Replies to the comments by anonymous referee #1:

We would like to thank the reviewer for their interest and comments on the manuscript. Below the reviewer's comments are in italic and the replies in normal font.

*The manuscript from Kittel et al. presents a validation study of Sentinel-3A/B (S3- A/B) SAR altimeters measurement over the whole Zambezi basin. Time series at 175 virtual stations data have been extracted on the river network, floodplain, reservoirs and wetland. Only 6 in situ gages could be used to validate this database, showing a RMSD between 3 to 31 cm. However, no direct validation can be done for the remaining 169 VS and especially over wetlands (except that the seasonal cycle is well captured and coherent with past in situ observation or nearby VS). Some discussions on the benefits and drawbacks from 1. the open loop tracking mode and 2. the different processing available on two platforms (SciHub and GPOD) to process S3 data complement the manuscript.*

*General comments: It should be noted the important work done by the authors to extract this unprecedented database of WSE time series over the whole Zambezi basin and the interesting discussion on the open loop mode and the SAR altimetry processing. However, the authors should better highlight the new discovery from their manuscript and why it has to be published in HESS and not in a more specific remote sensing journal. This is my main concern and the reason why I suggest major revision. As stated by the authors: "The objectives of the study are to evaluate the density of valuable observations and establish a WSE monitoring network. Additionally, we demonstrate the potential application of Sentinel-3 for monitoring river interactions with wetlands and floodplains." The issue is that validation and discussion on SAR and open loop mode have already been done in Jiang et al. (2020) over rivers in China. The submitted manuscript confirms some conclusions from this paper over another basin, but does not bring new information concerning S3 measurements, nor on the hydrology of the Zambezi basin. The application of radar altimetry for monitoring interactions between river, floodplains and wetlands has already been investigated by other studies with different radar altimetry missions. Another previous study from this group (Michailovsky et al., 2012), also studied the Zambezi basin with the Envisat radar altimeter and derived discharges from these WSE with different methods. The main benefit of the submitted manuscript is the important database of WSE over the Zambezi basin derived from S3 missions. So, according to me, the submitted manuscript is a database presentation paper, but the database does not seem to be freely accessible, like other global altimetry database (e.g. Hydroweb, DAHITI...).*

We thank the reviewer for the summary and general comments about the manuscript.

Indeed the validation is challenged by the lack of concurrent in-situ data and only 6 in-situ gauges were located close enough to VS to ensure direct validation of the satellite performance. We expanded the validation by considering the hydrological patterns at additional stations with historical records. However, extracting the full Sentinel-3 dataset has the largest potential value in supplementing ground observations in poorly gauged catchments.

As the reviewer correctly points out an important aim of the study is to demonstrate the extraction of a catchment-scale WSE monitoring network from Sentinel-3 observations. To address these main concerns, we rewrote the introduction and objectives of the study to more clearly reflect this, and the discussion in the following sections has been adapted accordingly (see also specific suggestions below).

The database will be publicly available in conjunction with the paper and a link will be provided in the reviewed version. The python code used for processing will also be published. The purpose is not the specific Zambezi-database (although that is an important product of the study) but rather to demonstrate that by using the publicly available processing platforms, such databases can be created for any catchment globally. We believe that a framework to extract catchment-scale monitoring networks to suit specific study areas has a wide range of applications in hydrology, which is why we believe HESS is a good target journal for publication.

*Specific comments:*

*Few clarifications are needed in the abstract. For example, give the name of the two datasets the first time you mention them (line 4). Especially, the sentence "Additional VS are available in both the Copernicus Open Access Hub and GPOD", seems to suggest that these two datasets are different from the two platform mentioned on line 4, which is not the case. That's why, when reading only the abstract, this sentence is confusing, especially the term "additional". It is not clear from which dataset the Copernicus Hub and GPOD provide additional information.*

We have reformulated the abstract accordingly including:

- Moving the introduction of the processing platforms to l. 6
- Clarified the number of stations referred to in the abstract on l. 9

*Line 8: Give the meaning of RMSD acronym.*

The acronym has been defined.

L. 10: "The Root Mean Square Deviation (RMSD)"

*Line 17: I have some doubts about using S3A/B as a SWOT surrogate. SWOT will do quasi global observations over two swaths, providing not just WSE, but also water extent and surface water slope, which could not be derived from S3A/B only. Besides, the temporal/space resolutions are coarser for S3A/B.*

Indeed S3A/B could be used as a <u>partial</u> surrogate until SWOT launch. This has already been explored using CryoSat-2; however, Sentinel-3 operating in SAR mode and the two-satellite constellation has a good spatial resolution as well – as seen in the Zambezi – which could provide similar information where the tracks are appropriately located. Of course, the expectation is that SWOT will provide unique information compared to existing missions, but there is value in exploring existing missions as well as synthetic SWOT data in preparation for mission launch. We have removed the reference to SWOT in light of this and other comments.

*Line 18/19: This sentence is quite general. Similar conclusions were also reached in Jiang et al. (2020) for rivers in China. Besides, in the submitted manuscript, there is no comparison with other mission that does not have SAR mode. So it is difficult to conclude from this manuscript only that SAR mode brings more information than mission with LRM mode.*

We modified the part of the final sentence of the abstract referencing the SAR instrument, to instead reflect the reformulated objectives of the study: extracting a uniquely dense Sentinel-3 WSE monitoring network at catchment scale and the importance of considering the pros and cons of the processing options on publically available data processing platforms.

L. 18-19: “These results highlight the benefit of the high spatio-temporal resolution of the dual-satellite constellation, which holds important implications for future hydrology-oriented missions.”

*Lines 27-30: References provided here correspond to only few studies linked to these subjects. That’s why I suggest to add “e.g.” before the references in brackets.*

L. 28-38: We agree and “e.g.” has been added to the list of references where relevant.

*Line 36: Getting “up-to-date” reference for the databases is very difficult (for example Cretaux et al., 2011 corresponds to the old “lake” version of Hydroweb). To overcome this issue, you could rather point out to the web link for each database. It’s just a suggestion, so I let the authors decide if they want to do that or not. There are other altimetry databases than the ones cited in this sentence, like HydroSat (http://hydrosat.gis.uni-stuttgart.de/php/index.php) and GRRATS (Coss et al. 2020, https://doi.org/10.5194/essd-12-137-2020; https://podaac.jpl.nasa.gov/dataset/PRESWOT_HYDRO_GRRATS_L2_VIRTUAL_STATION_HEIGHTS_V1). And for lakes, there is the G-REALM database (https://ipad.fas.usda.gov/cropexplorer/global_reservoir/).*

Thank you for the suggestion and the additional databases – we agree that the references are not up-to-date, we use the links instead as suggested.

L. 81-85: “Several databases provide global, ready-to-use and publicly available time series of WSE for inland water bodies derived from satellite altimetry observations, including from Sentinel-3 e.g. Hydroweb (http://hydroweb.theia-land.fr/), DAHITI (https://dahiti.dgfi.tum.de/en/) and HydroSat (http://hydrosat.gis.uni-stuttgart.de/php/index.php).”

*Line 47: For S3 mission, you should rather cite the S3 mission requirements document (S3 MRD), available at http://esamultimedia.esa.int/docs/GMES/GMES_Sentinel3_MRD_V2.0_update.pdf, rather than Jiang et al. (2020).*

We agree, the citation has been be corrected:

L. 49: “The satellites both carry dual-frequency (Ku- and C-band) Synthetic Aperture Radar Altimeters (SRAL) on board, building on the heritage of the CryoSat-2 and Jason missions (Drinkwater and Rebhan, 2007).”
L. 68-69: “Sentinel-3 is a marine and land mission, with the altimetric gauging of inland water being a secondary objective to the ocean and ice topographic mission objectives (Drinkwater and Rebhan, 2007).”

*Line 44: “Sentinel-3 mission is a marine and land mission” This sentence is of course true, but it could give the feeling that both ocean and land requirements are considered equally, which is not the case for the altimeter part of the mission. Indeed, it is worth pointing out that for the topography component of S3 mission “Altimetric gauging of river and lake water levels is a secondary mission objective [. . .]. This requirement shall not compromise the ability of the altimeter to meet the primary ocean and ice topographic mission objectives.” (section 4.4.2 in S3 MRD).*

Thank you for pointing out this detail – we changed the text to reflect this and to mention the effort put into updating the OLTC hydrology targets to highlight the focus on inland water applications:

L. 68-74: “Sentinel-3 is a marine and land mission, with the altimetric gauging of inland water being a secondary objective to the ocean and ice topographic mission objectives (Drinkwater and Rebhan, 2007). However, the OLTC tables on-board Sentinel-3A and Sentinel-3B contain over 65,000 virtual stations, or hydrological targets, defined using state-of-the-art water surface masks and high resolution Digital Elevation Models. The OLTC is expected to be a key factor in establishing global databases of water level and to be integrated on future altimetry missions (Le Gac et al., 2019). It is therefore important to understand the implications of the open-loop tracking mode and interactions between the OLTC and post-processing choices on the WSE datasets.”

*Line 62: “To allow continuation of the historical ERS/Envisat time series, the Sentinel3 orbit is similar to the orbit of Envisat” This sentence is confusing, as S3A/B cannot continue VS from ERS-1/2 and Envisat, as the orbit and its phasing is not the same. You can argue that S3 provide more spatial sampling than some other missions (e.g. Jason series), but it is not a direct continuation of previous ERS and Envisat ones.*

Indeed, the statement can appear unclear. In the mission summary, it is stated: ‘The mission provides data continuity for the ERS, ENVISAT and SPOT satellites’; however it is true that the altimeter does not provide a direct continuation of the ERS/ENVISAT VS on land. To avoid confusion, the sentence has been removed, and instead focus is put on the spatial sampling as suggested.

L.75-80 : “The Sentinel-3 tracks are spaced 52 km apart at the Equator, offering a high spatial density of potential virtual stations (VS) on rivers globally, with a return period of 27 days. This is interesting when compared to traditional short-repeat missions such as the Jason mission (10 days repeat period and 315 km inter-track interval) or Envisat (35 days and 80 km) and geodetic missions such as CryoSat-2 (369 days and 7.5 km). Sentinel-3 could potentially provide a much denser VS network than Jason-2 while maintaining a relatively short return period. This creates interesting possibilities for monitoring rivers and wetlands at catchment scale.”

*Line 64-67: These sentences are confusing for people who know nothing about the OLTC. It should be clearly stated that the “on board Hydrology Database (HDB) targets” is part of OLTC table. It should be introduced earlier, in the OLTC description section.*

We reorganized the text to introduce HBD earlier with the OLTC as suggested. The OLTC and HDB are now introduced together, and section 2.2.4 more clearly introduces the OLTC and its targets.

L.69-72: “However, the OLTC tables on-board Sentinel-3A and Sentinel-3B contain over 65,000 virtual stations, or hydrological targets, defined using state-of-the-art water surface masks and high resolution Digital Elevation Models. The OLTC is expected to be a key factor in establishing global databases of water level and to be integrated on future altimetry missions (Le Gac et al., 2019).”

*Line 137: Could you provide more information on this receiving window? The explanation provided in the current manuscript is interesting, but it is still difficult to understand clearly what this receiving window is and why it is needed. In the manuscript, it is written that it should “not to be confused with the on board reception window”, but it’s not clearly defined. It is important to better explain it for readers not familiar with SAR altimeter processing (and even more, for those not familiar with altimetry at all).*

We expanded this section and the altimetry processing section to better differentiate between the two. The on-board reception window is the vertical window that is recorded by the altimeter whereas the receiving window is the matrix within which the pulses are stored prior to processing. Shifts in topography may mean that the 128 bin radar window cannot store the elevation of all the samples in the echogram. Using a larger window to store the range samples ensures that the return power of all the echoes can be stored inside the same radar window and that the leading edge (which is later retracked to obtain the WSE) is not truncated. Examples and further details can be found in Dinardo et al. (2018 - Advances in Space Research 62 (2018) 1371–1404).

L. 179-189: “The range window is the vertical window during which the altimeter records the return echo from the emitted pulse. For satellites operating in closed-loop mode, there may be a transition phase before the range window is correctly positioned in regions with rapidly changing topography (Dinardo et al., 2018). If the topography is too steep, the standard fixed-size receiving window of 256 samples cannot store the elevation of all the samples in the echogram prior to Level-1b processing (e.g. Figure 5 in Dinardo et al. (2018)). By extending the receiving window, all the echoes can be stored in the same matrix without truncating the leading edge, which will be retracked to obtain the WSE. In open-loop mode, truncation might occur close to changes in the OLTC, where the receiving window may still be positioned according to the previous target. OLTC targets might be far apart due to space limitations of the OLTC (Le Gac et al., 2019), resulting in steep changes when a new target is introduced. Extending the receiving window can accommodates these sudden shifts in the position of the range window as well. We therefore process all tracks using a double and triple receiving window, to identify where the extension might be useful. ”

*In section 2.3.3, please cite briefly the corrections taken into account in the two datasets.*

In the Scihub dataset, the files contain the already “corrected altimeter elevation from OCOG (ice-1) retracker” and only the geoid needs to be subtracted. In GPOD the instrumental corrections are applied already and only the geophysical corrections need to be handled and they are already aggregated. The corrections include:

- Instrumental corrections: USO drift correction, internal path correction, distance antenna-COG and Doppler-slope correction
- Geophysical corrections: GIM-derived ionospheric correction, model dry tropospheric correction, model wet tropospheric correction, solid earth tide height, geocentric pole tide height and and ocean loading tide.

The corrections are provided individually, but this greatly simplifies the task for the less experienced user. We have added the following details in the manuscript.

L. 208-212: "In both datasets, instrumental corrections have already been applied to the 20Hz retracked range, $R_{unc}$ (i.e. USO (Ultrastable Oscillator) drift correction, internal path correction, distance antenna-COG (Center of Gravity) and Doppler corrections). $R_{unc}$ must also be corrected for geophysical and propagation effects (i.e. pole tides, solid Earth tides, ionosphere, and dry and wet troposphere), here summed into $R_{geo}$ to obtain the corrected range, $R_c$ (Eq. 1)"

L. 214-219: "In the GPOD dataset, the geophysical corrections are aggregated and provided as a single variable to be subtracted from the retracked range. In the SciHub dataset, the geophysical corrections have already been subtracted from the OCOG-retracked elevation. In both cases, all corrections are also available separately."

*Line 170: According to Jiang et al. (2020), the RIP is in Watt, so please indicate the unit in "(>10ˆ-13)"*

L. 204: Unit added to RIP criteria

*Lines 174-175: Could you provide some estimates of the two DEM errors (provided in the DEM reference paper or in the DEM quality matrix, for the Zambezi basin). It would help the reader to assess if the 30m threshold is much above the DEM accuracy.*

We have added the following to the manuscript:

L. 227-231: "The expected uncertainty of the MERIT DEM is less than 2 m for 58% of land pixels globally (Yamakazi et al., 2017). Based on the project accuracy matrix, ACE-2 has an accuracy better than 10 m for over half of the virtual stations in the basin and better than 16 m throughout the catchment (Berry et al., 2019, 2010). Thus, we do not expect a significant number of false negative outliers due to DEM accuracy based on the allowed window of uncertainty. One exception may be new dams and reservoirs, altering the surface elevation by more than 30 m; however, this does not appear to be an issue in this catchment."

*Line 178: According to Jiang et al. (2020), the fit is a gaussian fit, isn't it? It could be worthwhile to mention it (and maybe to add a sentence to explain why the fit is needed).*

In this paper, we calculate the Stack Peakiness using the maximum and mean RIP, therefore no fit is applied to the RIP beforehand. We will remove "fitted" from the text to avoid confusion.

*Line 195: "Retrieving the untracked range gives an assessment of whether the expected WSE was within the on board reception window", I agree, but this statement is very general and you could better explain* *how you will use this information. If you don't know the expected WSE (which is the case for 169 of your VS), I don't see how you can really make use of this information. Will you compare it to DEM?*

We expand this sentence slightly to better introduce the use of the untracked range. It allows us to track how the range changes when new targets are uploaded and to identify whether the OLTC is at the source of problems with the data.

The first outlier filtering is indeed through comparison with the DEM but using the retracked WSE, not the untracked range. If the difference is too large, it can be assumed that the WSE will be outside of the listening window. This of course only allows very coarse filtering. We use the DEM as a reference, but most importantly it can help explain why some VS fail. If we are very far from the DEM it is unlikely that the target was sensed at all. Of course there is a risk in some cases that the DEM is so wrong that we lose information due to this filtering (e.g. due to dam construction). We do not expect this to be the case in the Zambezi basin.

With regards to the untracked range, the examples where we see large errors, the untracked range is off by far more than the expected DEM error.

L. 246-251: "The tracker range is the on board positioning of the expected leading edge according to the OLTC. Plotting the along-track tracker range reveals how the range window position changes based on the OLTC targets and updates to the OLTC. The on-board surface elevation must be correct and the surface elevation must be within the range window to obtain useful observations of the water surface. The tracker range also provides insight into the Level-1b processing options of the two datasets, particularly where the range window is repositioned. If this occurs close to a virtual station, there may be impacts on the tracker range depending on how the transition is handled, e.g. by extending the receiving window."

*Line 211: "WRMSD (Weighted RMSD) by dividing with the residuals with the in-situ standard deviation" it not clear, please rephrase Equation 3, to be coherent with the text change D_{RMS} with RMSD*

L. 264: Indeed, it should be: "WRMSD (Weighted RMSD) by dividing the residuals with the in-situ standard deviation"

Equation 3 was modified in line with HESS recommendations to avoid abbreviations in equations – for clarity and because it is a widely used abbreviation, we chose to retain WRMSD/RMSD in the text.

*Line 217: "We correct for datum shifts by using the WSE amplitude and therefore expect a bias of 0 cm." You need to provide more explanation. First, how did you use the amplitude and to compute what? Second, I don't understand why you need to correct datum shifts, as you already removed to time series "mean level at overlapping sensing dates is subtracted". So why is it needed to add any other bias correction?*

The amplitudes are used for comparison with the ground observations – the section is indeed unclear, as it is the same bias correction mentioned in two different ways. This will be rephrased for clarity.

L. 261-263: “In order to account for any vertical bias between the two ground and satellite observations, the mean level at overlapping sensing dates is subtracted from the in-situ and satellite WSE respectively.”

*Lines 244-251: All the criteria used by the authors are not easy to follow, as they depend of the dataset and the product level. It should be better explained in the methodology section, with a clear flowchart of the process and a more in depth explanation of all the criteria used.*

Thank you for the suggestion – we have added a flowchart to the paper to better illustrate the processing steps and to reorganize the methods section accordingly, which will hopefully clarify the following sections. For the particular section, we suggest to already mention in the methods that the NP is used as a selection criteria. The criteria are the same across datasets, however MP and SP are not calculated for the SciHub dataset as the RIP is not available.

Figure 2 added to the manuscript.

*Line 250: “we use NP alone as the L1b selection criterion” but how did you use NP? Using which threshold? It is somewhat difficult to understand why NP is a good criterion, as multiple targets could be in the waveform and it does not mean that the altimeter is not observing the target of interest. It is especially true for small tributaries, where there are a lot of missing data on Figure 2. The missing data could also be due to your criteria. Could you discuss it in more details?*

We have clarified the wording in section 2.3.6:

L. 241-245: “MP and NP are indicators of the presence and number of bright targets respectively, while SP and PP provide information on the shape of the waveform. A river-like surface is typically smooth and highly reflective, resulting in quasi-specular reflections. This will typically translate into narrow, peaky waveforms and consequently high SP and PP values. We use NP to classify the VS at Level-1b, assuming stations with over 90% single-peak waveforms are likely to be good water targets with useful time series.”

Indeed multiple targets could be in the waveform, however that increases the risk of retracking errors if there are multiple high power targets. The missing data in Figure 2 is not due to this criteria as it is only based on what WSE observations could be extracted after corrections, water mask selection and filtering.

We also checked all rejected stations and found the following cases:

- Most have very little valid data at all, or several outliers (rejected on criteria of 80% data should be available). For some of these stations, dedicated (most likely manual) processing could help retrieve information if they were located in areas of interest
- Data loss due to OLTC update
- A few stations have seasonal water observations – but with a very wide spread – this is the case for VS on narrow river targets in wetlands.

- The stations rejected based on the single peak criteria mostly have very large across-track standard deviations, suggesting it is not unlikely that the waveform is contaminated by other bright targets and justifying the rejection of the VS.

Some of the retained VS might also require some degree of manual validation or outlier removal, however the proposed filtering greatly reduces the task (> 200 VS to check versus just over 100). It also allows users to group VS that they wish to further inspect and validate and to provide tools for pre-selection and evaluation. We propose to summarize this information in the revised manuscript.

To clarify this, we have re-written section 3.1. including adding

L. 303-306: “Furthermore, as the SP and PP cannot be calculated based on the waveforms processed on SciHub, the VS are evaluated at Level-1b based on the NP. We select stations with predominantly single-peak waveforms (along-track median NP = 1 in over 90% of the observations associated to the VS). In total, 101 Sentinel-3A and 103 Sentinel-3B have complete records and promising waveform statistics.”

L. 311-319: “The rejection rate is higher in the SciHub dataset, with rejected stations throughout the basin. This is mainly due to the lower percentage of missing data in the Level-2 data. OCOG is an empirical retracker, less likely to fail on non-water waveforms. Samosa+ is a physical retracker developed for coastal regions but suited to inland water targets. If the model misfit is too high, the retracker fails and the VS is rejected based on this missing data.

A closer look at the stations with a large fraction of missing observations or multi-peak waveforms in both datasets revealed that at some stations, outliers caused the rejection but could be removed with dedicated, manual post-processing if the stations were located in areas of interest. In several cases, the rejected stations were located on narrow rivers crossing seasonal floodplains, with along-track standard deviations exceeding the seasonal variation. This was mostly the case when the station was rejected based on the single-peak criteria, justifying the rejection of the station. The proposed approach allows users to group the VS for further inspection, e.g. starting out with the VS most likely to hold useful river WSE observations.”

*Line 254: “The rejection rate is higher in the SciHub dataset, with rejected stations throughout the basin.” This sentence seems to meet the concern expressed in my previous comment. “*

Several of the stations rejected had missing data in the GPOD dataset because the retracker failed to fit a model waveform to the observed waveform, suggesting the target is not a good water target. The OCOG retracker is less sensitive to the shape of the waveform. The higher rejection rate balances this. The response to the previous comment also address this concern.

*Table 2: What is the line “OLTC” in Table 2? It is not explained in the table legend, nor in the text.*

We modified the line in the table (now Table 3): it is the stations with data only after the OLTC update in March 2019.

Table 3 caption: “We consider S3A VS with data only after the OLTC update in March 2019 (line "OLTC v. 5") as well as the two processing settings on GPOD (line "3x window extension") separately.”

*Figure 4: This figure does not seem useful, except to state that after OLTC update there is mainly 1 peak in the waveform. But as the NP before the update is not provided, it is difficult to estimate the improvement.*

We have removed the figure and instead written in the text that the OLTC update also improves the NP statistics (as shown already in Table 2).

L. 292-296: “At 30 Sentinel-3A stations, no observations were available in the either dataset before the March 2019 OLTC update, suggesting the water surface elevation was outside the range window prior to the update causing the poor results prior to the update. Indeed, at over 90% of these stations, the Level-1b statistics are consistent with water targets.”

*Lines 266-267: “The OLTC contains targets based on elevation information from hydrology databases (e.g. Hydroweb), virtual stations networks and the global ACE2 DEM (Altimeter Corrected Elevations v.2 Digital Elevation Model)” Actually it depends of the OLTC version you are considering, as stated later in your paragraph. According to https://www.altimetry-hydro.eu/ here are the different OLTC table versions over inland waters: - For S3A: * DEM: v5 (Date start: 2019-03-09) * DEM: v4_2 (Date start: 2016- 05-24, Date end: 2019-03-01) * DEM: v4_1 (Date start: 2016-04-18, Date end: 2016- 05-24) - For S3B: * DEM: v2_0 (Date start: 2018-11-27) * DEM: v1(tandem) (Date start: 2018-06-06, Date end: 2018-10-16) Especially, on the https://www.altimetry-hydro.eu/ you can see that ACE2 DEM is heavily used in v4_2 for S3A, but not used at all in v5 over the Zambezi basin, as shown on Table 3 but not clearly stated in the text. Besides, at line 268 and in other part of the manuscript, it is written that the table has been updated in March 2019. It is true for S3A, but not for S3B, which has been updated sooner (after the end of the tandem phase in November 2018). The OLTC versions are given in Table 3, but never really explained in the text. A good reference for OLTC tables' generation is (with some validation): Le Gac S., F. Boy, D. Blumstein, L. Lasson and N. Picot (in press). Benefits of the Open-Loop Tracking Command (OLTC): Extending conventional nadir altimetry to inland waters monitoring. Advances in Space Research, https://doi.org/10.1016/j.asr.2019.10.031 I think putting a table to summarized all these OLTC versions and dates could be useful in the manuscript, with some information on OLTC generation (see Le Gac et al., in press). These information should be put somewhere in section 2.*

We thank the reviewer for the citation suggestions – we incorporated them in the methods section as suggested. The update indeed only refers to the Sentinel-3A OLTC as the Sentinel-3B update as made prior to the beginning of the datasets considered. We will make sure this is clear in the manuscript.

Indeed the targets mainly consist of HDB targets after the update – however they still rely on high resolution DEMs – as we understand, ACE-2 is still used to define many hydrology targets. We are very interested in further information if other high resolution DEMs are used instead of ACE-2 for the HDB targets.

Section 2.2.4 now introduces the OLTC separately.

*Figure 5: On the map, the black line (sub-basin boundaries?) are not defined, does not seem to be useful and make the map difficult to read. I suggest removing them. Where they are close, S3A and S3B VS are difficult to differentiate. Maybe use different color or level of grey between the two missions. On the sub-plots, write when it is S3A or S3B. In the legend, write to refer to figure 2 for the location of the map within the Zambezi basin (blue polygon on figure 2).*

Agreed – we will remove the lines, increase the difference between the two mission markers and refer back to Figure 2 (now 3).

Figure 5 has been modified in line with both reviewers' suggestions.

*Line 280: "no new targets were uploaded to the OLTC in March 2019 near the two S3A VS" Just to be sure, even if no new targets has been added in march 2019 near these VS, it does not mean that the OLTC table has not been updated in March 2019 for these VS. Is it the case? From figure 5 even if it is the case, the updated value should be pretty similar, as the time series seems pretty stable before and after March 2019.*

Based on the online OLTC webpage, the existing targets were only updated with no significant change in height, suggesting there is no point in splitting the time series in before and after the OLTC update.

L. 330-331: "The OLTC did not significantly change at the VS considered, meaning WSE observations are available for the entire Sentinel-3 sensing period."

*Line 288: "Samosa+ retracker outperforms the OGOC retracker", first replace OGOC with OCOG. Second, from this sentence, I was expecting much better results with Samosa+ than with OCOG, whereas on table 4, SAMOSA+ is better only by few cm (or %, even most of the times few tenth of %). So I would encourage the authors to add this quantitative information to alleviate this sentence. Besides, Samosa+ comes from GPOD, whereas OCOG comes from SciHub, and processing between these two platforms are different (not just the used retracker, but also the data selection and probably other processing, corrections...) as described on sections 2.3.1 and 2.3.2. How these differences could impact the results shown on Table 4?*

Thank you for pointing out the spelling mistake.

The main difference is linked to a few outliers in the SciHub dataset, which might skew the along-track mean slightly. Indeed, it is more accurate to state that the GPOD processing package is slightly better than the SciHub standard product.

Section 3.3.1: Modified text to refer to GPOD/SciHub instead of Samosa+/OCOG
L. 339-341: "The GPOD dataset performs better than the SciHub dataset at all stations, improving the RMSD with between 1.1 cm (7.5%, at Kalabo) and 10.2 cm (39.2% at Chavuma); except Matongo Platform, where the SciHub dataset improves the RMSD by 1.4 cm (4.5%)."

*Table 4: For Chavuma station, Samosa+ RMSD is equal to 15.8cm and 3.3%, whereas for OCOG the RMSD is 25.6cm and 3.6%. How an almost 10 cm difference in RMSD between Samosa+ and OCOG only translates into 0.3% increase? I think there is an issue with the % computation (or with the RMSD value).*

*Besides, the 9th column entitled "Relative RMSD" corresponds to WRMSD in the text, please replace "Relative RMSD" with "WRMSD" for consistency.*

Indeed, there was an error in the table as the values for Chavuma and Ngonye Falls were exchanged – thank you for pointing this inconsistency out.

Table 5: The correct RMSD relative to the yearly amplitude is 5.4% at Chavuma and 3.6% at Ngonye Falls.

*Line 315: "If we consider the stations, which are valid across datasets", how do you define "valid" here? Could you recall the criteria here?*

We have clarified how we refer to the selected stations in order to nuance the term "valid" – we consider the stations with single peak waveforms and a low degree of missing data as more reliable than those with multi-peak waveforms and a high degree of missing data. These are now referred to as "selected".

L. 362-363: "Fig. 7 shows boxplots of all selected VS based on the evaluation of the Level-1b and Level-2 data (< 20% missing data and along-track NP = 1 for 90% of the tracks)."

*Line 316: "The number of VS is quadrupled compared to using the global database Hydroweb", it is impressive. However, it should be noted that all Zambezi VS on Hydroweb have an "expert validation criteria" (see http://hydroweb.theia-land.fr/?lang=en&basin=ZAMBEZI and https://theia.sedoo.fr/wpcontent-theia/uploads/sites/2/2020/04/Handbook_Hydroweb-V2.0-1.pdf). Are all the 145 VS being individually checked and validated (coherent seasonal cycle and amplitude from upstream to downstream VS)? Coherent amplitude and seasonal cycle has been shown only for 10 VS (and compared to in situ gage data only for 6 gages) in the manuscript.*

Yes indeed. Of course, this is why this number can be increased this dramatically at catchment scale. We are aware that the goal of global database can not be to provide all VS for all catchments, therefore we see a value in providing tools and lessons-learned in processing the data at catchment-scale as highly valuable data may be available. The data access is also faster when new satellites are launched (e.g. S3-B) allowing faster uptake of the data.

L. 375-381: "If we consider the stations with less than 20% missing data and over 90% single-peak waveforms, there are 204 Sentinel-3 VS in the Zambezi, which contain potentially valuable information about WSE. Thus, automatically processing all Sentinel-3 observations within an area of interest can provide a highly valuable addition to global altimetric WSE databases, by increasing the spatial density of VS at catchment scale. The assessment based on the degree of missing data and on single-peak waveforms constitutes a preliminary validation of the virtual stations, although dedicated outlier filtering and validation might be necessary at some stations to ensure consistency with the catchment dynamics."

*Line 320: "At four stations in the Upper Zambezi, there are no valid observations at any of the VS prior to the OLTC update (Fig. 8)" I don't see how figure 8 shows that there is no valid observation before OLTC update, as figure 8 is only showing data after (S3A) OLTC update.*

The figure shows no data as no data could be processed before the update: i.e. due to no-data values, or too far from the DEM or very low backscatter.

L. 384: “At four stations in the Upper Zambezi, there are no observations prior to the OLTC update (Fig. 8).”

*Figure 9: Concerning the zoom on the WSE vs. latitude plot (between -12.01◦N and -11.81◦N), it might be because of the color code, but it seems “after Schihub” WSE is in between 1050m and 1100m, whereas “After (GPOD/3x” WSE is in between 1000m and 1050m and “After (GPOD/2x” WSE is below 950m. I don’t understand why there are not more consistent. I understand it is near the transition, which affect GPOD when changing the receiving window, but why is it that different, especially why “GPOD/3x” is above “GPOD/2x” and not below (by tripling the window, you should have more data after the transition)? Besides, on the WSE vs. latitudes plots, I would suggest to draw all “Before” curves with dashed lines, to make them easier to differentiate with the “After” curves.*

We suspect it is before too much weight is given to the next target, over-smoothing the transition. The algorithm as we understand is developed closed-loop where you want a faster transition, which is what happens. In open-loop the fast transition already occurs and the algorithm introduces an artificial transition. We have been in contact with GPOD who confirmed that the results where as expected. The performance at this VS explains why processing options are so significant at certain locations.

Thank you for the suggestion for the figure.

Figure 9 has been updated accordingly: the “Before” curves with dashed lines and the y-axis label has been corrected.

*Line 350: “According to the OLTC website,” please give the URL of this website (I guess it is https://www.altimetry-hydro.eu/)*

This line has been removed to ensure that the section about the OLTC is concise and reflects the findings of this study in particular.

*Section 4.2, which VS is considered here? A86 VS on figure B1? Besides, it to better see the impact of the platform processing versus the OLTC value, it could be good to show the OLTC table value (i. e. position of the tracking window), rather than the retracked value converted to WSE. It would help to show the transition and why you need to extend the receiving window with GPOD and then you can discuss the difference between the two platforms.*

We have added detail about the VS considered. We noted in this context that a number of VS where erroneously left out from, so a slight renumbering is necessary. The shown height is the tracking window position – we will correct the y-axis label accordingly.

L. 407: “at is A102 on the Kafue”

*Lines 370-372: The second option is the one chosen during the March 2019 update, isn’t it?*

Actually, both options are true in this case – the target was defined earlier, but for the GPOD dataset, an extension of the receiving window is still necessary.

L. 425-428: “In the example above, the latter is necessary when using the GPOD dataset, and although not critical to data retrieval, the position of the target was also shifted in the OLTC update of March 2019. Based on these findings, we recommend using the triple window extension when processing catchment scale datasets on GPOD to maximize the number of VS.”

*Line 389: “This is likely due to the frequent cloud cover over the floodplain.” Or maybe due to vegetation cover masking water?*

This is a very good point – yes.

L. 446-448: “This is likely due to the frequent cloud cover over the floodplain or vegetation masking the water surface in optical images, stressing the importance of integrating SAR imagery into water mask processing.”

*Line 412: the references provided here are just examples of studies using altimetry to calibrate and update hydrology model, so I suggest putting “e.g.” before the references.*

L. 482: e.g. has been added.

*Lines 423-428: There is not just Park (2020) and your study which investigated connectivity between river and floodplains. Could you increase your references list?*

The citation is a single example of course, we have increased the reference list, including by adding a paragraph in the introduction better showing this.

L. 38-46: “Wetlands and floodplains provide important economic and ecological services and are intrinsically linked to river dynamics. Several studies have used altimetry WSE to characterize river-floodplain interactions (e.g. Park et al., 2020, Zakharova et al., 2014, Ovando et al., 2018, DaSilva et al., 2012). Park et al. (2020) recently showed the potential in using satellite altimetry for this purpose using Jason-2 WSE in the Amazon and Zakharova et al. (2014) assessed the seasonal variability of boreal wetlands in Western Siberia using Envisat altimetry. Due to the temporal resolution of Envisat (35 days), an interannual characterization of the wetland processes was not possible. By definition, the satellite orbit is a compromise between spatial and temporal sampling. Dettmering et al. (2016) used Envisat altimetry to characterize water levels in the Pantanal Wetlands but their methods were constrained by the accuracy of the method compared to the level variations in large regions of the Pantanal. They cited SAR technology as a potential solution to overcome these limitations.”

L. 496-499: “Furthermore, the accuracy achieved at in-situ station Kalabo in the Barotse floodplain (2.9 cm with the GPOD dataset) is promising in terms of characterizing level variations in the decimeter range. This has important implications for successful monitoring of wetlands and floodplains with smaller level fluctuations (Dettmering et al., 2016).”

*Line 429: "The cross-sections extracted over floodplains are similar to observations expected from the future SWOT" I disagree with this statement. Even if Sentinel-3 mission provides much more spatial observations than other altimetry missions (like Jason series), it is not comparable to SWOT measurements, which will provides images of WSE. So rephrase this sentence accordingly.*

*Line 430: Concerning SWOT mission, I think a better reference for the reader will the SWOT Science Requirements Document (SRD) rather than Domeneghetti et al. (2018). SWOT SRD could be accessed with the following link:*
*https://swot.jpl.nasa.gov/system/documents/files/2176_2176_D61923_SRD_Rev_B_20181113.pdf*

*Line 432: "Similar information can already be extracted from the Sentinel-3 dataset in selected locations" Similarly to my previous comment, I think this sentence should be rephrased. S3 is providing WSE, but not water mask and of course slope could be computed between close VS, but it is far from being the one expected from SWOT images. . .*

> In response to the three comments above:
> Based on reviewers comments, we have removed the reference to SWOT and instead focus on the spatio-temporal sampling and performance of Sentinel-3 for hydrological applications. We have entirely re-written section 4.4 to focus on hydrological applications.

*Lines 445-446: "We extract over 360 virtual stations from each satellite of which over 70 are validated based on the waveforms and temporal coverage for each Sentinel-3 satellite" Why stating this in the conclusion and not in the core of the manuscript? In the abstract 170 VS are mentioned. The same goes for the 70 validated VS.*

> We state it here as a concluding remark and have reviewed the numbers mentioned. We instead cite the 204 promising Sentinel-3 VS in the conclusion out of 731 total VS.
>
> L. 509-511 "In total, the spatial coverage of the dual-satellite mission consists of 731 potential virtual stations in the Zambezi, of which 204 show promising results based on the evaluation of Level-1b waveforms and Level-2 WSE observations across datasets."

*Section 4.4 and 5: I find it strange to have perspectives before conclusions...*

> We have rewritten the section and the conclusion in order to ensure perspectives are placed after the conclusion.

Replies to the comments by anonymous referee #2:

We would like to thank the reviewer for their interest and comments on the manuscript. Below the reviewer's comments are in italic and the replies in normal font.

*The paper describes the computation and exploitation of satellite altimetry water level time series in the Zambezi basin. According to the authors, the aim of the study is "to assess the potential of the Sentinel-3 mission in hydrological applications". For that purpose, they compare different satellite altimetry pre-processing options (from two different databases) and they analyze the impact of open loop processing. Moreover, a validation by comparison with (few) in-situ ground stations is performed. For three different wetlands within the study basin, the potential of Sentinel-3 for monitoring the interaction of river and floodplain is shown.*

*General comments: This is an interesting topic worth publishing. However, some aspects of the paper are not innovative and had been published before by some of the same authors (e.g. OLTC impact by Jiang et al., 2020). Moreover, some parts of the manuscript are quite technically without providing the (less experienced) readers a recommendation on which processing option to use. In my opinion, the most interesting and innovative part of the study is the approach of automatically processing all possible VS of both satellites in the entire basin with the aim to use these time series for assessment of wetland-river interactions. Thus, my recommendation would be to focus on this part of the study by adding a bit more statistics (how many potential VS, how many valid VS, how many VS gained by OLTC,. . .) and some citations of existing work on wetlands based on satellite altimetry (e.g. Zakharova et al., 2014; Dettmering et al., 2016; Park, 2020). In addition, a (at least theoretical) comparison to classical missions can be added discussing the benefit of the dual satellite constellation (with respect to spatial and temporal coverage) and the measurement mode (SAR/OLTC).*

We thank the reviewer for the interest in the manuscript and the comments. We agree on the analysis of the major contribution and propose to better highlight this in the introduction. We also propose to add a flowchart to the methods section, allowing a better overview of the different processing steps for reproduction. Finally, the Zambezi network and generic processing tools will be published with the final manuscript.

In terms of the statistics requested, we have updated Table 3 and Table 4 and rewritten section 3.1.

The suggestions for additional citations regarding wetland studies have been added to the text in the introduction:

L. 38-46: "Wetlands and floodplains provide important economic and ecological services and are intrinsically linked to river dynamics. Several studies have used altimetry WSE to characterize river-floodplain interactions (e.g. Park et al., 2020, Zakharova et al., 2014, Ovando et al., 2018, DaSilva et al., 2012). Park et al. (2020) recently showed the potential in using satellite altimetry for this purpose using Jason-2 WSE in the Amazon and Zakharova et al. (2014) assessed the seasonal variability of boreal wetlands in Western Siberia using Envisat altimetry. Due to the temporal resolution of Envisat (35 days), an interannual characterization of the wetland processes was not possible. By definition, the satellite orbit is a compromise between spatial and temporal sampling. Dettmering et al. (2016) used Envisat altimetry to characterize water levels in the Pantanal Wetlands but their methods were constrained by the accuracy of the method compared to the level variations in large regions of the Pantanal. They cited SAR technology as a potential solution to overcome these limitations."

We thank the reviewer also for the suggestions for the discussion. Section 4.4 has been rewritten with a focus on the density compared to Envisat and a mention of the potential accuracy of Sentinel-3 in terms of studying wetlands.

L. 473-480: "The high number of VS throughout the basin can form the basis of a dense monitoring network. Michailovsky et al. (2012) assessed the number of VS in the Zambezi from Envisat and found 423 crossing points against 731 with Sentinel-3, and after careful evaluation, 31 VS had useful records. Although all 204 VS were not manually checked, the results in this study confirm that this number is greatly increased with Sentinel-3. The spatio-temporal sampling of altimetry missions often constrains monitoring capabilities. Particularly the dual-satellite configuration of Sentinel-3 thus offers new, interesting possibilities in a hydrological context. It is important to note that the success is entirely dependent on the accuracy of the OLTC tables as data is missing from the Sentinel-3A records in large part due to the latency between mission start and OLTC update."

L. 496-499: "Furthermore, the accuracy achieved at in-situ station Kalabo in the Barotse floodplain (2.9 cm with the GPOD dataset) is promising in terms of characterizing level variations in the decimeter range. This has important implications for successful monitoring of wetlands and floodplains with smaller level fluctuations (Dettmering et al., 2016)."

*Specific comments:*

*Line 5: If the objective of the study is to "evaluate the density of valuable observations", you should add some more statistics on the number of VS (see general comment).*

The objective is to show the value of processing Sentinel-3 at catchment scale, illustrating the performance for the Zambezi basin. We have added the requested statistics from the general comment.

We have updated Tables 3 and 4 for this purpose (previously 2 and 3).

*Line 18: In my opinion, the paper is not showing the benefits of SAR (with respect to what? LRM?). The denser track network is due to the orbit configuration not the measurement mode, and there is not comparison to LRM data. The RMSD values are similar to those from LRM missions. So, how is the benefit demonstrated?*

The results support the progress in results observed in past papers as well, where the RMSD is lower with SAR missions than LRM (e.g. in comparison to Michailovsky's results with Envisat). Direct comparison is difficult due to the lack of overlap in space and time. But we agree that this is not a key investigation in this paper and instead, we now highlight the benefit of the spatio-temporal sampling achieved by the dual-satellite constellation and orbit.

L. 18-19: “These results highlight the benefit of the high spatio-temporal resolution of the dual-satellite constellation, which holds important implications for future hydrology-oriented missions.”

*Line 44: Sentinel-3 is not only an ESA mission => Copernicus*

Thank you for pointing this out – indeed, Sentinel-3 is part of the Copernicus program and the mission is developed by ESA in this context.

L.47: “The Sentinel-3 mission was developed by the European Space Agency (ESA) mission for the Copernicus program.”

*Section 2.2: What about adding additional information on in-situ validation observations and OLTC targets?*

Section 2.2.4 and 2.2.5 have been added, incorporating the information about the in-situ stations and OLTC table from other sections.

*Line 104/105: Please add some more information on the stream burning. I’m not sure what is meant here.*

This is part of the data processing for the river network database, as detailed in the cited paper.

We selected the dataset from Yan et al. (2019) because they defined the river networks globally (thus the same dataset can be used for other study cases) and because in addition to a river delineation algorithm, they burnt in a river line to the DEM, increasing the accuracy of the river location, particularly in flat areas.

L. 122-124: “Yan et al. (2019) included a stream burning step prior to the application of the river delineation algorithm to improve the river localization compared to the DEM processing alone particularly over plain areas.”

*Section 2.3.3: Some detailed info on the corrections is missing (e.g. which models).*

We have added details about the different corrections as well as how they are provided in each dataset. In both cases we use the recommended corrections from each processing platform.

L. “In both datasets, instrumental corrections have already been applied to the 20Hz retracked range, Runc (i.e. USO (Ultrastable Oscillator) drift correction, internal path correction, distance antenna-COG (Center of Gravity) and Doppler corrections). Runc must also be corrected for geophysical and propagation effects (i.e. pole tides, solid Earth tides, ionosphere, and dry and wet troposphere), here summed into Rgeo to obtain the corrected range, Rc (Eq. 3)”

L. “In the GPOD dataset, the geophysical corrections are aggregated and provided as a single variable to be subtracted from the retracked range. In the SciHub dataset, the geophysical corrections have already been subtracted from the OCOG-retracked elevation. In both cases, all corrections are also available separately.”

*Line 171: Sigma0==backscatter?*

Yes, it is the backscatter coefficient, now indicated L. 204.

*Section 2.3: I recommend to provide also the web addresses of GPOD and SciHub (in the text or alternatively in Refs or Acknowledgements.*

Good point.

L. 163 and L. 164 web addresses have been added.

*Line 174/175: Are these DEMs good enough to be used in this context. My personal experience is that at least ACE2 includes really large outliers in some regions.*

ACE-2 has an accuracy of 5-10 m at most VS in the basin (and almost always less than 16 m). The choice of DEM might bias the selection, however the +/- 30 m window should not be a problem.

L. 227-231: “The expected uncertainty of the MERIT DEM is less than 2 m for 58% of land pixels globally (Yamakazi et al., 2017). Based on the project accuracy matrix, ACE-2 has an accuracy better than 10 m for over half of the virtual stations in the basin and better than 16 m throughout the catchment (Berry et al., 2019, 2010). Thus, we do not expect a significant number of false negative outliers due to DEM accuracy based on the allowed window of uncertainty. One exception may be new dams and reservoirs, altering the surface elevation by more than 30 m; however, this does not appear to be an issue in this catchment.”

*Line 200: “are processed” => how? Median/mean*

L. 260: “We calculate the along-track mean of all observations retained at a given virtual station to produce a WSE time series. “

*Line 204: “six”. Where are these stations located. Maybe you can reference to a figure.*

Indeed the locations are not presented until Figure 5 – we have added the stations to the catchment basemap (Figure 1) to show the geographical coverage of the gauging stations.

Added to Figure 1.

*Line 210: RMSD or D_{RMS}? Please make consistent*

Equation 3 was modified in line with HESS recommendations to avoid abbreviations in equations – for clarity and because it is a widely used abbreviation, we chose to retain WRMSD/RMSD in the text.

L. 263-265: “Performance is evaluated by calculating the RMSD (Root Mean Square Deviation), $D_{RMS}$, between the relative in-situ ($w_g$) and satellite ($w_s$) levels (Eq. 3), and the WRMSD (Weighted RMSD).”

*Line 231: “two the” => “the” or “the two”*

L. 287: “the two”

*Figure 2: I can’t find any black cycle in the plot. On the other hand blue lines (which I assume to be rivers) not covered by data. The black lines are a bit confusing here. I guess these are sub-basin borders. Please indicate or remove. The additional maps seems to be in the Annex, not in the supplementary material.*

The reference to the additional maps should indeed be the Annex. We agree that the subbasin borders do not carry significant information in this case and have removed them.

Thank you for pointing out that the circles were missing. There are parts of the river, which fall between tracks and are thus not sensed by either satellite.

Figure 3 has been updated.

*Title of 3.1: This is quite technically. What about using a title indicating the aim of this section, e.g. comparison of different L1b pre-processing*

As we have rewritten section 3 and 3.1, the title now refers to the evaluation of the VS in the catchment.

3.1 Evaluation of Sentinel-3 VS in the Zambezi catchment.

*Figure 3: What does OLTC stands for here (black and orange)? Before/after OLTC update? Please clarify.*

Figure 3 caption: “ ”OLTC” indicates Sentinel-3A stations where observations are only available after the OLTC update in March 2019.“

*Table 3: Please provide the sum over the entire basin. Include description of GPOD/SciHub version for VS no (I guess it should be 2x, 3x?)*

Table 4 has been updated with the basin totals and with new lines to better identify the source of the number of VS.

*Section 3.3.1. What about adding a discussion on the impact of low number and distribution of the validation sites. Are the validation numbers representative for the entire basin?*

Of course the validation is limited by the low number of validation sites. However, section 3.3.2 confirms that the hydrological patterns are reliable in other parts of the basin as well. This pattern of data availability is also why S3 holds high value in a catchment with low gauging density.

L. 348-350: “The in-situ stations are mainly located in the Upper Zambezi, therefore the validation is geographically constrained. However, the river morphology at the ground stations is diverse, ranging from 95 m wide rivers to 35-600 m on the Barotse floodplain. Therefore the validation is presumed to be an encouraging indication of the performance basin-wide.”

*Figure 5: in-situ (black) lines are not visible. Are they always available for the whole period? Are there more than one observation available per epoch (=> single alongtrack measurements instead of mean/median?) Can you add RMSD here?*

We have stippled the S3 lines to make the underlying black lines visible. The in-situ observations are available until April 2019 at all six stations.

In some cases, there are more than one observation – indicated by the points – whereas the line indicates the mean WSE, which is compared to the in-situ observations. The RMSD is given in Table 4.

Figure 5 has been updated.

*Line 288: OGOC => OCOG*

Thank you for pointing this out.

*Table 4: is the difference only due to the retracker? Might the pre-processing play a role? Is the Relative RMSD == WRMSD?*

Indeed the pre-processing might also play a role, although both are intrinsically linked to the processing platform and to each other. For more clarity, we refer to the datasets by the platform rather than the retracker in 3.3.1.

We have corrected to WRMSD in Table 4.

*Figure 6: I can not find any orange lines here. . .*

There are indeed no observations from those decades.
We have removed orange lines from the legend of Figure 6.

*3.3.3: What about adding some more information and interpretation here.*

We have added a discussion linking back to the in-situ stations discussed in the two previous sections, which indicate annual amplitudes in the order of 5-10 m. Furthermore, Figure 7 provides a summary of the Sentinel-3 observations, suggesting that in some cases further manual validation might be necessary, i.e. to remove large outliers or confirm that the patterns are hydrologically consistent.

L. 365-367: "We note that for Sentinel-3B, the amplitudes are smaller than for Sentinel-3A. This is due to the length of records, with indications of 2019 being a dryer year than 2016-2018, as seen in Fig. 5 at Senanga and Kalabo, and when comparing the Sentinel-3B records to in-situ records in Fig. 6."

L. 371-381: "If we consider the stations with less than 20% missing data and over 90% single-peak waveforms, there are 204 Sentinel-3 VS in the Zambezi, which contain potentially valuable information about WSE. Thus, automatically processing all Sentinel-3 observations within an area of interest can provide a highly valuable addition to global altimetric WSE databases, by increasing the spatial density of VS at catchment scale. The assessment based on the degree of missing data and on single-peak waveforms constitutes a preliminary validation of the virtual stations, although dedicated outlier filtering and validation might be necessary at some stations to ensure consistency with the catchment dynamics."

*Line 323-324 (and in some other parts of the manuscript): I'm not sure whether it is fair to compare with global WSE databases. Since these databases aim in providing input for hydrological research, the focus is on long time-series. For sure, they are also able to process these VS - however, this has no priority given the short time series of less than 2 years.*

The comparison should be seen as an encouragement to explore the public processing platforms, which provide access to the full Sentinel-3 dataset, beyond what is available on the databases. The databases provide an excellent starting point, however, at catchment scale (including for smaller rivers) or where short time series would have useful applications there may be more information available. This paper illustrates how much additional data can be obtained through automatic extraction from the full dataset.

L. 377-378: "Thus, automatically processing all Sentinel-3 observations within an area of interest can provide a highly valuable addition to global altimetric WSE databases, by increasing the spatial density of VS at catchment scale."

*Line 342: Is there any statistics available on the percentage of improvement/degradation by OLTC in this region?*

We are not sure we understand the question – to obtain statistics a simultaneous closed-loop mission would be necessary. What we do see is cases where the time series stops after the update and a loss of data due to the time lag between mission launch and table update. This is quite significant as large amounts of data are potentially useless when the OLTC is not up to date.

*Line 349ff: "mamsl": all other heights are provided with respect to a geoid. Why not these ones? At least you should explain the abbreviation.*

The elevation is from the OLTC database (altimetry-hydro.eu) and thus actually relative to a geoid. We have corrected the unit to avoid confusion.

L. 411-415: "The tracker range from the SciHub dataset suggests that the range window was correctly positioned within +/- 10 m of the surface elevation at around 1111 m (Le Gac et al., 2019). The discrepancy can instead be attributed to the waveform processing, as illustrated in Fig. 11. After the OLTC update a target is defined for the VS at 1113 m and the transition occurs earlier on the pass. The altimeter reception window has shifted just enough that the VS elevation is within the receiving window for all three 415 datasets, including the GPOD dataset with the double extended receiving window.

*Line 369: options to mitigate: Do you have any recommendation for the users? What preprocessing should I use?*

This is a tricky question with no clear single answer. In some cases, the dedicated inland water options outperform the standard processing (as would be expected), in others they appear to actually worsen the results. The take-home message is that the choice of preprocessing does indeed matter and based on the virtual station and its location it might be worthwhile to consider several. We do recommend using the 3x extension for GPOD processing to maximize the number of VS.

L. 427-428: “Based on these findings, we recommend using the triple window extension when processing catchment scale datasets on GPOD to maximize the number of VS.”

*Figure 12: Is there any color change in c) and d) depending on waveform misfit?*

Indeed – in this particular case, the misfit is generally quite low with no significant change, making the misfit information superfluous.

Figure 12 has been modified.

*Line 385/386: Are there no unique track numbers?*

The given track numbers are the relative track numbers which are the same across cycles – and all data will belong to those same tracks.

L. 440-441: “Rather than grouping by coordinates, we here assess all unique passes, known to cross floodplains.”

*Figure 13: What are the vertical blue lines in crossing tracks 741 and 498? Where are the VS located for tracks 498 and 085? What are the stars and cycles in the left hand plot?*

The vertical blue lines are the water occurrence (we will add this to the figure caption) as seen in the basemap on the left. The VS are the cycles and stars in the left hand plot and are indeed missing from the legend (in Figure 14 and 15 as well).

*Figure 15: left and right?*

Left and right are erroneous in this case and have been removed.

*4.4 This is more a summery than perspective. . . Moreover, perspective should be placed after conclusions. . . Line 409: “first” => where is second?*

We have rewritten section 4.4 and changed the title to “Hydrological applications” as it is part of section 4 Discussion.

*Line 429-434: Please reformulate this paragraph: SWOT will provide much more information than S3, especially in cross-track direction. Also CS2 can already extract similar information in selected locations.*

The section has been reformulated and there is no longer a reference to SWOT in line with comments received on this part.

*Line 441: “should”? => is or is not improving!*

The point addressed here is the expectation to OLTC vs. closed-loop rather than the conclusion of this study. The conclusion has been reformulated, removing this particular sentence.

*Line 446: I don’t think that you should name that a “validation”*

L. 509-510: “In total, the spatial coverage of the dual-satellite mission consists of 731 potential virtual stations in the Zambezi, of which 204 show promising results based on the evaluation of Level-1b waveforms and Level-2 WSE observations.”

*Line 447: Again: My feeling is, that this is not a fair comparison. Hydroweb is a global database not aiming in complete coverage of entire basins.*

We completely agree that a comparison would not be fair – our intent with the comparison of the number of VS is to highlight the benefit of extracting data beyond what is already available on such databases, when looking at altimetry data at catchment scale. This is important for regional to local hydrological studies. Furthermore, we ease the WSE data retrieval for hydrologists. By showing the numbers together, we hope to encourage interested users to also consider the full dataset on publically available processing platforms.

L. 516-517: “The proposed approach illustrates the potential of considering the full Sentinel-3 records to achieve complete basin coverage, a substantial supplement to the WSE time series available on global altimetry databases.”

*Line 452-458: I suggest shifting this paragraph to line 443 (as second paragraph of this section). This would make the paper end with the application, which is the overall focus of your paper according to line 69.*

Indeed, thank you for this suggestion. We have rewritten the conclusion, effectively removing this paragraph to better highlight the focus of the paper.

# Sentinel-3 radar altimetry for river monitoring - a catchment-scale evaluation of satellite water surface elevation from Sentinel-3A and Sentinel-3B

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**Abstract.** Sentinel-3 is the first satellite altimetry mission to operate in Synthetic Aperture Radar (SAR) mode and in open-loop tracking mode nearly globally. Both features are expected to improve the ability of the altimeters to observe inland water bodies. Additionally, the two-satellite constellation offers a unique compromise between spatial and temporal resolution with over 65,000 potential water targets sensed globally. In this study we evaluate the possibility to extract river water surface elevation (WSE) at catchment level from Sentinel-3A and Sentinel-3B radar altimetry, using Level-1b and Level-2 data from two public platforms: the Copernicus Open Access Hub, (i.e. SciHub), and GPOD (Grid Processing on Demand). The objectives of the study are to evaluate the density of valuable observations ~~and establish~~ in establishing a WSE monitoring network ~~.~~ ~~Additionally, we~~ and to demonstrate the potential application of Sentinel-3 for monitoring river interactions with wetlands and floodplains. We select the Zambezi River as a study area. In the Zambezi basin, ~~175~~ 204 virtual stations (VS) contain useful WSE information in both datasets~~, far exceeding the number of VS available in standard databases. The RMSD is between 2.7 cm and 31.2~~. The Root Mean Square Deviation (RMSD) is between 2.9 cm and 31.3 cm at six VS where in-situ ~~stations and the~~ data are available, and all VS reflect the observed WSE climatology throughout the basin. ~~Additional VS are available in both the Copernicus Open Access Hub and GPOD (Grid Processing on Demand)~~Some VS are exclusive to either the SciHub or GPOD datasets, highlighting the value of considering multiple processing options beyond global altimetry-based WSE databases. In particular, we show that the processing options available on GPOD ~~strongly~~ affect the number of useful VS; ~~in particular~~specifically, extending the size of the receiving window, considerably improved data at 13 Sentinel-3 VS. ~~The number of VS delivering usable data increased after the Open-Loop Tracking Command (OLTC) on board Sentinel-3A was updated. However,~~ This was largely related to the open-loop tracking mode~~poses two new challenges:~~ : while correct on board elevation information is crucial, ~~and~~ steep changes in the receiving window position can have detrimental effects on the WSE observations if post-processing options are not adapted. Finally, we extract Sentinel-3 observations over key wetlands in the Zambezi basin. We show that clear seasonal patterns are captured in the Sentinel-3 WSE, reflecting flooding events in the floodplains. These results highlight the ~~potential of using Sentinel-3 as a SWOT (Surface Water and Ocean Topography) surrogate while awaiting the mission launch. The results show the~~ benefit of the ~~high-resolution Synthetic Aperture Radar (SAR) altimeter,~~

~~as well as the benefits and disadvantages of the open-loop tracking mode~~high spatio-temporal resolution of the dual-satellite constellation, which holds important implications for future hydrology-oriented missions.

## 1 Introduction

~~Reliable water monitoring data hold very high value for water science disciplines including hydrological modelling and engineering applications, such as operational~~ Monitoring river water levels is an important step in hydrological studies, including characterization of the river dynamics, flood monitoring and forecasting, and ~~planning/designing~~ the planning and designing of water resources infrastructure. ~~However, the~~ The last decades have seen a steady decline in available water monitoring information, particularly in Africa (Hannah et al., 2011; Vörösmarty et al., 2001). ~~Water surface elevation (WSE) is an important quantity in hydrological applications and is traditionally recorded using~~ Furthermore, it is often impractical to measure water levels in floodplains in-situ~~instruments~~. In the last ~~over~~ 25 years, satellite radar altimetry has ~~provided an~~ therefore provided an important, alternative source of ~~WSE observations~~water surface elevation (WSE) observations at so-called virtual stations (VS), or crossings between the satellite tracks and river center line.

Advancements in instrument design and processing tools have steadily improved the accuracy of data products to the order of decimeters (e.g. Vu et al. (2018); and Villadsen et al. (2016) for a summary of mission performance evaluations across the literature). Satellite radar altimetry has been ~~used to monitor water level and~~ widely used in hydrological studies, for instance to monitor and quantify storage variations at regional scale ~~(Arsen et al., 2015; Boergens et al., 2017; Jiang et al., 2017a; Kleinherenbrink et a~~ (e.g. Arsen et al., 2015; Jiang et al., 2017a; Boergens et al., 2017; Kleinherenbrink et al., 2015; Villadsen et al., 2015), to assess river dynamics and estimate river discharge ~~(Michailovsky et al., 2012; Roux et al., 2010; Tarpanelli et al., 2017), and to support hydrodynamic modelling (Domeneghetti et al., 2014; Kittel et al., 2018; Michailovsky et al., 2013; Schneider et al., 2017). Water level observations are useful to~~ (e.g. Domeneghetti et al., 2014; Kittel et al., 2018; Michailovsky et al., 2013; Schneider et al., 2017; Bogni and to constrain hydrologic/hydrodynamic model parameters ~~. Getirana and Peters-Lidard (2013); Liu et al. (2015); Jiang et al. (2019b) all used altimetry WSE to calibrate hydrodynamic models. In~~ (e.g. Getirana and Peters-Lidard, 2013; Liu et al., 2015; Jiang et al., 2019b) . Altimetry has proven extremely valuable in poorly gauged regions for hydrologic modelling. For example, in Kittel et al. (2018), WSE from Envisat and Jason-2 was used to calibrate a rainfall-runoff model of the Ogooué River. The observations supplemented historical discharge records by providing contemporary observations of river levels, and were shown to help constrain ~~the~~ routing model parameters in the poorly gauged catchment. ~~Several databases provide global and publicly available time series of WSE for inland water bodies derived from satellite altimetry observations (Berry et al., 2005; Crétaux et al., 2011; Schwatke e , including the operational database Hydroweb, which contains updated WSE time series from Sentinel-3 observations (Rosmorduc, 2016) .~~

~~Advancements in instrument design and processing tools have steadily improved the accuracy of data products to the order of decimeters (e.g. Vu et al. (2018); and Villadsen et al. (2016) for a summary of mission performance evaluations across the literature). In particular, Synthetic Aperture Radar (SAR) altimeters reduce the size of the along-track footprint and have improved the number of targets and potential accuracy in coastal areas and over inland water by reducing land contamination~~

~~(Dinardo et al., 2018; Jiang et al., 2017b; Nielsen et al., 2017; Wingham et al., 2006)~~Wetlands and floodplains provide important economic and ecological services and are intrinsically linked to river dynamics. Several studies have used altimetry WSE to characterize river-floodplain interactions (e.g. Park, 2020; Zakharova et al., 2014; Ovando et al., 2018; da Silva et al., 2012; Dettmering et . Park (2020) recently showed the potential in using satellite altimetry for this purpose using Jason-2 WSE in the Amazon and Zakharova et al. (2014) assessed the seasonal variability of boreal wetlands in Western Siberia using Envisat altimetry. Due to the temporal resolution of Envisat (35 days), an interannual characterization of the wetland processes was not possible. By definition, the satellite orbit is a compromise between spatial and temporal sampling. Dettmering et al. (2016) used Envisat altimetry to characterize water levels in the Pantanal Wetlands but their methods were constrained by the accuracy of the method compared to the level variations in large regions of the Pantanal. They cited SAR technology as a potential solution to overcome these limitations.

The Sentinel-3 mission was developed by the European Space Agency (ESA) ~~Sentinel-3 mission is a marine and land mission currently operating~~ mission for the Copernicus program. The mission currently operates in a two-satellite constellation: Sentinel-3A and Sentinel-3B launched in February 2016 and April 2018 respectively. The satellites both carry dual-frequency (Ku- and C-band) Synthetic Aperture Radar Altimeters (SRAL) on board, building on the heritage of the CryoSat-2 and ~~the Jason missions (Jiang et al., 2020)~~Jason missions (Drinkwater and Rebhan, 2007). In Synthetic Aperture Radar (SAR) mode, the altimeter has a higher along-track resolution of ~~300m~~ 300 m compared to 1.64 km in Low Resolution Mode (LRM). The instruments operate 100% in SAR mode between 60°N and 60°S, making Sentinel-3 the first satellite altimetry mission to provide near global coverage in SAR mode. SAR altimeters have improved data quality and accuracy in coastal areas and over inland water thanks to the smaller along-track footprint, which is less affected by land contamination (Dinardo et al., 2018; Jiang et al., 2017b; Nielsen et al., 2017; Wingham et al., 2006). Thus smaller water bodies, including narrower rivers can be sensed by the altimeter (Villadsen et al., 2016).

The on board tracking mode of Sentinel-3 is different from the previous SAR altimetry mission CryoSat-2. The tracking mode determines how the range window is re-positioned as the satellite proceeds along its orbit. The positioning of the range window, which is typically 60 m wide, ensures that the ~~return echo of the transmitted microwave pulse~~ echo reflected by expected surface targets is correctly recorded by the altimeter. CryoSat-2 and SARAL/AltiKa both operate in closed-loop, that is, the range window is positioned based on information from previous measurements. However, if the satellite fails to correctly record the river echo, e.g. in steep river valleys where the satellite records the valley top instead of the valley bottom, the error will be transmitted to future measurements as the satellite locks on the wrong target. Studies have demonstrated this challenge for steep-river valleys, e.g. in France (Biancamaria et al., 2018) and in China (Jiang et al., 2017b). In open-loop mode, a priori information about the surface topography controls the range window position, in the form of an on board lookup table, i.e. the Open-Loop Tracking Command (OLTC) tables. Previous studies have demonstrated the advantages of open-loop tracking and have indicated that Sentinel-3 is less affected by abrupt changes in topography, provided the on board elevation information is correct (Jiang et al., 2020, 2019a). Sentinel-3 is a marine and land mission, with the altimetric gauging of inland water being a secondary objective to the ocean and ice topographic mission objectives (Drinkwater and Rebhan, 2007). However, the OLTC tables on-board Sentinel-3A and Sentinel-3B contain a database of over 65,000 virtual stations, or hydrological targets, defined using state-of-the-art water surface masks and high resolution Digital Elevation Models. The OLTC is expected to be a key factor in establishing global databases of water level and to be integrated on future altimetry missions (Le Gac et al., 2019). It is therefore important to understand the implications of the open-loop tracking mode and interactions between the OLTC and post-processing choices on the WSE datasets.

~~To allow continuation of the historical ERS/Envisat time series, the~~ The Sentinel-3 ~~orbit is similar to the orbit of Envisat. At the equator,~~ tracks are spaced 52 km apart at the Equator, offering a high spatial density of potential virtual stations (VS) on rivers globally, with a return period of 27 days. ~~A number of VS are already available from Sentinel-3A, based on the on board Hydrology Database (HDB) targets; however, a much higher number of VS are potentially available when considering all crossings between river centerlines and satellite ground tracks. For instance, there are over 300 potential Sentinel-3A VS in the Zambezi basin of which only 38 VS are available on~~ This is interesting when compared to traditional short-repeat missions such as the Jason mission (10 days repeat period and 315 km inter-track interval) or Envisat (35 days and 80 km) and geodetic missions such as CryoSat-2 (369 days and 7.5 km). Sentinel-3 could potentially provide a much denser VS network than Jason-2 while maintaining a relatively short return period. This creates interesting possibilities for monitoring rivers and wetlands at catchment scale.

Several databases provide global, ready-to-use and publicly available time series of WSE for inland water bodies derived from satellite altimetry observations, including from Sentinel-3 e.g. Hydroweb (http://hydroweb.theia-land.fr/)~~. Furthermore, the~~ , DAHITI (https://dahiti.dgfi.tum.de/en/) and HydroSat (http://hydrosat.gis.uni-stuttgart.de/php/index.php). However, they do not provide full catchment-scale coverage and there is a time-lag between data acquisition and the inclusion of the VS in the database. The Sentinel-3 dataset is available on public processing platforms with dedicated tools for WSE extraction over inland water. In order to benefit from the high spatio-temporal coverage of Sentinel-3 and large number of hydrological targets, automatic processing workflows and evaluation tools are necessary. For instance, the mission has operated in dual-satellite constellation since November 2018, providing ~~at least one~~ over a year of non-time critical data from Sentinel-3B not yet available on the aforementioned databases.

The aim of this study is to ~~assess~~ demonstrate the potential of the Sentinel-3 mission in hydrological applications (e.g. monitoring, modelling and river-floodplain interactions) by extracting a catchment-scale WSE monitoring network of ~~Sentinel-3 VS . Where ground observations are available, we~~ VS using the full Sentinel-3 records. We evaluate the satellite performance directly against in-situ data ~~. We~~ where these are available and investigate the impact of processing choices ~~, by evaluating the implications of the open-loop tracking mode and on board OLTC for hydrological applications~~on the WSE time series at selected VS. Finally, we explore the potential of the dual-satellite constellation for spatio-temporal monitoring of wetlands and floodplains~~using Sentinel-3. The purpose of these investigations is to confirm that the network can serve as a useful supplement to the in-situ gauging stations by capturing temporal dynamics across the catchment.~~

. To address these objectives, we ~~extract all available Sentinel-3A and Sentinel-3B observations over the Zambezi basin using~~ use two publicly accessible databases ~~. We~~ and present an automatically extracted catchment-scale river WSE monitoring network based on Sentinel-3 radar altimetry for the Zambezi. All processing steps are performed on publicly accessible databases or using open-access code.

## 2 Data and study area

### 2.1 The Zambezi~~basin~~

The Zambezi ~~basin~~ is the largest river in Southern Africa and drains 1,390,000 ~~km2~~ km$^2$ stretching over eight countries (Fig. 1). Water resources in the basin are crucial for human consumption, hydropower production, irrigation and ecosystem services (Beilfuss, 2012). There are three distinct seasons: the wet and warm season from November to April, the cool and dry season from May to July and the hot and dry season between August and October. The river and its tributaries display a strong seasonal signal, which should be reflected by the satellite altimetry dataset.

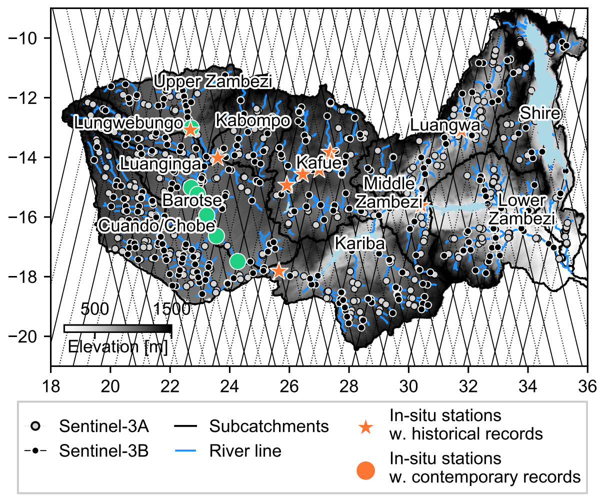


**Figure 1.** Base map of the study area with in-situ stations used for validation of the Sentinel-3 WSE time series. All Sentinel-3 tracks and river-track-crossings (VS) are shown for the entire Zambezi basin.

Previous studies have evaluated other altimetry missions over the Zambezi, providing a reference in terms of performance of new satellites (Michailovsky et al., 2012; Michailovsky and Bauer-Gottwein, 2014). As shown in ~~Figure 1~~Fig. 1, satellite tracks cross the river and its tributaries at multiple locations, and several ground-tracks cross important wetlands (e.g. the Barotse floodplain, Chobe floodplain and the Kafue flats).

Water resources in the Zambezi River basin are increasingly subject to stress, as several drought episodes have affected Southern Africa in the last 30 years (Abiodun et al., 2019). Monitoring is key to adaptation and mitigation efforts. Remote sensing observations of WSE can provide useful monitoring information and inform forecasting and planning tools in poorly instrumented areas. The collection of consistent water level remains a challenge for the member states, especially in the upper parts of the Zambezi, where system failure and vandalism are a constant disruption of the existing ground monitoring system. Thus, a WSE monitoring network based on altimetry observations could ensure steady information on water levels in the catchment even if the existing ground system is not in operation.

## 2.2 Auxiliary data

### 2.2.1 Virtual station localization

A virtual station is defined as the intersection between a river line and a satellite ground track. Each time the satellite returns on the given pass, new observations of the river can be added to the WSE time series at the virtual station. The river line is from the open data set of global river networks from Yan et al. (2019), which is based on two DEMs (Digital Elevation Model): the SRTM (Shuttle Radar Topography Mission) and ASTER GDEM v.2 (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) datasets at 90 m and 30 m resolutions respectively. ~~The dataset was selected as it includes~~ Yan et al. (2019) included a stream burning step prior to the application of the river delineation algorithm ~~, which is particularly useful for plain areas. The burnt-in river line is obtained from Google Earth, using the highest possible image resolution and manually drawing the river line as close as possible to the centerline~~to improve the river localization compared to the DEM processing alone particularly over plain areas.

### 2.2.2 Water mask

To ensure that observations are over water, we use v.1.1 of the water occurrence maps from Pekel et al. (2016). The maps are based on 3 million satellite images from Landsat from 1984 to 2018 and indicate seasonal and annual changes in global surface water occurrence at 30-meter resolution. The occurrence map indicates the percentage occurrence of water. We use a threshold of 10% water occurrence frequency over the 34 years of record. A low threshold is chosen on purpose to ensure all valuable data, including seasonal water, is extracted at the cost of a higher outlier frequency. This ensures that data points are not masked out because of low water occurrence probability, which could be partly due to cloud cover.

### 2.2.3 Digital elevation model

We use the MERIT DEM (Multi-Error-Removed Improved-Terrain DEM) as reference surface elevation (Yamakazi et al., 2017). MERIT is based on widely used DEMs, including SRTM, which have been corrected for several error sources (speckle noise, tree height bias etc.). It is provided at ~~3sec~~ 3 sec resolution and referenced to the EGM96 geoid. We reproject the DEM onto the EGM2008 geoid using the VDatum software (Myers et al., 2007), to consistently use the same geoid for all datasets.

### 2.2.4 OLTC Tables

The OLTC contains targets based on elevation information from either hydrology databases (e.g. Hydroweb), virtual stations networks and the global ACE2 DEM (Altimeter Corrected Elevations v.2 Digital Elevation Model). Details about the generation of the OLTC tables for inland water targets can be found in Le Gac et al. (2019). The on-board table is updated periodically for both satellites. Relevant for this study in particular, is the March 2019 update of the Sentinel-3A OLTC. The OLTC can be visualized on www.altimetry-hydro.eu, where contributions can be submitted for future updates. An overview of the OLTC updates on-board the two satellites is shown in Table 1. In this paper, the latest Sentinel-3B update in June 2020 is not considered due to the limited records available at time of writing. Since March 2019, over 65,000 virtual stations on inland water bodies are defined on-board Sentinel-3A and Sentinel-3B.

**Table 1.** OLTC versions considered in this study. The number of targets corresponds to the latest version and can be visualized and found on www.altimetry-hydro.eu.

| | Sentinel-3A | Sentinel-3B |
|---|---|---|
| Initial version | 4.2 (24/05/2016) | 2.0 (27/11/2018) |
| Update | 5.0 (09/03/2019) | |
| Targets | 33,261 | 32,515 |

In total, there are 87 new hydrology targets over the Zambezi River from hydrology databases represented in v. 5 of the Sentinel-3A OLTC, compared to only two in v. 4.2, which mainly used ACE2 DEM data. In v. 4.2, 64 additional targets were defined at virtual stations. These targets have been updated with refined elevation information in v. 5 to improve spatial coverage. The Sentinel-3B OLTC v. 2 contains 115 hydrology targets.

#### 2.2.5 In-situ water level stations

Level observations from 14 operational gauging stations were kindly provided by the Zambezi River Authority (ZRA), who maintain the dataset. Six of the in-situ gauging stations were in sufficient proximity to a Sentinel-3 virtual station (< 20 km) and located on the same stream, and therefore suitable for direct comparison. The catchment areas are sufficiently similar between the in-situ and virtual stations to justify comparison (e.g. no major tributaries between the two stations): the contributing areas differ by less than 5.5% in all cases. At all selected stations the level records were labeled as "Very good quality" and provided at daily temporal resolution, with an accuracy of 1 mm.

Additionally, historical records from 2000-2010 were available at 12 additional gauging stations. At ten stations, the in-situ station and Sentinel-3 VS were located on the same stream and within close enough proximity to be representative of similar catchment areas. All stations considered are shown in Fig. 1.

### 2.3 Sentinel-3 Level-1b and Level-2 data

Table 2 summarizes mission specifications for the Sentinel-3 satellites. Level-1b and Level-2 data for the area of interest are retrieved from 1) the ESA GPOD SARvatore (Grid Processing on Demand SAR Versatile Altimetric Toolkit for Ocean Research and Exploitation) service (available on https://gpod.eo.esa.int/) and 2) the Copernicus open access hub, SciHub (available on https://scihub.copernicus.eu/). Both services are freely available upon registration and use the exact same Level-1a data for processing. With the exception of in-situ observations, none of the processing steps or data are catchment specific.

**Table 2.** Sentinel-3 mission specifications.

| | Sentinel-3A | Sentinel-3B |
|---|---|---|
| Launch | 16/02/2016 | 25/04/2018 |
| Data coverage | 01/06/2016 - present | 01/11/2018 - present |
| Planned Lifespan | 7 years | 7 years |
| Elapsed lifespan | 4 years | 2 years |
| Orbit | Polar, sun-synchronous | |
| | 27 day repeat cycle | |
| Ground track separation | 104 km at the Equator | |
| | (52 km in two-satellite constellation) | |
| Instrument | Synthetic Aperture Radar Altimeter (SRAL) | |
| | Ku-band | |
| | (300 m resolution after SAR processing) | |
| Operating mode | Open-loop | |
| Footprint | 300 m x 1.64 km (along-track x across-track) | |

Figure 2 illustrates the processing workflow used for the two datasets from download to the data later presented in the results section. The Level-1b data and Level-2 data are specific to the two databases ~~. Both~~ and both datasets contain the auxiliary data necessary to compute the water surface elevation. ~~In both datasets , geoid data is provided. Although both use the EGM2008 geoid model, the geoid model parameters as well as the geophysical corrections can differ slightly. We observe a bias between the two datasets of varying magnitude throughout the basin. Therefore, only the relative change in water surface elevation will be considered when comparing the datasets~~The datasets are evaluated at multiple stages. The following sections detail specific processing on each of the two platforms, and provide additional information on each local processing step.

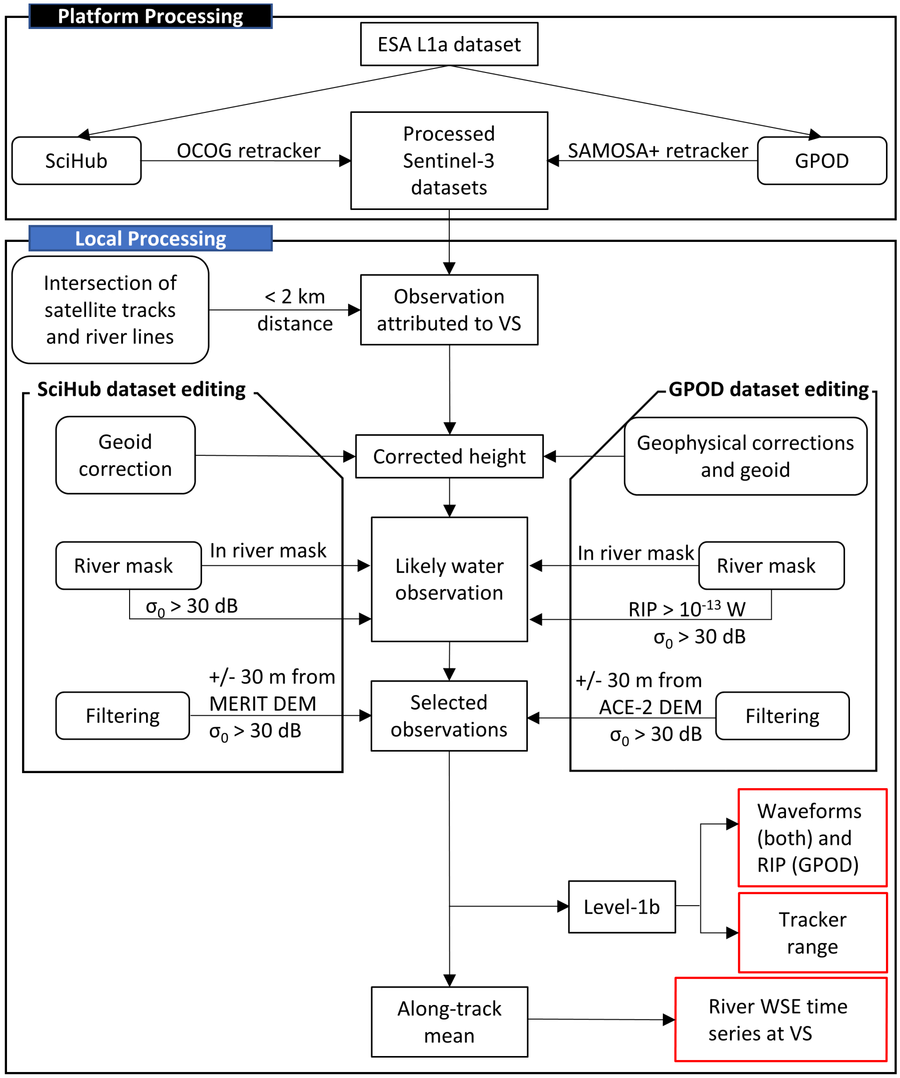


**Figure 2.** Outline of the processing workflow applied in this study. The differences between the two datasets are highlighted left (GPOD) and right (SciHub).

#### 2.3.1 GPOD ~~Processing~~processing

A processing configuration tailored for inland water is available on GPOD. In particular, four specific options are applied during processing (Dinardo et al., 2018):

– A Hamming weighting window is applied on the burst data prior to the azimuth Fast Fourier Transform (FFT) to reduce the impact from off-nadir bright targets by reducing the side-lobes of the Delay-Doppler beam

– A factor two oversampling of the radar waveform prior to the range FFT to improve sampling efficiency of peaky echoes from bright targets

– An extension of the receiving window N times, to better accommodate the ~~L1b~~ Level-1b echoes in the receiving window over rough topography.

~~A double or larger extension of the receiving window (N≤2) is recommended for~~

The range window is the vertical window during which the altimeter records the return echo from the emitted pulse. For satellites operating in closed-loop mode, there may be a transition phase before the range window is correctly positioned in regions with rapidly changing topography (Dinardo et al., 2018). ~~The~~ If the topography is too steep, the standard fixed-size receiving window of 256 samples ~~may not be able to store the full L1b echo and may result in a truncation of the leading edge.This has been reported for satellites operating in closed-loop mode, where there may be a transition phase before the window has been positioned correctly by the satellite~~cannot store the elevation of all the samples in the echogram prior to Level-1b processing (e.g. Figure 5 in Dinardo et al. (2018)). By extending the receiving window, all the echoes can be stored in the same matrix without truncating the leading edge, which will be retracked to obtain the WSE. In open-loop mode, ~~truncations are most likely to~~ truncation might occur close to changes in the OLTC, where the receiving window may still be positioned according to the previous target. ~~Inland water~~ OLTC targets might be far apart due to space limitations of the OLTC (Le Gac et al., 2019), resulting in steep changes when a new target is introduced. Extending the receiving window can accommodates these sudden shifts in the position of the range window as well. We therefore process all tracks using a double and triple receiving window, to identify where the extension might be useful. ~~This window is not to be confused with the on board reception window, which determines when the altimeter records the return echo from the emitted pulse, and cannot be modified by on-ground processing.~~

GPOD uses the Samosa+ retracker to retrieve the nadir range. Samosa+ is a physically-based retracker specifically dedicated to coastal regions and described in detail in Dinardo et al. (2018). The GPOD datasets are referred to as the ~~“GPOD dataset”~~ "GPOD dataset" in the following sections, with 2x and 3x respectively indicating the double and triple receiving window extension.

### 2.3.2 Copernicus Open Access Hub ~~Processing~~processing

The Copernicus Open Access Hub (previously Sentinels Scientific Data Hub) provides Sentinel-3 SAR data at various processing levels, including Level-1b and Level-2. In the Level-1b dataset, the echo waveforms are provided, in ~~“counts”~~ "counts" and are therefore not directly comparable to the GPOD waveforms. In the ~~level-2~~ Level-2 dataset, several retrackers are used. Over land, the empirical OCOG (Offset Center of Gravity) retracker is used ~~(Jain, 2015)~~(Wingham et al., 1986). The resulting dataset is referred to as the ~~“SciHub dataset”~~ "SciHub dataset" in the following sections.

### 2.3.3 ~~Water Surface Elevation~~

~~In both datasets, the 20Hz retracked range, $R_{unc}$, must be corrected for a number of geophysical and propagation effects (i.e. pole tides, solid Earth tides, ionosphere, and dry and wet troposphere), summed into $R_{geo}$ to obtain the corrected range, $R_c$ (Eq. 1).~~

$$R_c = R_{unc} - R_{geo}$$

~~The water surface elevation is the satellite's altitude, h, relative to the reference WGS84 ellipsoid minus the corrected satellite range. The final WSE, $H_{WSE}$, is projected onto the EGM2008 geoid, by subtracting the geoid height, $H_{Geoid}$ (Eq. 2).~~

$$H_{WSE} = h - R_c - H_{geiod}$$

~~All variables are expressed in meters. The corrections are provided along with the retracked data in each respective dataset.~~

### 2.3.3 Data selection

First, we coarsely select observations less than 2 km from a virtual station. We then filter the observations over the water occurrence mask. The along-track resolution is 300 m. Therefore, a buffer of one observation around each water body is allowed. The water mask is based on Landsat observations and thus sensitive to cloud and tree cover. In order to avoid ~~that~~ discarding valid observations over water ~~are discarded based on an unreliable~~ due to gaps in the water mask, observations with high maximum Range Integrated Power (RIP) ($> 10^{-13}$ W) or a high backscatter coefficient (~~>30~~ $\sigma_0 > 30$ dB) are also classified as water ~~. The $\sigma_0$~~ at this stage. The backscatter coefficient threshold is set based on trial and error for the basin and previous studies (e.g. Michailovsky et al. (2012)).

This step also ensures that valid observations are not removed, in case smaller tributaries are not present in the water mask. ~~The final outlier removal at this stage is~~

### 2.3.4 Correction of the retracked range

The retracked range must be corrected for instrumental and geophysical effects. In both datasets, instrumental corrections have already been applied to the 20 Hz retracked range, $R_{unc}$ (i.e. USO (Ultrastable Oscillator) drift correction, internal path correction, distance antenna-COG (Center of Gravity) and Doppler corrections). $R_{unc}$ must also be corrected for geophysical and propagation effects (i.e. pole tides, solid Earth tides, ionosphere, and dry and wet troposphere), here summed into $R_{geo}$ to obtain the corrected range, $R_c$ (Eq. 1).

$$R_c = R_{unc} - R_{geo} \tag{1}$$

In the GPOD dataset, the geophysical corrections are aggregated and provided as a single variable to be subtracted from the retracked range. In the SciHub dataset, the geophysical corrections have already been subtracted from the OCOG-retracked elevation. In both cases, all corrections are also available separately.

The water surface elevation is the satellite's altitude, h, relative to the reference WGS84 ellipsoid minus the corrected satellite range. The final WSE, $H_{WSE}$, is projected onto the EGM2008 geoid, by subtracting the geoid height, $H_{Geoid}$ (Eq. 2).

$$H_{WSE} = h - R_c - H_{geiod} \tag{2}$$

All variables are expressed in meters. The corrections and geoid data are provided along with the retracked data in each respective dataset. Although both use the EGM2008 geoid model, the geoid model parameters as well as the geophysical corrections can differ slightly. We observe a bias between the two datasets of varying magnitude throughout the basin. Therefore, only the relative change in water surface elevation will be considered when comparing the datasets.

#### 2.3.5 Outlier filtering

Outlier filtering is based on digital elevation values using the ~~ACE2~~ ACE-2 DEM included in the GPOD dataset, and the MERIT DEM for the SciHub dataset. Differences in height exceeding 30 m are considered as outliers. The expected uncertainty of the MERIT DEM is less than 2 m for 58% of land pixels globally (Yamakazi et al., 2017). Based on the project accuracy matrix, ACE-2 has an accuracy better than 10 m for over half of the virtual stations in the basin and better than 16 m throughout the catchment (Berry et al., 2019, 2010). Thus, we do not expect a significant number of false negative outliers due to DEM accuracy based on the allowed window of uncertainty. One exception may be new dams and reservoirs, altering the surface elevation by more than 30 m; however, this does not appear to be an issue in this catchment. A $\sigma_0$ threshold of 30 dB ensures that only observations of bright targets (such as water) are included in the final selection used to produce WSE time series at each VS.

#### 2.3.6 Level-1b waveforms

To evaluate and summarize the Level 1b waveforms, we calculate the following parameters (Jiang et al., 2020):

- Stack Peakiness (SP): ratio between the maximum ~~fitted~~ RIP and sum of ~~fitted~~ RIP
- Maximum Power (MP): maximum value of a waveform
- Pulse Peakiness (PP): ratio between maximum power and the sum of the waveform
- Number of peaks (NP): number of peaks in a waveform – a peak is defined as exceeding 25% of the MP (Jiang et al., 2020)

MP and NP are indicators of the presence and number of bright targets respectively, while SP and PP provide information on the shape of the waveform. A river-like surface is typically smooth and highly reflective, resulting in quasi-specular reflections. This will typically translate into narrow, peaky waveforms and consequently high SP and PP values. ~~The parameters are useful when comparing effects of the OLTC update for Sentinel-3A as well as processing parameters for both satellites.~~ We use NP to classify the VS at Level-1b, assuming stations with over 90% single-peak waveforms are likely to be good water targets with useful time series.

~~In order to evaluate the open-loop mode, we use the tracker range.~~ The tracker range is the on board positioning of the expected leading edge according to the OLTC. Plotting the along-track tracker range reveals how the range window position changes based on the OLTC targets and updates to the OLTC. The on-board surface elevation must be correct and the surface elevation must be within the range window to obtain useful observations of the water surface. The tracker range also provides insight into the Level-1b processing options of the two datasets, particularly where the range window is repositioned. If this occurs close to a virtual station, there may be impacts on the tracker range depending on how the transition is handled, e.g. by extending the receiving window.

On Sentinel-3, the tracker range is positioned at bin 43 (counting from 0, also called the nominal tracking position), one-third of the full window. The positioning of the window is done through the so-called window delay, or the delay between the pulse emission and the time of record of the tracker range. The epoch is the distance between the ~~tracker range~~ nominal tracking position and the retracking position after ~~L2~~ Level-2 processing. The GPOD dataset contains the epoch (in m), which can be converted to number of bins and used to extract the retracking position. Repositioning to the center of the original reception window requires taking into account 1) oversampling and 2) the receiving window extension (~~2 x or 3 x~~2x or 3x), as described in ~~2.3.1~~Section 2.3.1. The tracker range (in m ~~, referenced to bin 43,~~ and referenced to the nominal tracking position) is directly provided in the enhanced measurement file from SciHub.

~~Retrieving the untracked range gives an assessment of whether the expected WSE was within the on board reception window, meaning whether any useful data will be retrievable or not. Furthermore, it provides insight into the behavior of the two datasets at virtual stations close to sharp changes in the reception window positioning. Finally, the retracking position indicates whether the range was correctly retracked, when compared to the waveform.~~

#### 2.3.7 Level-2 WSE

~~All~~ We calculate the along-track mean of all observations retained at a given virtual station ~~are processed~~ to produce a WSE time series. ~~A backscatter coefficient threshold of 30 dB ensures that only observations of bright targets (such as water) are included in the final selection used to produce WSE time series at each VS.~~

~~Level observations from 14 operational gauging stations were kindly provided by the Zambezi River Authority (ZRA), who maintain the dataset. Six of the in-situ gauging stations were in sufficient proximity to a Sentinel-3 virtual station (< 20 km) and located on the same stream, and therefore suitable for direct comparison. Furthermore, we verify that the catchment area is sufficiently similar between the in-situ and virtual stations to justify comparison (e.g. no major tributaries between the two stations). The contributing areas differ by less than 5.5% in all cases. At all selected stations the levelrecords were labelled as "Very good quality" and provided at daily temporal resolution, with an accuracy of 1 mm.~~

At six VS, the time series was evaluated against ground observations of water level. In order to account for any vertical bias between the two ~~datasets~~ground and satellite observations, the mean level at overlapping sensing dates is subtracted from the in-situ and satellite WSE respectively. Performance is evaluated by calculating the RMSD (Root Mean Square Deviation),

$D_{RMS}$, between the relative in-situ ($w_g$) and satellite ($w_s$) levels (Eq. 3), and the WRMSD (Weighted RMSD) by dividing with the residuals with the in-situ standard deviation.

$$D_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(w_{g,i} - w_{s,i})^2} \tag{3}$$

Based on past mission performance as summarized in Villadsen et al. (2016), RMSD values below 30 cm are considered good, between 30 and 60 cm are considered moderate. We calculate Pearson's correlation coefficient to evaluate the linear correlation between the in-situ and remote sensing WSE. The correlation coefficient should be above 0.9. ~~We correct for datum shifts by using the WSE amplitude and therefore expect a bias of 0 cm.~~

Additionally, ~~historical records from~~ the annual water level variations recorded by Sentinel-3 were assessed against records from ten in-situ gauging stations using historical observations from 2000-2010~~were available at 12 additional gauging stations~~. Although the stations could not be used directly due to the lack of temporal overlap, they can still support a visual assessment of the annual water level variations recorded by Sentinel-3. ~~At ten stations, the in-situ station and Sentinel-3 VS were located on the same stream and within close enough proximity to be representative of similar catchment areas.~~

## 3 Results

The Sentinel-3 VS in the Zambezi are shown in Fig. 3. ~~The~~ In total, 364 Sentinel-3A and 367 Sentinel-3B virtual stations were identified. At each VS, the percentage of missing data is calculated as the number of days with WSE observations divided by the number of days the satellite passed over the VS. ~~There are 80 VS for~~ In general, the VS with complete records are predominantly located on higher level branches and tributaries of the basin and close to or on floodplains (Fig. 3). These targets are generally wider, perennial and the topography flatter. Conversely, several rejected VS are located in the headwater subcatchments on smaller tributaries.

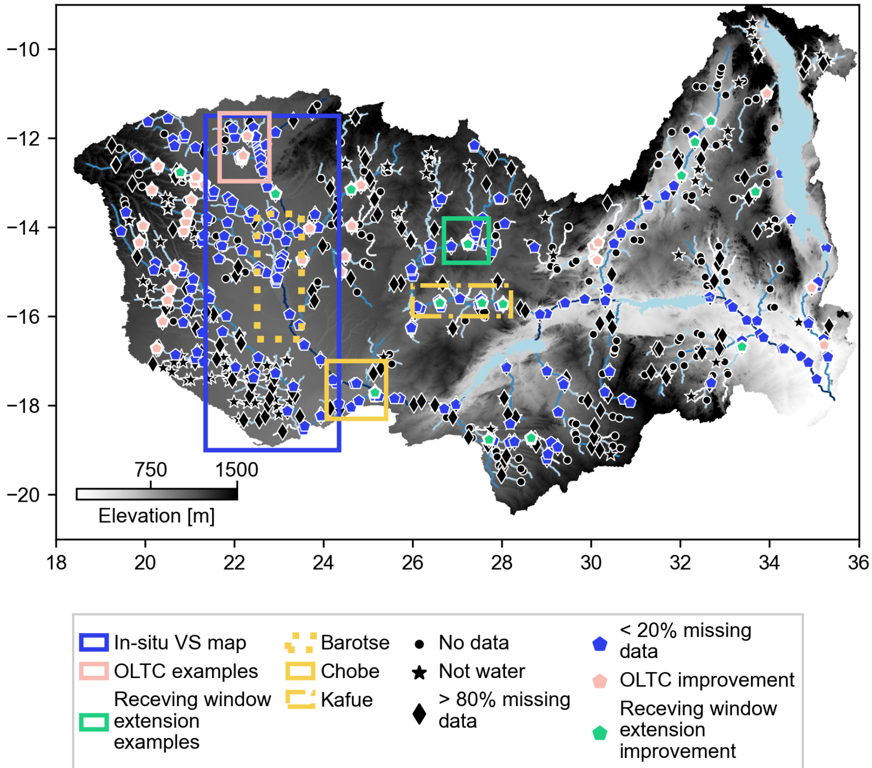


**Figure 3.** Zambezi Sentinel-3A and 3B VS after outlier filtering. Stations which improved by modifying processing steps (either on board through the Sentinel-3A OLTC update or on-ground by extending the receiving window on GPOD) are highlighted separately. The frames indicate examples highlighted in the next sections of this study. Additional maps are included in the supplementary material (Figs. A1, A2, and A3).

### 3.1 Evaluation of Sentinel-3 VS in the Zambezi catchment

Table 3 summarizes the number of Sentinel-3A and ~~101 VS for~~ Sentinel-3B ~~with complete WSE time series in both the GPOD and SciHub datasets (<~~in the Zambezi catchment with less than 20% missing data ~~)~~(L2 columns) in either dataset and in both. The rejection rate is slightly higher when using the GPOD dataset than when using the SciHub dataset (respectively ~~54% and 50% for Sentinel-3B and 35% and 31% for Sentinel-3A~~67% and 62% for Sentinel-3A and 66% and 63% for Sentinel-3B). This difference can be attributed to the higher proportion of no-data values and the generally lower $\sigma_0$ values in the GPOD dataset. The higher percentage of no-data values is due to the nature of the Samosa+ retracker: it is a physically based model and more sensitive to erroneous waveforms than the empirical OCOG retracker. ~~The lower backscatter values are~~ $\sigma_0$ is inherently related to the ~~L1b processing and~~ Level-1b processing how the waveform is derived ~~. $\sigma_0$ is inherently related to the L1b processing~~ and will be different in ~~two the datasets. Generally~~the two datasets. We note that, $\sigma_0$ is around 30% higher in the SciHub dataset. We use the same threshold because the intention is to remove obvious non-water targets. Increasing the threshold for the OCOG dataset did not improve outlier filtering as clearly defined non-water targets still had much lower $\sigma_0$ values, ~~and some SciHub~~

~~observations with~~ while some SciHub outliers had very high backscatter ~~values were clearly not valid observations of water level~~ (high standard deviation within the selected pass, no consistent seasonal pattern, poor L1b statistics etc.).

~~We note that~~ At 30 ~~VS have valid data only after the OLTC update of~~ Sentinel-3A ~~in March 2019. At 25 VS, extending the receiving window by a factor of three rather than two, increases the data coverage in the GPOD processing workflow. These VS are considered separately in the following sections. In general, the valid VS are predominantly located on higher level branches and tributaries of the basin and close to or on floodplains (Fig. 3). These targets are generally wider, perennial and the topography flatter. Conversely, several rejected VS are located in the headwater subcatchments on smaller tributaries. Although missing data represents less than 20%, the data is not necessarily useful and further analysis is required to evaluate the quality of the WSE observations at the VS properly~~stations, no observations were available in the either dataset before the March 2019 OLTC update, suggesting the water surface elevation was outside the range window prior to the update causing the poor results prior to the update. Indeed, at over 90% of these stations, the Level-1b statistics are consistent with water targets. We also see that for 13 VS a triple extension of the receiving window improves the time series from the GPOD dataset, confirming the importance of considering this option at certain locations.

**Table 3.** ~~Zambezi Sentinel-3A~~ Number of VS fulfilling criteria on Level-1b (L1b, % of VS retained from Level-2) and ~~3B~~ Level-2 (L2) in GPOD and SciHub datasets using the Samosa+ and OCOG retrackers respectively, and in both datasets. We consider S3A VS with data only after ~~outlier filtering. Stations which improved by modifying processing steps (either on board through~~ the OLTC update ~~or on-ground by extending~~ in March 2019 (line "OLTC v. 5") as well as the ~~receiving window~~ two processing settings on GPOD (line "3x window extension") ~~are highlighted~~ separately. The ~~frames indicate examples highlighted~~ total contains all stations present in ~~the next sections of this study~~both datasets.~~Additional maps are included in the supplementary material (Fig. A1, A2, and A3).~~

| | GPOD | | SciHub | | Both | |
|---|---|---|---|---|---|---|
| | L2 | L1b | L2 | L1b | L2 | L1b |
| Sentinel-3A - 364 VS | | | | | | |
| OLTC v. 4.2 | 82 | 75 (91%) | 105 | 89 (85%) | 78 | 68 (87%) |
| 3x extension | 7 | 6 (86%) | - | - | - | - |
| OLTC v. 5 | 32 | 31 (97%) | 34 | 28 (82%) | 30 | 27 (90%) |
| Total | 121 | 112 (93%) | 139 | 117 (84%) | 115 | 101 (88%) |
| Sentinel-3B - 367 VS | | | | | | |
| | 113 | 107 (94%) | 134 | 116 (87%) | 109 | 98 (90%) |
| 3x extension | 10 | 7 (70%) | - | - | - | - |
| Total | 123 | 114 (93%) | 134 | 116 (87%) | 117 | 103 (88%) |

### 3.2 ~~L1b at selected VS~~

~~The first step in validating the selected VS is to evaluate whether observations are over water . To assess this, we evaluate the~~ We evaluate the Level-1b data, to assess whether the observations at the VS are consistent with observations of water (L1b ~~data (Fig. 4 and~~ columns in Table 3). In the GPOD dataset, a high percentage of the VS have high PP and SP values (respectively above 0.1 and 0.2) combined with single peak waveforms (NP = 1) and high power (MP > ~~1e-15 in Watts~~$1e^{-15}$ W). High SP and PP values indicate a quasi-specular reflection, consistent with river surfaces, while ~~unique peaks~~ a unique peak and high power indicate low contamination from surrounding bright targets. ~~We see in Fig. 4 that the bulk of the rejected waveforms are rejected because of the NP criterion~~

The majority of stations with complete time series also have a high number of single-peak waveforms. A number of VS ~~might~~ have high PP and SP values but ~~contaminated waveforms , likely~~ multi-peak waveforms due to nearby bright targets ~~. As~~ (Fig. 4). Furthermore, as the SP and PP cannot be calculated based on the waveforms processed on SciHub, ~~we use NP alone as the L1b selection criterion. We see that the L1b selection process counterbalances the lower rejection rate in~~ the ~~SciHub dataset.~~ VS are evaluated at Level-1b based on the NP. We select stations with predominantly single-peak waveforms (along-track median NP = 1 in over 90% of the observations associated to the VS). In total, 101 Sentinel-3A and 103 Sentinel-3B have complete records and promising waveform statistics.

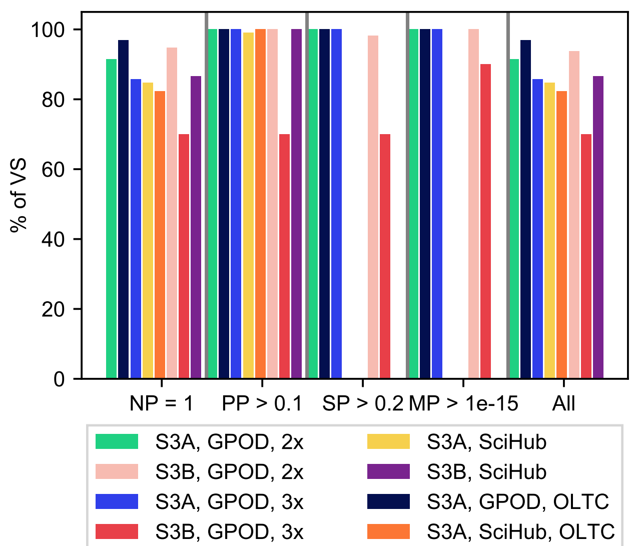


**Figure 4.** Stations fulfilling the L1b selection criteria in percentage of VS selected based on ~~L2~~ Level-2 data. Note that ESA SciHub does not provide the waveform in power; therefore, SP and MP are not calculated and are not part of the ~~“~~"all criteria fulfilled~~”~~" evaluation. "OLTC" indicates the waveform statistics after the OLTC update on Sentinel-3A in March 2019.

The ~~VS with valid Level 2 WSE time series but invalid waveform statistics from the GPOD datasets are spread throughout the catchment with most stations on Luangwa and on the Lower Zambezi (both S3A and S3B) and on the Kafue (S3A). The~~ rejection rate is higher in the SciHub dataset, with rejected stations throughout the basin. This is mainly due to the lower percentage of missing data in the Level-2 data. OCOG is an empirical retracker, less likely to fail on non-water waveforms.

Samosa+ is a physical retracker developed for coastal regions but suited to inland water targets. If the model misfit is too high, the retracker fails and the VS is rejected based on this missing data.

~~Number of VS fulfilling criteria on Level-1b and Level-2 (% of VS retained) in the SciHub and GPOD datasets using the OCOG and Samosa+ retrackers respectively. We consider S3A VS with data only after the OLTC update as well as the two processing settings on GPOD (2x and 3x window extension) separately. L2L1bL2L1bL2L1b2x extension 8175 (93%)10860 (56%)8049 (61%) 3x extension 62 (33%)--60 (0%) OLTC 3431 (91%)39 25 (64%)30 24 (80%) 2x extension 103 96 (93%)13979 (57%)10166 (65%) 3x extension 19 11 (58%)--186 (33%)~~

~~Fig. ?? shows the L1b statistics at the VS where data improved after the OLTC update or by extending the receiving window on the GPOD processing platform. The post-update statistics are shown with the 3x receiving window extension for the GPOD dataset. Several Sentinel-3A VS had no dataat all prior to the OLTC update. The GPOD dataset has more stations with NP > 1 after the OLTC update than the SciHub dataset. The waveform statistics suggest that using a dedicated processing setup such as the one on GPOD is beneficial; however,~~ A closer look at the ~~correct options must be applied to achieve optimal results~~stations with a large fraction of missing observations or multi-peak waveforms in both datasets revealed that at some stations, outliers caused the rejection but could be removed with dedicated, manual post-processing if the stations were located in areas of interest. In several cases, the rejected stations were located on narrow rivers crossing seasonal floodplains, with along-track standard deviations exceeding the seasonal variation. This was mostly the case when the station was rejected based on the single-peak criteria, justifying the rejection of the station. The proposed approach allows users to group the VS for further inspection, e.g. starting out with the VS most likely to hold useful river WSE observations.

It is interesting to note that ~~a high number of VS that~~ 13 VS were improved by extending the receiving window ~~, are rejected based on the waveform criteria~~in the GPOD dataset. Extending the receiving window ensures that the leading edge of the L1b echo is preserved. This is an advantage at VS where topography changes abruptly, as the full return echo can be contained in the receiving window from all beams used during multi-looking. ~~However, it also increases the likelihood of including contamination from other bright targets, increasing the number of significant peaks in the waveform.~~

~~Number of peaks (NP) in waveform at stations improved by the OLTC update and by the 3x bin extension using GPOD processing. See the additional material for localization of the VS shown in the plot.~~

### 3.2 ~~OLTC tables~~

~~The OLTC contains targets based on elevation information from hydrology databases (e.g. Hydroweb), virtual stations networks and the global ACE2 DEM (Altimeter Corrected Elevations v.2 Digital Elevation Model)~~

### 3.2 OLTC tables and geographical location of hydrological targets

Table 4 shows the geographical distribution of the VS selected in section 3.1 in the Zambezi basin and the corresponding number of expected VS based on the OLTC. The Sentinel-3A OLTC ~~was updated in March 2019 with additional information for inland water targets. In total, there are over 80 new targets over the Zambezi River from hydrology databases represented in the new OLTC, compared to only two in version 4.2. In version 4.2, 64 targets were defined at ground track -river crossings~~

~~and assigned ACE2 heights. These targets have also been updated with refined elevation information in OLTC version 5 to improve spatial coverage. The OLTC~~ update introduced several new VS, which had no useful information prior to the update. Most new VS are located in the Western part of the catchment (Upper Zambezi, Lungwebungo and Cuando/Chobe), where there were fewer targets in ~~version~~ v. 4.2. ~~Only VS validated at Level 1b and Level 2 are included in Table 4.~~ The number of VS consistently exceeds the number of targets, which is to be expected for plane areas, where even a single target may be sufficient to correctly track the WSE at multiple nearby crossing points.

**Table 4.** OLTC targets before and after March 2019 for the Zambezi catchment and their source (ACE-2 – global DEM or hydrology databases, HDB) – the targets are obtained from https://www.altimetry-hydro.eu/. The ~~numbers in parenthesis are the~~ Hydroweb Theia S3A VS ~~available~~ within each watershed ~~(~~are available on http://hydroweb.theia-land.fr/). The VS are grouped by major watersheds and according to the processing setting required. In the column "OLTC" VS with data only after the OLTC update are indicated. The total sums correspond to the values in Table 3.

| | S3A | | | | | | | | | S3B | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OLTC Version | v. 4.2 | | v. 5 | Number of VS | | | | | | v. 2 | Number of VS | | |
| | ACE2 | HDB | HDB | GPOD Hydroweb | GPOD 2x | GPOD OLTC | GPOD 3x | SciHub | SciHub OLTC | HDB | GPOD 2x | GPOD 3x | SciHub |
| Upper Zambezi and Luena | 0 | 0 | 6 | ~~11 (~~1~~)~~ | 6 | 4 | 0 | ~~6~~ 7 | ~~3~~ 4 | 8 | ~~21~~ 22 | ~~1~~ 0 | ~~13~~ 21 |
| Kabompo | 0 | 0 | 3 | ~~4 (~~3~~)~~ | 1 | 3 | 0 | ~~2~~ 1 | ~~2~~ 3 | 2 | 1 | ~~0~~ 1 | 2 |
| Lungwebungo | 3 | 0 | 7 | ~~13 (~~3~~)~~ | ~~8~~ 5 | 7 | 0 | ~~9~~ 5 | ~~7~~ 8 | 8 | ~~10~~ 8 | ~~2~~ 1 | ~~8~~ 11 |
| Luanginga | 0 | 0 | 0 | ~~11 (~~0~~)~~ | 8 | 3 | 0 | ~~11~~ 9 | 3 | 0 | 5 | 0 | ~~3~~ 5 |
| Cuando/Chobe | 1 | 0 | 2 | ~~18 (~~4~~)~~ | 12 | 6 | 0 | 15 | ~~5~~ 6 | 3 | 21 | ~~2~~ 0 | ~~18~~ 23 |
| Barotse | 5 | 0 | 5 | ~~6 (~~5~~)~~ | 3 | 3 | 0 | ~~5~~ 4 | ~~2~~ 3 | 18 | 11 | 1 | ~~10~~ 11 |
| Middle Zambezi (Kariba) | 15 | 1 | 9 | ~~2 (~~0~~)~~ | 3 | 0 | 0 | ~~2~~ 3 | 0 | 12 | ~~4~~ 5 | ~~1~~ 0 | ~~2~~ 6 |
| Kafue | 7 | 0 | 17 | ~~18 (~~14~~)~~ | 17 | 0 | ~~1~~ 4 | ~~16~~ 26 | 0 | 14 | ~~15~~ 14 | ~~2~~ 1 | ~~10~~ 14 |
| Mupato | 2 | 0 | 3 | ~~3 (~~2~~)~~ | 3 | 0 | 0 | 2 | 0 | 4 | 2 | 0 | ~~1~~ 2 |
| Luangwa | 4 | 0 | 9 | ~~8 (~~6~~)~~ | 6 | 3 | ~~0~~ 1 | ~~7~~ 4 | ~~2~~ 0 | 6 | 4 | ~~1~~ 2 | 3 |
| Lower Zambezi (Tete) | 25 | 1 | 20 | 8 ~~(8)~~ | 7 | 0 | 1 | ~~7~~ 9 | 0 | 33 | 8 | 0 | ~~3~~ 8 |
| Shire | 2 | 0 | 6 | ~~6 (~~2~~)~~ | ~~1~~ 4 | 2 | 0 | ~~3~~ 4 | 1 | 7 | 3 | 1 | ~~3~~ 5 |
| Total | 64 | 2 | 87 | 48 | 75 | 31 | 6 | 89 | 28 | 115 | 107 | 7 | 116 |

### 3.3 WSE Evaluation

#### 3.3.1 Validation at in-situ stations

The retracked WSE data are compared to the in-situ gauge levels at six locations in the basin; where VS and in-situ stations are sufficiently close geographically (Fig. 5). In all six cases, the twice-extended receiving window is sufficient~~and no new~~

~~targets were uploaded to the OLTC in March 2019 near the two S3A VS~~. The OLTC did not significantly change at the VS considered, meaning WSE observations are available for the entire Sentinel-3 sensing period.

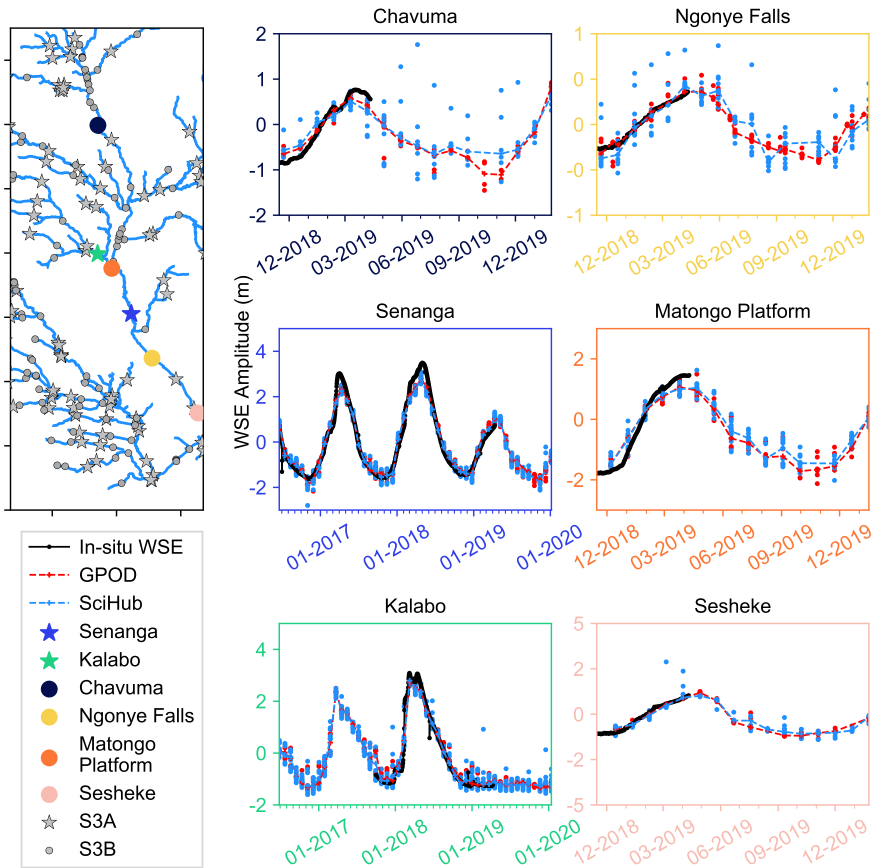


**Figure 5.** In-situ and satellite WSE at six locations in the Upper Zambezi basin (blue polygon on Fig. 3). The plot colors correspond to the marker colors for each station in the map. The lines indicate the along-track mean WSE.

Performance at all six stations is highly satisfactory, based on visual inspection, performance statistics and in comparison to performance reported in past studies (Villadsen et al., 2016). The RMSD between the in-situ and satellite relative river levels is below 30 cm at five out of six stations, only the Matongo Platform has a moderate RMSD of 32 cm (Table 5). The largest RMSD are seen for the two VS furthest away from the closest in-situ gauge (19.3 km for Senanga and 15.8 km for the Matongo platform). The systematic deviations between the in-situ and satellite WSE is to be expected given the long distance. For the remaining four stations, the RMSD is less than 15 cm with the ~~Samosa+ retracker~~GPOD dataset. Michailovsky et al. (2012) obtained RMSD between 24 and 106 cm at Envisat VS in the Zambezi catchment. The improvement in performance is consistent with the instrumental improvement between the two missions. ~~Furthermore, the Samosa+ retracker outperforms the OGOC retracker~~ The GPOD dataset performs better than the SciHub dataset at all stations, improving the RMSD with between

1.1 cm (7.5%, at Kalabo) and 10.2 cm (39.2% at Chavuma); except Matongo Platform, where the ~~OCOG retracker~~ SciHub dataset improves the RMSD by ~~1.3 cm~~ 1.4 cm (4.5%).

The WRMSD from the GPOD dataset varies between ~~4.4~~4.9% and 18.9% of the in-situ standard deviation (Table 5). Thus, the error represents less than 20% of the variation in water level expected at each given location. The error is equivalent to ~~1.3~~1.5-6.3% of the mean annual amplitude. This confirms a low degree of uncertainty relative to the seasonal water level amplitudes. A closer look at the seasonal deviations provides additional insight into the uncertainty. As expected from Fig. 5, the underestimation of the peak water level is the main source of error at Senanga and Kalabo, whereas the error is similar across seasons at Ngonye Falls and Chavuma, and larger in the dry season at Sesheke and Matongo Platform.

**Table 5.** Performance statistics compared to neighboring in-situ gauge stations using ~~S~~the G. ~~Samosa+ on~~ GPOD processing platform and ~~O~~S. ~~the OCOG retracker from~~ SciHub, to ~~retrack~~ obtain satellite WSE. The relative RMSD is given in percent of the in-situ standard deviation. At all six stations, observations are available until April 2019. All the stations have complete WSE records since the start of the Sentinel-3A time series (June 2016), with the exception of Kalabo (October 2017).

| In-situ station | VS platform and ID | Distance to VS [km] | River width [m] | RMSD [cm] (% of the mean annual amplitude) | Dry season RMSD [cm] | Wet season RMSD [cm] | WRMSD [%] | $r^2$ |
|---|---|---|---|---|---|---|---|---|
| Senanga | S3A | ~~19.3~~ 19.5 | 260 | ~~S~~G. 25.8 (~~5.4~~5.6) | 15.2 | 36.4 | 17.9 | 0.987 |
| | A062 | | | ~~O. 28.1 (5.9~~S. 28.2 (6.1) | 16.0 | 39.6 | 19.6 | 0.985 |
| Kalabo | S3A | 4.8 | 35-600 | ~~S~~G. 13.6 (3.1) | 8.6 | 18.8 | 9.4 | 0.998 |
| | A037 | | (floodplain) | ~~O. 15.1~~ S. 14.7 (3.4) | 11.4 | 18.6 | ~~10.4~~10.1 | 0.998 |
| Ngonye Falls | S3B | 1.7 | 1100 | ~~S. 2.7 (1.3~~G. 2.9 (1.5) | 3.0 | ~~2.2~~3.7 | ~~4.4~~4.9 | ~~0.998~~0.997 |
| | B077 | | | ~~O~~S. 7.2 (~~5.3~~3.6) | 7.0 | 7.3 | 12.0 | 0.992 |
| Chavuma | S3B | 7.6 | 210 | ~~S~~G. 15.8 (3.3) | 15.9 | 15.7 | 11.9 | 0.997 |
| | B021 | | | ~~O. 25.6 (3.6~~S. 26.0 (5.4) | ~~25.4~~25.5 | ~~25.9~~26.6 | ~~19.3~~19.6 | ~~0.979~~0.973 |
| Matongo Platform | S3B | 15.8 | 95 | ~~S. 31.2~~ G. 31.3 (6.3) | 35.3 | 28.2 | 18.9 | 0.990 |
| | B068 | | | ~~O~~S. 29.9 (6.0) | 32.0 | 28.4 | 18.1 | 0.992 |
| Sesheke | S3B | 2.7 | 430 | ~~S~~G. 10.5 (1.7) | 13.6 | 7.8 | 5.4 | 0.991 |
| | B078 | | | ~~O. 14.7~~ S. 15.4 (2.5) | 19.2 | 12.2 | ~~7.5~~7.9 | ~~0.978~~0.979 |

The in-situ stations are mainly located in the Upper Zambezi, therefore the validation is geographically constrained. However, the river morphology at the ground stations is diverse, ranging from 95 m wide rivers to 35-600 m on the Barotse floodplain. Therefore the validation is presumed to be an encouraging indication of the performance basin-wide.

### 3.3.2 Evaluation of hydrological pattern at catchment level

In-situ water level observations are available at ten other locations, where records end in the 2000s. As there is no overlap between the in-situ and VS time series, the stations cannot be used to quantitatively validate the nearest virtual stations.

Instead, we visualize the annual water level variations to evaluate whether the time series appear coherent with the expected hydrologic patterns (Fig. 6).

In general, the patterns at several stations are coherent with the annual hydrological cycle observed in the corresponding region over the last two decades. The WSE observed by the satellite corresponds well with the amplitudes recorded at the gauging stations. The satellite time series appear smoother (e.g. at stations 3045, ~~5940~~ 4669 and 5099). This is logical as the 27-day return period increases the risk of missing the peak or low flow compared to a daily gauging record. We do note some obvious outliers, e.g. at station ~~1950~~5650, in the Sentinel-3A time series.

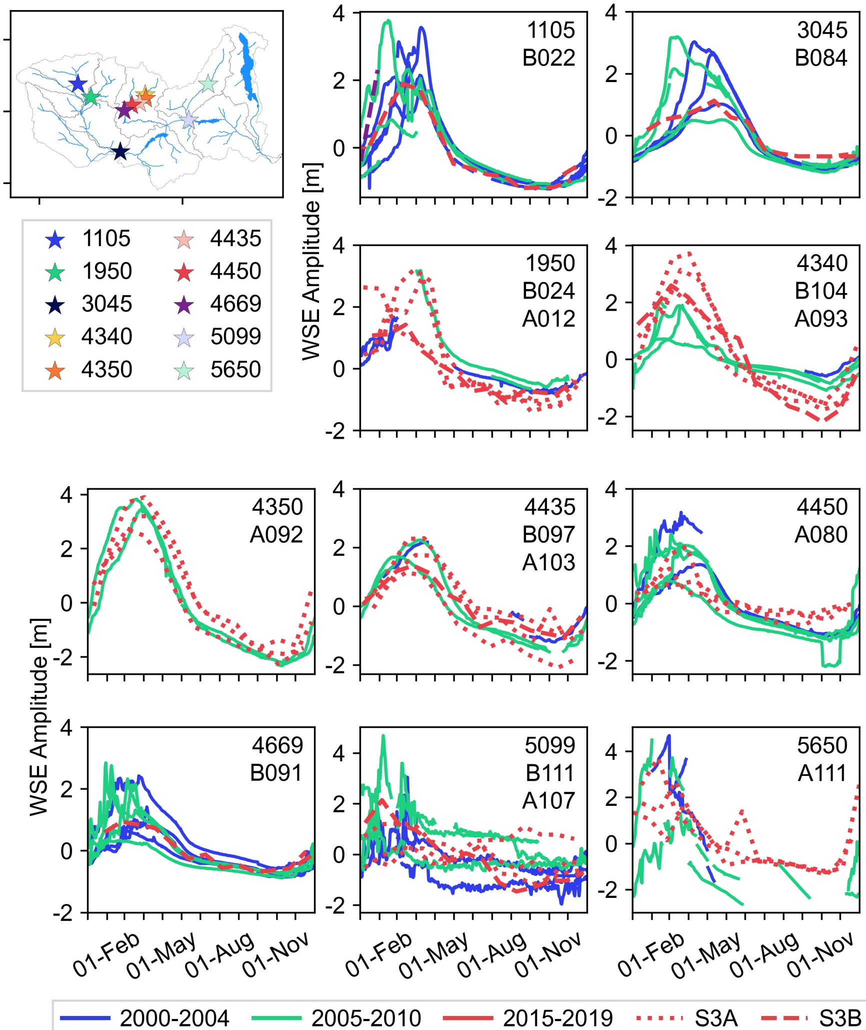


**Figure 6.** Comparison between in-situ annual WSE and satellite WSE at ten VS in the Zambezi basin. The colors indicate the time of observation. All elevations are referenced to the long-term average WSE to avoid bias due to the vertical datum. Stations 4340-4669 are all located on the Kafue in close proximity.

### 3.3.3 Annual amplitude of WSE

Fig. 7 shows boxplots of all ~~useful~~ selected VS based on the evaluation of the ~~L1b and L2 data~~ Level-1b and Level-2 data (< 20% missing data and along-track NP = 1 for 90% of the tracks). The boxes delimit the IQR (Inter-Quartile Range – or between the first and third quartiles, $Q_{75}$ and $Q_{25}$ respectively) and the whiskers extend from $Q_{25} - 1.5 \times IQR$ to $Q_{25} + 1.5 \times IQR$. The amplitude within the whiskers varies between 1 m and 8.3 m. We note that for Sentinel-3B, the amplitudes are smaller than for Sentinel-3A. This is due to the length of records, with indications of 2019 being a dryer year than 2016-2018, as seen in Fig. 5 at Senanga and Kalabo, and when comparing the Sentinel-3B records to in-situ records in Fig. 6.

A closer look at the WSE recorded at the selected VS reveals a large number of extreme values in the initial dataset (Fig. 7, a). Even after outlier removal, there are still stations with very large amplitudes (> 20 m), which, based on the overall basin statistics, is unlikely. Ground observations of WSE indicate annual amplitudes in the order of magnitude of 5 m and similar values are obtained from Sentinel-3 at directly comparable stations.

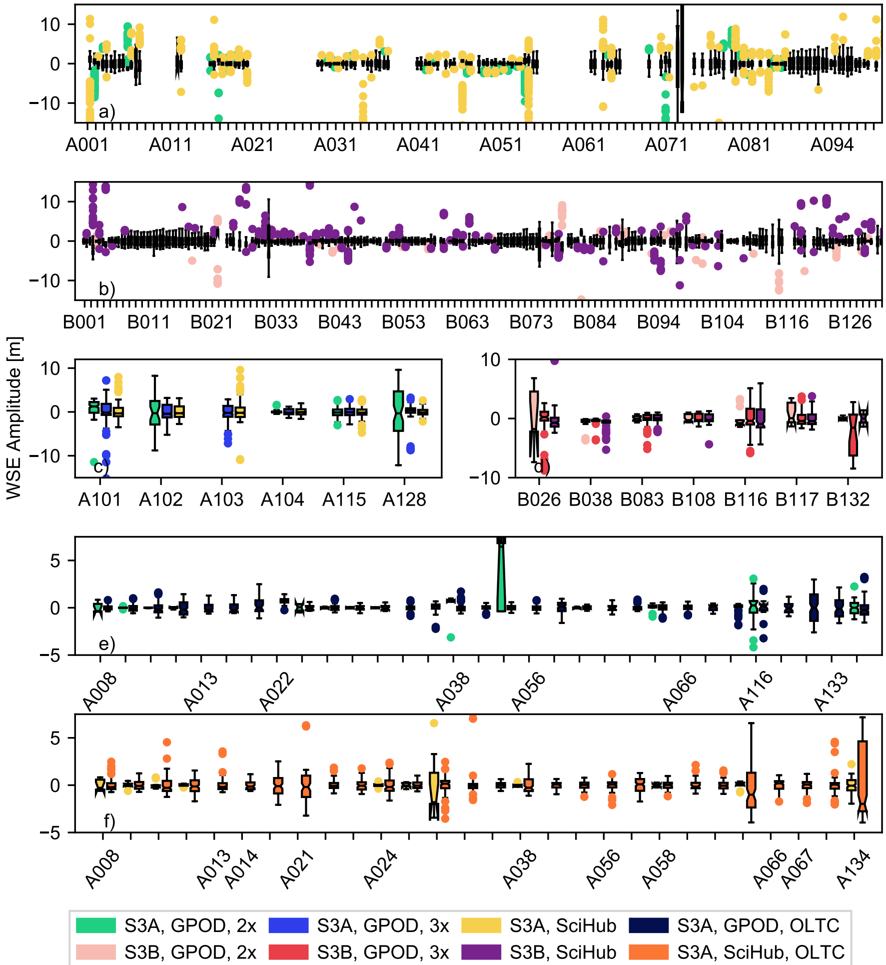


**Figure 7.** Boxplots of valid WSE for each VS (along the x-axis): a) all S3A VS, b) all S3B VS, c) S3A VS improved with the 3x receiving window extension, d) S3B VS improved with the 3x receiving window extension, and e) and f) S3A VS with observations after OLTC update only in the GPOD dataset and SciHub datasets respectively. The gaps in a) and b) correspond to the VS shown in c), d), e) and f). The points are WSE outside of 1.5 times the InterQuartile Range (IQR), a common measure to identify outliers, to improve readability; the extreme outliers are cropped out of the plots. See Appendix for coordinates of the VS.

There are outlier removal approaches, which could be used to address this issue (e.g. IQR outlier removal, where points outside of the boxplot whiskers would be removed); however, in several cases the filtering also removes peak annual discharge. In some cases, the 3x window extension reduces this amplitude, as does the OLTC update. At other stations, the amplitude increases with the temporal coverage and data volume. If we consider the stations ~~, which are valid across datasets, there are 145~~ with less than 20% missing data and over 90% single-peak waveforms, there are 204 Sentinel-3 VS in the Zambezi, which contain potentially valuable information about WSE. ~~The number of VS is quadrupled compared to using the global database Hydroweb~~Thus, automatically processing all Sentinel-3 observations within an area of interest can provide a highly valuable addition to global altimetric WSE databases, by increasing the spatial density of VS at catchment scale. The assessment based on the degree of missing data and on single-peak waveforms constitutes a preliminary validation of the virtual stations, although dedicated outlier filtering and validation might be necessary at some stations to ensure consistency with the catchment dynamics.

~~Boxplots of valid WSE for each VS (along the x-axis): a) all S3A VS, b) all S3B VS, c) S3A VS improved with the 3x receiving window extension, d) S3B VS improved with the 3x receiving window extension, and e) and f) S3A VS with observations after OLTC update only in the GPOD dataset and SciHub datasets respectively. The points are WSE outside of 1.5 times the InterQuartile Range (IQR), a common measure to identify outliers, to improve readability; the extreme outliers are cropped out of the plots. See Appendix for coordinates of the VS.~~

## 4 Discussion

### 4.1 ~~Open-loop mode~~Catchment-scale processing and processing options

At four stations in the Upper Zambezi, there are no ~~valid observations at any of the VS~~ observations prior to the OLTC update (Fig. 8). ~~These stations are good examples that illustrate the value of an up to date and precise OLTC to fully benefit from the open-loop mode. We note that SciHub points are more scattered than the GPOD points, although the final time series is similar.~~ The four VS are ~~amongst the VS which are~~ unavailable on global river WSE databases from radar altimetry (e.g. Hydroweb, DAHITI)~~, illustrating the benefit of the proposed workflow to fully exploit the~~ . These examples illustrate benefit from processing the Sentinel-3 ~~dataset at catchment level.~~ records on GPOD or SciHub as Level-1a data is published. For global databases, it might be impractical to process short time series (in this case less than a year), although they might contain useful information for hydrological studies at catchment level. Furthermore, the OLTC update and ensuing increase in number of hydrology targets increase the number of potential VS, and are key to the success of the open-loop tracking mode (Le Gac et al., 2019). Unfortunately, at 30 VS in the Zambezi two and a half years of Sentinel-3A observations are invalid due to the lack of OLTC targets.

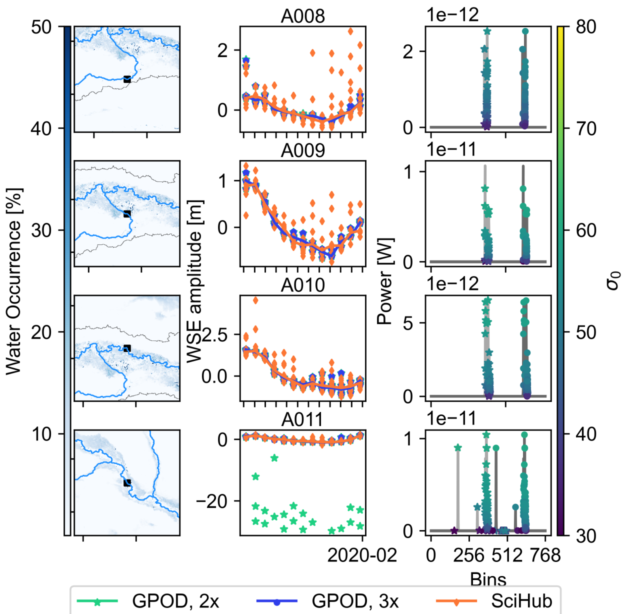


**Figure 8.** WSE time series in the Upper Zambezi and GPOD waveforms after the OLTC update. For clarity, we only show the GPOD waveforms, as the conclusions are not affected by the Level-1b processing in any of these cases. Due to the window extension and padding of the Hamming window on GPOD, the waveforms are shifted by respectively 256 and 512 bins for the double and triple extensions respectively.

~~Although the WSE time series are almost identical, Fig. 8 reveals several outliers at the last VS when using the standard GPOD processing options for inland water. This is caused by incorrect retracking (points on the y = 0 axis in the waveform subplot) and erroneous heights (WSE 10 to 20 m below the mean WSE). At the three other VS, increasing the window extension factor has no effect.~~

Fig. 9 illustrates the stack waveforms for ~~the last track~~ VS A011 before and after the OLTC update and the positioning of the altimeter reception window. ~~Before, the power was six orders of magnitude lower and the resulting WSE was 400 m below the DEM elevation.~~ The bright water target is clearly visible in the stack waveform after the OLTC update, whereas the waveform prior to the update is clearly just noise. A closer look at the tracker range clearly indicates the discrepancy between the on board elevation information and the actual surface elevation ~~(Fig. 9). Furthermore,~~ before the update. The changes in the on board DEM after the OLTC update introduce sharp transitions in the reception window close to the VS, mimicking the effect of steep topographical changes~~, even in relatively flat regions~~. The short closed-loop transition during the OLTC update reveals that ~~this is exactly the case~~ the topography at the target ~~. Therefore, processing decisions cannot be based on the topography alone but should take into account the on board information as well.~~

~~L1b data at VS on ground track 135 (descending path). a) Tracker range before, during and after the OLTC update and outliers using GPOD dataset with double window extension, b)-e) waveform statistics – the waveforms have been processed~~

~~on GPOD: b) and c) stack waveforms d) Range Integrated Power (RIP) and e) waveforms before and after the Sentinel-3A OLTC update.~~

~~The maximum RIP and backscatter coefficients are equivalent for the two setups and the only difference is~~ is in fact relatively flat. Fig. 8 reveals several outliers at the last VS (A011) when using the standard GPOD processing options for inland water (GPOD 2x). This is caused by incorrect retracking (points on the y = 0 axis in the waveform ~~misfit. The data does not offer insight into why the retracker fails at this location~~subplot) and erroneous heights (WSE 10 to 20 m below the mean WSE). At the three other VS, increasing the window extension factor has no effect. The time series at ~~this location does indicate~~ A011 indicates that the triple extension may be more robust ~~. Sentinel-3A briefly operated in closed-loop during the update period, between 1st of March 2019 and 9th of March 2019. Fig. 9 shows the tracker range during the update in black. The closed-loop mode performs very well and appears to capture changes in topography left out because of memory limitations imposed on the OLTC. This example illustrates that~~ even for plain areas. Therefore, processing decisions should not be based on the topography alone but instead take into account the on board information as well. Furthermore, we note that while the along-track spread of the ~~benefit from open-loop over closed-loop tracking mode is clearly limited to VS where adequate elevation data is available in the OLTC. There is a risk of loss of data if the OLTC is not precise or dense enough. In that case, closed-loop mode may be preferable, particularly where topography does not change too abruptly~~SciHub WSE is wider than the GPOD 3x observations, the final time series are similar.

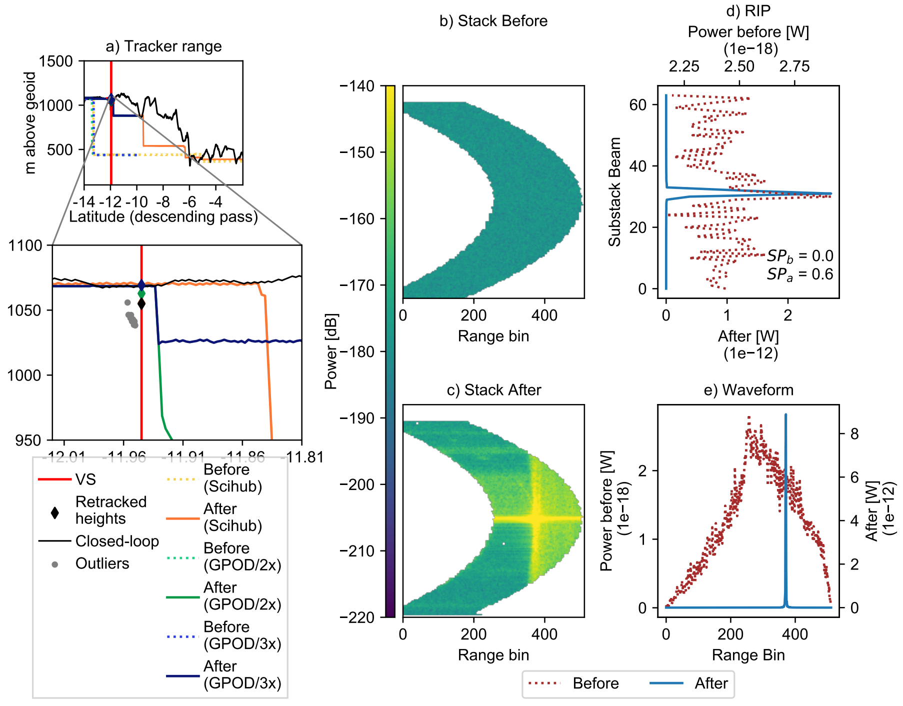


**Figure 9.** Level-1b data at VS on ground track 135 (descending path). a) Tracker range before, during and after the OLTC update and outliers using GPOD dataset with double window extension, b)-e) waveform statistics – the waveforms have been processed on GPOD: b) and c) stack waveforms d) Range Integrated Power (RIP) and e) waveforms before and after the Sentinel-3A OLTC update.

### 4.2 ~~Waveform processing -~~ Processing options on GPOD~~versus baseline processing~~

The ~~L1b~~ Level-1b processing steps to generate the waveforms are different on GPOD and SciHub, and at some VS, this has clear consequences. ~~Although the OLTC update has increased the number of VS in the Zambezi by 24 across datasets, we observe cases where the double extension dataset only contains data after the update, whereas extending the receiving window or using the baseline processing from SciHub yields valid data. We consider a virtual station on the Kafue at~~ Fig. 10 shows the waveforms and WSE time series at VS A102 on the Kafue, located at 1116 ~~mamsl elevation. According to the OLTC website, there was no target near the VS prior to the OLTC update and the reception window was positioned at 978 mamsl based on the previous target. The reception window is more than 30 m below the target and the satellite should not have sensed the VS prior to March 2019. However, the~~ m above the geoid. Using the OCOG retracker and the standard SciHub dataset successfully produces a WSE time series with a clear seasonal pattern. When using the GPOD dataset, a 3x extension of the receiving window is necessary to obtain data at this particular VS.

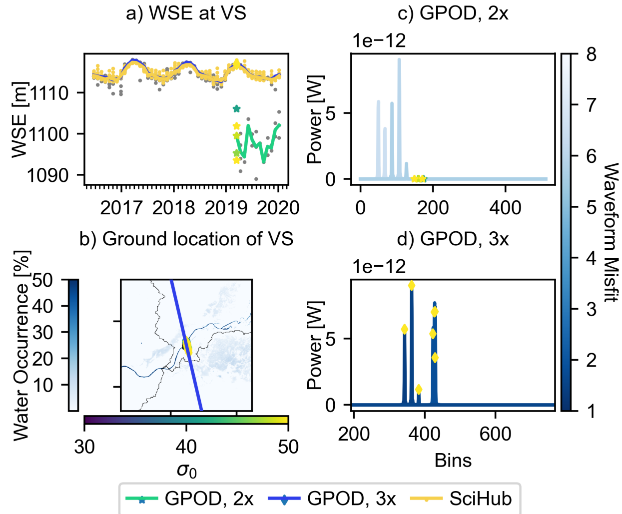


**Figure 10.** Comparison of WSE time series (a) and waveforms (c and d) at the VS on the Kafue (b) using the GPOD dataset with the Samosa+ retracker applying a double (c) and triple (d) extension of the receiving window and the SciHub dataset. The misfit parameter is provided with the GPOD dataset and is a measure of fit of the waveform model from the Samosa+ retracker to the actual model.

The tracker range from the SciHub dataset suggests that the ~~window was actually positioned~~ range window was correctly positioned within +/- 10 m of the surface elevation at around 1111 ~~mamsl; therefore, the discrepancy must be related~~ m (Le Gac et al., 2019). The discrepancy can instead be attributed to the waveform processing, as illustrated in Fig. 11. After the OLTC update a target is defined for the VS at 1113 ~~mamsl~~ m and the transition occurs earlier on the pass. The altimeter reception window has shifted just enough that the VS elevation is within the receiving window for all three datasets, including the GPOD dataset with the double extended receiving window.

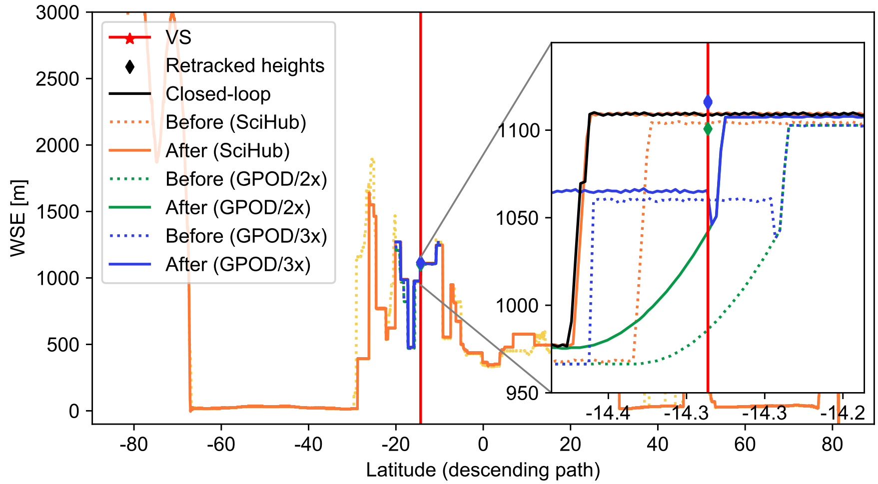


**Figure 11.** Tracker range for the three possible processing setups before and after the OLTC update.

The standard processing produces an abrupt change in the tracker range, consistent with the Sentinel-3 operating mode, where a target is retained until a new one is defined. If we consider the standard GPOD processing, the transition between two targets is smoothed. ~~When the window is increased, the L1b~~ Increasing the window preserves the Level-1b echoes leading edge ~~is preserved (Dinardo et al., 2018). This creates~~ (Dinardo et al., 2018), creating a stepwise transition (Fig. 11). ~~A~~ The effect of the pseudo-DEM is akin to that of sharp changes in elevation in coastal or mountainous areas for closed-loop operations (Dinardo et al., 2018). While a smoother transition may be an advantage for closed-loop processing, as demonstrated in Dinardo et al. (2018), however in open-loop processing, where the targets are immediately known, an unnecessary delay is introduced and the window extension becomes necessary to mitigate this.

~~Fig. 10 shows the waveforms and WSE time series at the station. The consequences of the different tracker range is clear: using the OCOG retracker and the standard SciHub dataset successfully produces a WSE time series with a clear seasonal pattern. When using the GPOD dataset, a 3x extension of the receiving window is necessary to obtain data at this particular VS.~~

~~Comparison of WSE time series (a) and waveforms (c and d) at the VS on the Kafue (b) using the GPOD dataset with the Samosa+ retracker applying a double (c) and triple (d) extension of the receiving window and the SciHub dataset. The misfit parameter is provided with the GPOD dataset and is a measure of fit of the waveform model from the Samosa+ retracker to the actual model.~~

~~The effect of the pseudo-DEM is akin to that of sharp changes in elevation in coastal or mountainous areas for closed-loop operations (Dinardo et al., 2018). Abrupt changes in topography – or too far apart targets – can cause truncations in the waveform leading edge due to erroneous positioning in time of the radar's reception window. The options to mitigate include~~ In such cases, mitigation options include ensuring that the target is defined early enough on the track to avoid consequences for the dataset and extending the receiving window and thus making sure that the full echo can fit in the receiving window and that the leading edge is preserved (Dinardo et al., 2018)~~or ensuring that the target is defined early enough on the track to avoid consequences for the dataset~~. In the example above, the latter is necessary when using the GPOD dataset, and although not critical to data retrieval, the position of the target was also shifted in the OLTC update of March 2019. Based on these findings, we recommend using the triple window extension when processing catchment scale datasets on GPOD to maximize the number of VS.

### 4.3 River-floodplain interaction

The Zambezi is ~~intrinsically linked~~ home to several significant wetlands, e.g. the Barotse floodplain, Kafue Flats and Chobe floodplain. At some VS, the WSE will reflect the river-floodplain interaction. Fig. 12 is an example from ~~an S3B VS in~~ the Barotse floodplain (VS B074). The crossing tracks are both close to the river. The ascending track directly crosses the river, the waveforms and backscatter coefficients closely support a good target. We do see multiple peaks in the waveform as the target nears the edge of the river. The other track crosses the floodplain. When considering the two tracks separately, the interaction is clearly visible: the river level rises until it reaches the floodplain level. Subsequently, the river floods and water levels in the floodplain increase, before decreasing again after the wet season. The river level decreases further to its original level, 1.5 m below the floodplain. The coupling is particularly visible during the flood recession phase~~, the early~~. The increase of the floodplain ~~begins~~ appears to begin right before the river reaches the floodplain level. It is unclear whether this is due to the local topography or to artifacts due to the track orientation.

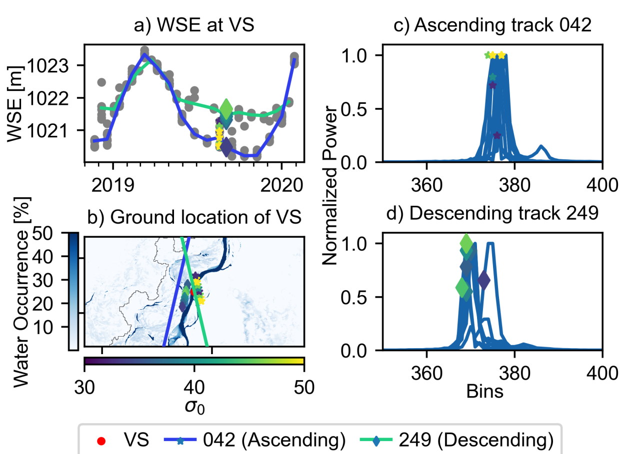


**Figure 12.** Demonstration of river-floodplain interactions at ~~a~~ VS B074 on the Barotse floodplain. a) WSE at VS with highlighted observations showed in b) along with the water extent map and ground tracks, c) and d) waveforms from the observations from the two respective passes. The observations plotted are the same in a-d to illustrate the different data dimensions (ground location, WSE and backscatter coefficient).

The findings in Fig. 12 motivated an analysis of entire tracks crossing the floodplains. Rather than grouping by coordinates, we here assess ~~specific relative~~ all unique passes, known to cross floodplains. The seasonal flooding dynamics are clearly visible at all three evaluated floodplains. Darker blue colors indicate higher water occurrence. The tracks in Fig. 12 correspond to track 498 (descending) and 85 (ascending) in Fig. 13. It is interesting to note the drought in 2019, which is clearly visible in all three wetlands, particularly at the Sentinel-3A VS on track 741, which appears to suggest the level has remained ~~2m~~ 2 m below the mean well into the 2019-2020 wet season. It is interesting to note that there are several valuable observations along Sentinel-3B ground track 498, although the water occurrence is 0%. This is likely due to the frequent cloud cover over the floodplain ~~.~~ or vegetation masking the water surface in optical images, stressing the importance of integrating SAR imagery into water mask processing.

The datasets also hold valuable information regarding slope in the wetland. This is a particular feature of the orientation of the wetland compared to the satellite tracks, which creates a spatially dense sampling pattern along the river line and floodplain. This could be useful in hydrologic/hydrodynamic modelling of the river in the region.

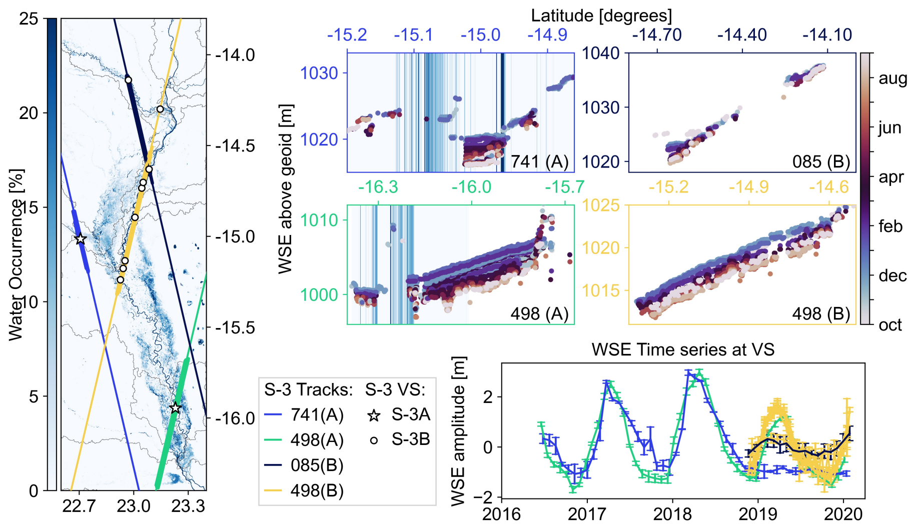


**Figure 13.** Floodplain dynamics in the Barotse floodplain as observed by Sentinel-3A (ground track 741 and 498) and Sentinel-3B (ground track 85 and 498). The WSE cross-sections are in order of crossing tracks from West to East. The cyclical color scheme shows the WSE amplitude over the hydrological year. The line colors in the time series correspond to the track colors from the map and the width of the line indicates the observations shown in the scatter plots. The error bars reflect the standard deviation for each pass used in the time series. The water occurrence thresholds are deliberately set from to 0-10% to enable the visualization of the floodplain.

In the Kafue Flats, we see seasonal patterns, with high flow occurring in spring and low flow starting in the late summer (Fig. 14). We also see gradual smoothing in the WSE time series as the distance to the Itezhi-Tezhi reservoir upstream decreases. The upstream WSE is driven by reservoir release with sharp changes in WSE, whereas wetland processes smooth the downstream WSE. There are no valid VS on the tributaries located very close to frequently flooded areas (Sentinel-3B track 298 and Sentinel-3A track 541). The time series at the VS on Sentinel-3A track 070 and Sentinel-3B track 184 both present a sharp increase in January 2019 followed by a sharp return to the previously low level. The pass standard deviation is also larger in the upstream part. The tracks are both in the upstream part of the wetland, with nearby seasonally flooded areas. Both findings are coherent with the results from Jiang et al. (2020), which identified nearby bright targets such as small lakes and ponds as a key source of errors for Sentinel-3. In this case, there are either no observations or unlikely ~~artefacts~~ artifacts in the time series.

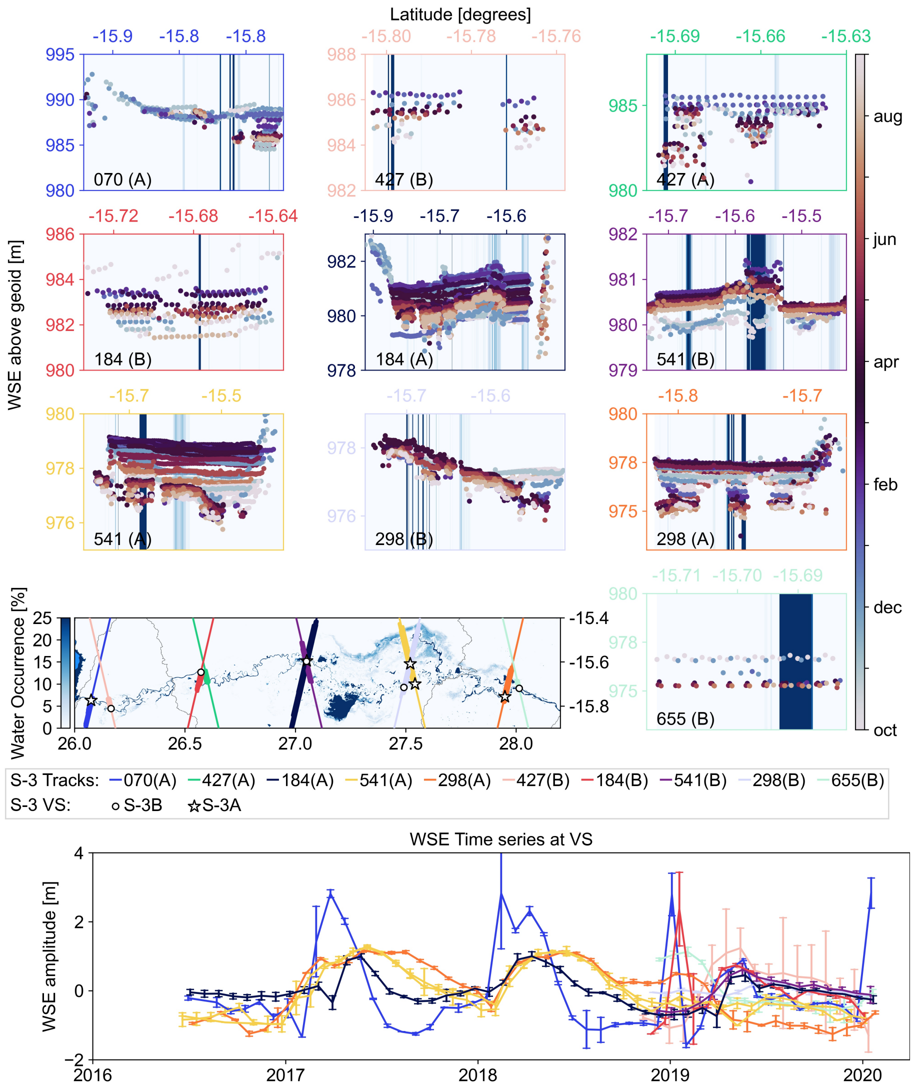


**Figure 14.** Floodplain dynamics in the Kafue Flats as observed by Sentinel-3A and Sentinel-3B. The tracks are ordered by longitude moving left to right on the map. The WSE cross-sections are in order of crossing tracks from West to East. The line colors in the time series correspond to the track colors from the map and the width of the line indicates the observations shown in the scatter plots. The frame colors and line colors in the time series correspond to the track colors from the map. The error bars reflect the standard deviation for each pass used in the time series. The water occurrence thresholds are deliberately set from to 0-10% to enable the visualization of the floodplain.

The WSE in the Chobe region reflect the dry 2019 wet season – the peak WSE is lower than the previous two years on record (Fig. 15). We see two different behaviors at the VS in the wetland region. In the Southern portion, prior to confluence with the Zambezi River, the amplitude is smaller. The wet season is slightly delayed with a more gradual decrease after the peak WSE height; however, in winter 2019-2020, the level has continued to decrease, as seen at all VS in the region. On the Zambezi, the annual amplitude is closer to 5m and there is a clear attenuation in the maximum water level in the 2019-2020 season compared to previous years. This was clear at station 3045 in Figure 6 as well compared to records from 2000-2010.

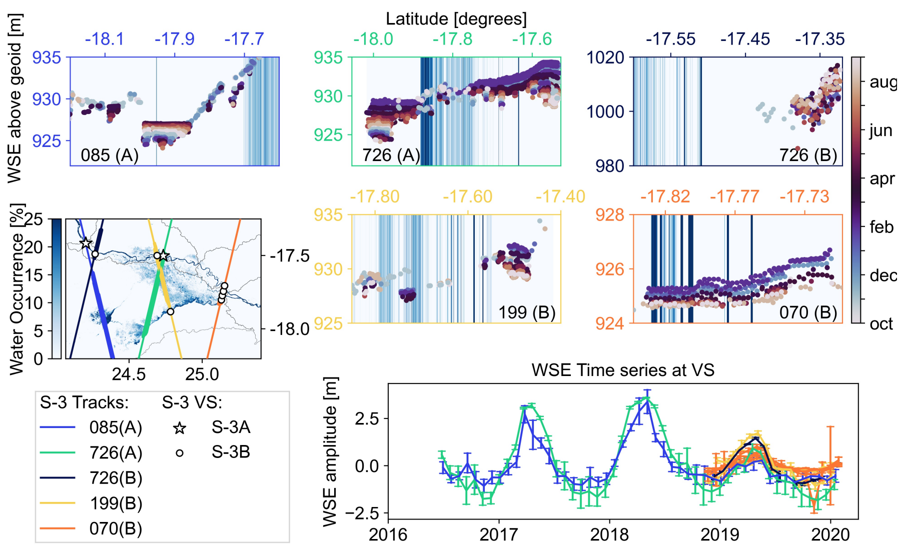


**Figure 15.** Floodplain dynamics in Chobe as observed by Sentinel-3A ~~(left)~~ and Sentinel-3B~~(right)~~. The WSE cross-sections are in order of crossing tracks from West to East. The cyclical color scheme shows the WSE amplitude over the hydrological year. The line colors in the time series correspond to the track colors from the map and the width of the line indicates the observations shown in the scatter plots. The error bars reflect the standard deviation for each pass used in the time series. The water occurrence thresholds are deliberately set from to 0-10% to enable the visualization of the floodplain.

## 4.4 ~~Perspectives~~Hydrological applications

This study explores the potential for extracting Sentinel-3 WSE at catchment-level. ~~The perspectives are two-fold. First, we~~ We present a dense monitoring network for the Zambezi basin, with high spatial coverage and monthly observations of WSE. In this study, the availability of in-situ records is limited relative to the catchment size. Although the performance of the Sentinel-3 satellites cannot be fully validated in the entire catchment, previous studies confirm the performance observed in this study (Jiang et al., 2020). The potential value of altimetry VS is high in poorly gauged catchments and subcatchments, where altimetry may be the only source of water level observations. The high number of VS throughout the basin can form the basis of a dense monitoring network. Michailovsky et al. (2012) assessed the number of VS in the Zambezi from Envisat and found 423 crossing points against 731 with Sentinel-3, and after careful evaluation, 31 VS had useful records. Although all 204 VS were not manually checked, the results in this study confirm that this number is greatly increased with Sentinel-3.

The spatio-temporal sampling of altimetry missions often constrains monitoring capabilities. Particularly the dual-satellite configuration of Sentinel-3 thus offers new, interesting possibilities in a hydrological context. It is important to note that the success is entirely dependent on the accuracy of the OLTC tables as data is missing from the Sentinel-3A records in large part due to the latency between mission start and OLTC update.

Satellite observations of WSE have been used in several studies to obtain information on river dynamics and to calibrate and update hydrological models ~~(Domeneghetti, 2016; Dubey et al., 2015; Finsen et al., 2014; Schneider et al., 2018a)~~ (e.g. Domeneghetti, 2016; Dubey et al., 2015; Finsen et al., 2014; Schneider et al., 2018a). Schneider et al. (2018b) and Jiang et al. (2019b) have explored the value of high spatial resolution in calibrating hydrodynamic model parameters by using altimetry WSE observations. Jiang et al. (2019b) evaluated the value of calibrating with different spatio-temporal densities and their results reveal a high benefit from the high spatial distribution of CryoSat-2 and Envisat observations as opposed to the Jason missions. The Sentinel-3 orbit is similar to the Envisat orbit ~~to provide continuity~~with the added benefit of the two-satellite constellation; therefore, we expect similar results from the integration of Sentinel-3 WSE observations in a similar setup. Furthermore, calibration and assimilation approaches created for CryoSat-2 can also be applied where Sentinel-3 runs parallel to the river line.

~~The availability of in-situ records is limited relative to the catchment size. Although the performance of the Sentinel-3 satellites cannot be fully validated in the entire catchment, previous studies confirm the performance observed in this study (Jiang et al., 2020). The potential value of altimetry VS is high in poorly gauged catchments and subcatchments, where altimetry may be the only source of water level observations.~~

~~Furthermore,~~ Similarly, we show that Sentinel-3 can be used to provide spatio-temporal characterization of floodplains, as clear seasonal patterns can be seen where the satellite ~~crosses~~ ground tracks cross wetlands and floodplains. The connectivity between river and floodplains is an important hydrogeomorphic process, which can significantly alter the floodplain landscape. ~~Park (2020) showed the potential in~~ Several studies have characterized wetland dynamics using satellite altimetry~~for this purpose using Jason-2 WSE in the Amazon. The results from this study suggest that~~ ; for instance Park (2020), Zakharova et al. (2014). Sentinel-3 ~~may be~~ is an interesting candidate for similar studies due to the closer ground-track spacing and reduced footprint from the SAR altimeter.

~~The cross-sections extracted over floodplains are similar to observations expected from the future SWOT (Surface Water and Ocean Topography) mission (Domeneghetti et al., 2018). Amongst other variables, observations of WSE, water extent and slope are expected from SWOT. Another novel dataset will be 2-dimensional observations of WSE and water extent within two 50-km wide swaths. Similar information can already be extracted from the Sentinel-3 dataset in selected locations. SWOT is expected to be launched in 2021; therefore, the Sentinel-3 dataset represents a highly valuable source of information and training datasets~~For this application as well, the spatio-temporal sampling of the dual-satellite configuration provides a uniquely advantageous compromise between spatial and temporal resolution. Furthermore, the accuracy achieved at in-situ station Kalabo in the Barotse floodplain (2.9 cm with the GPOD dataset) is promising in terms of characterizing level variations in the decimeter range. This has important implications for successful monitoring of wetlands and floodplains with smaller level fluctuations (Dettmering et al., 2016).

## 5 Conclusions

Satellite radar altimetry has been widely used in the past decades to bridge the gap between data requirements in hydrologic/hydrodynamic simulations and in-situ data availability. ~~In this study, we explore the capabilities of Sentinel-3 to provide catchment-scale WSE observations for monitoring purposes. The network can be used to supplement limited in-situ records for monitoring applications and to inform hydrologic/hydrodynamic models. The~~ The dual satellite mission Sentinel-3 joins a new generation of satellites carrying high-resolution SAR altimeters. It is the first mission in a near-polar orbit to carry SAR altimeters and use open-loop tracking ~~. The open-loop tracking mode should improve the positioning of the altimeter range window over narrow targets or rugged topography,e. g. several rivers, where the surface elevation is known.~~

with over 65,000 hydrological targets globally. In this study~~we~~, we explore the capabilities of Sentinel-3 to provide catchment-scale WSE observations for hydrological applications. The network can be used to supplement limited in-situ records for monitoring applications and to inform hydrologic/hydrodynamic models.

We have extracted all Sentinel-3A and Sentinel-3B virtual station datasets over the Zambezi river basin in Africa ~~at processing level 1B and 2~~ and developed an automatic workflow to remove outliers, retaining only clear water targets and provide ~~reliable~~ WSE at all possible locations in the basin. ~~We extract over 360 virtual stations from each satellite of which over 70 are validated~~ In total, the spatial coverage of the dual-satellite mission consists of 731 potential virtual stations in the Zambezi, of which 204 show consistently promising results based on the ~~waveforms and temporal coverage for each Sentinel-3 satellite. The proposed approach more than triples the number of VS compared to the global database Hydroweb.~~ evaluation of Level-1b waveforms and Level-2 WSE observations across datasets. Where in-situ gauging stations are available, the RMSD is less than 32 cm ~~. We show that a dense, Sentinel-3~~ and there is good coherence with expected hydrological patterns throughout the catchment. A uniquely dense, WSE monitoring network can be extracted at catchment scale ~~, using global datasets and~~ by using publicly available processing tools to process the Sentinel-3. The dataset can be used to monitor river WSE and river-floodplain interactions. In particular, we see significant potential for wetlands parallel to satellite tracks, e.g. the Barotse floodplain in the Zambezi.

~~In addition, the upgrade of the OLTC on board Sentinel-3A directly increased the number of VS. Thus, higher coveragecan be attained when adequate targets are defined on board. Surprisingly, we note that the GPOD-processed data fails at several VS, although the dataset produces more robust data overall. Analysis links one source of the problem to the L1b processing and open-loop tracking mode. Increasing the receiving window appears to mitigate this , making the option highly relevant on the GPOD platform, as more targets can be successfully processed. While the open-loop mode combined with the high-resolution SAR altimeter provides clear advantages in processing narrow targets, the sharp changes in reception window position introduced by the on board pseudo-DEM can have similar impacts as sharp changes in topography.~~ The proposed approach illustrates the potential of considering the full Sentinel-3 records to achieve complete basin coverage, a substantial supplement to the WSE time series available on global altimetry databases. We demonstrate how this can be achieved on publicly available processing platforms and provide an example for the Zambezi. The dual satellite constellation provides a useful and unique spatio-temporal coverage of river and wetland WSE with important implications for future hydrology-oriented missions.

*Code and data availability.* The python code used in this study is publicly available on GitHub: https://github.com/KittelC/s3_catch. All data sets used in this study are derived from publicly available resources. The database of the Zambezi virtual stations is available on the GitHub repository.

## Appendix A: Supplementary information on VS location

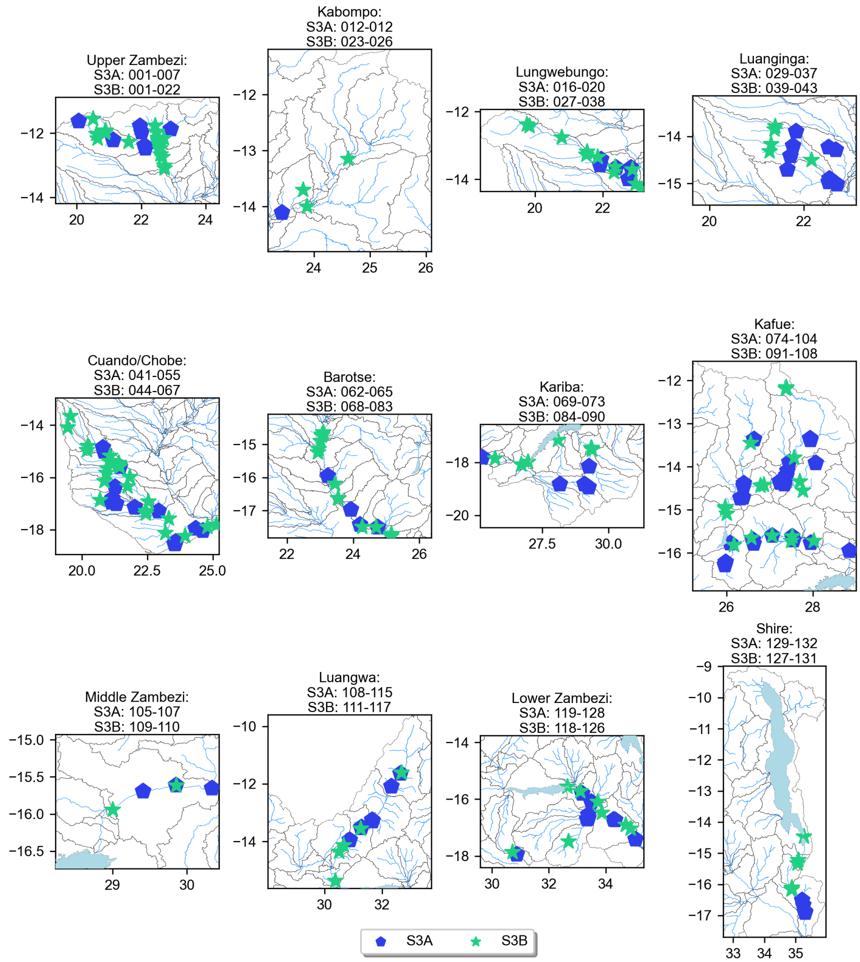


**Figure A1.** All Sentinel-3 VS considered in this study.

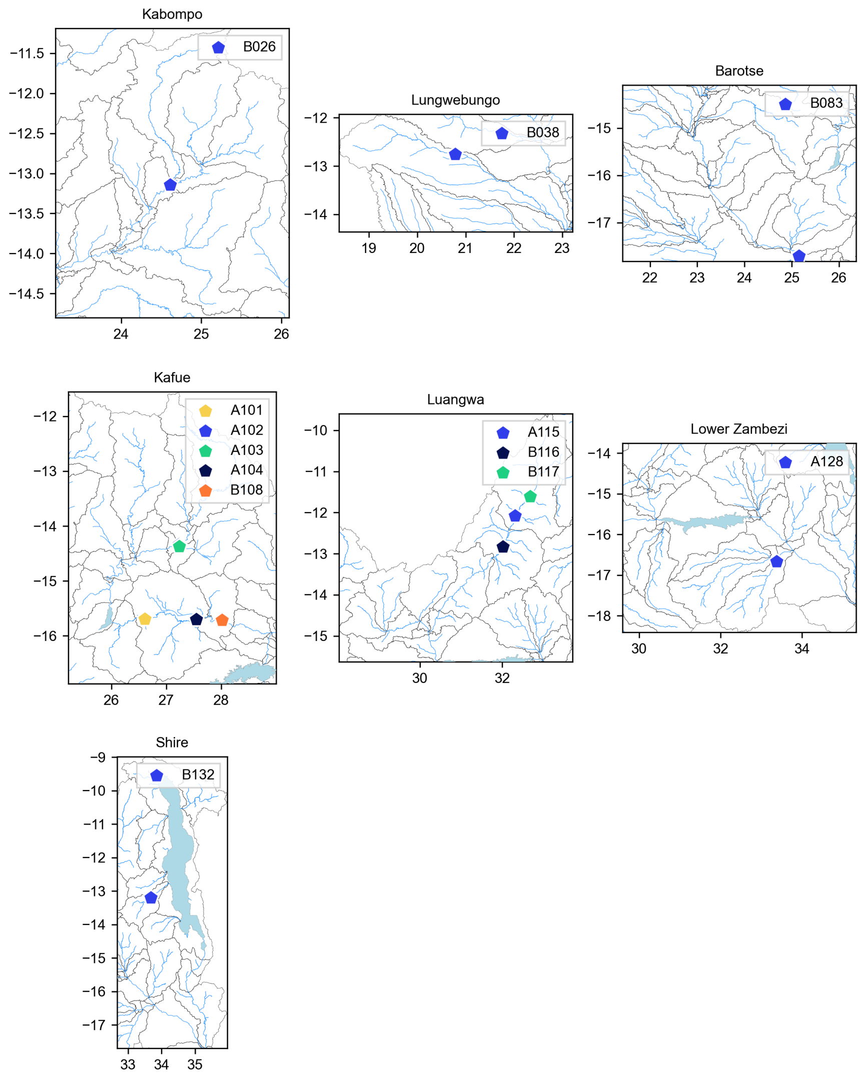


**Figure A2.** S3A and S3B VS improved by the 3x window extension in the GPOD processing options~~and outperforming SciHub as a result~~.

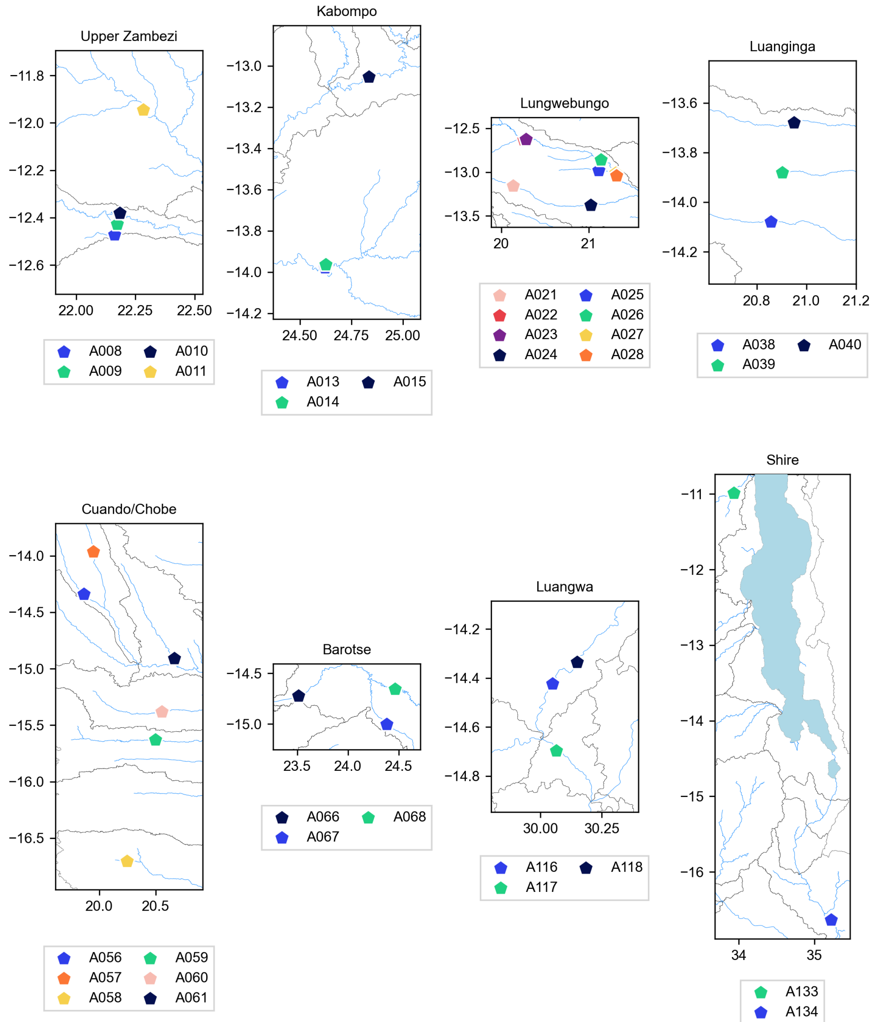


**Figure A3.** Sentinel-3A VS improved by the OLTC update in the GPOD and SciHub datasets.

*Author contributions.* Cécile M. M. Kittel and developed the methodology and code with inputs from Liguang Jiang. The work was supervised by Peter Bauer-Gottwein and Christian Tøttrup. Cécile M. M. Kittel prepared the manuscript including the figures and tables with contributions from all the co-authors.

*Competing interests.* The authors declare that they have no conflict of interest

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