



## Quantifying the impact of land cover changes on hydrological responses in India

Shaini Naha\*, Miguel A Rico-Ramirez and Rafael Rosolem  
Civil Engineering Department, University of Bristol, Bristol, BS8 1TR, UK

5 \* Corresponding author email: [sn17546@bristol.ac.uk](mailto:sn17546@bristol.ac.uk)

### Abstract

The objective of this study is to assess the impacts of Land Use Land Cover change on the hydrological responses of the Mahanadi river basin, a large river basin in India. Commonly, such assessments are accomplished by using distributed hydrological models in conjunction with different land use scenarios. However, these models through their complex interactions among the model parameters to generate hydrological processes, can introduce significant uncertainties to the hydrological projections. Therefore, we seek to further understand the uncertainties associated with model parameterization in those simulated hydrological responses due to different land cover scenarios. We performed a sensitivity-guided model calibration of a physically semi-distributed model, the Variable Infiltration Capacity (VIC) within a Monte Carlo Framework to generate behavioural models for subcatchments of the Mahanadi river basin. These behavioural models are then used in conjunction with historical and future land cover scenarios from the recently released, Land use Harmonisation (LUH2) to generate hydrological predictions and related uncertainties from behavioural model parameterisation. The LUH2 dataset indicates a noticeable increase in the cropland (23.3% cover) at the expense of forest (22.65% cover) by the end of year 2100 compared to the baseline year, 2005. As a response, simulation results indicate a median percent increase in the extreme flows (defined as the 95th percentile or higher river flow magnitude) and mean annual flows in the range of 1.8 to 11.3% across the subcatchments. The direct conversion of forested areas to agriculture (on the order of 30,000 km<sup>2</sup>) reduces the Leaf Area Index and which subsequently reduces the Evapotranspiration (ET) and increases surface runoff. Further, the range of behavioural hydrological predictions indicated variation in the magnitudes of extreme flows simulated for the different land cover scenarios, for instance uncertainty in far future scenario ranges from 17 to 210 cumecs across subcatchments. This study indicates that the recurrent flood events occurring in the Mahanadi river basin might be influenced by the changes in LULC at the catchment scale and suggests that model



parameterisation represents an uncertainty, which should be accounted for in the land-use change impact assessment.

35 **Keywords:** Land cover change, Variable Infiltration Capacity (VIC), LUH2, Sensitivity Analysis, calibration, hydrological components

### 1. Context and Background

Land use and land cover change (LULC) induced by the rapid anthropogenic activities, is one of the major causes of change in hydrological and watershed processes (Rogger et al., 2016).  
40 Alterations of existing land cover types and land management practices in a catchment can thereby, significantly modify the rainfall path into runoff by changing the hydrological dynamics such as surface runoff, baseflow, Evapotranspiration (ET), water holding capacity of the soil, interception and groundwater recharge, thus reflecting a change in the water demand (Berihun et al., 2019; Bosch and Hewlett, 1982; Costa et al., 2003; Foley et al., 2005;  
45 Garg et al., 2017; Hamman et al., 2018; Mao and Cherkauer, 2009; Rogger et al., 2016; Zhang et al., 2014). For instance, developing countries like India are facing rapid growth in population which has prominent effects on LULC dynamics through deforestation, rapid urbanization, and agricultural intensification, subsequently modifying the hydrological cycle in many river basins of India. A recent analysis on global land cover change have shown a  
50 significant increase of 82% in the croplands in India (Chen et al., 2019a; IPCC, 2019). Therefore, a comprehensive understanding and evaluation of land cover change impacts on hydrological processes are essential for decision makers to plan environmental policies which focuses on water resource allocations, riparian ecosystem protection and river restoration (Chen et al., 2019b; Chu et al., 2013).  
55 Many studies have attempted to evaluate the hydrological responses to different LULC patterns on specific geographic locations (Abe et al., 2018; Chu et al., 2013; Eum et al., 2016; Li et al., 2015; Ma et al., 2010; Rodriguez and Tomasella, 2016; Viola et al., 2014; Woldesenbet et al., 2017) including Indian river basins (Babar and Ramesh, 2015; Dadhwal et al., 2010; Das et al., 2018; Gebremicael et al., 2019; Wilk and Hughes, 2002). Most of these studies used  
60 physically distributed hydrological models (e.g., SWAT, VIC, MIKE-SHE) to simulate the complex hydrological processes and to examine the impact of LULC changes on those processes. Conventionally, this is done by calibrating and validating the hydrological model against the observed data and then setting up that single calibrated model for a baseline land



cover scenario. The calibrated model is then run for different land use scenarios and  
65 subsequently the differences in simulations are compared. However, it is widely recognised  
that hydrological predictions obtained from single calibrated model can be biased and  
therefore the measure of their reliability is always questionable (Beven and Binley, 1992;  
Huang and Liang, 2006). There may exist 'equally probable parameter set' or 'behavioural set'  
70 that can yield equally good or acceptable model predictions, due to the complex interactions  
among the model parameters to represent the complex hydrological processes. This is known  
as equifinality and is considered as one of the main sources of uncertainty in hydrological  
modelling (Her et al., 2019). Recent climate change studies have acknowledged the  
uncertainties stemming from model parameters, and therefore they take into account these  
uncertainties while predicting the hydrological responses due to climate change (Chaney et  
75 al., 2015; Feng and Beighley, 2020; Her et al., 2019; Huang and Liang, 2006; Joseph et al.,  
2018; Mockler et al., 2016; Singh et al., 2014). However, little is known about the  
contributions of model parameter uncertainties to the land use change impacts and thus, very  
few studies exist (Breuer et al., 2006; Chen et al., 2019b) which reported that uncertainties  
associated with the model parameters could significantly influence land cover change impacts  
80 and hence should not be overlooked while modelling hydrologic responses to LULC change.  
This paper specifically focusses on the Mahanadi River basin, an easterly flowing river basin  
in India. Eastern part of India is amongst the most rapidly changing landscape over the  
country, specifically, Mahanadi river basin has undergone drastic land cover changes in the  
last decades (Behera et al., 2018; Dadhwal et al., 2010). In this study, we address the science  
85 questions:

1. What are the expected impacts of LULC changes on the water balance of the Mahanadi River basin?
2. How these predicted impacts vary as a result of model parameter uncertainties?

The major objectives of this study are:

- 90 1. To predict the changes in hydrological processes owing to historical and future changes in LULC
2. To understand the contribution of uncertainty from hydrologic parameterization to the hydrologic projections due to LULC change.



95 To this end, a large scale physically semi-distributed hydrological model, the Variable  
Infiltration Capacity (VIC) (Liang et al., 1994) and historical and future land cover scenarios  
from the Land Use Harmonisation 2 (LUH2) database (Hurtt et al., 2011) are used to simulate  
the discharge and other hydrological components at daily time scales in the Mahanadi river  
basin. The ability of VIC to simulate the impacts of LULC changes on hydrology are well  
100 documented in various research articles (Garg et al., 2017, 2019; Hurkmans et al., 2009; Mao  
and Cherkauer, 2009; Patidar and Behera, 2019; Zhang et al., 2014).

We first perform sensitivity analysis of the model parameters and calibrate the hydrological  
model using Monte Carlo simulations to identify behavioural model simulations that implicitly  
account for the uncertainties from model parameterisation. Behavioural models are then  
105 used to predict the hydrological impacts due to different LULC scenarios. The land cover  
scenarios used in this study are most up-to-date scenarios which represents future changes  
in the LULC based on Shared Socioeconomic Pathways (SSPs). Previous studies (Breuer et al.,  
2006; Chen et al., 2019b) have focussed only on the historical land use scenarios to evaluate  
the hydrological impacts, however and to our knowledge , this is the first study that uses  
110 applications of the VIC model in conjunction with future land cover datasets produced under  
combined SSP and RCP scenarios. While most past studies in other catchments used  
aggregated (monthly) time steps to model the change, we use daily time steps to capture the  
dynamics of daily flow variability. Moreover, analysis in most land use impact studies is limited  
just with the streamflow, missing an overall picture of the hydrological processes.

115

## 2. Research Area

### Geographical Overview

The Mahanadi River basin is located in the eastern part of India (Figure 1) and drains an area  
120 of 141,589 km<sup>2</sup>, which nearly accounts for 4.3% of the total geographical area of India. The  
basin has a varying topography with its lowest elevated area (-17 m) lying in the coastal  
reaches and the highest elevated area (1323 m) in the northern hills. The basin is  
characterized by tropical climate zone and receives rainfall from southwest monsoons which  
commences in June and lasts till October. The average annual rainfall is 1200 mm, with 90%  
125 of the total annual rainfall occurring during the monsoon months (Jin et al., 2018). The mean  
annual discharge is 1895 m<sup>3</sup>/s. The basin is also subjected to spatial variability in terms of



receiving rainfall which has resulted in floods in some parts of the basin and drought in others. Notice that about 65% of the basin is placed upstream of the Hirakud dam. The Hirakud dam with a gross storage capacity of 8.136 km<sup>3</sup> is the major hydro project in the river basin  
130 constructed in the year 1957 to alleviate the flood problems and to serve multiple other purposes such as irrigation, hydropower generation and supplying drinking water. Despite its significant storage capacity, the large flows from upstream of dam and middle reaches of the catchment causes devastating floods during the monsoon in the deltaic region of the basin. About 48% of the total area is under agriculture (Figure 2a), out of which 30% is cropped  
135 during the kharif season or monsoon (June–Oct) and 15% is under double or triple irrigation. The remaining 3% of the area is cropped during Rabi and zaid season (winter and summer respectively). Deciduous Broadleaved Forest (DBF) being dominant among other forest types, covers 25% of the basin area (Figure 2a). Built up, plantation, grassland, shrubland, water bodies and other forest types constitute the rest 22 % of the basin area. Comparison of the  
140 local historical LULC maps of 2005 and 2014, obtained from the National Remote Sensing Centre (NRSC), shows an increase in the agricultural land from about 43 to 48% at the expense of fallow land, built up areas and water bodies while changes in forest covers were insignificant. In addition, loamy and clayey are the major soil types covering roughly 53% and 42% respectively of the total basin area (NBBSS-LUP, India). Approximately 90% of the basin  
145 has moderately shallow to deep soil having depths greater than 50 cm.

### 3. Materials and Methods

#### 3.1 Variable Infiltration Capacity (VIC) model

150 The VIC model is a semi-distributed, land surface hydrologic model which solves both water and energy balance within the grid cells (Cherkauer and Lettenmaier, 1999). VIC maintains sub-grid heterogeneity in land cover classes i.e. divides each grid into tiles based on number of land cover classes, and also considers sub-grid variability in the soil moisture storage capacity (Liang et al., 1994). Surface runoff in VIC is generated through an infiltration excess  
155 by using the Xiangjiang formulation (Zhao et al., 1980) in the upper two soil layers. Baseflow is generated from the third soil layer by applying the Arno formulation (Franchini and Pacciani, 1991). Actual Evapotranspiration of each grid cell in VIC is obtained by summing up three types of evaporation: Evaporation from bare soil, evaporation from canopy layer for each



160 vegetation type, transpiration from different vegetation types; and then weighted by the  
fractional area of each vegetation class. VIC computes Potential Evapotranspiration using the  
Penman-Monteith equation. The amount of rainfall intercepted by the canopy is calculated  
as a function of Leaf Area Index (LAI).

To obtain the discharge at the basin outlet, the VIC model is coupled to a stand-alone routing  
165 model (Lohmann et al., 1996). This routing model follows a simple river routing scheme where  
runoff and baseflow are first routed to the edge of the grid cells using an instantaneous unit  
hydrograph and finally transported to the river/channel network using a linearized St.  
Venant's equation. More details about the structure and formulations of the model can be  
found in the literature (Gao et al., 2010; Liang et al., 1994).

170 In this study, we implement VIC model, version 4.2.d in the water balance mode at a daily  
time step and at a grid resolution of  $0.05^\circ$  over the 5 subcatchments of the Mahanadi River  
basin. Flows are routed to the subcatchments of Basantpur (Ba), Kantamal (Ka), Kesinga (Ke),  
Sundergarh (Su) and Salebhata (Sa) (Figure 1). We abstained from routing the flow for the  
entire Mahanadi River basin due to the presence of a major water management structure,  
175 Hirakud dam at the middle reach of the basin.

### 3.2 Datasets

The key input data required by the VIC model are meteorological forcings (precipitation,  
maximum temperature, minimum temperature and wind speed), soil type, land cover  
180 information and topographic features. Topographical features are determined using the 30-  
meter CARTO-DEM (Cartosat-1 Digital Elevation Model), a national DEM developed by ISRO  
(Indian Space Research Organization) (Sivasena Reddy and Janga Reddy, 2015). The Mahanadi  
River basin is delineated and is converted into grid format of resolution  $0.05^\circ$  constituting of  
4807 grids within the basin area. Daily gridded precipitation (resolution,  $0.25^\circ$ ) and maximum  
185 and minimum temperature (resolution,  $1^\circ$ ) for the time period (1988-2010) are obtained from  
India Meteorological Department (IMD) (Pai et al., 2014). Soil textures are derived from the  
digitized soil map as provided by National Bureau of Soil Survey and Land Use Planning  
(NBSSLUP) (Scale 1:250000). Land cover maps from two different sources i.e., local and global,  
are used in this study. The local LULC map is derived from National Remote Sensing Centre  
190 (NRSC), India of year 2005 (scale 1:250000; resolution 56 meters) and is used in the model  
runs while performing sensitivity analysis, model calibration and validation. Global land cover



scenarios are obtained from LUH2 which are used in model simulations for predicting impacts of land cover changes on hydrological components. All LULC maps used in this study are reformatted and reclassified into USGC LULC types as required by the VIC model (Figure 2a).  
195 The observed discharge at daily scales at multiple gauges (Fig 1) for the simulated time (1988-2010) are obtained from the Central Water Commission (CWC), India, for validating the simulated discharge.

### 3.3 Model parameters

We have selected 16 VIC model parameters (Table 1) for the Sensitivity Analysis (SA). The  
200 choice of parameters was based on our preliminary experiments and expected sensitive properties from previous studies (See description below Table 1). Typical calibration in VIC involves only streamflow related parameters as also recommended by VIC model developers (Gao et al., 2010; Gou et al., 2020; Xie et al., 2007). However a few studies have reported that some vegetation parameters are sensitive to the runoff in the VIC model (Demaria et al., 2007;  
205 Joseph et al., 2018). Parameters subjected to SA in this study include, among others, rarely implemented soil properties: Bulk Density (BD), Fractional water content at wilting point ( $Wp_f$ ) and at critical point ( $Wcr_f$ ); vegetation properties: architectural resistance ( $r_{arc}$ ) Stomatal Resistance ( $r_{min}$ ); and routing parameters: velocity ( $v$ ) and diffusion ( $diff$ ). A multiplier of  $Wcr_f$  is used to compute  $wp_f$ , to meet the criteria that soil moisture at wilting point should always  
210 be less than soil moisture at critical point and the multiplier is tested for sensitivity rather than the actual parameter. Similar approach is followed by Rosolem et al., (2012) while testing sensitivity of parameters in a land surface model. Feasible ranges (minimum and maximum values) of soil parameters (BD,  $Wcr_f$ ,  $K_{sat}$ ,  $Exp$ ) are obtained based on average hydraulic properties of USDA soil textural classes (Cosby et al., 1984; Rawls et al., 1998; Reynolds et al.,  
215 2000) considering only the dominant soil textures within the basin. Ranges for the rest of the soil parameters are based on suggestions from the VIC model developers and published studies. Feasible ranges of the vegetation parameters are obtained based on the recommended ranges provided in the Land Data Assimilation System values for the dominant vegetation types in the basin. Our preliminary experiments suggest Canopy height is not  
220 sensitive hence, Roughness length (RL) and Displacement Heights (Disp), which are computed from canopy height are not accounted for SA.



In addition, the LAI is an important vegetation factor, having substantial control over the water balance by directly influencing the ET rates (Gao et al., 2010; Matheussen et al., 2002). LAI is specified at a mean monthly basis in VIC. We compared the monthly mean LAI averaged  
225 over the time period (2000-2015) from MODIS AQUA/TERRA with the LAI values from GLDAS database for the river basin. We observed that the monthly mean LAI of all the LULC types from MODIS captures the phenological characteristics more realistically than the GLDAS LAI (Fig 2b) which shall have further implications on water balance. We find the range of MODIS LAI obtained for each LULC type are well in agreement with the LAI values obtained in a nearby  
230 Indian river basin (Patidar and Behera, 2019).

Another important factor linking vegetation characteristics to hydrological processes in VIC is the root zone distribution. Typically, root zone allocation in VIC requires user-defined root-zone depths and fractions for each land cover types that are kept fixed during the calibration process. We derived root zone depths and estimated the fractions of roots in each zone  
235 following (Zeng, 2002) for each vegetation type, and used a simplified approach to vary the root zone distributions with respect to the soil depths during calibration. This ensures root zone properties vary for different model calibration with a reduced number of parameters, hence providing a more manageable calibration strategy. For details on our root allocation approach, please refer to the Supplement (Sect. S1)

## 240 3.4 Experimental design

### 3.4.1 Morris Method for Sensitivity Analysis

SA of the chosen sixteen VIC-3L parameters (Table 1) are conducted using the Morris, (1991) method. This method requires Monte Carlo simulations where the model is run with a specified number of samples and measures the change in the model output by varying one  
245 parameter at a time. We used One at a Time Latin Hypercube Sampling (LHS-OAT) strategy, to form a total number of 1200 model parameter sets. This method proposed two sensitivity measures: (1) the mean ( $\mu$ ) of the elementary effects which estimates the direct effect of the input parameter on model output (2) the standard deviation ( $\sigma$ ) of the Elementary Effects which estimates the interaction between the input parameters on the model output. We  
250 tested the sensitivity of model parameters on the Kling-Gupta efficiency (KGE) metric (Eq. 1-3) (Gupta et al., 2009) computed using observed daily streamflow values over 20 years (1990-2010) of simulation period.



$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}, \quad (1)$$

$$\alpha = \frac{\sigma_{sim}}{\sigma_{obs}} \quad (2)$$

$$\beta = \frac{\mu_{sim}}{\mu_{obs}} \quad (3)$$

255 Where  $r$  is the linear correlation between observed and simulated discharge,  $\alpha$  is an estimate of flow variability error and  $\beta$  is a bias term.  $\sigma_{sim}$  and  $\sigma_{obs}$  are standard deviations in simulated and observed discharge, respectively.  $\mu_{sim}$  and  $\mu_{obs}$  are mean of simulated and observed discharge, respectively.

260 We first visually inspect SA results and assume a screening threshold value for the sensitivity index, below which the parameters can be regarded as either completely insensitive or less influential. This is a common practice followed in previous SA studies (Gou et al., 2020; Sarrazin et al., 2016; Tang et al., 2007; Vanrolleghem et al., 2015). Next, to achieve a more objective screening convergence result, we compute the width of the 95% confidence interval of the sensitivity indices (Herman et al., 2013; Wang and Solomatine, 2019) and then use maximum width of the 95% confidence interval, as a statistic (Sarrazin et al., 2016), across the lower influential input to verify if the screening convergence has reached. For a detailed explanation about the steps we took for the SA experiments, please refer to the Supplement 270 (Sect. S2).

#### 3.4.2 Model Calibration and Validation

275 Next, we calibrate sensitive parameters separately on a subbasin level for the time (1990-2000) with a 2-year warm up period (1988-1999), using a sequence of Monte-Carlo simulation, by generating 5000 near-random parameter sets from within the specified range using LHSM with uniform distribution. We use KGE (Eq. 1) as the objective function to assess the model performance in the calibration period. The KGE metric balances the contribution to the error coming from all three main components, namely correlation (e.g., timing/dynamics), variability (e.g., seasonality), and systematic bias, and is now a widely used metric in hydrometeorological studies (Gupta et al., 2009; Knoben et al., 2019). KGE ranges in 280  $[-\infty, 1]$  with larger values indicating better performance. Additionally, we use the PBIAS to evaluate our model performance especially to account for the high flow conditions. We adopt a common practice of selecting the best model simulations by using a top certain percentage



of the total simulations (Chaney et al., 2015; Mockler et al., 2016). This is relevant in our study  
285 as choosing model simulations based on a particular KGE score is subjective given that the  
behavioural performance, as well as the behavioural parameters, vary across the  
subcatchments. Therefore, we first assess the performance of top 10%, 5% and 2% of model  
simulations at every subbasin and choose the top 2% based on overall model performance  
across the subcatchments, hence not compromising with the performance quality and also  
290 accounting for equifinality. These behavioural models are further used to simulate  
streamflow in the validation period (2001-2010) for all the subcatchments.

#### 3.4.3 LULC scenarios

All the simulations in the calibration and validation period are performed using a static local  
295 LULC map of year 2005 derived from NRSC. Simulations using this land use map shall be  
termed as NRSC2005 henceforth. Next, we used a set of land use scenarios based on Socio-  
economic Pathways (SSPs) and Representative Concentration Pathways (RCPs), from the  
recently released , Land Use Harmonization Project (LUH2) data set (release “LUH2v2h” and  
LUH2v2f) for the time period of (850–2005) and (2015-2100) respectively (Hurtt et al., 2018)  
300 (See Table S2, Supp. Sect.). The LUH2 approach estimates the gridded land use fractions,  
annually at a resolution of 0.25°.

The land cover maps from LUH2 are processed and converted to a LULC map of Mahanadi  
basin extent showing a single vegetation coverage at each grid cell of 0.25° and further  
converted to VIC grid size of 0.05 deg. The land use classes are reduced to simplify our model  
305 application, and consequently remapped to the VIC land use classes by assuming all primary  
(Forested or Non-forested) and secondary (Forested and Non-forested) land to Deciduous  
Broadleaf Forest (DBF), Managed pasture and Rangeland are considered as Grassland and all  
crops are merged into a single Cropland class. Urban land and water bodies are retained (See  
Table S3, Supp. Sect). It is worth mentioning that the ‘potentially non-forested secondary  
310 land’ class in the LUH2 datasets matched to the forested areas in NRSC2005 and hence both  
mapped into (Deciduous Broadleaf Forest) DBF which is the dominant forest type in the basin  
(Fig S5 in the Supplementary section).

We used the behavioural models to simulate discharge for the baseline scenario using land  
cover map from LUH2 of year 2005 so as to attain more confidence in the future scenarios.  
315 We compare LULC maps, NRSC2005 and LUH2005 (Figure 3) and observe spatial patterns of



the most dominant land-use classes, Cropland (CL) and Forest (F), shows a similar spatial distribution and having comparable aerial coverage. The only notable difference in both maps is that the Barren ground (BG) class is missing in LUH2005. Table 2 shows the percentage of area covered by each land use classes in the basin. Note that we will refer to DBF as Forest (F) henceforth.

Among the future scenarios, owing to the large computational demand of our simulations, we only considered the ‘worst’ case scenario, RCP3.4 SSP4, which resulted in maximum change in the land cover fractional area (Figure 4). Land cover changes and fractional area covered in other future scenarios are shown in Fig S6 in supplementary section. Four distinct years have been chosen for this study: 2005 (Baseline), 2015 (Present), 2050 (Near Future) and 2100 (Far Future) to study the impacts of LULC change in the Mahanadi river basin. A sharp decrease in the forest cover is observed at the expense of agriculture in the years 2050 and 2100 (Figure 4). We run the behavioural models three times using the individual LUH datasets: (1) with land use map ‘LUH2015’, termed as the ‘present’ (P) scenario (2) with land use map ‘LUH2050’, termed as the ‘Near Future’ (NF) scenario (3) and with land use map ‘LUH2100’ which is termed as the ‘Far Future’ (FF) scenario. To account for the extreme hydrological effects that these changes could cause, two hypothetical scenarios are framed (1) ‘All Cropland’ (CL) scenario where all the grassland and forest areas are transformed into cropland (2) ‘All Forest’ (F) scenario where all the cropland and grassland areas are transformed into forest. The urban and water bodies in these hypothetical scenarios are retained as per the baseline scenario. In all the five cases of model simulations, meteorological forcing for the time (2001-2010) is held constant i.e., the daily precipitation, maximum and minimum temperatures and wind speed are same across all the scenarios. Therefore, any changes observed in the hydrological components in these scenarios will be only due to the change in land use. The percent areas covered by each land use classes at all subcatchments across the scenarios are shown in Table 4.

## 4. RESULTS

### 4.1 Sensitivity Analysis, Model Calibration and Validation

It is to be noted that SA is conducted for all subbasins individually, hence the Morris screening results obtained for each subbasin are independent of each other. However, we observe that the non-influential parameters match closely with each other across subbasins (Fig S2). Based



on the Morris sensitivity measures, there are six sensitive (or influential) parameters namely *dsm<sub>max</sub>*, *d<sub>2</sub>*, *bin<sub>f</sub>*, *v*, *ws* and *ds*. The rest of the parameters (*r<sub>min</sub>*, *d<sub>3</sub>*, *wc<sub>r<sub>f</sub></sub>*, *wp<sub>f</sub>*, *r<sub>arc</sub>*, *Exp*, *BD*, *diff*, *d<sub>1</sub>*, *ksat*) are either relatively non-influential or having negligible impact in the KGE performance. *d<sub>2</sub>* is the most important soil layer probably because it is the thickest soil layer where most of the roots are found, which is expected to exert strong controls on ET. *Dsm<sub>max</sub>*, *ds* and *ws* are the baseflow related parameters, interlinked with each other, associated with the third soil moisture layer *d<sub>3</sub>*, having a higher impact on low flows. We discard a common set of parameters prior to the model calibration based on weighted average of the sensitivity indices of the subbasins. The weights are assigned based on catchment area. Figure 5 shows the influential and non-influential parameters for the entire basin. The total number of model simulations performed are sufficient to achieve the stability of the screening results (See Figure S3, Supp. Sect). More details on the Morris screening results are given in the Supplement that accompanies this paper (Sect. S2.2).

Figure 6 shows the performance of VIC with respect to KGE in the calibration and validation period for all the subcatchments in the highest order of their catchment size. The KGE range for the calibration and validation of daily streamflow for all subcatchments are listed in Table S4 in Supplementary section. In overall, evaluation result suggests the model reproduced the observed flows remarkably well with the median KGE values of 0.85, 0.86, 0.82, 0.75, 0.63 in calibration and 0.77, 0.82, 0.72, 0.60, 0.59 in validation at Basantpur, Kantamal, Kesinga, Salebhata and Sundergarh, respectively. However, we observe a relative reduction in the daily KGE values at the smaller subcatchments (Sundergarh and Salebhata) in both calibration and validation period. The PBIAS values obtained in the calibration period (Fig S8, Supp Sect.) indicate that the model tends to be more biased (positively) as the catchment size decreases and that the largest catchment, Basantpur is least biased. The median PBIAS values at Sundergarh and Salebhata are +9% and +23% respectively in the calibration period and +19% and +55% in the validation period. It is to be noted that subbasins analyzed are human intervened and observed streamflow are controlled by minor reservoirs and dams which will affect the VIC simulations especially in the smaller subcatchments. Moreover, non-consideration of groundwater recharge and irrigation in VIC can also possibly affect performance at smaller subcatchments. Figure S7 (Supp. Sect.) shows that the models reproduced the daily and monthly flows consistently when compared to the observed flows in both calibration and validation period.



380 Figure 6b shows that the distribution of behavioral parameters within their respective  
variability ranges differs from one parameter to another as well as across subcatchments. The  
behavioral models at all subcatchments are scattered nearly across the entire range of  
parameter space for *ds* and *ws*, reflecting high effect on modelled streamflow through their  
interaction with other parameters. Contrarily, behavioral parameter ranges of *binf*, *dsmax* *d2*  
and *v* are relatively constrained across subcatchments, towards either higher, mid, or lower  
385 values indicating direct influence of these parameters on the behavioral simulations. For  
instance, higher values of *d2* and *v*, lower values of *dsmax* and mid values of *binf* resulted in  
the behavioral model simulations at the smaller subcatchment, Salebhata. Thickness of  
second soil layer, *d2* is the most identifiable parameter across all subcatchments.

#### 390 4.2 Baseline scenario performance

We compare the performance of calibrated VIC models in the baseline scenario (using  
LUH2005) against the validation performance (using the NRSC2005) for the period 2001-2010.  
The boxplots in Figure 6a shows daily KGE values for the baseline and validation simulations  
for all subcatchments studied here. The median KGE values for the baseline at Ba, Ka, Ke, Su  
and Sa are 0.62, 0.64, 0.58, 0.62 and 0.72 respectively. The model performed better at the  
395 smaller subcatchments, Sa and Su in the baseline whereas decline in the performance is  
observed at subcatchments, Ba, Ka and Ke. PBIAS values (Fig S8, Supp. Sect.) indicates that  
baseline simulations are more biased (negatively) than validation simulations at bigger  
catchments. The median PBIAS values at Ba, Ka and Ke are -28%, -29% and -33% respectively.  
400 This underestimation can be attributed to the absence of 12% Barren Ground in the baseline  
land cover, which is replaced by croplands (4%), forests (5.02%), grasslands (4.57). The  
increase in flows due to the increase in cropland is compensated by the decrease in flows due  
to the increase in forest. Therefore, the underestimation in the simulated flows using  
LUH2005 may result from the increasing grasslands which increased LAI, thus resulting in an  
405 increase in ET and decrease in surface runoff, respectively. Contrarily, a slight positive bias of  
3% is observed at the smallest subcatchment (Sa) in the baseline simulation, compared to  
+55% in the validation simulation. KGE values obtained across calibration, validation and  
baseline period indicates an overall good performance of the basin as per the existing studies  
using KGE as a performance metric (Knoben et al., 2019). In overall, baseline land cover map,



410 LUH show comparable model performance against local land cover map, NRSC, in the  
historical period with the model being able to capture the seasonality and Land Use/ Land  
Cover dynamics while simulating the daily flows.

### 4.3 LULC impacts and uncertainties

Figure 7 shows percent change in annual average of extreme flows (i.e., 95th percentile or  
415 higher) for the time 2001-2010 in scenarios NF, FF, All Cropland (CL) and All Forest (F) with  
respect to baseline scenario for the behavioural models. The range of percent change  
represents the related uncertainty in model predictions arising from the behavioural model  
parameters. We observe an insignificant positive change in projected extreme flows in the  
present (P) scenario despite a major increase 6% to 36% in croplands replacing forests across  
420 four out of five subcatchments (not shown Figure 7). We observe a prominent increase in the  
extreme flows at all subcatchments in both future scenarios (NF and FF). The projected  
change in extreme flows in NF ranges between 1.3% and 10.7% across the subcatchments.  
The median percent change in the NF scenarios at subcatchments Ba, Ka, Ke, Su and Sa are  
3.6%, 2.6%, 1.8%, 8.1% and 3.8%, respectively. This increase in extreme flows in NF can be  
425 attributed to the reduction in forest cover (-20% to -42%) at the expense of cropland (+7% to  
+48%) across the subcatchments. Percent increase of slightly higher magnitudes are observed  
in FF scenario in response to further increase in croplands. The projected changes in extreme  
flows in FF ranges between 1.4% and 15.4% across the subcatchments. The median percent  
change in FF scenario at subcatchments Ba, Ka, Ke, Su and Sa are 4%, 2.8%, 2.3%, 11.3% and  
430 4.1% respectively in response to reduction in forest cover (-19 to -50%) at the expense of  
cropland (+19 to +54%) across the subcatchments. As anticipated, maximum percent increase  
in the extreme flows (1.2 to 20.5%) are observed in hypothetical 'All Cropland' scenario where  
all forests and grasslands are replaced by cropland and maximum reduction (-2 to -41%)  
observed in 'All forest' scenario where all the croplands and grasslands are converted to  
435 forests. The projected percent changes in mean annual flows are slightly higher than the  
extreme flows across all scenarios and subcatchments. The median values in both future and  
CL scenario shows slightly higher positive percent change in the range of 3 to 11% and higher  
negative percent change -5 to -25% in F scenario.

Maximum increment in extreme flows and annual flows across all scenarios, is recorded at  
440 the largest subcatchment Basantpur which is in the range of 194 to 496 cumecs and 31 to 35



cumecs respectively. The maximum reduction of 712 cumecs and 59 cumecs is observed in 'All Forest' scenario at Basantpur. Much lesser change in terms of magnitudes is observed in the annual flows compared to the extreme flows. This can be explained by the fact that the basin receives approximately 85% of the total annual rainfall during the monsoon months (June-Sept). Therefore, with negligible changes occurring during rest of the year, changes in extreme flows occurring only during the monsoon months are masked out when computed for the entire year. We further computed the difference between maximum and minimum values (ranges) of projected extreme flows as a measure of the amount of uncertainty contained in ensemble predictions made using land cover scenarios and multiple (behavioural) parameter sets (Table 4). Among all the scenarios, maximum uncertainty is observed in the hypothetical 'All Forest' scenario followed by 'All Cropland' scenario. In overall the uncertainty of hydrological model parameterization is observed at the largest subcatchment Basantpur and decrease with respect to the decrease in the catchment size.

We analysed the water balance components to understand the factors causing changes in the streamflow. We notice that the model is able to estimate all the water budget components and maintain proper closure of the water balance in all the scenarios across the subcatchments. In overall, we found that the increase in the mean annual flows is caused due to the increment in runoff and reduction in ET across all subcatchments. Positive median changes are observed in runoff in scenarios (NF, FF and CL) ranging between (2.8 to 14) % and negative changes of (-4 to -37) % in F scenario. Negative median changes are observed in ET in scenarios (NF, FF and CL) ranging between (-1.4 to -3.4) % and positive changes of (1.9 to 7.8) % in F scenario. Removal of forests at the expense of cropland decreases the LAI of the natural vegetation and hence decreases ET. Moreover, the removal of forest cover reduces the root water uptake by plants which increases the water content of the second and third layer of the soil. The top thin soil layer in VIC model helps in partitioning the rainfall amount into direct runoff and the amount entering the soil. Therefore, the increase in the cropland results in more direct runoff thus reducing the soil moisture content in the first soil layer. The increase in runoff is not significant, despite the occurrence of major deforestation in the future scenarios. This is because the decrease in ET due to forests removal is compensated as increment in croplands also leads to a major increase in ET rates, which is why we do not see a sharp reduction in the ET rates. Negligible changes are observed in baseflow while slight increase in total soil moisture is noticed across the subcatchments (Not shown). The water



balance indicates that 15 to 21% of precipitation is direct runoff and 64 to 80% is ET across all subbasins and all land cover scenarios whereas negligible baseflow and soil moisture change  
475 are observed. This is probably because the third soil moisture layer in the model does not reach saturation to cause the non-linear baseflow, as precipitation in the basin is highly concentrated in only three to four months in monsoon and rest of the year remains dry. 4.3.

## 5. Discussions

Performing a comprehensive sensitivity analysis and model calibration enhances the accuracy  
480 for predicting hydrological responses, which subsequently improves the representations of changes in the hydrological regime due to land cover changes. Our SA results are in agreement with existing studies conducted on several basins using VIC which show *binf* and *d2* are the most sensitive parameters (Demaria et al., 2007; Gou et al., 2020; Lihare et al., 2020; Yeste et al., 2020). Moreover, not all the parameters recommended for calibration by VIC model  
485 developers (*binf*, *d1*, *d2*, *d3*, *ds*, *dsmax* and *ws*) are sensitive to this basin which is also in line with Findings of Bao et al., (2011), Demaria et al., (2013) and Gou et al., (2020) for other basins. For, instance, first- and third-layer soil depth (*d1* and *d3*) are not found sensitive in this study. *d1* is the thinner topmost soil layer having not much control on ET and subsurface  
490 layer, hence not contributing to the soil moisture uptake through the roots. We found that soil properties impose greater control on model performance than the vegetation parameters. However, while varying soil depths influences the ET rates by posing indirect influences on both timing and magnitude of the soil water available for ET, varying root depths and fractions (using our root zone allocation approach) has provided substantial  
495 control over the water balance by directly influencing the ET rates, thereby improving KGE (not shown). The weakness in reproducing flows at smaller subcatchments in Mahanadi basin are also reported previously in some studies (Kneis et al., 2014; Mishra et al., 2008; Nayak, Venkatesh, Thomas, & Rao, 2010).

LUH2 is a new dataset, not yet extensively used in basin-scale hydrology. A recent study by  
500 Krause et al., (2019) predicted worldwide increment in runoff (67%) and a variable response of ET across different land use scenarios using LUH2 dataset. The major changes occurring in Mahanadi in the future scenarios as predicted by LUH2 agrees with a recent study by Behera



et al., (2018) in the same basin, wherein they found a prominent conversion of DBF to croplands in year 2025 relative to year 2005.

505 Our findings indicate increase of 27-496 cumecs in extreme flows and 2.6-35 cumecs in annual mean flows due to deforestation, across the subbasins and scenarios (including the hypothetical cropland scenario). These increasing trends are consistent with other studies in the Mahanadi river basin in India (Dadhwal et al., 2010), neighbouring basins (Das et al., 2018; Kundu et al., 2017) and elsewhere (Abe et al., 2018; Berihun et al., 2019; Cornelissen et al., 510 2013; Costa et al., 2003). Kundu et al., (2017) found an increase in runoff and decrease in ET due to the expansion in projected agricultural land in Narmada river basin in India. Das et al., (2018) predicted that deforestation, urbanization and cropland expansion in eastern river basins of India, in the future would increase runoff and baseflow and decrease ET%. We found a small change in mean annual discharge as well as in water balance components despite a 515 major change in land cover. This correlates with research (Ashagrie et al., 2006; Fohrer et al., 2001; Hurkmans et al., 2009; Kumar et al., 2018; Patidar and Behera, 2019; Rogger et al., 2016; Viglione et al., 2016; Wagner et al., 2013; Wilk and Hughes, 2002) wherein they have reported that the impacts of land cover change on water balance components in a large-scale river basin are too small to be detected due to the compensation effects. Wilk and Hughes, (2002) 520 showed that removal of large forests led to little or no changes in annual runoff in large heterogeneous catchments in South India. Patidar and Behera, (2019) in a recent study in a large river basin in India, reported that the conversion of forest to agriculture may not alter the water balance significantly as the impacts on ET and runoff cancels out at the basin scale. The range of these hydrological estimates (Figures 7, 8 and Table 4) provides more 525 straightforward and explicit quantification of uncertainty than other statistical measures such as variance, interquartile ranges (Her et al., 2019). Our results suggest that even a small set of calibrated models can predict a wide range of flows through different hydrological processes occurring within the basin and therefore the impacts of uncertainty derived from model parameters on the relative changes cannot be neglected. The uncertainty due to model 530 parameters did not alter the trend of changes in extreme flow, mean annual flow and hydrological components due to land use change in comparison to the baseline simulations. However, a considerable variation is observed especially in the magnitudes of extreme flows simulated for the different land cover scenarios. For instance, the competing interactions among  $D_s$  and  $W_s$ , lead to the varying hydrological processes occurring within the basin,



535 thereby affecting the partition of water in the soil column. Similar conclusions are outlined in  
Chen et al., (2019) that the projected monthly and annual flows simulated for different land  
use scenarios were having significant uncertainty due to model parameterization. In addition,  
we found that the trends within the scenarios especially in the mean annual flows, runoff and  
ET are not consistent. For instance, we expect the increase in flows to be more in Far Future  
540 scenarios than Near Future, given that the increase in agricultural land in the Far Future is  
relatively more. However due to different parametrization, some models predicted decrease  
in Far Future flows relative to Near Future (Fig 7). This clearly indicates that the impact of land  
use could be biased when a single model prediction is used, as the impacts could be  
potentially hidden within simulation uncertainty derived from model parameters (Chen et al.,  
545 2019). Only a small percentage of model simulations (2%; 100 model simulations) with  
relatively high daily KGE scores ( $KGE > 0.8$  at 3 out of 5 subcatchments) were used for assessing  
the impacts, yet significant variations in extreme flow magnitudes and trends (in some cases)  
are observed. Therefore, selecting models with relatively lower KGE values might have led to  
larger uncertainty bound and inconsistent trends in the relative change. Equifinality in  
550 hydrological modelling and its influence on hydrological analysis of climate change has been  
discussed in several studies. However, its influence on hydrological analysis of land cover  
change has not been studied enough to provide a clear idea about the contributions of model  
parameter uncertainty to hydrological projections. Our results thus underline the importance  
of considering model uncertainty and consequently equifinality while modelling the  
555 landcover change impacts.

## 5. Conclusions

In this study an attempt is made to quantify the hydrologic response of the subcatchments of  
Mahanadi River basin owing to different land cover scenarios obtained from LUH, through the  
560 implementation of a sensitivity based calibrated semi-distributed hydrological model. Our  
findings are insights to the plausible hydrological scenarios in future at a river basin level  
which is a crucial step forward for a developing country in the context of today's increasing  
focus on integrated water resources management (IWRM) in River basins. In overall, VIC  
captured the observed daily flows well in calibration, validation and baseline period across  
565 subcatchments. Deforestation at the expense of cropland dominated the land cover change



processes across all scenarios and subcatchments, which has led to an increase in the extreme flows and mean annual flows. Analysis of other hydrological components have shown that the increase in flows is caused by the increase in runoff and decrease in ET. The uncertainties due to model parameterization in land use change impacts, varies from one subcatchment to another. The uncertainties did not alter the trend of changes when compared to the baseline; however, a considerable variation is observed especially in the magnitudes of extreme flows simulated for the different land cover scenarios. This result suggests a significant constraint on the usage of hydrological models for the variations of extreme flows due to land use change, even with high KGEs at daily time step as the impacts could be potentially hidden within simulation uncertainty derived from the model parameters. The uncertainties from model parameters thus should be considered in land use change impact assessment for more robust and reliable analysis, which shall make the land cover change mitigation strategies and water resources management plans more effective.

This study indicates that the recurrent flood events occurring in the Mahanadi River basin might be influenced by the changes in LULC at the catchment scale. It is worth mentioning that existing studies (Asokan and Dutta, 2008; Ghosh et al., (2010) had predicted an increase in the extreme flows during the monsoon which if combined with the impacts resulting from land cover changes might result in adverse flooding in the basin. Therefore, Future studies shall focus on modelling the combined impacts of climate and land cover changes on hydrology of Mahanadi River basin, considering the uncertainties from model parameterization, which is currently lacking in many studies.

#### **Data availability.**

Dem is freely available from <https://bhuvan-app3.nrsc.gov.in/data/download/index.php>. Unit Hydrograph is adopted from <https://vic.readthedocs.io/en/vic.4.2.d/Documentation/Routing/UH/>. Daily gridded rainfall, maximum and minimum temperature are freely available from [http://www.imdpune.gov.in/Clim\\_Pred\\_LRF\\_New/Grided\\_Data\\_Download.html](http://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html). Wind speed data is freely available from [https://psl.noaa.gov/cgibin/db\\_search/DBSearch.pl?Dataset=NCEP+Reanalysis+Daily+Averages](https://psl.noaa.gov/cgibin/db_search/DBSearch.pl?Dataset=NCEP+Reanalysis+Daily+Averages) LUH2 datasets are downloaded from <https://luh.umd.edu/data.shtml>. Observed discharge data are available from <http://cwc.gov.in/>. The source code for VIC-3L version 4.2.d is available from <https://github.com/UW-Hydro/VIC/releases/tag/VIC.4.2.d>.

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



**Author's Contribution.** SN, MRR and RR designed this study. SN performed the model simulations. MR and RR assisted SN in analysing and discussing the results. SN wrote the manuscript and MR and RR commented on the manuscript.

**Acknowledgements.** This work was partially funded by the BEMUSED project funded by Natural Environment Research Council (NERC; grant number NE/R004897/1) and by the International Atomic Energy Agency of the United Nations (IAEA/UN) under the Coordinated Research Project (CRP D12014).

## REFERENCES

- Abe, C. A., Lobo, F. de L., Dibike, Y. B., Costa, M. P. de F., Dos Santos, V. and Novo, E. M. L. M.: Modelling the effects of historical and future land cover changes on the hydrology of an Amazonian basin, *Water (Switzerland)*, 10(7), doi:10.3390/w10070932, 2018.
- Ashagrie, A. G., De Laat, P. J. M., De Wit, M. J. M., Tu, M. and Uhlenbrook, S.: Detecting the influence of land use changes on discharges and floods in the Meuse River Basin - The predictive power of a ninety-year rainfall-runoff relation?, *Hydrol. Earth Syst. Sci.*, 10(5), 691–701, doi:10.5194/hess-10-691-2006, 2006.
- Babar, S. and Ramesh, H.: Streamflow response to land use-land cover change over the Nethravathi River Basin, India, *J. Hydrol. Eng.*, 20(10), doi:10.1061/(ASCE)HE.1943-5584.0001177, 2015.
- Bao, Z., Liu, J., Zhang, J., Fu, G., Wang, G., Yan, X., Zhang, A., Xu, Q. and Shang, M.: Estimation of baseflow parameters of variable infiltration capacity model with soil and topography properties for predictions in ungauged basins, *Hydrol. Earth Syst. Sci. Discuss.*, 8(4), 7017–7053, doi:10.5194/hessd-8-7017-2011, 2011.
- Behera, M. D., Tripathi, P., Das, P., Srivastava, S. K., Roy, P. S., Joshi, C., Behera, P. R., Deka, J., Kumar, P., Khan, M. L., Tripathi, O. P., Dash, T. and Krishnamurthy, Y. V. N.: Remote sensing based deforestation analysis in Mahanadi and Brahmaputra river basin in India since 1985, *J. Environ. Manage.*, 206, 1192–1203, doi:10.1016/j.jenvman.2017.10.015, 2018.
- Berihun, M. L., Tsunekawa, A., Haregeweyn, N., Meshesha, D. T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A. A., Sultan, D., Yibeltal, M. and Ebabu, K.: Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia, *Sci. Total Environ.*, 689, 347–365, doi:10.1016/j.scitotenv.2019.06.338, 2019.
- Beven, K. and Binley, A.: The future of distributed models: Model calibration and uncertainty prediction, *Hydrol. Process.*, 6(3), 279–298, doi:10.1002/hyp.3360060305, 1992.
- Bosch, J. M. and Hewlett, J. D.: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, *J. Hydrol.*, 55(1–4), 3–23,



- doi:10.1016/0022-1694(82)90117-2, 1982.
- 635 Breuer, L., Huisman, J. A. and Frede, H. G.: Monte Carlo assessment of uncertainty in the simulated hydrological response to land use change, *Environ. Model. Assess.*, 11(3), 209–218, doi:10.1007/s10666-006-9051-9, 2006.
- Chaney, N. W., Herman, J. D., Reed, P. M. and Wood, E. F.: Flood and drought hydrologic monitoring: The role of model parameter uncertainty, *Hydrol. Earth Syst. Sci.*, 19(7), 3239–3251, doi:10.5194/hess-19-3239-2015, 2015.
- 640 Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R. K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tømmervik, H., Bala, G., Zhu, Z., Nemani, R. R. and Myneni, R. B.: China and India lead in greening of the world through land-use management, *Nat. Sustain.*, 2(2), 122–129, doi:10.1038/s41893-019-0220-7, 2019a.
- 645 Chen, Y., Xu, C. Y., Chen, X., Xu, Y., Yin, Y., Gao, L. and Liu, M.: Uncertainty in simulation of land-use change impacts on catchment runoff with multi-timescales based on the comparison of the HSPF and SWAT models, *J. Hydrol.*, 573(December 2018), 486–500, doi:10.1016/j.jhydrol.2019.03.091, 2019b.
- Cherkauer, K. A. and Lettenmaier, D. P.: Hydrologic effects of frozen soils in the upper Mississippi River basin, *J. Geophys. Res. Atmos.*, 104(D16), 19599–19610, doi:10.1029/1999JD900337, 1999.
- 650 Chu, M. L., Knouft, J. H., Ghulam, A., Guzman, J. A. and Pan, Z.: Impacts of urbanization on river flow frequency: A controlled experimental modeling-based evaluation approach, *J. Hydrol.*, 495, 1–12, doi:10.1016/j.jhydrol.2013.04.051, 2013.
- 655 Cornelissen, T., Diekkrüger, B. and Giertz, S.: A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment, *J. Hydrol.*, 498, 221–236, doi:10.1016/j.jhydrol.2013.06.016, 2013.
- Cosby, B. J., Hornberger, G. M., Clapp, R. B. and Ginn, T. R.: A Statistical Exploration of the Relationships of Soil Moisture Characteristics to the Physical Properties of Soils, *Water Resour. Res.*, 20(6), 682–690, doi:10.1029/WR020i006p00682, 1984.
- 660 Costa, M. H., Botta, A. and Cardille, J. A.: Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia, *J. Hydrol.*, 283(1–4), 206–217, doi:10.1016/S0022-1694(03)00267-1, 2003.
- 665 Dadhwal, V. K., Mishra, N. and Aggarwal, S. P.: Hydrological Simulation of Mahanadi River Basin and Impact of Land Use / Land Cover Change on Surface Runoff Using a Macro Scale Hydrological Model, *ISPRS TC VII Symp. – 100 Years ISPRS, Vienna, Austria, XXXVIII*, 165–170, 2010.
- 670 Das, P., Behera, M. D., Patidar, N., Sahoo, B., Tripathi, P., Behera, P. R., Srivastava, S. K., Roy, P. S., Thakur, P., Agrawal, S. P. and Krishnamurthy, Y. V. N.: Impact of LULC change on the runoff, base flow and evapotranspiration dynamics in eastern Indian river basins during 1985–2005 using variable infiltration capacity approach, *J. Earth Syst. Sci.*, 127(2), 1–19,



doi:10.1007/s12040-018-0921-8, 2018.

Demaria, E. M., Nijssen, B. and Wagener, T.: Monte Carlo sensitivity analysis of land surface parameters using the Variable Infiltration Capacity model, *J. Geophys. Res. Atmos.*, 112(11), 1–15, doi:10.1029/2006JD007534, 2007.

675 Demaria, E. M. C., Maurer, E. P., Sheffield, J., Bustos, E., Poblete, D., Vicuña, S. and Meza, F.: Using a gridded global dataset to characterize regional hydroclimate in central Chile, *J. Hydrometeorol.*, 14(1), 251–265, doi:10.1175/JHM-D-12-047.1, 2013.

Eum, H. II, Dibike, Y. and Prowse, T.: Comparative evaluation of the effects of climate and land-cover changes on hydrologic responses of the Muskeg River, Alberta, Canada, *J. Hydrol. Reg. Stud.*, 8, 198–221, doi:10.1016/j.ejrh.2016.10.003, 2016.

680 Feng, D. and Beighley, E.: Identifying uncertainties in hydrologic fluxes and seasonality from hydrologic model components for climate change impact assessments, *Hydrol. Earth Syst. Sci.*, 24(5), 2253–2267, doi:10.5194/hess-24-2253-2020, 2020.

Fohrer, N., Haverkamp, S., Eckhardt, K. and Frede, H. G.: Hydrologic response to land use changes on the catchment scale, *Phys. Chem. Earth, Part B Hydrol. Ocean. Atmos.*, 26(7–8), 577–582, doi:10.1016/S1464-1909(01)00052-1, 2001.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. and Snyder, P. K.: Global consequences of land use, *Science (80-. )*, 309(5734), 570–574, doi:10.1126/science.1111772, 2005.

Franchini, M. and Pacciani, M.: Comparative analysis of several conceptual rainfall-runoff models, *J. Hydrol.*, 122(1–4), 161–219, doi:10.1016/0022-1694(91)90178-K, 1991.

695 Gao, H., Tang, Q., Shi, X., Zhu, C. and Bohn, T.: Water budget record from Variable Infiltration Capacity (VIC) model, *Algorithm Theor. Basis Doc. Terr. Water Cycle Data Rec.*, (Vic), 120–173 [online] Available from: [http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Water+Budget+Record+from+Variable+Infiltration+Capacity+\(+VIC+\)+Model#2](http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Water+Budget+Record+from+Variable+Infiltration+Capacity+(+VIC+)+Model#2), 2010.

700 Garg, V., Aggarwal, S. P., Gupta, P. K., Nikam, B. R., Thakur, P. K., Srivastav, S. K. and Senthil Kumar, A.: Assessment of land use land cover change impact on hydrological regime of a basin, *Environ. Earth Sci.*, 76(18), 1–17, doi:10.1007/s12665-017-6976-z, 2017.

Garg, V., Nikam, B. R., Thakur, P. K., Aggarwal, S. P., Gupta, P. K. and Srivastav, S. K.: Human-induced land use land cover change and its impact on hydrology, *HydroResearch*, 1, 48–56, doi:10.1016/j.hydres.2019.06.001, 2019.

705 Gebremicael, T. G., Mohamed, Y. A. and Van der Zaag, P.: Attributing the hydrological impact of different land use types and their long-term dynamics through combining parsimonious hydrological modelling, alteration analysis and PLSR analysis, *Sci. Total Environ.*, 660, 1155–1167, doi:10.1016/j.scitotenv.2019.01.085, 2019.



- 710 Gou, J., Miao, C., Duan, Q., Tang, Q., Di, Z., Liao, W., Wu, J. and Zhou, R.: Sensitivity Analysis-Based Automatic Parameter Calibration of the VIC Model for Streamflow Simulations Over China, *Water Resour. Res.*, 56(1), 1–19, doi:10.1029/2019WR025968, 2020.
- Gupta, H. V., Kling, H., Yilmaz, K. K. and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, *J. Hydrol.*, 377(1–2), 80–91, doi:10.1016/j.jhydrol.2009.08.003, 2009.
- 715 Hamman, J. J., Nijssen, B., Bohn, T. J., Gergel, D. R. and Mao, Y.: The variable infiltration capacity model version 5 (VIC-5): Infrastructure improvements for new applications and reproducibility, *Geosci. Model Dev.*, 11(8), 3481–3496, doi:10.5194/gmd-11-3481-2018, 2018.
- 720 Her, Y., Yoo, S. H., Cho, J., Hwang, S., Jeong, J. and Seong, C.: Uncertainty in hydrological analysis of climate change: multi-parameter vs. multi-GCM ensemble predictions, *Sci. Rep.*, 9(1), 1–22, doi:10.1038/s41598-019-41334-7, 2019.
- Herman, J. D., Kollat, J. B., Reed, P. M. and Wagener, T.: Technical Note: Method of Morris effectively reduces the computational demands of global sensitivity analysis for distributed watershed models, *Hydrol. Earth Syst. Sci.*, 17(7), 2893–2903, doi:10.5194/hess-17-2893-2013, 2013.
- 725 Huang, M. and Liang, X.: On the assessment of the impact of reducing parameters and identification of parameter uncertainties for a hydrologic model with applications to ungauged basins, *J. Hydrol.*, 320(1–2), 37–61, doi:10.1016/j.jhydrol.2005.07.010, 2006.
- 730 Hurkmans, R. T. W. L., Terink, W., Uijlenhoet, R., Moors, E. J., Troch, P. A. and Verburg, P. H.: Effects of land use changes on streamflow generation in the Rhine basin, *Water Resour. Res.*, 45(6), 1–15, doi:10.1029/2008WR007574, 2009.
- 735 Hurtt, G. C., Chini, L. P., Frohling, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P. and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, *Clim. Change*, 109(1), 117–161, doi:10.1007/s10584-011-0153-2, 2011.
- 740 Hurtt, G. C., Chini, L. P., Sahajpal, R., Frohling, S. E., Boudirsky, B., Calvin, K. V., Doelman, J. C., Fisk, J., Fujimori, S., Goldewijk, K. and others: LUH2: Harmonization of global land-use scenarios for the period 850–2100, AGUFGM, 2018, GC13A--01, 2018.
- IPCC, I. P. O. C. C.: Special report on global warming of 1.5 C (SR15), 2019.
- 745 Jin, L., Whitehead, P. G., Rodda, H., Macadam, I. and Sarkar, S.: Simulating climate change and socio-economic change impacts on flows and water quality in the Mahanadi River system, India, *Sci. Total Environ.*, 637–638, 907–917, doi:10.1016/j.scitotenv.2018.04.349, 2018.
- Joseph, J., Ghosh, S., Pathak, A. and Sahai, A. K.: Hydrologic impacts of climate change:



- Comparisons between hydrological parameter uncertainty and climate model uncertainty, *J. Hydrol.*, 566(September), 1–22, doi:10.1016/j.jhydrol.2018.08.080, 2018.
- Knoben, W. J. M., Freer, J. E. and Woods, R. A.: Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores, *Hydrol. Earth Syst. Sci.*, 23(10), 4323–4331, doi:10.5194/hess-23-4323-2019, 2019.
- Kumar, N., Singh, S. K., Singh, V. G. and Dzwauro, B.: Investigation of impacts of land use/land cover change on water availability of Tons River Basin, Madhya Pradesh, India, *Model. Earth Syst. Environ.*, 4(1), 295–310, doi:10.1007/s40808-018-0425-1, 2018.
- 755 Kundu, S., Khare, D. and Mondal, A.: Individual and combined impacts of future climate and land use changes on the water balance, *Ecol. Eng.*, 105, 42–57, doi:10.1016/j.ecoleng.2017.04.061, 2017.
- Li, Z., Deng, X., Wu, F. and Hasan, S. S.: Scenario analysis for water resources in response to land use change in the middle and upper reaches of the heihe river Basin, *Sustain.*, 7(3), 3086–3108, doi:10.3390/su7033086, 2015.
- 760 Liang, X., Lettenmaier, D. P., Wood, E. F. and Burges, S. J.: A Simple hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, *J. Geophys. Res.*, 99(D7), 14415–14428, 1994.
- Lilhare, R., Pokorny, S., Déry, S. J., Stadnyk, T. A. and Koenig, K. A.: Sensitivity analysis and uncertainty assessment in water budgets simulated by the variable infiltration capacity model for Canadian subarctic watersheds, *Hydrol. Process.*, 34(9), 2057–2075, doi:10.1002/hyp.13711, 2020.
- Lohmann, D. A. G., NOLTE-HOLUBE, R. and Raschke, E.: A large-scale horizontal routing model to be coupled to land surface parametrization schemes, *Tellus A*, 48(5), 708–721, 1996.
- 770 Ma, X., Xu, J. and van Noordwijk, M.: Sensitivity of streamflow from a Himalayan catchment to plausible changes in land cover and climate, *Hydrol. Process.*, 24(11), 1379–1390, doi:10.1002/hyp.7602, 2010.
- Mao, D. and Cherkauer, K. A.: Impacts of land-use change on hydrologic responses in the Great Lakes region, *J. Hydrol.*, 374(1–2), 71–82, doi:10.1016/j.jhydrol.2009.06.016, 2009.
- 775 Matheussen, B., Goodman, I. A., Lettenmaier, D. P., Kirschbaum, R. L. and O’Donnell, G. M.: Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada), *Hydrol. Process.*, 14(5), 867–885, doi:10.1002/(sici)1099-1085(20000415)14:5<867::aid-hyp975>3.0.co;2-5, 2002.
- 780 Mockler, E. M., Chun, K. P., Sapriza-Azuri, G., Bruen, M. and Wheeler, H. S.: Assessing the relative importance of parameter and forcing uncertainty and their interactions in conceptual hydrological model simulations, *Adv. Water Resour.*, 97, 299–313, doi:10.1016/j.advwatres.2016.10.008, 2016.



- 785 Morris, M. D.: Factorial sampling plans for preliminary computational experiments, *Technometrics*, 33(2), 161–174, 1991.
- Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S. and Mukhopadhyay, B.: Development of a new high spatial resolution ( $0.25^\circ \times 0.25^\circ$ ) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region, *Mausam*, 65(1), 1–18, 2014.
- 790 Patidar, N. and Behera, M. D.: How Significantly do Land Use and Land Cover (LULC) Changes Influence the Water Balance of a River Basin? A Study in Ganga River Basin, India, *Proc. Natl. Acad. Sci. India Sect. A - Phys. Sci.*, 89(2), 353–365, doi:10.1007/s40010-017-0426-x, 2019.
- Rawls, W. J., Gimenez, D. and Grossman, R.: Use of soil texture, bulk density, and slope of the water retention curve to predict saturated hydraulic conductivity, *Trans. ASAE*, 41(4), 795 983, 1998.
- Reynolds, C. A., Jackson, T. J. and Rawls, W. J.: Estimating soil water-holding capacities by linking the Food and Agriculture Organization soil map of the world with global pedon databases and continuous pedotransfer functions, *Water Resour. Res.*, 36(12), 3653–3662, 2000.
- 800 Rodriguez, D. A. and Tomasella, J.: On the ability of large-scale hydrological models to simulate land use and land cover change impacts in Amazonian basins, *Hydrol. Sci. J.*, 61(10), 1831–1846, doi:10.1080/02626667.2015.1051979, 2016.
- 805 Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., Chaplot, V., Gallart, F., Glatzel, G., Hall, J., Holden, J., Holko, L., Horn, R., Kiss, A., Quinton, J. N., Leitinger, G., Lennartz, B., Parajka, J., Peth, S., Robinson, M., Salinas, J. L., Santoro, A., Szolgay, J., Tron, S. and Viglione, A.: *Water Resources Research*, (June 2013), 5209–5219, doi:10.1002/2017WR020723.Received, 2016.
- 810 Rosolem, R., Gupta, H. V., Shuttleworth, W. J., Zeng, X. and De Gonçalves, L. G. G.: A fully multiple-criteria implementation of the Sobol’ method for parameter sensitivity analysis, *J. Geophys. Res. Atmos.*, 117(7), 1–18, doi:10.1029/2011JD016355, 2012.
- Sarrazin, F., Pianosi, F. and Wagener, T.: Global Sensitivity Analysis of environmental models: Convergence and validation, *Environ. Model. Softw.*, 79, 135–152, doi:10.1016/j.envsoft.2016.02.005, 2016.
- 815 Singh, R., Wagener, T., Crane, R., Mann, M. E. and Ning, L.: A vulnerability driven approach to identify adverse climate and land use change combinations for critical hydrologic indicator thresholds: Application to a watershed in Pennsylvania, USA, *Water Resour. Res.*, 50(4), 3409–3427, doi:10.1002/2013WR014988, 2014.
- 820 Sivasena Reddy, A. and Janga Reddy, M.: Evaluating the influence of spatial resolutions of DEM on watershed runoff and sediment yield using SWAT, *J. Earth Syst. Sci.*, 124(7), 1517–1529, 2015.
- Tang, Y., Reed, P., Wagener, T. and Van Werkhoven, K.: Comparing sensitivity analysis



- methods to advance lumped watershed model identification and evaluation, *Hydrol. Earth Syst. Sci.*, 11(2), 793–817, doi:10.5194/hess-11-793-2007, 2007.
- 825 Vanrolleghem, P. A., Mannina, G., Cosenza, A. and Neumann, M. B.: Global sensitivity analysis for urban water quality modelling: Terminology, convergence and comparison of different methods, *J. Hydrol.*, 522, 339–352, doi:10.1016/j.jhydrol.2014.12.056, 2015.
- Viglione, A., Merz, B., Viet Dung, N., Parajka, J., Nester, T. and Blöschl, G.: Attribution of regional flood changes based on scaling fingerprints, *Water Resour. Res.*, 52(7), 5322–5340, 2016.
- 830 Viola, M. R., Mello, C. R., Beskow, S. and Norton, L. D.: Impacts of Land-use Changes on the Hydrology of the Grande River Basin Headwaters, Southeastern Brazil, *Water Resour. Manag.*, 28(13), 4537–4550, doi:10.1007/s11269-014-0749-1, 2014.
- 835 Wagner, P. D., Kumar, S. and Schneider, K.: An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune, India, *Hydrol. Earth Syst. Sci.*, 17(6), 2233–2246, doi:10.5194/hess-17-2233-2013, 2013.
- Wang, A. and Solomatine, D. P.: Practical experience of sensitivity analysis: Comparing six methods, on three hydrological models, with three performance criteria, *Water (Switzerland)*, 11(5), 1–26, doi:10.3390/w11051062, 2019.
- 840 Wilk, J. and Hughes, D. A.: Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment, *Hydrol. Sci. J.*, 47(1), 19–30, 2002.
- Woldesenbet, T. A., Elagib, N. A., Ribbe, L. and Heinrich, J.: Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia, *Sci. Total Environ.*, 575, 724–741, doi:10.1016/j.scitotenv.2016.09.124, 2017.
- 845 Xie, Z., Yuan, F., Duan, Q., Zheng, J., Liang, M. and Chen, F.: Regional parameter estimation of the VIC land surface model: Methodology and application to river basins in China, *J. Hydrometeorol.*, 8(3), 447–468, doi:10.1175/JHM568.1, 2007.
- Yanto, Livneh, B., Rajagopalan, B. and Kasprzyk, J.: Hydrological model application under data scarcity for multiple watersheds, Java Island, Indonesia, *J. Hydrol. Reg. Stud.*, 9, 127–139, doi:10.1016/j.ejrh.2016.09.007, 2017.
- 850 Yeste, P., García-Valdecasas Ojeda, M., Gámiz-Fortis, S. R., Castro-Díez, Y. and Jesús Esteban-Parra, M.: Integrated Sensitivity Analysis of a Macroscale Hydrologic Model in the North of the Iberian Peninsula, *J. Hydrol.*, 590(September 2019), 125230, doi:10.1016/j.jhydrol.2020.125230, 2020.
- 855 Zeng, X.: Global Vegetation Root Distribution for Land Modeling, *J. Hydrometeorol.*, 2(5), 525–530, doi:10.1175/1525-7541(2001)002<0525:gvrdf>2.0.co;2, 2002.
- Zhang, T., Zhang, X., Xia, D. and Liu, Y.: An analysis of land use change dynamics and its impacts on hydrological processes in the Jialing River Basin, *Water (Switzerland)*, 6(12), 3758–3782, doi:10.3390/w6123758, 2014.



860 Zhao, R. J., Zhang, Y. L., Fang, L. R., Liu, X. R. and Zhang, Q. S.: The Xinanjiang model  
 Hydrological Forecasting Proceedings Oxford Symposium, IASH, 1980.

Table 1: VIC and routing model parameters tested for sensitivity analysis and feasible ranges.

Parameters	Description	Units	Minimum	Maximum
<b>Soil parameters</b>				
$W_{crf}$	Fraction of water content at critical point <sup>b</sup>	-	0.40	0.60
$W_{pf}$ * ( $W_{pf} = M * W_{crf}$ )	Fraction of water content at wilting point <sup>b</sup>	-	0.50	0.99
BD	Bulk density of soil (used in VIC estimation of porosity) <sup>b</sup>	Kg/m <sup>3</sup>	1350	1550
Ksat	Saturated hydraulic conductivity <sup>b</sup>	mm/day	240	840
Exp	Parameter characterizing the variation of saturated hydraulic conductivity with soil moisture <sup>b</sup>	-	10	30
d1	Thickness of first soil layer <sup>a</sup>	m	0.01	0.3
d2	Thickness of second soil layer <sup>a</sup>	m	0.31	3.5
d3	Thickness of third soil layer <sup>a</sup>	m	0.31	3.5
<b>dsmax</b>	<b>Max. velocity of baseflow<sup>a</sup></b>	<b>mm/day</b>	<b>10-4</b>	<b>10<sup>1.48</sup></b>
<b>ds</b>	<b>Fraction of max. velocity of baseflow<sup>a</sup></b>	-	<b>10-4</b>	<b>10<sup>0</sup></b>
<b>binf</b>	<b>Parameter to describe the Variable Infiltration Curve<sup>a</sup></b>	-	<b>10-4</b>	<b>10<sup>0.6</sup></b>
<b>ws</b>	<b>Fraction of maximum soil moisture of the third layer<sup>a</sup></b>	-	<b>10-4</b>	<b>10<sup>0</sup></b>
<b>Vegetation parameters</b>				
$r_{arc}$	Architectural Resistance <sup>b</sup>	(sm <sup>-1</sup> )	20	70
$r_{min}$	Minimum stomatal resistance <sup>b</sup>	(sm <sup>-1</sup> )	100	170
<b>routing</b>				
v	Flow velocity <sup>b</sup>	m/s	0.1	3
diff	Flow diffusivity <sup>b</sup>	m <sup>2</sup> /s	500	5000

865 \*  $W_{pf}$  is analyzed based on its multiplier (i.e., the  $M$  term in  $W_{pf}$  parameter's equation). Although description and units refer to actual parameter in VIC, parameter range represent the multiplier values (instead of actual parameter).  
 Parameter names in bold are sampled on log domain. "a" indicates parameters that are suggested by VIC model developers as the most sensitive parameters (Gao et al., 2010). "b" indicates parameters suggested in the literatures to be tested for sensitivity (Demaria et al., 2007; Gou et al., 2020; Joseph et al., 2018; Yanto et al., 2017).

870



**Table 2.** Percent of each Land use type in NRSC2005 and LUH2005 in the entire Mahanadi river basin (WB – Water Body; ENF – Evergreen Needleleaf Forest; DBF – deciduous Broadleaf Forest; GL- Grassland; CL- Cropland; U – Urban)

	LULC classes (%)	NRSC2005	LUH2005
875	WB	2.6	0.76
	ENF	0.08	0
	DBF	35.98	41
	GL	0.13	4.7
880	CL	49	53
	U	0.52	0.4
	BG	12.3	0

**Table 3:** Land cover area change across all subcatchments of Mahanadi river basin

LULC classes (%)	Baseline 2005	Present 2015	Near Future 2050	Far Future 2100	All Cropland	All Forest	All Grassland
<b>Basantpur</b>							
CL	40	54	69	78			
F	54	41	23	16			
GL	0	4.4	6.3	4.3	94	94	94
w	4.5	0.5	0.5	0.5			
U	0.5	0.6	1.2	1			
<b>Kantamal</b>							
CL	51	44	58	70			
F	44	51	33	25			
GL	0	5.3	7.6	5	95	95	95
w	5.4	0	0	0			
U	0	0	0	0.8			
<b>Kesinga</b>							
CL	44	50	62	73			
F	50	45	30	22			
GL	0	5	7	5	94	94	94
w	5.4	0.1	0.1	0			
U	0	0	0.8	0.6			
<b>Salebhata</b>							
CL	29	67	77	83			
F	50	29	17	15			
GL	0	3.5	4.3	2	79	79	79
w	5	0	0	0			



885

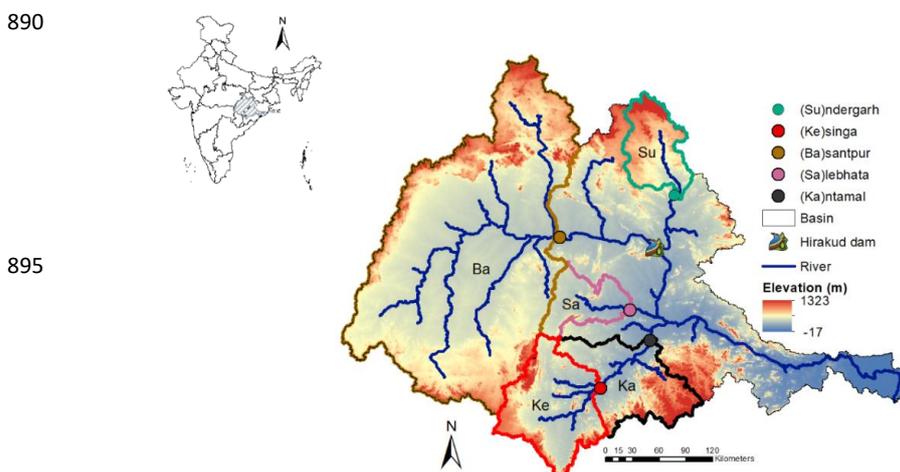
U	0	0	0.7	0.5			
Sundergarh							
CL	34	61	73	83			
F	61	34	19	11			
GL	0	0.5	7.1	5	95	95	95
w	3.5	0	0	0			
U	0	0	0.5	0.5			

**Table 4** Ranges of percent change, change in flows, and uncertainty (i.e., difference between max. and min. predicted flow) in extreme and mean annual flows in all the scenarios with respect to the baseline scenario.

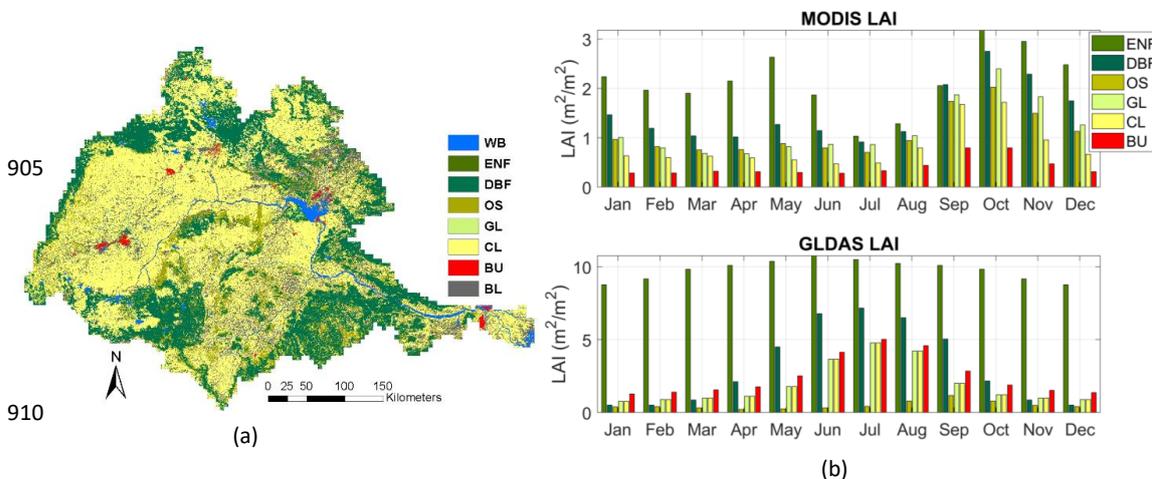
Mean annual extreme	Ba	Ka	Ke	Su	Sa
<b>Near future</b>					
Change (%)	2.3 to 5.5	1.4 to 4.7	1.3 to 2.7	4.7 to 10.7	2.7 to 4.3
change (cumecs)	132 to 289	62 to 166	42 to 77	32 to 75	27 to 41
Uncertainty(cumecs)	157	104	36	41	14
<b>Far future</b>					
Change (%)	2.4 to 6.5	1.4 to 5.6	1.6 to 3.5	6 to 15.4	3 to 4.7
change (cumecs)	137 to 347	63 to 195	51 to 100	42 to 109	28 to 45
Uncertainty(cumecs)	210	132	49	67	17
<b>Cropland</b>					
Change (%)	2.4 to 1.2	1.2 to 8.6	2.1 to 5.7	6.5 to 20.5	5 to 8.5
change (cumecs)	124 to 496	51 to 301	67 to 164	45 to 147	49 to 81
Uncertainty(cumecs)	372	250	97	102	32
<b>Forest</b>					
Change (%)	-4 to -14.4	-2 to -11.4	-2.6 to -6.6	-15.8 to -41	-13.5 to -22
change (cumecs)	-218 to -712	-85 to -400	-86 to -190	-109 to -289	-131 to -213
Uncertainty(cumecs)	494	315	104	180	82
Mean annual flows	Ba	Ka	Ke	Sa	Su
<b>Near future</b>					
Change (%)	3.7 to 7.6	2.5 to 6.13	2.4 to 4.2	4.9 to 9.7	3.4 to 4.6
change (cumecs)	21 to 31	8.6 to 16	5.2 to 7.5	34 to 61	2.6 to 3.3
Uncertainty(cumecs)	10	7.4	2.3	27	0.7
<b>Far future</b>					
Change (%)	3.4 to 7.9	2.12 to 6.5	3.4 to 4.6	6 to 13.2	3.24 to 4.6
change (cumecs)	19 to 32.6	7.3 to 16.8	5 to 8.8	4 to 8.3	2.4 to 3.3
Uncertainty(cumecs)	13.6	9.5	3.8	4.3	0.9
<b>Cropland</b>					
Change (%)	2.8 to 8.5	1 to 7.7	2.1 to 5.6	6 to 16	4.1 to 6.6



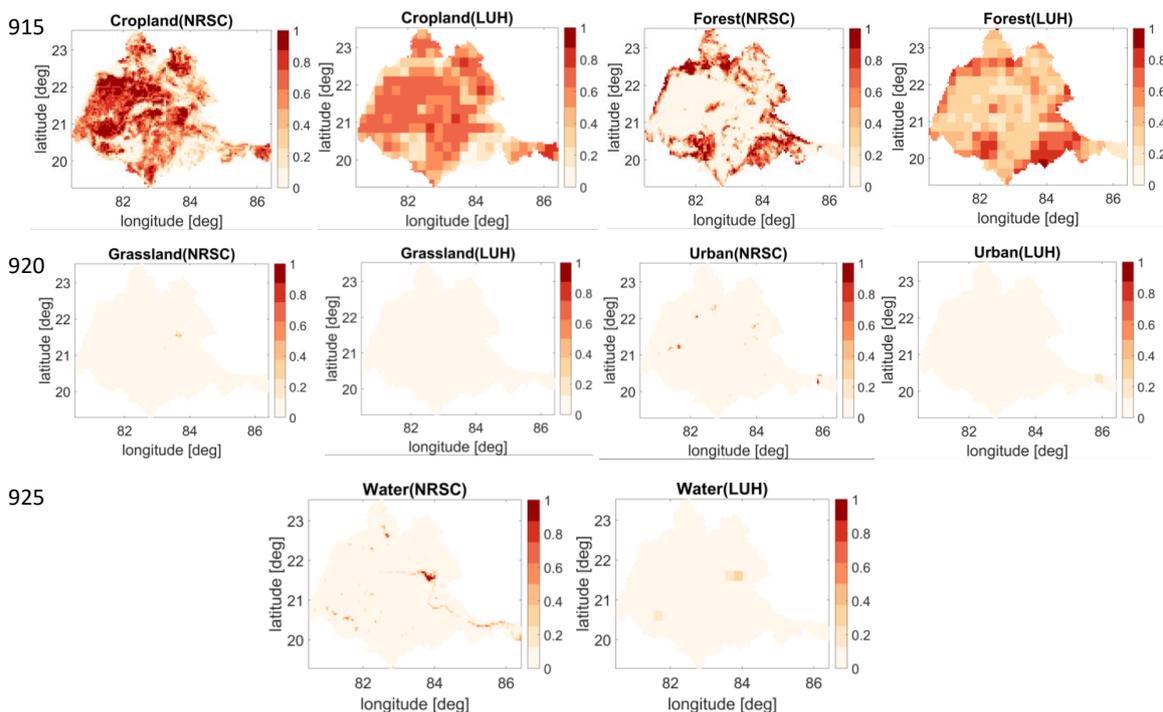
change (cumecs)	15.6 to 35	3.4 to 20	4.7 to 12	4.2 to 10	3.1 to 5
Uncertainty(cumecs)	19.4	16.6	7.3	5.8	2
<b>Forest</b>					
Change (%)	-4.6 to -14.34	-2.4 to -11.1	-2.9 to -7.2	-14.5 to -34.2	-12 to -18.6
change (cumecs)	-26.2 to -59	-8.2 to -29	-6.4 to -15.8	-10.2 to -21.3	-9.1 to -13.3
Uncertainty(cumecs)	33	20.8	9.4	11	4.2



890  
 895  
**Figure 1:** The Mahanadi river basin boundary and its subcatchments Basantpur, Kantamal, Kesinga, Sundergarh and Salebhata (indicated with Ba, Ka, Ke, Su, Sa respectively).



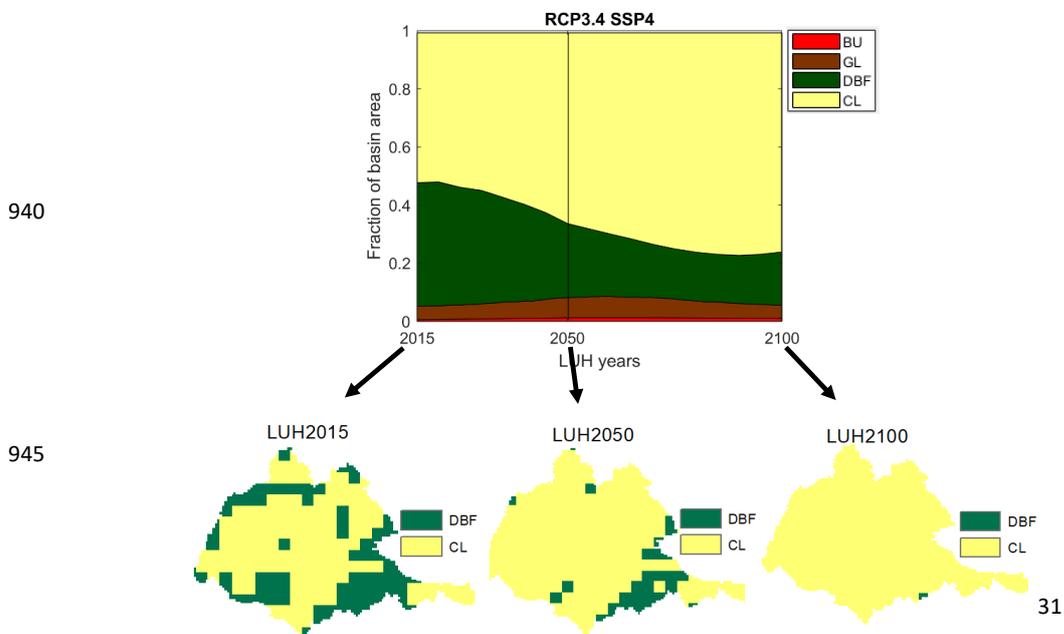
905  
 910  
**Figure 2:** (a) LULC map of Mahanadi River basin from NRSC of year 2005 (b) Comparison of LAI values from MODIS, averaged over the time period, 2000-2015 and GLDAS.



930

**Figure 3.** Comparison of spatial patterns of land cover types from NRSC and LUH for the baseline year, 2005. All land cover classes shown here are resampled to the model grid resolution of 5km. The color bar represents the fraction of area covered by each land cover type.

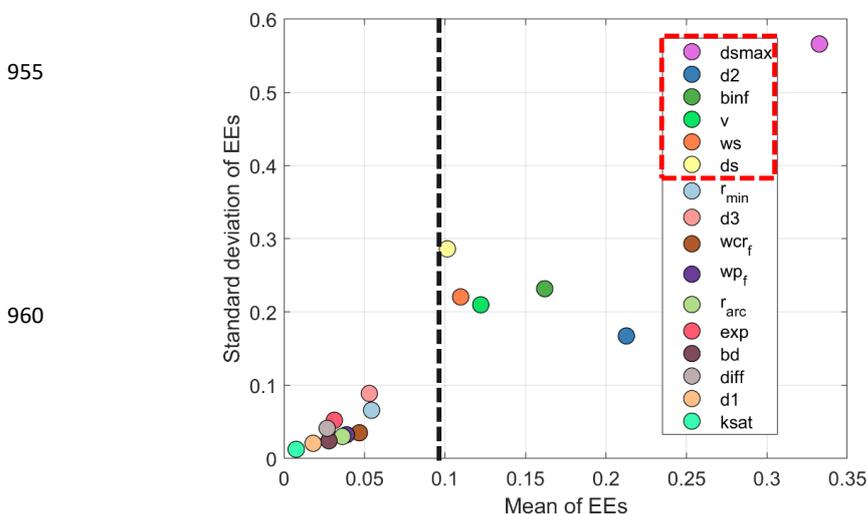
935



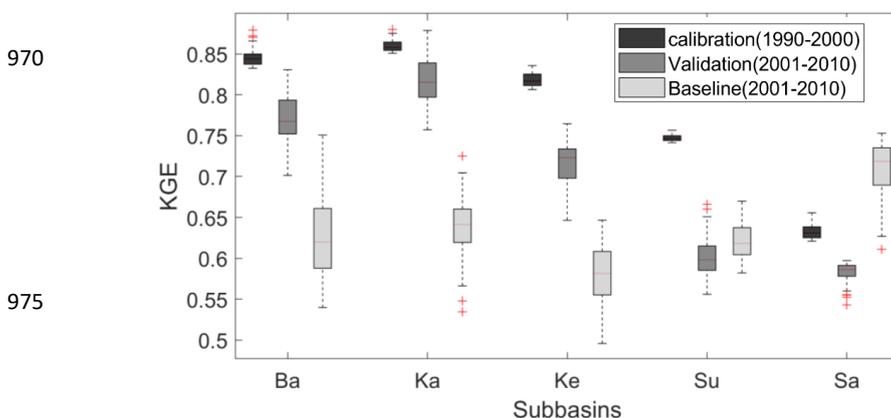
945



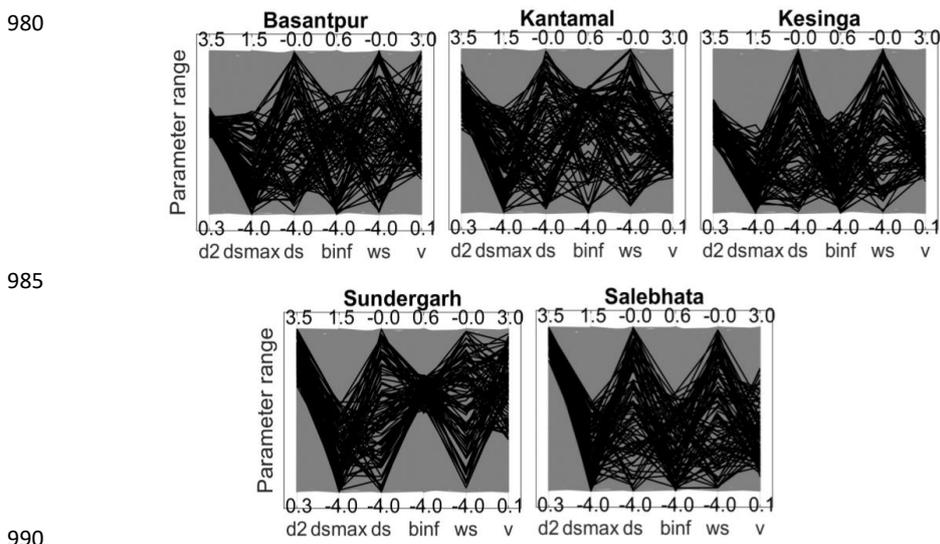
**Figure 4:** Top: Fraction of catchment area occupied by Land use classes for scenario RCP3.4 SSP4 Bottom: land cover scenarios from LUH (resolution- 25 km) for years 2015, 2050 and 2100 used in this study. LUH land cover classes shown here are resampled to the model grid resolution and only the predominant class is shown here for clarity. For actual model simulations VIC accounts for the individual proportion for each land cover type at each grid point.



**Figure 5:** Sensitivity indices (Mean and Standard deviation) of Morris Method for VIC-3L parameters for Mahanadi river basin. Parameters listed on the right side are from highest ranking (dsmax) to lowest ranking (ksat) order. Black dashed vertical line is the screening threshold. Parameters screened out are lying within the red dashed box.



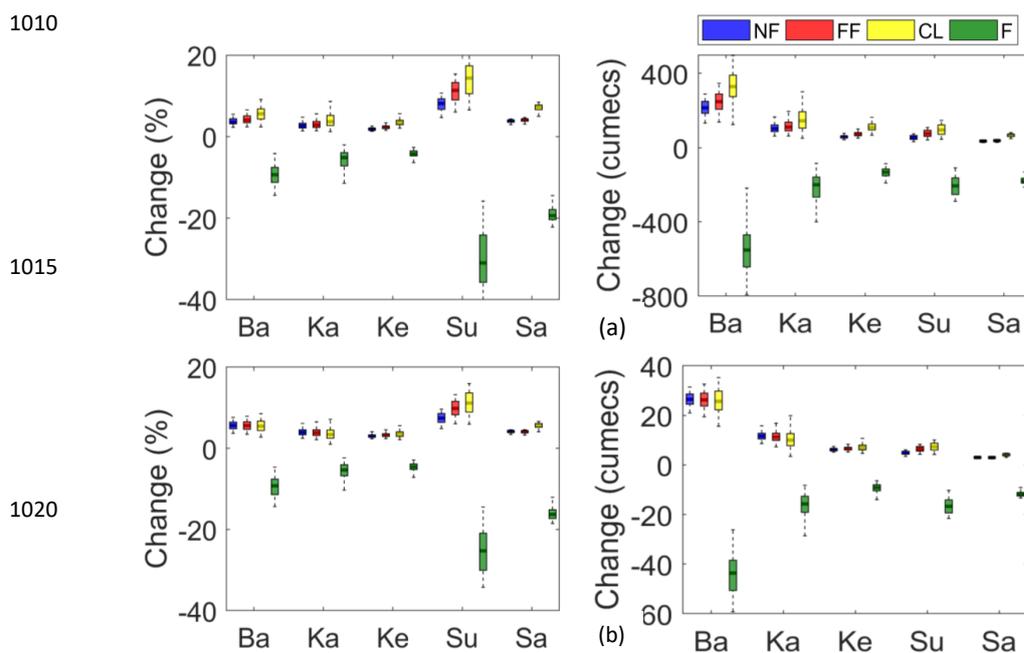
**Figure 6: (a)** Box plot showing KGE range for calibrated, validated and baseline scenario simulations.



**Figure 6: (b)** Parallel coordinate plot representing VIC-3L behavioural parameterization for all subcatchments obtained during model calibration. Lines in red are simulations where KGE lies within top 2% i.e., behavioural simulations and lines in grey are non-behavioural simulations. Behavioural KGE at Ba, Ka, Ke, Su and Sa ranges from 0.83 to 0.88, 0.85-0.88; 0.81-0.84; 0.74-0.76 and 0.62 to 0.66 respectively. Parameters are defined in Tables 1.

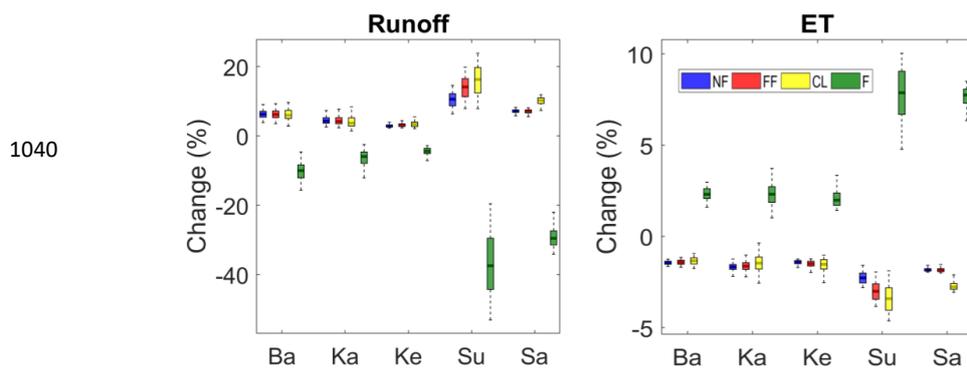
1000

1005



**Figure 7:** (a) (left) Percent change in extreme flows (i.e., 95th percentile or higher) (right) Change in extreme flows in cumecs (b) (left) Percent change in mean flows (right) Change in mean flows in cumecs, averaged annually over the time (2001-2010) in the Near future (NF), Far future (FF), Cropland (CL) and Forest (F) scenarios with respect to baseline scenario for all the subcatchments. Please note that the climate forcing is kept fixed for the period corresponding to year (2001-2010) The results are shown for the behavioural model simulations obtained through calibration.

1035



1040

1045

**Figure 8:** Percent change in (left) mean runoff (right) mean ET averaged annually over the time (2001-2010) in the Near future (NF), Far future (FF), Cropland (CL), Forest (F) scenarios with respect to baseline scenario for all the subcatchments. Please note that the climate forcing is kept fixed for the period corresponding to year (2001-2010). The results are shown for the behavioural model simulations obtained through calibration.

1050

1055

1060