# Assessment of Spatial-temporal Variations of Drought indicated by Agricultural and Hydrological Parameters in Eastern Part of Satara District of Maharashtra, India

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***Abstract***
*Agricultural and hydrological drought monitoring is paramount for crop management in a populous country like India. The present work aims to assess the spatio-temporal variations of hydrological and agricultural drought using remote sensing and GIS techniques. In the present study, satellite-borne Landsat data were used for monitoring agricultural drought while groundwater level data were used to assess hydrological drought.*

*The results revealed that VCI illustrates moderate drought conditions during pre-monsoon and normal conditions during post-monsoon. TCI and VHI show moderate to extreme drought conditions in April and fair to moderate drought conditions in December. The SWI reveals that the study area is prone to moderate to severe drought conditions. The present investigation is useful to spatio-temporal scale with a better understanding of the past drought events and it will be helpful for future drought mitigation.*

**Keywords:** Hydrological Drought, Agriculture Drought, Standardized Water-level Index (SWI), Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI).

## Introduction
Drought is a frequent feature of the climate that is having a profound effect on the earth's surface and society.[10,22,23,33] It is one of the most costly, deadliest and widespread natural disasters among the all natural disasters, which impacts on the economic and agricultural sectors, water resources, natural ecosystems and community activities.[22]

Nevertheless, a unanimously accepted definition of drought is still missing,[22,27,32] due to differences in hydrological, meteorological component and socio-economic factors along with the stochastic nature of water demand in various regions of the world.[31] For these reasons, it is significant to examine of drought episodes and the assessment of their severity.

The remote sensing data have been widely used for drought assessment and indices development in the last decade.[6,9,17,29] Spaceborne observation can provide real-time monitor in to an atmospheric and surface variables from rainfall to soil moisture, therefore, vegetation indices have been proven usefulness in this field.[19,30] The availability of precise satellite-based Climate Data Records[1,7,20] facilitated information at the spatio-temporal scale with a better understanding of the past drought events and it helps to consolidate monitoring strategies.

Remote sensing information based vegetation health index (VHI)[14,17] is a broadly used for assessment of agricultural drought.[4,18,24,26] It is a combination of two indices namely the Vegetation Condition Index (VCI) including information on visible (VIS) and near infrared (NIR) portions of the electromagnetic spectrum and the Thermal Condition Index (TCI) depending on the thermal infrared (TIR). The VCI index is generally estimated by using the Normalized Difference Vegetation Index (NDVI) and it counts the vegetation water stress; the TCI assesses the thermal stress of vegetation and is based on either the top-of atmosphere brightness temperature or Land Surface Temperature (LST).

It is not possible to assess, monitor, interpret and address drought using a single parameter because duration, magnitude and the spatial extent are not fixed. Therefore, the present study aims to carry out spatio-temporal analysis variations of hydrological and agricultural drought and comparative analysis using four indices namely Standardized Water Level index (SWI) Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI) which are selected by application of use as well as data availability. Indices are selected from a list given in the Handbook of drought indices by WMO.[28]

## Study Area
The study area is the eastern Satara district which is located in the Drought Prone Area (DPA) of Maharashtra State as shown in fig. 1. The mean annual precipitation over the study is about 532 mm The mean maximum temperature varies from 38 to $40^0$ C (usually occurring in May) and minimum temperature varies from 11 to $16^0$ C (usually occurring in January).[8] More than 80% of the study area receives rainfall during the southwest monsoon season (June–September). Agriculture is the main economic activity in the study area.

The income sources of study are crop farming, livestock ranching, farm labor and small businesses which are 60.88%, 20%, 17.65% and 0.88% respectively. There are two main agricultural seasons i.e. Kharif (hot wet season from June to September) and Rabi (cool dry season from November to March). The hottest season (April and May) is called summer. Almost every year, a large part of the study area is under water stress due to the erratic nature of rainfall.

The study area extends between $17^0$ 22' 57" to $18^0$ 6' 03" North latitude and $74^0$ 09' 38" to $74^0$ 55' 32" East longitude. The total area of the proposed study is 3894 $km^2$ and it comprises Man, Khatav and Phaltan tehsils of Satara district. The average height of the study area is about 713 meters. The maximum height is 1004 meters observed towards the western part of the study area. The lowest elevation is observed towards the extreme eastern part where the height is 423 meters.

## Research Methodology

**Standardized Water level Index (SWI):** The standardized water level index (SWI) was calculated according to Bhuiyan.[2] SWI has been developed to measure the groundwater recharge deficit. The ground water level data collected from the GSDA Satara (Groundwater Survey and Development Agency) is used in order to assess hydrological drought in the study area; 45 wells have been analyzed from 1991 to 2018 for pre-monsoon and post-monsoon groundwater levels. The SWI expression stands as:

$$SWI = (W_{ij} - W_{im}) / \sigma$$

where $W_{ij}$ is the seasonal water level for the ith well and jth observation, $W_{im}$ its seasonal mean and $\sigma$ is its standard deviation.

The severity of the hydrological drought is measured using SWI values. Positive anomalies represent drought conditions whereas negative anomalies show no drought or normal conditions. Point values of SWI corresponding to the wells were interpolated using Inverse distance weighting (IDW) technique to generate SWI maps.

**Table 1**
**Classification of SWI values**

| Drought Classes | Criterion |
|---|---|
| Extreme Drought | SWI > 2.0 |
| Severe Drought | SWI >1.5 |
| Moderate Drought | SWI > 1.0 |
| Mild Drought | SWI > 0.0 |
| No Drought | SWI < 0.0 |

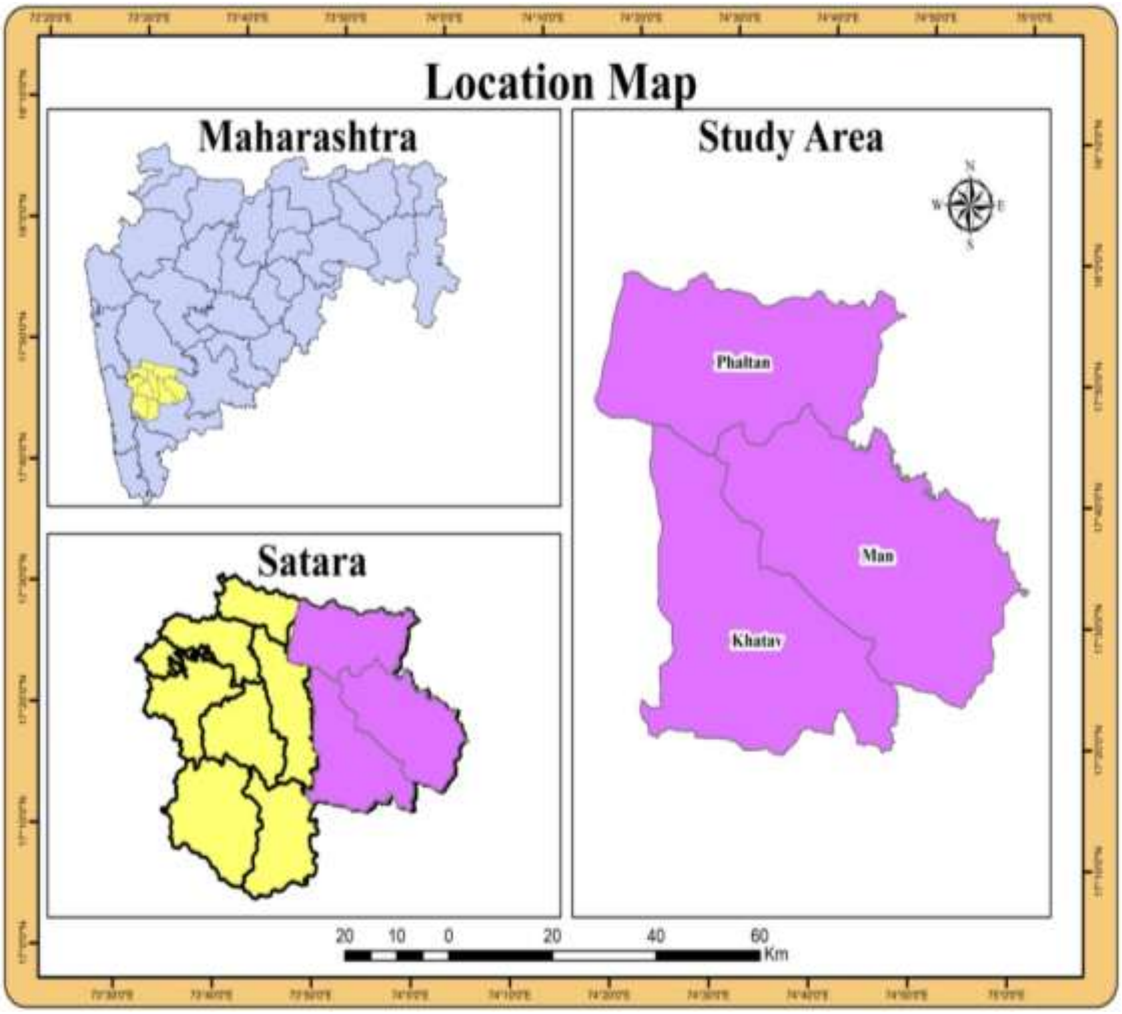



**Fig. 1: Geographical Location of the Study Area**

**Vegetation Indices**

**Data Background:** Satellite data was downloaded from the USGS (United States Geological Survey Website). The data were downloaded from four different satellites: Landsat 4, Landsat 5, Landsat 7 and Landsat 8. Landsat images have medium resolution with spatial resolution of 30 m.

## Methodology

**NDVI:**

NDVI= (NIR-R) / (NIR+R)

where NIR= near infrared band and R= Red band.

**LST**: For the land surface temperature (LST) calculation, thermal bands were used. The six number band for Landsat 4, 5 and 7 and bands number ten and eleven for Landsat 8 were used. The thermal infrared sensor calculated top of the atmosphere (TOA) radiances, from which brightness temperature can be obtained using Plank's law.[5] The formulas used for the conversion of the digital number to land surface temperature are illustrated in table 2.

The K1 and K2 constants values for the Landsat sensors are listed in table 3. The values of the central wavelength (λ) for the different thermal bands are provided in table 4.

**Vegetation Condition Index (VCI):** Vegetation Condition Index (VCI) was first introduced by Kogan.[17] It is an indicator of the status of the vegetation cover as a function of minimum and maximum NDVI encountered for a given ecosystem over many years. VCI is defined as:

VCI = (NDVI- NDVImin)/ (NDVImax- NDVImin) *100

where NDVImax NDVImin is calculated from long-term record for a particular month and j is the index of the current month. VCI separates the short-term weather-related NDVI fluctuations from the long-term ecosystem changes.[13,16] Therefore, NDVI represents the dynamics of seasonal vegetation;

**Temperature Condition Index (TCI):** TCI was also suggested by Kogan.[17] It was developed to reflect vegetation response to temperature i.e. higher is the temperature, the more extreme is the drought. TCI is based on brightness temperature and represents the deviation of the current month's value from the recorded maximum. TCI is defined as:

TCI= (BT max- BT)/ (BTmax- Btmin) *100

where BT is brightness temperature. Maximum and minimum BT values are calculated from the long-term record of remote sensing images for a particular period j. Low TCI values indicate very hot weather. TCI provides the opportunity to detect subtle changes in plant health due to the effects of heat, as drought increases when moisture is reduced and high-temperature increases.[12] The TCI values (<40) represent plant stress due to dryness by excessively high temperatures.

**Table 2**
**Formulas for the conversion of the DN to LST**

| Processing Steps | Formulas |
|---|---|
| Conversion of DN (Digital Number) to Satellite Brightness Temperature | $TB = K2 / ln( (K1 / L\lambda) + 1)$ |
| Calculation of the Land Surface Temperature in Kelvin | $T = TB / [ 1 + (\lambda * TB / \rho)\ ln\varepsilon ]$ |
| Conversion from Kelvin to Celsius | $Tc = T - 273$ |

**Table 3**
**K1 and K2 Constants values for the Landsat satellites**

| Constant | Landsat 4 | Landsat 5 | Landsat 7 | Landsat 8 (Band 10) | Landsat 8 (Band 11) |
|---|---|---|---|---|---|
| K1 | 671.62 | 607.76 | 666.09 | 774.89 | 480.89 |
| K2 | 1284.30 | 1260.56 | 1282.71 | 1321.08 | 1201.14 |

**Table 4**
**Wavelength for Landsat satellites**

| Satellite | Band number | Wavelength (µm) |
|---|---|---|
| Landsat 4, 5 and 7 | 6 | 11.45 |
| Landsat 8 | 10 | 10.8 |
| Landsat 8 | 11 | 12 |

**Vegetation Health Index (VHI):** The combination of VCI and TCI and correlating it with soil moisture and thermal stress gives total vegetation health condition. The equation for VHI is given by:

$VHI$=0.5$VCI$ ×0.5$TCI$

where VCI= seasonal average Vegetation Cover, TCI = seasonal average Thermal stress.

VHI, the contribution of moisture and temperature during the plant cycle is not known yet, the same weight is assumed and both VCI and TCI are given (Kogan, 2001).

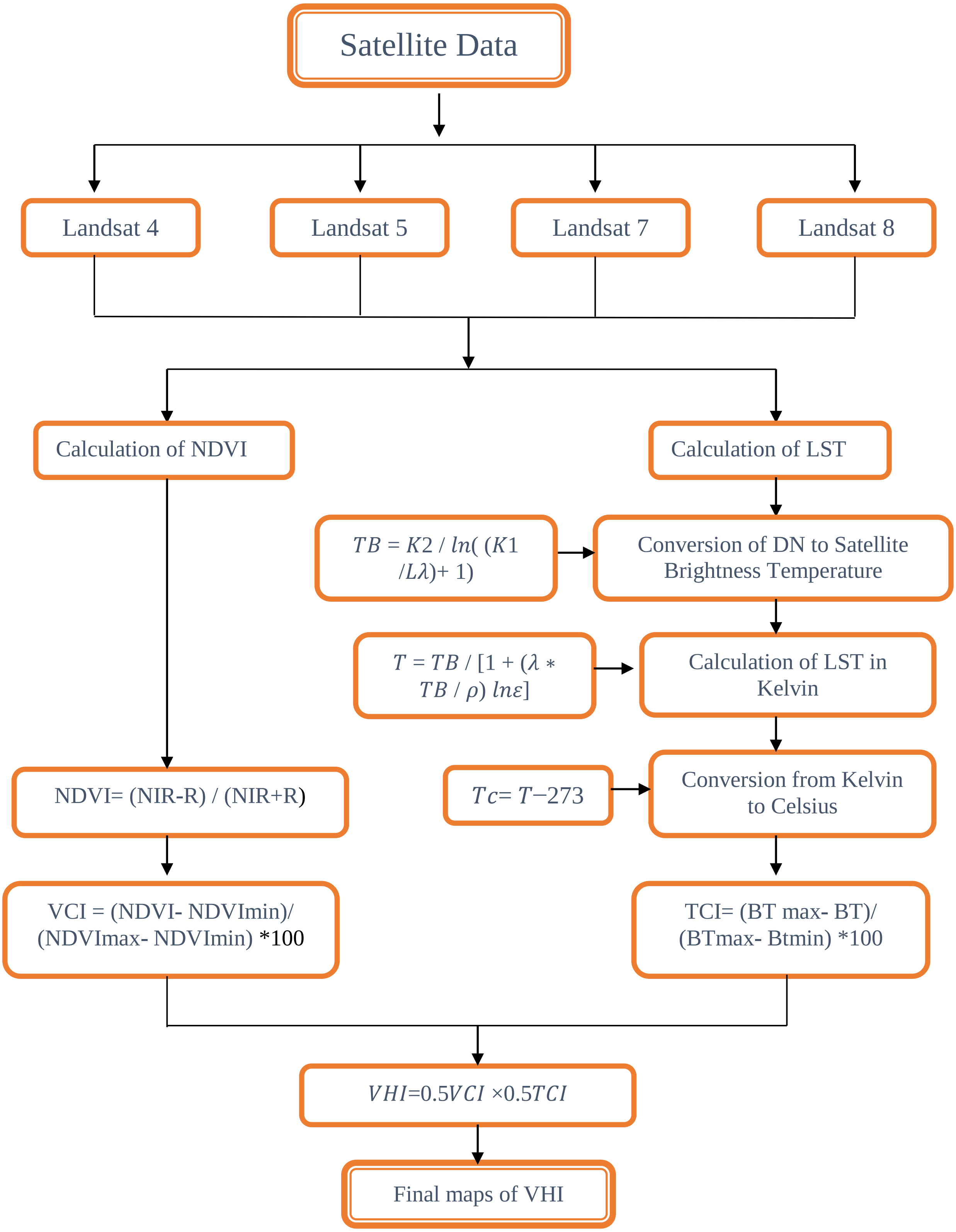



**Fig. 2: Research Methodology for the VHI calculation**

VCI, TCI and VHI values are measured in range from 1% to 100%. The range between >40 % to 100% indicates above normal condition of vegetation while the values ranging from 30% to 40% indicate the mild drought conditions; 20% to 30% indicates moderate drought conditions, 10% to 20% represent severe drought conditions and 1% to 10% indicate extreme drought conditions[16] (Table 5).

The resulted images of VCI, TCI and VHI were classified based on drought severity classification proposed by Kogan.[16] The flow chart represents the systematic phases of research methodology for VHI (Fig. 2).

**Table 5**
**Classification of the VCI, TCI and VHI values**

| Drought Classes | Values |
|---|---|
| Extreme Drought | <10 |
| Severe Drought | <20 |
| Moderate Drought | <30 |
| Mild Drought | <40 |
| No Drought | >40 |

## Results and Discussion

**Hydrological Drought:** The classification has been prepared for 28 years (1991 to 2018) for the pre-monsoon period as described in table 6. The effects of drought on hydrological components are observed in many ways such as decreased river flows, decline lake water levels and groundwater aquifers. Furthermore, drought reduces water content in the soil, which harms soil fertility, biodiversity and can lead to wildfires.[11] The undulating topography and hard rock structure play a very crucial role in the infiltration of water within the earth's surface.

Nearly about 14, 8, 2.42 and 2.7 years have extreme, severe, moderate and mild hydrological drought conditions respectively during pre-monsoon period in the study area. The erratic nature and insufficient rainfall are the main factors behind frequent drought conditions in the study area. Besides, the study area also has undulating topography and hard rock structure which create aquifer recharge difficult.

The classification for 28 years (1991 to 2018) during the post-monsoon in different drought conditions is represented in table 7. The dug well and bore well are the main sources of irrigation in the study area.

Nearly about 79.69% of farmers are using dug well to irrigate their crops in the study area. Excessive pumping of groundwater ultimately impacts on groundwater depletion, which is an important concern for Maharashtra State.

During 1998-2000, about 19 out of 35 districts in the Maharashtra State declined in ground water level by more than 4m (20 cm/year).[21] Approximately 16, 6, 2.36 and 1.6 years have experienced extreme, severe, moderate and mild hydrological drought conditions respectively during post-monsoon period in the study area.

Spatio-temporal variation of hydrological drought due to groundwater recharge deficit in the study area is depicted fig. 3. Time series analysis of SWI maps reveals hydrological drought in the study area from 1991 to 2018 and both the pre-monsoon and post-monsoon periods follow an alternate pattern with minor local variations.

During both pre-monsoon post-monsoon periods, most of the part in the study area experienced moderate to extreme hydrological droughts in the last two decades. The hydrological drought situation degraded gradually in the following years.

Before the commencement of the 1991 monsoon, many parts of the study area were hit by mild to moderate drought and one major pocket in the northwest suffered from severe hydrological drought. In the years 1992 and 1994 during the pre-monsoon season, major parts of the study area had moderate to severe drought and some parts suffered extreme hydrological drought.

In the year 1993, the post-monsoon water level was normal in major parts of the study area except some discrete pockets in the west and east.

In 1995, hydrological drought conditions again were worst during the post-monsoon. The year 1996 during both pre-monsoon and post-monsoon northern part of the study area suffered moderate to severe hydrological drought.

The hydrological drought conditions more deteriorate during the post-monsoon period of 2000 when except the north-west and south-east sector of the study area, they are affected by moderate to severe hydrological drought. In years 2003, 2004 and 2006, major parts of the study area also suffered moderate to extreme drought.

The drought condition worsened gradually from the pre-monsoon of 2007 onwards and in the post-monsoon period of 2007, almost the entire study area was in the grief of acute drought. There was a drought in the post-monsoon period of 1995, 1999, 2000, 2007 and 2010, as groundwater level went down due to insufficient rainfall in that year (fig. 3).

The years 2015, 2016, 2017 and 2018 during the pre-monsoon period, many pockets in the study area suffered moderate to severe hydrological drought conditions.

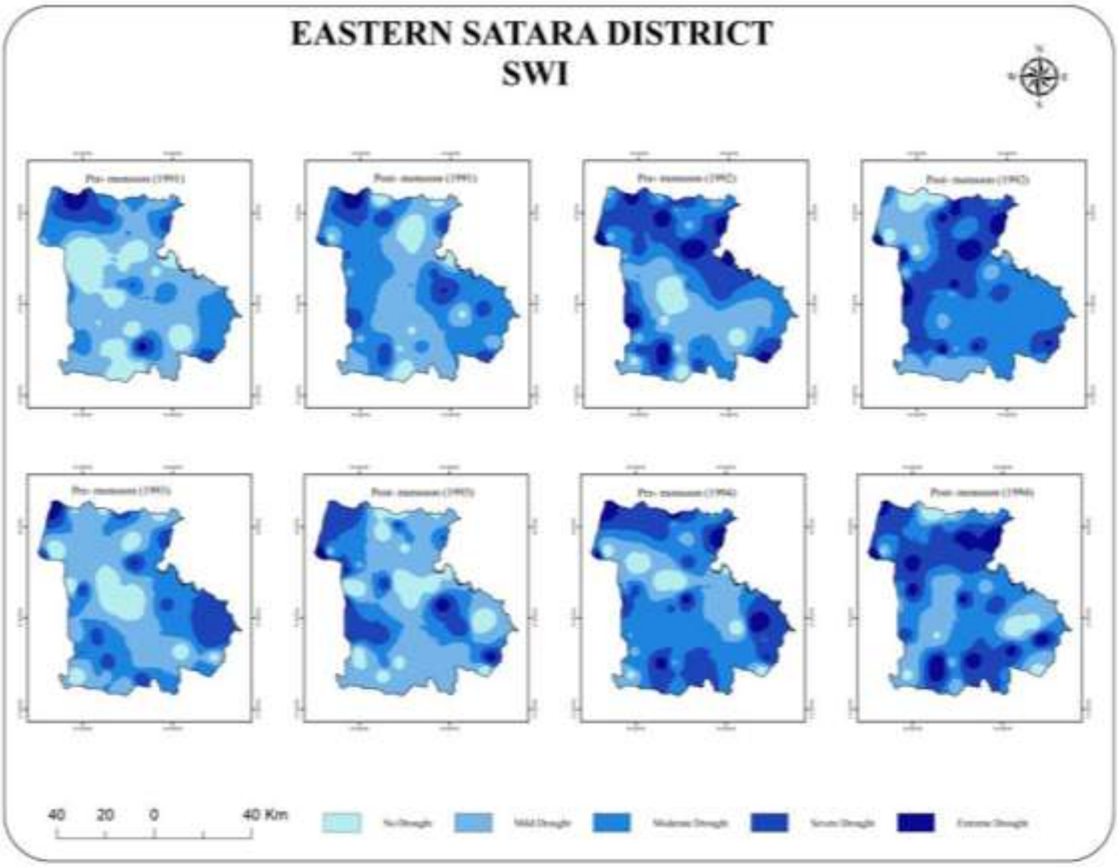
**Agricultural Drought:** The spatio-temporal variations in vegetation cover are studied for the study area. Agricultural drought has been assessed through three indices as described by the handbook of drought indices. Maharashtra faced the drought-hit periods during the years 1918, 1972, 1987, 2000, 2002, 2009 and 2015.

**Table 6**
**Classification of year in different drought conditions based on SWI values (during pre monsoon)[2]**

| | SWI Classification of year | | | | | | |
|---|---|---|---|---|---|---|---|
| **Tehsil** | **location of well (Villages)** | **Extreme Drought** | **Severe Drought** | **Moderate Drought** | **Mild Drought** | **No Drought** | **Grand Total** |
| KHATAV | Ambavade | 15 | 9 | 1 | 3 | | 28 |
| | Aundh | 16 | 9 | 1 | | 2 | 28 |
| | Bhushangad | 19 | 5 | 2 | 1 | 1 | 28 |
| | Budh | 15 | 7 | 5 | | 1 | 28 |
| | Chitali | 16 | 7 | 1 | 4 | | 28 |
| | Datewadi | 18 | 7 | | 1 | 2 | 28 |
| | Katarkhatav | 16 | 6 | 3 | 2 | 1 | 28 |
| | Kokarale | 11 | 16 | | | 1 | 28 |
| | Kuroli | 16 | 8 | 1 | | 3 | 28 |
| | Lalgun | 13 | 8 | 5 | 2 | | 28 |
| | Mayani | 16 | 8 | 2 | | 2 | 28 |
| | Mol | 17 | 6 | 3 | 1 | 1 | 28 |
| | Musandwadi | 17 | 5 | 6 | | | 28 |
| | Pusesavali-new | 14 | 11 | 1 | | 2 | 28 |
| | Vardhangad | 14 | 7 | 5 | 2 | | 28 |
| | Wakeshwar | 14 | 9 | | 5 | | 28 |
| | Yeliv | 13 | 8 | 5 | 2 | | 28 |
| MAN | Bidal | 11 | 13 | 2 | 2 | | 28 |
| | Dhuldev | 11 | 15 | | | 2 | 28 |
| | Divad | 12 | 14 | | | 2 | 28 |
| | Kasarwadi | 13 | 10 | 5 | | | 28 |
| | Mhaswad | 15 | 6 | 5 | 1 | 1 | 28 |
| | Mogarale | 15 | 7 | 3 | 2 | 1 | 28 |
| | Pandherewadi | 13 | 13 | | | 2 | 28 |
| | Ranand | 14 | 12 | | | 2 | 28 |
| | Shenwadi | 13 | 12 | 1 | 2 | | 28 |
| | Shindi kh. | 16 | 8 | 2 | | 2 | 28 |
| | Shingnapur | 15 | 8 | 3 | 2 | | 28 |
| | Shirtav | 16 | 9 | 1 | | 2 | 28 |
| | Takewadi | 17 | 6 | 5 | | | 28 |
| | Valai | 14 | 10 | | 3 | 1 | 28 |
| | Varkute malvadi | 18 | 4 | 2 | 2 | 2 | 28 |
| | Wawarhire | 12 | 13 | | 2 | 1 | 28 |
| PHALTAN | Adarki bk | 12 | 11 | 5 | | | 28 |
| | Adarki kh | 17 | 5 | 4 | 2 | | 28 |
| | Dudhebavi | 18 | 5 | 1 | 3 | 1 | 28 |
| | Gokhali | 16 | 8 | 1 | 1 | 2 | 28 |
| | Khunte | 12 | 13 | | 2 | 1 | 28 |
| | Murum | 17 | 7 | 3 | | 1 | 28 |
| | Padegaon | 19 | 6 | | 1 | 2 | 28 |
| | Phaltan(MCI) | 13 | 11 | 1 | 2 | 1 | 28 |
| | Rajuri | 12 | 15 | | | 1 | 28 |
| | Somanthali | 16 | 6 | 5 | 1 | | 28 |
| | Tathavada | 20 | 3 | 3 | 1 | 1 | 28 |
| | Vadale | 16 | 8 | | 4 | | 28 |
| Overall Study area | | 14 | 8 | 2.42 | 2.07 | 1.51 | 28 |

**Table 7**
**Classification of year in different drought conditions based on SWI values (during post monsoon)[2]**

| | SWI Classification of year | | | | | | |
|---|---|---|---|---|---|---|---|
| **Tehsil** | **location of well (Villages)** | **Extreme Drought** | **Severe Drought** | **Moderate Drought** | **Mild Drought** | **No Drought** | **Grand Total** |
| KHATAV | Ambavade | 17 | 7 | 2 | 1 | 1 | 28 |
| | Aundh | 19 | 4 | 2 | 2 | 1 | 28 |
| | Bhushangad | 16 | 7 | 3 | | 2 | 28 |
| | Budh | 16 | 7 | 2 | 3 | | 28 |
| | Chitali | 19 | 4 | 2 | 1 | 2 | 28 |
| | Datewadi | 19 | 6 | 2 | | 1 | 28 |
| | Katarkhatav | 16 | 9 | 1 | | 2 | 28 |
| | Kokarale | 15 | 10 | 1 | | 2 | 28 |
| | Kuroli | 18 | 7 | 2 | | 1 | 28 |
| | Lalgun | 17 | 9 | | | 2 | 28 |
| | Mayani | 21 | 4 | | | 3 | 28 |
| | Mol | 14 | 10 | 2 | | 2 | 28 |
| | Musandwadi | 20 | 1 | 3 | 3 | 1 | 28 |
| | Pusesavali-New | 22 | 2 | 2 | | 2 | 28 |
| | Vardhangad | 19 | 3 | 2 | 2 | 2 | 28 |
| | Wakeshwar | 16 | 6 | 6 | | | 28 |
| | Yeliv | 17 | 6 | 2 | 1 | 2 | 28 |
| MAN | Bidal | 19 | 3 | 3 | 3 | | 28 |
| | Dhuldev | 17 | 7 | 2 | | 2 | 28 |
| | Divad | 12 | 12 | 4 | | | 28 |
| | Kasarwadi | 18 | 7 | 1 | 1 | 1 | 28 |
| | Mhaswad | 13 | 9 | 6 | | | 28 |
| | Mogarale | 20 | 4 | | 2 | 2 | 28 |
| | Pandherewadi | 20 | 4 | 2 | | 2 | 28 |
| | Ranand | 13 | 9 | 4 | 2 | | 28 |
| | Shenwadi | 13 | 13 | | | 2 | 28 |
| | Shindi Kh. | 19 | 6 | | 1 | 2 | 28 |
| | Shingnapur | 14 | 8 | 4 | 1 | 1 | 28 |
| | Shirtav | 19 | 5 | 2 | | 2 | 28 |
| | Takewadi | 18 | 4 | 2 | 3 | 1 | 28 |
| | Valai | 19 | 4 | 1 | 3 | 1 | 28 |
| | Varkute Malvadi | 18 | 6 | 2 | | 2 | 28 |
| | Wawarhire | 17 | 7 | 1 | 1 | 2 | 28 |
| PHALTAN | Adarki Bk | 12 | 12 | 2 | 2 | | 28 |
| | Adarki Kh | 18 | 4 | 2 | 2 | 2 | 28 |
| | Dudhebavi | 18 | 7 | 2 | | 1 | 28 |
| | Gokhali | 10 | 14 | 2 | | 2 | 28 |
| | Khunte | 16 | 10 | | 1 | 1 | 28 |
| | Murum | 15 | 9 | 2 | | 2 | 28 |
| | Padegaon | 13 | 13 | | 1 | 1 | 28 |
| | Phaltan(MCI) | 19 | 1 | 6 | 2 | | 28 |
| | Rajuri | 15 | 9 | 2 | | 2 | 28 |
| | Somanthali | 15 | 9 | 1 | 1 | 2 | 28 |
| | Tathavada | 21 | 3 | 1 | | 3 | 28 |
| | Vadale | 17 | 5 | 2 | 4 | | 28 |
| Overall study area | | 16 | 6 | 2.36 | 1.86 | 1.72 | 28 |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SWI
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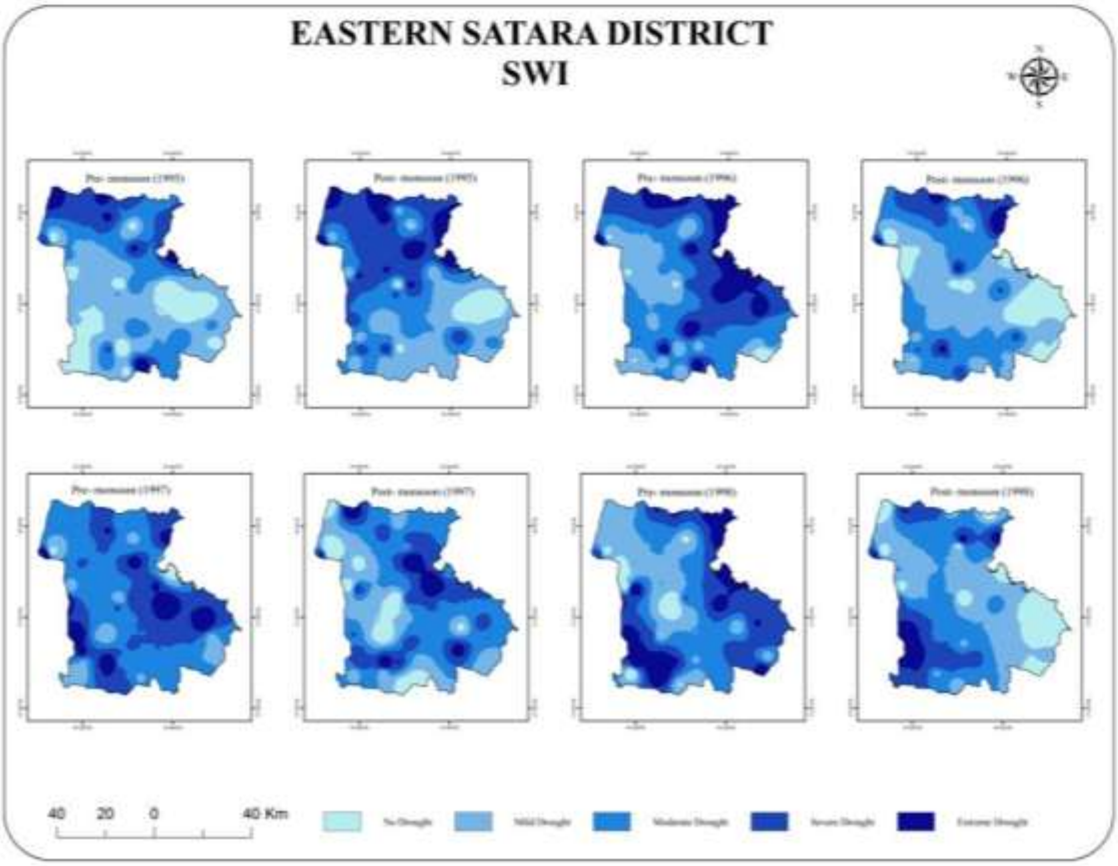
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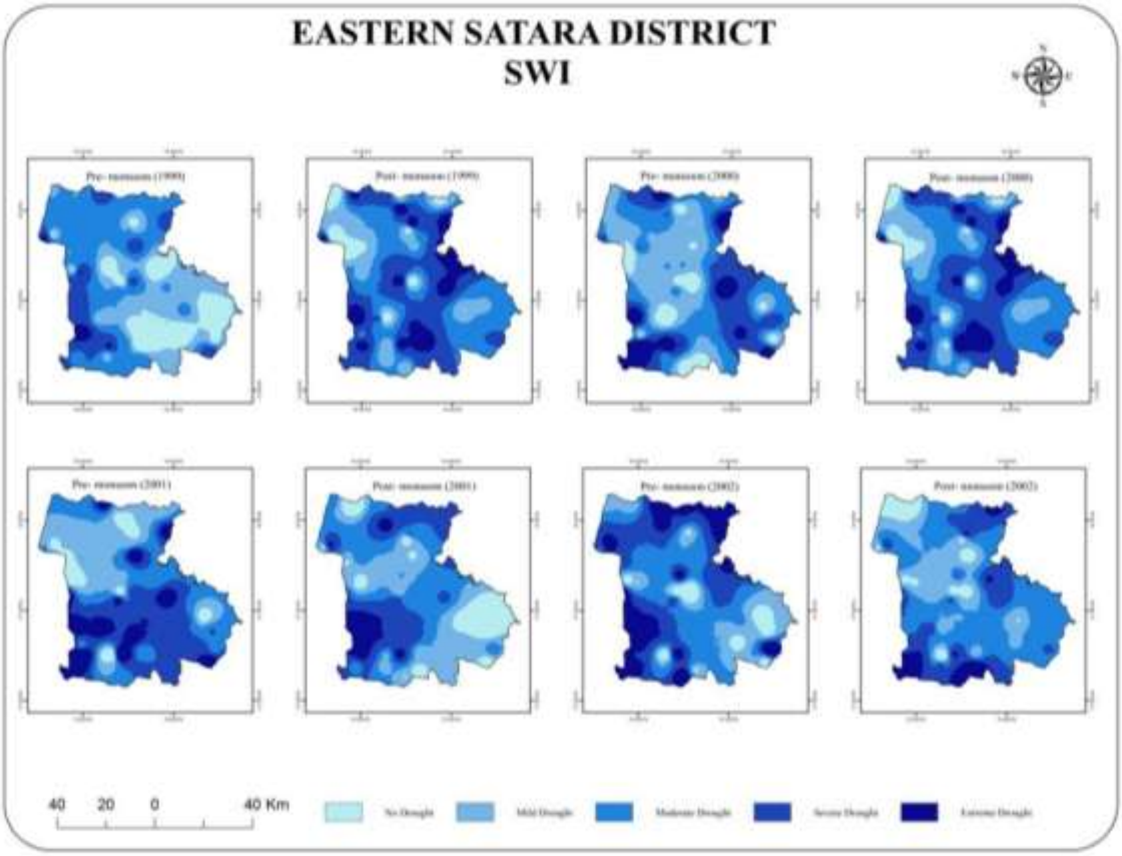
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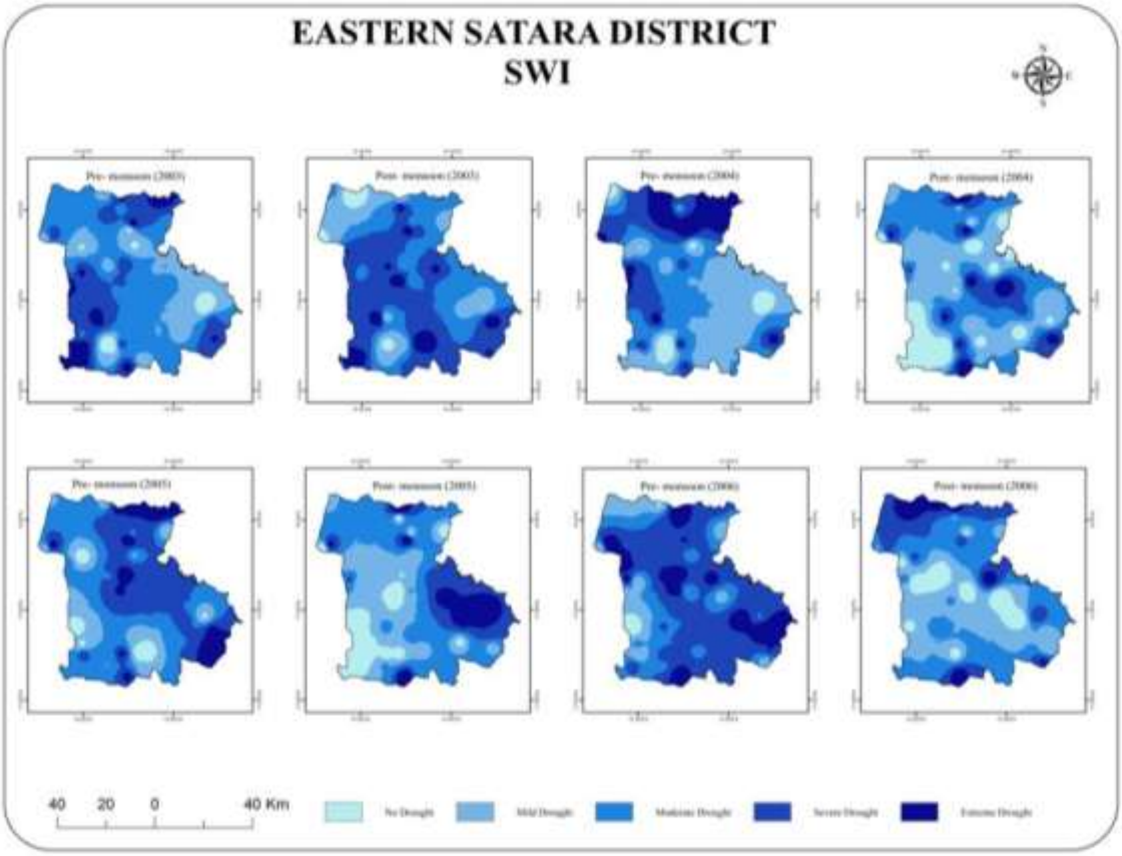
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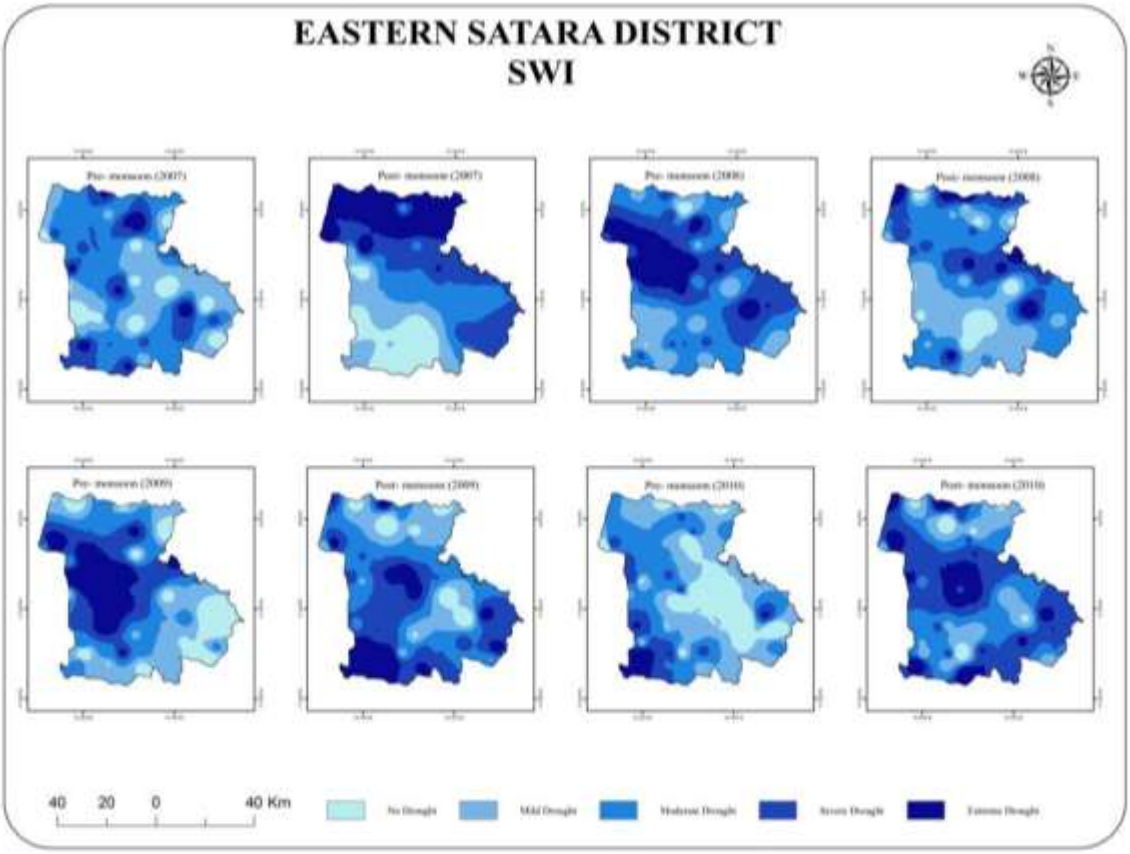
SWI
40 20 0 40 Km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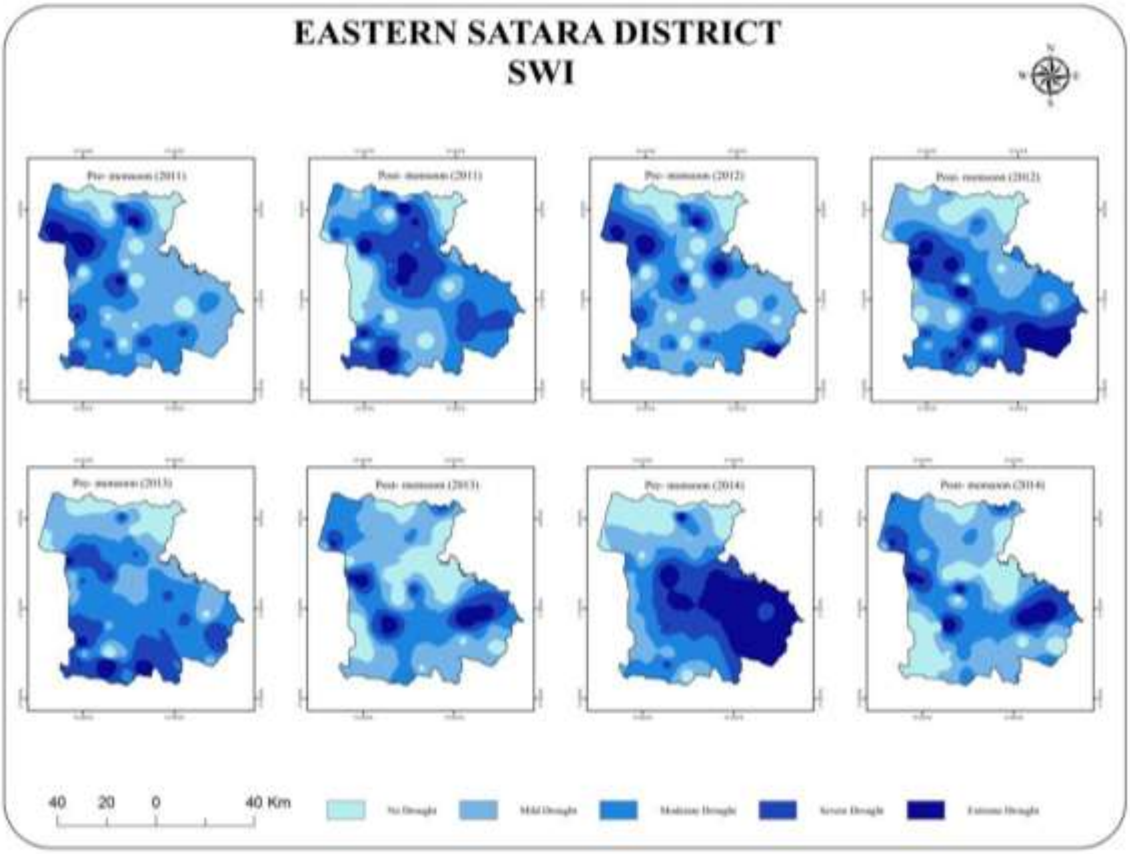
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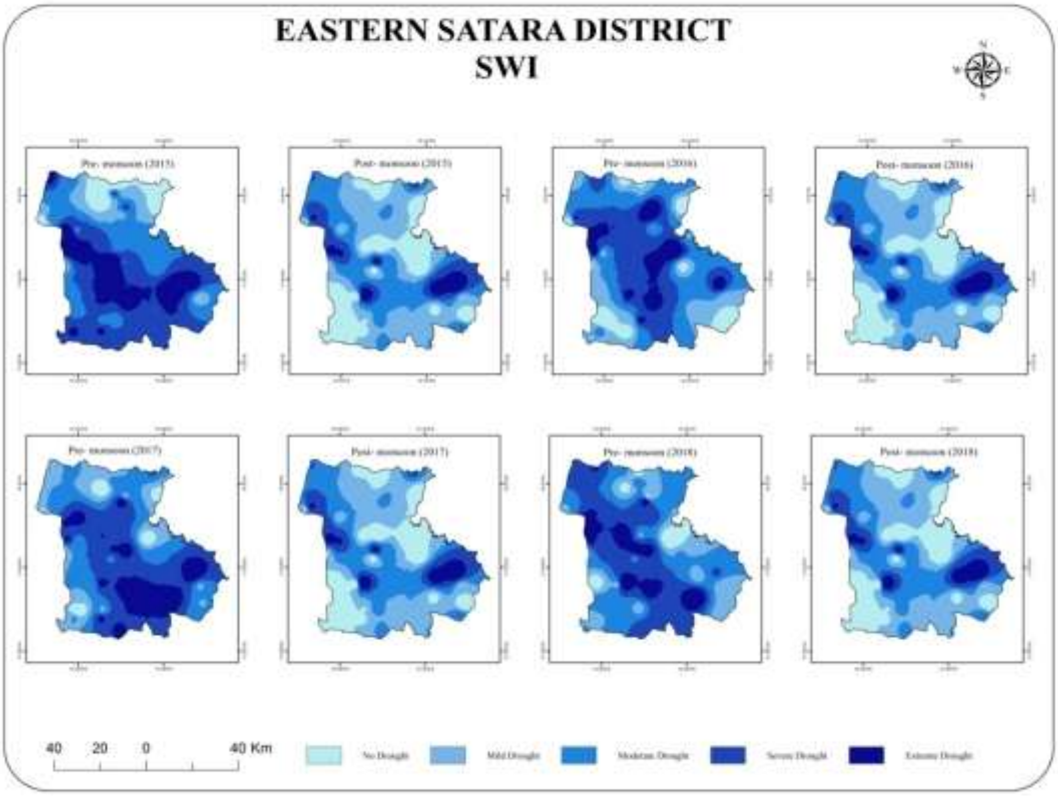


**Figure 3: Spatial variation of hydrological drought due to ground water recharge deficit**

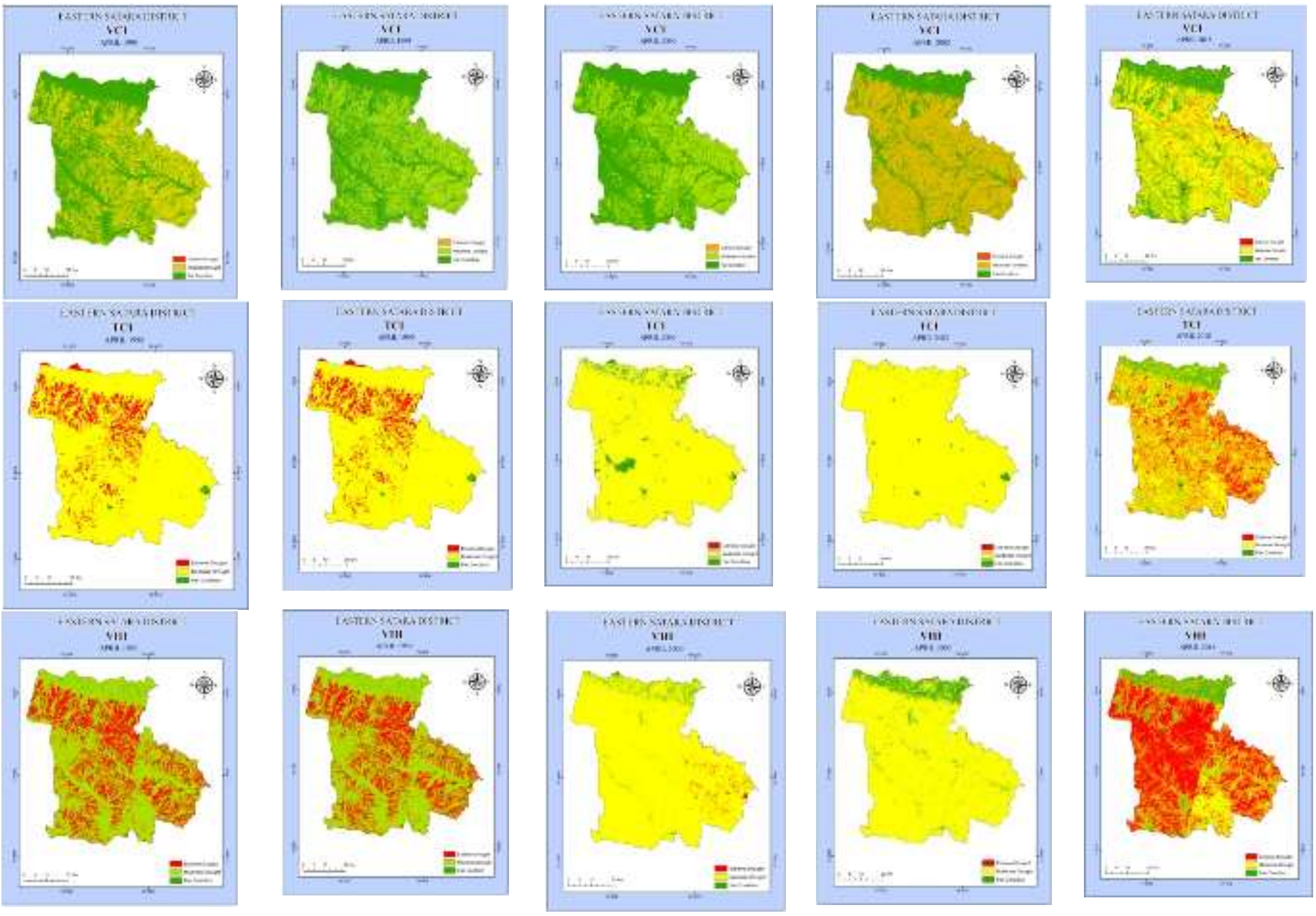


**Figure 4: Spatial variation of drought due to soil moisture, thermal stresses and Vegetation health for April**

Thereafter, drought risk maps have been produced using Landsat data for the drought years. Vegetation indices for April and December are being used to assess the effects of drought on vegetation over the years in the study area. Vegetation Condition Index (VCI) is based on Normalized Difference Vegetation Index (NDVI), the Temperature Condition Index (TCI) resulting from Land Surface Temperature (LST) and both combined indices produced Vegetation Health Index (VHI). The spatial variation of drought affecting the vegetation cover, thermal stress and vegetation health is illustrated in figure 4 and figure 6.

According to VCI, years 1998, 1999, 2002 and 2018 over the large part of study area suffered moderate drought conditions during pre-monsoon season due to acute water stress. Except northern part of study area, these areas are well irrigated because of Nira canal which help to keep the area green even during the drought year.

The vegetation condition was found normal in western part of the study during the pre-monsoon period in year 2000. The uneven distribution and deficit rainfall have great influence on vegetation health in the study area. It was found that years 1998, 1999, 2000, 2002 and 2018 over the large part of the study area experienced fair conditions during post-monsoon period.

TCI shows moderate drought in 2000 as the vegetation conditions were better in 2000 as compared to 1999. The TCI during pre-monsoon period for 1998, 1999, 2002 and 2018 shows high thermal stress in the study area.

Therefore, the total vegetation health for the study area during all four years shows extreme to moderate drought conditions in the study area. The lower values of TCI represent vegetation stress due to high temperature while VCI shows healthy and unstressed vegetation for higher values.[3]

There is no direct relationship between VCI, TCI and precipitation.[26] Extremely unhealthy vegetation (very low VHI) is generally associated with severe moisture (low VCI) and thermal stress (low TCI) and vice versa. However, the health of vegetation can be represented by several combinations of VCI and TCI. The VHI maps for 1998, 1999 and 2018 demonstrate moderate to extreme drought conditions during per-monsoon period.

The maps for 2000 and 2002 reveal moderate drought conditions during pre-monsoon period. VHI maps for post-monsoon period show normal to moderate drought condition in the study area. The calculations of evapotranspiration (ET) assess crop water stress conditions correlate it to results from VCI, TCI and VHI indices. The evapotranspiration was calculated using the equation of Penman-Monteith (figure 5). The evapotranspiration rate was high during the pre-monsoon period (April and May) which creates adverse effects on vegetation condition and is highly prone to drought.

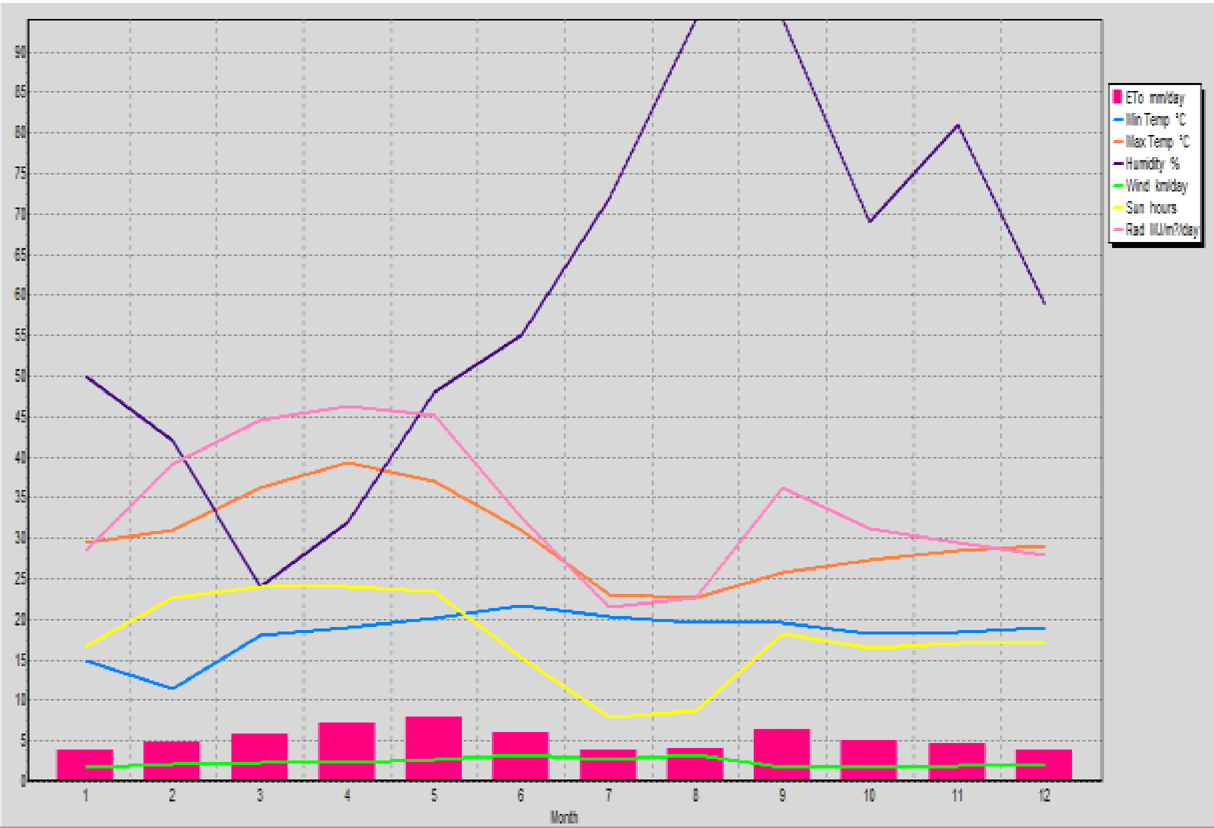


**Figure 5: ET (mm/month) for study area using Penman Monteith equation**

**Figure 6: Spatial variation of drought due to soil moisture, thermal stresses and Vegetation health for December**

**Table 8**
**Correlation coefficient among different indices along with P value for the test of significance**

| | | VHI | TCI | VCI |
|---|---|---|---|---|
| TCI | correlation coefficient | 0.630 | | |
| | P-value for the test for significance | 0.000 | | |
| | | | | |
| VCI | correlation coefficient | 0.393 | 0.200 | |
| | P-value for the test for significance | 0.005 | 0.164 | |
| | | | | |
| VCI | correlation coefficient | 0.172 | -0.238 | 0.206 |
| | P-value for the test for significance | 0.232 | 0.095 | 0.152 |

**Comparison and Correlation:** Rainfall and evapotranspiration are the main responsible factors for drought, while groundwater levels also influence drought conditions. Agriculture drought is a manifestation of meteorological and hydrological droughts.[2] The various drought indices resultant maps indicate hydrological and agricultural drought conditions in the study area. They are not linearly correlated with one another (Fig. 7).

Furthermore, intensity, severity, spatial extent, speed, development and duration of drought are also different in the different region, therefore, it is quite common that when one drought index identifies drought at a particular place, another drought index indicates a normal condition at the same place and time.[2] During the years 1998, 1999, 2000 and 2002, the study area encountered successive poor monsoons and non-monsoon periods resulting in insufficient aquifer recharge, therefore moderate to severe hydrological droughts are found in almost the entire study area except some pockets.

Consequently, the study area has extreme stress on vegetation health resulting in acute agricultural drought during that year. In the year 2018, the entire study area received good rainfall resulting in normal conditions of groundwater level, so vegetation health was excellent during this period.

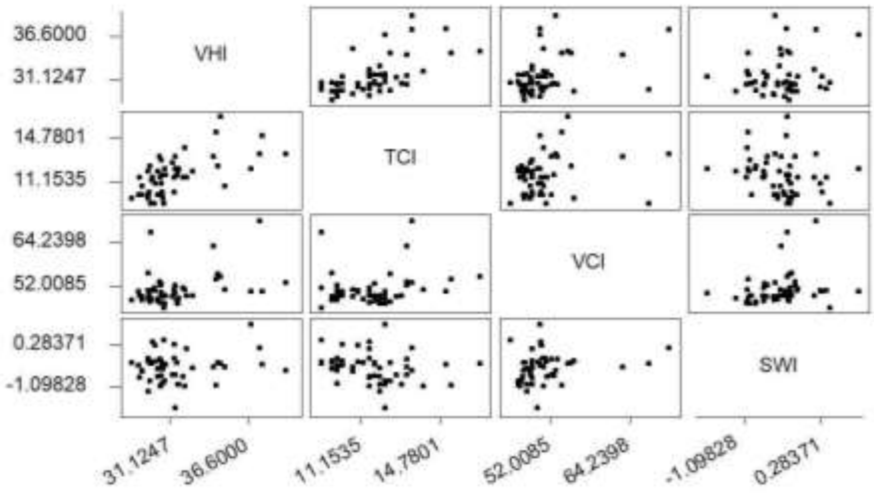


**Fig.7: Correlation coefficient among different indices**

The correlation coefficient among different indices along with P-value for the test of significance is shown in table 8. There was no significant difference observed in agricultural drought indices and hydrological drought index.

## Conclusion

The present study attempts to assess the spatio-temporal extent of agricultural and hydrological drought over the study area using VCI, TCI, VHI and SWI indices. The SWI index was used to assess groundwater conditions in the study area whereas VCI, TCI and VHI indices were studied to assess the agricultural drought conditions in the study area. SWI found that in the years 1992 and 1994 during the pre-monsoon season, major parts of the study area were facing moderate to severe drought and some parts suffered extreme hydrological drought.

In the years 2003, 2004 and 2006, major parts of the study area suffered moderate to extreme drought. The drought condition worsened gradually from the pre-monsoon of 2007 onwards and in the post-monsoon period of 2007, almost the entire study area was in the grief of acute drought. There was a drought in the post-monsoon period of 1995, 1999, 2000, 2007 and 2010, as groundwater level went down due to insufficient rainfall in that year. In the years 2015, 2016, 2017 and 2018 during the pre-monsoon period, many pockets in the study area suffered moderate to severe hydrological drought conditions. The most notable discovery of the SWI time-series map is the alternative change of drought and drought patterns over time.

VCI shows moderate drought conditions during the pre-monsoon period whereas the normal conditions during the post-monsoon period. TCI and VHI show moderate to extreme drought conditions during the pre-monsoon while normal to moderate drought conditions during the post-monsoon period. The SWI reveals that the study area is prone to moderate to severe drought conditions whereas VCI, TCI and VHI reveal that the study area is prone to moderate drought conditions. The present study has used various drought indices based on different hydrological and agricultural parameters that may reflect different aspects of drought. The present investigation is useful for better understanding of the past drought events at spatio temporal level and it will be helpful for future drought mitigation.

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