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Precepts for Groundwater Drought Index in Kerala: A Case Study from Chaliyar River Basin

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Abstract: Groundwater Drought Index (GWDI) is recognized as one of the key Hydrological Indices of drought. But the evolution of drought from meteorological to hydrologic drought is not instantaneous and is dominated by several physical mechanisms. In Kerala due to heterogeneity of terrain, the occurrences of drought at different temporal and spatial scales do not fit into the broad indices of standard GWDI. Hence drought prediction has become a major challenge to decision and policy makers as it fails to address multiple causative factors to recognize the actual ground realities. This paper is an effort to bring out the meteorological, hydrogeological and hydrological factors based on which an attempt has been made to review the groundwater drought index to suggest an improved groundwater deficit class by studying the extreme climate eventualities during 2016 (drought) and 2018 (flood). The progression of drought and its corresponding effect on groundwater regime in Chaliyar river basin has been studied in detail. Based on the typical response of drought conditions in different physiographic zones, a modified GWDI from the case study is proposed.

Keywords: Groundwater level, Groundwater drought index, Hydrogeology, Spatial analysis.

INTRODUCTION

Extensive impacts of drought in past decades at regional and global scales call for improved capability to cope with drought (Below et al., 2007; Sheffield & Wood, 2012; Zengchao Hao et al., 2018). Drought prediction plays a key role in drought early warning system to mitigate its impact. In Kerala, the decreasing rainfall over the region, late onset of the monsoon, failure of the monsoon, and break in monsoon etc lead to many drought situations (Nathan, 2000). The challenges related to prevention, mitigation and management of drought requires a detailed understanding of its symptoms and careful review of its causative factors. Apart from the meteorological factors, the imprints of drought and its persistent response in a terrain give possible clue for effective forecasting. The purpose of early forecasting is to devise new strategies for mitigation and management so that distress and disruption caused to the socio-economic fabric of rural communities can be minimized. The Manual of Drought Index, 2009 published by Department of Agriculture, Cooperation, and Farmers Welfare, Government of India was the first attempt of its kind at putting together the expert knowledge on the nature of drought, social parameters for early detection of the symptoms and eventual declaration of drought with methodologies, strategies for response and mitigation in one single document. The document was later modified and revised in 2016. This was based on practical research, realizing ground realities by inputting knowledge and experience gained over the years. The revised document was added with new scientific indices and parameters such as hydrological indicators for more accurate assessment of drought. The revised module recommended quick and time-bound sample field survey for the confirmation of technical indicators of drought in order to secure a holistic understanding of ground realities. Groundwater drought is a distinctive class of drought resulting from the decrease in groundwater recharge (Goodarzi et al., 2016) and the decrease in groundwater storage and discharge (Mishra and Singh, 2010). In a highly heterogeneous terrain like Kerala, the aquifer response to change in water levels, rainfall and other drainage characteristics would need careful study to address various hydrological parameters for more accurate drought predications. Kerala witnessed an extreme drought in 2016 and extreme monsoon in 2018. This provided an opportunity to study the extreme climatic behavior on groundwater regime by assessing the impact of those events with respect to groundwater drought.

STUDY AREA

The Chaliyar river forms the third largest river in Kerala.

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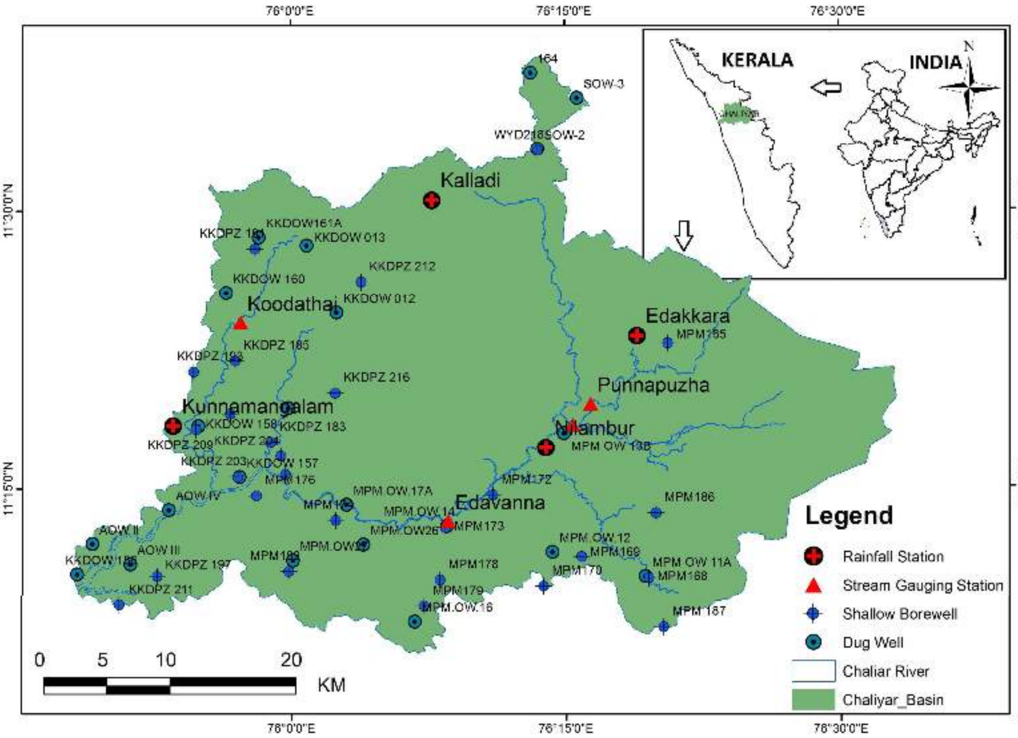

Fig.1. Location map of the study area.

The river has a total lengh of 169 km originating from the Western Ghats in Tamil Nadu, with a total drainage area of 2923 km^2. It is bound by latitudes 11º06'07''N and 11º33'35''N, and longitudes 75º48'45''E and 76º33'00''E falling in Survey of India (SOI) degree sheets 58A and 49M (Fig.1). The river basin is undammed and hence the anthro-pogenic influence on hydrodynamic system is minimum. This is also one of the perennial rivers where the typical lateritic and crystalline aquifer system within the basin is well developed.

ENVIRONMENTAL SETTINGS

The Chaliyar river drainage system comprises six major streams viz., Chaliyarpuzha, Punnapuzha, Kanjirapuzha, Karimpuzha, Iruvahnipuzha and Cherupuzha (Fig. 2). Most of these streams are dendritic in nature and have their origin in the Nilgiri hills in the east and Wayanad hills in the north, where they form a number of rapids and waterfalls. The whole drainage system is channeled through Nilambur of Malappuram district and flows out in Kozhikode district before it joins the sea near Beypore. The morphology of Chaliyar river drainage basin with oval shaped Nilambur valley in the centre where most of its tributaries flowing SE, S, SW, W and NE get merged and then flow SW is typical for Chaliyar river (Latha and Manju Vasudevan, 2016). The basin spread across four districts viz. Kozhikode, Malappuram, Wayanad in Kerala and Nilgiri district of Tamil Nadu covering four major physiographic zones of Kerala viz, highland, midland, lowland and coastal plains. The highlands are depicted by the hill ranges of Nilgiri and Wayanad plateau of the Western Ghats with elevations > 600 m above mean sea level forming an important physiographic province. Elambaleri hill is the highest peak having a height of 2260 m from where the Chaliyar river originates (Rohtash et al., 2019). The midland region of the Chaliyar river drainage basin with elevation ranging from 300 to 600 m and occupying a very narrow strip of elongated spurs separated by ravines merge with relatively gentler slopes of the lowlands. Lowlands consist of dissected peneplain with an altitudinal range of 10-300m and includes the Nilambur valley, which runs in NE-SW direction and is broadest in the central part with an elevation ranging between 10 and 40 m above MSL. The floodplains, river terraces, channel and valley fills, colluvium and isolated mounds and hills are parts of the lowlands, and are typical to the Kerala coast. The coastal plain in the west is devoid of delta where the river debouches into the sea with an elevation reaching a maximum of 10 m above MSL (Thakural et al., 2019). The topography is very rugged on the east and the crest of the mounds and hills are generally very sharp and narrow with very steep slopes. Deep gorges and mountain-fed streams are characteristics of the hill ranges. The drainage basin is underlain by laterites and Precambrian crystalline group of rocks. The laterites and weathered

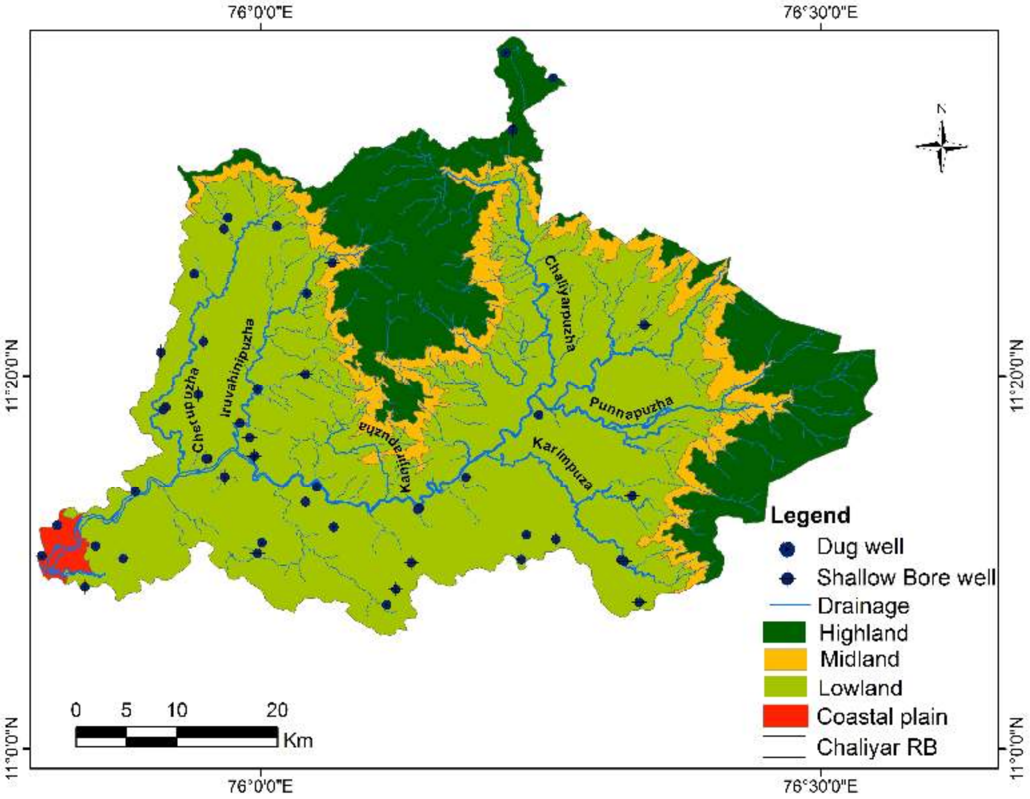

Fig.2. Map showing Physiography of Chaliyar basin with drainage

crystallines form the dynamic aquifer system in the vast lowland and midland regions which is typical of Kerala. The laterites and weathered crystallines are largely interconnected that forms the potential phreatic aquifer in the region. The presence of large shallow interconnected fractures that controls the movement of groundwater in the shallow zone is identified through pumping response in the midland regions of Kerala (Kukillaya, 2007).

MATERIALS AND METHODS

The monthly groundwater level data from 36 shallow monitoring wells of Groundwater Department, Kerala from 2006 to 2018 have been selected for the present study. The rainfall data from 4 rain gauge stations and stream discharge data from 4 stream gauging stations monitored by IDRB, Irrigation Department, Kerala during the same period also have been used. To understand dynamic response to water table, the wells tapping laterite and shallow weathered crystalline aquifers up to a total depth of 30mbgl alone are considered. The dynamic aquifer response to groundwater table during extreme summer months (March, April and May) of 2016 and extreme monsoon months (June, July and August) of 2018 are subjected for a detailed study. The decadal trend of groundwater levels, groundwater fluctuation, rainfall distribution, stream discharge, surface runoff etc. were estimated and analysed. The adaptive response to groundwater levels in the basin during two extreme climatic events were studied in detail through GIS spatial interpolation. To get more accurate results on the behavior of groundwater table in the basin, the eastern hilly forest cover is excluded from spatial interpolation. Assimilations are made in GIS to understand the adaptive response of terrain with respect to standard Groundwater Drought Indices (GWDI) for both higher and lower classified values. The ground truth verifications were also done to appreciate the sensitivity of the terrain at selected points.

DATA ANALYSIS

Depth to Groundwater Levels

The dynamic response to groundwater is a significant factor that determines groundwater recharge. The analysis of average depth to decadal groundwater levels within the basin indicates groundwater level ranges from 0.72 mbgl to 12.37 mbgl during May 2016. Whereas the average decadal groundwater levels during Aug. 2018 ranges from 0.83 mbgl to 10.22 mbgl. The detailed analysis of well frequency revealed that depth to water level (DTW) of 79% of wells during the peak summer

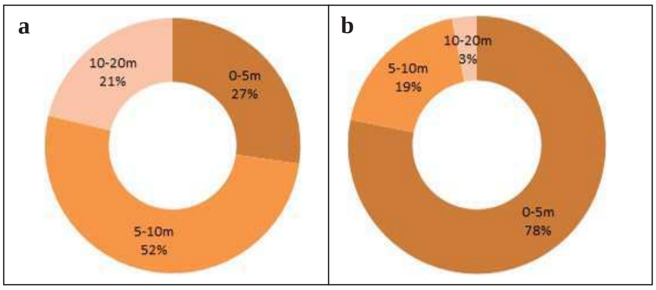

Fig.3. Well frequency for different ranges of DTW in **(a)** May 2016. **(b)** August 2018

month of 2016 and 97% of wells during peak monsoon month of 2018 were <10 mbgl (Fig.3a and 3b).

The categorization of change in groundwater level with respect to the decadal mean indicates a fall in the range of 0-2m noticed in 78.8% of wells and a fall in the range of 2-4m noticed in 12.1% of wells. An overall fall in water level with respect to decadal mean noticed in 90.9% of wells during May 2016. This was regarded as the maximum fall exhibited during the extreme summer months of 2016. The change in water level (fluctuation) during Aug. 2018 indicates an overall rise in water level in 84.4% of wells (Table 1). The detailed analysis indicates rise in water level in the range of 0-2m noticed in 71.9% of wells and a rise of 2-4m noticed only in 9.4% of wells. It is pertinent to note that rise and fall are mostly accounted within the range of 0-2mbgl indicating shallow range of fluctuation in the zone of dynamic groundwater recharge. The decadal trend of fluctuation in Chaliyar basin implies the terrain response is very sensitive in the shallow groundwater regime that requires small classifed intervels to define fluctuations at an appreciable level.

Trend Analysis of Groundwater Levels

The long term behavior of groundwater within the basin is studied by analyzing the rate of rise and fall in water levels stretched over the summer and monsoon months of 2016 and 2018 respectively. A statistical analysis was carried out for water level of individual wells through GWDES software. An average number of 150 data of individual wells from January 2006 to December 2018 were studied to understand the long term behavior of groundwater levels (Table 2). The long term trend analysis of groundwater levels within the basin indicates the rate of groundwater fall ranges from -0.07cm/yr to -0.22cm/yr. An overall falling trend is noticed in 83.33% of the wells. The rising trend is noticed in the rest of the wells ranging from +0.004 cm/yr to +0.028 cm/yr. The wells situated in the topographic lows and those close to the coastal areas indicate rise in groundwater levels where the rate of fluctuation is rather slow.

Well Hydrographs

The study of individual wells at different depths and geomorphic zones within the basin during the period 2006 to 2018 were carried out by superimposing the well hydrographs of open wells and shallow bore wells. The analysis of data from the open well and shallow bore well situated in Kallikavu area reveals that the groundwater levels are overlapping each other (Fig. 4a). These wells situated in the midland area at an altitude of 52.556 m above msl where the shallow bore well records an average water level ranges from 0.16 mbgl to 5.19 mbgl. The groundwater level of open wells range from 1.01 mbgl to 7.35 mbgl indicating interconnected aquifers in the midland terrain. The pattern of fluctuation of these closely spaced wells are almost uniform with an overall decreasing trend indicating a general behavior of open wells and shallow bore wells in the area. However, the recession limbs on the hydrograph of shallow bore well display bimodal peaks which is distinct throughout the period indicating similar recharge-discharge condition existing in the area irrespective of SW and NE monsoons.

The open wells and shallow bore wells in the low land area at Puthupadi also show overlapping of groundwater levels. The fluctuation of open well ranges from 1.88 mbgl to 4.95 mbgl. Whereas, in the case of shallow bore wells it ranges from 0.08mbgl to 5.61mbgl respectively. The superimposed hydrographs of these wells clearly indicates a similar pattern of flutuation which is almost uniform irrespective of well types (Fig.4b). An overall falling trend is noticed in these wells also indicating a similar behavior of groundwater levels, as seen elsewhere in other physiographic zones.

In the coastal alluvium, the well hydrographs of open wells and shallow tube wells indicate that the groundwater level fluctuation ranges from -0.03 mbgl to 5.24 mbgl and -0.41 mbgl to 3.35 mbgl respectively (Fig.4c). The superimposed hydrographs indicates a non-uniform bimodal peaks in the

Table 1. Categorization of rise and fall in groundwater levels with respect to decadal mean

Period	Rise in meters		Fall in meters		% Rise			% Fall		
	Min	Max	Min	Max	0-2m	2-4m	>4m	0-2m	2-4m	>4m
May 2016	0.265	0.715	0.08	3.27	9.1	0.0	0.0	78.8	12.1	0.0
Aug. 2018	0.095	3.675	0.41	1.17	71.9	9.4	3.1	15.6	0.0	0.0

Table 2. Trend Analysis of Groundwater Level from January 2006 to December 2018

Sl. No .	Location	Well No	No. of Data	Rise (m/yr.)	Fall (m/yr.)	Intercept
1	Chathamangalam	KKDOW 158	123	-	0.052	5.598
2	Chathamangalam	KKDPZ 184	151	0.014	-	4.973
3	Kodiyathur	KKDPZ 204	154	-	0.219	5.042
4	Kodiyathur	KKDPZ 205	154	-	0.007	5.683
5	Mavoor	KKDOW 157	154	-	0.028	6.573
6	Mavoor	KKDPZ 203	155	-	0.220	5.261
7	Nallalam	KKDOW 156	154	-	0.060	1.865
8	Puthuppadi	KKDOW 013	154	-	0.008	3.853
9	Puthuppadi	KKDPZ 191	151	-	0.019	4.068
10	Puthur	KKDPZ 185	154	-	0.072	5.740
11	Ramanattukara	KKDPZ 197	155	-	0.021	0.653
12	Thamarassery	KKDOW 160	154	0.028	-	3.941
13	Thazhekode	KKDOW 159	152	0.004	-	7.630
14	Thiruvambadi	KKDOW 012	149	0.009	-	4.861
15	Thiruvambadi	KKDPZ 212	152	-	0.012	2.659
16	Cherukavu	MPM.OW25	127	0.009	-	1.917
17	Edavanna	MPM.OW.14	150	-	0.022	10.023
18	Edavanna	MPM173	154	-	0.008	6.951
19	Karakunnu	MPM178	153	-	0.026	7.527
20	Kavanoor	MPM.OW26	148	-	0.077	2.236
21	Kuzhimanna	MPM.OW27	150	-	0.085	3.050
22	Kuzhimanna	MPM182	152	-	0.049	9.924
23	Narukara	MPM.OW.16	151	0.071	-	6.744
24	Trikkalangode	MPM179	154	-	0.060	2.974
25	Vazhakkad	MPM176	152	-	0.025	4.671
26	Nilambur	MPM OW 13B	116	-	0.075	3.516
27	Chokkad	MPM186	129	-	0.085	8.383
28	Kalikavu	MPM OW 11A	152	-	0.023	4.301
29	Kalikavu	MPM168	154	-	0.026	2.567
30	Mampad	MPM172	154	-	0.093	3.872
31	Vazhikkadavu	MPM185	130	-	0.057	1.751
32	Wandoor	MPM.OW.12	151	-	0.039	8.485
33	Wandoor	MPM169	153	-	0.100	1.086
34	Ambalavayal	164	156	-	0.030	3.916
35	Nenmeni	SOW-3	155	-	0.061	7.265
36	Muppainad	SOW-2	155	-	0.036	8.317

rising limbs indicating a slightly different pattern of fluctuation in the coastal alluvium during the monsoon periods. This typical behavior of fluctuation was already reported in other coastal segments in Kerala (Lal Thompson and Rajamanickam, 2006). The negative values indicate excess runoff from the basin during monsoon months across the low lying coastal area.

Trend of Rainfall Distribution

On an average about 3000 mm of rainfall occurs annually in the basin which is close to the State average of 3100mm. The modeling studies of rainfall in the Chaliyar basin carried out during the period from 1993 to 2011 on seasonal and annual scale noticed both increasing and decreasing trends, even though they are statistically insignificant (Rohtash et.al., 2019). However, Thakural et al. (2019) noticed seasonal and temporal variation within the basin which is significant for drought characterization. Hence the local rainfall variablity in the basin have been studied for Nilamboor, Kunnamangalam, Edaakkara, Kalladi stations during the last ten years (2009 to 2018). It is significant to note that the precipitation was found to be high along the N and NE segments. The decadal average rainfall at Kalladi area was 3600mm. Whereas the decadal average rainfall at Kunnamangalam, Nilambur and Edakkara were 3127 mm, 2656 mm and 1564 mm respectively. The study on the decadal annual distribution of rainfall further indicates the lowest rainfall of 1941mm recorded in the year 2016 and

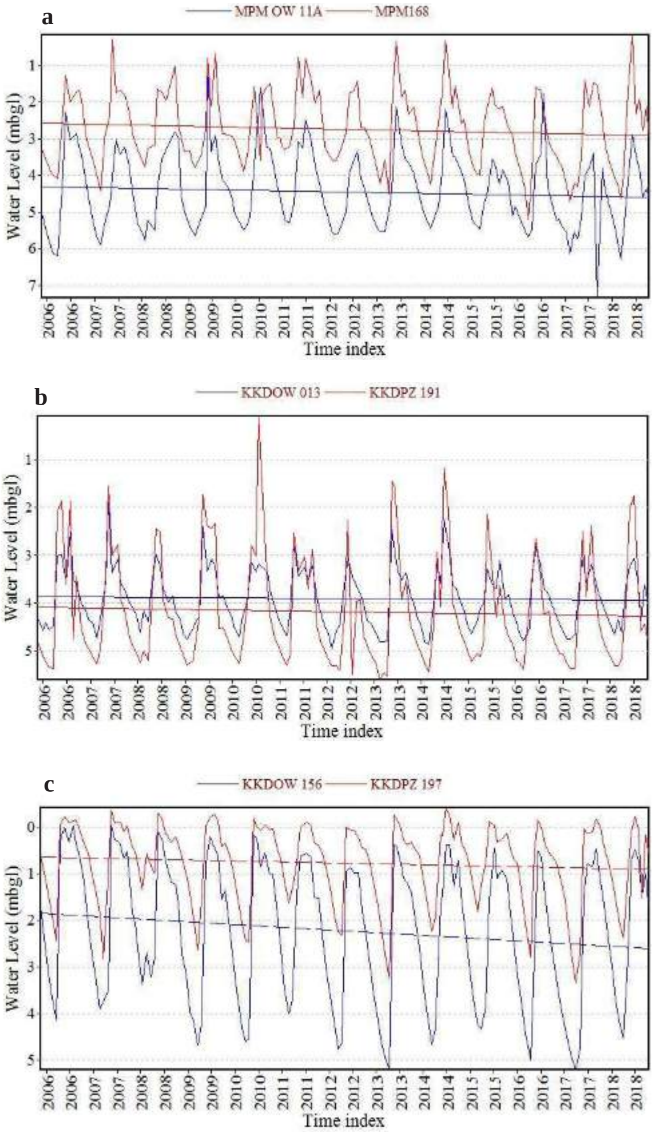

Fig.4. Well Hydrograph of open well and shallow bore well at **(a)** Kallikavu. **(b)** Puthupadi. **(c)** Well Hydrograph of Open well and shallow Tube well in the Coastal alluvium

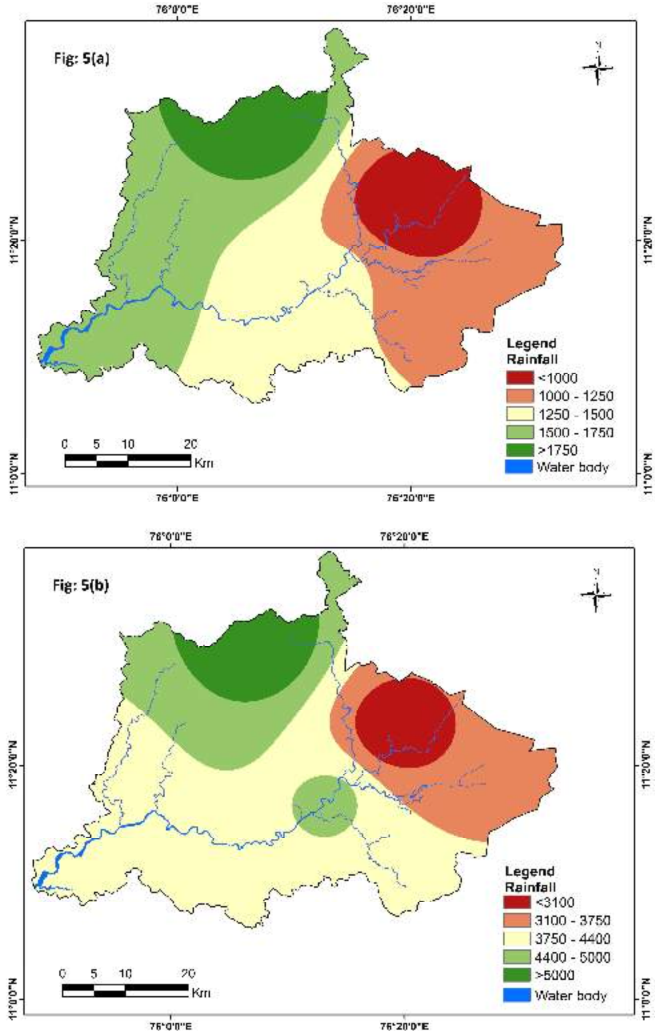

Fig.5. Spatial annual rainfall distribution in Chaliyar basin during **(a)** 2016. **(b)** 2018

the highest rainfall of 4714mm in the year 2018. The spatial interpolation of annual rainfall during 2016 and 2018 are given in the Figs. 5a and 5b.

Surface Runoff

Any change in rainfall and its pattern highly influences stream flow derived largely through surface runoff. The hydrological model prepared for the Chaliyar basin observed that even though stream flow exhibited a declining trend it is not severe as to adversely affect agricultural activities in the basin (Raneesh and Thampi Santosh, 2011). The flow across the stream channel during the last ten years were calculated based on the volumetric flow computed from the four stream gauging stations within the basin. The runoff was estimated from the monthly stream discharge data collected during the period from Jan. 2009 to July 2019. Chaliyar was considered as a perennial river but major portions of the stream was found dry during the extreme summer months of 2016. The analysis of runoff data reveals that the annual peak discharge curves during 2016-2017 almost touches zero for all stations (Fig.6). The total pre-monsoon runoff at Karimpuzha station was nil. But the same for Koodatai, Mukkom and Punnapuzha stations were meagre with low discharge values of 0.100 cumecs, 3.970 cumecs, 0.201 cumecs respectively indicating the lowest summer discharge in the decade. This clearly indicates the cessation of base flow during the lean period of 2016 which might have led to drying up of stream beds elsewhere in the basin. However, the runoff estimated at Karimpuzha, Koodathai, Mukkam and Punnapuzha were 291.386 cumecs, 149.809 cumecs, 147.383 cumecs and 142.01 cumecs

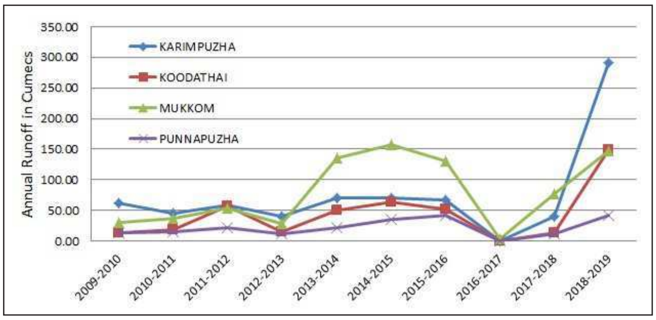

Fig.6. Annual runoff of Chaliyar basin at different stations.

respectively during the monsoon months of 2018. The extreme monsoon rainfall possibly induced heavy runoff. The drainage charecterstics, highly undulating terrain morphology, geology etc. of the area controls the rainfall runoff within the basin. The positive relationship among rainfall, runoff and sediment discharge was reported earlier suggesting precipitation and run-off exert a first order control in the basin (Rohtash et al., 2019).

Change in Groundwater Level with Decadal Mean

The study on the change in groundwater level of each well with respect to decadal mean has been carried out to understand the progression of drought effects within the basin (Fig. 7a and 7b). The study indicates that 57.1% of wells were showing fall in groundwater levels during the summer month of March 2016. The fall in water level was noticed in 82.9% of wells during the month of April 2016. The fall in water level was progressing and it reached its maximum during the month of May 2016 registering a fall in 90.9% of the wells in the basin. This is the highest seasonal decline of groundwater level due to the long absence of seasonal rainfall. However, during the month of June 2018, 73.6% of wells were showing fall in groundwater level with respect to decadal mean. The rise in groundwater level of 26% noted during the month of June 2018. It further increased to 64.7% during July 2018 and reached its maximum of 81.3% during the month of Aug. 2018 respectively. It is seen that in spite of heavy rainfall the aquifer recovery has not reached maximum as compared with May 2016.

Standard Groundwater Drought Index (GWDI)

The rate of depletion of groundwater table is useful for making an assessment of groundwater availability for agriculture and drinking water supply purposes. The monthly groundwater level data are required for a minimum period of 10 years for computation of mean value of monthly groundwater depletion rate. When rate of depletion of groundwater table in a given month/period is more than the corresponding mean value then it is an indication of water deficit condition. The computation procedure for Groundwater Drought Index (GWDI) proposed in the manual for drought management in 2016 is as follows:

$$GWDI_{ij} = \frac{MGWD_j - GWD_{ij}}{GWD_{iMax}}$$

Where,

$GWDI_{ij}$ = Groundwater Drought Index for ith month and jth year.
$MGWD_j$ = Mean depth to groundwater table below surface (in meter)
GWD_{ij} = Depth to groundwater table in ith month and jth year (in meter).
GWD_{imax} = Maximum depth to groundwater table in ith month in available data set for n number of years (in meter).
i = 1, 2, 3, 4, …………, 12.
j = 1, 2, 3, ……………, n.
n = total numbers of years for which monthly groundwater records are used.

Chaliyar river basin comprise of a well developed aquifer system that spreads across the major physiographic divisions in Kerala. The basin was undergoing intensive human activities

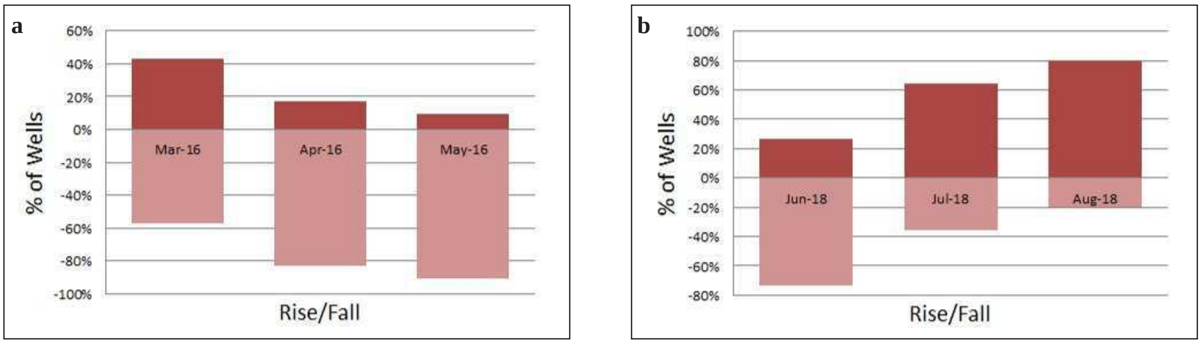

Fig.7. Change in groundwater level with decadal mean in **(a)** 2016. **(b)** 2018

and exposed to significant drought and monsoon periods during 2016 and 2018 respectively. The Groundwater Drought Index (GWDI) proposed in the drought manual 2016 disclaims the limitation of this index due to non-availablity of real time groundwater level data on monthly scale. To overcome the mentioned limitation, monthly groundwater level data from the monitoring wells of Groundwater Department has been used. As a case study, GWDI is applied over extreme summer months from March to May 2016 and excess monsoon months from June to Aug. 2018. To avoid getting misleading projections, GWD_{imax} has been taken carefully, analyzing the groundwater levels of individual wells by comparing the outlier values in the historical dataset. To get most accurate results, the eastern forest cover is excluded from spatial interpolation. The Standard Groundwater Drought Index (GWDI) of March, April, May 2016 and June, July and August 2018 have been prepared for Chaliyar basin to assess the status of groundwater drought conditions. The drought index maps for the respective months were prepared along with modified drought index maps based on mathematical assimilations. The assimilations were carried out for two upper and lower values at classified intervals of -0.05 and -0.10 with respect to the standard values. The long term trend analysis of groundwater levels and comparision of change in groundwater levels with decadal mean during extreme months of 2016 and 2018 have been used for comparision of Standard and Modified drought index values. These maps were then compared with base flow, rainfall and further cross checked with ground realities to evolve the modified values (Table 3).

Modified Groundwater Drought Index

The maps generated on Standard and Modified GWDI during extreme summer 2016 and monsoon 2018 months were paired and presented in Figs. 8a-b, 9a-b, 10a-b, 11a-b, 12a-b, 13a-b respectively. The maps give an overall glimpse on the progression of drought on temporal and spatial scales. It is seen that, when 57.1% of wells are showing falling groundwater levels as compared to the decadal mean a "normal" class is depicted during the month of March 2016 (Fig. 8a-b). There is no change in the groundwater deficit class noted during the month of April 2016 even though 82.9% of groundwater levels in the wells were actually falling (Fig. 9a-b). However, during the month of May 2016 when the area was fully drought hit "mild" to "moderate" occurence of drought could be noticed only in small pockets (Fig. 10a-b). The zero to low base flow, meagre summer rainfall of 120mm and fall in groundwater levels of 90.9% noticed in wells during this extreme period were not fully manifested in the standard GWDI. However progression of drought from normal to "mild", "moderate", "severe" and "extreme" deficit classes could be derived from the assimilated values during these three extreme summer months. The change in groundwater level with decadal mean indicates a fall in water level noticed in 57.1% of wells in March 2016 and 90.9% of wells in May 2016. The analysis indicates the progression of drought took almost 2 months (60 days) to reach its full extent. The modified GWDI applied is in good agreement with the change in groundwater levels with respect to decadal mean and base flow. The modified groundwater drought index with a class interval of -0.05 appears to be realistic with regard to the actual terrain response within the basin.

Table 3. Standard and Modified Groundwater drought Index and Groundwater deficit class

Groundwater Drought Index (GWDI)	Modified Groundwater Drought Index (GWDI)	Groundwater Deficit class
>-0.15	>-0.05	Normal
-0.16 to -0.30	-0.06 to -0.10	Mild
-0.31 to -0.45	-0.11 to -0.15	Moderate
-0.46 to -0.60	-0.16 to -0.20	Severe
<-0.60	<-0.20	Extreme

It is observed that only 26.4% of wells showed a rise in groundwater level in the wake of monsoon during June 2018. The standard drought index indicates dynamic improvement in drought condition in the southern segment. When modified drought index is applied; a significant shift from "normal" to "mild class" could be noticed in the undulting terrain where the distribution of rainfall is also maximum giving imprints of dynamic aquifer recharge. (Fig.11a-b). During the month of July 2018 the progressing monsoon induced further changes in the aquifer system and the rise in water level could be seen in 64.7% of wells. The standard groundwater drought index did not respond to those changes. But the modified drought index applied is reasonable to adapt those changes with "mild drought" seen as patches in places when aquifer recovery was progressing (Fig.12a-b). Inspite of heavy precipitation, 81.3% of aquifer recovery alone could be achieved by August 2018. It was found that the rainfall received during the monsoon spell of 2018 alone was 3354 mm, that accounts 69% of the annual rainfall received during the same year. The change in water level with decadal mean indicates fast aquifer recovery during the initial 30 days as noted by the rise in groundwater level from 26.4% to 64.7% of wells during the month of July 2018. The recovery in the next 30 days was slow as indicated from the maximum recovery of 81.3% noted in wells during the month of Aug. 2018. The heavy precipitation/rapid rainfall (typically occuring for few days or weeks) in a highly sloping terrain leads to high surface runoff and reduced potential groundwater recharge. Though the runoff was quite high, the water table recovery during the month of Aug. 2018 was

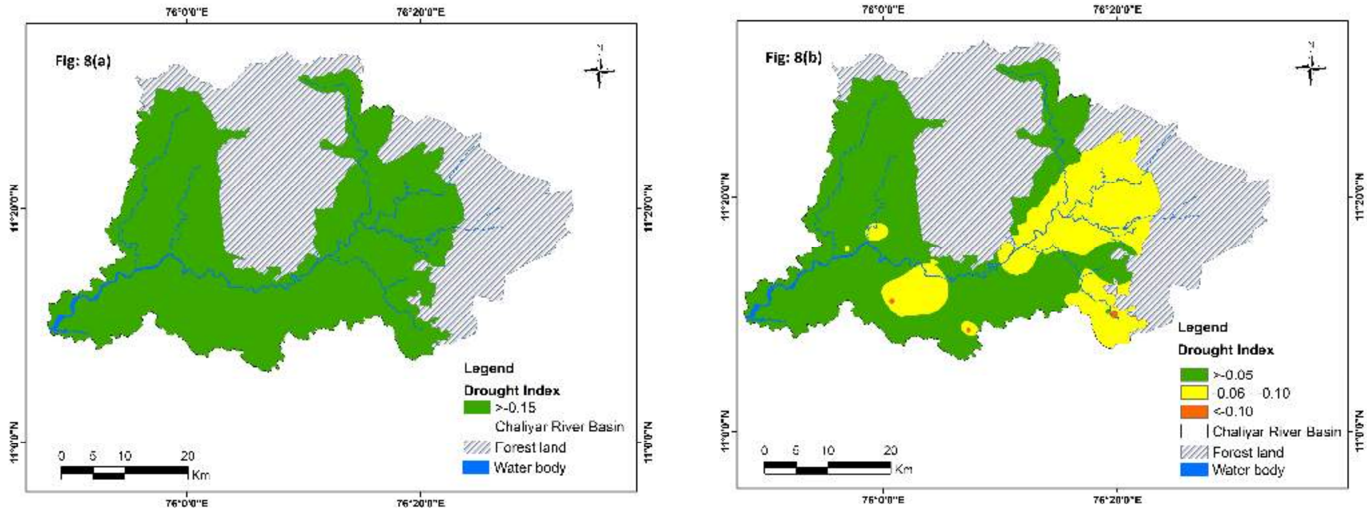

Fig.8. (a) Standard groundwater drought index map during March 2016. **(b)** Modified groundwater drought index map during March 2016

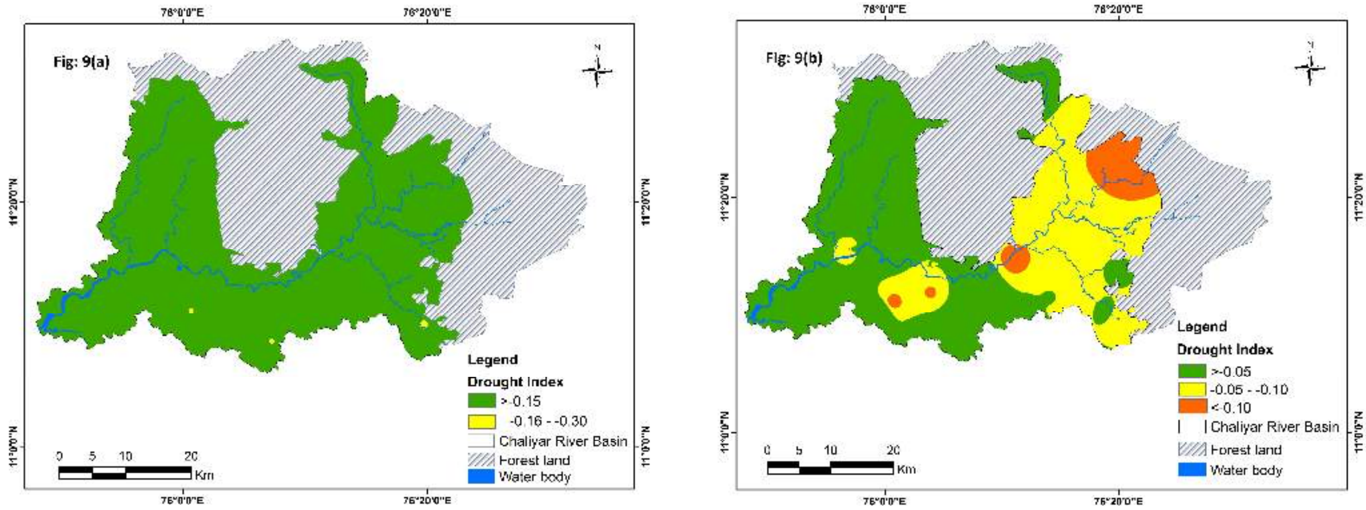

Fig.9.(a) Standard groundwater drought index map during April 2016. **(b)** Modified groundwater drought index map during April 2016

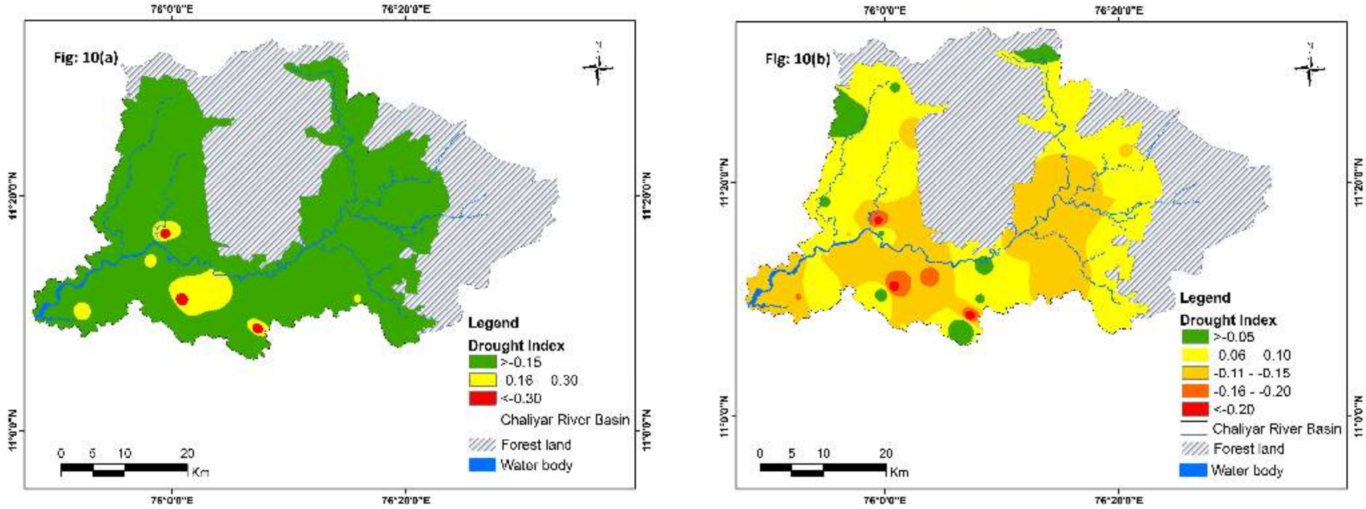

Fig.10. (a) Standard groundwater drought index map during May 2016. **(b)** Modified groundwater drought index map during May 2016.

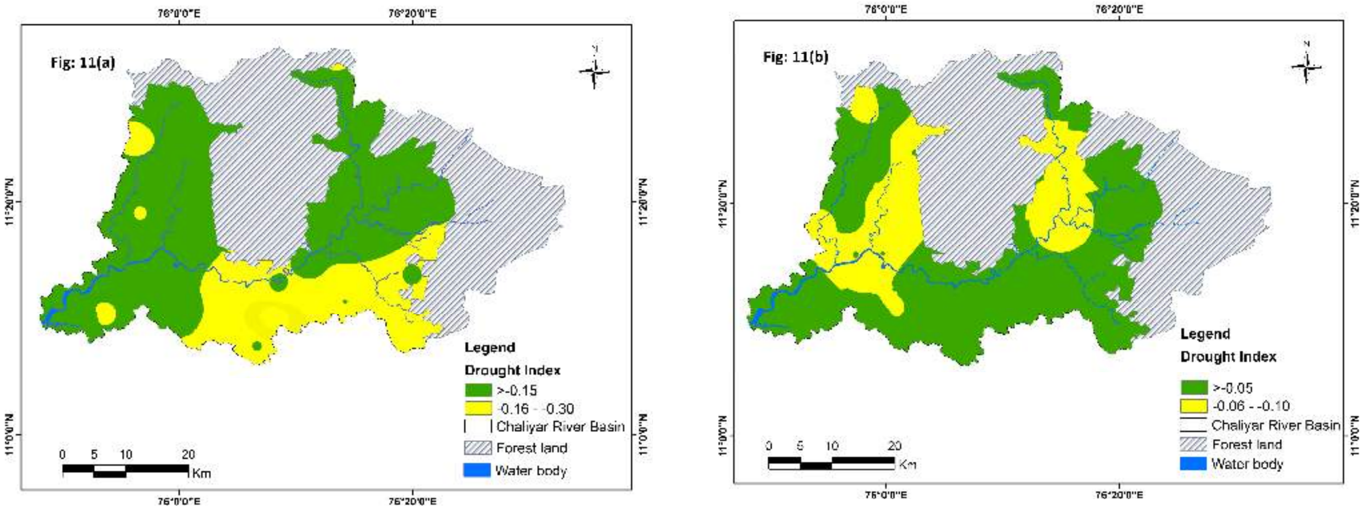

Fig.11. (a) Standard groundwater drought index map during June 2018. **(b)** Modified groundwater drought index map during June 2018

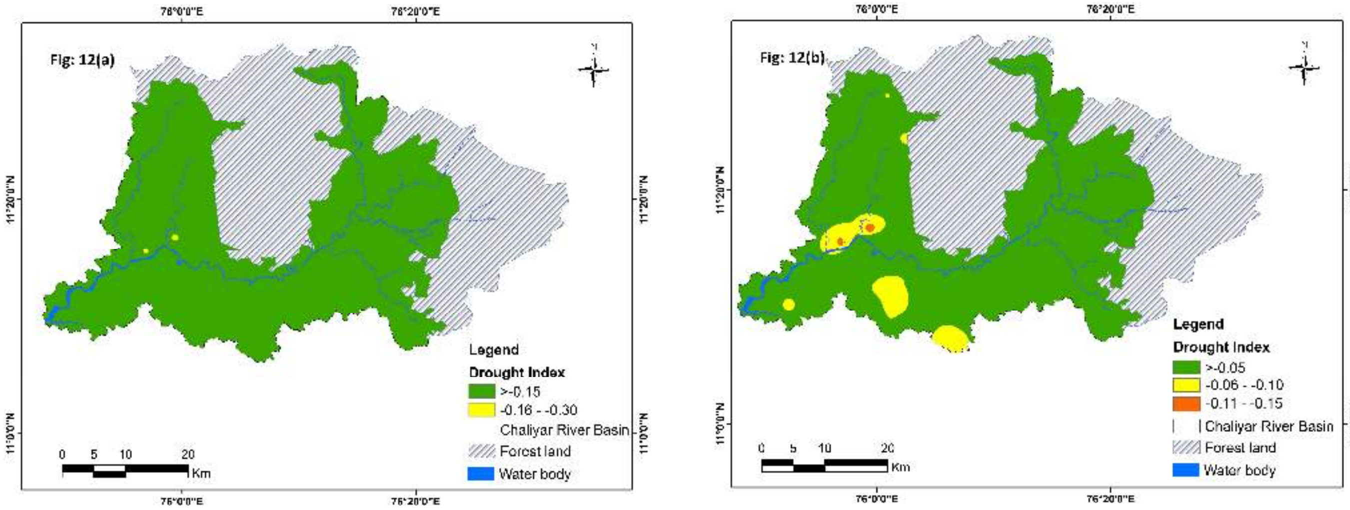

Fig.12. (a) Standard groundwater drought index map during July 2018. **(b)** Modified groundwater drought index map during July 2018

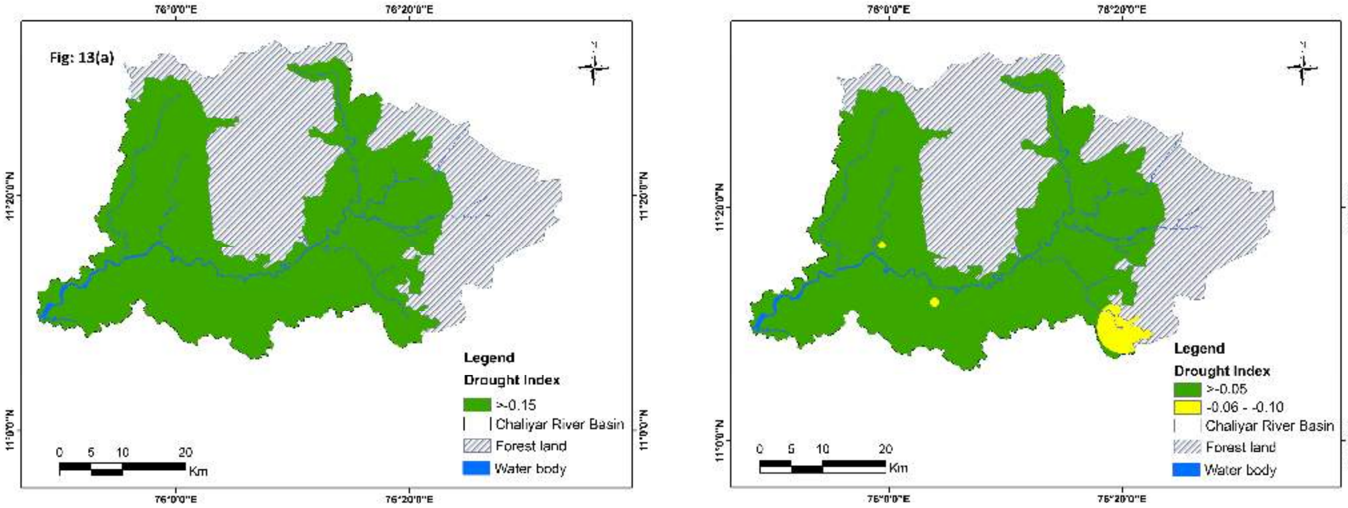

Fig.13. (a) Standard groundwater drought index map during Aug. 2018. **(b)** Modified groundwater drought index map during Aug. 2018

appreciable (Fig.13a-b). The standard GWDI values fits in to the "normal" class where as modified GWDI exhibits "mild" indications only at few places giving imprints of delayed recovery. This is in good agreement with the class derived from the modified values thus giving a better picture of aquifer recovery during the monsoon phase.

DISCUSSIONS AND CONCLUSIONS

The study reviewed the Standard Groundwater Drought Index (GWDI) and its applicability on the occurance of groundwater deficit condition in Chaliyar basin. The behavior of groundwater table during the summer months of 2016 and monsoon months of 2018 had been analysed in detail. The pictorial results generated through standard and various classified values have been studied, analysed, compared, and correlated. The long term trend analysis of groundwater levels within the basin indicates an overall falling trend noticed in 83.33% of the wells. The rate of groundwater fall ranges from -0.07 cm/yr to -0.22 cm/yr indicating the stage of groundwater development in the basin is increasing. An attempt has been made in this paper to provide a comprehensive idea of groundwater drought through interpretation and correlation of various drought parameters. It was found that during the extreme summer months the total rainfall received in the basin was 120 mm and the estimated base flow during the period was almost nil. The comparative analysis of water levels with decadal mean during the peak summer month of May 2016 depict a fall in 90.9% of the wells. But the standard GWDI applied over the basin during the extreme drought period of March to May 2016 did not show any significant indication of drought. However, the modified GWDI derived through assimilations applied over the basin with a class interval of -0.05 is found to be in good agreement with aquifer response. The physical development of drought in the basin found to have reached its peak in 60 days. The progression of drought from normal to "mild", "moderate", "severe" and "extreme" deficit classes could be derived from the assimilated values during the three extreme summer months.

The basin received a heavy precipitation of 3354 mm during the period from June to Aug. 2018 contributing 69% of the annual rainfall received during the same year. But 81.3% of aquifer recovery alone could be achieved during the extreme monsoon event. It was found that initial recovery of water level within 30 days was fast as compared to the next 30 days within the basin. This could be attributed to the nature of aquifer system, recharge potential of aquifer, intensity of rainfall and other hydro-geomorphic conditions. The comparision of different scenario with rainfall-runoff, change in groundwater level with decadal mean, and long term trend analysis of groundwater levels hold good agreement with the modified drought deficit class. The detailed analysis of data and combination of various factors operating within the basin offer better understanding and better monitoring of drought conditions for typical undulating lateritic aquifers having high rainfall and low range of groundwater level fluctuation in Chaliyar basin.

It is stressed that the modified drought index derived from the case study will not only benefit the drought research community but also would help decision makers to provide an essential element in early drought warning and risk management more effectively. Moreover the exploratory analysis implies that a uniform Standard Groundwater Drought Index for the whole of India is not viable and realistic. The indices should be State specific based on the terrain characteristics and hydrometeriological factors. The modified groundwater drought index (GWDI) and corresponding deficit class derived from the case study may be incorporated in future in groundwater management plan in Kerala.

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