To: Hydrology and Earth Systems Sciences Discussion

Re: Interactive comment on "A review of applications of satellite SAR, optical, altimetry and DEM data for surface water modelling, mapping and parameter estimation"
by Z. N. Musa et al.

Anonymous Referee #1

<u>Answers to Reviewer #1</u>

The responses to the individual comments of the reviewer are detailed below.
(Note: *Reviewer comments are in italic,* authors' responses are in normal text)

<u>Thank you for your comments. Please find the answers below.</u>

Comment1: The review has also been written at the time of a step-change in the capabilities of remotely sensed data for improving surface water monitoring and modelling, yet there is little about future directions, and it is an ill-balanced review that does not mention the future as well as the past

ANSWER: We acknowledge that undertaking a review of past work without discussing the future direction in satellite utilization for hydrological applications, makes the review incomplete. We will revise the conclusion section of the paper to include future applications of satellite data for hydrological research. Please see the text to be added in comment 5 and 7.

Comment2: Probably the section most lacking in detail is section 2.1 on SAR data applications, which is also one of the most important. There don't appear to be any references after 2010, but the area has had a substantial number of new references since then. Unfortunately there has just been a review of this topic published (Yan et al., 2015), which goes into much more detail than is presented here, and is not referenced here.

ANSWER: The reasons that contributed in reducing the number of recent papers referenced in the review include the following:

1. Considering that the topic 'use of satellite data for model calibration and validation' can make a review on its own because of the may techniques that have been used, we decided to take out all such references from the paper before submission. The scope of the paper was therefore narrowed to cover only direct applications of satellite data for mapping, modelling etc. Consequently, many of the more recent publications were taken out.

2. Very recent publications like Yan et al., (2015) were not included in the review because the preparation of the manuscript began in 2014 before this publication appeared in March 2015. However we acknowledge that we should update the paper at the moment of submission of the reviewed version of the manuscript, in case it passes the discussion phase. We thank you for pointing us to the paper and we will include it in the revised manuscript.

- Indeed the reviewer is right and the paper needs to include more recent publications. The section on SAR applications will be revised and more papers will be added to update it. The revised section on SAR will be extended to include the following:

" Satellite data is used to calibrate hydrologic models especially in un-gauged catchments (Vermeulen et al, 2005; Sun, et al., 2009). Calibration of flood inundation models can be done using several model parameters, but the most sensitive parameter that shows a direct relation with water stage and therefore flooding extent and timing is the channel roughness (Schumann et al., 2007).

Woldemicheal et al., (2010) showed that for braided rivers where the hydraulic radius is obtained from indirect sources like satellite data, Mannings roughness coefficients can be used to minimize computed water level outliers. Roughness coefficient values to be used for calibration can be determined via flood modelling where the measured data are available.

Satellite based maps of flood extent have been used to calibrate flood inundation models either based on single or multiple flood events (Di Baldassarre, et al., 2009). Horritt (2006) calibrated and validated a model of uncertain flood inundation extent for the Severn River using observed flooded extent mapped from satellite imagery. Model accuracy was checked using reliability diagrams, and model precision was checked using an entropy-like measure which computes the level of uncertainty in the flood inundation map. The ensemble model outputs were compared with ERS and Radarsat data for calibration using the measure of fit. The results showed that the mapped flood extent produced only a modest reduction in the uncertainty of model predictions because the timing of satellite passes did not coincide with the flood event. Di Baldassarre, et al., (2009) showed that satellite flood imagery acquired during an event can be reliable for flood mapping. They used imagery of a single event covered by two satellite passes captured almost at the same time to develop a method to calibrate flood inundation models based on 'possible' inundation extents from the two imageries. Hydrodynamic flood model extents were compared with the satellite flood extent maps in order to calibrate the floodplain frictional parameters and determine the best satellite resolution for flood extent mapping. In spite of their different resolutions the result showed that both satellite imageries could be used for model calibration, but different frictional values had to be used in the model.

For un-gauged basins where hydrological data is inaccessible, satellite measurement of river width can be used for hydrological model calibration (Schumann, et al., 2013; Sun, et al., 2009). River width can be estimated from several sources of satellite data; making it more readily available than discharge or water level. The uncertainties in this methodology include: the satellite estimation of the river width, the power relation between the discharge and river width (which is an approximation of the conditions at a river cross section when there is no backwater effect) and the assumption of a stable/static river cross section. All these sources of uncertainty are lowest for the period of satellite data acquisition and increase in with change in season and hydraulic conditions (Sun, et al., 2010). Sun, et al., (2009) used measured river width from satellite SAR imagery to calibrate HYMOD hydrological model. The model calibration based on river width gave 88.24% Nash coefficient, with a larger error during low flow than high flow periods; implying its usefulness for flood discharge calculations. From the results, braided rivers showed lower errors for good Q-W relations from satellites. However, a small error in width measurement can lead to a large error in discharge estimation as the discharge variability was much larger than the width variability. Sun, et al., (2010) used the GLUE methodology to reduce this uncertainty in calibration of river width -to- discharge estimation with the HYMOD hydrological model. From 50000 samples of the parameter sets, 151 (Likelihood=RMSE values) succeeded as behavioral sets to be used in the model to simulate the measured satellite river widths. River discharge simulated with the successful parameters (Likelihood = Nash-Sutcliffe efficiency) gave good discharge simulation with a correlation $R^2 = 0.92$.

Model use in forecasting is affected by the progation of the input uncertainties which make it less accurate. Data assimilation can be used to reduce the accumulation of errors in hydralic models. Assimilation combines model predictions with observations and quantifies the errors between them in order to determine the optimal model and improve future forecastes (Mcmillan, et al., 2013). Types of assimilation techniques include Kalman filter (and its variations), particle filter and variational technique. Particle filter assimilation is a bayesian learning system which accounts for input data uncertainty propagation by selecting suitable input data from randomly generated ones without assuming any particular distribution of their PDF (Noh, et al., 2011). Particle filter technique was used in studies like Matgen, et al., (2010), Giustarini, et al., (2011) where input data are in form of ensemble flow outputs of a hydrological model. In Giustarini, et al., (2011) to assimilate water levels derived from two SAR images of flooding in the Alzette River into a hydraulic model, 64 upstream flows were generated from an ensemble hydrologic model and used as the upstream boundary conditions. The most commonly used data assimilation technique however, is the Kalman filter which is a state-space filtering method which assumes a gausian distribution of errors. Vermeulen et al., (2005) used SAR derived flood maps and time series data to make flood forecasting more accurate through data assimilation. The assimilation process based on kalman filtering technique used adaptation factors to muliply the original model output and adaptation factor in order to generate a new parameter value. The process included calculation of water levels/discharge on the Rhine River by combining hydrologic modelling of the sub-basins and hydraulic modelling using downstream measured data. Data assimilation was done using measured water levels to determine the roughness coefficients which calibrate the calculated water levels. The model output water levels were compared with water levels derived from flood maps but because the natural flow of the channel or floodplain has been modified, good results were only obtained when the geo-referencing of the map is deliberately shifted or the flooding extent is exaggerated by adding some random noise over a large area of 7-12km. Barneveld, et al., (2008) applied the same method and models for flood forecasting on the Rhine River and produced good results of 10 day forecasts; therefore assimilating data for natural catchments results in better forecast model values. More information on hydrologic data assimilation techniques can be found in Matgen, et al., (2010) and Chen, et al., (2013).**"**

References to be included in the above text of the revised manuscript are

Vermeulen, C. J. M., Barneveld, H. J., Huizinga, H. J. & Havinga, F. J., 2005. *DATA-ASSIMILATION IN FLOOD FORECASTING USING TIME SERIES AND SATELLITE DATA.* Tromso, ACTIF/Floodman/FloodRelief,

Sun, W., Ishidaira, H. & Bastola, S., 2009. ESTIMATING DISCHARGE BY CALIBRATING HYDROLOGICAL MODEL AGAINST WATER SURFACE WIDTH MEASURED FROM SATELLITES IN LARGE UNGAUGED BASINS. *Annual Journal of Hydraulic Engineering,* Band 53, pp. 49-54.

Sun, W., Ishidaira, H. & Bastola, S., 2010. Towards improving river discharge estimation in ungauged basins: calibration of rainfall-runoff models based on satellite observations of river flow width at basin outlet. *Hydrology and Earth Sysytem Sciences,* Band 14, p. 2011–2022.

Schumann, G. et al., 2007. Deriving distributed roughness values from satellite radar data for flood inundation modelling. *Journal of Hydrology,* 344(1-2), p. 96–111.

Woldemicheal, A., Degu, A., Siddique-E-Akbor, A. & Hossain, F., 2010. Role of Land–Water Classification and Manning's Roughness Parameter in Space-Borne Estimation of Discharge for Braided Rivers: A Case Study of the Brahmaputra River in Bangladesh. *IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING.*

Di Baldassarre, G., Schumann, G. & Bates, P. D., 2009. A technique for the calibration of hydraulic models using uncertain satellite observations of flood extent. *Journal of Hydrology,* 367(3-4), p. 276–282

Horritt, M. S., 2006. A methodology for the validation of uncertain flood inundation models. *Journal of Hydrology,* 326(1-4), p. 153–165.

Schumann, G. J.-P. et al., 2013. A first large-scale flood inundation forecasting model. *Water Resources Research,* Band 49, p. 6248–6257.

Mcmillan, H. et al., 2013. Operational hydrological data assimilation with the recursive ensemble Kalman filter. *Hydrology and Earth System Sciences,* Band 17, pp. 21-38.

Matgen, P. et al., 2010. Towards the sequential assimilation of SAR-derived water stages into hydraulic models using the Particle Filter: proof of concept. *Hydrology and Earth System Sciences,* Band 14, p. 1773–1785.

Giustarini, L. et al., 2011. Assimilating SAR-derived water level data into a hydraulic model:a case study. *Hydrology and Earth System Sciences,* Band 15, p. 2349–2365

Noh, S., Tachikawa, Y., Shiiba, M. & Kim, S., 2011. Applying sequential Monte Carlo methods into a distributedhydrologic model: lagged particle filtering approach with regularization. *Hydrology and Earth System Sciences,* Band 15, pp. 3237–3251

Barneveld, H., Silander, J., Sane, M. & Malnes, E., 2008. *APPLICATION OF SATELLITE DATA FOR IMPROVED FLOOD FORECASTING AND MAPPING.* Toronto, Canada, s.n

Chen, H. et al., 2013. Hydrological data assimilation with the Ensemble Square-Root-Filter:Use of streamflow observations to update model states for real-time flash flood forecasting. *Advances in Water Resources,* Band 59, p. 209–220.

Comment3: The review of Yan was written specifically to cover a perceived gap, since the review before that was published five years earlier. Some of the topics covered in the Yan review that are not mentioned here are: The use of the new high resolution SARs for flood detection (e.g. CSK, TerraSAR-X, RADARSAT-2, PALSAR), including mapping of flooding in urban as well as rural areas. The CSK constellation satellites can have a revisit interval of 12 hours for a flood, which is sufficiently frequent to capture floods in medium-sized catchments. Also, there is no mention here of the Sentinel-1 constellation (the first of which is already working), which will give high resolution images in near real-time (making them suitable for flood forecasting operations), on an almost daily basis in Europe. The methods used to derive flood extent data from SAR images are also not considered e.g. Martinis et al., 2009, 2011).

ANSWER: We found the above mentioned paper useful for our review of satellite data for hydrological research, because it addresses flood modelling, which is one of the areas included in our review. However the two papers differ in scope and objectives, particularly in the following ways:

1. Yan et al., (2015) reviewed the satellite data product (e.g. DEM, SAR); thus they explain the mission, pre/post data processing, accuracy assessment, error estimation etc. We review what

the data has been used for; therefore we explain why the research was undertaken, what satellite data was used, how, where and the results obtained.

2. Due to the objectives of Yan et al., (2015), their review includes urban flooding and rainfall/ runoff modelling; these are excluded in our review since it is limited to water flowing within channels and coasts. Consequently, references used within the two papers cannot be same. Similarly, our objectives allow us to cover applications of optical satellite data in more detail than is obtained in Yan et al., (2015).

3. Due to our interest on applications, we only mention a particular satellite when discussing its use within a paper, therefore we do not provide a list of available satellite data. However, it is within the scope of Yan et al., (2015) to provide details on available and future satellite missions.

Comment4: Despite the fact that the words "parameter estimation" are included in the title, there is no discussion of assimilation of observations (e.g. SAR-derived water levels) into hydraulic models, which has been a big trend over recent years (e.g. Matgen et al, 2010, Garcia-Pintado et al. 2015). However, it is possible to estimate a number of model parameters using these observations, including channel friction and river bathymetries, as well as river inflows.

ANSWER: Indeed for hydraulic modelling, river channel parameters like bathymetry and channel friction are indispensible. Assimilation of satellite data in hydraulic modelling will be added in the revised manuscript.

"Parameter estimation" here refers to estimation of "water levels/ depths, discharge, slope and velocity".

Comment 5: The future SWOT satellite, which will produce global surface water maps every 11 days or so, from which surface water slope and river discharge will be estimated, which will be a substantial advance on current-day satellite data acquisition capabilities

ANSWER: This is an important suggestion. The SWOT satellite data will indeed be very useful for parameter estimation. We will include this in the revised conclusion section to read as follows:

" Upcoming satellite missions like Surface Water & Ocean Topography (SWOT) made especially to survey global surface water have specifications that will enable better use of satellite data in hydrology. SWOT which uses a wide-swath altimetry technology will also observe the fine details of the ocean's surface topography, and measure how water bodies change over time with repeated high-resolution elevation measurements. The mission, scheduled to be launched in 2020 is an international collaboration between the US National Aeronautics and Space Agency (NASA) and Centre National E'tudes Spatiales (CNES) of France; supported by the Canadian Space Agency (CSA) and the UK Space Agency (UKSA) (Pavelsky, et al., 2015). Another product of international cooperation that will support hydrological research is the Jason3 altimetry mission from NOAA, due to be launched in July 2015. The Jason3 mission is dedicated to the measurement of sea surface height, wave, wind speed, and will provide useful data to monitor sea level rise, coastal areas modelling of oil spills, forecasting of hurricanes etc. To enable precise detection of sea level change, Jason3 combines GPS, radar altimetry, and a microwave radiometer to produce data within 1cm accuracy every 10 days (NOAA, 2015). Jason3 is jointly owned by US National Oceanic and Atmospheric Administration (NOAA), CNES-France, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and US NASA."

References to be included in the above text of the revised manuscript are

Pavelsky, T. et al., 2015. SWOT 101: A Quatum Improvement of Oceanography and Hydrology from the Next Generation Altimeter Mission. [Online] Available at: https://swot.jpl.nasa.gov/files/swot/SWOT-101_Jan2015.pdf [Zugriff am 29 May 2015].

NOAA, S. I. C., 2015. *Jason3*. [Online] Available at:

http://www.nesdis.noaa.gov/jason-3/?CFID=731ecb89-8379-48fc-ad50-959546e71739&CFTOKEN=0 [Zugriff am 29 May 2015].

Comment6: Section 2.2 on altimetry applications is more complete. Again SWOT needs to be mentioned in this section for its altimetric as opposed to its flood extent measurements.

ANSWER: As mentioned in the previous comment, we will include SWOT mission in the conclusion section.

Comment7: In section 2.4 (Satellite derived DEM applications) no mention is made of the global TanDEM-X WorldDEM, which should be available at the end of this year, and should allow better hydraulic modelling of remote rivers than has been possible to date with the SRTM DEM. There are also a number of flood modelling studies using SRTM that have not been mentioned (see Yan et al., 2015).

ANSWER: Due to differences of scope and objectives, some references used in Yan et al., (2015) cannot be used here. However we will reference Yan et al., (2015) which include these references. We will include TanDEM-X in the revised conclusion section as follows:

"Available literature show that efforts have been made to develop an empirical relationship between satellites derived surface water extents (including flooded areas) with river stage or discharge. Such a relationship has been established for braided rivers; for non-braided rivers the results have depended on the river system, thus inundation area can increase or decrease with stage. With better SAR missions such as TerraSAR-X- TanDEM-X formation, DEM data with good vertical accuracy are now available for better hydraulic flood modelling. TanDEM-X has 12.5m spatial resolution and produces less than 2m vertical accuracy (DLR, 2015). Other satellite products that will improve the accuracy of satellite data based research in hydrology include: Cosmo-SkyMed from the Italian Space Agency, RadarSat2 from the Canadian Space Agency, and Sentinel-1 from ESA (Schumann, et al., 2015). Others are Global Precipitation Measurement (GPM) from Japan Space Agency/USA, Soil Moisture Active Passive (SMAP) from USA."

References included in the above text of the revised manuscript are

DLR. (2015). Earth Observation: TanDEM-X - the Earth in three dimensions. Abgerufen am 01. June 2015 von http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10378/566_read-426/#/gallery/345

Schumann, G. J.-P., Bates, P., Neal, J., & Andreadis, K. (2015). Measuring and Mapping Flood processes. In P. Paron, & G. Di Baldassare (Hrsg.), *Hydro-Meteorological Hazards, Risks, and Disasters* (S. 35-64). Amsterdam,Netherlands: Elsevier.

SHORT COMMENTS

Comment8: P4859 l9: The optical satellites are in near earth orbit. . .. . .. Not solely, they can be in geostationary orbit (e.g. SEVIRI on the Geostationary Ocean Colour Imager).

ANSWER: As rightly pointed out by the reviewer, this sentence is wrong. Section of Page 4859 l9 will be corrected to read as follows:

"Depending on the mission specifications satellites are placed on different kinds of orbits around the earth. The orbits include: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geo-Synchronous orbits (GSO); variations of these classes of orbits are the polar orbit, the Geostationary orbits, the Molneya orbit and the sun-synchronous orbit. Most optical satellites used for hydrological applications are in near earth orbits and are therefore able to provide detailed data at high ground resolution...".

Comment9: P4859 l23: . . ..very low radar return. ... Say this is because SAR is a side-looking instrument in order to get range resolution.

ANSWER: Section of P4859 l23 will be corrected to read as follows:

"SAR is a side looking instrument that sends out signals inclined at an angle. For water bodies the reflectivity of SAR waves is spectacular giving a very low radar return and very dark images"

Comment10: P4860 l6: . . . review excludes certain applications. ... Should mention that satellite measurement of soil moisture is excluded also.

ANSWER: we will include soil moisture measurement among areas excluded in the review.

Comment11:P4862 l20: . . ..two clusters of roughness values are enough. . . Enough for what?

ANSWER: We will complete this sentence as follows:

"The results showed that two clusters of roughness values are enough to measure the parameter sensitivity"

Comment12: P4862 p17: it would be worth giving the typical altimeter footprint at this point, to show how wide the rivers detected must be.

ANSWER: The a sentence on altimeter footprints will be added as:

"Typical altimeter footprints are in kilometres; e.g. ENVISAT ranges from 1.6-10.8km, TOPEX/POSEIDON from 2.0-16.4km"

Comment13: P4866 l8: This work of Cretaux et al 2011 has already been mentioned in the previous section.

ANSWER: Correction will be done accordingly.

Comment14: P4868 l4: In this first sentence of section 2.4, mention SAR interferometry was used to produce SRTM. Give the resolution of SRTM in this paragraph. Why does the accuracy of SRTM given not tie up with that quoted in Yan et al. (2015)?– the figures given here seem too accurate.

ANSWER: The section will be updated as follows:

" SRTM which was obtained through SAR interferometry of C-band signals, is available in 30m and 90m spatial resolutions, with an approximate vertical accuracy of 3.7m, but reaches a range of 1.1-1.6m on flatter floodplains (Syvitski, et al., 2012)."

Reference included in the above text of the revised manuscript are

Syvitski, J. P., Overeem, I., Brakenridge, R. G., & Hannon, M. (2012). Floods, floodplains, delta plains — A satellite imaging approach. *Sedimentary Geology, 267-268*, 1-14. doi:10.1016/j.sedgeo.2012.05.014

The sentence on vertical accuracy of SRTM will be corrected as per suggestion.

Comment15: P4868 l17: how were the brightness temperatures of the floodplain used?

ANSWER: As suggested by the reviewer, we will include how the AMSR-E brightness temperatures were used. Explanation is as follows:

"The ratio of land area brightness temperatures to water area brightness temperature gave the discharge estimator; chosen dry areas were used as calibration areas for measurements over water covered areas. A rating curve of the ratio versus discharge was then used to extract the discharge values"

Comment16: P4869 l21: mention CSK, RADARSAT-2 and PALSAR as well as TerrSAR-X.

ANSWER: Correction will be done accordingly.

Commet17: P4871 l15: mention that the great advantage of satellite DEMs is that they are global or near-global, unlike airborne measurements of surface height.

ANSWER: Correction will be done as per suggestion.

Comment18: P4871 l 18: . . . satellite based DEMs are those generated from radar echoes of spot heights. . .. This misses out satellite interferometry completely!

ANSWER: The sentence will be corrected as follows:

> "Generally satellite based DEMs are either generated from radar echoes of spot heights, or from SAR interferometry. However.."

Comment19:P4872 l 3: how about mentioning the advantages of SWOT in this paragraph?

ANSWER: As mentioned above, we will add these to the conclusion section. Please see the conclusion text which is mention at comment 5.

TECHNICAL CORRECTIONS

ANSWER: Thank you for the technical corrections. We will implement them in the final version of the manuscript.