INTEGRATION OF SATELLITE, GLOBAL REANALYSIS DATA AND MACROSCALE HYDROLOGICAL MODEL FOR DROUGHT ASSESSMENT IN SUB-TROPICAL REGION OF INDIA

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ABSTRACT:

Change in soil moisture regime is highly relevant for agricultural drought, which can be best analyzed in terms of Soil Moisture Deficit Index (SMDI). A macroscale hydrological model Variable Infiltration Capacity (VIC) was used to simulate the hydro-climatological fluxes including evapotranspiration, runoff, and soil moisture storage to reconstruct the severity and duration of agricultural drought over semi-arid region of India. The simulations in VIC were performed at 0.25˚ spatial resolution by using a set of meteorological forcing data, soil parameters and Land Use Land Cover (LULC) and vegetation parameters. For calibration and validation, soil parameters obtained from National Bureau of Soil Survey and Land Use Planning (NBSSLUP) and ESA's Climate Change Initiative soil moisture (CCI-SM) data respectively. The analysis of results demonstrates that most of the study regions (> 80%) especially for central northern part are affected by drought condition. The year 2001, 2002, 2007, 2008 and 2009 was highly affected by agricultural drought. Due to high average and maximum temperature, we observed higher soil evaporation that reduces the surface soil moisture significantly as well as the high topographic variations; coarse soil texture and moderate to high wind speed enhanced the drying upper soil moisture layer that incorporate higher negative SMDI over the study area. These findings can also facilitate the archetype in terms of daily time step data, lengths of the simulation period, various hydro-climatological outputs and use of reasonable hydrological model.

1. INTRODUCTION

Drought is a complex hydrological phenomenon, which spread frequently over worldwide with the alteration in hydrological cycle. During last century, the extent of droughts increased more than 50% all over the world. The assessment of drought phenomenon is rely upon the duration, severity and impact area because it is context-dependent and varies among climatic zones (McKee et al., 1993). The majority of Indian economy is dependent upon agriculture sector and accounts about 18 percent of India's gross domestic product (GDP) (https://www.omicsonline.org/open-access/agriculture). Hence, the agricultural related practice such as monitoring of agricultural drought has an important role in irrigation scheduling and thus influencing the productivity and economic condition. The extremity of agricultural drought can be best estimated by the soil moisture (SM) levels. Deficit in soil moisture due to rainfall shortage is highly correlated with drought phenomenon. Monitoring of the agricultural drought using soil moisture have been of immense interest to agronomist, policy makers and planners since the onset of this type of drought is begins when the soil moisture availability to plants drops at level that adversely affects the crop yields. Therefore, the root zone SM put forth antecedent conditions, which indicates potential and available water storage. There are various indices which monitored agricultural drought using SM in which one the Soil Moisture Deficit Index (SMDI) is the important variable for flood and drought forecasting.

In previous studies, the agricultural drought indices were computed using SM content from in situ measurements, remotely sensed SM observations and simulations from different models. There are various hydrological models are being used which often provide more imminent to outputs for monitoring droughts. The Soil Water Assessment Tool (SWAT) model (Narasimhan and Srinivasan, 2005), Tiled European Centre for Medium -Range Weather Forecast (ECMWF) Scheme for Surface Exchange over Land (TESSEL) model(Dutra et al., 2008), One layer Water-Budget model (Hao and Agha Kouchak, 2013) and the Variable Infiltration Capacity (VIC) models (Sheffield et al., 2004; Wu et al., 2007; Sheffield and Wood, 2008; Wang et al., 2011) are commonly used in simulation of SM for developing agricultural drought indices. Recently, Tang Cet al. (2009), Sheffield & Wood (2007), have successfully monitored the drought condition using VIC model. Therefore, in purview of the above, we simulate hydrological parameters in Indian continent for quantification of agricultural drought using VIC derived hydrological parameters. In present study, we applied one-fourth degree (0.25˚) resolution; however drought tends to be persistent over large scale so for this purpose one-fourth degree is adequate.

Thus, the goal of this study was set to verify the suitability of hydrological VIC model for assessing agricultural drought at weekly temporal resolution with no hysteresis. The weekly drought monitoring can help farmers to adapt management measures in real time for preventing crop losses. This is the burning issues especially in developing countries like India to safeguarding food security, water and soil management, especially in the era of climate change with special interest in rainfed agro-ecosystem where the deficit of soil moisture that available to plant, directly affects agricultural activities consequently an induces social and economic conflicts. The SMDI were computed over Bundelkhand region of India on a weekly time scale from July 1998 to October 2015 for Kharif season using VIC simulated soil moisture at one forth degree spatial resolution.

2. MATERIALS AND METHODOLOGY

2.1 Study Area

The Bundelkhand region (22741.88 km2) lies at the central part of India located below the Indo-Gangetic plain to the north with the undulating Vindhyan mountain range spread across the northwest to the south. The Uttar Pradesh region of Bundelkhand is worst affected drought area, lies between 24°18' and 26°45' N latitudes and 78°16' and 81°56' E longitude (Figure 1).The main rivers are the Yamuna, Sindh, Betwa, Ken, Bagahin, Tons, Pahuj, Dhasan and Chambal, and constitute the part of Ganga basin. The topography of the region is highly undulating, with rocky outcrops and boulder-strewn plains in a rugged landscape. The major soils include alluvial, medium black, and mixed red and black soils. In the most parts of Bundelkhand, gram and wheat were the main rabi (post monsoon) crops and jowar, bajra and pulses were the main Kharif (monsoon) crops. The majority of crops are coarse cereals like ragi, kodon, sawan, kakun and kutki (millets) of Kharif season (http://www.bundelkhandinfo.org.in/economy/agriculture).

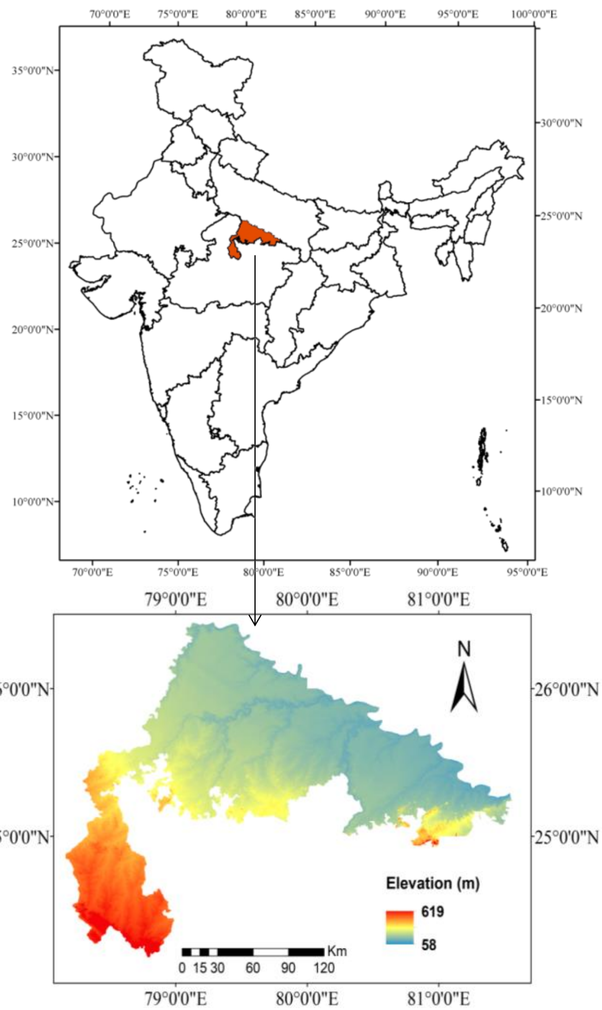


Figure 1. Study area map with Digital Elevation Model (DEM)

2.2 Datasets

The analysis of drought is based on simulated hydrological parameters (soil moisture, rainfall, evaporation, transpiration and runoff) from a land surface hydrological VIC model simulation. We have used meteorological forcing data (temperature, precipitation and wind), soil parameters, and vegetation parameters and LULC for simulation. The station based daily precipitation (0.25˚) and temperature (1˚) data were obtained from Indian Meteorological Department (IMD), while wind speed data was obtained from National Centers for Environmental Prediction (NCEP). Indian National Bureau of Soil Survey and Land Use Planning (NBSS &LUP) soil map was used to provide the information of soil characteristics such as soil depth, texture etc. For land cover classification, we have used Landsat 5 satellite data for the October 2011. For land cover classification, we have followed hybrid classification approach employing supervised and indices (vegetation, soil and water) based technique. The ESA remote sensing Climate Change Initiative soil moisture (CCI-SM) combined product used in this study for the model calibration and validation.

2.3 The VIC hydrological model

The Variable Infiltration Capacity (VIC) model derived variables was used in this study to assess agricultural drought over Indian sub-tropical region Bundelkhand. VIC is a macroscale hydrologic model that addresses full water and energy balances, originally developed by Xu Liang at the University of Washington (Das et al., 2018). This model has its wide application in the area ranges from water resource management to climate change. This model, balance both the water and surface energy budgets grid wise whereas sub grid variations are computed statistically. The VIC is used to quantifying the dominant hydro-meteorological components at the grid level. The grid resolution can vary from 3 km to about 2-degree resolution. The model computes vertical energy and moisture flux specifically in each grid considering soil properties and vegetation coverage. The VIC model has been tested and applied at a range of spatial scale over the years, from large river basin to continental and global scale. VIC has been well tested and applied at large scale over long period (Lohmann et al., 1998a, b; Sheffield and Wood, 2007; Shi et al., 2008). It has also been examined by soil moisture and globally by snow cover data (Nijssen et al., 2001; Maurer et al., 2002). Further, for detail study of model, the reader can be referred to Liang et al. (1994 and1996).

For calibration of model soil parameters are applied in the current study. The soil layer depths (d1 and d2), infiltration curve parameter (binff), fraction of maximum velocity of baseflow (Ds) and fraction of maximum soil moisture where non-linear baseflow begins (Ws) are derived for calibration (Das et al., 2018). The model is validated using ESA derived CCI-SM for three years 2007, 2008 and 2009 at daily time steps (Figure 2. and Table 1.)

2.4 Soil Moisture Deficit Index (SMDI)

The daily soil moisture of the VIC model output for the layer depth one was averaged over a 7-day period for converting weekly SM for the Kharif season during the 18-year period (1998-2015). The long-term median, minimum and maximum was calculated for a particular weeks. Then the weekly percentage of soil moisture deficit ($SD_{k,i}$)for each week i and year k is calculated using following conditional expression:

$$SD_{k,i} = \frac{SM_{k,i} - SM_{median\ ,i}}{SM_{median\ ,i} - SM_{min\ ,i}} * 100\ If\ SM_{k,i} \leq SM_{median\ ,i}$$

$$SD_{k,i} = \frac{SM_{k,i} - SM_{median\ ,i}}{SM_{max\ ,i} - SM_{median\ ,i}} * 100\ If\ SM_{k,i} > SM_{median\ ,i}$$

where, $SM_{k,i}$ is the VIC derived SM for the current week i and year k (1998 to 2015), and the $SM_{median,i}$ $SM_{max,i}$ and $SM_{min,i}$ denotes the long-term median, maximum and minimum values of the current week i during the Kharif season (July-October), respectively. Then the weekly SMDI was computed as:

$$SMDI_i = 0.5\ X\ SMDI_{i-1} + \frac{SD_i}{50}$$

Where, $SMDI_{i-1}$ is the SMDI of the previous week and SD_i is the soil moisture deficit in percentage for current week i. The SMDI was initialized as $SMDI=SD_1/50$.

Table 1. Drought Category according to the SMDI

Dynamic Range	SMDI values
No Drought	0 or more
Mild	-1 to -0.01
Moderate	-2 to -1.01
Severe	-3 to -2.01
Extreme	-4 to -3.01

3. RESULTS AND DISCUSSIONS

The VIC simulated SM shows the better agreement with observed (CCI-SM) SM with R^2 values 0.74, 0.39 and 0.42 for the year 2007, 2008 and 2009 respectively for the selected grid in the study area. The results are showed in Table 2 and Figure 2. The SMDI are derived using simulated SM gives the overall estimation of agricultural drought in the study area.

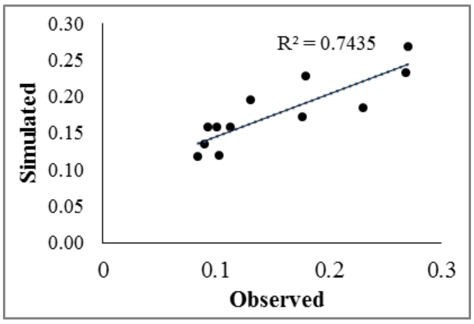


Figure 2: Scatter plot showing agreement between observed and simulated values for the year 2007

Table 2. R^2 values for observed and simulated SM

Years	Point1	Point2	Point3
2007	0.74	0.81	0.82
2008	0.39	0.33	0.38
2009	0.42	0.32	0.25

3.1 Drought Weeks Captured by SMDI

The number of weeks captured having mild, moderate, severe and extreme drought for the study period is shown in Figure 3. The study involves Kharif period for the drought evaluation as the major crops grown in study site are of Kharif season. Since the each week had a different category of drought with available data along the study period, the comparison was made using number weeks for different drought categories. The analysis shows that year 2001, 2002, 2006, 2007 and 2008 has 5, 6, 3, 2 and 2 numbers of extreme droughts. Severe drought is observed in year 2007, 2008, 2009 and 2014 with number of drought weeks 6, 5, 7 and 8 respectively. It is observed that year 2001, 2002, 2007, 2008 and 2009 was drought year (Gupta et al., 2014; Kundu et al., 2016).

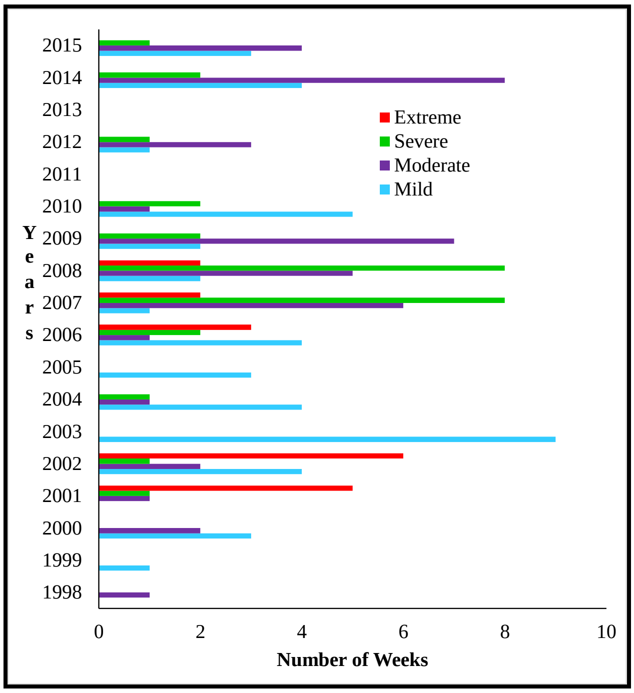
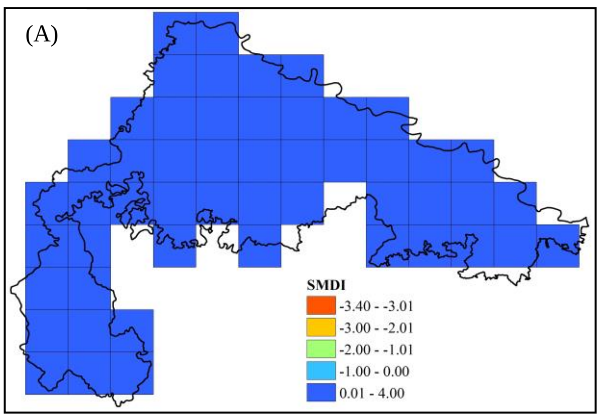


Figure 3: Number of weeks with drought severity (mild, moderate, severe and extreme) estimated by SMDI for the study period

3.2 Spatial Comparison

The spatial distributions of estimated agricultural drought maps are shown in Figure 4(A-D). The SMDI were spatially described for 28th week i.e., July 9-15 for the year 2001, 2002, 2009 and 2010. The selected week corresponds to the beginning of Kharif season. In Bundelkhand region, the monsoon arrives late so for that the crop was sowed from generally 2nd or 3rd week of July. Year 2001 are wet year with positive SMDI values varies from 0.01 to 4 whereas, 2002 was drought year with SMDI values -1.0 to -3.4. Year 2009 and 2010 represents the moderate severe and moderate drought with SMDI values mostly in the range of -2.0 to -3.0 and -1.0 to -2.0 respectively.



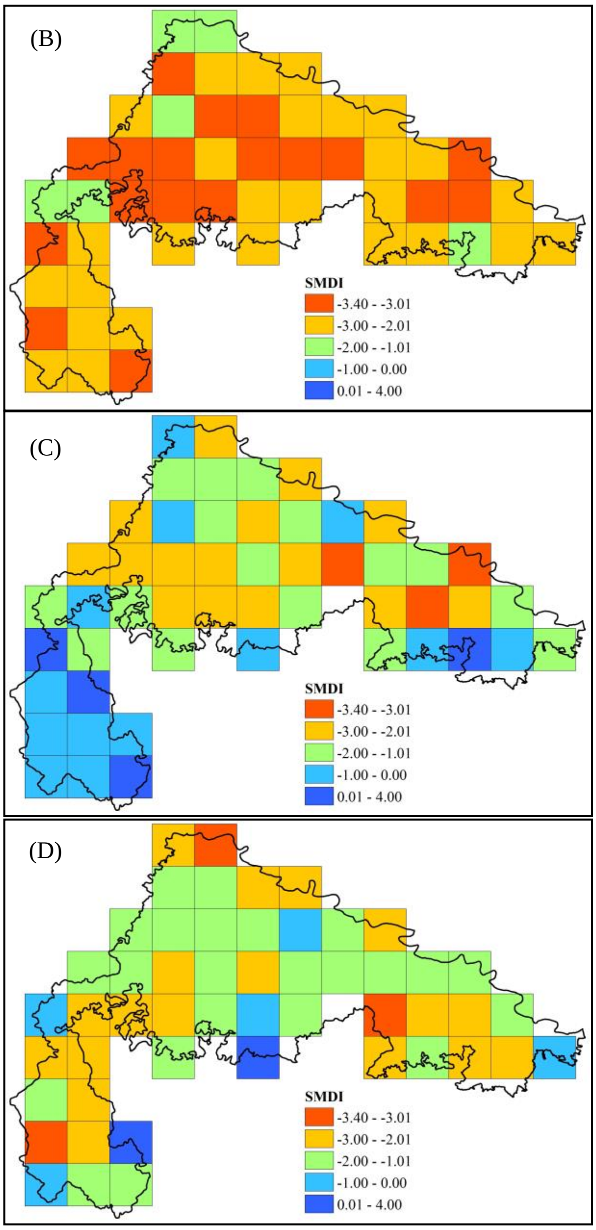


Figure 4: Maps of SMDI for July 9-15 of the year 2001 (A), 2002(B), 2009(C) and 2010(D) respectively

4. CONCLUSION

The present study explores the suitability of hydrological model for estimating soil moisture derived SMDI for monitoring agricultural drought spatially and represents the prototype for modelling drought over the large scale as well as remote areas where ground measured data are limited. This work has potential to draw the attention of national/international science communities and useful for societal benefits. Agricultural drought monitoring is a burning issue especially in developing country for safeguarding food security, water and soil management, especially in the era of climate change.

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