., Fu, L.-L. and Callahan, P. S.: Satellite Altimetry, in Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications, vol. 69, edited by L. Fu and A. Cazenave, pp. 2504–2510, Academic Press., 2001.

Chow, V. T.: Open Channel Hydraulics, McGraw-Hill., 1959.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., Mcnally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N. and Vitart, F.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137(656), 553–597, doi:10.1002/qj.828, 2011.

Dehecq, A., Gourmelen, N., Shepherd, A., Cullen, R. and Trouvé, E.: Evaluation of CryoSat-2 for height retrieval over the Himalayan range, in CryoSat-2 third user workshop, March 2013, Dresden, Germany., 2013.

DHI: MIKE 11 - A Modelling System for Rivers and Channels - Reference Manual, Hørsholm, Denmark., 2015.

Domeneghetti, A., Tarpanelli, A., Brocca, L., Barbetta, S., Moramarco, T., Castellarin, A. and Brath, A.: The use of remote sensing-derived water surface data for hydraulic model calibration, Remote Sens. Environ., 149, 130–141, doi:10.1016/j.rse.2014.04.007, 2014.

Enjolras, V. M. and Rodriguez, E.: Using Altimetry Waveform Data and Ancillary Information From SRTM, Landsat, and MODIS to Retrieve River Characteristics, IEEE Trans. Geosci. Remote Sens., 47(6), 1869–1881, doi:10.1109/TGRS.2008.2006365, 2009.

European Space Agency and Mullar Space Science Laboratory: CryoSat Product Handbook., 2012.

European Space Agency (ESA): Geographical Mode Mask, [online] Available from: https://earth.esa.int/web/guest/-/geographical-mode-mask-7107, 2016.

García-Pintado, J., Neal, J. C., Mason, D. C., Dance, S. L. and Bates, P. D.: Scheduling satellite-based SAR acquisition for sequential assimilation of water level observations into flood modelling, J. Hydrol., (495), 252–266, doi:10.1016/j.jhydrol.2013.03.050, 2013.

Getirana, A. C. V.: Integrating spatial altimetry data into the automatic calibration of hydrological models, J. Hydrol., 387(3–4), 244–255, doi:10.1016/j.jhydrol.2010.04.013, 2010.

Global Runoff Data Center (GRDC): Global Runoff Database, 2015.

Havnø, K., Madsen, M. N. and Dørge, J.: MIKE 11 - A Generalized River Modelling Package, in Computer Models of Watershed Hydrology, edited by V. P. Singh, pp. 733–782, Water Resource Publications., 1995.

Hossain, F., Maswood, M., Siddique-E-Akbor, A. H., Yigzaw, W., Mazumdar, L. C., Ahmed, T., Hossain, M., Shah-Newaz, S. M., Limaye, A., Lee, H., Pradhan, S., Shrestha, B., Bajracahrya, B., Biancamaria, S., Shum, C. K. and Turk, F. J.: A promising radar altimetry satellite system for operational flood forecasting in flood-prone bangladesh, IEEE Geosci. Remote Sens. Mag., 2(3), 27–36, doi:10.1109/MGRS.2014.2345414, 2014.

Jain, S. K., Agarwal, P. K. and Singh, V. P.: Brahmaputra and Barak Basin, in Hydrology and Water Resources of India, vol. 57, pp. 419–472, Springer Netherlands, Dordrecht., 2007.

Jarihani, A. A., Callow, J. N., McVicar, T. R., Van Niel, T. G. and Larsen, J. R.: Satellite-derived Digital Elevation Model (DEM) selection, preparation and correction for hydrodynamic modelling in large, low-gradient and data-sparse catchments, J. Hydrol., 524, 489–506, doi:10.1016/j.jhydrol.2015.02.049, 2015.

Md Ali, A., Solomatine, D. P. and Di Baldassarre, G.: Assessing the impact of different sources of topographic data on 1-D hydraulic modelling of floods, Hydrol. Earth Syst. Sci., 19, 631–643, doi:10.5194/hess-19-631-2015, 2015.

Michailovsky, C. I., McEnnis, S., Berry, P. A. M., Smith, R. and Bauer-Gottwein, P.: River monitoring from satellite radar altimetry in the Zambezi River Basin, Hydrol. Earth Syst. Sci., 16(7), 2181–2192, doi:10.5194/hess-16-2181-2012, 2012.

Michailovsky, C. I., Milzow, C. and Bauer-Gottwein, P.: Assimilation of radar altimetry to a routing model of the Brahmaputra River, Water Resour. Res., 49(8), 4807–4816, doi:10.1002/wrcr.20345, 2013.

Mirza, M. M. Q.: The Choice of Stage-Discharge Relationship for the Ganges and Brahmaputra Rivers in Bangladesh, Nord. Hydrol., 34(4), 321–342, doi:10.2166/nh.2003.019, 2003.

NASA: NASA Science Missions - SWOT, [online] Available from: http://science.nasa.gov/missions/swot/ (Accessed 1 May 2016), 2016.

NASA Landsat Program: Landsat 7 and 8 NDVI 32-day composites, as available at https://earthengine.google.com/, [online] Available from: https://explorer.earthengine.google.com/#detail/LANDSAT%252FLE7_L1T_ANNUAL_NDVI (Accessed 1 May 2016), 2016.

Neal, J., Schumann, G. and Bates, P.: A subgrid channel model for simulating river hydraulics and floodplain inundation over large and data sparse areas, Water Resour. Res., 48, W11506, doi:10.1029/2012WR012514, 2012.

Neal, J. C., Odoni, N. A., Trigg, M. A., Freer, J. E., Garcia-Pintado, J., Mason, D. C., Wood, M. and Bates, P. D.: Efficient incorporation of channel cross-section geometry uncertainty into regional and global scale flood inundation models, J. Hydrol., 529, 169–183, doi:10.1016/j.jhydrol.2015.07.026, 2015.

Nielsen, K., Stenseng, L., Andersen, O. B., Villadsen, H. and Knudsen, P.: Validation of CryoSat-2 SAR mode based lake levels, Remote Sens. Environ., 171, 162–170, doi:10.1016/j.rse.2015.10.023, 2015.

Nielsen, S. A. and Hansen, E.: Numerical simulation of the rainfall runoff process on a daily basis, Nord. Hydrol., 4, 171–190, 1973.

O'Loughlin, F., Trigg, M. A., Schumann, G. J. P. and Bates, P. D.: Hydraulic characterization of the middle reach of the Congo River, Water Resour. Res., 49(8), 5059–5070, doi:10.1002/wrcr.20398, 2013.

O'Loughlin, F. E., Neal, J., Yamazaki, D. and Bates, P. D.: ICESat-derived inland water surface spot heights, Water Resour. Res., 52(4), 3276–3284, doi:10.1002/2015WR018237, 2016.

Paiva, R. C. D., Collischonn, W., Bonnet, M.-P., de Gonçalves, L. G. G., Calmant, S., Getirana, A. and Santos da Silva, J.: Assimilating in situ and radar altimetry data into a large-scale hydrologic-hydrodynamic model for streamflow forecast in the Amazon, Hydrol. Earth Syst. Sci., 10(3), 2879–2925, doi:10.5194/hess-17-2929-2013, 2013.

Papa, F., Frappart, F., Malbeteau, Y., Shamsudduha, M., Vuruputur, V., Sekhar, M., Ramillien, G., Prigent, C., Aires, F., Pandey, R. K., Bala, S. and Calmant, S.: Satellite-derived surface and sub-surface water storage in the Ganges–Brahmaputra River Basin, J. Hydrol. Reg. Stud., 4, 15–35, doi:10.1016/j.ejrh.2015.03.004, 2015.

Robert Brakenridge, G., Cohen, S., Kettner, A. J., De Groeve, T., Nghiem, S. V., Syvitski, J. P. M. and Fekete, B. M.: Calibration of satellite measurements of river discharge using a global hydrology model, J. Hydrol., 475, 123–136, doi:10.1016/j.jhydrol.2012.09.035, 2012.

Rodríguez, E., Morris, C. S. and Beiz, E. J.: A Global Assessment of the SRTM Performance, Photogramm. Eng. Remote Sens., 72(3), 249–260, doi:10.14358/PERS.72.3.249, 2006.

Rosmorduc, V.: Hydroweb Product User Manual V1.0., 2016.

Santos da Silva, J., Calmant, S., Seyler, F., Rotunno Filho, O. C., Cochonneau, G. and Mansur, W. J.: Water levels in the Amazon basin derived from the ERS 2 and ENVISAT radar altimetry missions, Remote Sens. Environ., 114(10), 2160–2181, doi:10.1016/j.rse.2010.04.020, 2010.

Sarkar, A., Gard, R. D. and Sharma, N.: RS-GIS Based Assessment of River Dynamics of Brahmaputra River in India, J. Water Resour. Prot., 4(2), 63–72, doi:10.4236/jwarp.2012.42008, 2012.

Scagliola, M.: CryoSat footprints - Aresys Technical Note., 2013.

Schumann, G. J. P., Neal, J. C., Voisin, N., Andreadis, K. M., Pappenberger, F., Phanthuwongpakdee, N., Hall, A. C. and Bates, P. D.: A first large-scale flood inundation forecasting model, Water Resour. Res., 49(10), 6248–6257, doi:10.1002/wrcr.20521, 2013.

Schwatke, C., Dettmering, D., Bosch, W. and Seitz, F.: DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry, Hydrol. Earth Syst. Sci., 19, 4345–4364, doi:10.5194/hess-19-4345-2015, 2015.

Sentinel-1 Team: Sentinel-1 User Handbook., 2013.

Tarpanelli, A., Brocca, L., Barbetta, S., Faruolo, M., Lacava, T. and Moramarco, T.: Coupling MODIS and Radar Altimetry Data for Discharge Estimation in Poorly Gauged River Basins, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 8(1), 141–148, doi:10.1109/JSTARS.2014.2320582, 2015.

Tourian, M. J., Tarpanelli, A., Elmi, O., Qin, T., Brocca, L., Moramarco, T. and Sneeuw, N.: Spatiotemporal densification of river water level time series by multimission satellite altimetry, Water Resour. Res., 52, 1140–1159, doi:10.1002/2015WR017654, 2016.

Trigg, M. A., Wilson, M. D., Bates, P. D., Horritt, M. S., Alsdorf, D. E., Forsberg, B. R. and Vega, M. C.: Amazon flood wave hydraulics, J. Hydrol., 374, 92–105, doi:10.1016/j.jhydrol.2009.06.004, 2009.

Tropical Rainfall Measurement Mission Project (TRMM): Tropical Rainfall Measurement Mission Project (TRMM) 3-Hourly 0.25 deg. TRMM and Others Rainfall Estimate Data, 2011.

Villadsen, H., Andersen, O. B., Stenseng, L., Nielsen, K. and Knudsen, P.: CryoSat-2 altimetry for river level monitoring - Evaluation in the Ganges-Brahmaputra basin, Remote Sens. Environ., 168, 80–89, doi:10.1016/j.rse.2015.05.025, 2015.

Wingham, D. J., Francis, C. R., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., de Chateau-Thierry, P., Laxon, S. W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P. and Wallis, D. W.: CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields, Adv. Sp. Res., 37(4), 841–871, doi:10.1016/j.asr.2005.07.027, 2006.

Yamazaki, D., Baugh, C. A., Bates, P. D., Kanae, S., Alsdorf, D. E. and Oki, T.: Adjustment of a spaceborne DEM for use in floodplain hydrodynamic modeling, J. Hydrol., 436–437, 81–91, doi:10.1016/j.jhydrol.2012.02.045, 2012a.

Yamazaki, D., Lee, H., Alsdorf, D. E., Dutra, E., Kim, H., Kanae, S. and Oki, T.: Analysis of the water level dynamics simulated by a global river model: A case study in the Amazon River, Water Resour. Res., 48(9), W09508, doi:10.1029/2012WR011869, 2012b.

Yan, K., Tarpanelli, A., Balint, G., Moramarco, T. and Di Baldassarre, G.: Exploring the Potential of SRTM Topography and Radar Altimetry to Support Flood Propagation Modeling: Danube Case Study, J. Hydrol. Eng., 20(2), doi:10.1061/(ASCE)HE.1943-5584.0001018, 2014.

Yoon, Y., Durand, M., Merry, C. J., Clark, E. a., Andreadis, K. M. and Alsdorf, D. E.: Estimating river bathymetry from data assimilation of synthetic SWOT measurements, J. Hydrol., 464–465, 363–375, doi:10.1016/j.jhydrol.2012.07.028, 2012.

Figures and tables

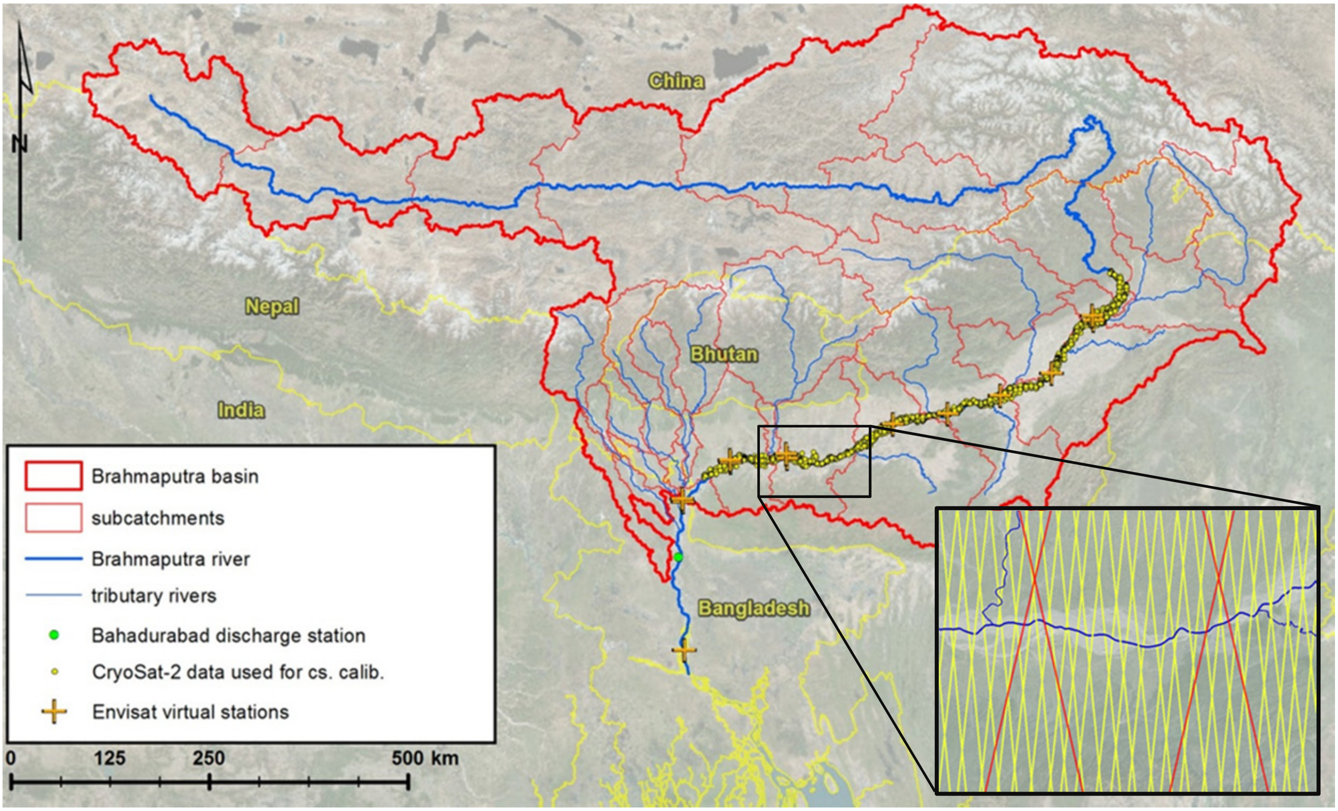

Figure 1: Brahmaputra basin model base map, showing the altimetry data used for the water level calibration (the entire upstream part of the Brahmaputra is also covered by the SARIn mode of CryoSat-2). Map inset: Ground tracks of CryoSat-2 (yellow) and Envisat (red)

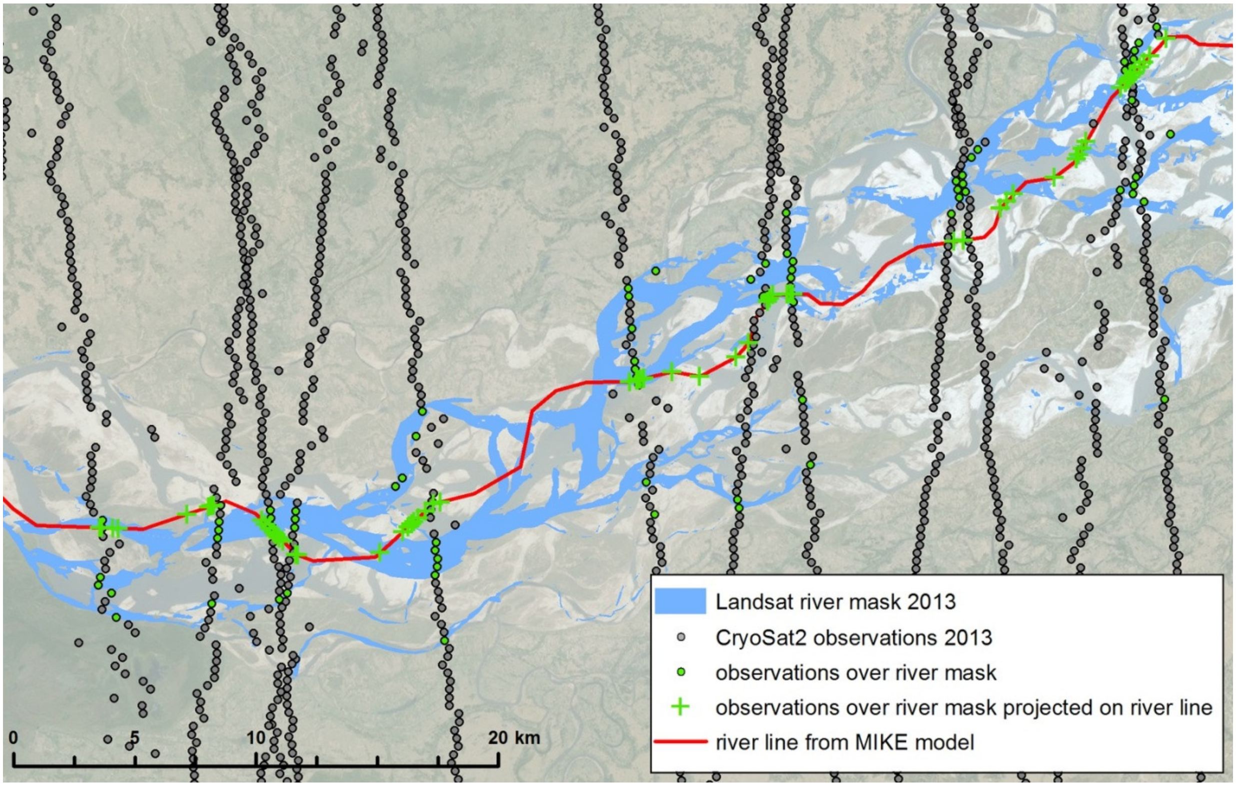

Figure 2: Section of the Brahmaputra in the Assam Valley showing the Landsat river mask, the CryoSat-2 observations and their mapping to the 1D river model, all for 2013

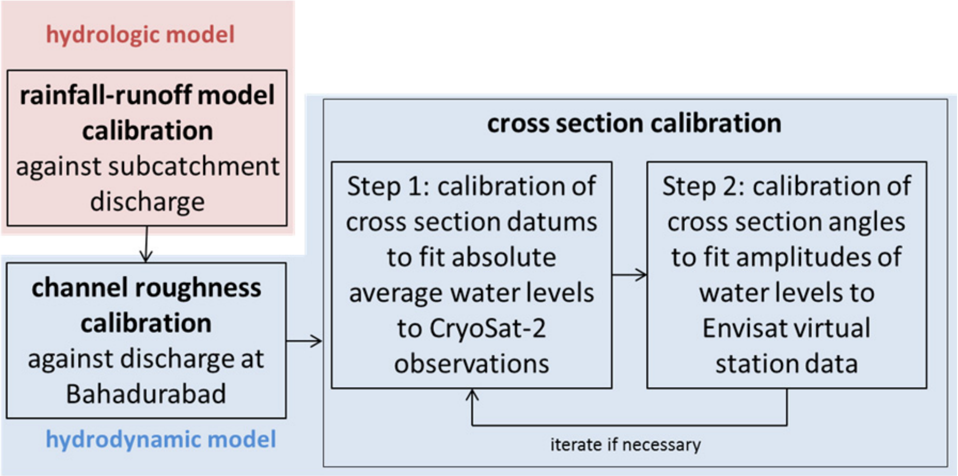

Figure 3: Flow chart showing the hydrological and hydrodynamic model calibration~~ of both discharge and water levels in the hydrodynamic model~~.

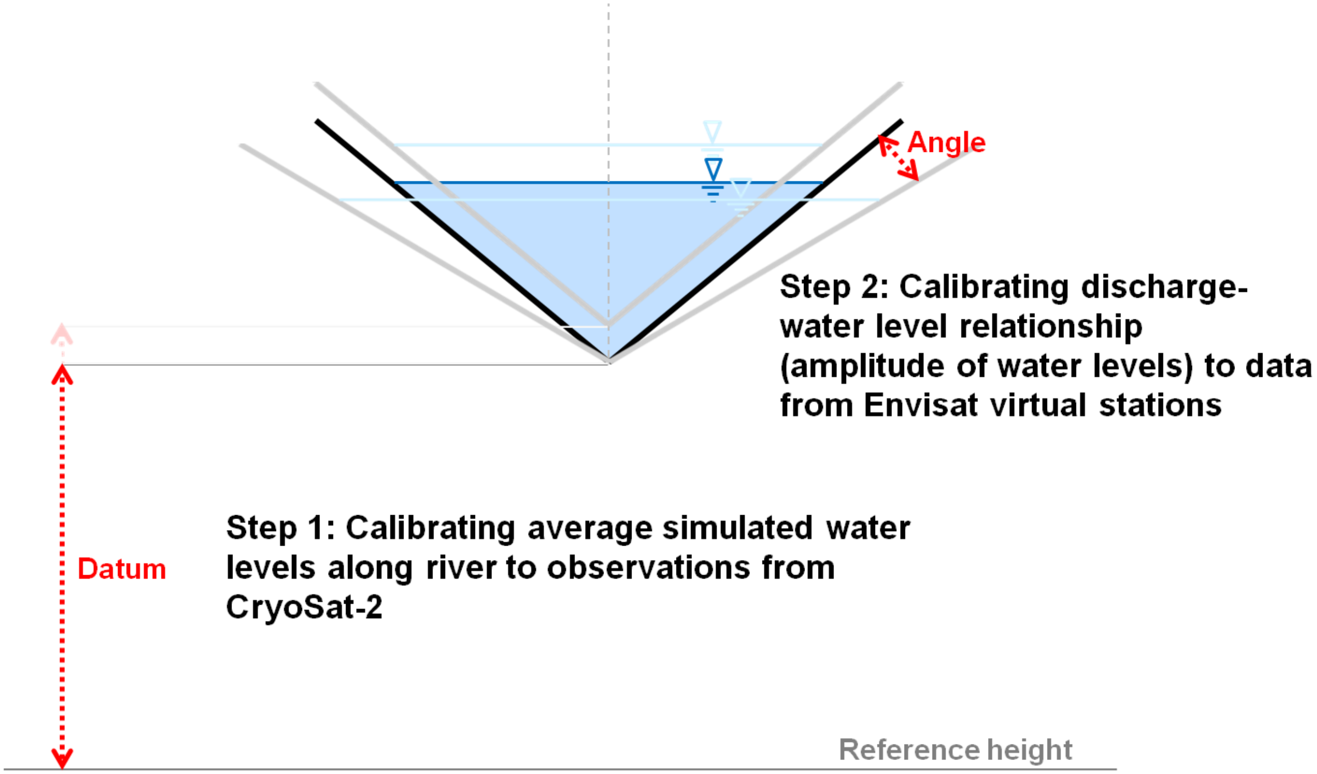

Figure 4: Sketch of the two-step cross section calibration with their calibration parameters.

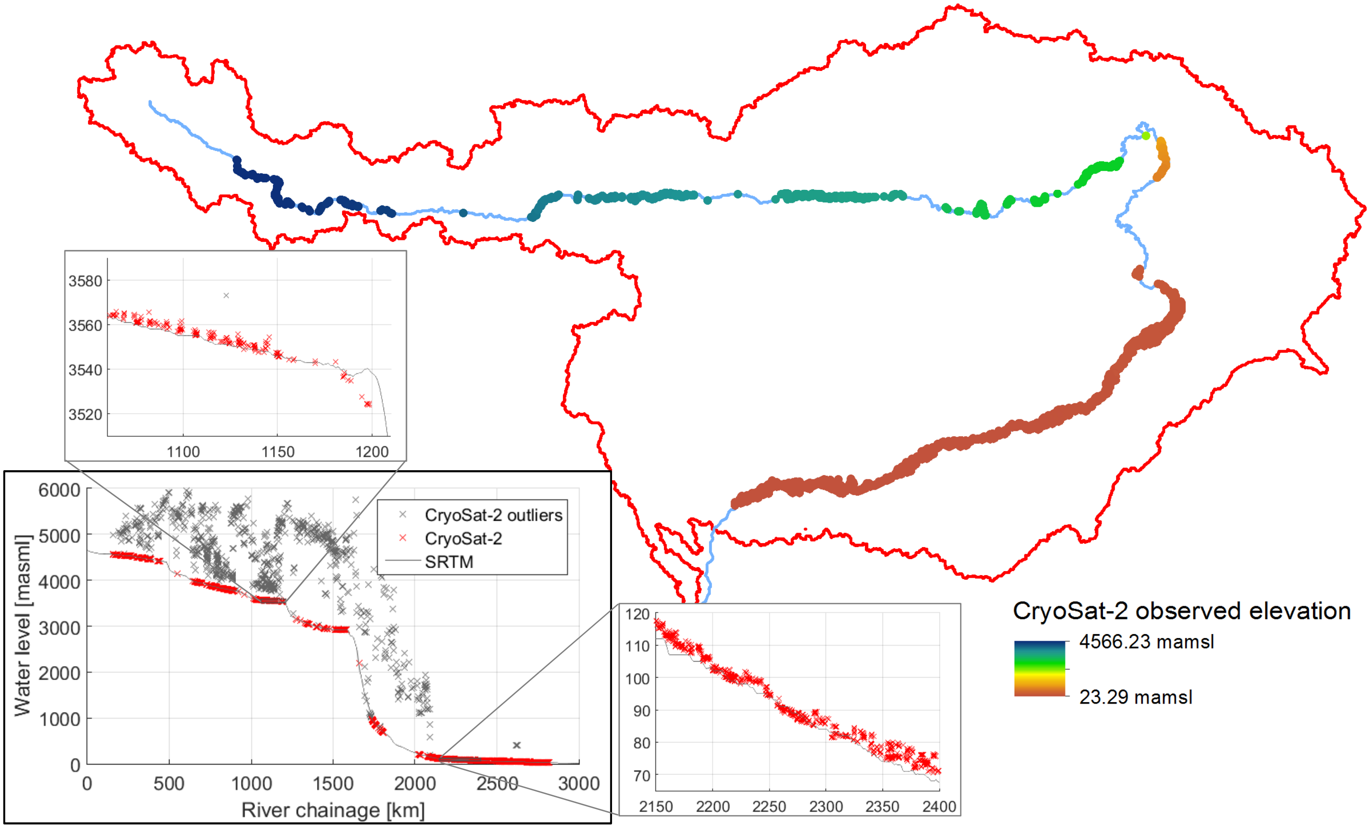

Figure 5: CryoSat-2 observations along the Brahmaputra River from 2010 to 2013. The map only displays the outlier-filtered observations, the longitudinal profiles show both outliers and the outlier-filtered data.

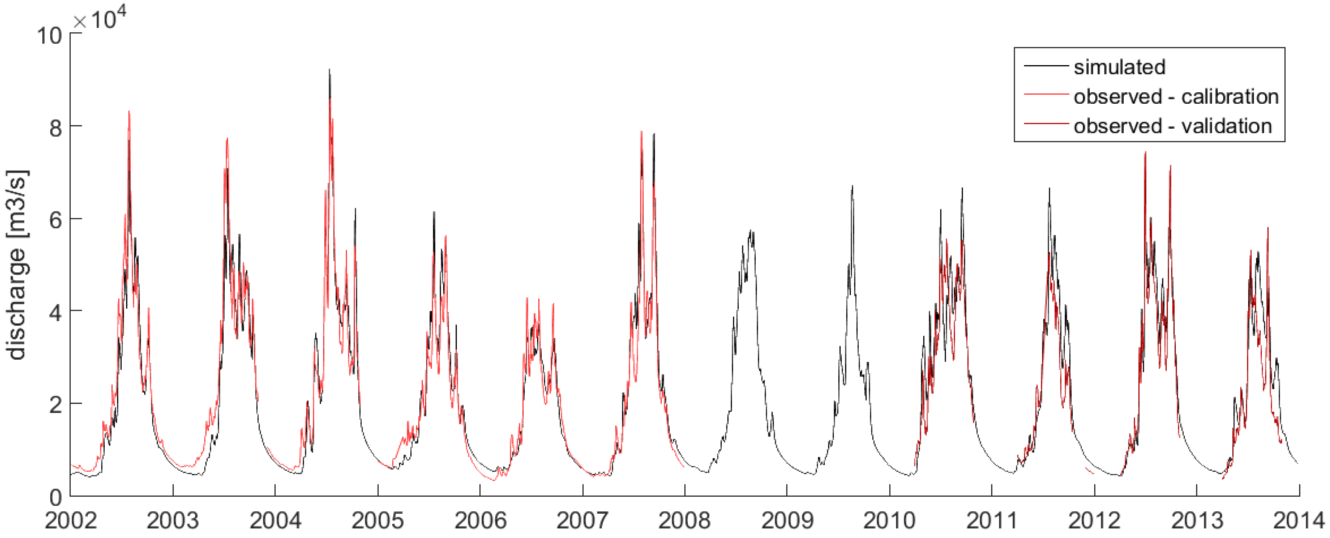

Figure 6: Observed vs. simulated discharge from the hydrologic-hydrodynamic model at Bahadurabad station. 2002 – 2007: calibration period. 2010 – 2013: validation period.

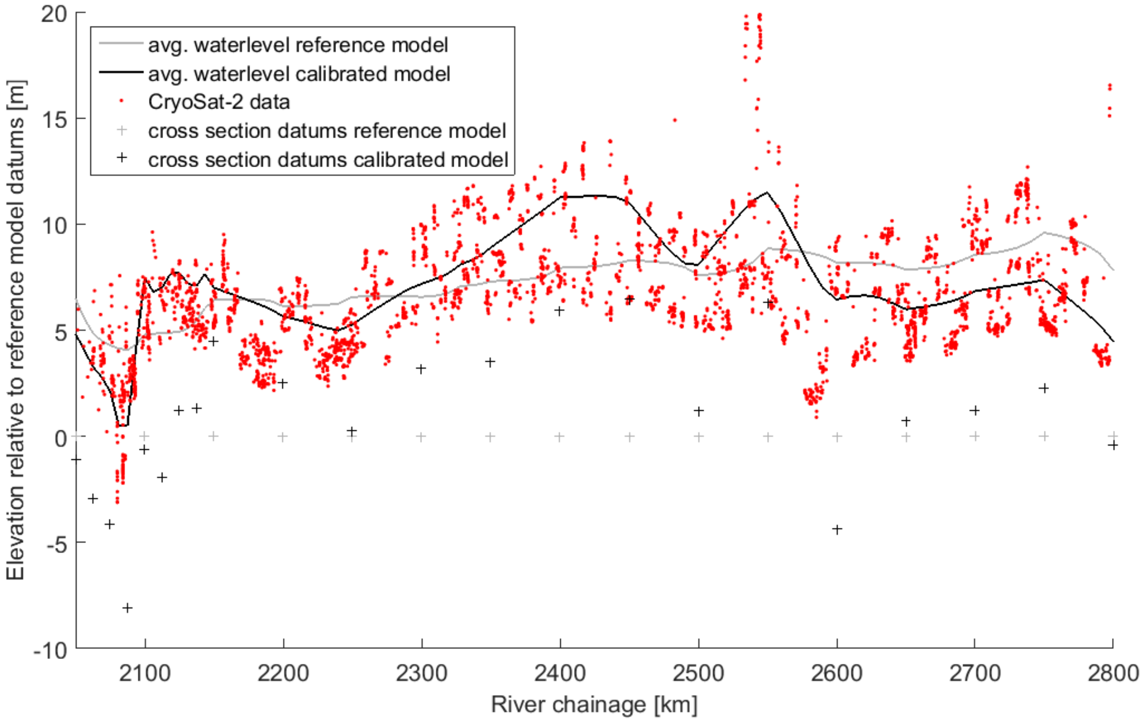

Figure 7: Result of ~~water level~~cross section calibration step 1 for the Assam Valley for the period 2010 to 2013. All levels are shown relative to the reference model's cross section datums based on the SRTM DEM.

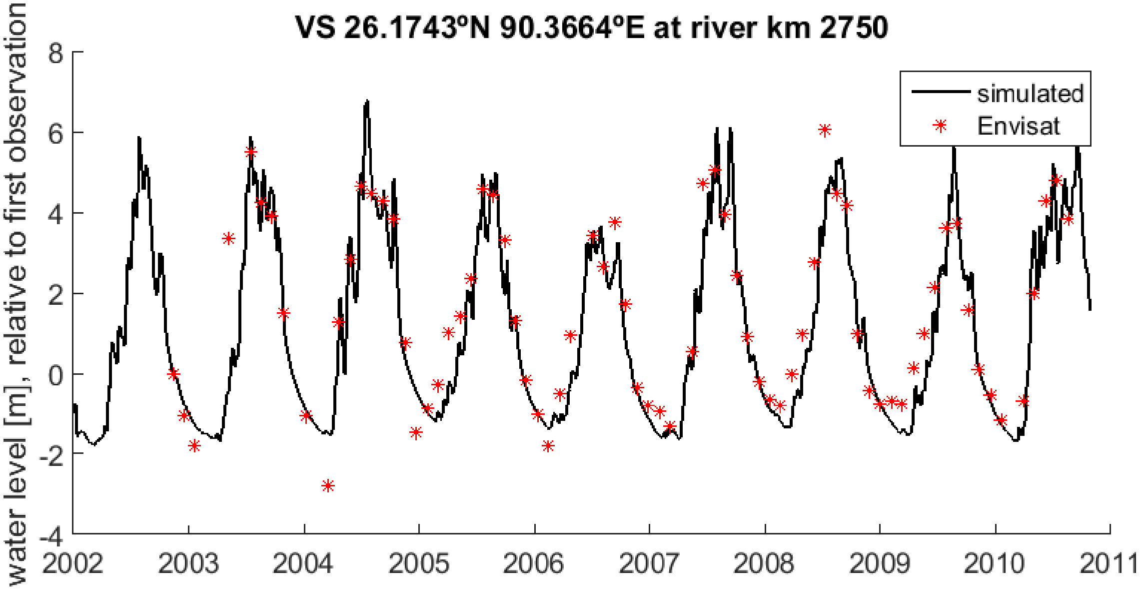

Figure 8: Result of ~~water level~~cross section calibration step 2 for one virtual station. All levels are relative to the water levels at the time of the first Envisat observation

Table 1: Decision variables, constraints, and objective functions of the genetic algorithm used for the two-step ~~water level~~cross-section calibration

	Calibration parameters	**Constraints**	**Objective function**
Step 1: fitting absolute average water levels to CryoSat-2 observations	24 cross section datums, from river km 1950 to 2800	Cross section datums continuously decreasing from upstream to downstream	RMSE between CryoSat-2 observations and average simulated water levels from 2010 to 2013
Step 2: fitting amplitude of water levels to Envisat virtual station data	27 cross section angles, from river km 2050 to 1800	Cross section datums without neighbouring virtual stations linearly interpolated from their neighbours	RMSE between yearly amplitudes of Envisat virtual station data and of simulated water levels from 2002 to 2010

Table 2: Number of CryoSat-2 observations and outliers over the river mask of the Brahmaputra River from 2010 to 2013. River km 2100 and downstream is also referred to as Assam Valley.

	entire Brahmaputra	**river km 0 – 2100**	**river km 2100 – 2820**
all CryoSat-2 observations	4806	2092	2714
outliers	938	934	4
filtered CryoSat-2 observations	3868	1158	2710

Table 3: Performance criteria for simulated discharge Q_{sim} at Bahadurabad station. Bias is given as $(Q_{sim} - Q_{obs})/Q_{sim}$.

	RMSE [m^3/s]	NSE [-]	bias [%]
Calibration period 2002 – 2007	4329	0.93	-2.1
Calibration period, high-flow only	5323	0.89	-2.3
Validation period 2010 – 2013	6873	0.81	11.2

Table 4: Performance criteria for simulated discharge in the calibration subcatchments. 2002 - 2007. * indicates subcatchments in the Brahmaputra basin.

	Q_{sim}, mean	Q_{obs}, mean	RMSE [m^3/s]	NSE [-]
Arun	437	529	259	0.65
Bagmati	254	110	364	-0.18
Bheri	252	307	115	0.88
Gandhak 1	720	955	535	0.80
Kaligandaki	236	403	264	0.69
Karnali	398	513	281	0.68
Lohit*	453	919	1045	0.03
Rapti 1	241	115	212	0.12
Sankosh 1*	184	348	246	0.40
Sunkoshi	517	745	426	0.75
Tamor	201	416	392	0.39
mean	354	487	376	0.47

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