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Regional groundwater drought mapping for sustainable management

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Abstract Groundwater is one of India's most important natural resources. Overexploitation of groundwater takes place during the period of scarcity and droughts in order to meet the irrigation demand and other requirements. Classifying the region according to the risk level is the first step in a process to bring groundwater to a sustainable level of management. The Palar Basin located in Tami Nadu State, India, is selected as the study area. Thirty years of groundwater level data from 80 observation wells located within the basin are used for the analysis. A statistical method developed by Herbst is used to estimate groundwater drought intensity during dry periods. The drought risk index was estimated for each well and a groundwater risk area map was generated using GIS. This map will be useful for decision making in pursuit of sustainable development and management of groundwater.

Key words drought; GIS; groundwater; risk index; risk mapping

INTRODUCTION

The freshwater resources of the Earth are limited and should be used in a sustainable manner, in order to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. In most countries, surface water resources have been exploited to the full extent and, as the next source under development, groundwater should be utilized in a sustainable way. The sustainability of groundwater resources is a function of many factors, including depletion of groundwater storage due to drought or irrigation development, reductions in streamflow, potential loss of wetland and riparian ecosystems, land subsidence, saltwater intrusion, and changes in groundwater quality. Groundwater resources are the major source of water during periods of drought. Indiscriminate exploitation of groundwater during drought periods will lead to a lowering of water tables beyond replenishable limits, deterioration of water quality, etc. Groundwater resources can be used effectively if their sustainability is planned long before drought periods. In order to achieve this, there is a need to identify the regions that are being pushed into groundwater deficit and risk conditions. The objectives of the present study are: (i) to analyse the spatial variation of long-term groundwater level during the crop seasons of the study basin; (ii) to carry out the monthly groundwater drought analysis using the Herbst method; and (iii) to develop a groundwater risk index and to identify the risk areas and to reclassify the regions according to sustainability using GIS.

STUDY AREA

The Palar River Basin in Tamil Nadu State, India, was chosen as the study area. It has an area of 18 300 km^2, and lies between latitudes 12º14'40"N and 13º37'00"N and longitudes 77º48'40"E and 80º14'40"E. This basin covers 44 administrative blocks either fully or partly. Physiographically, the Palar Basin can be divided into three broad units comprising the Western Plateau region, the Central Hill and Valley complex region and the Eastern Plain region. The average annual rainfall for the basin is 1040.44 mm. The annual surface and groundwater potentials are 1758 Mm^3 and 2610.32 Mm^3, respectively. There are 248 924 dug (open) wells and 1401 tube (bore) wells in the basin. The direct ayacut (irrigation system) comprises 60 972 ha and the indirect ayacut extends over 120 445 ha. Even though the basin receives a considerable amount of rainfall, surface flow only occurs for a few days and the river is dry during most of the year. Due to rapid infiltration, the major portion of the rainfall is stored in the groundwater system and the basin is treated as a groundwater reservoir. Hence, it is imperative to assess the groundwater risk areas of the basin for planning sustainable development of groundwater resources.

LONG-TERM GROUNDWATER LEVEL ANALYSIS

The main indicators of groundwater sustainability are water level, water quality, and yield. The change in groundwater storage during the crop seasons has been analysed from data available on water level fluctuations in the study area. Three crop seasons are adopted in the Palar Basin, and these are Sornavari (April–August), Samba (August–January) and Navarai (December–April). There are 80 observation wells distributed within the basin to monitor the groundwater level. The long-term average groundwater fluctuation for each administrative block during the crop seasons was calculated from 30 years of monthly groundwater level data, and the results are presented in Table 1.

As seen from Table 1, the groundwater level fluctuation for the region varies temporally between the seasons. It is higher in the Samba season during which the first paddy crop is grown. During the Navarai season, there is considerable fluctuation during which the second paddy crop is grown. In the Sornavari season, the water level fluctuation is lower than in the other two seasons and only dry crops are grown that require less water. Groundwater level fluctuation varies spatially within the basin for each season. It ranges from 0.88 m in Lathur to 3.49 m in Cheyyar during the Sornavari season. High spatial variation is found during the Samba season from 1.98 m in Tellar to 6.88 m in Jolarpettai. The extent of variation is less pronounced during Navarai, and ranges from 1.14 m in Lathur to 4.07 m in Arani. Groundwater fluctuation is very high in the administrative blocks of Jolarpettai, Polur, Vellore, Chetpet, K. V. Kuppam, Turinjapuram, Walajapet, Cheyyar, Arcot, Arani, Pernampet, Uttiramerur, Kalasappakkam and Chithamur, compared to other blocks, during all crop seasons. This may be due to severe exploitation of groundwater. In blocks such as Padapai, Katpadi, Pudupalaiyam, Tiruporur, Tellar, Madanur and Lathur, the groundwater fluctuation is less compared to other blocks. This may be due to conjunctive use of surface and groundwater for irrigation.

Table 1 Average seasonal groundwater fluctuation in Palar Basin.

Sl. no	Name of block	Seasonal groundwater fluctuation (m)		
		Sornawari (Apr–Aug)	Samba (Aug–Jan)	Navarai (Dec–Apr)
1	Padapai	1.30	2.17	1.44
2	Nemili	1.95	3.19	2.21
3	Katpadi	1.30	2.33	1.92
4	K.V.Kuppam	1.97	4.98	2.65
5	Polur	3.26	6.22	3.05
6	Pudupalaiyam	1.46	2.56	1.39
7	Tirukalukundram	1.99	3.83	2.48
8	Walajabad	2.59	3.66	1.67
9	Acharapakkam	2.13	4.30	2.59
10	Kanchipuram	2.33	3.58	1.50
11	Tiruporur	1.05	2.36	1.63
12	Madurantakam	1.70	4.02	2.82
13	Turinjapuram	2.06	5.38	3.95
14	Tellar	1.16	1.98	1.41
15	Anaikkavur	2.38	4.34	2.37
16	Peranamallur	1.77	4.25	2.96
17	Timiri	2.50	4.61	2.82
18	Walajapet	2.51	6.01	4.31
19	Kandili	1.31	3.86	2.69
20	Jolarpettai	2.36	6.88	5.69
21	Kattankulattur	0.96	3.11	2.56
22	Pernampet	2.04	4.53	3.08
23	Gudiyattam	2.30	4.32	2.45
24	Cheyyar	3.49	5.49	2.26
25	Vandavasi	2.55	4.12	2.01
26	West Arani	1.58	3.38	2.44
27	Anaicut	2.41	4.76	2.95
28	Vellore	2.10	6.03	4.39
29	Kanniyambadi	1.35	3.86	2.78
30	Arani	2.25	5.93	4.07
31	Madanur	1.25	2.33	1.42
32	Chengam	1.72	3.84	2.28
33	Alangayam	1.90	3.77	2.34
34	Arcot	2.36	5.10	3.12
35	Uttiramerur	3.42	5.01	2.80
36	Lathur	0.88	1.81	1.14
37	Vembakkam	2.09	3.60	2.15
38	Tiruppattur	1.15	2.99	2.18
40	Kalasappakkam	2.19	5.58	3.97
41	Chetpet	2.24	5.78	3.81
42	Sriperumbudur	2.59	3.66	1.67
43	Chithamur	3.24	5.74	2.13
44	Javadi Hills	2.47	6.01	4.53

GROUNDWATER DROUGHT ANALYSIS

Groundwater drought is actually associated with meteorological drought but with a time lapse. Broadly, it refers to the decline in groundwater. The temporal occurrence of dry spells and their intensity and the duration of groundwater drought were assessed by the Herbst (1966) method which is described below. Herbst developed a method to assess the meteorological drought severity using rainfall data, which is applied to the groundwater level data in this study. The effective available groundwater (Q_e) of a particular month is calculated by adding the actual available water (Q) to the excess or deficit of the previous month's available water from the long-term mean monthly available water. In calculating this carry-over, a weighting factor (W) is included.

$$Q_e = Qi + (D_{i\text{-}1} * W_{i\text{-}1}) \quad (1)$$

$$D_{i\text{-}1} = (Q_{i\text{-}1} - Q_k) \quad (2)$$

where Q_k is the respective long-term mean available water for the month i–1 (for example, if the month (i–1) is January, k will take the value of 1). The weighting factor is given by:

$$W_{i-1} = 0.1\ (1 + Q_{i-1} * 12/Q_y\ ) \quad (3)$$

where Q_y is the mean annual available groundwater. The deviation ($Q_{ei} - Q_k$) of a month's effective available groundwater from the long-term mean available groundwater of that particular month is calculated. Only the months with negative deviations, i.e. deficiencies, are considered for further calculations. The onset and termination of drought periods are determined by comparing the deficiencies with a 12 value sliding scale. This sliding scale is prepared as:

$$SS\ (r) = MMMR + (r - 1)\ MI \quad (4)$$

where SS is the sliding scale; $MMMR$ is the maximum of mean monthly available groundwater; r is the order of the month from 1 to 12; and MI is the monthly increment given by:

$$MI = \frac{MAD - MMMR}{11} \quad (5)$$

where MAD is the mean annual deficiency (addition of all mean monthly deficiencies) of available groundwater.

The drought severity is determined by:

$$I_n = \frac{\sum_{i=m_1}^{m_2} \left(MD_i - MMD_i \right)}{\sum_{i=m_1}^{m_2} MMD_i} \quad (6)$$

$$I_h = I_m * T \quad (7)$$

where MD is the monthly deficit of available groundwater; MMD is the mean monthly deficiency of available groundwater; I_m is the average monthly drought intensity; m_1 is the month when the drought started; m_2 is the month when the drought terminated; T is the duration of drought = $m_2 - m_1$; and I_h is the weighted index of drought.

A computer program was developed to carry out the drought analysis by the method. Historical groundwater level data for the study basin with reference to mean sea level was used as input to the program. The outputs of the program are onset, termination, and duration and severity index of each dry spell.

GROUNDWATER RISK MAPPING

An attempt was made in the present study to develop the groundwater risk index that reflects the drought vulnerability. The groundwater drought risk index is a function of intensity, duration and frequency of dry spells. It is the ratio of total drought severity and total duration of the droughts. The total drought severity is obtained by multiplying the drought intensity and drought duration of each dry spell. A groundwater drought risk map of the basin was generated by interpolating the groundwater drought risk index value of each well, using MapInfo GIS software. The groundwater drought risk area map shows the status of groundwater vulnerability within the administrative blocks.

RESULTS AND DISCUSSION

Groundwater drought analysis

Long-term monthly water levels from 80 wells in the Palar Basin were analysed to determine dry spells using the Herbst method. Table 2 shows the results for a well located in the Alangayam block. Seven dry spells with drought intensity that ranges from 0.49 to 1.77 were evident for well number 23079 (Fig. 1) and water level fluctuated from 10.52 m to 17.8 m during the period 1975 to 1998. Drought with a considerable intensity of 1.36 prevailed during March 1987 to December 1992. The water level fluctuation was 4.5 m during this drought period and the subsequent rise in groundwater level by up to 17.8 m indicates the severe exploitation of groundwater during the drought period.

Spatial variation of groundwater drought intensity

Most of the wells experienced dry conditions during 1983, and spatial variation of drought intensity during this year are shown in Fig. 2, which reveals the drought intensity varied from 0.0 to 4.0 over the entire basin. Tail-end blocks of the basin were severely affected with intensity ranging from 2.0 to 4.0 and the Lathur and Tirukalukundram blocks were especially severely affected. The administrative blocks of Walajapet, Katpadi, Kanniyambadi, Timiri, Arani, Kanchipuram, Walajabad,

Table 2 Groundwater drought assessment for the Alangayam block.

Sl. no	Onset	Termination	Duration (months)	Intensity
1	January, 1975	April, 1977	27	0.49
2	October, 1980	October, 1981	12	0.96
3	October, 1982	September, 1983	11	1.77
4	November, 1984	April, 1985	5	0.26
5	March, 1987	December, 1992	69	1.36
6	August, 1993	January, 1994	5	0.77
7	October, 1995	July, 1996	9	1.50

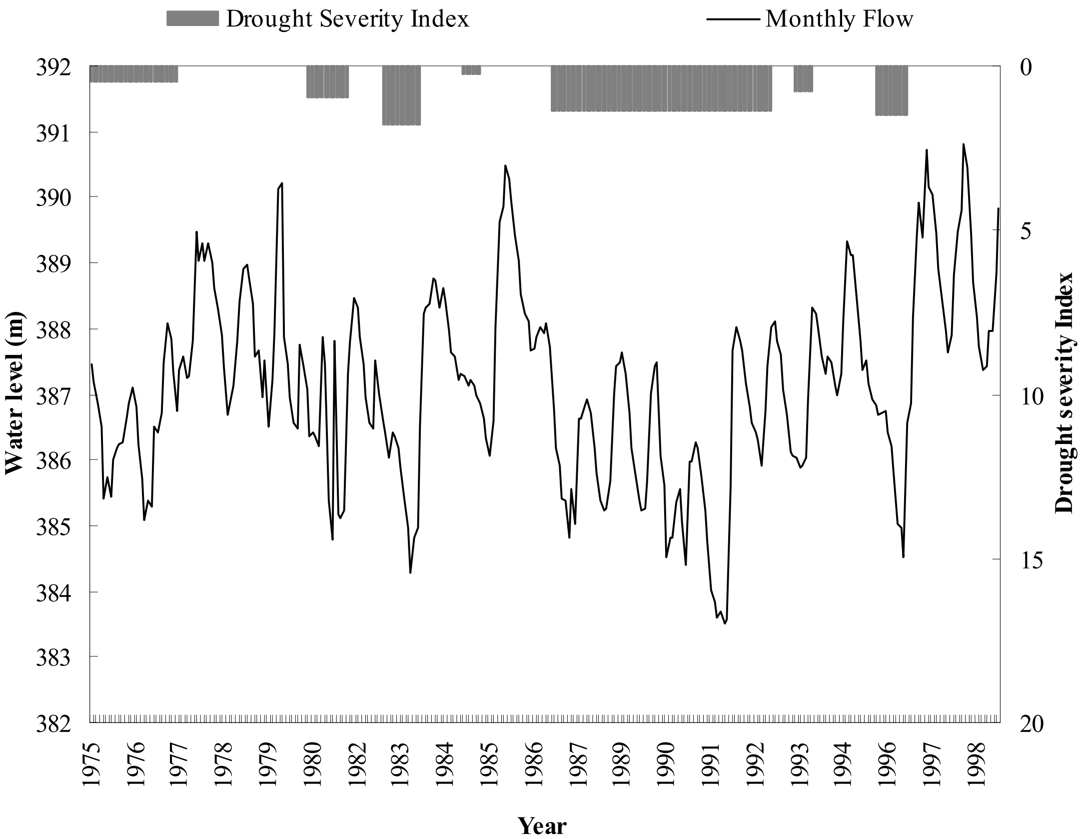

Fig. 1 Groundwater drought assessment for the Alangayam block.

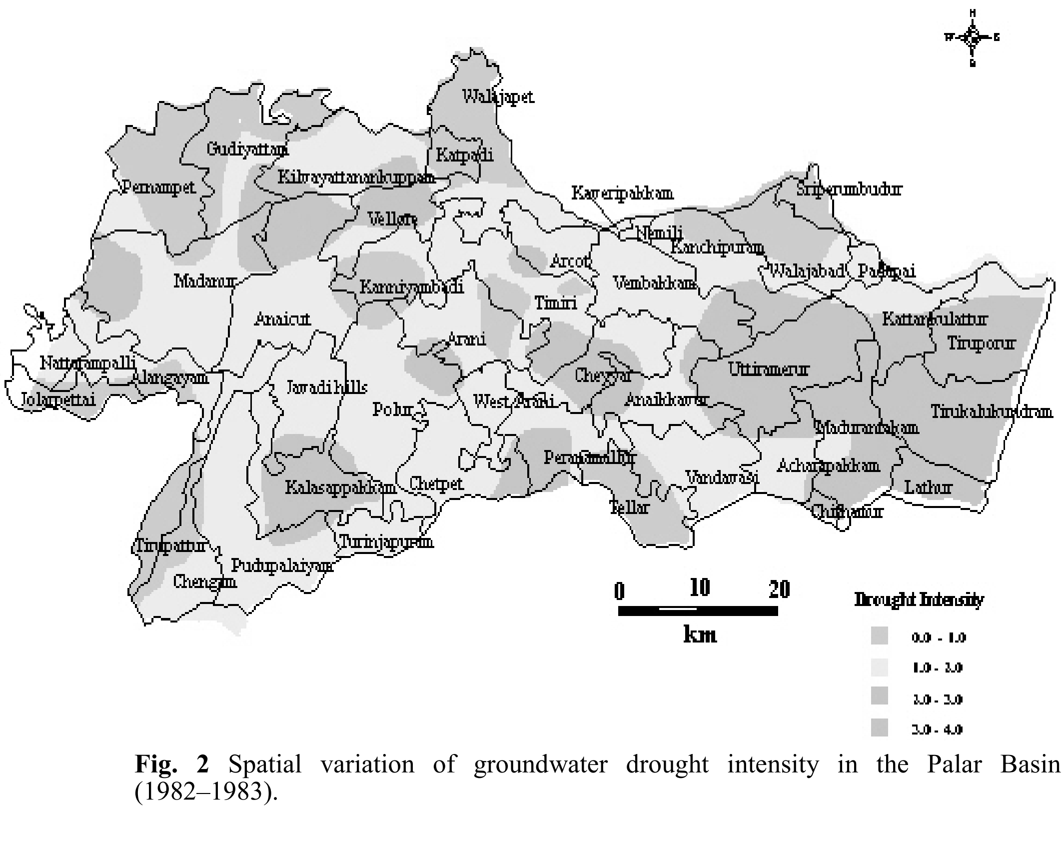

Fig. 2 Spatial variation of groundwater drought intensity in the Palar Basin (1982–1983).

Sriperumbudur, Jolarpettai, Tiruppattur and Pernampet were least affected, and other parts of the basin were subjected to mild drought intensity. The pattern of drought intensity for 1983 reflects not only the low rainfall but the distribution of groundwater over-exploitation.

Groundwater drought risk area mapping

Evaluation of drought risk due to the occurrence of dry spells is important to promote a pro-active approach to mitigate the effects of drought on water resources. A groundwater drought risk index was evaluated for 80 wells and ranged from 0.46 to 0.68. A groundwater risk map was generated by interpolating the drought index of each well using MapInfo GIS software (Fig. 3, Table 3). It is evident that a considerable portion of the Upper Palar is subject to a mild groundwater deficit. In contrast, the middle parts of the Palar Basin are subject to moderate and severe drought risk indicating that severe exploitation is taking place in that region. Regions identified as being at high risk are to have priority management attention with groundwater management plans being started immediately. Those at medium risk are to have plans prepared over a 5-year period. Those in the low risk category are to be regularly reviewed and steps taken to prevent them becoming stressed.

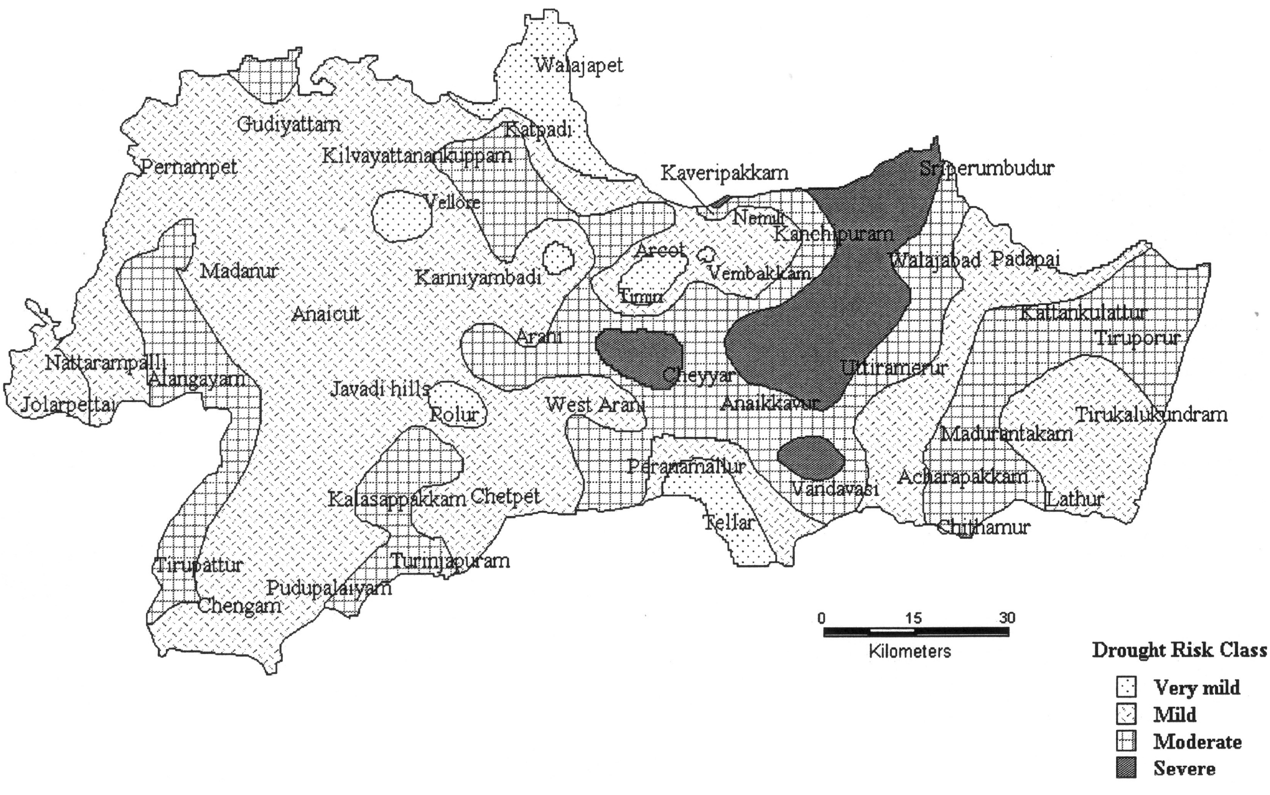

Fig. 3 Groundwater risk areas of the Palar Basin.

Table 3 Groundwater drought risk assessment in Palar Basin.

Sl.No	Well Number	Name of the Block	Risk Index	Risk Class	Sl.No	Well Number	Name of the Block	Risk Index	Risk Class
1	13005	Madurantakam	0.60	Moderate	35	23093ay	Timiri	0.57	Mild
2	13008	Tirukalukundram	0.55	Mild	36	23115	Tiruppattur	0.58	Moderate
3	13010	Kanchipuram	0.66	Severe	37	2401	K.V.Kuppam	0.59	Moderate
4	13013	Uttiramerur	0.56	Mild	38	2402	Katpadi	0.59	Moderate
5	13018	Walajabad	0.66	Severe	39	u23015	Nemili	0.53	Mild
6	13240	Uttiramerur	0.56	Mild	40	u23029	Kaveripakkam	0.65	Severe
7	13241	Madurantakam	0.58	Moderate	41	u23031	Walajapet	0.51	Very mild
8	13245	Acharapakkam	0.56	Mild	42	23010	Pudupalaiyam	0.53	Mild
9	13252	Lathur	0.55	Mild	43	23013	Tellar	0.47	Very mild
10	23047	Kattankulattur	0.60	Moderate	44	23014	Anaikkavur	0.61	Moderate
11	23021	Kanchipuram	0.64	Severe	45	23015	Peranamallur	0.59	Moderate
12	23019	Uttiramerur	0.68	Severe	46	23016ay	Vandavasi	0.57	Mild
13	u23047	Uttiramerur	0.53	Mild	47	23008	Turinjapuram	0.57	Mild
14	u23048	Walajabad	0.58	Moderate	48	23020	Anaikkavur	0.60	Moderate
15	23025ay	Timiri	0.50	Very mild	49	23021ay	West Arani	0.60	Moderate
16	23027	Ambur	0.57	Mild	50	23024	Vembakkam	0.51	Very mild
17	23028	walajapet	0.48	Very mild	51	23056	Cheyyar	0.55	Mild
18	23032	Madanur	0.53	Mild	52	23057	Cheyyar	0.67	Severe
19	23042	Kandili	0.58	Moderate	53	23059	Vembakkam	0.56	Mild
20	23046	Jolarpettai	0.50	Very mild	54	23060	Vembakkam	0.58	Moderate
21	23049	Madanur	0.61	Moderate	55	23061	Vandavasi	0.65	Severe
22	23050	Pernampet	0.53	Mild	56	23064	Peranamallur	0.60	Moderate
23	23052	Gudiyattam	0.54	Mild	57	23068ay	Arani	0.58	Moderate
24	23053	Gudiyattam	0.57	Mild	58	23077	Arani	0.55	Mild
25	23072	Anaicut	0.57	Mild	59	23088ay	Arani	0.68	Severe
26	23073	Anaicut	0.52	Mild	60	23094	Polur	0.47	Very mild
27	23074	Vellore	0.49	Very mild	61	23095	Polur	0.61	Moderate
28	23075	Kanniyambadi	0.54	Mild	62	23097	Kalasappakkam	0.54	Mild
29	23079	Madanur	0.54	Mild	63	23098	Kalasappakkam	0.55	Mild
30	23080	Ambur	0.59	Moderate	64	23101a	Chetpet	0.53	Mild
31	23089	Timiri	0.46	Very mild	65	23117	Chengam	0.57	Mild
32	23090	Timiri	0.58	Moderate	66	23121	Pudupalaiyam	0.57	Mild
33	23091	Timiri	0.57	Mild	67	23126	Polur	0.61	Moderate
34	23092	Walajapet	0.58	Moderate					

CONCLUSION

Regional groundwater drought analysis was undertaken in the present study and the groundwater risk levels were determined for each administrative block. The drought risk map, prepared in this investigation, reflects the overall groundwater drought risk condition of the blocks. This map will be very useful for the administrators in prioritizing the blocks for mitigating the effects of groundwater drought and in making the decisions to frame groundwater management strategies for sustainable management.

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