Response to reviewer 2

Responses to the comments are shown in black and proposed changes to the manuscript are shown in blue.

This manuscript tested a time varying model parameter framework at a river basin under significant land cover changes in the last few decades. The employed framework is based on Locally Linear Dual EnKF proposed by the authors in the previous studies and is applied to the two conceptual hydrologic models (i.e. HBV and HyMOD).

The manuscript shows interesting result and well written in general. However, I have concerns regarding practical applications of the tested approach and the objectives of this research from the following aspects.

We thank the reviewer for their time and appreciate the overall positive assessment of the manuscript. We address concerns regarding practical applications below.

1. In the abstract, the authors stated "rapid land use change impacts on catchment hydrology" and "therefore modeling methodology of such change is important" in the first and second sentences. First of all, please clarify "for what purpose" such modelling representing the land cover change is thought to be needed. This could be, for example, estimating future water resources under further land cover and climate changes or identifying the physical mechanisms of the impact of land cover change on hydrology. Please explain in the introduction for what objective the authors think the modeling with time varying parameter is necessary.

We have stated in the introduction that the purpose of the time varying parameter framework is to provide accurate hydrologic predictions even when catchment conditions are changing (see Lines 31-32). We also discussed that the time varying parameter framework could be used to isolate whether changes to streamflow dynamics are driven by climatic or land cover changes (see Lines 57 – 59). We propose to add additional discussion as outlined in the response to the next comment.

2. Based on the firs point, please explain how the applied framework with the EnKF can achieve the objectives. Obviously the presented approach requires a full set of input and output to estimate the parameter changes. Suppose that this approach now successfully estimates the time-varying parameters in the HBV model, how can this information be useful for water management, given already land cover change has happened and streamflow change has been already detected in the actual catchment.

The Locally Linear Dual EnKF can be useful for retrospective analysis of variations to model parameters. From a prediction perspective, the framework is useful for short term predictions (or forecasts) of hydrologic variables in catchments that are undergoing change. The reason it can be used in this context is because parameters are being updated on-the-fly, in response to the observations that are being assimilated (as stated in Lines 62 – 64). It cannot be used for water management over a long time horizon, as this requires explicit prior information about future land use change. The purpose of this approach is to infer changes to catchment

properties from hydrologic observations, at the time scale of the observation frequency. Therefore, it is not suited to water management purposes over a long time horizon, as this requires explicit prior information about future land use change.

We propose to insert the following sentence at Line 64, before "The method was applied…":

"Its purpose is to infer changes to catchment properties (e.g. land cover change) from hydrologic observations, without prior knowledge of such changes, at the time scale of the observation frequency. It can therefore be used to either retrospectively estimate time variations in model parameters or for short-term predictive modelling."

3. Related to the above point, please state clearly the main objective of this research in the introduction. Is the main objective here to test the time varying model parameter framework in the data limited catchment? In such case, what is the criteria to conclude the objective has been achieved. The EnKF may show the parameter changes, but is it enough to validate the method? Or is the main objective here to compare the two model structures?

The main objectives here are:

1) To investigate the efficacy of the time varying parameter method in a medium sized catchment with realistic land cover change. This goes beyond previous work which focused on small experimental catchments that had drastic land use changes that are easier to infer from streamflow; and
2) To highlight the importance of the chosen model structure in ensuring the success of the time varying parameter method.

The above statements were provided in the Abstract (see Lines 9 – 11), Introduction (see Lines 61 – 76) and Conclusion (Lines 380 – 390).

In regards to validation of the time varying parameter method, its efficacy was assessed based on the ability to represent all aspects of the streamflow hydrograph. In Section 4, we showed that time varying parameter HBV model provided a good representation of baseflow, total and direct runoff (see Figure 7 and 8, and discussion in Lines 329-361). We also showed that the time varying parameter HyMOD model did not represent all aspects of the hydrograph. This showed the importance of the chosen model structure in determining the success of the time varying parameter method.

With the above main review comments, I have the followings minor comments.

1. Abstract L18 and L57: "it serves as an effective tool for separating the influence of climatic and land use change": is this really true? As a result of the EnKF, it is possible that the both effects of land cover and climate changes may be reflected in the wrong way. Given such an ill-identified potential, please explain the logic and actual steps to distinguish the impacts of the two changes.

The logic here is that if the observed changes to streamflow are driven by changes to meteorological forcings, then there should be no changes to the model parameters (assuming the prior parameterisation and model represent the catchment properties and processes well). In this case, any changes to meteorological forcings would be translated through to simulated

streamflow, so that the prior streamflow closely matches the observed streamflow. This means there will be a small to negligible update of the parameters (see equation 1 of the manuscript, where the term $(y_t^i - \hat{y}_t^i)$ will be small). We also provided additional analysis with a resampled forcing time series and the TVP-HBV model to demonstrate that climatic changes were not the main driver of observed changes to streamflow (see lines 363 – 378).

2. P7 L122 Subsection of "2.1 " may be eliminated because no "2.2" exists.

This change will be incorporated in the revised manuscript.

3. P10 L206 Is the covariance matrix (sigma) also updated in the sequential Kalman Filter algorithm? Please clarify this part and show the equation if it is also updated.

The term $\boldsymbol{\Sigma}_{t-1}^{\theta}$ is simply the sample covariance of the updated (or posterior) parameter ensemble $\{\boldsymbol{\theta}_{t-1}^{i+}\}_{i=1:n}$ at time *t-1*. In Ensemble Kalman Filtering, the covariance matrix is not explicitly updated, but is replaced by the sample covariance of the updated parameter/state members. The equation for updating the members is given in equations 1 and 3 of the manuscript.

We will insert the word “sample” before “covariance matrix” in line 206.

4. P10 L218 The same comment is also applied to the Kalman gain of the model parameters.

We are unclear as to the meaning of this comment. The Kalman gain is what is used to update the model parameters.

As with the previous comment, we can insert the word “sample” before “cross covariance” in Line 222 and before “error covariance matrix” in Line 224.

5. P12 L261 How did you select the tuning parameter s2? The used values in this manuscript should be shown. Table 4 shows "Initial s2 (VVM)" which confuses me because I thought that s2 were set as constant value for each parameter.

An explanation of how the s^2 parameter was tuned was provided in Section 3.2.1 (please see Lines 261 – 263). The values used are shown in Table 4, and are constant values.

The column header in Table 4 will be changed from “Initial s2 (VVM)” to just “s2.” We apologise for the error here.

6. P17 "a MASH undertaken..." Please add a brief explanation of the MASH approach.

We propose to add the following discussion at Line 140 before “A steady increase in …”:

“The MASH tool can be used to qualitatively assess interannual variations in the seasonal pattern of a variable. It works by calculating a statistic of the data (e.g. mean) over the same block of days in each year.”