Analysis of extreme hydrological event using Gravity Recovery and Climate Experiment (GRACE)

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Abstract: The Gravity Recovery and climate experiment (GRACE) is a very important tool to monitor the changes in water resources over the globe which was launched as a twin satellite on May 2002 in lower earth orbit by NASA and German aerospace center. The objective of this work is to study the severity of extreme hydrological events with gravity recovery and climate experiment in Maharashtra, India and for validation, the 2005 flood and 2009-2010 drought of Maharashtra are considered. The GRACE provides 250 gravity profiles per day and that lead to change in water storage within the earth surface. The terrestrial water storage can be determined by taking the average of monthly GRACE anomaly and can be represented by the equivalent water thickness over the earth. The data from GRACE as terrestrial water storage represents the combination of the surface as well as subsurface water and therefore it is an important tool to analyze the overall changes in terrestrial water storage. This study includes the analysis of extreme hydrological events of the 2005 flood and 2009-2010 drought in Maharashtra. For drought, the terrestrial water storage data of GRACE from Jet Propulsion Laboratory (JPL) is used and the monthly average is calculated from the year 2002 to 2015 for determining the monthly deficit in terrestrial water storage. The monthly deficit will represent the drought severity by multiplying duration of deficit and its magnitude. The same approach is used for analyzing flood by GRACE, in which the excess terrestrial water is calculated from its monthly average of GRACE terrestrial water storage anomaly. The data shows the average magnitude of 2009-2010 is -157.794 mm, the highest deficit in the GRACE series. The summer of 2010 also showed the deficit of about - 101.774 mm and the deficit can be observed as a negative value in the deficit curve from May 2009 to May 2010, a twelve-month drought duration. Similarly the 2005 flood can be observed as a positive values in deficit curve, the highest is observed 47.6325 mm and positive graph is maintained throughout the monsoon in 2005 to 2007 which represents the above-average values of terrestrial water storage and the Average magnitude in the year 2005 and 2007 is about 36.60625 mm which shows the good monsoon conditions with correlation coefficient of 0.729 with precipitation deficit curve. As GRACE is capable of providing the surface as well as subsurface water storage data, it can be a very powerful tool to analyze the different hydrological events. It can also be useful for verifying the impact of climate change on terrestrial water storage for near real-time information as it provides monthly data and wide spatial resolution.

Keywords: Extreme hydrological events; GRACE; Drought; Flood; water deficit; Climate change;

I. Introduction

The World Meteorological Organization in 1986 says the drought is a persistent prolonged deficit of precipitation. Drought occurs in climatic zones where the relative precipitation is low and not only precipitation but factors like temperature, humidity, rainfall distribution, and its intensity during cultivation period of crops affect the characteristic, severity and duration of drought(Wilhite, 2000). The UN Convention to combat drought and desertification (UN Secretariat General, 1994) says drought as a phenomenon that causes serious hydrological

imbalances due to significantly below normal precipitation and it affects the land resources and its production system. Food and Agriculture Organization (FAO 1983) of the UN defines the drought as a percent of year when crop lacks moisture. Drought in small agricultural fields can also be monitor by Streamflow when the observation of the annual value of daily streamflow is smallest(Gumbel, 1963). Maximum people are affected by drought than any other natural hazard as it affects the food chain which eventually harms the ecosystem.(Gumbel, 1963; Jomaa, Saab, Skaf, El Haj, & Massaad, 2019; Kay, Rudd, Davies, Kendon, & Jones, 2015) Drought can depend on the reduction in terrestrial water storage and can lead to crop failure and water quality deterioration. It also affects the socio-economic conditions of human habitats.(Swenson, Wahr, & Milly, 2003) and such complex hydraulic event may cause major economic damages (Peters et al., 2002) in the country like India where monsoon is predominant and more than 20% deficiency in southwest monsoon consider as a dry year which sometimes shows the reduction of 2 Mha in cultivation land like in 2009-2010. (Murthy, Chakraborty, Sai, & Roy, 2011)

Soule and Mooley, 1980, used Standardized Precipitation Index (SPI) as a basic indicator for drought analysis and it is easy to interpret and spatially invariant and its probabilistic approach may be useful to analyses risk (Tehrany, Pradhan, & Jebur, 2013) SPI gives a better representation of dryness and wetness than other Indices like PDSI but it may not give better picture of monthly water balanced based drought indices and it will only give the transformation of probability of observed precipitation. To study drought in India due to southwest monsoon from June to September, the Standardized Precipitation Index is used.(Pai, Sridhar, Guhathakurta, & Hatwar, 2011) Evaluation of drought requires specific time scale, it also helps to study its impact and it also helps to analyze active and break events in drought. (Pai et al., 2011)'s Study shows SPI is the better index for analyzing drought than Percent of Normal Precipitation for Marathwada.

Healthy vegetation and crops can be judged by satellite-based vegetation index for the signature of droughts on crops as it gives the spectral reflectance ratio between Near Infrared and Red spectrum of electromagnetic wave(Kogan, 1990). (Burgan & Hartford, 1993) studied relative greenness as the percent value of a pixel with reference of average historical greenness of pixel. Drought characteristic can be studied by Normalized Difference Vegetation Index (NDVI) based index as the deviation from mean as the reference of the standard deviation of a pixel for the selective period (Peters et al., 2002)

Gravity Recovery and Climate Experiment (GRACE) was launched by NASA and German Aerospace Center (DLR) for monitoring gravitational changes on earth with the help of K-band Microwave ranging sensor and global positioning system receiver(J. L. Chen, Rodell, Wilson, & Famiglietti, 2005; J. L. Chen, Wilson, Tapley, & Ries, 2004; Swenson & Wahr, 2002; Swenson et al., 2003). Change in gravity may lead to change in mass and it can further be converted into a change in water resources in equivalent water thickness.(J. Chen et al., 2018; Feng et al., 2013; Hasan, 2009; Sharma, 2014) GRACE data is processed and corrected by Jet Propulsion Laboratory (JPL) by NASA, GFZ German Research Centre for Geosciences and Center for space research, university of Texas.(Swenson et al., 2003)

This paper discuss about the application of Gravity Recovery and Climate Experiment to analyze the extreme hydrological event. The paper is divided into the three sections, first section discuss about the data used to analyze the extreme hydrological event specially drought and flood. The next section discusses about the findings for analyzing drought by different drought index and compassion with the GRACE based drought index. This section also give a glimpse about the analysis of historical flood event based on the terrestrial water storage for the major basins in India like Indus, Ganges, Godavari, Krishna, Narmada and Mahanadi. The final section discusses about the future scope of the finding the conclusion. This section is also

provides the insight about the application of the GRACE data for analyzing and prediction of the extreme hydrological events.

II. Data and Methodology

The Marathwada is an administrative region of Maharashtra comprise of eight districts which expands from North latitude 17°5’ to 20°5’ and east longitude 70°5’ to 78°5’. The total geographical area of Marathwada is about 64,000 sq. Km. The Marathwada is located at central Maharashtra and comes under semi-arid region with rainfall of 700 mm and maximum and minimum temperature is about 40° C and 6° C respectively. (Ramachandran et al., 2019) Marathwada have black cotton soil and with the relatively low humidity it makes good environment to cultivate cotton, sugarcane, wheat and other rainfall dependent crops.

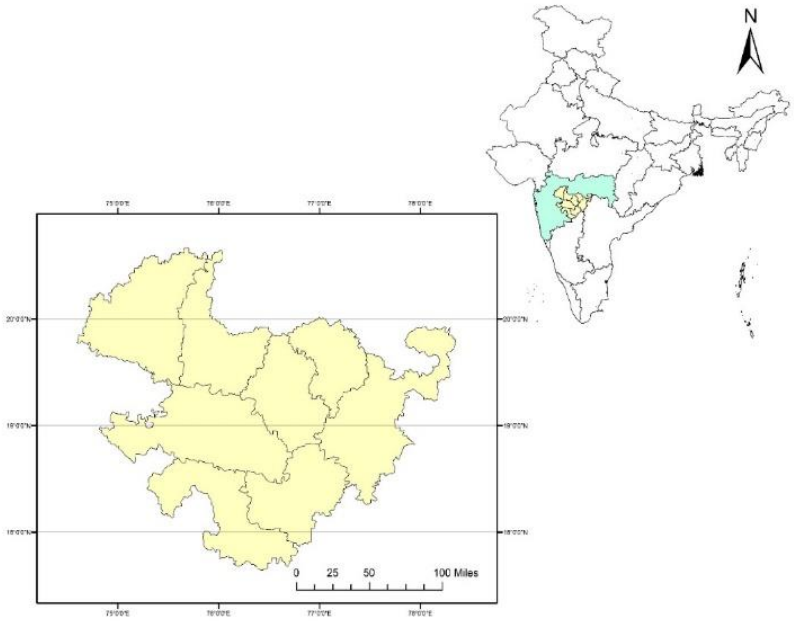

Fig 1: Location of Marathwada as a study area on Map of India and Maharashtra.

The rainfall pattern of Marathwada is changing throughout the year for last few decades. Data shows the decreasing trend of annual rainfall of Marathwada from 1901 to 2017. As the rainfall days and intensity for June and September is shrinking and opposite treed is observed in July and August. From the data we can state that the rainfall days are shrinking and that is affecting the total crop cultivation period. The crop production is mostly depending on rainfall and by decreasing trend one can say that the frequency of drought is increasing. From the data decreasing trend is observed in rainfall for month June from 1901 to 2017 and increasing trend is observed in mid monsoon months like August and July from 1901 to 2017.

The objective of this study is to find out the reliability of the GRACE-based drought index for Marathwada region. The drought in Marathwada is monitored by standardized precipitation index (SPI) as it gives the idea about precipitation deficit it fails to analyze the drought for Rabbi or post-monsoon crops. The GRACE-based data can be used to determine the monthly terrestrial water storage (TWS). TWS can be used to represent the actual water availability throughout the year for the cultivation of crops.

This study includes the determination of standardized precipitation index (SPI), NDVI-based drought index and GRACE-based drought index for Marathwada region. The monthly GRACE

based index is then compared with monthly SPI and NDVI- based drought index or Standardized vegetation index.

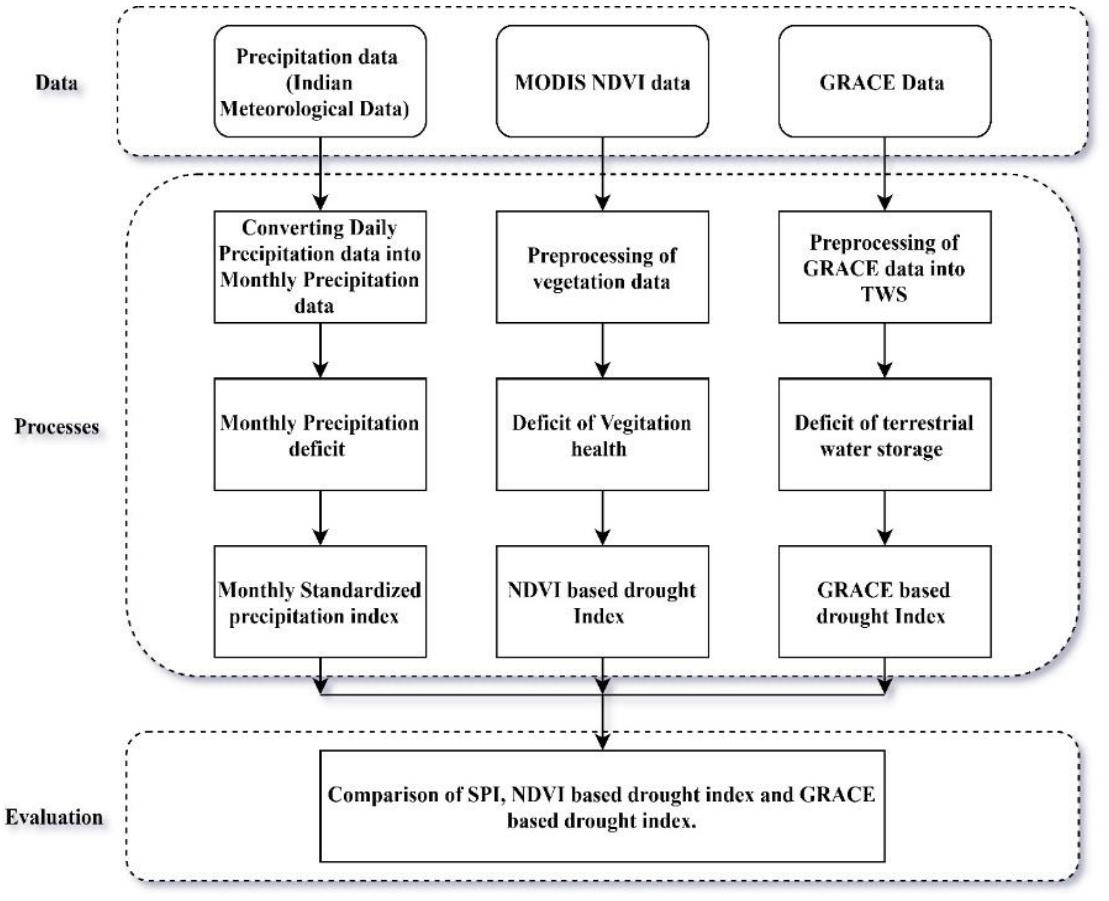

Fig 2: Flowchart of methodology for evaluating standardized drought index, NDVI based drought index and GRACE terrestrial water storage based drought index.

Figure represent the flow of methodology for evaluating different drought index along with GRACE based drought index. For calculating Standardized vegetation index the daily precipitation data form Indian meteorological department is used and then it was converted into monthly rainfall data form year 2002 to 20011. NDVI based drought index is calculated with the help of regional MODIS NDVI data (https://glam1.gsfc.nasa.gov/). The regional NDVI data is then used to calculate the monthly healthy vegetation deficit. The NDVI based drought index may be used to determine the agricultural condition of Marathwada. The GRACE based drought index is calculated for monthly terrestrial water storage. The data is obtained from the processing center of GRACE Website of Center for Space Research (CSR) of University of Texas at Austin. (http://www.csr.utexas.edu/grace). The monthly data is then used to determine the deficit of monthly terrestrial water storage and then the index is calculated. The GRACE's terrestrial water storage is comprise of different water resources so the drought index may replicate the total deficit of all water resources

Standardized Precipitation Index

The standardized precipitation drought index is calculated based on the average precipitation deficit. The SPI can be calculated in the monthly, 3-month, 6-month, 9-month and 12-month interval. In this study the monthly SPI is used. The SPI is easily calculated. The SPI gives the good interpretation of drought for monsoon season spatially and temporally. SPI gives a better

representation of dryness and wetness than other Indices like PDSI but it may not give better picture of monthly water balanced based drought indices and it will only give the transformation of probability of observed precipitation.

NDVI-based Drought Index

For calculating NDVI-based drought index Moderate resolution imaging spectroradiometer (MODIS) vegetation index product is used (Lan, Zhang, Lacey, Hoffmann, & Wu, 2009). NDVI is used to determine the condition of healthy vegetation. It ranges from -1 to 1. These values represent the health of vegetation. Values near one represent the healthy vegetation. It is calculated by taking ratios of spectral reflectance of NIR and Red spectrum of electromagnetic wave (Bechtel et al., 2012)

NDVI-based drought index is calculated by taking difference between NDVI values ($NDVI_{ij}$) of each Pixel with monthly average ($\overline{NDVI\ ij}$) of each pixel and then it is divided by the standard deviation. For developing drought index, the deficit in vegetation health index (D_{VI}) is calculated.

$$D_{VI} = NDVI_{ij} - \overline{NDVI\ ij} \qquad (1)$$

Vegetation drought index is then calculated by dividing the deficit vegetation health index by the monthly standard deviation of NDVI ($\bar{\sigma}$)

$$VDI = D_{VI} / \bar{\sigma} \qquad (2)$$

By NDVI-based drought index, the drought severity is dived into five categories from very poor to very good. Following are the classification and NDVI- based drought index values(Peters et al., 2002)

NDVI-Based drought index range	**Classes**
0 – 0.05	Very Poor
0.05 - 0.25	Poor
0.25 – 0.75	Average
0.75 – 0.95	Good
0.95 – 1.00	Very good

Table 1: Classification based on the normal probability distribution of NDVI-based drought index into five classes.

The above classification is based on the normal probability distribution of NDVI. The classes very poor or poor represent the lower NDVI values than the average value of that month of year. Similarly the good and very good represent the high NDVI values than the average values of NDVI of that month in the year.

GRACE- based Methodology

Gravity recovery and climate experiment (GRACE) was launched as a joint mission by German space research agency and NASA to determine the change in gravitation filed of earth. To determine the change in gravitational field of earth the two satellites with precise distant meter and GPS is launched in 2002. The change in distance between two satellites is then converted

and downscaled into gravitational change of earth. Further the data is downscaled and processed to use as a change in terrestrial water storage. The Terrestrial water storage of GRACE data can is then converted into the equivalent water thickness to replicate the change in water storage, especially ground water. The change in terrestrial water storage shows not a single water resources but complex combination of different water resources and segregating these water resources may require different observed data and other information. Proposed drought index involved the overall terrestrial water storage and the monthly deficit is calculated by taking difference between the monthly terrestrial water storage and monthly average terrestrial water storage. To form the index the terrestrial water deficit is then dived by the standard deviation of monthly GRACE data. The index is calculated based on the water storage deficit (D_{WS}). The water storage deficit is calculated by taking difference between the monthly values of terrestrial water storage (WS_{ij}**)** for i^{th} month of j^{th} year to the monthly average of series of terrestrial water storage ($\overline{WSij}$).

$$D_{WS=} WS_{ij} - \overline{WSij} \qquad (3)$$

The GRACE based drought index (GDI) is then calculated by dividing water storage deficit (D_{WS}) by its standard deviation ($\bar{\sigma}$)

$$GDI= D_{WS} / \bar{\sigma} \qquad (4)$$

The GRACE based drought index represent the actual deficit in the water storage and replicate the actual drought condition for year. The GRACE based drought index may be the actual measurement of the drought for post-Monsoon crops. The severity can be calculated by considering peak value of drought index and period can be calculated by considering the start and end of t6he negative graph which represent the values below average. The negative value of GRACE based drought index shows the drought period and positive value represent non-drought or average to good water storage condition.

III. Result and Discussion

2009 Marathwada drought analysis

Drought occur in 2009-2010 was one of the extreme drought of Marathwada and all over India and it was considered as the worst drought in 40 years by The Economic Times. In this study the severity of drought is calculated using change in GRACE terrestrial water storage data and drought index is formed as already discussed in methodology which include the calculation of monthly water deficit for Marathwada region. The GRACE based drought index gives the idea about the deficit in the total terrestrial water storage by considering the monthly average of GRACE 15 year series. For year 2009-2010 the negative value is observed from May 2009 to January 2010 and it drops again in March 2010. The negative value of GRACE based drought index shows the occurrence of drought in mid-May till next year monsoon. The values of GRACE based drought index is noted as -3.759 in September-October 2009.

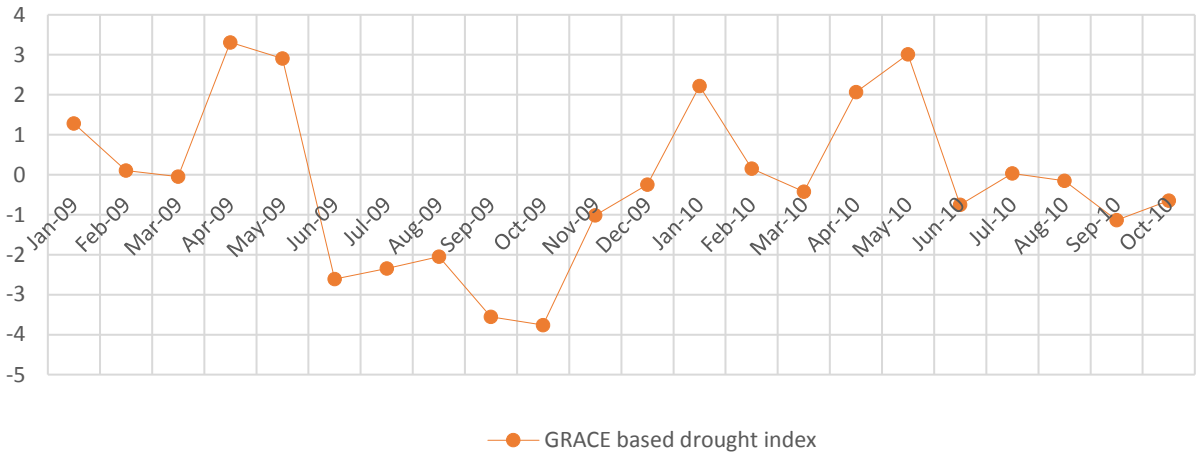

Fig 3: The GRACE based drought index for Marathwada

As GRACE terrestrial water storage include not only surface water but it includes soil moisture and ground water storage. Comparing GRACE based drought index with other conventional drought index like Monthly Standardized Precipitation Index (SPI-1) and NDVI based drought index, the GRACE based drought characterization is validated. The monthly SPI shows the peak negative values in month of June 2009 as -1 which shows the historically low deficit in rainfall.

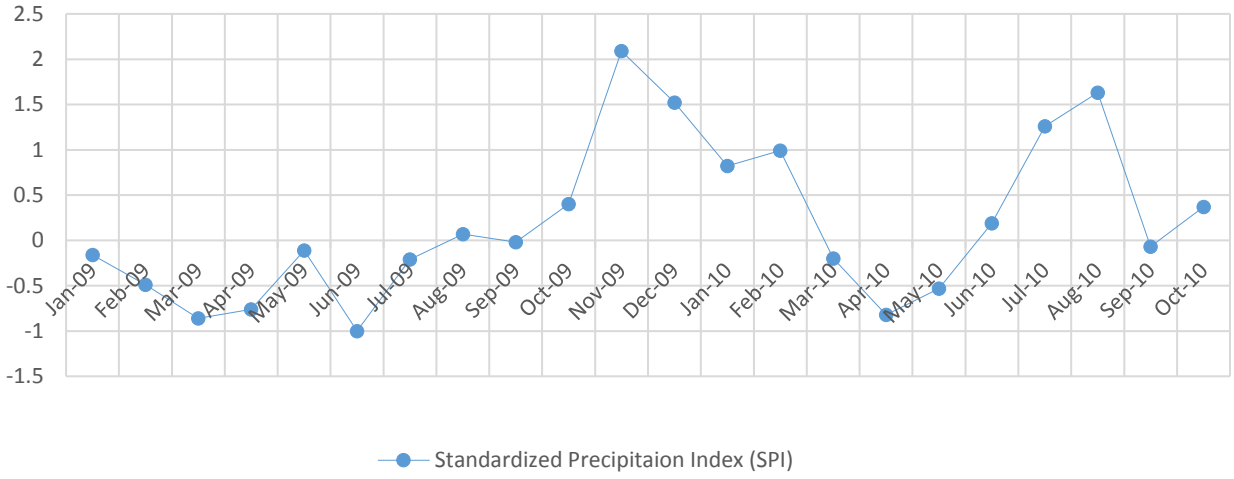

Fig 4: The Standardized Precipitation Index (SPI) for Marathwada

This low rainfall is going to affect the total terrestrial water storage throughout the year and it replicate in the drought index which is based on NDVI and GRACE. The NDVI based drought index shows the monthly vegetation health deficit. The NDVI based drought index shows the negative value in the post monsoon month as the low rainfall affect the vegetation health throughout the year. The GRACE based drought index shows the both scenario of SPI and NDVI based drought index as it covers the soil moisture, groundwater storage and surface water storage altogether. The NDVI based drought index shows relatively good values in monsoon period as the vegetation health is directly proportional to the availability of water into root zone of vegetation. The crop production can be judge by the NDVI based drought index.

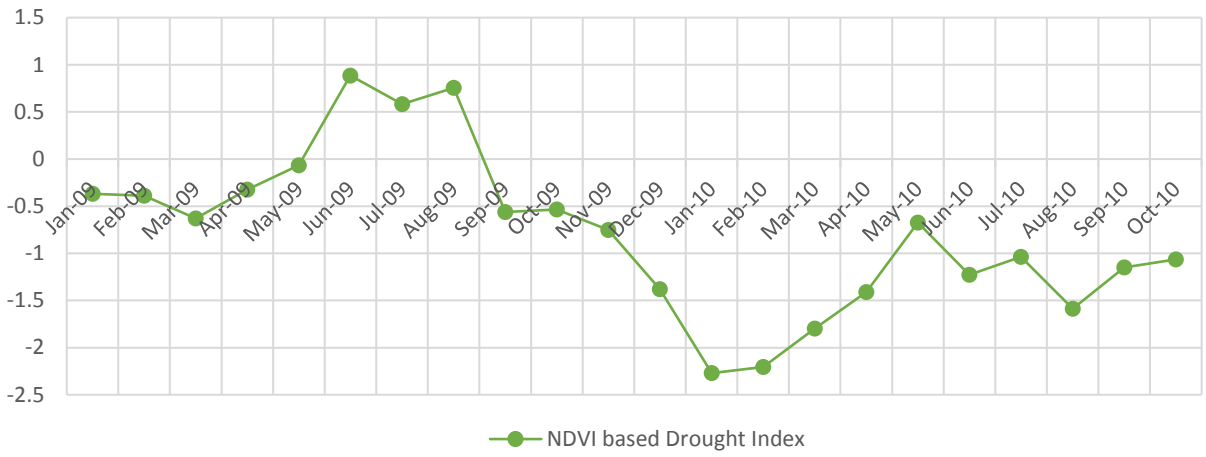

Fig 5: NDVI based drought index for Marathwada

The comparison of NDVI and GRACE based drought index shows the very good correlation for Monsoon season and relatively good correlation for post and pre monsoon seasons. The SPI shows the poor correlation with other drought index as it only shows the deficit of rainfall.

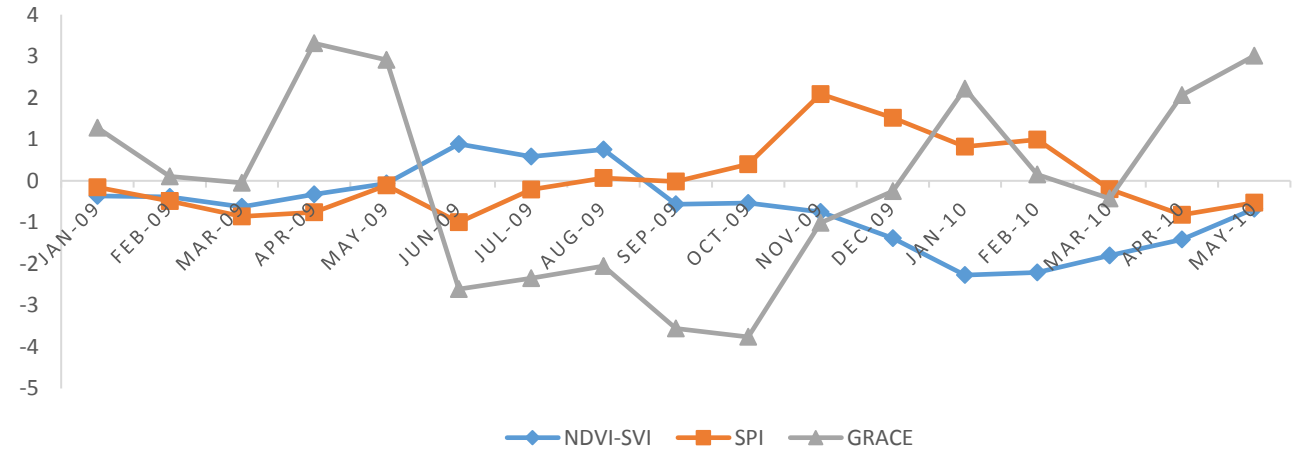

Fig 6: The line plot of different index for drought year 2009-2010

Indices	Pre-Monsoon	Monsoon	Post-Monsoon
NDVI and GRACE based drought index	**0.5631**	**0.7973**	**0.6914**
SPI and GRACE based drought index	0.0667	0.001	**0.729**
SPI and NDVI based drought index	**0.5332**	0.2273	0.1776

Table 2: Correlation of GRACE based drought index with NDVI based drought index and SPI for Pre-Monsoon, Monsoon and Post-Monsoon seasons for year 2009.

Basin analysis

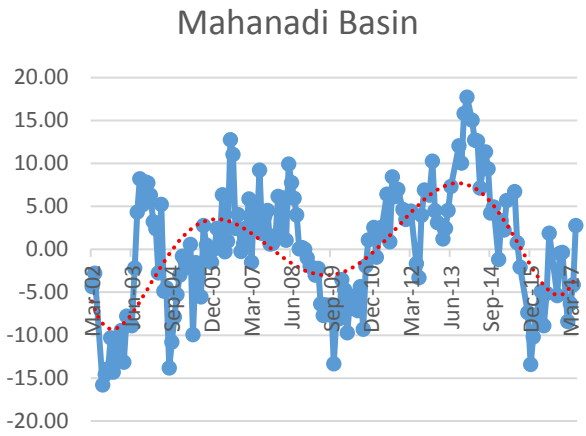

Fig 7: The Terrestrial water storage of Mahanadi basin

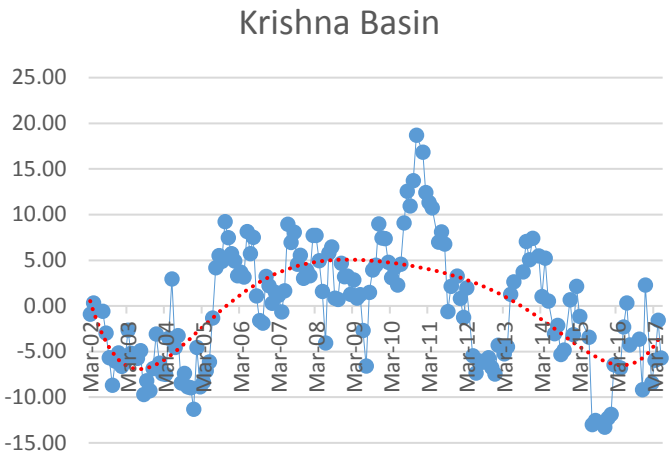

Fig 8: The Terrestrial water storage of Krishna basin

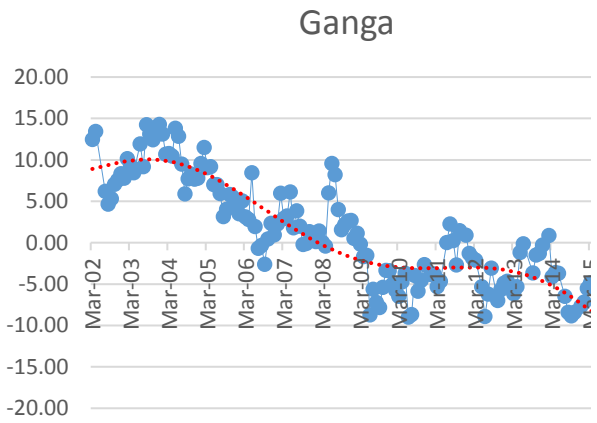

Fig 9: The Terrestrial water storage of Ganges basin

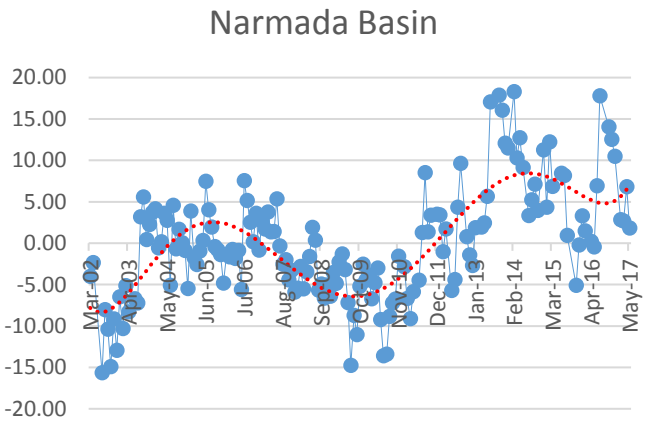

Fig 10: The Terrestrial water storage of Narmada basin

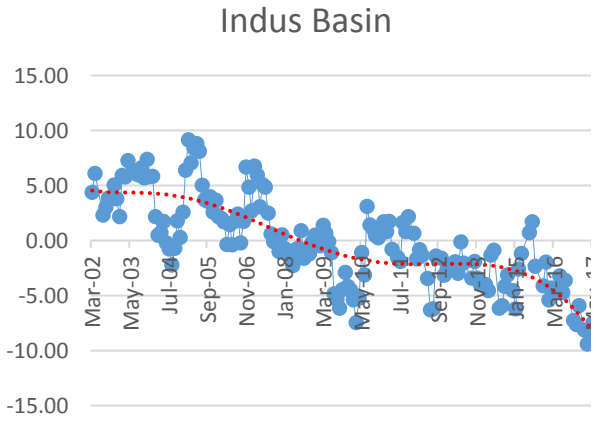

Fig 11: The Terrestrial water storage of Indus basin

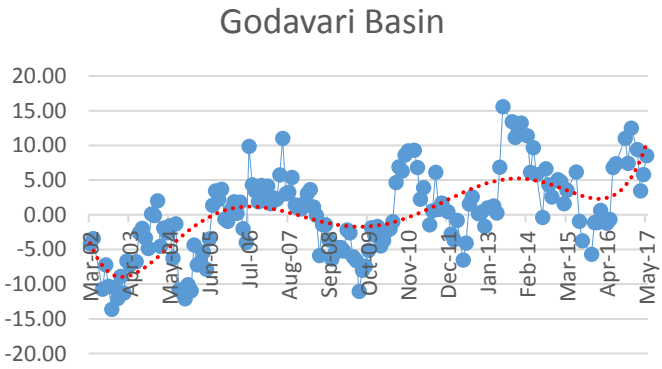

Fig 12: The Terrestrial water storage of Godavari basin

The above graph shows the terrestrial water storage of major basins in India. The red line is six degree polynomial which shows the seasonal flood and drought when the line is in increasing or decreasing trend respectively. The average linear trend shows the overall performance of the basin. The northern basins like Ganges and Indus is having the continues deceasing trend through the historical period of GRACE, which shows the reduction in the terrestrial water storage, specially the ground water storage as it is well known that the river basins of Ganges and Indus are exploding for urbanization in India and Pakistan. The southern basins shows the frequent floods and drought by its change in trends. The Mahanadi shows the maximum variation in the trend as the frequency of flood and drought is higher.

IV. Conclusion and summary

The study shows the GRACE based drought index include all aspects of water storage deficit including groundwater and soil moisture which important for region like Marathwada as many farmers depends on ground water resources like well and borewells. NDVI based drought index fails to show the monsoon drought condition but it can be used to for characterization of post monsoon drought as it shows the vegetation health index. The Standardized Precipitation index may show the rainfall deficit for monsoon season but it fails to recognize drought and its severity in post and pre monsoon period. As 2009 and 2004 drought shows significant correlation with GRACE based drought index and NDVI based drought index, one should adopt these indices for characterization of drought. The duration and severity can also be calculated by GRACE based drought index more accurately. The GRACE based drought index shows the reasonable precision for monthly drought analysis where the groundwater is the major source of water. Gravity recovery and climate experiment have a capability of providing monthly terrestrial water storage data. After 2017 the GRACE-FO is providing data with more accuracy so the real time drought characterization is possible for large area as the spatial resolution of GRACE is good. The prediction of drought can be possible with the help of GRACE mission as the terrestrial water storage is depends on the rainfall in the Marathwada as it is the only source of water. The GRACE is very string tool to understand the ground water changes in the region and it will help to policymaker to understand the drought condition and can plan the new agricultural pattern in Marathwada. The GRACE based drought index shows good correlation with NDVI based drought index which replicate the vegetation and crop health. The researcher may use GRACE based drought index to analyze the local condition of drought according to the use of different water resources. The Stream flow drought index (SFDI) will also use to judge the GRACE based drought index where the crop cultivation is depending on only single stream of water. The GRACE can also use to identify the basin performance by the historical terrestrial water storage analysis. The floods can be analyze by determining the above average trend of the GRACE index. The reliability of this drought index can be calculated by comparing different drought indices in the different categories like hydrological droughts, meteorological drought and agricultural drought.

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