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Drought Hazard Assessment in Ponnaiyar River Basin, India Using Remote Sensing and Geographic Information System

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Abstract: *Due to the increase of water demand and threatening climate change, in the recent years have witnessed much focus on global drought scenarios. In India, Tamil Nadu have deficient rainfall (921 mm) compared to national average of (1200 mm) leading to over-reliance on irrigation for agriculture, and increasing extraction of groundwater reserves (estimates show over 60 percent of reserves are already exhausted) pose a big issue for the future and its indicate the continuing susceptibility of the society to drought. This study demonstrates the cumulative drought hazard assessment using climatic, biophysical and social factors in the Ponnaiyar River basin, Tamil Nadu, India. It was hypothesized that the key climatic, biophysical and social factors that define meteorological drought hazard, it is rainfall, normalized deviation of rainfall whereas for agricultural drought hazard were soils, geomorphology, drainage density, land use, and relief, and for hydrological drought hazard, it is lithology, depth to water table, and surface water bodies. The construction for the derivation of an agricultural, meteorological, and hydrological drought hazard map was created through the development of a numerical weighting scheme to evaluate the drought potential of the classes within each factor. A cumulative map created through spatial join of all the three types of drought provided a drought hazard scenario in totality. The area with different severity of drought hazards under cumulative drought hazards scenario is about 40% of the area under high to very high drought scenario. It is revealed the immediate attention have made to groundwater development for sustainable environment in the study area.*

Keywords: *Remote sensing, GIS, normalized weight, drought hazard, Southern India*

1. Introduction

In many parts of the world, water scarcity occurring frequently due to mainly in agricultural activities and population growth. The water scarcity is being further compounded by droughts which affect both surface water and groundwater resources and can lead to reduced water supply, deteriorated water quality, crop failure, and disturbed riparian habitats. Drought is related to deficiency of precipitation over an extended period of time, usually for a season or more (Mishra and Singh, 2010; Murthy et al (2011). The Meteorological Department of the Government of India has defined an area as drought hit when annual rainfall is less than 75% of the normal, (i.e., the rainfall deficit is 25% to 50%) and severe drought when deficiency is above 50% (WMO, 1975). The Irrigation Commission assumed that the area is drought hit if the irrigated area falls short by 70% of the irrigable area (NRSA, 2005). So, when the irrigated area is less than 30% of the irrigable area, the areas are to be called as drought prone (WMO, 1993).

In the scientific literature, four types of droughts are commonly distinguished: meteorological or climatological, hydrological, agricultural or vegetative, and socioeconomic (Rasmussen et al. 1993; Wilhite and Glantz 1985; Heim 2002; Knutson et al (1998); Li and Makarau (1994); Mckee et al (1993); Mckee et al (1995); Murthy et al (2007). Meteorological drought results from a shortage of precipitation, while hydrological drought describes a deficiency in the volume of water supply (Wilhite 2000a; Obasi (1994); Ogallo (1994); Palmer (1968); Shafer and Dezman (1982) and Singh et al (2003). Agricultural drought plays a major role in the economy of agrarian countries like India where more than 68% people are dependent upon agriculture. About 16% of India's total area is drought-prone and about 50 million people are annually affected by drought. The drought-prone areas of the country are mainly confined to western and peninsular India mainly arid, semi-arid, and sub humid regions. The arid tract of western part of India is under threat of severe droughts due to paucity, abnormality of rainfall and severe climatic characteristics (Jain et al.,(2010); Srinivasulu et al (2002); Subrahmanyam (1981); Subrahmanyam et al (1979); Thiruvengadachari and Gopalkrishna (1993); Wilhelmi and Wilhite (2002a); Wilhelmi and Wilhite (2002b); Wilhite (1993); Wilhite (1997); Wilhite (2000b); Wilhite and Vanyarkho (2000); Wu and Wilhite (2004).

As the remote sensing technology makes more and more process, with the development of geographic information system (GIS) and Global Positioning System (GPS), the real-time monitoring of drought over the large areas can be achieved. Remote sensing and GIS techniques are increasingly being regarded as a useful drought detection techniques, as evidenced by

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its use across many parts of the world. Satellite remote sensing enables continuous drought monitoring over a variety of spatial and temporal scales that can help to generate timely information on drought onset, progress, and areal extent (Kogan, (1997); Zhang (2004). The main objective of the study was to assess the climate change on drought hazards through normalized weights on three GIS modules i.e. meteorological drought, agricultural drought and hydrological drought.

2. Study area

Ponnaiyar River basin an interstate river is one of the largest rivers of the state of Tamil Nadu, often reverently called 'Little Ganga of the South'. The river has supported may a civilizations of peninsular India across the history and continues to play a vital role in supplying precious water for drinking, irrigation and industry to the people of the states of Karnataka, Tamil Nadu and Pondicherry. The study area extends over approximately of 11,595 sq. km, and lies between 11˚35' and 12˚35' N latitudes and 77˚45' and 79˚55' E longitudes (Fig.1). Ponnaiyar River originates on the south eastern slopes of Chennakesava Hills, northwest of Nandidurg of Kolar district in Karnataka State at an altitude of 1000m above mean sea level (amsl).

The total length of Ponnaiyar River is 432km of which 85km lies in Karnataka state, 187km in Dharmapuri, Krishnagiri and Salem districts, 54km in Thiruvannamalai and Vellore districts and 106km in Cuddalore and Villupuram districts of Tamil Nadu. The Ponnaiyar basin is predominantly built up with granite and gneisses rocks of archean period. The granite is of very good quality and extensive outcrops and masses of it are commonly found. The chief components of rocks are hornblende and feldspar. Foliation is seldom seen. In the plains of reserve forest, quartz is found commonly. The diamond granite is also found in scattered pockets in the area of Chitteri hills in Dharmapuri and Krishnagiri sub-divisions. Charnockite rocks of archean period are also seen in some areas. Alluvium and sand-dunes of quaternary period are also seen at a few places. The fifteen years (2000-2014) average annual rainfall in the basin is 969 mm. The catchment falls under the tropical belt. The climate in general is hot; April and May being the hottest months of the year when the temperature rises to 34˚C.

3. Methodology

In the present study, there are three major drought factors such as climate, biophysical and social factors were selected with reference to the drought literature, data availability and severity of drought depends on influence of uneven monsoon, low crop production and groundwater over exploitation in Ponnaiyar river basin. These factors were assigned into combination of normalized weights model based on knowledge and literatures, then integrated to climatic factors as meteorological drought, biophysical factors as agricultural drought and social factors as hydrological drought. Using the union option available in ArcGIS software, the three drought scenario further integrated into cumulative drought for understating the climate change accelerating drought condition in the study area. The methodologies adopted in the present study are shown in Figure 2.

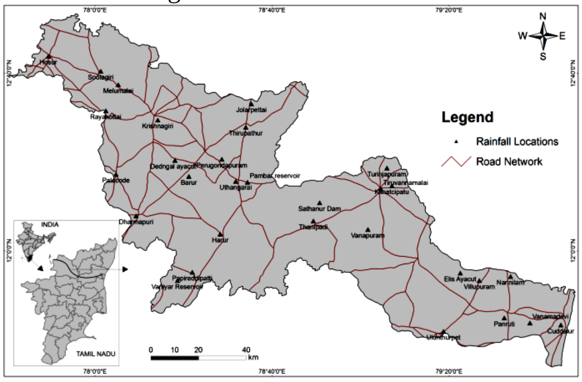

Figure 1. *Location of the study area (Ponnaiyar River basin) shows rainfall locations and road network.*

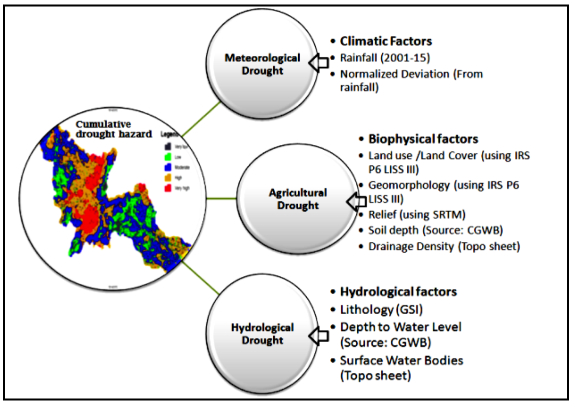

Figure 2. *Methodology adopted in the present study*

3.1 Climatic factors

In the present study, the annual average rainfall and normalized deviation of rainfall were utilized as climatic factors. The rainfall (Rf) is one of the most important hydrologic parameters and it was considered as a major source of recharge (Musa et al. 2000; Magesh et al. 2012; Shekhar and Pandey 2014). It is an important element to assess the water input to the basin and to understand the flourish or deficit condition of water resource (Anbazhgan and Jothibasu, 2016a). Adiat et al. (2012) proved that the rainfall has a significant effect on percolation and groundwater potential mapping accuracy. The monthly records of rainfall amount for thirty rain-gauge stations within the study area for a period of 15 years (2000–2014) were obtained from the Tamil Nadu State Surface and Groundwater Division database. The resulting map was classified into five major classes: 688-850, 850-923, 923-987, 987-1046 and 1046-1195 mm/year (Fig. 3a). Average annual rainfall in the study area varies in the range of 688 mm to 1195 mm. North eastern and south western part receive high rainfall (>987mm) whereas southeastern and northwestern part receive low rainfall (<923mm). High rainfall reported during the period from 2005 to 2010 indicates that the ground water regime got highly recharge, whereas low rainfall reported during the year 2000 to 2004, contribute less to ground water aquifer and that period faced severe drought condition. In order to assess the variability and erratic nature of rainfall, normalized deviation (ND) was calculated in the study area.

$$\text{Normalized deviation (ND)} = (P_{tot}-P)/P \quad (1)$$

Where P_{tot} is the total annual precipitation in mm for a particular year and
P is the average annual rainfall for the area.

The normalized deviation rainfall range map for the study area was prepared from rainfall records using IDW interpolation techniques in GIS. The resulting map was classified into five major classes: -0.40 to -0.10, -0.10 to 0.01, 0.01 to 0.12, 0.12 to 0.21 and 0.21 to 0.41 (Fig.3b). The precipitation normally does not exceed double the mean precipitation in drought prone area. Hence the deviation ranges between +1 and -1. The negative index always indicates the deficiency in rainfall. Areas with high deficiency rainfall may be more prone to drought in comparison with areas under positive during the rainfall season.

3.2 Biophysical factors

The biophysical factors of land use / land cover, geomorphology, relief, soil depth and drainage density were identified to derive agricultural drought. Land use and soil is important ecological factors for life. Land use types play a significant role, which directly or indirectly influence on some of hydrological processes components such as infiltration, evapotranspiration and run-off generation. Land use types within the study area are agriculture land, built-up land, forest cover, river, water body, barren land, and grass land (Fig.4a). Built-up areas, which are mostly made by impervious surfaces, increase the storm run-off and inundation (Shafapour Tehrany et al. 2013). On the other hand, agricultural areas are less prone to flooding due to the positive relationship between infiltration capability and vegetation density. The land use / land cover map was prepared from IRS P6 LISS III image through supervised classification using maximum likelihood algorithm, and false color composite (FCC) techniques in ENVI 4.3 software.

The various geomorphic units were interpreted using IRS P6 LISS III color composite image as well as the observations made in the field such as topography, relief, aspect factor, soil and vegetative cover. Geomorphological investigations include the delineation and mapping of landforms and drainage characteristics that could have a direct control on the occurrence of groundwater and drought characteristics. The basin area is covered by alluvial plain, coastal plain, denudational hills, flood plain, pediment inselberg complex, pediplain, reservoir, residual hill and structural hills (Fig.4b). The hilly terrain mainly comprising the runoff zone over the steeply sloping land and characterized by shallow depth of soils (less than 2 m) is highly prone to drought. On the contrary, the plain areas with gentle slopes and due to deep soil cover (about 10–20 m) have high surface water retention capability and shallow groundwater conditions are least prone to drought. The undulating terrains have intermediate drought hazards depending upon depth to bed rock, soil texture, and hydraulic gradient.

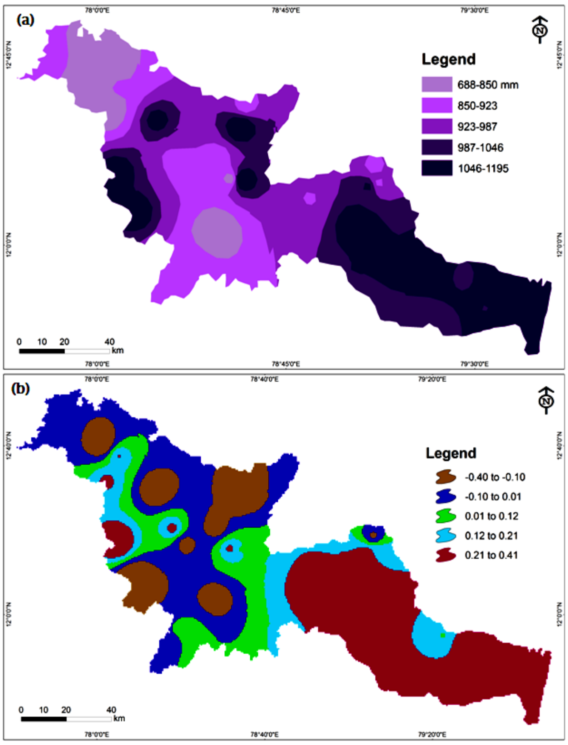

Figure 3 *Climatic factors (a) rainfall distribution and (b) normalized deviation of rainfall*

Shuttle Radar Topographic Mission (SRTM) data were used to derive relief map of the study area. The altitude map was grouped into six classes: -4 to 205 m, 205–386 m, 386-556 m, 556–750 m, 750–1009 m, and 1009-1635 m based on the quantile classification method (Fig. 4c) (Tehrany et al. 2013). It was observed that the temperature decreases toward higher elevations. The high wind velocity during day time coupled with higher temperature at lower elevation results in higher evaporation and evapotranspiration losses. This results in faster and higher soil moisture deficit in these areas. Therefore, regions with lower elevation are more vulnerable to drought as compared to regions located at higher elevations in the undulating plateau type of physiographic setting present in the area.

Soil depth is one of the most important factors in the surface and subsurface runoff generation and infiltration process (Mogaji et al., 2014). The soil depth map was obtained from the Central Groundwater Board (CGWB, 2012). There are four classes of soil depth in the study area (Fig. 4d). The shallow depth soil due to high porosity and less permeability help in retaining soil moisture for longer period of time during drought as compared to moderate and deep soil where high internal drainage results in faster loss of soil moisture. Therefore, shallow and moderately shallow soil depths are relatively less vulnerable to drought as compared to deep and very deep. In order to determine drainage density of study area, Line Density tool in ArcGIS 9.3 was used. The drainage density quantity of study area was computed through sum of lengths of streams in the mesh (km), and area of the grid (km^2). The drainage density map of the study area was divided to five classes such as very low (<0.72 km/km^2), low (0.72-1.45), moderate (1.45-2.17), high (2.17-2.90) and very high (>2.90) (Fig. 4e), and it reveals that high drainage density is observed in the center of the study area. It is considered that an area with high drainage density has more water contact areas as compared to area with no drainage. Negating the influence of other factors, it can be remarked that areas with high drainage density are less prone to drought and vice versa.

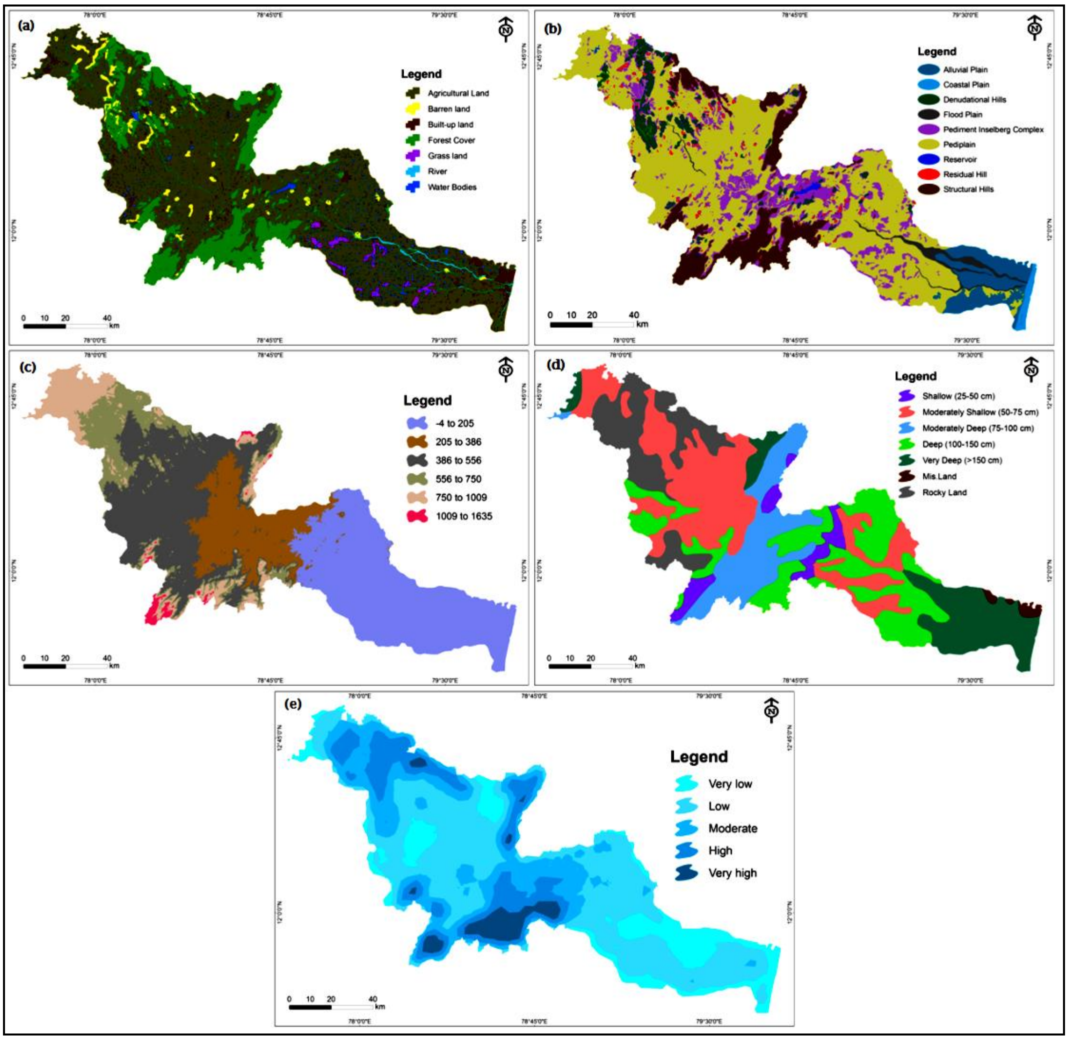

Figure 4. *Biophysical factors of the study area (a) land use / land cover, (b) geomorphology, (c) relief, (d) soil depth, and (e) drainage density*

3.3 Social factors

The lithology is considered as one of the most important indicators of hydro-geological features which play a fundamental role in both the porosity and permeability of aquifer materials (Ayazi et al., 2010; Charon, 1974). The analog lithology map (1:100,000) was obtained from the Geological Survey of India (GSI, 1997) and the digital lithology map was generated using ArcGIS 9.3 (Fig. 5a). Generally drought hazard can be more over metamorphic terrains as compared to sedimentary terrain. Rao and Briz-Kishore (1991) indicated that water level is one of the most important hydro-geological factors. The water table level dataset of the study area was acquired from the State Surface and Groundwater Division. In the present study, the depth to dater level varies from <5 to >40 m (Fig. 5b). Areas with shallow water table can provide soil moisture during periods of soil moisture deficit and, therefore, are less vulnerable to drought as compared to the areas where ground water exists at deeper levels. Water bodies comprising of surface ponds, reservoirs, rivers, and streams were demarcated from satellite data and digitized in the form of polygon map (Fig. 5c). Areas surrounding large water bodies and perennial rivers are less vulnerable to drought due to subsurface flow from areas of higher water table near them. Also, they can provide lifesaving irrigation to nearby agricultural lands.

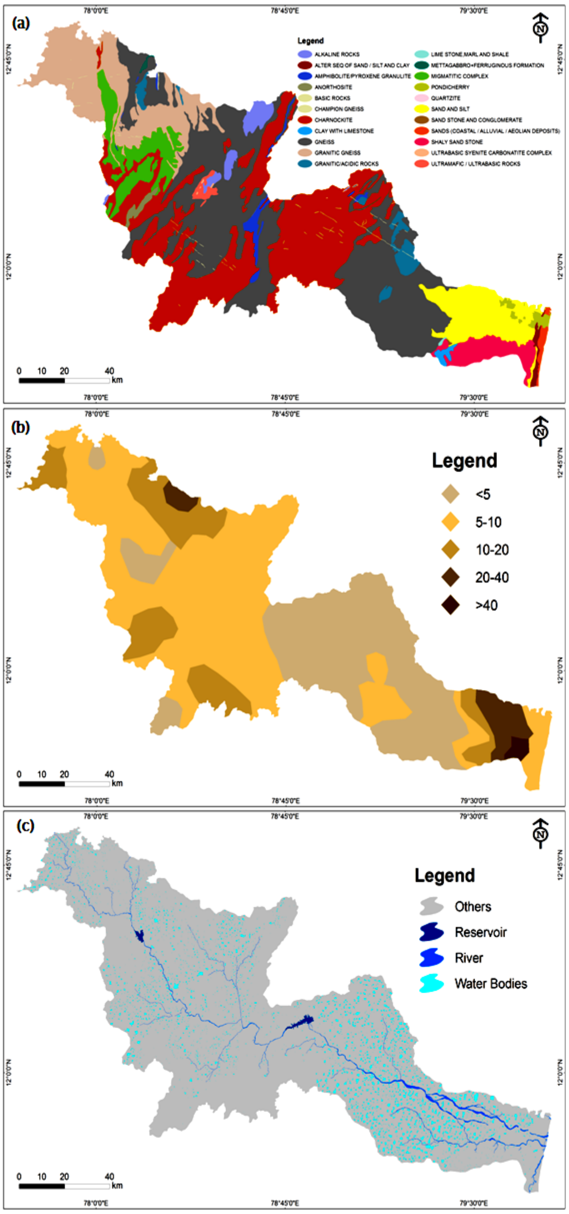

Figure 5. *Social factors used in the present study (a) lithology, (b) depth to water level and (c) surface water bodies*

3.4 Spatial drought hazard map preparation

In the present study, to preparation an individual drought hazard map comprising meteorological, agricultural, and hydrological drought in Ponnaiyar River basin, the various drought hazard factors were combined among three types of drought considered for analysis through the 'union' mathematical function in ArcGIS. The numerical weighting scheme was used to assess the relative drought hazard potential of each factor. Each class of eleven hazard factor map has been assigned a relative weight as 1, 2, 3… with 1 being considered least significant in regard to drought hazard and highest number being considered most significant (Table 1). The choice of weights was based on an informed assumption on relative contribution of each class to drought hazard. The given weights were normalized for each map so that difference in the number of classes in all maps can be brought to same scale with value of weights in the range of 0 less than 1. For normalization, weights of each class were recalculated by dividing the class weight by cumulative weight of all the classes. All the maps in the polygon (vector) format were converted into raster format with a grid cell size of 25 m.

The weighted maps were cumulated by spatial join in GIS using the parameters selected for each types of drought. As all the weighted maps in GIS database were co-registered with their respective cell coordinates, weights of individual cell in all input maps were joined by adding their normalized values in the attribute table. A high numeric value within each category was assumed to be indicative of a geographic area that is likely to be more susceptible to drought. The resulting map was reclassified into five classes, identifying geographic areas with 'very low', 'low', 'moderate', 'high', and very high hazard using natural break method.

Table 1. *Area statistics, weights, and normalized weights assigned to various drought hazard factors*

Factor class name	Area	Area	Weig	Normal
Rainfall distribution (mm)				
688-850	1336	12	5	0.333
850-923	2544	22	4	0.267
923-987	2690	23	3	0.200
987-1046	2177	19	2	0.133
1046-1195	2848	25	1	0.067
Normalized deviation (ND)				
-0.40 to -0.10	1550	13	5	0.294
-0.10 to 0.01	3075	27	4	0.235
0.01 to 0.12	1587	14	3	0.176
0.12 to 0.21	1372	12	3	0.176
0.21 to 0.41	4011	35	2	0.118
Agricultural drought				
Land use / land cover				
Agricultural Land	8196	71	5	0.263
Built-up land	392	3	2	0.105
Forest Cover	2015	17	4	0.211
River	145	1	1	0.053
Water Bodies	435	4	1	0.053
Barren land	276	2	3	0.158
Grass land	136	1	3	0.158

Geomorphology				
Pediplain	6435	55	3	0.111
Pediment Inselberg	1941	17	4	0.148
Structural Hills	1417	12	5	0.185
Residual Hill	99	1	5	0.185
Denudational Hills	504	4	5	0.185
Reservoir	29	0	1	0.037
Flood Plain	259	2	1	0.037
Alluvial Plain	809	7	2	0.074
Coastal Plain	102	1	1	0.037
Relief				
-4 to 205	3894	34	5	0.250
205 to 386	1755	15	5	0.250
386 to 556	3355	29	4	0.200
556 to 750	1344	12	3	0.150
750 to 1009	1121	10	2	0.100
1009 to 1635	126	1	1	0.050
Soil depth				
Shallow (25-50 cm)	495	4	1	0.059
Moderately Shallow	3420	29	2	0.118
Moderately Deep (75-	1635	14	3	0.176
Deep (100-150 cm)	2645	23	4	0.235
Very Deep (>150 cm)	1675	14	5	0.294
Rocky Land	1630	14	1	0.059
Mis.Land	95	1	1	0.059
Drainage Density				
Very low	1735	15	5	0.333
Low	5236	45	4	0.267
Moderate	2443	21	3	0.200
High	1665	14	2	0.133
Very high	516	4	1	0.067
Lithology				
Gneiss	4089	35	5	0.068
Charnockite	3299	28	4	0.054
Granitic gneiss	1546	13	5	0.068
Mettagabbro+ferrugin	10	0	5	0.068
Basic rocks	26	0	4	0.054
Amphibolite/pyroxene	131	1	5	0.068
Migmatitic complex	610	5	4	0.054
Granitic/acidic rocks	225	2	5	0.068
Champion gneiss	4	0	5	0.068
Alkaline rocks	192	2	5	0.068
Ultramafic / ultrabasic	57	0	4	0.054
Ultrabasic syenite	4	0	4	0.054
Quartzite	4	0	5	0.068
Anorthosite	55	0	4	0.054
Sand and silt	786	7	2	0.027
Pondicherry	71	1	1	0.014
Sands (coastal /	55	0	1	0.014
Alter seq of sand / silt	45	0	1	0.014
Shaly sand stone	343	3	1	0.014
Lime stone,marl and	5	0	1	0.014
Sand stone and	3	0	1	0.014
Clay with limestone	35	0	2	0.027
DWL (m, bgl)				
<5	3688	32	1	0.067
5-10	5780	50	2	0.133
10-20	1604	14	3	0.200
20-40	453	4	4	0.267
>40	70	1	5	0.333
Surface Water Bodies				
Others	10998	95	3	0.429
River	151	1	1	0.143
Reservoir	34	0	1	0.143
Water Bodies	412	4	2	0.286

Area statistics of each drought severity class was computed for each types of drought. Further, the classified agricultural, meteorological, and hydrological drought hazard maps were aggregated in GIS with final weights in each cell being classified using natural break method to develop a cumulative drought hazard map. Area statistics, weights, and normalized weights assigned to various drought hazard factors are given in Table 1.

4. Results and discussion

4.1 Meteorological drought hazard

The meteorological drought hazard map derived from climatic factors indicates very high hazard are shown in the entire northwestern and central parts, whereas lower hazard is observed in the eastern parts (Fig. 6). Lower hazard areas of local extent are present within very high hazard areas near Krishnagiri district and Dharmapuri district indicating changes in local biophysical setting. The pattern of meteorological drought largely confirms to the topography and rainfall of the region. The areas located at more than 480 m above mean sea level (amsl) altitude receiving rainfall of more than 1,000 mm with deficient of normalized deviation are largely under lower drought hazard. The area statistics of various categories under meteorological drought revealed that 53 % of the area is under very low to low hazard, whereas 27 % of the area is characterized by high and very high hazard (Table 2).

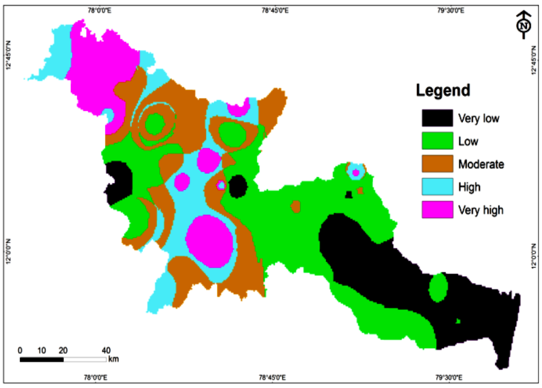

Figure 6*. Meteorological drought hazard of the Ponnaiyar River basin*

4.2 Agricultural drought hazard

Agricultural drought show high variation in terms of relief as very high and high drought hazard is observed at lower (below 688 m) as well as higher (above 1046 m) relief areas (Fig. 7). High and very high agricultural drought hazard generally corresponds to areas with low drainage density and lower relief. At slightly higher elevation areas like Tiruvannamalai, water table located at a depth of more than 4 m from ground surface during peak monsoon season in the month of August is the controlling factor in inducing high agricultural drought hazard. Agricultural lands with shallow soil depth, high drainage density located over moderate relief of 923–967 m can be under low and very low agricultural drought hazard. The area statistics of various categories under agricultural drought revealed that 23 % of the area is under very low to low hazard, whereas 59 % of the area is characterized by high and very high hazard. In terms of hydrological drought, major parts of the basin are under high and very high drought hazard. Lower hydrological drought hazard areas are characteristically associated with alluvium and flood plain.

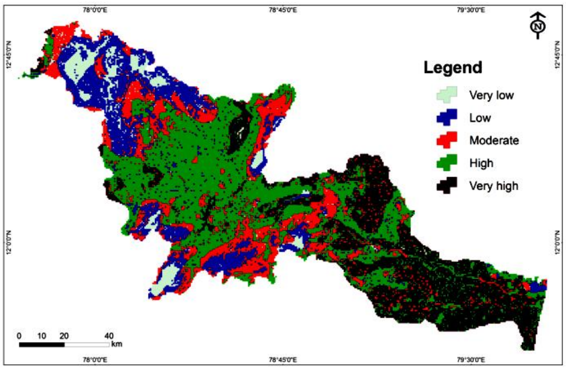

Figure 7. *Agricultural drought hazards in Ponnaiyar River basin*

4.3 Hydrological drought hazard

The dominant hilly topography in the region of higher rainfall results in more runoff and less recharge of groundwater. Therefore, major parts of the basin come under hydrological drought. The area statistics of various categories under hydrological drought revealed that 5% of the area is under very low to low hazard, whereas 63% of the area is characterized by high and very high hazard. By comparing the percentage of area of the high and very high classes of drought, it can be determined which of the types of drought is the most significant for the region (Fig.8). Hydrological drought was analyzed to cover largest area at 63 % followed by meteorological (57 %) and then agricultural drought (59 %). This indicates that hydrological conditions are not conducive for drought mitigation by irrigation through groundwater sources in this area. Impacts of agricultural drought can be minimized by properly selecting a crop sowing period by selecting rainfall patterns and probabilities of rainfall failures and selecting suitable crops and their soil moisture requirements during initial crop sowing and crop maturity stages.

4.4 Cumulative drought hazard

The cumulative drought hazard scenario developed by combining the meteorological, agricultural, and hydrological drought hazard indicated that overall drought hazard is more pronounced in the central and northern regions of the Ponnaiyar River basin (Fig. 9). Areas under very low and low drought hazard are mainly found over shallow soil depth situated over regions with relatively higher relief (1046 m) in the vicinity of forest areas that receive higher rainfall (1,000 mm) with less normalized deviation. Areas with high and very high drought hazard are coinciding with areas receiving less than 1,000 mm of monsoon rainfall with high ND and lower relief areas with lower drainage density. Lithological variations and aquifer yield control the drought hazard to a certain extent as relatively lower hazard was observed over areas with alluvium. Geomorphologically, the areas over pediplain and alluvial plain are under high drought hazard, whereas over pediment inselberg complex (and denudational hills, very high drought hazard exists. The area with different severity of drought hazards under cumulative drought hazard scenario (viz. very low (7 %), low (17 %), moderate (35 %), high (31), and very high (9 %)) revealed high drought proneness of the area.

Table 2. *Statistical analysis agricultural, meteorological, hydrological, and cumulative drought hazard*

Drought category	Meteorological drought		Agricultural drought		Hydrological drought		Cumulative drought	
	Area (Sq.km)	%	Area (Sq.km)	%	Area (Sq.km)	%	Area (Sq.km)	%
Very low	2498	22	823	7	194	2	783	7
Low	3594	31	1912	16	384	3	1978	17
Moderate	2394	21	1998	17	3709	32	4099	35
High	1596	14	4042	35	5370	46	3639	31
Very high	1513	13	2820	24	1938	17	1096	9

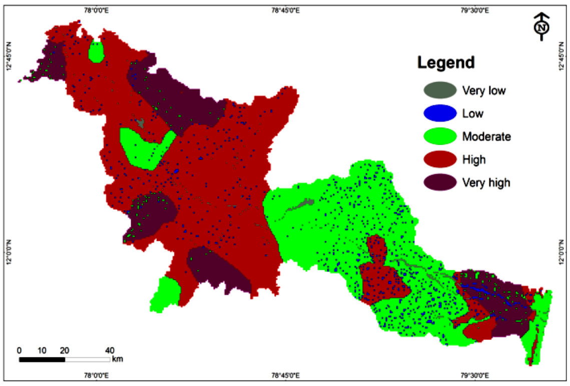

Figure 8. *Hydrological drought hazard of the study area*

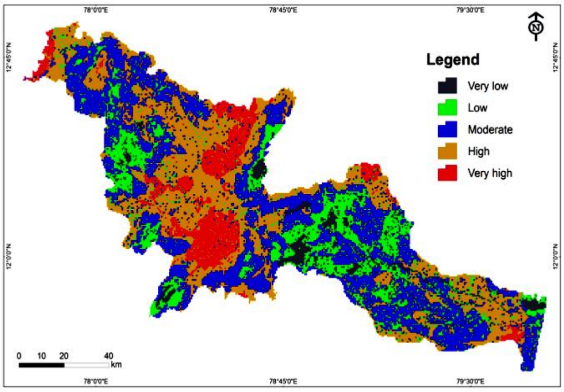

Figure 9. *Cumulative drought hazard of Ponnaiyar River basin*

5. Conclusions

It is predictable that the future will witnessed increase dynamics in hydro-meteorological variables around the world which will lead to frequent droughts whose impacts will be compounded by growing water demands. Although significant progress has been achieved in drought modeling, much work remains ahead. This contribution provides a review of the methods used for modeling different components of droughts, which will be useful for different sectors dealing with water resources directly or indirectly. Hydrological drought was analyzed to cover largest area at 63 % followed by meteorological (57 %) and then agricultural drought (59 %).

This indicates that hydrological conditions are not conducive for drought mitigation by irrigation through groundwater sources in this area. Impacts of agricultural drought can be minimized by properly selecting a crop sowing period by selecting rainfall patterns and probabilities of rainfall failures and selecting suitable crops and their soil moisture requirements during initial crop sowing and crop maturity stages. The high drought hazard of the area under hydrological drought indicates inadequate groundwater potentials and, therefore, necessitates the development of surface water harvesting structures like check dam, subsurface dykes, and farm pond to provide lifesaving irrigation facilities during drought periods.

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