MICRO-LEVEL DROUGHT VULNERABILITY ASSESSMENT USING STANDARDISED PRECIPITATION INDEX, STANDARDISED WATER-LEVEL INDEX, REMOTE SENSING AND GIS

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ABSTRACT: The present day drought management practices adopt crisis management approach and not development programs for self sustainability. Drought vulnerability (Geographical, Meteorological, and Bio-physical, Agriculture, Water resources and Demographic) assessment using exposure, sensitivity and adaptability is attempted in this study and demonstrated over a river basin, tributary of Krishna river system India. Satellite information and ground based observations and derivative indices such as Standardized Precipitation Index (SPI), Rainfall Anomaly Index (RAI), and Standardized Water Level Index (SWI) were used in the drought vulnerability assessment.

1. INTRODUCTION

Drought is a recurrent phenomenon causing socio-economic imbalance in rural areas. Drought is defined as the extreme persistence of precipitation deficit for a specific period of time over a region. The precipitation deficiency instigates meteorological drought which subsequently impacts soil moisture content, water availability and crop growth and production. Climate change studies indicate that the Tropical Asia and Africa could experience a significant change in the frequency of drought occurrence and intensity, that could affect the sustainable livelihood. Agriculture continues to be sensitive to drought conditions despite technological developments in weather analysis and crop management. The adversities arising out from drought management emphasize the importance of short and long term strategies at different ground levels - macro (region/country), meso (state/district/country) and micro-levels (village/ communities, etc.). Drought plans prepared place greater emphasis on drought mitigation as crisis management and not long / short term measures to cope-up with situations. Identification of vulnerability, sensitivity and adaptive capacity would help in preparedness and mitigation process.

Several indices and methods have been developed using meteorological, hydrological, vegetation and soil parameters to identify and monitor droughts at various temporal and spatial scales. These indices are categorized based on *meteorological* (Standardized precipitation index (SPI), Rainfall anomaly index (RAI), Palmer drought severity index (PDSI), soil moisture (Crop moisture index(CMI), Crop water stress index), *hydrological* (Water stress index) and *satellite* (NDVI, Enhance vegetation index (EVI)) based indices (Wilhite and Smith 2005). These indicators can't express formation mechanism of crop drought well. There exists good correlation between NDVI and SPI in predicting agriculture drought (Dutta *et al*., 2012). SPI was used to assess meteorological droughts and SWI for the groundwater fluctuation and droughts events. Decrease in groundwater recharge followed by fall in groundwater levels and a decrease in groundwater discharge (van Lanen and Peters 2000). Groundwater recharge deficit is assessed by standardized water level index (SWI) (Bhuiyan 2004). The micro level impact at village and household levels, result in a considerable intensification of household food insecurity, water related health risks and loss of livelihoods in the agricultural sector.

The objective of this study is to develop a methodology in delineating village vulnerable to drought (settlement unit).

2. METHODOLOGY

Spatial and non-spatial information collected from rain gauges, land use/land cover from satellite data, water availability using SWAT, ground water level, village area from population census information were geo-referenced and created a geo-data base using ArcGIS 9.2 platform. Rainfall (1986 to 2013) from 18 rain gauges was used to assess the yearly, monthly and annual rainfall distribution. The weekly rainfall was used to estimate rainfall deficiency and supplementary irrigation requirement. Rainfall anomaly index (RAI) and Standardized precipitation index (SPI) were calculated and interpolated spatially. Surface runoff (water availability) of the basin and sub-basins were computed using Soil and Water Assessment Tool (SWAT) model and the results were statistically calibrated and validated. The groundwater level fluctuations (pre-monsoon and post-monsoon) were used in the Standardized water-level index (SWI). Parametric classifications of indices were made and weights of individual parameters were assigned in arriving at the integrated drought vulnerability.

2.1 Peddavagu, river basin

This approach was demonstrated at Peddavagu, sub-basin of Krishna river system (Figure 1) flowing through semi-arid region in the south central peninsular India, that experiences drought events every alternate year. The climate of the area transits from tropical to subtropical Climate. The region has four distinct climatic seasons as summer, winter, south west and north east monsoon. The mean annual rainfall in the basin is around 663 mm. It is received mainly during the south-west (June - September) monsoon season. The summers are relatively hot and the period is from March to May with temperature ranging from 32 to 41.5ºC. The winter temperature ranges from 16.9 to 19.1ºC i.e. from November to January. Agriculture and allied activities are the main livelihood opportunities of the rural families in the Basin. The region follows two agricultural seasons, viz, kharif (June to October) and rabi (November to March). Paddy is grown in the basin, along with other crops as sorghum, pearl millet, finger millet, maize, groundnut, castor, vegetables, sunflower, chilli, and red gram are also being cultivated. Kharif crop cultivation is dependent on rainfall and groundwater, but rabi crop is solely dependent on groundwater owing to the depletion of water in surface water bodies. Irrigation water during rabi season is from groundwater. The major soils found in the basin are clayey soils, cracking clay soils, gravelly clay soils, gravelly loam soils, and loamy soils. The basin has experienced severe droughts in 1997, 1999, 2002 and 2004 and incurred huge losses to farm community. There is a long history of out-migration of people (mostly farmers) from this region and it increases with passing years and severity of drought. Traditional cascade systems of tanks prevalent are not in operational conditions. The basin has 4 reservoirs and 1556 tanks that store runoff. The reservoirs in the region were reported to have storage of less than half of the actual capacity due to low rainfall runoff and degradation. The low runoff also has similar impact on tanks located in the basin. Agriculture is primarily rain fed with a kharif crop cultivation of 16.3 % of the basin while one third is left fallow (16.6%). The kharif and rabi cultivation is limited to bore well irrigation support. Regions with more crop acreage are susceptible to more financial losses during droughts and accordingly highly vulnerable. The surface and groundwater irrigated area information was used in determining the sensitivity of an area.

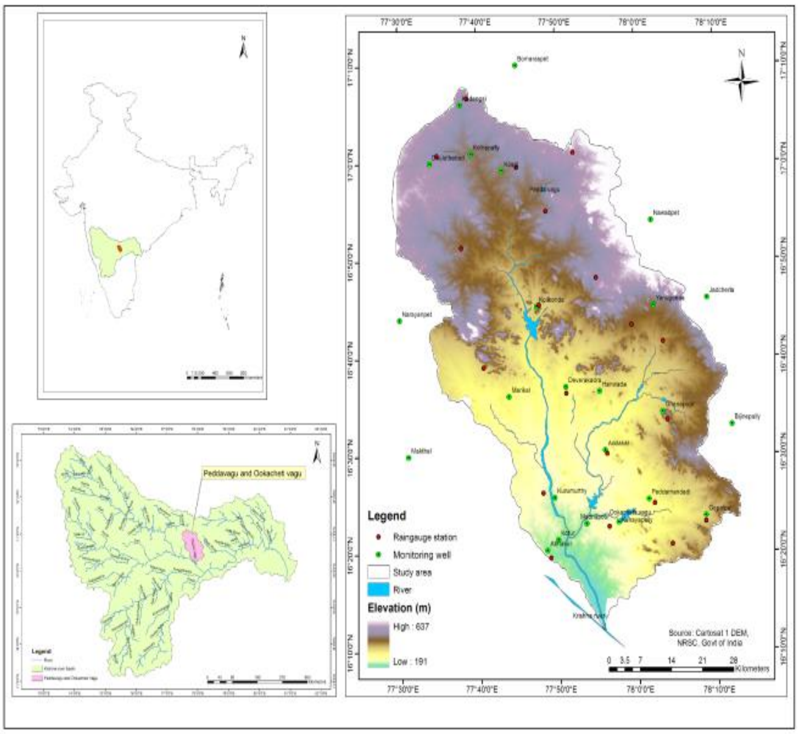

Figure 1. Location of Peddavagu river, tributary of Krishna river system India

3. PARAMTER ASSESSMENT

3.1 Meteorological

18 rain gauges spread around this region have recorded annual rainfall of 1350mm (maxi) in 2012 and 240 mm (mini) at in 2004. The uneven distribution of rainfall and dry spells exert more pressure on available water resources during crop growth stages. The years with 12 to 15 dry spells during kharif (June – October) season have resulted in severe drought years (1999, 2002, 2004, 2006 and 2008). The frequencies of dry spells were determined for kharif season and were incorporated in assessing the exposure to drought.

Percentage annual rainfall departure from the long term mean annual rainfall was used for drought assessment. Percent rainfall variation of each year was further categorized into four percentage ranges i.e. 0 to 10, 10 to 15, 15 to 20 and greater than 20.

$$\text{Percentage of deviation} = \frac{(P_{act} - P)}{P} X\ 100 \tag{1}$$

Where, P_{act} - Precipitation of the region, P – Mean precipitation of the region. Even during the mean rainfall periods, the available rainfall is not sufficient to meet all the water requirements in many parts of the basin. The deficit volume of 20 to 40% is extracted either from surface water bodies or groundwater aquifers based on availability.

Rainfall Anomaly Index (RAI) is used to assess and identify droughts, drought severity and variability by comparing with some established rainfall amount. It is estimated as below for positive anomalies:

$$RAI = \frac{+3[RF - MRF]}{[MH10 - MRF]} \tag{2}$$

and for negative anomalies:

$$RAI = \frac{-3[RF - MRF]}{[ML10 - MRF]} \tag{3}$$

Where, RAI represents the annual RAI, RF is the actual rainfall for a given year, MRF is mean rainfall of the total length of record, MH10 is the mean of the 10 highest values of rainfall on record, and ML10 is the mean of the 10 lowest values of rainfall on record. A ranking of nine classes of rainfall abnormality ranging from extremely wet to extremely dry and range of each class.RAI ranges less than -3 are categorized as extreme droughts, -3 to -2.1 as severe droughts and -2.1 to -1.2 as medium droughts. Visual interpretation of annual and kharif RAI time series show that both have the same pattern but the magnitude varied over the time at all the stations.

Standardized precipitation index (SPI) is based on the probability distribution of precipitation. SPI can be calculated for short times scales representing soil moisture and estimate the frequency and duration of droughts. It is calculated using continuous monthly precipitation data at 1-,2-,3-, 6-, 9-and 12- months time scale for a desired period based on long-term precipitation. The long term record is fitted with probability distribution, which is then transformed into a normal distribution so that the mean SPI of a location and the desired period is zero.SPI is estimated as:

$$\text{SPI} = \frac{(X_{IJ} - X_I)}{\sigma} \tag{4}$$

Where, X_{ij} - mean precipitation for time scale i in the year j, X_i - Mean precipitation for time scale i, σ_i - Standard deviation of precipitation for time scale i. Four classes of – mild, moderate, severe and extreme drought category was made. SPI drought assessment indicated that extreme droughts occurred in 1997, 1999 and 2004 and Moderate and severe droughts in 1986, 1994, 1997, 1999, 2002, 2004, 2006 and 2008. Furthermore, point indices values were used to generate spatial drought severity maps using interpolation (Figure 2). RAI and deficit rainfall methods have identified more number of droughts and were in agreement with drought declarations made by the government for this region. SPI identified less number of severe and extreme droughts as it is more based on soil moisture assessment while RAI and deficit rainfall methods were purely rainfall based.

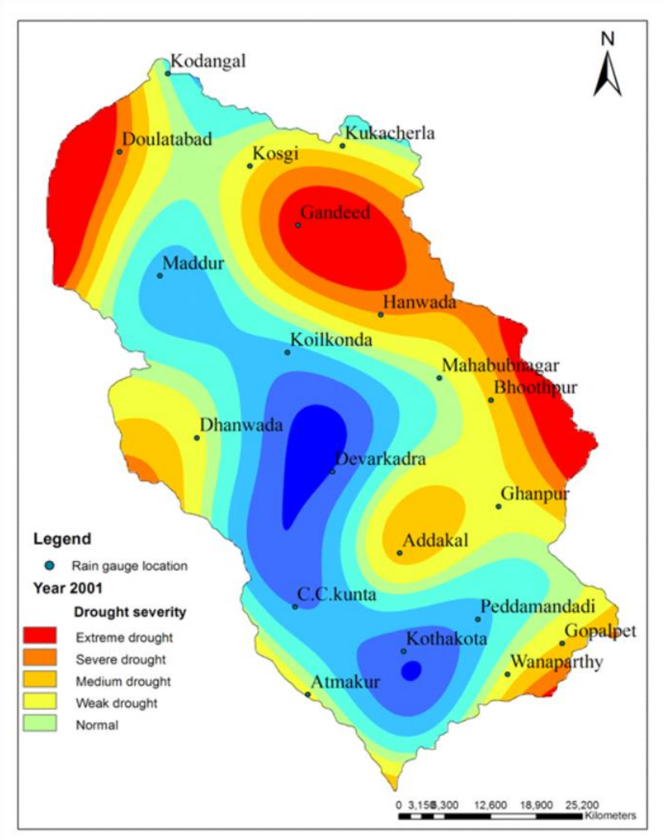

Figure 2. Rainfall Anomaly Index based drought assessment for the year 2001

3.2 Satellite based

Satellite image of Landsat 7 TM of 30th October 2008 was classified into six classes, viz. agriculture (711.6km^2), fallow (724.2km^2), forest (1129.4km^2), settlement (124.1km^2), wasteland (1134.4km^2) and water (529.3km^2) using digital image classification technique.

Normalized Difference Vegetation Index (NDVI) is the normalized reflectance difference between the near infrared and visible bands is used extensively in vegetation health/condition monitoring. It measures the changes in chlorophyll content (i.e. absorption of visible red (VR) radiation) and spongy mesophyll (i.e. reflected near infra red radiation (NIR)) within the vegetation canopy. Higher NDVI represent greater vigor and photosynthetic capacity (or greenness) of the vegetation, while lower NDVI values indicate lack of vigor and absence of vegetation (Chen and Brutsaert, 1998). NDVI was used in drought monitoring and assessment (Ji and Peters, 2003; Wan *et al*., 2004).

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \quad (5)$$

The NDVI values are generally represented as a ratio ranging from -1 to 1, extreme negative values represent water, values around zero represent bare soil and values near to 1 represent green vegetation.

3.3 Hydrological

During minimum (dry) and maximum (wet) rainfall years the surface water runoff was estimated (SWAT model) to be 9.9 TMC and 40.3 TMC, otherwise it less than 25TMC. It was observed that the basin never received sufficient rainfall to meet the water demands of the basin.

The pre-monsoon and post-monsoon groundwater fluctuation analysis shows that the abstraction is comparatively higher than the recharge rate with ±2 to 4m bgl variations. Moreover, the SWI analysis shows that the river basin experienced mild to moderate droughts during the observation period (1998-2011) except during severe meteorological drought years (1998, 2002, 2004 and 2008). The valleys and plateaus from the center of the basin towards south experienced mild droughts (0 to 20% deficit) are having good potential to explore groundwater for irrigation during dry spells. SWI gives inferences about groundwater levels fluctuations based on aquifer recharge, as an indirect reference to drought. Unlike other ground based indices, SWI index positive values correspond to drought and negative values to "no drought". It is calculated as shown below:

$$SWI = \frac{(W_{ij} - W_{im})}{\sigma} \quad (6)$$

Where, W_{ij} represents seasonal water level in *i*th well and *j*th observation, W_{im} is the seasonal mean, σ is standard deviation.

SWI assessment of pre-monsoon and post-monsoon groundwater levels shows the groundwater recharge of a local, which provides the groundwater availability of a local and adaptive capacity offered during drought situations. SWI depicts the five drought classes of groundwater abnormality ranging from extreme, severe, moderate, and mild and none severity based on recharge/fluctuation. The spatial extent and variation of groundwater drought severity (Figure 3) for post-monsoon, monsoon and pre-monsoon were mapped for 2001, 2004, 2005 and 2011 years. The mapping of spatial variation and extent of SWI values using interpolation was considered imperative to get insights about the spatial drought severity variation and extent of droughts.

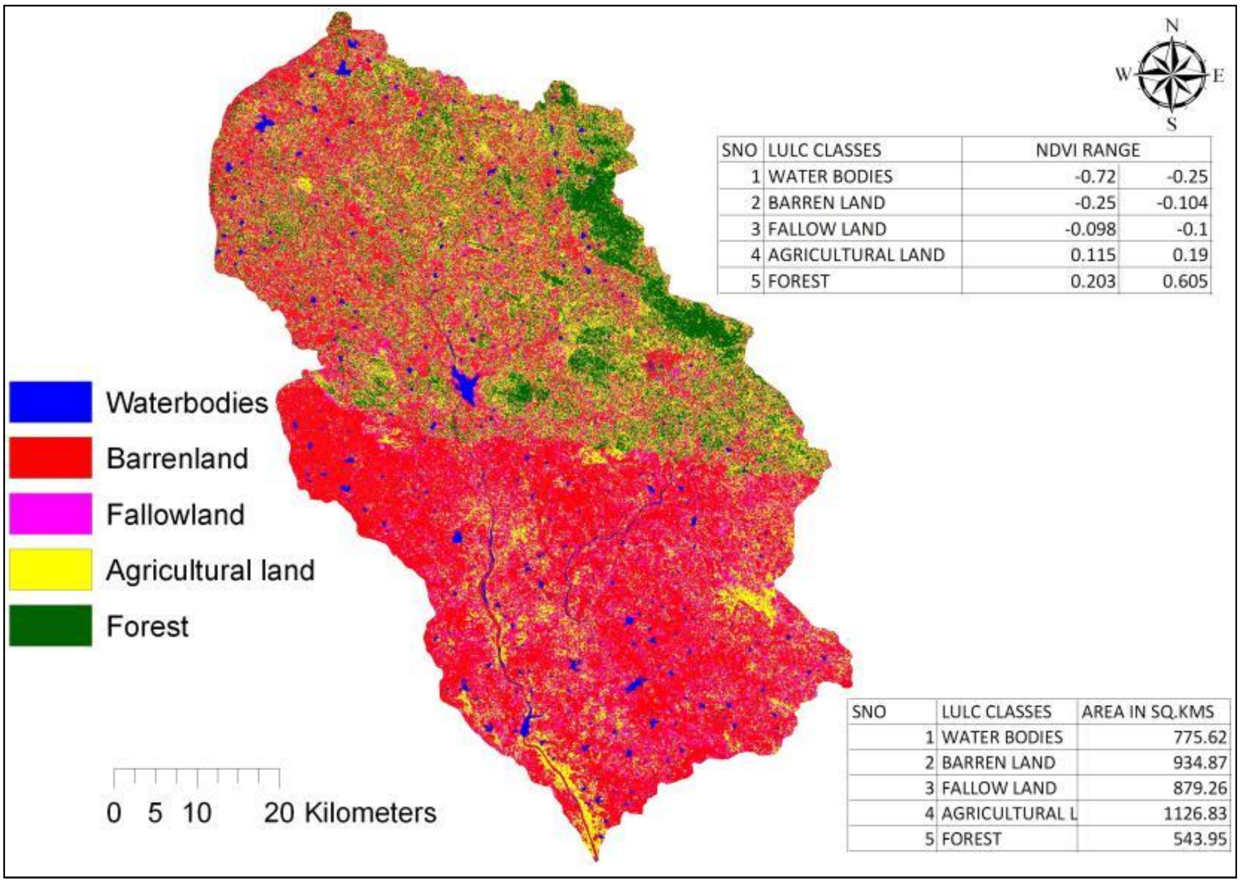

Figure 3. NDVI and land use/cover of Peddavagu river basin

3.4 DROUGHT VULNERABILITY INDEX

Vulnerability is the product of exposure, sensitivity and adaptive capacity. *Exposure* is the direct danger (stressor), and the nature and extent of changes to a region's climate variables (temperature, precipitation, extreme weather events). *Sensitivity* describes the human–environmental conditions that can worsen the hazard, ameliorate the hazard, or trigger an impact. *Adaptive capacity* represents the potential to implement adaptation measures that help avert potential impacts. The exposure and sensitivity together represent the *potential impact* and adaptive capacity is the extent to which these impacts can be averted. *Vulnerability index* is derived from set of indicators that can be used to compare with other regions. These indicators should have good internal correlation between them. The parameters that contribute to the drought vulnerability are Geographical (location) vulnerability that describes the historical events in terms of drought frequency (DF) and intensity of drought (DI). Meteorological vulnerability that summarize the rainfall and temperature conditions that influence the occurrence of drought such as, annual rainfall (AR), Seasonal rainfall (SR), monthly rainfall (MR), weekly rainfall (WRF), periods of dry spell (DS) and temperature variation (TV). Bio-physical vulnerability indicates the land surface slope (SL) and water holding capacity of soil (WC) that supports the vegetation growth. Agriculture vulnerability indicates the existing status of Vegetation covers (VC), Cultivated area (CA), Changes in cultivated area (CCA), type of crop such as dry cropped (DCA) area and wet cropped (WCA) area amongst the cultivated area, that uses irrigation facility (IA), and the variation in crop production (CP). Water resources vulnerability include available irrigation facilities that supplement rainfed crops like surface runoff (SR) generated by rainfall, existing water holding/storable (WH) structure, water infrastructure (WS) that delivers water, ground water availability in terms of SWI (GR). The water availability of a region, demand water requirement (WR) for domestic and agriculture purposes, and water stress (WS). Demographic vulnerability are measured by the population density (PD), its literacy rate (LR), dominance of agriculture labor (AL) and the livestock density (LD). These parameters are were collected and analyzed for Peddavagu river were grouped and assigned rank and weightage. The ranking was given accordingly for each variable based on the impact on drought with 1 being low vulnerable to drought and 5 highly vulnerable. Weights are assigned based on the historical drought process.

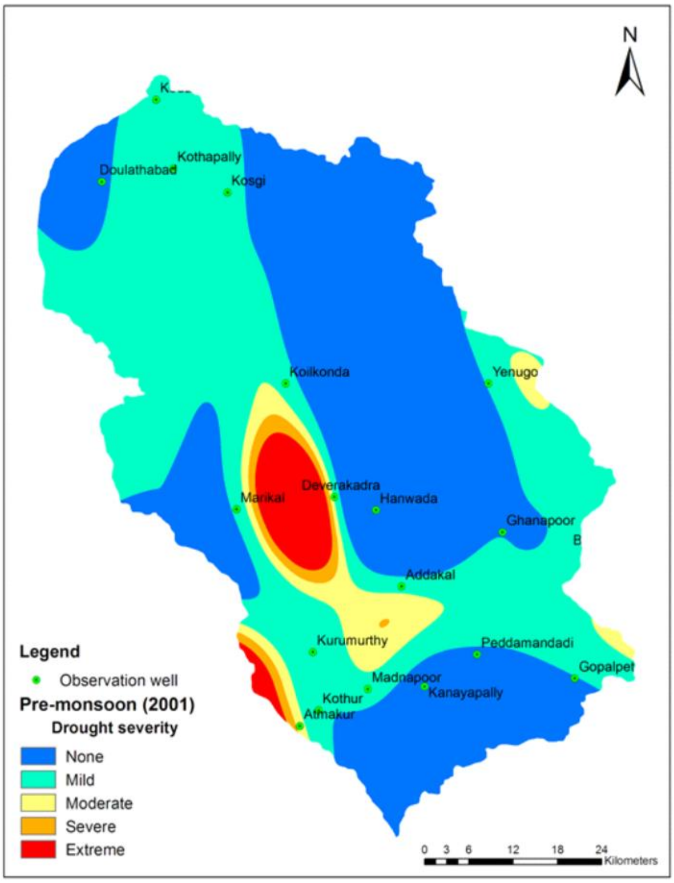

Figure 4. SWI based drought severity (pre-monsoon condition 2001)

Exposure Index (EI) of population and agriculture to drought event was assessed using the normalized values of Coefficient of annual rainfall variation, frequency of droughts, drought intensity, annual rainfall, seasonal rainfall, monthly rainfall, weekly rainfall, dry spells, water stress, population density (number / sq. km), dry crop area (%), wet crop area (%), the cultivated area (%), change in cultivated area, water stress, rainfall anomaly and soil moisture drought of a village area. *Sensitivity index* (SI) of a village was calculated as a sum of normalized values of sensitivity to agriculture, slope, crop production and percent of agricultural laborers' in a village. *Adaptive capacity index (*ACI*)*was calculated by normalizing the water infrastructure (tank area and reservoir area), surface runoff, AWC, groundwater recharge, livestock density and literacy rate. NDVI and irrigated area were used to estimate the sensitivity component of the vulnerability index. SPI and population density were used to assess the exposure component of the vulnerability. Weights were assigned to all the indicators under each component. The data ranges were normalized from 0 to 1. The Exposure Index, Sensitivity index, Adaptive capacity index and Drought vulnerability index (DVI) were computed as shown below. The adaptive capacity and vulnerability of the individual villages and the basin as entirety was classified into five equal class ranges and spatially shown in Figure 5.

$$\text{Exposure index }(\mathbf{EI}) = \frac{\mathrm{DF + DI + AR + SR + MR + WR + DS + TV + VC + CA + CCA + DC + WCA + PD + WS + RAI + SPI}}{17} \quad (7)$$

$$\text{Sensitivity index }(\mathbf{SI}) = \frac{\mathrm{IA + AL + SL + CP}}{4} \quad (8)$$

$$\text{Adaptive capacity }(\boldsymbol{ACI}) = \frac{\mathrm{WH + RO + WC + WI + GR + LD + WD + LR}}{8} \quad (9)$$

$$\text{Drought vulnerability index}(\boldsymbol{DVI}) = \frac{\mathrm{EI + SI + ACI}}{3} \text{ X } 100 \quad (10)$$

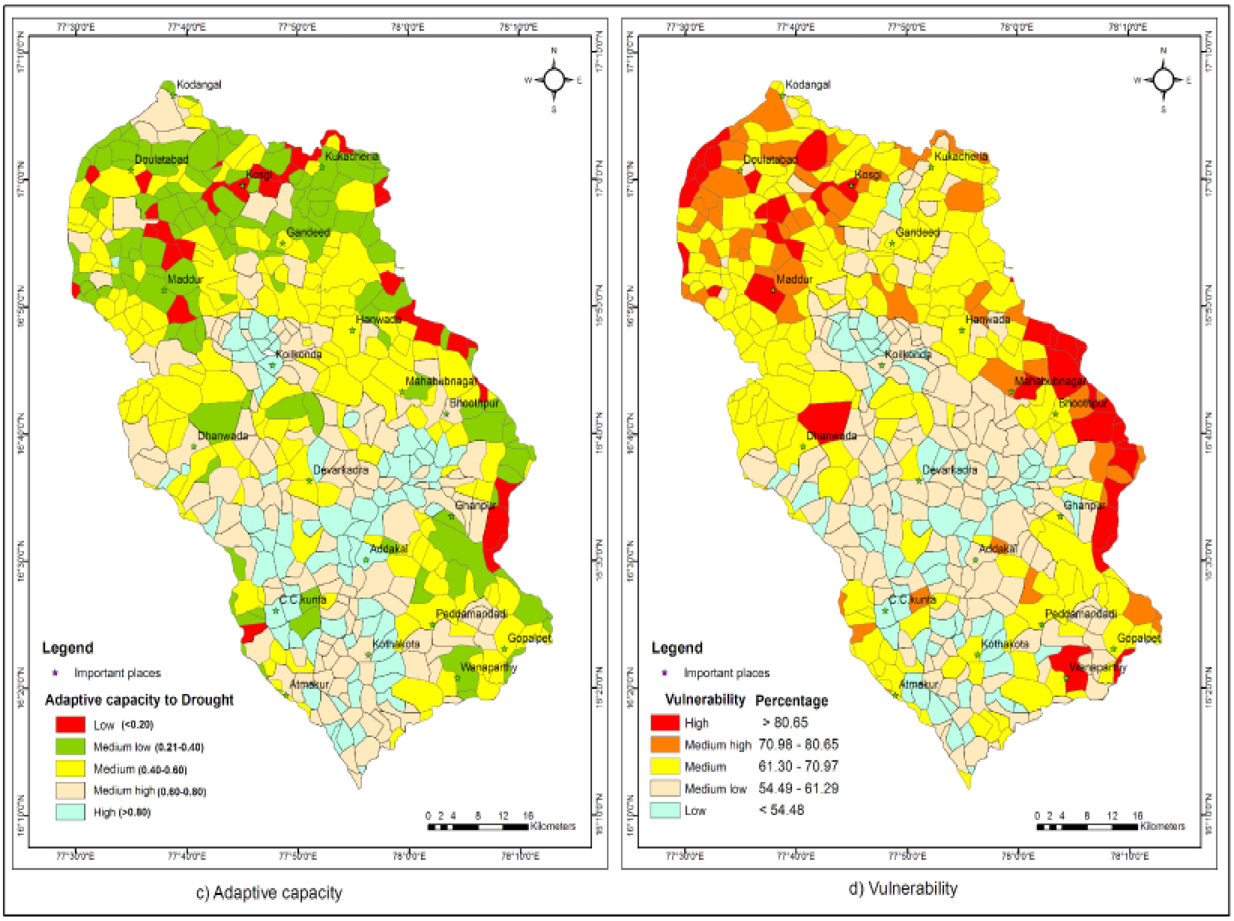

Figure 5. Adaptive capacity and vulnerability of villages in Peddavagu river

It is observed that 113 villages are grouped as high to medium high (> 80% sufferings) vulnerability to drought due to lack of surface water storages, and low groundwater recharge. In the event of rainfall failure, these regions experience water shortages for drinking and cultivation. 215 villages can experience medium vulnerability (61 to 70%), 168 villages could experience medium low vulnerability (54.4 to 61 %) as they have a better adaptive capacity due to the presence of surface water and groundwater storages. 550 to 650 mm rainfall would increase the pressure on the groundwater for drinking and cultivation. 72 villages along the river valley with good surface water storage accompanied with good groundwater potential have better adaptive capacity with low vulnerability (<54%).

4. CONCLUSIONS

The key factors integrated for drought vulnerability assessment were SPI drought index, land-use based on NDVI, population density, irrigated area, surface water storage and groundwater recharge.

The spatial variation of micro level (village) vulnerability was prepared based on surface water storage and groundwater recharge show that the adaptive capacity of a village has major influence on the vulnerability determination.

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