Applications of Hydrological Model Simulated Long Term Water Balance Components for India

Saksham Joshi[1], Venkat Raju Pokkuluri[1], Annie Issac[1], Venkateshwar Rao[1], Pamaraju Venkata Rao[1], and VINAY DHADWAL[2]

[1]National Remote Sensing Centre
[2]Indian Institute of Space Science and Technology

July 8, 2020

Abstract

Hydrological models are useful tools for simulating long-term trends in hydrological components resulting from climate and anthropogenic factors. In the present study, long-term hydrological components are simulated using Variable Infiltration Capacity – VIC, a process based model for the time period of 1971-2013 at a resolution of 5.5 km for entire India. The model was calibrated and validated against observed streamflow for all the southern river basins. The simulated soil moisture was also evaluated using in situ observations. It is observed that there is a slight increase in precipitation for Cauvery, Krishna, Ganga and Godavari basins. The model derived soil moisture was converted into percentage available soil moisture (PASM) taking into account of water holding characteristics of soils, which is depicting a good agreement in time and space. Floods and its return period were reconstructed and analyzed by calculating basin wise annual maximum streamflow for the entire period. This modeling framework is developed for the entire country which will contribute towards evaluating and planning for water resources management, its retrospective outlook, mitigating drought, periodic water budgeting, agriculture planning, and irrigation scheduling.

Applications of Hydrological Model Simulated Long Term Water Balance Components for India

Long Term Water Balance Components for India

Keywords: VIC Model, Flood, Soil Moisture, Surface Runoff, Drought, Hydrological Modeling

Abstract

Hydrological models are useful tools for simulating long-term trends in hydrological components resulting from climate and anthropogenic factors. In the present study, long-term hydrological components are simulated using Variable Infiltration Capacity – VIC, a process based model for the time period of 1971-2013 at a resolution of 5.5 km for entire India. The model was calibrated and validated against observed streamflow for all the southern river basins. The simulated soil moisture was also evaluated using in situ observations. It is observed that there is a slight increase in precipitation for Cauvery, Krishna, Ganga and Godavari basins. The model derived soil moisture was converted into percentage available soil moisture (PASM) taking into account of water holding characteristics of soils, which is depicting a good agreement in time and space. Floods and its return period were reconstructed and analyzed by calculating basin wise annual maximum streamflow for the entire period. This modeling framework is developed for the entire country which will contribute towards evaluating and planning for water resources management, its retrospective outlook, mitigating drought, periodic water budgeting, agriculture planning, and irrigation scheduling.

1 Introduction

India is the seventh largest country in the world in geographical area (Encyclopedia, Britanica), with fifteen unique agro climatic zones (Rai et.al, 2008). The country experiences, spatial and temporal variations of rainfall and temperature owing to the three varying climatic regimes in the country and the inherent intra-seasonal variability of the monsoon (Murari.L, 2005; Krishnamurthy V. and Shukla J.2000). These variations in climatology had resulted in occurrences of flood and drought events which adversely affect the agriculture sector (Singh et.al. 2011) of the country, which is the livelihood of 60% of population of the country (Census India, 2011)

India had experienced many drought and flood events in the recent past (De.et.al, 2005, Haider.et.al, 2019). Ganga, Brahmaputra, Godavari, Tapi and Mahanadi are the major flood prone river basins in the country (Das et.al, 2007). Occurrence of a flood event is dependent on the natural causes like intensity of rainfall, antecedent soil moisture conditions, topography, and anthropogenic causes like deforestation, poor land use practices, urbanization, etc (Tingsanchali, 2012). The eastern part of the country falling in the Brahmaputra basin, with steep terrain and high intensity of rainfall experiences frequent river flood events (NHC, Background Paper, 2006). Between 1996 and 2005, the annual flood damage is Rs. 4745 crores as compared to Rs 1805 crores which is average for the time period of 1955-2008 (NDMA, Report 2008).

Droughts are long duration disaster, which causes more life and property losses as compared to the short duration flood events. Drought is a natural phenomenon caused by below-normal precipitation over a prolonged period (Tallaksen and van Lanen 2004,Wilhite 2000, Mishra and Singh 2010). Below-normal water availability in rivers, lakes and reservoirs can cause water scarcity in combination with water demand, threatening water supply and associated food production (Döll et al 2009, Wisser et al 2010), this adverse impact cannot be compensated by the good or excess rainfall. India recorded 25 major drought years between 1871-2015 (Drought Manual 2016)

Hydrological models describe hydrological mechanism and rainfall-runoff response with spatial precipitation input for the defined terrain, land cover and soil conditions (Clark et. al. 2017, Sitterson et.al. 2017, Yin et. al 2018). The enhanced computation capabilities and availability of long term meteorological data in gridded format facilitated simulation of water balance components (WBCs) by hydrological models over longer time period at varying spatial resolutions. Hydrological model simulations based data sets, overcome the limitations of availability of data in time and space posed by the traditional observation based data sets (Lee et.al. 2017). Hydrological model simulated long term data sets of water balance components are very useful in the identification of historic extreme events like droughts and floods, which in turn provide basis for prediction of seasonal drought and flood events (Lee et.al. 2017, Etienne et.al. 2016, Hao et.al. 2016, Livneh et.al. 2016). The spatial map of long term average overland runoff can be used in the identification of flood vulnerable areas of the country (Zheng et. al 2008, Zaharia et.al 2015). The frequency analysis of the long term river discharge data gives information on the flood magnitudes and the associated return periods which is very necessary information for the development of the river basins (Tanaka et. al. 2016, Machado et. al 2015).The spatial and temporal distribution of soil moisture in relation to the corresponding of vegetation, topography, soil properties, and precipitation gives a spatial variability of the drought across the country (Famiglietti et al. 1999).

In this study long term (1971-2013) simulations of Variable Infiltration Capacity (VIC) model for India at a spatial resolution of 1/20° has been used to understand the long term variation in the climate hydrology over the country. The study also aims at the investigation of the historical drought and flood events based on simulated WBCs for India.Climate change is impacting hydrological dynamics, with a general tendency to amplify hydrological extremes like floods and drought (Fischer et al, 2016, Schleussner et al, 2017) in the recent past. The hydrological response to climate change is generally predicted using downscaled future climate projections to drive a hydrological model (Chiew et al., 2009; Teng et al., 2012, Zheng et.al 2009). An understanding of the variation in trends of the WBCs in spatial and temporal scales in the historical years will enhance the interpretation and information retrieval from the simulations for the future years.

2 Data and Methodology

2.1 Study Area

The study focuses on entire India, with all its river basins, excluding the trans- boundary areas of basins like Indus, Ganga and Brahmaputra situated in the north of the equator between 8°4' and 37°6' north latitude and 68°7' and 97°25' east longitude. The total geographical area of the country is 3,287,263 sq. Km and is divided into 23 river basins as seen in Figure 1.The country has a diverse topography varying from low lying coastal areas to elevated mountainous terrain. The elevation varies within a range of -2m to 8586 m above MSL. The country has 15 agroclimatic zones, varying from mountains (Himalayan region), Plains and Plateaus (Gangetic and Central), Desert and Coastal Regions. The river network over this terrain with a varying profile is dense with multiple reservoirs. Many rivers pass through tropical zone and are subjected to cyclonic storms and seasonal rainfall.

Figure1: River Basins of India

India experiences tropical monsoon climate, south, west, central and northern parts of India experiences frequent rains during south-west monsoon season. The eastern part of the country receives majority of its rainfall from north east monsoon (Guhathakurtha and Rajeevan 2008, Mondal et. al 2015). The maximum precipitation is usually observed in the months of July, August and first half of September. India receives 75-80% of rainfall during the monsoon season from June to September (Kakade and Kulkarni, 2017) and remaining during the north east monsoon months of October to December. This spatial and temporal non uniformity in rainfall calls for a national level study of water balance components for its utilisation in water resources management.

There is diverse spatial variation of temperature within a season (Roy, 2019). The year's coldest months are December and January, when the mean temperature in the north-west is around 10-15° C where as it increases to 20-25° C towards south- east part of India. In the hottest months the temperature varies around 32-40° C in most of the interior part of the country, where as in the arid regions of Rajasthan temperature peaks up to 45-50° C.

As India is agriculture dominant country, crop lands form the dominant land cover covering over 80% of the geographical area. Other dominant land covers are forest, urban areas etc (Roy and Giriraj, 2008). The country predominantly has clayey and loamy soil textures along with other textures like sandy clay loam and silty clay loam (Dharumarajan et.al. 2019).

2.2 VIC Model

VIC is a macro scale semi-distributed process based hydrological model that simulates the energy and water budgets, with the major hydrologic flux terms like evapotranspiration and state variables like soil moisture simulated at daily time step (Liang et. al, 1994). The study area was divided into grids, where the sub grid heterogeneity in the land cover classes is defined. The seasonal variation in the vegetation land cover class is characterized by the definition of monthly leaf area index (LAI), albedo and canopy resistance. The model estimates the reference potential evapotranspiration (ETo) for the meteorological input using Modified Penman Montieth (FAO-56) equation. For every grid the weighted average of the sum of canopy evaporation, crop transpiration and soil evaporation for different land cover classes gives the total evapotranspiration.

VIC model employs the structure of Xinaniang model for computation of infiltration and runoff (Zhao et.al. 1980, Ren-Jun Z. 1992). The model is called so as it assumes the infiltration capacity to vary within an area depending on the fraction of soil that is saturated. The model facilitates the definition of the sub surface soil profile in multiple layers. Each layer can be characterized by the soil hydraulic properties like bulk density, saturated hydraulic conductivity, permanent wilting point, field capacity etc, derived from the textural classification of the soil (Saxton and Rawls, 2006). The subsurface runoff is estimated in the model by Arno model (Francini and Paccini, 1991), which models situations of substantial subsurface storm flow by non- linear drainage. The model estimated runoff and base flow are routed to stream network and discharge is estimated at an outlet.

VIC model has been extensively used for hydrologic budgeting studies at water shed, regional, continental and global scales (Abdullah and Lettenmier 1997, Adam and Lettenmier 2008, Su et. al 2005, Tan et. al 2011, Hamman et. al 2016, Nijssen et. al 2001 a,b,c, Sheffield et. al 2009). VIC derived hydrologic fluxes and state variables are extensively used in the analysis of flood and drought conditions (Hamman et. al, 2018). VIC model is also used in the impact studies of climate change on hydrologic cycle.

2.3 Geospatial and Meteorological Data

The geospatial datasets used in the model development are summarized in Table 1. The observation based daily forcing from 1971 to 2013 was adopted from IMD data sets to drive the VIC model. The grid based IMD meteorological data included precipitation, minimum temperature and maximum temperature. The 0.25° x 0.25° gridded precipitation data covering the period of 1901 to 2015 was derived from 6995 rain gauge stations in India and interpolated by inverse distance weighted interpolation (IDW) (Pai et. al. 2014). The 1° x 1° gridded temperature data was derived from the observations from 395 quality controlled stations and interpolated by a modified version of the Shepard's angular distance weighting algorithm (Srivastava et. al 2009).

Table 1: Geospatial and Meteorological Datasets

2.4 Model Development and Calibration

Geographical framework setup at 3min (˜5.5km) grid level has been established for the entire India using VIC model version 4.1 (VIC-3L), which has been configured in Linux environment and model computations were carried out in water balance mode at daily time-step for the time period of 1971-2013. The outputs from model are surface runoff, evapotranspiration, baseflow, and layer-wise soil moisture and energy fluxes. Grid wise generated runoff and baseflow are routed through river drainage network to estimate daily discharge at basin outlet at daily time step (Lohmann D. et.al. 1996, Lohmann D et. al 1998). Simulated daily discharges are susceptible to errors due to inherent assumptions about travel times that must be made in the stream flow naturalization process, therefore the stream flows resulting from the routing model were accumulated to 10 day totals to minimize the effects of channel routing errors (Abdulla et. al 1996).

VIC-3L model has been optimized to obtain best agreement between model computed runoff and field observed discharge data with model specified calibration parameters. The model was calibrated for the time period of 1976-1985, at a ten daily time step. The uncalibrated model simulated discharge was compared with the observed discharges. A step by step modification of the model specified calibration parameters, was carried out with the objective function of maximising the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970).

Figure 2 shows observed and calibrated model simulated river discharge for the calibration period in Godavari, Mahanadi, Narmada, Subarnarekha, Baitarani & Brahmani, Mahi, Krishna and Tapi river basins. Ganga, Brahmaputra and Indus being transboundary rivers the observed data is restricted for public use therefore calibration is not showcased in this paper.

Model performance for the ten daily stream flow simulation is summarized in Table 2. A well calibrated model typically yields a NSE greater than 0.80 (Henriksen et al., 2008). In the study, Godavari, Mahanadi, Narmada and Subernarekhabasins was classified in "very good" performance status, Baitarani & Brahmani and Mahi performed fair whereas Tapi and Krishna are categorized in poor status. The poor performance can be attributed to the higher abstraction by reservoirs which is not accounted in the model.

Table 2: Basin Wise NSE Coefficient

Figure 2: Observed and Model Simulated River Discharge for the Calibration Period

2.5 Validation of State Variables and Hydrologic Fluxes

Soil moisture (SM) is the most relevant state variable which can be used as indicator of hydrologic conditions. The model simulated soil moisture for a soil column of 500 mm is validated with field observed soil moisture measured for the year 2013. Soil moisture data uniformly distributed over space for 130 locations (Figure 3) were compared with the VIC generated SM, for the entire column (500mm) of soil.

Figure 3: Soil Moisture Measurements across India

Pearson Correlation Coefficient (R^2) was used as an evaluation index for soil moisture and ET. Pearson Correlation coefficient shows the relationship between two variables and is also a suitable measure of its linear dependence. Pearson Correlation Coefficient ranges from -1 to 1. A correlation coefficient between .5 to 1.0 or -0.5 to -1.0, indicates a high correlation, whereas 0.3 to 0.5 or -0.3 to -0.5 and 0.1 to 0.3 or -0.1 to -0.3 represents medium and low correlations respectively (Sensue et.al.2015).

Model generated soil moisture is in good match with the field observed soil moisture on a day of spatially uniformly distributed rainfall as seen in Figure 4(a) with an R^2 value of 0.69. On the other hand on the day of regionalized rainfall the model simulated values had deviation from the observed values as seen in Figure 4(b) with an R^2 of 0.306. This variation in the correlation between model estimated and field observed soil moisture values can be attributed to the higher accuracy of precipitation data on a rainy day in comparison to a dry day.

Figure 4: Comparison of Field observed field SM with VIC modeled SM for entire column (a) uniformly distributed rainfall (b) regionalized rainfall (c) Over Agriculture (d) Over Non-agriculture

Figure 4(c) and (d) depicts the variation of soil moisture at two station points located in an agricultural and non-agricultural area respectively, with respect to time. In both the cases, the trend of temporal variation of model derived soil moisture is same as that of the field observed soil moisture. The only hydrological forcing for the estimation of fluxes in the current study is precipitation, neglecting other interventions like irrigation; hence there will be an underestimation of soil moisture values in an agricultural area as compared to non-agricultural area.

The major hydrological flux derived from the model is Evapotranspiration (ET). The model simulated ET values are validated with Flux tower ET measurements recorded over deciduous forest (Betul, India) and cotton agriculture field (Nagpur, India). The flux tower ET daily data wasobtained from National Remote Sensing Centre available from December, 2011 to May 2017 over forest land class, whereas from April to September, 2019 over agriculture land class.Weekly estimates of flux tower data were compared with model computed ET to assess the model performance with respect to simulations of ET. A scatter plot (figure 5) represents the Model-ET against measured ET over both land cover class. The model simulated ET had a higher correlation coeffient of 0.58 and 0.73 over forest and agriculture land class respectively.

Figure 5: Comparison of Flux Tower ET Measurements with VIC Model derived ET over (a) Forest (b) Agriculture Field

3 Result and discussion

In this section, the VIC model simulated long term hydrological records were used to investigate three areas: (1) Variation in climate hydrology between two historical periods; (2) Generating soil moisture stress scenarios using percentage available soil moisture index (PASM); and (3) Simulation of peak flows and predicting recurrence intervals of flood events from model simulation of peak flows

3.1 Variation in climate hydrology

Over the Indian subcontinent the long term average trends from 1986 – 2013 of water balance components were examined and temporal variation is plotted in figure 6. The mean Rainfall, Surface Runoff and Evapotranspiration for 28 years is found to be 1123, 399 and 650 mm/year respectively. The maximum runoff of 503mm was observed in the year 1990 which is 38% of the mean precipitation of the same year and lowest observed in the year 2000 i.e 317 mm which is 32% of the mean precipitaiton of the same year. The spatial distribution of the long term mean evapotrasnpiration and surface runoff has been generated and it is observed that north east region and the western ghats of India had higher evapotranspiration at a maximum of 711 mm within these 28 years.This can be attributed to the dense vegetation, high rainfall uniformly distributed through out the year.

Figure 6: Long term Seasonal (June to Oct) Mean Water Balance Components

Figure 7: Long term Seasonal (June to Oct) Mean Evapotranspiration and Runoff

Similarly minimum evapotranspiration of 603 mm was observed for the north west region of India including some part of Rajasthan, Punjab, Gujarat and Haryana due to arid and semi arid condition and low rainfall as shown in Figure 7.

The monthly variation in water balance components over the two historical periods (1986 – 1999; T1 and 2000 – 2013; T2) were compared over major river basins of India. From T1 to T2, precipitation has increased across all the basins taken up in this study with the maximum deviation in monsoon season (JJAS). PET is converted to AET based on prevalent SM content and LAI, hence Evapotranspiration peaks in the month of July and August due to higher soil moisture condition resulting from rainfall. Krishna Basin generate more winter runoff than the other basins due to the North East monsoon.

Figure 8: Monthly variation in water balance components over the two historical periods

3.2 Soil Moisture AvailabilityAssessment and Analysis

In this sub-section long term soil moisture records simulated by VIC model for top two layer upto the depth of 0.5 meter and soil hydraulic properties like field capacity and wiliting point were used to calculate percentage available soil moisture (PASM) stress index.PASM is an useful indicator of moisture stressed areas. PASM is defined as the ratio of Available Soil Moisture Content (AWC) to its Water Holding Capacity (WHC). The index values range from 0 to 100 with 0 and 100 indicating extreme dry and wet condition respectively; its classification is showcased in Table 3.The main advantage in using PASM is to monitor moisture stressed areas experiencing the soil moisture deficit; which is resultant of meteorological conditions i.e. temperature and precipitation.

$$PASM = [\frac{SMw\ -\ PWP}{FC\ -\ PWP}]\ X\ 100$$

Where SMw is the weekly calculated volumetric soil moisture (vol/vol) for the week, FC is the field capacity of soil (vol/vol) and PWP is the permanent wilting point of the soil (vol/vol).

Table 3: PASM based Soil Moisture Availability classification

The weekly PASM values under severe drought scenario (PASM ˜ 0 -25 %) were identified and aggregated for the months of June to September consitituting a total of 22 weeks. The mean seasonal PASM value was tabulated and found lowest for the year 1986, 1991, 2002, 2009 which is in concurent with the IMD drought Manual - 2016. The spatial variation of inseasonal PASM aggregated over weeks for the above mentioned years are showcased in figure 9. Overall moisture stressed states like Rajasthan, Haryana, Punjab, South Andra Pradesh, Karnataka, Tamil Nadu and parts of Gujrat were found to be under severe drought condition.

The droughtareal extent is also calculated year wise represented by the grid cells that witness at least 2 months (8 weeks) of drought. All the four years 1986, 1991, 2002, 2009 stands tall with more than 60 % of area under moisture stress (figure 10). In a nutshell, the four most severe moisture stress years of India are well represented in the drought overview.

Figure 9: Shows the spatial pattern of PASM for the four selected historical stressed years

Figure 10: Year Wise Drought Areal Extent

3.3 Flood Analysis

The magnitude and recurrence of flood events for four selected basins were generated using daily CWC observed streamflow data and model simulated discharge. Annual maximum streamflow (AMS) during the entire simulation period (1971 - 2013) for each basin was calculated. Figure 11 shows the variation of the relative percentage AMS anomaly between observed and simulated discharge.

The relative AMS anomaly was calculated by dividing the anomaly value with each of the mean AMS. The mean AMS for any particular basin is the average of all the years. The relative AMS anomaly was take up for comparison for each basin, because very basins has its own range of AMS. Among all the basins the simulated AMS values are in close agreement with the observed ones. The median, range and the minimum values of the simulated AMS anomaly are smaller than the observations.The differences in AMS anomalies can be attributed to (1) upstream abstraction/natural storages which are not considered in this study which affects the simulated flow simulations and (2) interpolation and merging of IMD gridded precipitation with satellite data. The Godavari basin has larger interannual variability in AMS when compared with other river basin.

Figure 11: Annual maximum streamflow(AMS) anomaly (%) during 1971 to 2013

Frequency of occurence and magnitude of any flood event is very important when it comes to the prediction and analysis of floods. The concept of return period is used to describe the likelihood of occurrences. Figure 12 shows the return period of all the AMS values for 43 years from 1971 to 2013. The Godavari river basin has the largest AMS values for all return periods with the mean value of AMS(57,376 m3/s) is nearly two times larger than that of the Narmada Basin whereas Subernarekha basin has the smallest AMS values for all the return period.

Figure 12: Return period of annual maximum streamflow from the simulated streamflow

4. Conclusions

The study was conducted for the period of 1971 – 2013 at 5.5 km grid spatial resolution over entire India to simulate long term hydrological fluxes. The simulated river discharge was calibrated with the CWC river discharge observation data. Due to the classified data of transboundary rivers of India such as Indus, Ganga and Brahmaputra; neighbouring basin model calibrated values were adopted. Futhermore, modeled soil moisture were evaluated against IMD insitu observation and ET against flux tower data. These well validated and reliable modeled estimates can contribute to water resource management, water budgeting, and irrigation planning.

Further to this, The model derived soil moisture was translated into percentage available soil moisture (PASM) as fraction of water holding capacity. The PASM depicted soil moisture stress condition showed a good agreement spatially and temporally with the published IMD drought manual – 2016.

To study floods and its return period; AMS during the entire simulation of 43 years was calculated. The large variability was observed in simulated streamflow which can be partially attributed to the no reservoir/lake wetland parametrization in the modeling simulation. Nonetheless this calibarted and validated model is beneficial for representing hydrological fluxes and extremes, which can serve as a tool to evaluate and plan water resources management and to assess the impact of future interventions and management activities.

Acknowledgements

Data Availability Statement: All hydrological and geo-spatial data used in this study can be obtained from responsible agencies listed below. Climatic data can be obtained from India Meteorological Department, Ministry of Earth Sciences (IMD-MoES; *http://www.imdpune.gov.in/Clim_-Pred_LRF_New/Grided_Data_Download.html#*). Soil data is taken from Harmonized World Soil Database (HWSD; http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/). Land use Land Cover data are available on Bhuvan open data archive portal (BHUVAN; *https://bhuvan-app3.nrsc.gov.in/data/download/index.php*). Digital elevation model can be retrieved from Shuttle Radar Topography Mission (SRTM; *http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1*).

VIC model source code can be obtained from VIC GITHUB repository (VIC;*https://github.com/UW-Hydro/VIC*). Model derived water balance components can be visualized and downloadable on Bhuvan web-portal (*https://bhuvan-app3.nrsc.gov.in/nices/*). Stream flow data can be obtained from India- Water Resources Information System (India-WRIS;*http://indiawris.gov.in/wris/*).Flux tower data were obtained from Agriculture and Forestry group of National Remote Sensing Centre, Hyderabad.

References

A.Mishra and V.P. Singh (2010), A Review of Drought Concepts, Journal of Hydrology, Vol. 391(1-2), 202-216

Abdulla, F. A. and Lettenmaier, D. P.(1997), Application of Regional Parameter Estimation Schemes to Simulate the Water Balance of a Large Continental River, Journal of Hydrology, 197, 258–285

Adam, J. C. and Lettenmaier, D. P(2008), Application of New Precipitation and Reconstructed Streamflow Products to Streamflow Trend Attribution in Northern Eurasia, Journal of Climate, 21, 1807–1828

Ajay Singh et.al (2011), Impact of Drought and Flood on Indian Food Grain Production, Challenges and Opportunities in Agrometerology Springer, Berlin, Heidelberg, 421-433

Anil Rai et.al. (2008), Development of Livelihood Index for Different Agro-Climatic Zones of India, Agricultural Economic Research Review, Vol. 21, 173-182.

Background Paper No.4 (2006), River flooding and Erosion in Northeast India, Northwest Hydrulics Consultants, Edmonton, Alberta, Canada

Census of India, 2011.Houselisting and Housing Census Schedule. Government of India

Clark et.al (2017), The evolution of process based hydrological models: historical challenges and the collective quest for physical realism, Hydrology and Earth System Science, Vol.21, 3427-3440

Dharumarajan S. et. al (2019), The need for digital soil mapping in India , Geoderma Regional, Vol.15, 1-12

Donald A Wilhite (2009), Drought Monitoring as a Concept of Drought Preparedness and Planning, Coping with Drought Risk Agriculture and Water Supply Systems, Springer

Drought Report (2006), Manual for Drought Management, Department of Agriculture, Cooperation & Farmers Welfare, Govt. of India , New Delhi

Etienne et.al (2016), Development of a Demand Sensitive Drought Index and its Application for Agriculture Over the Conterminous United States, Journal of Hydrology, Vol.534, 219-229

Fischer E. M. et.al (2016), Observed Heavy Precipitation Increase Confirms Theory and Early Models, Nature Climate Change, Vol.6, 986-991

Flamiglietti.J.S. et.al (2015), Ground- based investigation of Soil Moisture Variability within Remote Sensing Footprints during the Southern Great Plains 1997(SGP97)Hydrology Experiment, Water Resources Research, Vol.35(6), 1839-1851

Francini M. And Paccini M., 1991, Comparitive Analysis of Several Conceptual rainfall- Runoff Models, journal of Hydrology, Vol.122, 161-219.

Guhanthakurta P. and Rajeevan M. (2008), Trends of Rainfall Pattern Over India, International Journal of Climatology, Vol.28, 1453-1469

Hamman,J.et.al(2016).:The Land Surface Climate in the Regional Arctic System Model, Journal of Climate, doi:10.1175/JCLI-D-15-0415.1

Hamman,J.et.al(2018).:The Variable Infiltration capacity Model, Version 5: Infrastructure Improvements for New applicationsand Reproducibility, Geoscientific Model Development, doi:10.5194/gmd-2018-36

Hao Z. et.al (2016), A statistical method for categorical drought prediction based on NLDAS-2, Journal of Applied Meteorology and Climatology, Vol. 55(4), 1049-1061

Chiew F.H.S et.al (2009), Influence of Global Climate Model Selection on Runoff Impact Assessment, Journal of Hydrology, Vol.379, 172-180

India. Encyclopædia Britannica. Retrieved 17 July 2012. Total area excludes disputed territories not under Indian control.

Krishnamurthy V. and J. Shukla (2000), Intraseasonal and Interannual variability of Rainfall over India, Journal of Climate, Vol. 13, 4366-4377

L.M. Tallaksen, Henry A.J. van Lanen (2004), Hydrologic Drought: Process and Estimation Methods for Streamflow and Groundwater, Vol.48, Elsevier, Amsterdam

Lee et.al (2017), Development and Application of Improved Long Term Datasets of Surface Hydrology for Texas, Advances in Meteorology, Vol.2017, 1-13

Liang X. et.al (1994), A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, Journal of Geophysical Reserach Atmospheres, Vol.99-D7, 14,415-14,428

Livneh B. et.al (2016), The physics of drought in the U.S. Central Great Plains, Journal of Climate, Vol.29 (18), 6783-6804

Machado M.J.et.al (2015), Flood Frequency Analysis of Historical Flood Data Under Stationary and Non-Stationary Modelling , Hydrology Earth System and Sciences, Vol.19, 2561-2576

Mondal A. et. al (2015), Spatial and Temporal Analysis of Rainfall and Temperature Trend of India , Theoretical and Applied Climatology, Vol.122, 143-158

Murari Lal (2003), Global Climate Changei India's Monsoon and Its Variability, Journal of Environmental Studies and Policy, Vol. 6(1) ,1-34.

Nijssen, B et. Al (2001 a) Hydrologic Sensitivity of Global Rivers to Climate Change, Climatic Change, 50, 143–175.

Nijssen, B. et. Al (2001c) Global Retrospective Estimation of Soil Moisture Using the Variable Infiltration Capacity Land Surface Model, 1980-93, Journal of Climate, 14, 1790–1808

Nijssen, B.et. al.(2001b), Predicting the Discharge of Global Rivers, Journal of Climate, 14, 3307–3323,

P.S. Roy and A. Giriraj, (2008). Land Use and Land Cover Analysis in Indian Context. Journal of Applied Sciences, 8: 1346-1353

Petra Doll (2009), Vulnerability to the Impact of Climate Change on Renewable Groundwater Resources: A Global Scale Assessment, Environmental Research Letters, Vol. 4, 1-12

Ren-Jun, Z(1992). The Xinanjiang model applied in China. Journal of Hydrology, Vol.135, 371–381

S. B. Kakade and Ashwini Kulkarni (2017), Seasonal Prediction of Summer Monsoon Rainfall over Cluster Regions of Inida , Journal of Earth System Science, Vol.126(34), 1-15

S.K Das et.al (2007), Flood and Drought Management through Water resources Development in India, WMO Bullein, Vol 56(3)

Saxton K.E and RawlsW.J.(2006). Soil Water Characteristics Estimates by texture and Organic Matter for Hydrologic Solutions, Soil Science Society of America Journal, Vol.70, 1569–1578.

Sheffield, Jer. Al. (2009) Global and Continental Drought in the Second Half of the Twentieth Century: Severity-Area-Duration

Analysis And Temporal Variability Of Large-Scale Events, Journal of Climate, 22, 1962–1981

Schleussner C. et.al (2017), In the Observational Records Half a Degree Matters, Nature Climate Change, Vol.7, 460-462

Sitterson et. al. (2017), An Overview of Rainfall- Runoff Model Types, Office of Research and Development, National Exposure Research Laboratory, Georgia

Su, Fet.al (2005) Streamflow Simulations of the Terrestrial Arctic Domain, Journal of Geophysical Research: Atmospheres, 110

T. Tingsanchali (2012), Urban Flood Disaster Management, Procedia Engineering, Vol 32, 25-37

Tan, Aet. Al (2011) Change in Spring Snowmelt Timing in Eurasian Arctic Rivers, Journal of Geophysical Research: Atmospheres, 116

Tanaka T.et.al (2016), Frequency Analysis of Extreme Floods in a Highly Developed River Basin , Hydrology Earth System and Sciences, Vol.2016-225, 1-35

Teng. J et.al (2011), Estimating the Relative Uncertainties Sourced from GCMs and Hydrological Modles in Modeling Climate Change Impact on Runoff , Journal of Hydrometeorology, Vol.13, 122-139

U.S.De et.al. (2005), Extreme Weather Events over India in the last 100 years, Journal of Indian Geophysical Union, Vol. 9(3) ,173-187.

Yin et.al (2018), Comparing the Hydrological Responses of Conceptual and Process- Based Models with Varying Rain Gauge Density and Distribution, Sustainability, Vol.21, 1-22

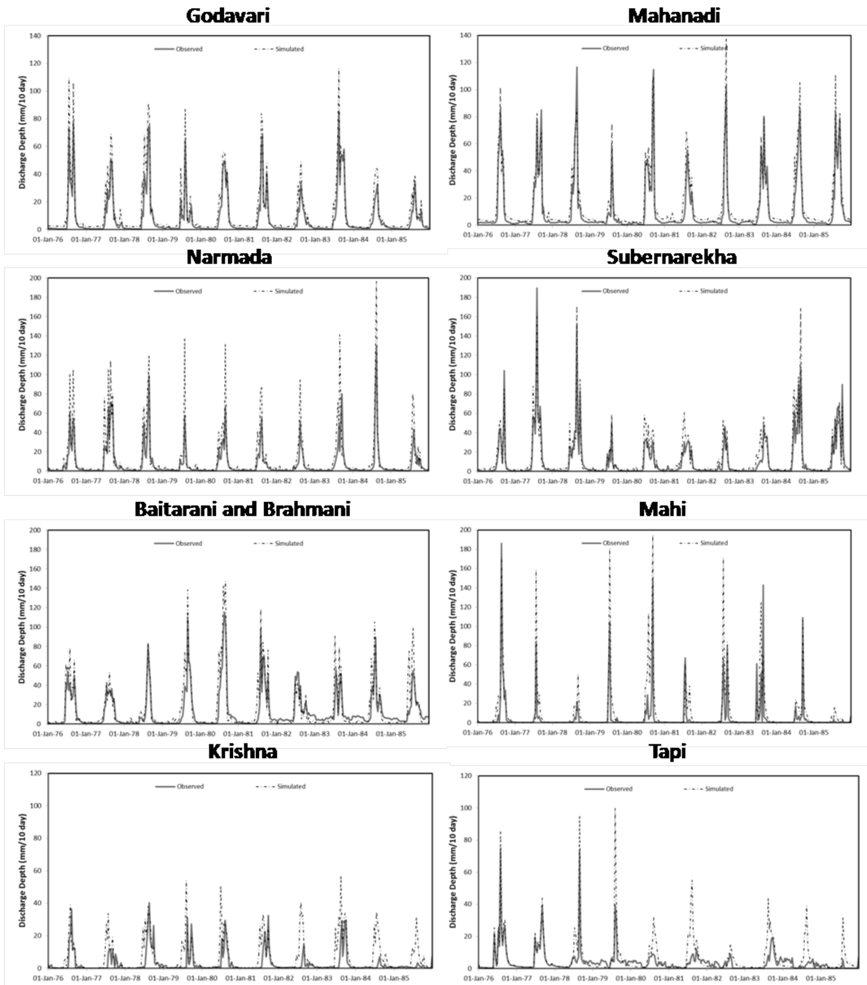
Zaharia L. et.al (2008), Assessment and Mapping of Flood Potential in Slanic Catchment in Romania, Journal of Earth System Science, Vol.124 (6), 1311-1324

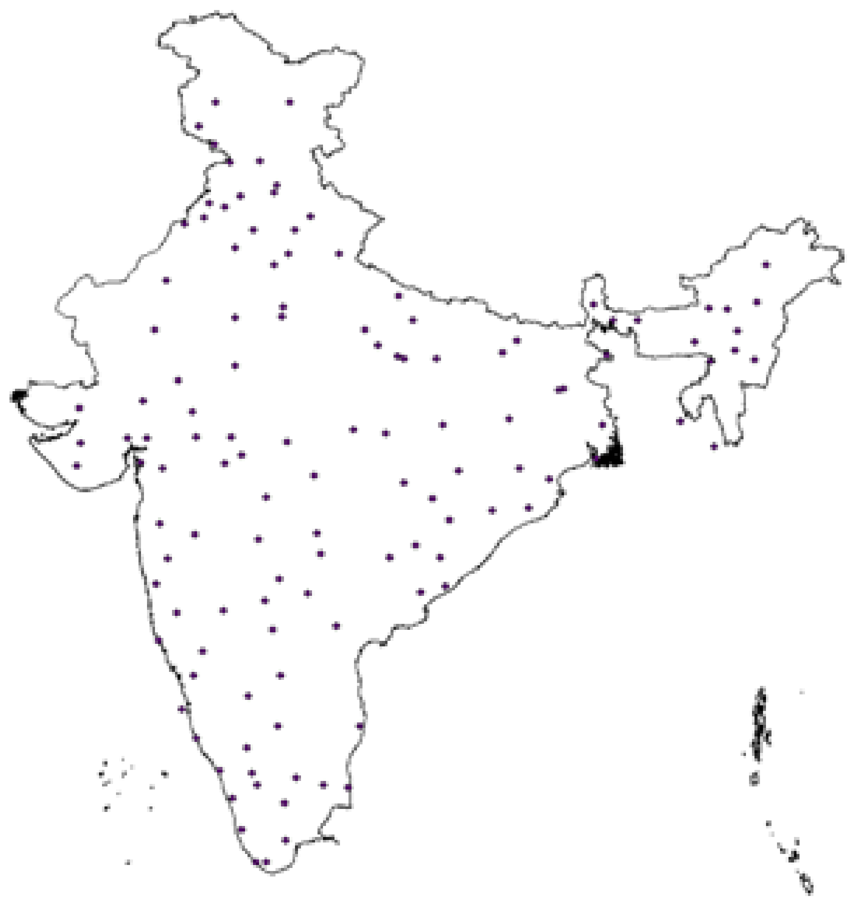
Zhao, R.J et.al(1980). The Xinanjiang Model. Proceedings of Oxford Symposium on Hydrology, Vol.135, 371–381.

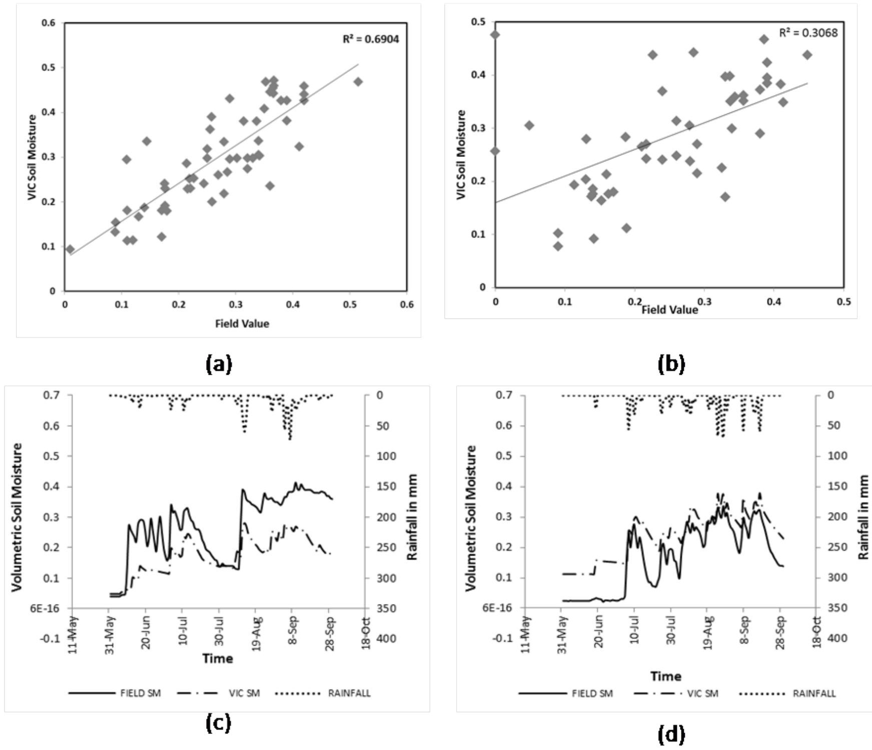
Zheng H. J et.al (2009), Responses of Streamflow to Climate and Land Surface Change in Headwaters of the Yellow River Basin , Water Resources Research, Vol.45, 1-9

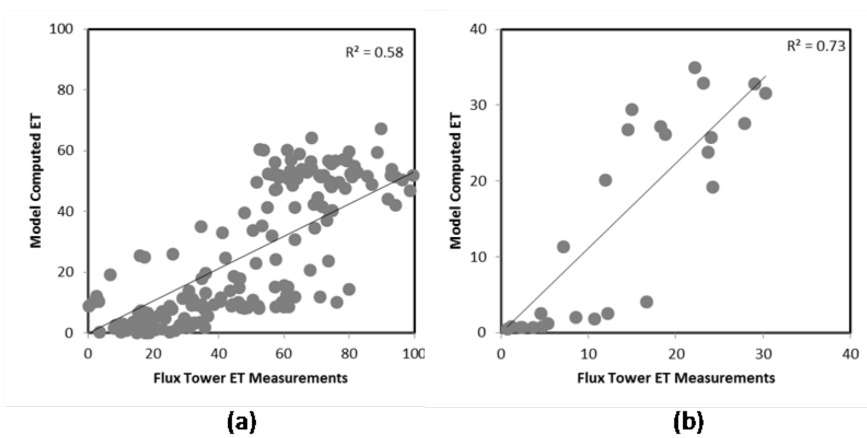
Zheng N. et.al (2016), A Distributed Flood Inundation Model Intergrating with Rainfall-Runoff Processing Using GIS and Remote Sensing Data, The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol.38 –B4, 1513-1518

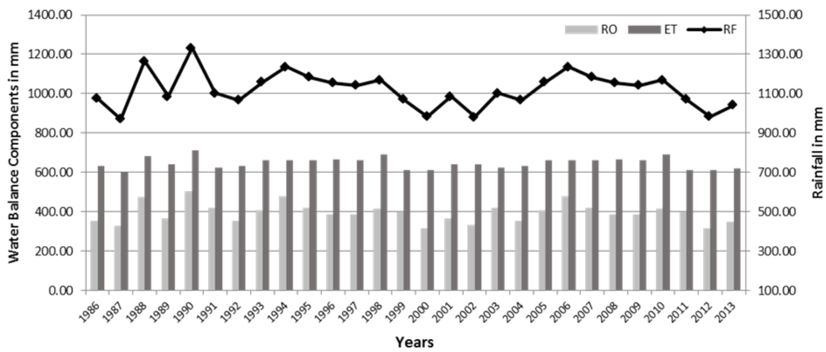

Indus
Brahmaputra
Ganga
Barak and others
Sabarmati
Mahi
Narmada
Subernarekha
Brahmani and Baitarni
Island
Mahanadi
Tapi
Godavari
Krishna
Pennar
Andaman and Nicobar
Cauvery
Lakshadweep

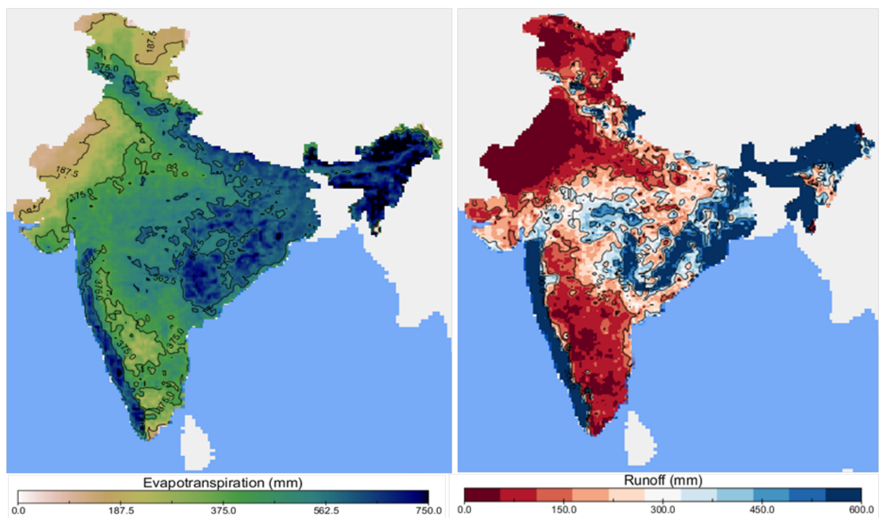

Godavari
Mahanadi
Narmada
Subernarekha
Baitarani and Brahmani
Mahi
Krishna
Tapi
Observed
Simulated
Discharge Depth (mm/10 day)
01-Jan-76
01-Jan-77
01-Jan-78
01-Jan-79
01-Jan-80
01-Jan-81
01-Jan-82
01-Jan-83
01-Jan-84
01-Jan-85

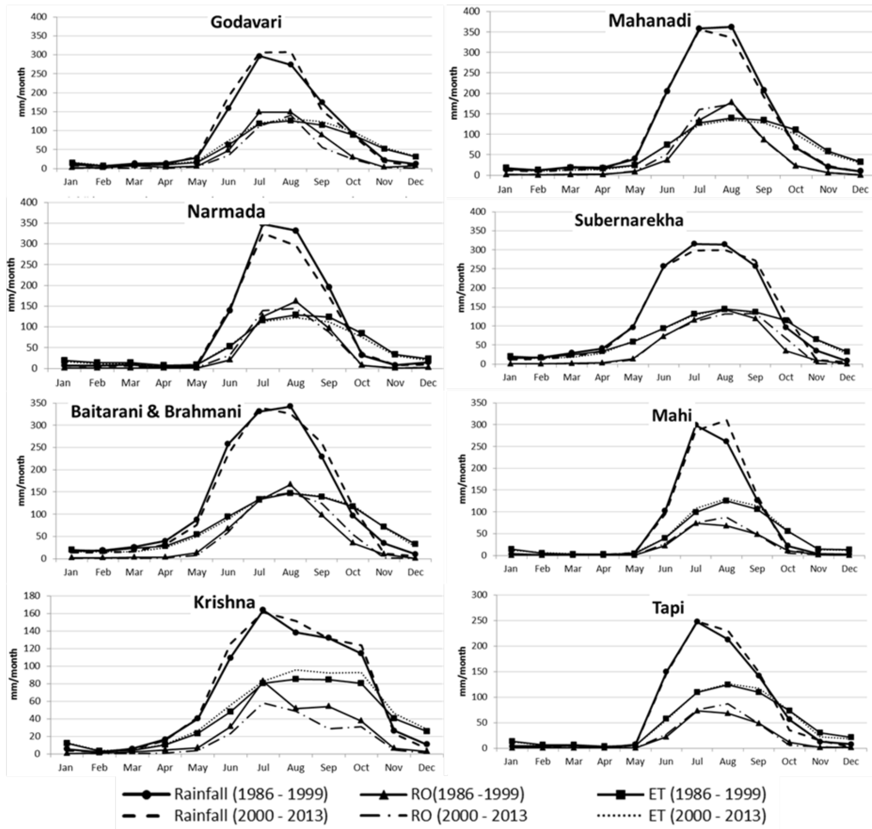


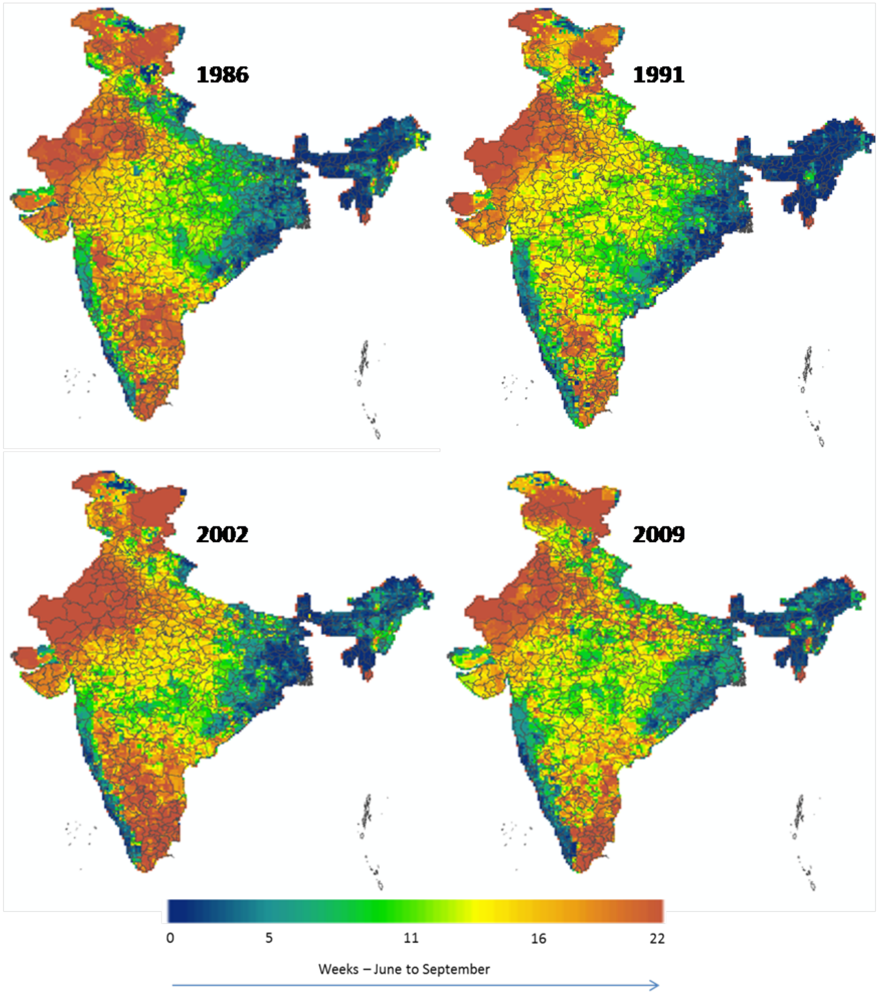

R² = 0.6904
VIC Soil Moisture
Field Value
(a)
R² = 0.3068
VIC Soil Moisture
Field Value
(b)
Volumetric Soil Moisture
Rainfall in mm
Time
FIELD SM
VIC SM
RAINFALL
(c)
Volumetric Soil Moisture
Rainfall in mm
Time
FIELD SM
VIC SM
RAINFALL
(d)

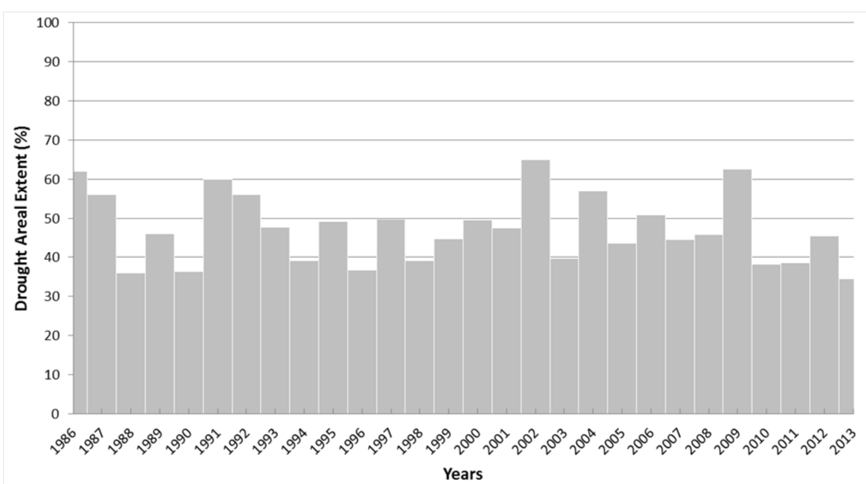

R² = 0.58
Model Computed ET
Flux Tower ET Measurements
(a)
R² = 0.73
Model Computed ET
Flux Tower ET Measurements
(b)

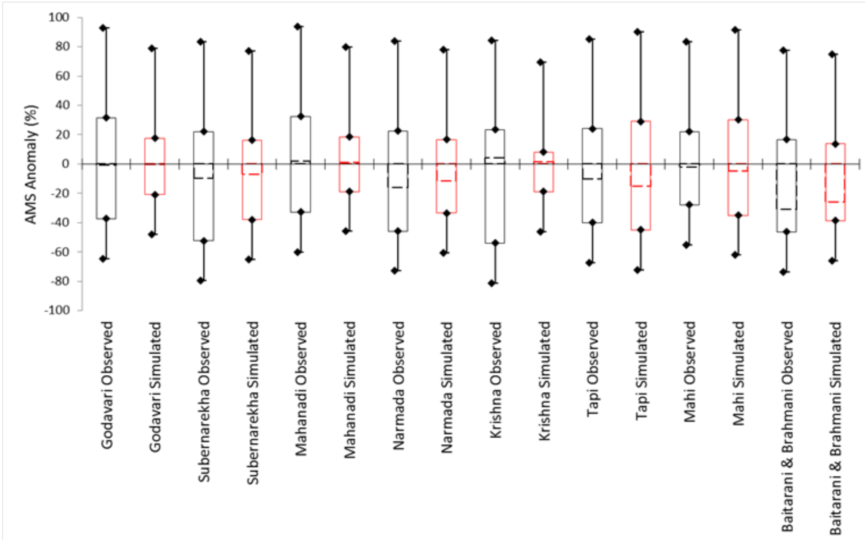

RO
ET
RF
Water Balance Components in mm
Rainfall in mm
Years
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
1500.00
1300.00
1100.00
900.00
700.00
500.00
300.00
100.00
1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013

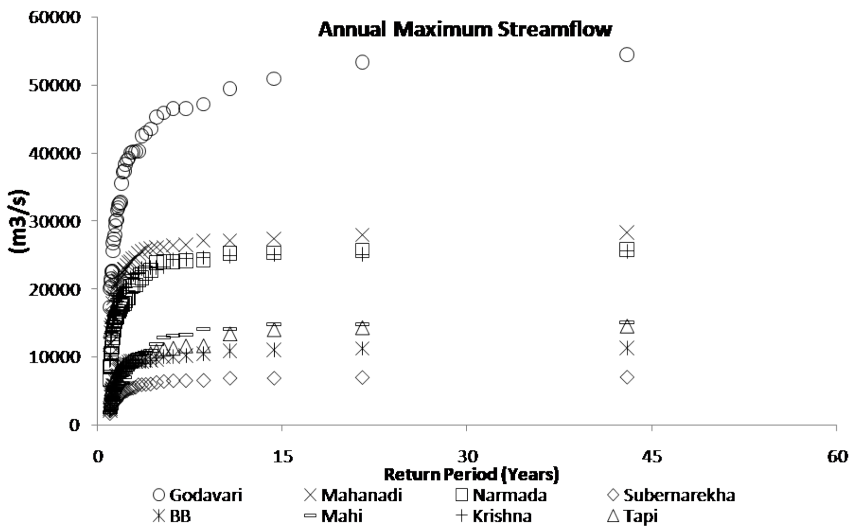

Evapotranspiration (mm)
0.0
187.5
375.0
562.5
750.0
Runoff (mm)
0.0
150.0
300.0
450.0
600.0


Godavari
Mahanadi
Narmada
Subernarekha
Baitarani & Brahmani
Mahi
Krishna
Tapi
mm/month
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Rainfall (1986 - 1999)
Rainfall (2000 - 2013)
RO(1986 -1999)
RO (2000 - 2013
ET (1986 - 1999)
ET (2000 - 2013)


1986
1991
2002
2009
0
5
11
16
22
Weeks – June to September


Drought Areal Extent (%)
100
90
80
70
60
50
40
30
20
10
0
1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
Years





Hosted file

`Table1.pptx` available at https://authorea.com/users/340880/articles/467925-applications-of-hydrological-model-simulated-long-term-water-balance-components-for-india

Hosted file

`Table2.pptx` available at https://authorea.com/users/340880/articles/467925-applications-of-hydrological-model-simulated-long-term-water-balance-components-for-india

Hosted file

`Table3.pptx` available at https://authorea.com/users/340880/articles/467925-applications-of-hydrological-model-simulated-long-term-water-balance-components-for-india