

Dear Paul,

I would like to thank you very much for your constructive criticism. I am confident that your comments will help us to improve the manuscript.

*Comment 1: Pg 1787 Line 25 – Pg 1788 Line 10: Some comment on the relative level of accuracy of the two techniques, and why one may be preferred over the other in certain situations would be useful.*

As it was mentioned in the manuscript, there are two main techniques for water level measurements from space:

1. Direct measuring techniques such as the proposed swath altimetry mission SWOT. This mission is planned to deliver water elevation products with an accuracy of 50 cm (Andreadis et al., 2007).
2. Indirect measuring techniques consisting of a merging of remotely sensed flood boundaries with digital elevation models. The reported root mean squared errors range from 20 cm (Schumann et al, 2008) to 3 m (Oberstadler et al., 1997) depending on floodplain topography, DEM accuracy and satellite sensors.

The reliability and repeatability are the main advantages associated with water level products stemming from wide-swath altimeter missions. However, the technique can only provide water level fluctuations in large rivers (50-100 m wide). Also, the data will provide surface water storage fluctuations at a sub-monthly time scale which appears to be insufficient for operational flood forecasting models.

The higher sampling rates of water level measurements obtained through indirect measuring techniques are the main advantage of this kind of techniques. However, the quality of the data is unknown *a priori* and depends on many factors (e.g. topography, sensor characteristics, digital elevation models). For water level measurements every 2-3 days this would be the preferred solution.

Additional information will be added to the text.

*Comment 2: Pg 1788 Line 20 “As a matter of fact, . . .” This isn’t fact. All observations of the system being modelled contain useful information – the difficulty is extracting it appropriately. If the uncertainties of a given observation are greater the simulation uncertainty, this suggests; if there is no other information (including a priori information) then your simulation uncertainties may be too small.*

I fully agree with you and will edit the text accordingly.

*Comment 3: Pg 1788 Line 25 – Surely also because on smaller catchments satellite passes are too infrequent? Also water level observations are probably still the most accurate observation available at a given point. More a case should be made for combining both.*

In the last couple of months we investigated ways for combining *in situ* hydrometric station data with remote sensing observations. It was the objective of these studies to assess the value of remote sensing data with respect to *in situ* water level measurements.

The characteristics of the two data products are as follows:

Remote sensing data:

- high spatial resolution (regional scale)
- low precision
- low temporal sampling

Field measurements:

- low spatial resolution (local scale)
- high precision
- high temporal sampling

This study gave some interesting preliminary results:

1. if a model behaves in a similar way in the entire model domain (i.e. river reach), a low number of measurement sites provides enough information for selecting the “good” models through the Particle Filter. As a consequence the model can be improved at every cross section.
2. However, if model performance varies along a river reach (with local bias being particularly significant), there is a risk of over-correcting the model by considering local data alone. This means that model improvements may be achieved at one site whereas the model performance may decrease at another site. Remote sensing provides a synoptic overview and this reduces the risk of overcorrecting the model.
3. The best results are obtained through a merging of *in situ* measurements and remote sensing observations.

A discussion on the value of remote sensing products with respect to *in situ* measurements will be added to the text. Moreover, we are currently preparing a manuscript that is specifically targeting this aspect.

*Comment 4: Pg 1789 Line 23 – Parameter updating has a significant history beyond the referenced paper. A more complete discussion would be useful, why prefer state updating to this? Are they actually different? The references in Smith et al. 2008 may be of use.*

Thank you for the references. We will develop this part of the manuscript.

We prefer state updating over parameter updating because parameter updating would violate a basic principle of physically based modelling, namely that the constants should stay constant while the variables vary. Our assumption here is that the forcing data (i.e. rainfall) is the only source of uncertainty. We know that this is debatable.

*Comment 5: Pg 1790 Section 2.1 – A proof of concept experiment should be representative enough of the real problem for any conclusions drawn to (hopefully) be transferable. Two immediate limitations of this experimental design are:*

*(a) The same model is calibrated as is used to generate the data; there is therefore no structural error.*

*(b) Failure to recognise potentially non-stationary bias and variance in the observational error structure.*

*These limitations are not even mentioned until the final paragraph of the conclusions, then only in passing without commentary as to their impact on the results presented.*

I fully agree with the limitations you listed. We will add them in a more prominent place in the manuscript and add a discussion on the impact on the results.

For the sake of simplicity we made the assumption that SAR-derived water stages are normally distributed. However, we believe that non-stationary variance in the observational data can be handled with the method we propose. Through an adjustment of the weighting procedure (Equation 1), the proposed method can be easily adapted to any form of (if necessary local) probability density function. In fact, cross section specific standard deviations can be considered. We will explain the flexibility of the Particle Filter in this respect in more detail in the re-submitted manuscript.

A more severe limitation relates to potentially non-stationary bias in the observational error structure. If a sufficient number of unbiased observations are available along the river reach, local bias in the observations may have no or little impact. However, if the observations are biased at a regional scale, there is a clear need to remove this bias before assimilation. This is clearly an aspect that needs to be investigated in future studies. A possible solution could be to identify and remove bias with respect to a number of hydrometric control measurements. This illustrates the need to combine *in situ* measurements and remote sensing observations.

In our experiment we did not consider structural error. We will further clarify the assumptions made in this study and highlight possible threats and limitations.

*Comment 6: Pg 1792 Section 2.2. – The presentation of the particle filtering algorithm is far too basic given this is a substantial part of the ‘novelty’ of the paper. Note the SIR still suffers from particle*

*degeneracy. I suggest the authors revisit some of the recent particle filter literature, for example the references in Smith et al. 2008 or Fearnhead 2002, and prepare a more detailed description.*

We will prepare a more detailed description of the particle filtering algorithm. Thanks for providing the two additional references. We would like to add that the scope of the paper was not to present an enhanced version of the particle filter. We want the methodology to be understandable and as easy as possible to use. We will clarify the description of the particle filtering algorithm in order to avoid any ambiguity. All information that is needed to duplicate the experiment will be available in the re-submitted version of the manuscript. Additional details on this particular filtering algorithm can be found in the specific literature (references to be added). Our objective was to apply and adapt existing algorithms for assimilating remote sensing-derived water stages in hydrologic-hydraulic models. The merging of remote sensing data and hydraulic model through a particle filter is in our opinion the most 'novel' part of the submitted manuscript.

We will add the most recent findings regarding the (remaining) degeneracy of the SIR.

*Comment 7: Pg 1793 Line 5 – You presume errors are uncorrelated in space and time. In reality this would appear highly optimistic. This and the above comments suggest your experiment suggest to me that this something of a best case scenario for how well the technique can perform.*

We recently tested the proposed methodology with "real event" data. Indeed, the experiment we conducted here can be considered as a "best case" scenario. In reality, it is highly probable that errors in observations and simulations are correlated in space and time. However, the particle filter can adapt to any kind of probability density function. If knowledge of correlations in space and time can be translated into site-specific probability density functions, the presented method can be easily adapted. We would like to mention that no or little research has been done on the correlation in time and space of remotely sensed water levels. For the sake of simplicity we assumed that observations are not correlated in space and time. More investigations on the characteristics of the data that are to be assimilated in hydraulic models are necessary.

The comments that we received from all the reviewers emphasize the need to clarify the assumptions we made and to discuss the limitations and possible impacts of the proposed method with respect to real event case studies. Also, we will take a more conservative approach with respect to our conclusions.

*Comment 8: Pg 1794 Line 12 – Here and elsewhere (e.g. Pg 1799) model 're-initialization' is mentioned. What do you mean by this? Is it the simple substitution of new water levels into the model or is the model allowed to process them in some way to stabilise itself?*

The re-initialization corresponds to the substitution of water levels in the model. These water levels are the re-sampled model simulations at each cross section. Hence there is no need for the model to stabilize itself. In our opinion this is one of the main strengths of the particle filtering algorithm.

We clarified this processing step in the re-submitted manuscript.

*Comment 9: Pg 1976 Section 2.4 – this means of ensemble generation makes some significantly different assumptions to those in the formal Bayesian particle filter? State these. How do you combine the two approaches? Is this the best way to go or should the flow observations be assimilated into the hydrological model that is being used to drive the hydraulic model in a consistent fashion?*

There are no significantly different assumptions between the ensemble generation and the bayesian filter since both methodologies are based on the computation of the sample mean, sample variance and residuals. The assimilation of discharge could be envisaged as a better approach.

However, the CLM uses a unit hydrograph approach for the runoff routing. This implies that a time delay exists between the time of generation of runoff and the arrival at the catchment outlet. Pauwels and De Lannoy (2009) have shown that, under these circumstances, assimilating discharge into a hydrologic model will lead to only a marginal improvement in the modeled discharge, and in certain cases even a worsening of the model results. This can be explained by the accumulation of model

error throughout the base time of the unit hydrograph. For this reason, assimilation of discharge observations into the CLM was not performed.

Pauwels, V.R.N., and G.J.M. De Lannoy, Ensemble-based assimilation of discharge into rainfall-runoff models: a comparison of approaches to mapping observational information to state space, *Water Resources Research*, 45(8), W08428, doi:10.1029/2008WR007590, 2009.

*Comment 10: Pg 1798 Lines 15 – what were the magnitudes of the other corruptions e.g. to the input data. Maybe these should be set out in Section 2.1. Was the variance presumed known in the data assimilation? You could integrate out the variance in the analysis. This could be done with an informative prior distribution based on published values and analytically given your simple error model. The posterior distribution could then be commented on.*

The magnitude of the noise is as follows:

forcings: 1% of the nominal value.

parameters: 10% of the nominal values.

The variance values were used in order to get a good ensemble spread. (i.e. uncertainty of observed states, in this case the water stages stage levels)

Your suggestion seems interesting. However, we did not assume to know the variance in the data assimilation. We aimed at developing a methodology that requires minimal a priori knowledge on the catchment and the model (in order to be applicable in ungauged catchments where remote sensing technologies show the highest potential for model improvements).

*Comment 11: Pg1801 - Interesting gain type correction. Does it fail systematically, for example on rising limbs of the hydrograph where the ratio of errors may change rapidly, particularly if the model or input has timing errors.*

We are aware of the fact that the proposed gain type correction systematically fails on rising limbs of the hydrograph because the ratio of errors changes rapidly and in an unpredictable way. The error model still improves the model results. During the recession periods the ratio of errors changes in a non significant way and the gain type correction provides good results. We believe that when calibration data is lacking there is probably no better way to regress the future error against the current error. An alternative could be to use an autoregressive model. The parameters of such a forecast model could be transferred from a neighbouring gauging station for which the same hydrologic model would provide discharge forecasts.

I thank you very much for your very helpful comments. I hope that I was able give you a satisfying answer to all your comments. Don't hesitate to contact me if you need any further clarification.

Sincerely,

Patrick Matgen