An Evaluation of Probability of Occurrence of Hydrological Extremes

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Abstract
The hydrological extremes viz. droughts and floods, are global recurring natural hazards which are dynamic with respect to space and time impacting many people. The increase in the number of instances of these hydrological events in the past has steered the research in the direction towards evaluation of probability of occurrence of droughts and floods on a catchment scale, for proper planning and decision making in ideal allocation of the scarce water resources and mitigation of flood. Understanding and evaluating hydrological extremes becomes important in terms of sizing of storage reservoirs for combating droughts and floods, while its prediction becomes the key in reduction of its consequences.

This study presents a summarized evaluation of probability of occurrence of floods and droughts in Bhavani basin of Kerala, using Herbst method, for a period of 40 years from 2002 to 2042, using streamflow data. As per the analysis, the most severe drought is expected to hit the basin in the year 2022-2023 while the worst flood is expected in the year 2040 -2041. The novelty of the study is in applying the Herbst method for evaluating the probability of occurrence of floods in a catchment area without adopting rigorous hydrological modelling techniques.

Keywords: Droughts, Floods, Herbst method, Severity, Effective streamflow.

Introduction

Droughts and floods may be considered as natural hydrological disasters which could pose a potential threat due to their co-existence, which unfortunately cannot be eliminated but could be effectively managed if the incidents are predicted well in advance. Hydrological droughts are instigated due to the persistent shortage of water resources[10], while the excess of precipitation received during a certain interval of time coupled with the inadequate capacity of the streams to contain the high flows within the banks can lead to floods.

Droughts and floods, which are primarily dependent on weather, are observed as recurring events in many parts of India due to the substantial difference in the climatic and rainfall patterns. Rainfall being the principal input to the hydrological budget, with plausible decrease in rainfall tied with increase in temperature, the rainfall in India is suspected to become more and more erratic in the future[4,20].

Drought is a normal part of climate in virtually all climate regimes, but it differs in terms of intensity, duration and spatial extent from place to place. Lack of water in the hydrological system, manifested in water bodies by low water levels refers to hydrological droughts[3], the characterization of which is said to be complete only if the severity of the drought, time of onset, duration of drought, the areal extent and its frequency of occurrence is ascertained in a catchment area.

The evolution of droughts starts from the natural climate variability, due to global warming, resulting in high temperatures, high wind intensity, low relative humidity leading to deficiency in precipitation. Further, the precipitation deficiency propagates through the hydrological cycle into soil moisture deficiency which is the primary cause for agricultural droughts, as well as a substantial reduction in the streamflow discharges in water bodies which are accentuated as the primary indicators of hydrological droughts.

There are scores of definitions for hydrological droughts. Tallaksen et al[18], defined hydrological droughts as the regional occurrence of below average availability of water for a prolonged period. Drying up of surface water bodies and drop in the groundwater levels due to long term meteorological droughts may also result in hydrological droughts[15]. The severity of the drought is ascertained based on various meteorological, agricultural or hydrological indices viz. Standardized precipitation Index (SPI), Palmer's Drought Severity Index(PDSI), Reconnaissance drought indices etc. The SPI index, which is solely based on precipitation, is used to quantify the precipitation deficiency during different seasons depending on long term seasonal mean precipitation and standard deviation[17].

Effective drought Index (EDI), which is a very useful index in identifying droughts that continue for several years, is based on effective precipitation[22], that calculates the daily drought severity. Palmer in 1965[14], developed a model based on existing regional soil moisture conditions and the normal soil moisture conditions using precipitation, temperature and soil moisture data. Palmer Drought Severity Index (PDSI), calculated on monthly basis, allows comparisons to be made between place to place and between seasons and months.

However, by using PDSI, the comparisons are only weakly justified physically and statistically[2]. Droughts which can be classified into four major types viz. meteorological droughts, identified as reduction in precipitation, agricultural droughts resulting due to lack of moisture in soil, hydrological droughts, manifested as low flows in streams and rivers and socio-economic droughts resulting due to human water use[23], must be studied and analyzed using different droughts indices primarily because their impacts are different affecting various sectors.

Many studies have been done in the past to understand and measure the different types of droughts in terms of severity expressed as drought indices. Most of the studies in the recent past have used the mean rainfall data for the analysis[6,8,9,12,13,19].

Among the different methods available for identifying meteorological and hydrological droughts, due to the extreme simplicity in applying the method to get reliable drought assessment, Herbst method has gained attention of many hydrologists[11].

Among the natural water disasters faced by mankind, floods are considered to be the most fearful not just because of the extensive economic damage caused, but also because of the sense of uncertainty in the minds of people for its aftermaths like landslides, spreading of diseases, lack of availability of food etc. The severity of flooding in a river is commonly categorized into mild, moderate and severe based on the extent of damage caused due to its occurrence.

When the stage of the river reaches up to the brim due to the excess rainfall received, it is called as a bank-full stage which quickly gets forwarded into an action stage where the people are advised to take up required action plan for mitigation before it eventually gets converted into the final flood stage which will pose hazard to the common people.

Therefore, for adequate flood preparedness, it demands an optimal flood forecasting system to be advocated[16]. Hydrological models used for flood forecasting, both deterministic and stochastic, are highly data intensive and demands the determination of model parameters representing the catchment properties, to be inputted into the model which eventually decides the amount of flood water generated.

Thus, the amount of precipitation received in a catchment area on real time basis along with the rate of change of stage of river and catchment properties are considered as important factors required to precisely forecast a flood event. The unequal distribution of water in hydrological cycle with respect to space and time will result in untimely occurrences of the hydrological hazards viz. droughts and floods, thus reinstating the importance of its timely prediction which otherwise will lead to fatal natural calamities. Accurate prediction of droughts and floods requires rigorous investigations on site and intense data requirement for hydrological modelling and simulations.

In the present study, a simple procedure using the popular Herbst method which is frequently used for drought analysis is used, to identify the probability of occurrence of droughts and floods, to assess and predict the probability of their occurrence. In catchment areas where streamflow is readily available, the adequacy of the Herbst method to rapidly and accurately evaluate both droughts and floods without applying any hydrological models is also tested.

Material and Methods

Study Area and Data: On the southwest coast of India, lies Kerala, a fertile strip of land wedged between Arabian sea and Western Ghats. This land of eternal beauty, bounded between 8°18’ N and 12°48’ N latitudes and 74° 52'E and 72°22'E longitudes has high mountains, hills, valleys, beautiful blue water bodies like lakes, rivers, backwaters as the unique geographical features of the state.

Bhavani basin (Fig. 1), located on the eastern border of Kerala with a catchment area spread of 562km^2, receives an annual average rainfall of 2600mm contributing to an annual average streamflow of 636.6Mm^3 to the river.

The Bhavani river, a major tributary of Kaveri river, originates from the Kunda mountains in the Nilgiris, makes a circuitous course through Attappady valley and returns to the shadow of the Nilgiri mountains.

The important stream gauging stations are in Chittoor and Chavadiyoor. Out of the 44 rivers of Kerala, Bhavani river is one among the three, which prefers Bay of Bengal to Arabian sea to empty itself. The streamflow data collected from Irrigation Design and Research Board (IDRB) for the Chittoor station is used for the analysis. Towards the upper reaches of the catchment, the basin receives heavy rainfall during both south west and north east monsoon seasons which gradually reduces towards the lower reaches of the catchment. The months from January to May is characterized by scanty rainfall which is less than half of the total rainfall received during the SW and NE monsoon seasons.

Herbst Method: The long term mean monthly deficit is considered as the truncation level in the analysis using Herbst method[7]. Herbst method, being primarily used in drought analysis, is tested for its competency in forecasting floods by comparing the results of the analysis with the actual occurrence of the event. The procedure of the analysis is as outlined below.

Methodology: 30 years of data collected prior to 2001, was used to synthesize streamflow for the period from 2002 - 2042 using suitable methods like Thomas Fiering model and artificial neural networks. The synthetized streamflow values using Thomas Fiering model is used in this analysis to find out the severity and duration of the drought event, as described in the steps below.

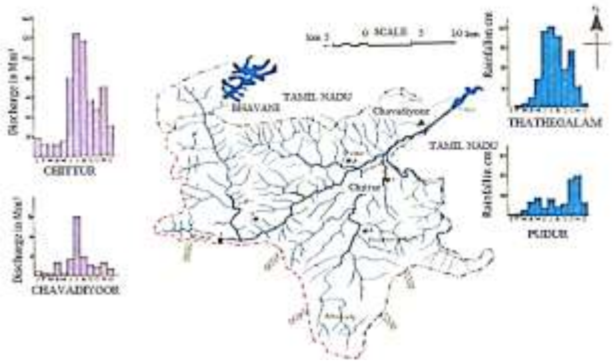


Fig. 1: Catchment Area under study: Bhavani Basin
(Source: ENVIS Centre: Kerala)[5]

Calculation of weighting factor, W_i: The weighting factor of each month was calculated using the equation:

$$W_i = 0.1\left[1 + \frac{Q_i * 12}{Q_y}\right] \quad (1)$$

where Q_y is the annual mean streamflow and Q_i is the mean streamflow of the month i.

Calculation of effective streamflow, Q_{eff} : The effective streamflow for each month can be calculated as Q_{eff}.

$$Q_{eff\,(i)} = Q_{act} \quad (2)$$

where Q_{act} is the actual streamflow for the first month of a year.

From the effective streamflow obtained, the mean streamflow for the month was subtracted.

This difference which is either positive or negative is then multiplied with the weighting factor for the next month and this was added to that month's actual streamflow, yielding the effective streamflow of that month. Thus, the effective streamflow values for all the 12 months were calculated.

Calculation of sliding scale: The monthly deficit (MD) for each month were evaluated as the difference of the effective stream flow and the mean monthly stream. Negative values obtained were written with the negative sign. The sum of the negative difference will give the mean annual deficit (AD).

The monthly increment 'x' was calculated for preparing the sliding scale.

$$x = \frac{AD - MMMS}{11} \quad (3)$$

where AD is the mean annual deficit and MMMS is the maximum of mean monthly stream flow.

The 12 values of the sliding scale were then prepared for each year viz. MMMS, MMMS+x, MMMS+2x …………. MMMS+11x.

Test for onset of drought and end of potential drought[7]: The test for the onset of the drought and end of potential drought is described in the flowchart below.

Test for termination of drought: The test for termination of the drought is done as enumerated below.

The termination of drought was then confirmed by performing the following two tests. 1st test is done to identify the actual termination while the 2nd test is done to infer the potential temporary interruption of drought.

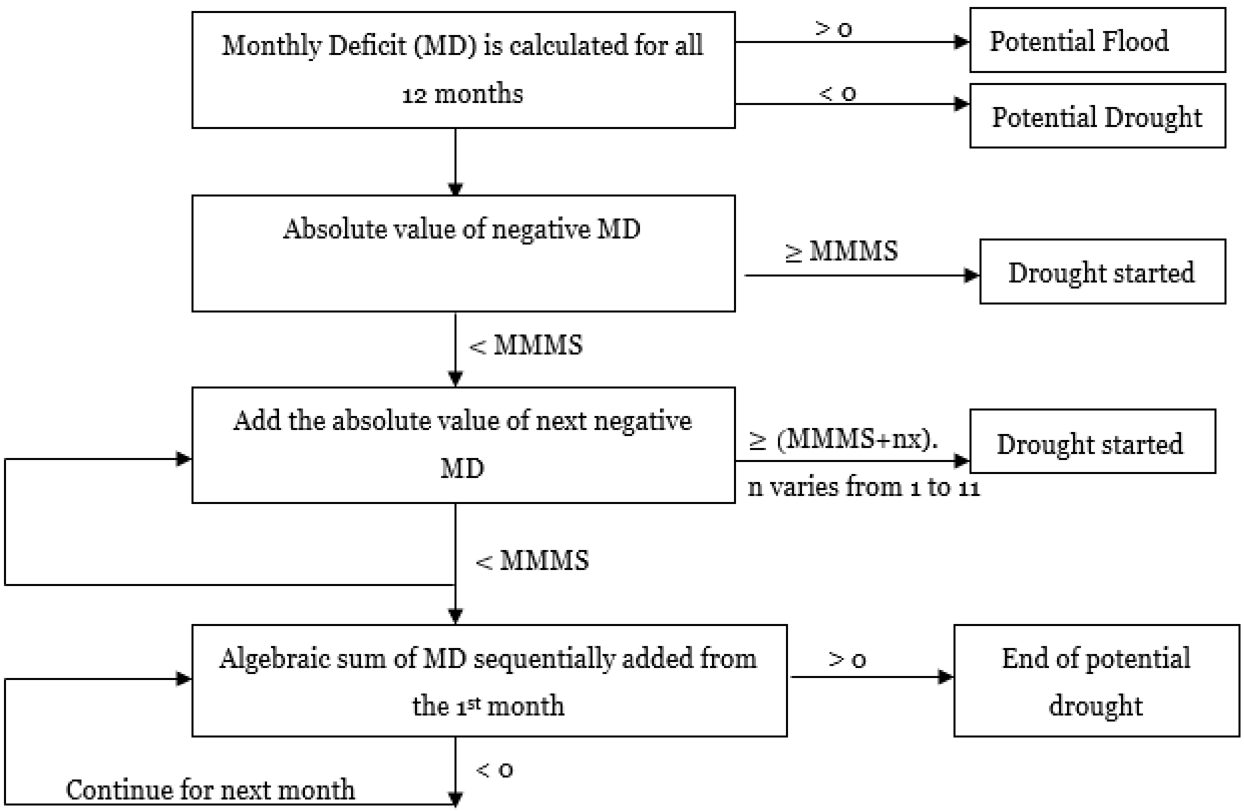
Test 1 for termination of drought: The actual stream flow from the 1st to the 3rd month of testing is summed up and compared with the three highest values of mean monthly stream flow. If the actual stream flow is higher, then the drought is considered to be terminated. If not, the sum of the 1st four months is compared with the four highest values of the mean annual stream flow and so on. In this way the sum of the twelve months stream flow is compared with the mean annual stream flow.

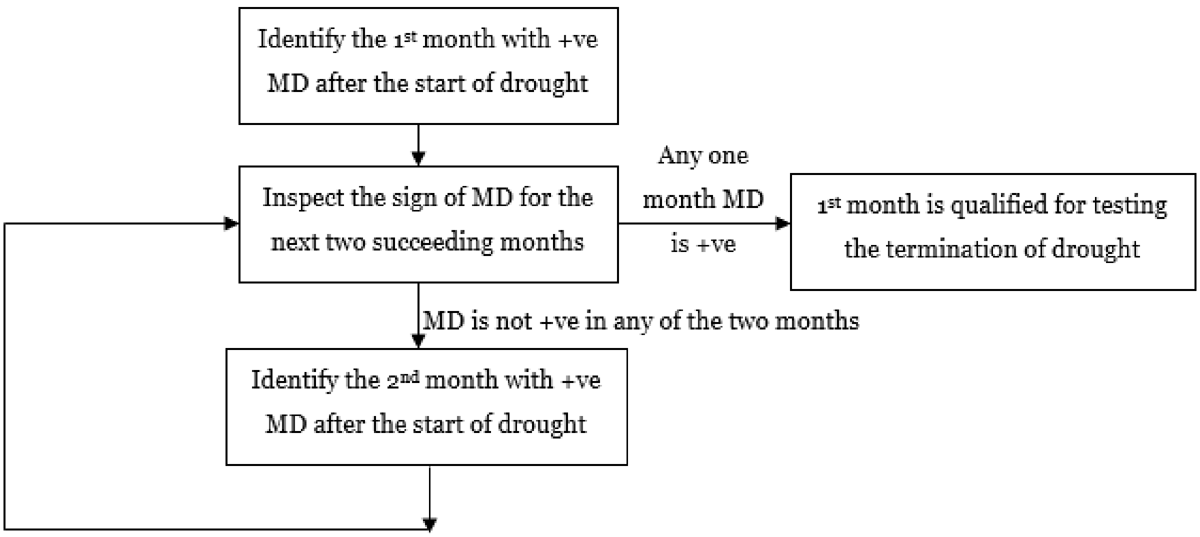
By this stage either the drought would be identified as terminated or drought the condition is resumed after a temporary interruption which is tested as described in test 2. Continue the test for a start of next drought from the 1st month with a negative difference following the month in which the drought ended.

Test 2 for temporary interruption of drought: In the first test for the termination of drought, the monthly deficit values are all added algebraically from the 1st to the nth month of the test. If the sum is negative before the termination is satisfied by the 1st test, the drought is only temporarily interrupted. Perform the test for termination from the 1st month with a positive difference following the month from which the previous test started.

The drought Severity is determined by the following expression proposed by Herbst.

$$X = Y.\,T \quad (4)$$





where X is the weighted index of drought, Y is the average monthly drought intensity and T is the duration of drought.

$$Y=\frac{\sum_{i=m2}^{m1}(MD_1-MMD_1)}{\sum_{i=m2}^{m1} MMD_1} \quad (5)$$

where MD is the monthly deficit, *MMD* is the mean monthly deficit, m1 is the month when drought started and m_2 is the month when drought is terminated.

Results and Discussion

The results of the analysis done by using the Herbst method are presented in tables 1, 2, 3 and 4 for few years viz. 2002, 2003 representing the beginning of the analysis and years viz. 2041 and 2042 towards the end. The probability of occurrence of drought, expressed in terms of the severity of the drought in million-meter cube (Mm^3) is presented in table 5. The negative sign portrays the chances of occurrence of the drought in the given year, while the positive sign signifies the probable chances of occurrence of excess streamflow in the corresponding year which may lead to floods. Mere calculation of severity will not necessarily help in identifying the exact time in a year when the drought gets initiated and gets terminated. The extremity of the drought is expressed by an index known as ‘the severity index’. The severity index values obtained by applying the Herbst method are presented in table 6 for the entire period considering water year from June to May and monthly deficit as the truncation level in this analysis.

The graphical variation of predicted effective streamflow and monthly deficit across a period of 24 months are shown in figures 2, 3, 4 and 5. India Meteorological Department (IMD) had declared Kerala to be drought hit in the years 2016 and 2017 which can be rightly identified in the analysis represented as a declining trend of effective streamflow and monthly deficit (as shown in the fig. 3) for the year 2016-2017 when the basin was under water stress during the period.

As per the analysis the probable years of occurrence of significant droughts of severity 1 and above are expected to affect the basin in the years 2002 -2003, 2007-2010, 2012-2014, 2015-2017, 2021-2023, 2024-2025, 2026-2032, 2038-2039, 2041-2042. The most severe drought is expected to hit the basin in the year 2022-2023 with a severity index of 5.773.

During the period 2002 - 2042, few years can be considered as no drought– no flood period where the severity values are between 0 and 1. The severity Index of zero (presented in table 6) and the positive severity values in million-meter cube (Table 5) presumes that the basin receives substantially high rainfall, with subsequent increase in average stream flow which can potentially lead to floods.

The analysis forecasted the occurrence of above average effective streamflow in the basin in the years 2018 and 2019 (Fig. 4) which was witnessed in the month of August 2018 and August 2019 when several parts of Kerala including the study area was shaken by floods. The severity index of zero in the year 2018-2019 in the table 6 can be correlated to the flood in Kerala that occurred in the month of August 2018[21].

Hence, the results obtained justifies the pertinence of Herbst method to rapidly assess the probability of occurrence of hydrological extremes in a catchment area.

Table 1
Analysis by Herbst Method: Year 2002

Month	Weighting Factor	Effective Streamflow	Monthly deficit	Sliding Scale	Excess-Deficit	Start/End of Drought
January	0.139	0.062	-0.148	1.286	-0.034	Drought Start
February	0.127	0.084	-0.063	1.352	0.000	
March	0.153	0.248	-0.036	1.419	0.000	
April	0.167	0.581	0.221	1.486	0.000	
May	0.154	0.309	0.021	1.552	0.000	
June	0.295	1.012	-0.032	1.619	0.000	
July	0.340	1.048	-0.238	1.686	0.000	
August	0.311	0.290	-0.840	1.753	-0.049	
September	0.249	0.340	-0.459	1.819	0.000	
October	0.223	0.761	0.101	1.886	0.000	
November	0.261	1.169	0.307	1.953	0.000	
December	0.176	0.207	-0.202	2.019	0.000	

Table 2
Analysis by Herbst Method: Year 2003

Month	Weighting Factor	Effective Streamflow	Monthly deficit	Sliding Scale	Excess-Deficit	Start/End of Drought
January	0.153	0.000	-0.210	1.286	-0.096	
February	0.137	0.000	-0.147	1.499	-0.052	
March	0.172	0.000	0.284	1.712	-0.103	
April	0.191	0.000	-0.360	1.925	-0.083	
May	0.173	0.000	-0.288	2.139	-0.090	
June	0.365	0.495	-0.550	2.352	0.000	
July	0.426	0.888	-0.398	2.565	0.000	
August	0.387	0.281	-0.850	2.778	-0.059	
September	0.303	0.658	-0.141	2.991	0.000	
October	0.277	0.761	0.100	3.204	0.000	Drought End
November	0.319	0.888	0.026	3.418	0.000	
December	0.204	0.005	-0.404	3.631	0.127	

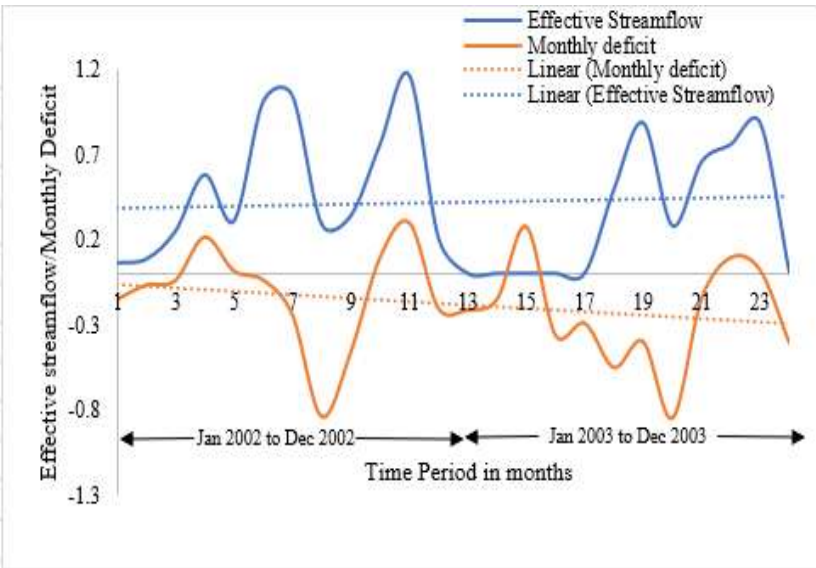


Fig. 2: Variation of effective streamflow and monthly deficit 2002-2003

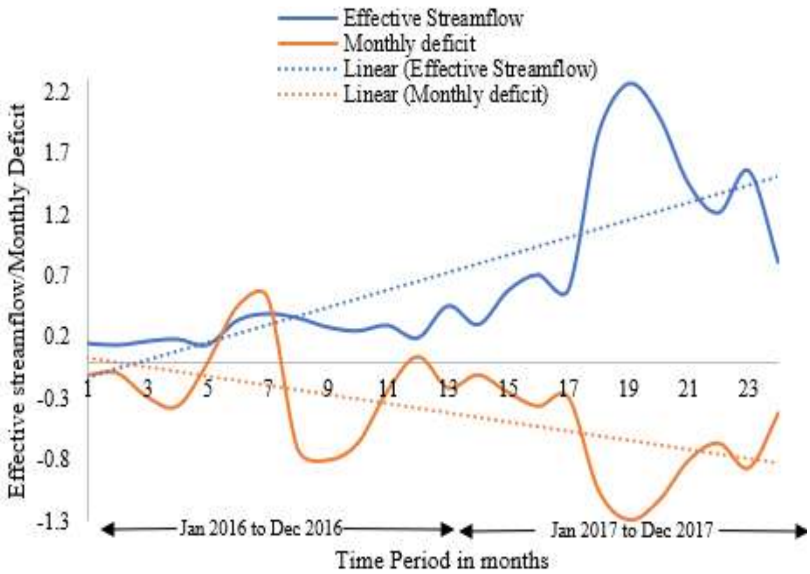


Fig. 3: Variation of effective streamflow and monthly deficit 2016-2017

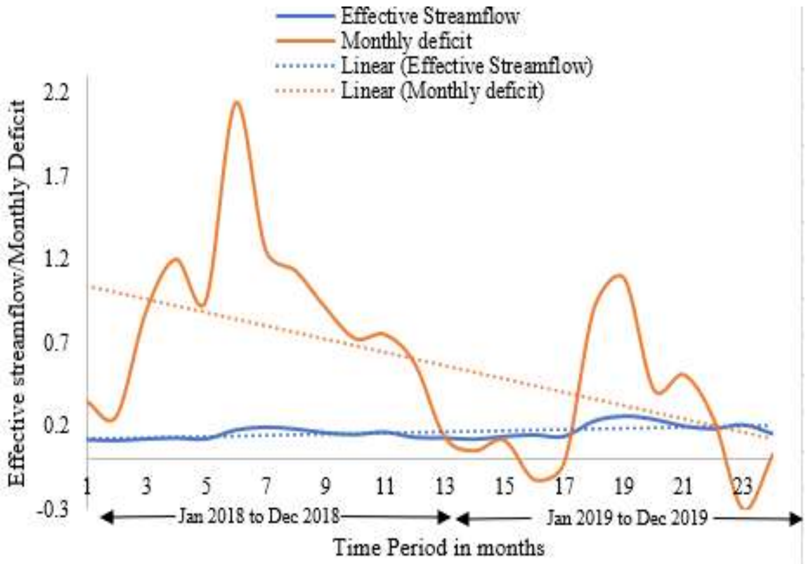


Fig. 4: Variation of effective streamflow and monthly deficit 2018-2019

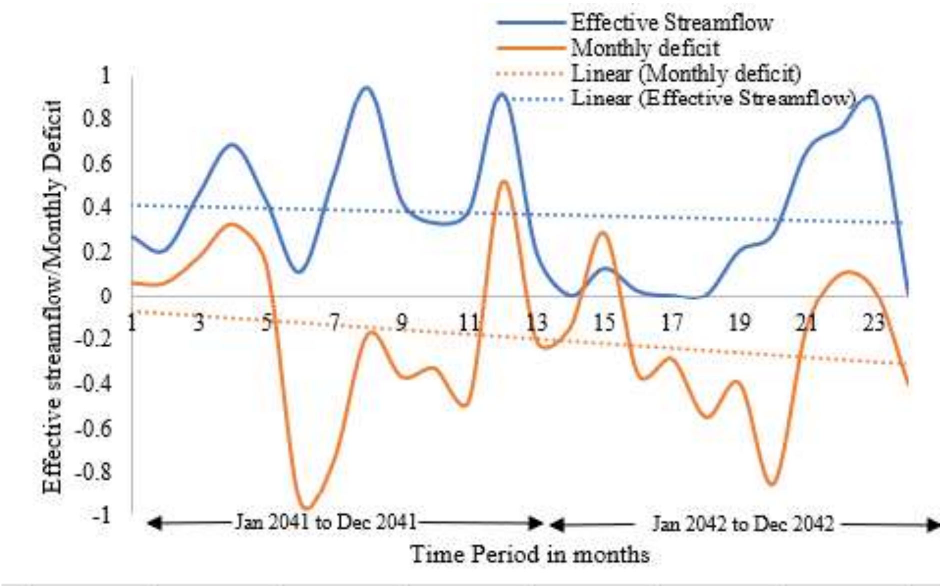


Fig. 5: Variation of effective streamflow and monthly deficit 2041-2042

Table 3
Analysis by Herbst Method: Year 2041

Month	Weighting Factor	Effective Streamflow	Monthly deficit	Sliding Scale	Excess-Deficit	Start/End of Drought
January	0.139	0.270	0.060	1.286	0.000	
February	0.127	0.206	0.060	1.445	0.000	
March	0.153	0.459	0.175	1.604	0.000	
April	0.167	0.684	0.324	1.764	0.000	
May	0.154	0.430	0.142	1.923	0.000	
June	0.295	0.108	-0.936	2.082	-0.228	Drought Start
July	0.340	0.541	-0.745	2.242	-0.015	
August	0.311	0.951	-0.180	2.401	0.000	
September	0.249	0.429	-0.369	2.560	0.000	
October	0.223	0.329	-0.332	2.719	0.000	
November	0.261	0.386	-0.476	2.879	-0.066	
December	0.176	0.922	0.514	3.038	0.000	

Table 4
Analysis by Herbst Method: Year 2042

Month	Weighting Factor	Effective Streamflow	Monthly deficit	Sliding Scale	Excess-Deficit	Start/End of Drought
January	0.148	0.194	-0.210	1.286	0.000	
February	0.133	0.000	-0.147	1.499	-0.052	
March	0.164	0.124	0.284	1.702	0.000	
April	0.182	0.020	-0.360	1.910	-0.064	
May	0.165	0.000	-0.288	2.118	-0.090	
June	0.336	0.000	-0.550	2.327	-0.337	
July	0.391	0.204	-0.398	2.535	-0.352	
August	0.356	0.281	-0.850	2.743	0.000	
September	0.281	0.658	-0.141	2.951	0.000	
October	0.250	0.761	0.100	3.159	0.000	
November	0.295	0.888	0.026	3.368	0.000	
December	0.193	0.005	-0.404	3.576	0.000	Drought End

Conclusion

The Herbst method of analysis presented in this study, predicts the most probable years of occurrences of drought and flood events from 2002 to 2042. The method demands minimum data requirement for the analysis and hence makes it very simple to be applied in any gauged catchment area with consistent streamflow discharge.

The streamflow data of the Chittoor station in the Bhavani basin of Kerala is used for the analysis, the results of the which assist in developing proper water management policies in the future for the study area. The severity Index values presented graphically in fig. 7 and tabulated in table 6, identifies 2022-2023 as the year in which the most severe drought is expected to hit the basin.

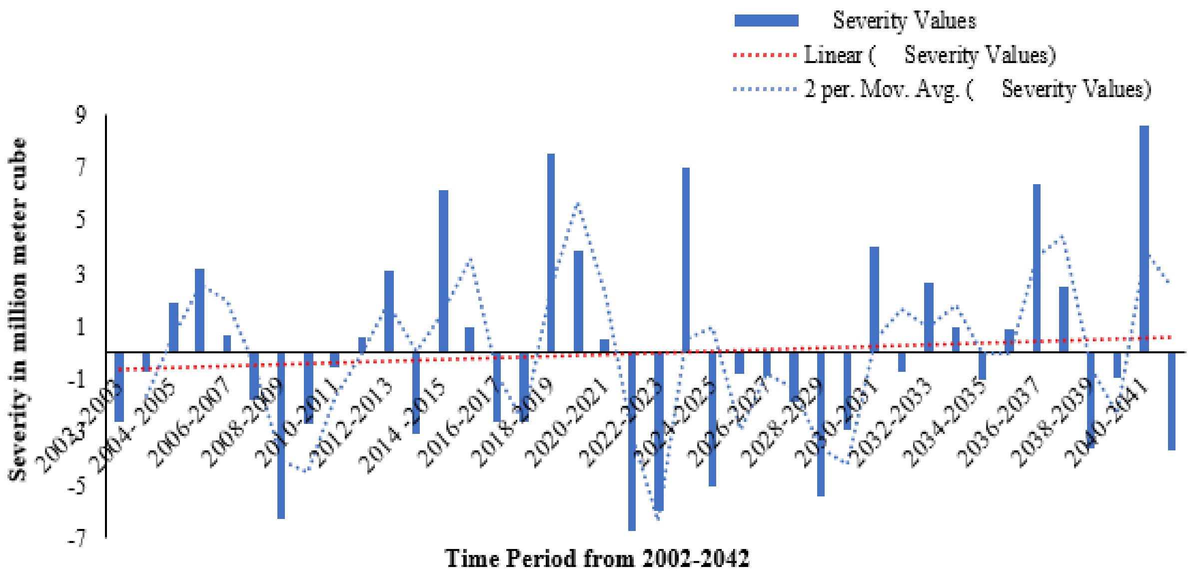


Fig. 6: Severity values in Mm^3 in Bhavani basin by Herbst Method (2002-2042)

Table 5
Severity Values in Mm^3

Year	Severity Values	Year	Severity Values
2002 -2003	-2.614	2022-2023	-5.9775
2003 -2004	-0.6564	2023-2024	7.0191
2004- 2005	1.9238	2024-2025	-5.0103
2005-2006	3.2002	2025-2026	-0.7590
2006-2007	0.7157	2026-2027	-0.8400
2007-2008	-1.7222	2027-2028	-1.7981
2008-2009	-6.2930	2028-2029	-5.4194
2009-2010	-2.6593	2029-2030	-2.9368
2010-2011	-0.5684	2030-2031	4.0041
2011 -2012	0.6088	2031-2032	-0.7263
2012-2013	3.1413	2032-2033	2.6781
2013-2014	-3.0489	2033-2034	0.9547
2014 -2015	6.1434	2034-2035	-0.9860
2015-2016	1.0218	2035-2036	0.9176
2016-2017	-2.5769	2036-2037	6.3645
2017-2018	-2.5756	2037-2038	2.5011
2018-2019	7.5827	2038-2039	-3.6014
2019-2020	3.8624	2039-2040	-0.9298
2020-2021	0.5646	2040-2041	8.6318
2021-2022	-6.688	2041 -2042	-3.648

Table 6
Severity Index by Herbst Method

Year	Severity Index	Year	Severity Index
2002 -2003	1.2126	2022-2023	5.7733
2003 -2004	0.0948	2023-2024	0.2653
2004 - 2005	0	2024-2025	3.5269
2005-2006	0	2025-2026	0.3151
2006-2007	0	2026-2027	1.1437
2007-2008	1.1146	2027-2028	1.3946
2008-2009	5.133	2028-2029	4.865
2009-2010	1.4549	2029-2030	2.0664
2010-2011	0.4917	2030-2031	1.0939
2011 -2012	0.6711	2031-2032	2.1315
2012-2013	1.7079	2032-2033	0
2013-2014	1.6086	2033-2034	0
2014 -2015	0	2034-2035	0.8989
2015-2016	1.0578	2035-2036	0.5039
2016-2017	2.8733	2036-2037	0
2017-2018	0	2037-2038	0.858
2018-2019	0	2038-2039	1.8603
2019-2020	0	2039-2040	0.8674
2020-2021	0	2040-2041	0
2021-2022	5.2288	2041 -2042	1.331

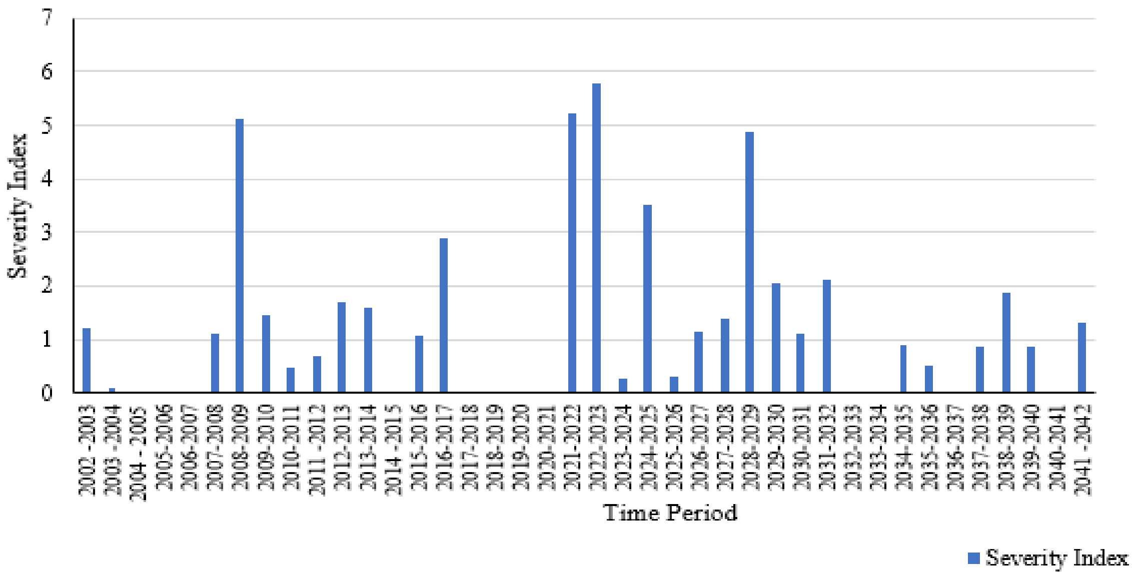


Fig. 7: Graphical representation of drought severity index in the basin

Further, the results of the study also indicate the year 2016 as a drought hit year with a severity Index of 2.873 which agrees well with the results of the study done by Abhilash et al[1], where the reported occurrence of the most disastrous droughts in Kerala is in the year 2016 with standard precipitation index value (SPI) of less than -2.0 across the state of Kerala in a time scale of 3 to 12 months.

Despite the reason that the monsoon in the years 2002-2003, 2007-2008, 2015-2016 were bad, it can be presumed that severity in these years did not scale up to the level as in the years 2008-2009 and 2016-2017[1]. The severity values trend line in fig. 6 provides warnings towards frequent chances of occurrence of droughts in the future at greater severities which must be tackled appropriately by adopting necessary precautionary measures well in advance.

The frequent occurrence of droughts and floods can be considered as one of the most serious hazards across the globe. Based on the analysis and discussions made above, it can be concluded that Herbst method assists in the realistic investigation and determination of the occurrence of hydrological drought, taking care of its carry over effect from one year to another emphasizing on the time of onset, duration and termination of hydrological droughts.

The prospect available in the Herbst method in identifying potential flood in the study area was also explored and validated with similar events in the past and is then applied for identifying the probability of their occurrences in the future. The results of the study recommend and promotes taking up intensive study on occurrence of floods and droughts on a catchment scale accurately by hydrological modelling techniques.

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