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.

Referee #2 G.J.-P Schumann

Answers to Reviewer #2

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

Thank you very much for your comments which value greatly. Please find the answers to your comments below.

Comment1*: this is a very broad review in the sense that many different topics are touched upon but what is missing in most sections is the detail. There has been a lot of progress in each of the topics treated but most of this progress comes short in many sections, especially the sections on optical, SAR and DEM*

ANSWER: We thank the review for the comment. In the new version of the manuscript we will revise the sections so that more details will be added to include information that was not included in the version that is now available for open discussion. The sections will be extended as follows:

On SAR

" 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 have 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. 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 behavioural 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 propagation of the input uncertainties which make it less accurate. Data assimilation can be used to reduce the accumulation of errors in hydraulic 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 Gaussian 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)."

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On Altimetry

"Lake water volumes were calculated for Lake Mead (USA) and Lake Tana (Ethiopia) using five altimetry data products: T/P (Topex/Poseidon), Jason-1, Jason-2, GFO (Geosat Fellow On), ICESat and ENVISAT (Duan & Bastiaanssen, 2013). The method used Landsat TM/ETM + imagery data to map the water surface areas using the Modified Normalized Difference Water Index (MNDWI) method which enables robust extraction of water bodies from optical data (Zhang, et al., 2006). The calculated water surface areas agreed with in-situ measured data with an R2 of 0.99for Lake Mead and 0.89 for Lake Tana with RMSEs of 2.19% for Lake Mead and 4.64%. The water volume was estimated using the lowest altimeter water level as the reference water level; this is then subtracted from all the other measurements to obtain the Water Level above Lowest Level (WLALL) to be used for volume estimation. Using regression analysis a relationship was established between the estimated water surface areas and the WLALL as A = f(WLALL) = aWLALL2 + bWLALL + c; where a, b, and c, are constants. The integral of this relation provides the Water Volume Above the Lowest Water Level (WVALL). The estimated water volumes agreed well with in-situ water volumes for both LakeMead and Lake Tana with R2>0.95and RMSE ranging between 4.6 and 13.1%.**"**

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On Optical

"Water reflects electromagnetic waves differently depending on its contents; pure clear water reflects differently from muddy water or water containing vegetation (floating or submerged). The amount of energy measured from the satellite sensor also depends on the bands used; blue band penetrates water up to 10m, red band is partially absorbed, and near infra-red band is totally absorbed. These sensor properties consequently affect the image, so that an image acquired using the blue band will measure reflectance from any submerged vegetation within its reach, while red/near infra-red images will show water as dark grey/ black respectively (Meijerink, et al., 2007).

To check for water surface change, satellite microwave data from AMSR-E satellite was used to calibrate CREST hydrologic model using ratio brightness temperature measurements over water bodies and calibrated dry areas (Khan, et al., 2012). The AMSR-E detected water surface signal frequency was compared with gauge flow with a probability of exceedance <25% and showed good agreement. The output of model calibrated with AMSR-E detected water surface signal showed good agreement with observed flow frequency. Results of validation were equally good with high correlation between model results and observed flows with probability of exceedance <25%. The output of the model calibrated with AMSR-E detected water surface signal showed good agreement with observed flow frequency (Nash-Sutcliff coefficient of 0.90 and a correlation coefficient of 0.80). "

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On DEM

"SRTM which was obtained through SAR interferometry of C-band signals is available in 30m and 90m spatial resolutions and an approximate vertical accuracy of 3.7m (Syvitski, et al., 2012). The vertical accuracy of SRTM is higher in areas with gentle slopes than on steep slopes; on low-lying floodplains SRTM has shown less than 2m accuracy. More information on SRTM DEM accuracy can be found in (Yan, et al., 2015; Jarihani, et al., 2015).). Syvitski, et al., (2012) adjusted SRTM data using ocean heights measured by the TOPEX/POSEIDON satellite altimeter to enable the mapping of floodplain zones. Advanced microwave Scanning Radiometer (AMSR-E) data provided brightness temperature measurements of the floodplain. 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. SRTM 30m data was combined with MODIS 500m water mask data to produce 30m static water masks of 2003 flooding along the Mississipi river (Li, et al., 2013). The method involved using SRTM to mark the minimum water level from the MODIS water mask, which is then used to calculate the maximum water-level for that pixel using a water fraction relation. All SRTM 30m pixels with heights between minimum and maximum water levels are classified as water, and all those with heights higher than the maximum level are classified as dry. Consequently, the 500m MODIS water mask is integrated into a 30m water mask with the SRTM. The results gave detailed flood maps with the same flooding coverage as the MODIS water masks but enlarged 18 times. The flood maps were compared with Landsat TM images of the flood and showed over 94% match in water area coverage. Errors/ mismatch were found to be mostly around areas with trees and vegetation cover"

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Comment2: What is also missing is a section on what comes next and what the new direction are/would be

ANSWER: Thank you for the comment. Authors found the comment very useful, indeed it is important to discuss the future direction in satellite utilization for hydrological applications in order to make the review complete. We will revise the paper to include future applications of satellite data for hydrological research. Please see the answer to comment 3.

Comment3: I would recommend restructuring the paper so that the sections that are currently are giving a concise summary of the most recent scientific and applied science progress and then a large/main section on how the near term direction may take place and what they should be.

ANSWER: As suggested by the reviewer, the structure of the revised manuscript will be revised to include the future directions. The outline of the new manuscript will be as follows:

1. Introduction
2. Overview of satellite data applications for surface water studies
3. Future needs and direction
    - Gaps and limitations
    - Data use strategies
    - Future direction
4. Conclusions

Comment4: The paper could do with more figures/illustrations

ANSWER: With the new changes to the manuscript more figures will be added to the revised version.

Comment 5: Some paragraphs need revision/rewording to make sure they transition better with sections that follow

ANSWER: The revised manuscript will be corrected as suggested.

Comment6: I really like section 3 but I think this should be turned into the main section. At the moment this section is really thin and a lot of interesting points will be missed by the reader

ANSWER: In the revised manuscript, section 3 will be restructured as presented in the outline under comment 3. It will be expanded to include the following:

" *Data use strategies*

Innovative methodologies are being introduced by scientists to better exploit satellite data to overcome the data limitations within present uncertainties. For example cloud filtering techniques have been developed that remove a high percentage of the clouds in optical data, thus adding to data availability. In terms of temporal limitations, combining MODIS data with its high temporal resolution with other types of satellite data is a technique that is now exploited more (Jarihani, et al., 2014). The technique generates new datasets that blend higher spatial resolution at the high temporal resolution of MODIS. When combined with DEM data for example, flood maps that provide daily information can be easily generated (Li, et al., 2013). SRTM has been combined with MODIS data to generate a 250m water mask called MOD44W; because of the high temporal resolution of MODIS this product can be updated regularly to provide static water masks (Li, et al., 2013).

Use of Satellite SAR for flood extent mapping and model calibration can be improved through combination with other higher resolution data to increase precision in flood height determination. To improve the vertical accuracy of SAR waterline extent during floods, Mason, et al., (2007) used waterline data extracted from ERS-1 SAR corrected with 1m resolution LIDAR heights (along the Thames River bank) to calibrate a LISFLOOD model of flood extent. The output waterline when compared with waterline measured from aerial photos showed a lower root mean squared error than those obtained using SAR data only.

Satellite DEMs that are enhanced through vegetation smoothing or hydrological correction have shown lower errors compared with the original data (Jarihani et al., 2015). Due to the availability of the hydrologically corrected SRTM DEM, a global static 30-m water mask has been generated which is very useful for flood detection especially in data scarce areas.

To improve the use of satellite altimetry data, interpolation methods have been developed to correct the data accuracy and precision by comparing the data with lakes and reservoir measurements. Thus the correlation with measured gauge data, range of RMSE and reduction in discrepancies have improved to levels >0.95 correlation during validation (Ričko, et al., 2012). Altimeter measurements over modified channels is however less reliable than that of natural catchments (Kim, et al., 2009).

The use of altimeter data is also limited by the poor temporal resolution of satellite altimeters; which range from days to several weeks. Belaud, et al., (2010) developed a method to interpolate river water levels in-between satellite observations in order to provide continuous data. The developed method used upstream ground station measurements and altimetry data as output to calibrate a propagation model by adjusting the satellite observed values. The propagation model used a transfer function to predict water level variations based on the relationship between the propagation times and water levels. The results were able to predict flood peaks during periods of no satellite coverage. Crétaux, et al., (2011) addressed the problem of data gaps by combining three sets of altimetry data (TOPEX/POSEIDON, ENVISAT1 and JASON2) with MODIS measurements of water extent to monitor wetlands and floodplains in arid/semi arid regions. The MODIS data was used to classify the open water pixels whose relative values were then extracted from altimetry data. The results provided relative water heights, due to the low temporal resolution of the altimetry data sets. Altimeter data from ICESat was used to calibrate a large scale LISFLOOD-FP hydro-dynamic flood model of the Zambezi River, Mozambique (Schumann, et al., 2013). Eight in-channel water levels from ICESat from one altimeter pass were used for calibration of model output. The models with a mean bias within one standard deviation of the ICESat values were accepted as comparable with Landsat measured flooding extents. The results showed 86% agreement between the Landsat flood extent and the accepted model outputs; corresponding to mean distance of 1.42-1.60 km. After calibration the model upstream boundary was changed to forecast flow values in order to forecast downstream flooding. The results correlated with the baseline model, but showed that with a lead time of 5 days, better basin wide precipitation observations will enable flood forecasting on the Zambezi.

Future direction

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). Although made for polar ice change estimation and monitoring, the high spatial coverage of Cryosat-2 is also being exploited for near-shore mapping and inland water monitoring; all evaluations have produced good results (Villadsen, Andersen, & Stenseng, 2014). Cryosat-2 has a drifting orbit and therefore (unlike all the other satellites) has little repetitive data (since repeat cycle is 369 days) but high spatial density coverage, which makes it good for hydraulic modelling. With successful use of Cryosat-2 data to obtain river water levels and topography, the use of drifting orbits is being proposed as more suitable for river water surface topography mapping, derivation of river profiles and building of pseudo time series (Bercher, et al., 2014).

Other satellite products that 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 Change Observation mission-water (GCOM-W) from Japan Space Agency (JAXA), Global Precipitation Measurement (GPM) from JAXA /USA, Soil Moisture Active Passive (SMAP) from USA.

To improve quality of satellite SAR and topographic data, new satellite missions with higher precision instruments are being planned. One of such missions is the Sentinel constellation that will consist of seven satellites; two of which (Sentinel 3 and 6) are especially dedicated to hydrological purposes. Sentinel 1 is already in orbit and undergoing calibration; it has a C-band SAR instrument to continue present C-band data provision. Sentinel 3 is planned to provide fast data for flood emergencies, therefore it has three instruments one of which is a dual-frequency (Ku and C band) advanced Synthetic Aperture Radar Altimeter (SRAL) that will provide accurate topographic data of oceans, ice sheets, sea ice, rivers and lakes (ESA, 2015). Sentinel 6, which will compliment the Sentinel 3 data, will carry on board a high precision radar altimeter. RADARSAT constellation, a new Low Earth Orbit (LEO) C-band SAR mission is under development by the Canadian space Agency (CSA). The constellation which will have several operating modes will provide interferometric SAR data that can be used for wetlands and coastal change mapping, flood disaster warning and response with resolutions 3, 5, 16, 30, 50 and 100m (Canadian Space Agency (CSA), 2015).

Other 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 Adminitration (NOAA), CNES-France, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and US NASA. "

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