Hydrological Impact Assessment due to Climate Change on Mahanadi Basin in India

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Abstract: The Mahanadi is one of the major rivers of India and among the peninsular rivers, in terms of water potential and flood producing capacity, it ranks second to the Godavari. The main objective of the study is to investigate the climate change related uncertainty in the estimation of extreme flood flows for the middle Mahanadi using a wide range of climate model scenarios. The historical trends of hydrological variables, such as number of rainy days, magnitude of intense rainfall and variation of runoff for four sub-basins of Mahanadi were detected using a non-parametric Mann-Kendall statistical test at 95\% significant level. The variation of rainfall shows that numbers of rainy days and total annual rainfall is decreasing. Kesinga sub-basin exhibited highest decrease in rainfall events in the Mahanadi basin. Analysis of daily rainfall indicated more frequent and larger-intense floods in the Mahanadi basin. Statistical downscaling approach has been applied for downscaling the precipitation data using change factor method. For downscaling, GCM data (RCP-2.6, 4.5 and 8.5) were downloaded from Environment Canada, Canadian Centre for Climate Modelling. Decadal rainfall projection shows that there is decrease in rainfall up to 35\% for some future projection scenarios. SWAT model has been calibrated and efficiency found to be varied between 63 to 82\% for different sub-basins using historical data. The future projections using SWAT model reveal that there is an increase in flood. Flow duration curves have been generated and the comparison of the 5\% dependable flows with the observed discharge (900 cumecs) and the SWAT simulated future discharges (1350cumecs) for RCP8.5 scenario indicate that there is a considerable increase in the extreme event floods at Kesinga during future time horizons. Similarly the comparison of the 10\% dependable flows based on the observed discharge and the SWAT simulated discharge also indicate considerable increase in the dependable flows. It is also found that the RCP-2.6 and RCP-4.5 show a moderate increase in the rainfall, whereas RCP-8.5 shows significant increase. It is also found that assured water availability (irrigation and drinking water) is decreasing for 75\% and 95\% dependable flow as per future projections of different scenarios.

Keywords: downscaling; flood; SWAT; change factor method

1. Introduction

It is widely recognized that hydrologic cycle will be intensified by increasing global temperatures, resulting from increased anthropogenic emissions of carbon dioxide. This will influence climate variables and will result in changes in climate. One of the expected consequences of climate change is increase in the magnitude and frequency of extreme hydrologic events (IPCC, 2007). The climate change impact assessments of extremes such as floods are of particular interest because floods usually have the greatest and most direct impact on our everyday lives, community and environment. Changes in the frequency of flooding events are expected and projected changes will have serious implications for planning, operation and design of water resources systems. However, quantifying the changes in extremes is subject to various sources of uncertainty and hence requires further investigation.

Assessment of climate change impacts on floods incorporates projection of climate variables into a global scale, downscaling of global scale climatic variables into local scale

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hydrologic variables and computations of risk of future extreme floods for purposes of water resources planning and management. Global scale climate variables are commonly projected by Coupled Atmosphere-Ocean Global Climate Models (AOGCMs), which provide a numerical representation of climate systems based on the physical, chemical and biological properties of their components and feedback interactions between these (IPCC, 2007).

A large number of hydrological and hydrodynamic models have been developed and performed in various applications such as flood routing, flood forecasting, water balance analysis, water quality modeling, hydro-climatological projections and extreme event analysis (Singh et al., 2017; Sun et al., 2016; Apurv et al., 2015). In the long term projections of hydrological variables, the coarse resolution GCMs cannot be directly coupled to hydrological models, because of the complexities involved in the coarse resolution GCMs and the simplification of the hydrological cycle. However, the downscaled GCM variables can be utilized as inputs to the hydrological and hydrodynamic models. Different downscaling methods have been developed to enhance the applicability of GCMs in highlighting smaller scale climatic variations. (Singh et al., 2017; Sun et al., 2016; Humphrey et al., 2016). Downscaling of the large scale GCMs variables can be performed in both spatial and temporal aspects with reference to local scale variables. According to Trzaska and Schnarr (2014), “Downscaling is a process that converts a large scale information (e.g. coarse resolution grid like 500×500 km²) to finer scale information (e.g. 50 ×50 km²)”. Downscaling can be utilized to convert coarser spatial resolution GCMs to any desired local grid cell (suppose 20 km², a higher resolution grid cell) or even at a specific point location (Shukla and Lettenmaier, 2013). Similarly, temporal downscaling can be referred to convert from coarser scale temporal GCM output (e.g. monthly precipitation) to finer scale GCM output (e.g. daily precipitation) (Xue et al., 2014). In climate modeling, there are two main categories of downscaling distinguished: (i) statistical/empirical downscaling (Wilby et al., 2014) and (ii) dynamical downscaling (Xue et al., 2014; Mishra et al., 2014; Shukla and Lettenmaier, 2013). The dynamical downscaling method has several numerical advantages over statistical modeling, while dynamical downscaling has found computationally intensive and requires a large amount of datasets and high level of manpower to interpret/produce results (Trzaska and Schnarr, 2014). Each downscaling method contains uncertainties and has their own limitations. No official guidance is available on downscaling or downscaling methods that best meet the user’s need. Therefore, the research community is still developing the downscaling methods.

There are few studies reported on global flood modelling under climate change. India has experienced several devastating climate extremes during recent decades. About 13.78% of India’s geographical area is subjected to flood disasters (Planning Commission 2011), and about 33 million people were affected by flooding from 1953 to 2000 (Kumar et al. 2005). Mumbai, India’s financial capital, received a record 944 mm rainfall on July 26, 2005, causing havoc and several casualties (Kumar et al. 2008). Impact of climate change on floods in India has been reported in many studies. Gosain et al. (2006 and 2011) modelled 12 river basins of India by using the SWAT model for control or present and GHG (greenhouse gases) or future climate scenario of simulated weather data of HadRM2. They reported that Godavari, Brahmani and Mahanadi may not have water shortage but predicted severe flood conditions. A few sub-basins of the Ganga, Brahmaputra, Krishna, Cauvery and Pennar show some decrease in the peak flow magnitudes. World Bank (2008) suggested that the probability of flood frequency and its intensity could increase dramatically in Mahanadi basin. The hydrological model projected daily outflow discharges at a gauge station (located

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in Naraj northwest of Jagatsinghpur) and results showed that under different scenarios, the probability of flooding will increase substantially. An increase of stream flow during 1956–2007 in the number of particular flood occurrences in Bahadurabad in the Brahmaputra River has been recorded (Climate Change Cell 2009). Dadhwal et al. (2010) reported an increase by 4.53% in the annual stream flow at the Mundali outlet in the Mahanadi basin attributed to a reduction in forest cover by 5.71% for the period 1972–2003.

The Soil and Water Assessment Tool (SWAT) developed by the USDA Agricultural Research Service (ARS) is a public domain and open-source integrated model and has been used worldwide for various applications. As a semi-distributed model, it allows the spatial variation of the parameters by dividing the basin into a number of sub-basins (Arnold et al., 1998; Srinivasan et al., 1998). SWAT model is widely used for climate change impact studies. Sood et al., 2013 reported the use of SWAT model to evaluate the impacts of a climate scenario based on IPCC A1B emissions on flows in the Volta River basin in West Africa for 2021–2050 and 2071–2100, using 1983–2012 as the reference period. Sun, et al., 2013 compared streamflow changes in the current years (1980–99) with the future (2030–49) and found that streamflow variations were more sensitive to changing climate in winter and spring than in the other two seasons.

Khalilian and Shahvari, 2019, studied the climate change impacts on runoff, aquifer infiltration, renewable water resources, and drought intensity in Salt Lake sub-basin, Iran, by the Soil and Water assessment tool (SWAT) model and the Standardized Precipitation Index (SPI) underA1B, A2, and B1 climatic scenarios. Githui et al., 2019 used SWAT model to investigate the impact of climatic change on streamflow of on the Nzoia catchment in the Lake Victoria basin in Kenya due to the changes in temperature and precipitation based on five GCM projections.

The study is concerned with the assessment of climate change impacts on floods in Mahanadi basin in India. The traditional way to address the problem is to develop climate scenarios from the GCMs and link the scenarios to a hydrological model from which peak flow values are extracted and analysed. In the investigation trend analysis has been proposed to examine the behavior of rainfall and runoff variables. Change factor method has been used for statistical downscaling of precipitation data. Subsequently, SWAT model has been used for the assessment of climate change impacts for the middle Mahanadi basin using a wide range of climate model scenarios.

2. Study Area and Data Availability

The Mahanadi is one of the major peninsular rivers of India draining into Bay of Bengal. It rises in a pool, 6 km from Pharsiya village near Nagri town in Raipur district of Chhattisgarh State at an elevation of 457 m. The Mahanadi splits into several streams just before falling into the Bay of Bengal (Figure 1). The total length of the river is about 851 km out of which 357 km is in Chhattisgarh and 494 km is in Orissa. The normal annual rainfall of the Mahanadi catchment is 141.7 cm. The maximum, minimum and the average annual weighted rainfall values are computed to be 3669.8 mm (Bulandarpura in 1944), 660.0 mm and 1458 mm respectively for the period from 1901 to 2008. The
Mahanadi Delta in Odisha has experienced several severe floods causing huge damages to life and property. An analysis of earlier historic flood events clearly reveals that even after construction of Hirakud Dam; the peak floods in the deltaic region are not reduced to a safe flood limit (24660 cumecs). This release combines with downstream contribution (Tel and its tributaries) and creates flood havoc at delta. In addition, a study on historic flood events in Mahanadi Delta (1969 to 2011) reveals that 69% major floods are caused due to contribution from downstream uncontrolled catchment beyond Hirakud reservoir up to Munduli (head of Mahanadi Delta), 23% were jointly due to contribution from Hirakud and its downstream catchment up to Munduli and another 8% major floods were caused due to contribution from Hirakud releases only. This shows that contributions from uncontrolled catchments beyond Hirakud up to Delta alone is sufficient to create flood havoc at delta, even if there is zero release from Hirakud reservoir. Therefore it is proposed to estimate hydrologic response under a changing climate. Middle Mahanadi basin, downstream of Hirakud dam comprises of Ong, Ib and Tel tributaries. Study area details are depicted in Fig.1 showing gauge and discharge sites. Daily discharge data maintained by Central Water Commission has been collected from following site Average gridded precipitation ($1^\circ \times 1^\circ$) from 1901 to 2004 has been purchase from Indian Meteorological Department, Pune and used for climate change investigation.

**Figure 1:** Map showing gauging site for Mahanadi basin

3. METHODOLOGY

**Mann Kendall Trend Analysis Test**

The non-parametric Mann-Kendall test which has been extensively used by many researchers (Taylor and Loﬁts, 1989; Burn, 1994 and Burn et al., 2004) has been used to identify the trends in the climatic variables, particularly the rainfall characteristics including the maximum dry spell lengths. One of the main considerations in applying this test is to identify whether the data is serially correlated and therefore the data series of various blocks

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were tested for serial correlation before applying the Mann-Kendall test. If the lag-1 autocorrelation \( r_1 \) is found to be non-significant at 95% confidence level, then the Mann-Kendall test is applied to the original data series \((x_1, x_2, \ldots, x_n)\), else the Mann-Kendall test is applied to the pre-whitened series obtained as \((x_2 - r_1x_1, x_3 - r_1x_2, \ldots, x_n - r_1x_{n-1})\) (Von Storch and Navarra, 1995 and Partal and Kahya, 2006).

**Statistical Downscaling**

Downscaling is a method for improving the spatial resolution of Global Climate Model (GCM) outputs. Two distinct groups of approaches can be followed for doing so. First group is known as the dynamic downscaling approach in which local physiographic information along with GCM boundary conditions are used to generate higher resolution Regional Climate Model (RCM) datasets. Another less computationally demanding approach for downscaling GCM data is known as statistical downscaling. It is based on the principle that regional data is dependent on large scale climate state as well as local physiographic features (IPCC, 2001). Historically observed climate variables are modified to include changes projected by climate models in future. These changes are incorporated into the observed data by using change factors (CFs) calculated from bias-corrected historical and future GCM data. CFs can be applied on different temporal scales (daily, monthly, seasonally or annually), can have different mathematical formulations (additive or multiplicative) and can vary in numbers (same or unique for different percentiles of a climate variable). Anandhi et al., 2011 gives a comprehensive overview of different change factor methodologies used in climate change impact studies.

**KnnCAD Version 4 Algorithm**

The weather generator of Eum and Simonovic (2008), KnnCAD V3 is a K-NN algorithm with principal component analysis in order to include multiple variables in the selection of the nearest neighbours. It was developed by Eum and Simonovic (2008) as an extension of the models of Sharif and Burn (2006), and Prodanovic and Simonovic (2008).

**SWAT Model Description**

The SWAT model is a watershed scale continuous-time model with a daily time step. SWAT is capable of simulating long-term yields for determining the effect of land-management practices (Arnold and Allen, 1999). There are many components of SWAT including hydrology, weather, soil temperature, crop growth, nutrients, pesticides, sediment yield, and agricultural management practices. The hydrological components of SWAT are based on the water balance equation applied to water movement through soil;

\[
SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_o - W_{seep} - Q_{gw})
\]

- \( SW_t \) = Soil water content at time \( t \);
- \( SW_0 \) = Initial soil water content;
- \( t \) = time (in days)
- \( R_{day} \) = amount of precipitation on day \( i \)
- \( Q_{surf} \) = amount of surface runoff on day \( i \)
- \( E_o \) = amount of evapotranspiration on day \( i \)
- \( W_{seep} \) = water percolation to the bottom of the soil profile on day \( i \)

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4. Results and Discussions

Spatial Interpolation of Observed gridded/GCM data
To predict a value for any unmeasured location, Inverse Distance weighted (IDW) uses the measured values surrounding the prediction location. The measured values closest to the prediction location have more influence on the predicted value than those farther away. IDW assumes that each measured point has a local influence that diminishes with distance. It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance, hence the name inverse distance weighted.

Trend analysis for discharge data
In the current investigation runoff data for gauging sites Sundergarh, Salebhata, Kesinga and Kantamal have been collected for the analysis. The nonparametric Mann-Kendall s test, was used to detect trends in runoff. Before applying the Mann-Kendall test, the data series were tested for serial correlation. If the lag-1 auto-correlation ($r_1$) was found to be non-significant at 95% confidence level, then the Mann-Kendall test was applied to the original data series ($x_1, x_2, \ldots, x_n$), otherwise the Mann-Kendall test was applied to the pre-whitened series obtained as ($x_2 - r_1x_1, x_3 - r_1x_2, \ldots, x_n - r_1x_{n-1}$). From the analysis, it is observed that Tel tributary (Kesinga and Kantamal gauging site) is experiencing increasing trend whereas Ong tributary (Salebhata gauging site) is experiencing decreasing trend.

Trend analysis for precipitation data
In this analysis MK test for the precipitation trend for period from 1961-2004 for four stations are carried out using spatially interpolated precipitation data. There is no significant statistical trend observed for daily and monthly precipitation data. During the non-monsoon season decreasing trend is observed for all stations but these are not significant. From the analysis, it is observed that the total numbers of rainy days are decreasing over the years and Kesinga sub-basin observed highest decrease in rainfall events in the Mahanadi basin. Analysis has been carried out, estimating number of rainfall events for four sub-basins for 50, 75, 100 mm intensity of rainfall and it is found that the both intense and less intense rainy days are increasing in the Mahanadi river catchment for all sub-basins except 1b sub-basin. In Sundergarh there is a slight decrease in the rainfall events for all intensities considered. This resulted in the increased dry spells within the catchment. From this analysis it is evident that though there is decrease in number of rainy days, rainfall intensity is increasing over Tel river basin. It may be noted that increasing trend is observed for discharge data for Kesinga and Kantamal gauging site.

Dynamically Downscaled RCM Data for Mahanadi Basin

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The CFM, or delta change factor method, is combined with KnnCAD to obtain climate change projections in the future period 2006–2049 and to evaluate the future performance of KnnCAD. CFM is a very common method for estimating climate change (Anandhi et al., 2011). Although more complicated methods exist, CFM is still widely applied in many studies. The newest representative concentration pathway (RCP) scenarios are used in this study. Each RCP is named after the level of radiative forcing, or overall warming power of human activities. In the investigation Environment Canada data from Canadian Centre for Climate Modelling and Analysis of model CanESM2, R1, R2, R3, R4, R5 of grid size (256 X 192) km downloaded. Data consists of historical data (1950 – 2005) and future projection 2006 - 2100 (e.g., RCP 2.6, 4.5, 8.5 Scenario). In this study, Change Factor Methodology (CFM) has been implemented for downscaling rainfall data from future time scale from year 2006 to 2049. Combinations of 75 GCM outputs have been used for downscaling rainfall data for four sub-basins of Mahanadi river.

Analysis has been conducted to see the variation of downscaled precipitation data for four sub-basins of Mahanadi river. It is worth mentioning that no variation is observed for daily, monthly and annual scale during the future projection period. A decadal variation of rainfall analysis has been future projection (2006-49) period and found that there is change in rainfall quantity. 10 to 32 % increase in rainfall is found for different RCPs in the mid-century period. The decadal rainfall variations for different RCPs for one scenario are presented in Fig 2. From the analysis it is found that there is increase in 10 % for low emission scenario but rainfall is increasing 32% for for RCP8.5.

![Fig 2: Plot for CanESM2_1960_2005_R1 & CanESM2_2006_2100_R1_RCP2.6 (X-axis: decadal year starting from 2006 and Y-axis: rainfall in mm)](image)

**SWAT model Application to Mahanadi Basin**

The SWAT model has been setup for Mahanadi basin with the inputs of DEM, land use, soil type, and climatic datasets. Topographic information were derived using Digital Elevation Model (DEM) data (the SRTM DEM have been used). The soil data available in NBSS&LUP, which contains soil maps at a 1:250,000 scale. Calibration of the model was
done by adopting the manual calibration procedure. The high resolution \((1^\circ \times 1^\circ)\) precipitation and temperature \((1^\circ \times 1^\circ)\) prepared by IMD (Rajeevan et al, 2006) has been used for providing the climatic inputs to the model. In the analysis, 5 years data has been used for warming up of SWAT model. Calibration of data for different gauging site such as Kantamal (1978 -2000), Kesinga (1983-1990), Salebhata (1978-1985) and Sundergarh (1983-1992) and rest of the data used for validation. It can be observed that the model has been well calibrated and the simulated flows closely follow the observed flows at all the tributaries as well as on the main river after taking into effect the storages in the dams and routing through the reservoirs and rivers. The measure of efficiency as expressed by Nash- Sutcliffe Goodness of fit at the various gauging sites during calibration is calculated. The efficiency varies between 68% at Salebhata to 82% at Kesinga, which can be considered to be reasonably good calibration.

![Graphs showing observed and computed discharges for various locations](image)

**Fig 3:** Observed and simulated flows during calibration period

Once the model has been calibrated effectively, the model needs to be validated with the independent data sets with the new climate data sets. The model has therefore been validated with the independent data set spanning 2001-05. The comparison of the observed and simulated flows during calibration period are presented in Figure 3. This model which has been calibrated and validated can now be used for the assessment of climate change impacts on water resources.

**Future Water Resources Scenario in Mahanadi Basin**

The variables pertaining to the maximum temperature, minimum temperature, and precipitation, projected for the future, have been used in the calibrated and validated SWAT model for Mahanadai basin at four gauging site. The SWAT model has been run with the

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alternate climate scenarios from the combination of RCM’s for the low emission scenario (RCP2.6) to high emission scenario (RCP8.5). The simulated outflows obtained from the SWAT model under these alternate climate scenarios have been analyzed further to detect the changes in the extreme events and water availability in the basin. The dependable flow analysis have been performed by fitting an empirical distribution (Weibull, 1951) to the simulated flows, and the dependable flows at 5%, 10%, 20%, 50%, 75%, 90% and 95% dependability have been identified. The dependable flows corresponding to 5% and 10% dependability are indicative of the extreme flood events, 50% dependability indicates the median flow, 75% dependable flow corresponds to the water availability for agriculture, and higher dependable flows corresponds the water availability for domestic drinking requirement. The comparison of the annual dependable flows at gauging sites, generated by the different RCM based SWAT simulations for RCP4.5 (low emission scenario) during the time horizons of 2006-40, 2041-70 and 2071-99, for Kesinga sub-basin is given in Figures 4. It can be observed that all RCMs simulate the dependable flows in comparable range.

**Fig 4:** Future Water Resources Scenario – Dependable Flows at Kesinga

From the analysis it is found that the comparison of the 5% dependable flows with different RCM simulated discharges for RCP8.5 scenario indicate that there is a considerable increase in the extreme event floods at for all the gauging sites during future time horizon. Similarly the comparison of the 10% dependable flows based on the RCM simulated discharge also indicate considerable decrease in the dependable flows. The dependable flow analysis based on model simulations for the future time horizons indicated that the magnitude of the flood events are expected to increase substantially in comparison to observed historic floods. All
the RCP scenarios show that there is an increase in intensities in the future. It is shown that the RCP-2.6 and RCP-4.5 show moderate increase in the intensities, whereas RCP-8.5 shows significant increase.

5. Summary and Conclusions

In the present study a statistical trend analysis (MK test) for the precipitation and runoff time series was carried out for Mahanadi river basin of Odisha. It was found that there is significant correlation in runoff data so pre-whitened series was obtained and then subjected to Mann- Kendall’s test. Daily discharge trends are analyzed for different gauging site and it is observed that Tel tributary is experiencing increasing trend whereas Ong tributary is experiencing decreasing trend. Daily, monthly and seasonal rainfall trends were analyzed for the period between 1961 and 2001. No trend is found for daily and monthly rainfall data but there is significant evidence of decreasing in precipitation during monsoon period for two stations (Salebhata and Sundergarh) in the catchment area using MK test. During the non-monsoon season decreasing trend is observed for all stations but these are not significant. Variation of rainfall shows that numbers of rainy days and total annual rainfall is decreasing. The total numbers of rainy days are decreasing over the years and Kesinga sub-basin observed highest decrease in rainfall events in the Mahanadi basin. From the analysis, it is found that though there is decrease in number of rainy days simultaneously rainfall intensity is increasing over Tel river basin. The precipitation data has been downscaled using delta change factor method, is combined with KnnCAD to obtain climate change projections in the future period 2006–2149 and to evaluate the future performance of KnnCAD. Decadal analysis of projected rainfall shows that there is decrease in rainfall for some scenarios 10 to 32%. SWAT has been applied for four sub-basin and analysis is used to generate future scenarios using downscaled data. SWAT model simulation shows that the increase in the extreme rainfall events will get translated into floods in Mahanadi basin. The dependable flow analysis based on model simulations for the future time horizons indicated that the magnitude of the flood events are expected to increase substantially in comparison to observed historic floods. It is observed from the results that the quantile based mapping approach is able to capture the statistical relationship between the GCM maximums and the observed subdaily maximums. Further, the modeling approach is also able to capture the changes in intensities between the current time period and future time period. All the RCP scenarios show that there is an increase in intensities of rainfall in the future. It is shown that the RCP-2.6 and RCP-4.5 show moderate increase in the intensities, whereas RCP-8.5 shows significant increase. The percentage increase in the extreme intensities is relatively higher for smaller return periods.

References


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