DEVELOPMENTS IN HYDROLOGICAL DROUGHT STUDIES

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INTRODUCTION

The occurrence of drought in India is not a recent phenomenon. The regular monitoring of rainfall in the country started in 1875 with the Indian Meteorological Department. Reliable information documents reveal that since 1800 there have been around 40 droughts in the country with varying degree of severity. Since the hydrological drought studies is a newly developed field and has come out of the meteorological drought (National Commission on Agriculture, 1976), the work is not available in this particular field. The research covering the area of meteorological drought is also not much available. However the data collected by IMD before independence were analysed (Dhar, O.N. et.al.) after independence giving detailed information of meteorological droughts starting since 1800.

Since independence the country has faced 11 drought years as 1965, 1966, 1969, 1973, 1974, 1976, 1980, 1985, 1986, 1987 and 1991. The most severe drought since independence was observed in 1965 in which about 54 percent of the country's area was affected by drought. In recent times, the country faced four droughts 1985, 1986, 1987 and 1991. It has been observed that intensity wise the drought of 1987 ranked second since independence. During the drought of 1987 about 50% of the country's area was affected by drought with about 18 percent negative departure in monsoon rainfall all over India and about 45 percent negative departure in monsoon rainfall over the drought affected area (Upadhyay and Gupta, 1989).

Different methods have been proposed from time to time for characterisation of meteorological drought. A number of definitions and classifications of drought are reported in scientific literature, Appa Rao (1986), Subramanyam (1967). There is no universally accepted definition of hydrological drought. Drought is generally understood as a period of extreme dryness due to lack of sufficient water. For a meteorologist, the drought is abnormal deficiency in rainfall due to different meteorological parameters. For agriculturist, it is lack of available soil moisture to the plant and for hydrologist, it is marked depletion of surface and ground water which dries up lakes, rivers, reservoirs and reduction in groundwater storage.

The Indian Meteorological Department (IMD) is mainly concerned with the study of meteorological drought. According to IMD, a meteorological subdivision (part of India) is considered to be affected by drought if it receives total seasonal rainfall less than 75% of the normal value.

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Sampath (1989) has reported that during 1987, 21 meteorological substations out of 35, recorded deficient rain leading to drought conditions. It was further reported that these subdivisions account for about 53 percent of the total food grain production in the country. A quick glance of food grain production figures indicates that during year 1987-88 the production was 138.41 million tones. The year 1985-86 through 1987-88 visualises declining trend of food grain production which fell from 150.4 million tones in 1985-86 to 138.41 million tones in 1987-88. The fluctuation of food grain production clearly show dependability of agricultural activities on the rainfall. A drought in turn leads to the reduction of agricultural and fodder production and low water availability for use. The drought characteristics and the associated problems vary from area to area depending upon the amount of variability of available water supplies and the demand of water for specific users.

Most of the drought studies conducted since independence in India are related to meteorological and agricultural aspects of drought and without giving much emphasis on hydrological aspects of drought. The hydrologist views drought as below normally water availability in streams, reservoirs, lakes, tanks and aquifers and its interaction with demand.

HYDROLOGICAL DROUGHT

The hydrological drought has been defined by many scientists abroad in terms of average low flow, deficiency of water supply, deficiency of precipitation, runoff accumulation of water in various storage capacities and water supply under a given water management system.

National Commission on Agriculture (1976) defined the hydrological drought as meteorological drought, if prolonged results in hydrological drought with marked depletion of surface water and consequent drying up of reservoirs, lakes, streams. cessation of spring flows and fall in groundwater levels.

The CWC (1982) defined the deficiency of runoff. An area is identified as hydrological drought affected if annual runoff is less than 75% of normal annual runoff, the year will be considered as drought year and if it occurs in 25 or more than 25% of years, then the area will be considered as drought prone. Drought is classified as severe drought depending upon the percent departure of runoff volumes as given below :

Percent departure 50% - severe
Percent departure 25-50% - moderate

A most important factor in understanding drought, often not included in definitions, that it is a "supply and demand" phenomena. A definition of drought which normally does not include reference to water requirement or demand can be regarded as inadequate. In general terms, the chief characteristics of drought is associated with a decrease of water availability in a particular period and over a particular area for specified use. Inspite of the lack of a unified definition of drought among the community of hydrologist, they tend to agree that it is basically a situation of water deficit for given use caused due to occurrence of below normal natural water availability. Drought is not solely a natural and statistical phenomena, it is also determined by intended water use of the region or area or need for water compared to natural supplies.

Basically a hydrological drought means a deficit of water supply in time and space and involves the following factors;

(a) Duration
(b) Areal extent
(c) Severity (intensity)
(d) Probability of occurrence
(e) Initiation and termination

The deficits in surface water are reflected through low stream flows which is a measure of drought. The drought phenomenon; is therefore better studied by analysing low stream flows of a basin for which local singularities are also eliminated. Hydrologists generally use analysis of low flow frequencies to define a hydrological drought on an annual basis. Here in this article an attempt has been done to review the various deterministic, statistical and stochastic approaches carried out in India since independence to analyse the low stream flows in order to investigate hydrological drought and to accordingly plan water resources management practices.

Drought Analysis Approach

The following set of decisions are to be considered for taking up a task of drought analysis (reviewed by Sikka, 1986).

Selecting nature of water deficit: The deficit may be in terms of streamflow or reservoir storages or groundwater levels for hydrological drought. Accordingly the variable(s) which defines the drought phenomena are identified and whether to use a point measurement or a total area value or whether intensities (or discharges), levels, stored water or similar variables are selected.

Selecting integral period of time: Integral period is the time period e.g., daily, weekly, 10 daily, monthly, seasonal, or yearly depending upon the purpose and type of study for which the hydrologic data is to be averaged for drought analysis or from which the minimum value for the period is picked. A short (i.e. monthly) and long averaging period (yearly) result in larger sample size and serial correlation and smaller sample size and correlation respectively. One has to be aware of the consequences in choosing the integral period of time.

Selecting truncation level: Truncation level is employed to separate drought from remainder of time series. It is a threshold level to define or separate drought from other events. It divides a time series into above normal and below normal sections. This should also reflect the socioeconomic demands on the available water supply. Generally, the investigators chose some measure of the central tendency of the drought sample e.g. mean, median and mode as the truncation level. Since the mean value is more sensitive to the extreme values of distribution, the use of mean may be considered more sensitive for drought studies where extreme droughts are generally of primary interest. The selection of truncation level is a function of the type of water deficit being considered. For example, average annual streamflow can be selected as truncation level for analysis of multi-year hydrologic droughts and mean soil moisture present during the growing season may be selected as a truncation level for agricultural droughts analysis. The demand need not be constant and it can be represented by some time varying truncation level. However, it is simple and less complex to use a constant value of truncation level.

Regionalisation: The method of regionalisation is employed because droughts are inherently regional in nature,thus their areal extent is an important characteristic to be considered. Moreover, limiting the analysis to a single site is generally not feasible because of small sample size i.e. hydrologic record and in such causes regionalisation provides a means of increasing the sample size. The regional hydrologic record can be extended by considering the inter-relationship between records covering a broad topographical area. The delineation of the study area is based on either geomorphologic or climatic or statistical homogeneity factors. Geomorphologic factors, which delineate an area include topography, local storages (lakes) and soil properties. In the statistical approach, sites are grouped on similar statistics of the hydrologic record. The method of regionalisation depends upon the particular method of frequency analysis used.

Methods of Drought Analysis

Number of drought indices, deterministic, stochastic and statistical approaches are used for hydrologic drought analysis.

Deterministic approach: The deterministic models are normally conceptual models. These models are assumed to follow a definite law of certainty. The difficulty arises due to number of parameters e.g. extent and duration of rainfall deficit, evaporation and upstream release which governs severity of drought i.e. low flow in stream.

Stochastic approach: Stochastic models of streamflows are becoming popular to produce a synthetic record of hydrologic data having an equal likelihood of occurrence as the historical record. All the research workers who worked on stochastic modelling for streamflow generation intended to extend the hydrologic time series by superimposing a random fluctuation on a deterministic component using the basic statistics of the historical records (e.g. mean, variance, serial correlation). Stochastic streamflow models attempt to preserve certain pre-selected statistical characteristics of the historical streamflows.

Statistical approach: These techniques can be employed to determine frequency of drought and variation in durations i.e. periods using past historical data. There are various statistical approaches available in the literature to analyse low flows both for gauged and ungauged catchments which include low flow duration curve. Low flow frequency analysis either using annual or partial series, study of deficit volume of stream flow below a threshold and reservoir capacity yield analysis. A few are simple indices, frequency analysis and statistical theory of runs.

Low Flow Analysis

When the flow in the stream or river is relatively too low or to be more specific it is lower than the threshold level that it does not meet the requirement of the specified established uses in the area, it can be said that the drought has set in. The short period of low streamflow occurring on an annual basis is termed as lowflow and the period of at least one year during which the average discharge for each year falls below the long term mean annual flow can be termed as drought event. The low flow in a stream during any year indicates the drought severity of that year. The magnitude of low flow determines the amount of water available for specified uses over a given period. The frequency of occurrence of low flow events reflects the risk of failure of a water supply scheme or project during drought. The concept of low flow, drought, high flow and flood is illustrated in Figure 1. Analysis of low flow is one of the aspects of investigating drought characteristics and planning, designing and management of water resources during drought.

Definition and concept of low flow

Low flow is defined on a seasonal basis and is linked with the, annual solar cycle and its regional or even local climatic conditions. It is also defined as the annually occurring minimum flow of short duration. For defining low flow three parameters magnitude, frequency and areal extent are needed. The mechanism of low flow may be sub-divided into the casual precipitation and the effect of the catchment characteristics, such as soil type, land use, topography, geology and stream pattern.

Importance of low flow

The knowledge of low flow is important when the supply is least able to meet the demands. Low flow of a stream vary annually, seasonally and daily. The low flow affects the society and create a situation of drought in following ways :

(a) When there is low flow in streams, the available water supply for domestic, municipal, industrial and agricultural uses gets reduced, which reduces reservoir storage thus indicating the situation of drought.

(b) Reservoir discharge and hydraulic head are reduced causing a reduction in the amount of hydroelectric power which may be generated during low flow period.

(c) Water quality of streams is degraded due to lack of sufficient water in stream during low flow or drought period.

(d) Diminished water quality and quantity affects the established life style and wild life during low flow period.

Therefore, it is clear from above consideration that the study of low flow which is an indication of hydrologic drought is an essential aspect of water resources analysis.

Statistical, Stochastic and Deterministic Methods for Streamflow Modelling

Analysis of low , stream flows is a suitable way of quantifying droughts. It has been found that during the periods of deficient precipitation the deviation from normal conditions is greater for streamflow than for rainfall. Low flow data are normally specified in terms of the magnitude of low flow for a given time interval within a year or season. The following three numerical characteristics are used to define the low flows : (a) the minimum flow value averaged over n consecutive days (1, 3, 5, 7, 10, 15, 30, 60, 90, 180 days and 1 year), (b) the dates of their occurrence; and (c) the frequency of occurrence. The low flow variables describing the different aspects of low flows for drought analysis as shown in Figure 1 are :

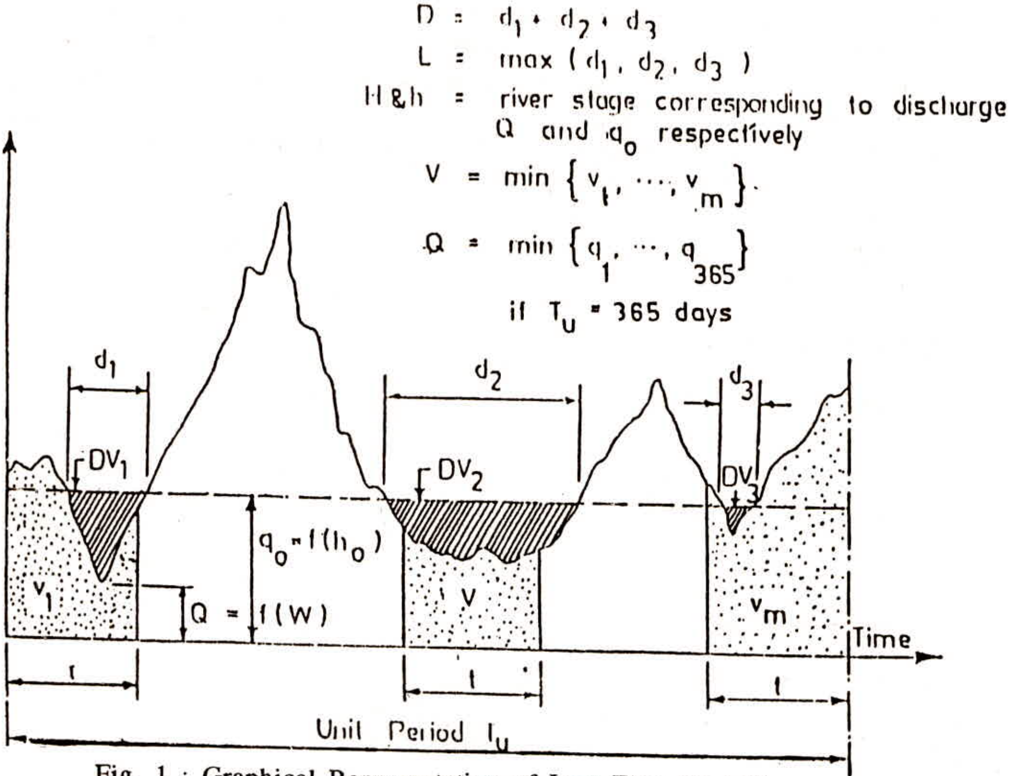

Fig. 1 : Graphical Representation of Low Flow Variables.

D	=	$d_1 + d_2 + d_3$
L	=	max (d_1, d_2, d_3)
H&h	=	river stage corresponding to discharge Q and q_0 respectively
V	=	min $\{v_1, \ldots, v_m\}$
Q	=	min $\{q_1, \ldots, q_{365}\}$
		if T_u = 365 days

(i) Low flow volume (V) is the minimum volume (V) for a given time interval t inside a specified time unit period T_u.

(ii) Low flow discharge (Q) at a particular site is the minimum instantaneous flow during a period T_u.

(iii) Low flow stage (H) is the water stage corresponding to the low flow discharge (Q), and

(iv) Low flow duration (D) is the total time for which the flows are smaller than a specified discharge q_0 or stage h_0 during T_u. The deficit volume (DV) has been described as one of the low flow measures alongwith deficit duration.

There are various methods available in the literature to analyse low flows both for gauged and ungauged catchments which include some deterministic models, low flow duration curve, low flow frequency analysis to describe probability of the magnitude of low flows, study of deficit volume of streamflow below a threshold stochastic modelling of streamflow for drought etc. Verma (1979) proposed a non-linear storage routing equation in combination with base flow recessions to predict low flows for effluent streams and developed a physical model for predicting low flows during droughts. However, the model was yet to be tested with field data. Detailed description of all these methods is beyond the scope of this article. Some of the methods have been reviewed and discussed briefly.

Low flow duration curve: In analysing the stream-flow droughts, one of the simplest techniques is to construct a flow duration curve for the given river or stream. It is a cumulative frequency curve that shows the percentage of time during which specified discharge were equalled or exceeded during the period of record. One way is to analyse the low flows over a given number of consecutive days and to estimate the recurrence interval of these events. This analysis is repeated for various periods of consecutive dry days to build up a series of curves. The procedure for estimating low flow duration depending upon the availability of data are available in the literature (Institute of Hydrology, Wallingford, 1980, Mc Mahon et al., 1982).

The flow duration curve for the ungauged catchments can be estimated from the relationship between the flow duration curve and catchment characteristics like rainfall, stream length, base flow index etc.

Flow frequency analysis: There is no single universally applicable statistical frequency distribution suitable for all rivers and drought indices. A number of theoretical distributions have been used to estimate the low flows of high recurrence interval. Various probability distribution function such Log normal 2, Log normal 3, Gamma 2, Pearson Type III, Log Pearson Type III, Wiebull etc. may be fitted to the low flow data. If the recurrence interval under consideration is less than N/3 years, where N is the sample size, the flow frequency curves may be used to estimate the low flow conditions.

The flow frequency curve is a graphical technique for estimating the probability that a year will contain an annual minima less than a given discharge. The curve can be drawn from daily or monthly flow data or from minima of any consecutive D day or month period. The low flow frequency curves are useful for reservoir capacity yield analysis. However, this approach gives biased results in that the flows into storage are overestimated, consequently storage need is underestimated. The other use of low flow frequency curves relates to the estimation of recurrence interval of low flow condition. Unlike flow duration curves, low flow frequency curves relates to the estimation of recurrence interval of low flow condition. Unlike flow duration curves, low flow frequency curves use data sequences that are independent and homogeneous and therefore can be used to determine the possibility of occurrence of a flow event of specified magnitude. In practice, two types of low flow frequency curves are used. One type, the annual series is based on the minimum flow event in each years of record and is used for events of less than 12 months duration. The second type, the partial series is used where frequencies of events lesser than 12 months duration are required. The guidelines for the estimation procedure depending on the availability of data are summarized by Institute of Hydrology, Wallingford (1980).

The low flow spell generally expressed in two ways namely, deficit volume of low flow spell and duration of low flow spell. Low flow duration is the total time for which the flows are smaller than a specified discharge (q_1) or stage (h_0) during a time unit period (T_u). If for a given q_1 or (h_0) and T_u there are K times in which the flows fall below q_0 then the low flow duration is $D = d_1 + d_2 + ...+ d_k$.

The deficit volume is one of the low flow measures alongwith the deficit duration. The deficit duration is the same as the durations d_1, d_2 ..... d_k etc. While the deficit volume is the volume relative to some demand flow (threshold discharge) required at beginning of the drought to prevent flow from falling below the demand levels for the duration of the drought.

National Institute of Hydrology (1986-87) briefly reported the various aspects of hydrological drought and concentrates on low flow as a measure of drought. A number of deterministic and statistical approaches suggested in India and abroad used for the determination of magnitude, frequency and duration of low flows have been reviewed. Few aspects of low flow forecasting in relation to drought have also been covered.

National Institute of Hydrology (1987-88) carried out low flow studies for the six sites of the Krishna basin namely, T. Ramapuram, Haralahalli, Wadakwal, Yadgir, Dhond and Narsingpur. The basin consists of parts of Maharashtra, Karnataka and Andhra Pradesh. It involves computation of low flow duration curves, flow frequency curves and low flow spells by utilizing 20 years stream flow data pertaining to all chosen sites of Krishna basin. In hydrologic studies, flow duration values of 90, 95, and 99% are used as measures of a stream's low flow potential. The 90% value is used as a measure of groundwater contribution to streamflow. The 10 days average flow when exceeded 95% of time of the duration of series called low flow index. The low flow index values were estimated from 10 days flow duration curves and given in Table 1.

Table 1: Low flow index for selected sites of Krishna basin.

Sl.No.	Site	Period of Analysis (Year)	L.F.I.(10^4 m^3 /Km^2)
1.	Dhond	1968-86	1.33
2.	Narsinghpur	1967-86	1.264
3.	Yadgir	1965-86	0.310
4.	Wadakwal	1965-86	0.289
5.	Haralahalli	1967-86	1.586
6.	T. Ramapuram	1966-86	0.629

The flow frequency curve for all chosen sites have also been developed. These curves can be used to estimate recurrence interval of any flow and can also be used to estimate the probability and return period of low flow condition.

The maximum deficit volume and maximum deficit duration based on above methodology were computed at different threshold limit for all chosen sites. Based on maximum deficit volume and maximum deficit duration drought intensity is estimated.

National Institute of Hydrology (1987-88). Statistical analysis of low flow in typical river basins to investigate drought characteristics.

Stochastic models of streamflows are becoming popular to produce a synthetic record of hydrologic data having an equal likelihood of occurrence as the historical record.

Rao (1988) applied a stochastic model using double exponential distribution function on Mahanadi basin on seasonal low flows up to Sambalpur and Naraj. For this study the daily discharge measurements at Sambalpur (1926-47) and Naraj (1926-45) were used and the occurrence of low flows in each year on a day, 7 day average and one month mean minimum flows have been compiled and used.

Verma (1979) used a deterministic model to estimate low stream flows for effluent when the variation in flow are small. The method of base flow recession coupled with non-linear storage routing to determine low flows for effluent streams was used. He estimated the parameters related to storage and outflow terms in the routing equation. The emphasis is given that the rate and duration of low flows is important to design economically many water supply and waste disposal works to determine the required capacity of storage reservoirs for the supply of water for various uses under drought conditions.

The proposed nonlinear storage routing equation in combination with base flow recession to predict low flow for effluent streams during drought. The model was based on the storage routing equation which is as follows :

$$I - Q = ds/dt$$

where;
$I = I(t) = \text{inflow}$
$Q = Q(t) = \text{outflow}$
$S = \text{Storage} = F(Q,I)$

Author assumed that $Q = KS^n$
where K and n are parameters

The final equation is of the form as follows :

$$t = \frac{Q^{1/n} - 1}{K^{1/n}\ (1-n)} \left[1-(q/q_o)^{1/n-1} \right]$$

from this equation, if Q_o and parameter K and n are known, the value of Q can be determined easily for given time t.
For determining the low flow during drought period it involves the determination of hydrograph of the watershed. The following equation was used for computing flow in an aquifer.

$$Q_t = Q_0 - tK$$

where;
Q_t = streamflow at time t
Q_0 = initial discharge at time t = 0
K = recession coefficient

Prediction of Drought

Hydrological drought indices are concerned with the effects of rainfall deficiencics on hydrological components such as surface water, ground water and soil moisture. The hydrological drought has been defined by various researchers as explained earlier. The runoff reduction ultimately results in lowering of water levels in reservoirs, tanks and streams causing situation of water deficit for the user in the area.

By simple drought indices

There are many indices used to describe features of drought suited to different water uses and hydrological regimes. A commonly used simplest index is to compare the depth of precipitation and runoff depth or volume for a given duration i.e. week, fortnight, month or a year, with the long term mean or standard period normal value for the given duration. Dry or wet periods can thus be designated, if the ratio of the considered hydrologic variable (e.g. rainfall or runoff) for the current year to the mean value is less or greater than unity. The numerical value of this index will give the drought severity.

A commonly used simplest index is to compare the depth of precipitation and runoff depth or volume for a given duration i.e. week, fortnight, month or a year, with the long term mean or standard period normal value for the given duration. Normally 80 and 100% exceedance frequency is considered in order to develop a regional drought summary based upon a number of flow records.

The other commonly used indices are aridity and humidity indices, climatic water balance approach to compute runoff surplus and deficit for drought analysis. Aridity index is the ratio of water deficiency (i.e. potential evapotranspiration PE-actual evapotranspiration AE) to water need (i.e. PE) expressed as percentage. Humidity index is the ratio of water surplus to water need expressed as percentage. Moisture index = Humidity index-Aridity index. Thornthwaite and Mather (1955) book keeping approach of climatic water balance has been extensively adopted by workers in India for drought analysis in different river basins. This approach relies heavily on the threshold concept that runoff does not occur until soil moisture capacity is filled. This assumption has limitations for the application as a watershed model. Sikka (1986) employed Budyko-Sellers climatic water balance model for drought analysis of Bikaner, Rajasthan. Improved hydrologic water balance models are required to be developed incorporating soil moisture and infiltration characteristics and ground water component for hydrologic drought analysis.

By water balance approaches

Subba Rao and Subrahmanyam (1961) estimated the yield from river basin by modification of water balance procedure. He made the modification in the water balance procedure as follows: (1) Reduced the potential evapotranspiration to 0.65 of its computed value; (2) Took the choice of 200 mm as field capacity and (3) Basin detention of 1/3 of the water surplus in any month for contribution to next month.

Chatterji et.al. (1978) worked out the water budget of different districts of Western Rajasthan for a normal year and for rainfall surplus year expected once in 5 years in Western Rajasthan where there is over exploitation of ground water resources due to occurrence of recurrent droughts. In this analysis, water use of the different components of land use like cropped area forests and fellow land etc. and the streamflow values of the Luni river system which is the only important river catchment in the region have been taken into account for the estimation of net surplus water available in the region. The suggested water balance equation also includes water in the underground aquifers and is as follows:

$$P = (E+SW+EW+GW+IGW+ISW-(SW+GW+IW+DSW+DGW))$$

where; P = Precipitation; SW = Surface water outflow; EW = Exported water; GW = Ground water outflow; IGW = Increase in ground water storage; ISW = Increase in surface water storage; SW =Surface water inflow; IW = Imported water; GW = Ground water inflow; DSW = Decrease in surface water storage, and DGW = Decrease in ground water storage.

By frequency analysis approaches

Frequency analysis is generally used for assessing the severity of extreme events for a given return period and has applications in the economic studies where the risk of any event occurring in a given design period can be calculated. The frequency analysis use data sequences that are independent and homogeneous and, therefore, can be used to determine the possibility of occurrence of a drought event of specified magnitude. The frequency analysis can be done by developing frequency curves from daily or monthly data or minima of any consecutive day or month period or by fitting theoretical frequency distributions such as Log Pearson Type III, Weibul etc. This approach can be applied to predict the occurrences of hydrological droughts using hydrological data such as streamflow and soil moisture.

By statistical theory of runs

The theory of runs have been used for analysis of hydrological drought using time series of streamflow. The fundamental parameters of the runs of an annual hydrologic series are shown in Fig. 2.

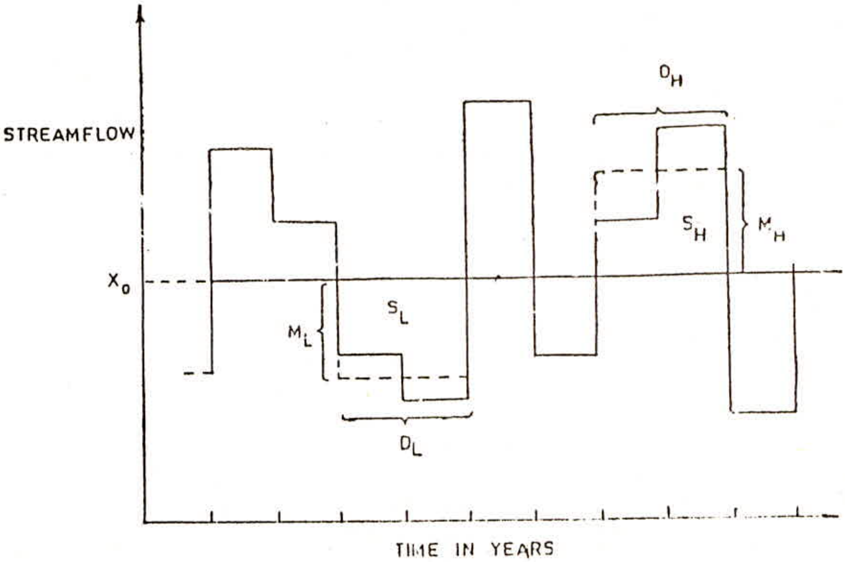

Fig. 2. Fundamental Parameters of the Runs of a Series.

The truncation level X_0 is selected arbitrarily to cut the hydrologic time series at several places to separate the time series into two new truncated series of positive and negative deviations. Depending upon the value of X_0, the drought defining parameters are defined. These parameters are the run sum (cumulative deviation from X_0), run intensity (average deviation from X_0) and run length (distance between successive crosses of X_0). The run sum, run intensity and run length are termed as drought severity, magnitude and duration respectively. These three parameters are the fundamental decriptors of hydrologic drought and are related by the expression :

$$\text{Drought severity } (S_l) = \frac{\text{Drought magnitude } (M_l)}{\text{Drought Duration } (D_l)}$$

The duration and severity can be considered to be the two primary parameters which depend directly on the annual time series of stream flow values and magnitude is taken to be a secondary parameter which depends on duration and severity. Knowing these drought defining parameters, the following statistical analysis is carried out to gain more understanding of the complex nature of prolonged droughts. (i) stationarity of event parameters in terms of any linear trend ; (ii) randomness in terms of lag-1 serial correlation, (iii) correlation between two of the three parameters for a single event, and (iv) cross correlation between the parameters of successive drought and high flow or non-drought events. The theory of runs is useful in analysing a sequential time series of stochastic or deterministic variables and is well suited for hydrological drought studies, using variables like streamflow and ground water.

Krishnamurty and Ramasastri (1979) studied on identification of hydrological drought on the basis of long term streamflow 1926 to 1961 data of Mahanadi river at Sambalpur/ Hirakud. Seven years of low stream flow were identified as 1962, 1965, 1966, 1969, 1972, 1974 and 1976 based on the statistical analysis and rainfall runoff relationships.

The theory of runs is applied to streamflow data for analysis of severity, magnitude and duration of hydrologic drought by selecting a suitable truncation level such as long term mean flow or so to separate drought from remainder events in the time series. Chander et al. (1979) applied the theory of runs to streamflow data of Krishna and Godavari for predicting hydrologic characteristics of droughts. In this study, the droughts are analysed using the concept of marginal probability distribution of successive events and run analysis. The methodology is useful in obtaining 180 lines over a given area for regionalisation of the magnitude and duration of drought. It was reported that data of Godavari river is random while the data of Krishna river is dependent.

Streamflow is one of the important hydrological parameters as it represents the runoff from a basin or catchment and determines the quantity of water available in various surface water resources. The precipitation deficiency is reflected in the resulted streamflow. Not only this, even the catchment characteristics, land use, vegetation etc. are also responsible for generated runoff. The drought phenomenon may be better studied from the hydrology of river basins for which local singularities are eliminated. The low stream flows and reduced reservoir storages are indicative of drought situations. When the flows are not sufficient enough to meet the required demand of water, it is considered that the drought has set in. The drought severity, frequency and duration can be studied by analysing the gross availability of streamflows, the flow duration characteristics of river flows and the extent to which the water is available in reservoirs. The stream flow characteristics and storages in reservoirs are analysed for periods of various durations using different statistical approaches to investigate drought characteristics depending upon the availability of data.

Forecasting of Monsoon and Non-monsoon Runoff

Drought prediction is one of the intriguing problem of drought studies. Prediction of drought can be considered as unpredictable with the present state of art on the subject using the hydrologic variables. Probabilistic forecasting of hydrologic variables like rainfall, streamflow, soil moisture and groundwater can be attempted for drought forecasting. The water resources planning and operation activities are dependent mainly on the monsoon behaviour that being a crucial period contributing 80-90 % of annual rainfall and runoff. The forecasting of monsoon runoff based upon the available rainfall data could be an important aspect for drought management in planning and operation of surface water reservoirs. The correct and timely assessment of water resources before the beginning of their utilisation period say before Rabi is a must.

A simple approach using correlation technique has been developed by National Institute of Hydrology (1986) for forecasting monsoon rainfall and runoff. The regression relationships have been developed to correlate monsoon runoff with the total runoff up to the end of June, July, August and September for Hirakud using runoff data from 1946 to 1982. These regression relationship have been used without updating the parameters and after updating the parameters of regression relationships to forecast the monsoon runoff. The efficiency of the regression relationship in calibration and forecasting has been computed. Similar relationships have also been developed to correlate monsoon rainfall with total rainfall upto the end of June, July, August and September.

The results based on the analysis of above data indicate that for Hirakud.

(i) The efficiency of monsoon runoff forecast are 71%, 81% and 98%, at the end of July, August and September respectively (Fig. 3).

(ii) The efficiency in identifying whether the current year is going to be below normal or above normal are 71%, 88%, 94% and 100% at the end of June, July, August and September respectively on the basis of 1968-82 runoff data.

(iii) The efficiencies of forecasting monsoon rainfall are 60%, 83% and 97% at the end of July, August and Sept. respectively on the basis of 1951-79, rainfall data.

(iv) The efficiency of regression relationship in identifying whether the current year is going to be below normal or above normal are 62%, 62%, 83% and 93% at the end of June, July, August and September respectively on the basis of 1951-79 data and 64%, 79%, 93% and 93% on the basis of 1968-79 rainfall data.

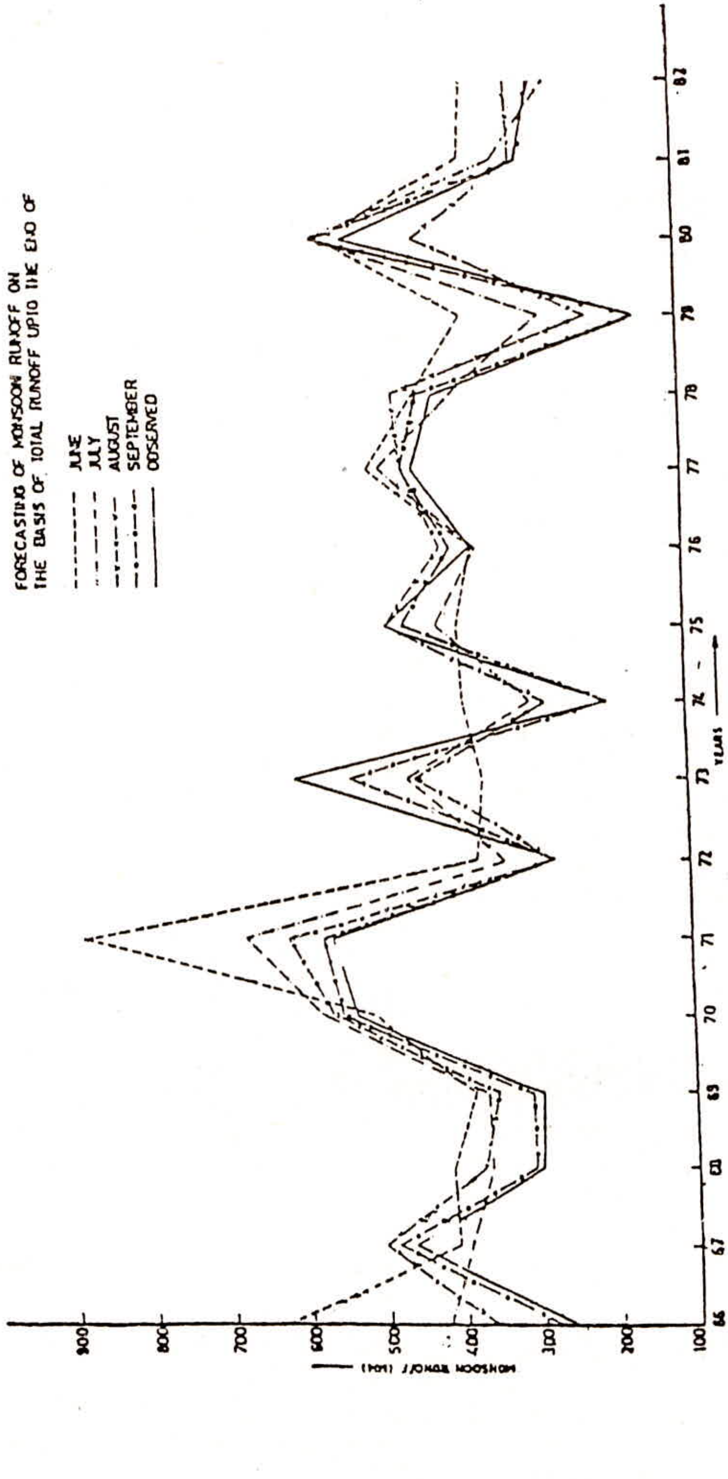

Fig. 3 Forecasting of Monsoon Runoff for the Period 1966-82

The results are based on the analysis of only one site and in order to arrive at definite conclusion it is proposed to carry out analysis for other basins also on the similar lines.

Seth and Singh (1988) described a methodology for forecasting the flows during non-monsoon season utilizing the base flow recession curves and incremental precipitation at various probability levels. The methodology has been tested using monthly rainfall and flow data of non-monsoon season for Mahanadi river at Hirakud. In this study, a methodology is described for forecasting of total flow for non-monsoon season in advance at the end of October and also monthly flows for each of the months from December to May. The methodology adopted for forecasting the flows during non-monsoon season utilizes the base flow recession curves and incremental precipitation at various probability levels.

The methodology adopted in the study is as follows :

(a) Relationships for total non-monsoon flows: As mentioned earlier, the total flows during non-monsoon season, Q_{NM} (mm) consist mostly of base flow and some contribution from non-monsoon rainfall R_{NM} (mm). Accordingly, following alternate relationships were studied :

$$Q_{NM} = A + B\,R_M + C\,R_{NM}$$
$$Q_{NM} = A + B\,Q_M + C\,R_{NM}$$

where; R_M = Total rainfall for preceding monsoon season in mm.;
Q_M = Total flow for preceding monsoon season in mm.;

A, B, C, are regression parameters.

(b) Relationships for monthly non-monsoon flows: These relationships are based on exponential nature of the base flow recession curve. In order to account for change in shape of recession curve with magnitude of flows during non-monsoon season, it is assumed that recession constant K would vary with Q_{NM} for each non-monsoon season and flow Q_0 for the month of November. The form of relationship is as follows :

$$Q_i = Q_0\ e^{-iK} + F_i\ R_i + C_i$$

where; Q_i = represents monthly flow in mm.;
R_i = monthly rainfall in mm., and
F_i = is monthly coefficient for months of December, January, February, March, April or May, and
Q_0 = is monthly runoff in mm for November
K = represents recession constant as a function of corresponding total non-monsoon flow Q_{NM} and Q_0.
C_i = is constant for particular month.

(c) Rainfall probability: In order to account for anticipated increase in baseflow due to likely amount of current rainfall R_i in non-monsoon months of December to May, a probability study of monthly rainfall in these months was carried out to determine probability of years with rainfall and probability of rainfall magnitudes.

$$\text{Probability of rainfall in a month or season} = \frac{\text{No. of years with some rainfall in that month or season}}{\text{Total number of years}}$$

The probability of rainfall magnitudes is ascertained by simple procedure of arranging the series in ascending order and estimating rainfall for 10, 50, 90, % levels for each of the six months and also for non-monsoon season.

Ground Water and Soil Moisture Deficit

Ground water is the main source of water supply in drought affected areas because of meagre surface water supplies during droughts. Statistics recently compiled on the use of groundwater and surface water show that in a number of States, groundwater is being over-exploited in certain pockets resulting in a fall in the water table. There are limited studies done to assess the impact of drought on ground-water in a scientific way. The common approach to carryout such study is to observe the fluctuations of water table and the construction of well hydrographs superimposed with rainfall. One of the problems in studying the impact of drought on groundwater is the correct assessment of draft. Another problem is that little information is available about the natural rainfall recharge. Some of the studies done in India in this regard are reviewed below.

A very little information is available about the rainfall recharge to groundwater. The recharge value of course would vary from one terrain to another depending upon the rainfall intensity and distribution, terrain characteristics etc. The studies conducted in the arid zones of Western Rajasthan by Chatterjee (1978) and Chatterjee et al. (1979) indicate that even for a drought year preceeded by a flood year, the groundwater storage does not meet the requirements of the area. Variation in static water level during pre and post monsoon period has been observed as 0.8 m and annual recharge to aquifer works out to 28.1 m.cm (million cubic meter) of which 11.52 m.cm are recoverable. The average annual rainfall of this region is 528.0 mm during normal years. It clearly indicates that the recharge is definitely low. In the central Maharashtra where the area is occupied by Deccan trap and average rainfall is 400 to 500 mm, it has been estimated on the basis of seasonal water level fluctuation that about 10% of the rainfall is added annually to groundwater reservoir (Singhal, 1979). Sarma et al. (1982) estimated by using hydrodynamic approach that ground water recharge in plain areas of the Visakhapatnam basin comes to about 35% of the total precipitation.

National Institute of Hydrology (1990) compared the ground water level of drought prone district in six states. The trends of ground water level are compared with rainfall. The decline in ground water level is a cause of failure of rainfall and over exploitation of ground water during drought periods.

Malik and Banerjee (1979) studied the influence of drought on groundwater storage particularly in Shallow, unconfined aquifers and proposed an exponential decay function to identify recession characteristics of the aquifer which can be used to predict groundwater levels under future drought conditions. Equation used is

$$H = h_o e^{-dt}$$

where, h_o = initial height of W.T. above m.s.l and
h = height of W.T. after time t above m.s.l.

Though, the simple Dupuit's assumption may not be that accurate as compared to latest developed techniques, but for easy solution of field problems this approach may be reasonable.

The long term forecasts of the future water table positions in shallow aquifers has also been done using above groundwater recession equation for single well which shows that logarithm of h decreases with time. In order to predict the future water levels in the well during the drought period, this line can be extended along the time axis. Mathematical models can be used to arrive at an optimal groundwater development policy incorporating spatially and temporally distributed ground water withdrawals.

The change in storage of ground water in an aquifer is reflected in the change in ground water level. Usually the change in ground water storage is a seasonal phenomenon but there will be an unexpected drop on ground water level during drought periods particularly in shallow, unconfined aquifers.

Mallick and Banerji (1979) Studied the physical process and the mathematical formula that is associated with the depletion of storage on the recession of water level in an aquifer. Usually the change in ground water level is seasonal phenomenon but there happens an unexpected drop on ground water level during drought period particularly in shallow, unconfined aquifers. The prediction of future water level positions in such conditions, their effect on ground water structures and the precautionary remedial measures have been discussed.

National Institute of Hydrology (1991) studied the effect of scarce rainfall during three successive drought years (1985-87) on groundwater. Statistical analysis of ground water level alongwith the precipitation has been carried out for 36 districts of Andhra Pradesh, Gujarat, Madhya Pradsh, Maharashtra and Rajasthan considering the data from 1976 to 1987. The trend of pre and post monsoon ground water has been analysed and has been correlated with seasonal rainfall.

Soil moisture is one of the important components of land phase of hydrologic cycle. Soil is the store house of water from where plants extract moisture for their evapotranspirational needs. Availability of useful soil moisture to the vegetation appears to be a better index for drought analysis. Soil moisture deficit affects the plant growth adversely. The infiltration and surface runoff are also affected by the soil moisture status. The catchment soil water deficit could be an indicator of hydrological drought as it governs runoff.

A multitude of soil moisture accounting models have been developed by several investigators through the world. The available soil moisture models differ from each other due to different methods used for computing potential evapotranspiration, actual evapotranspiration, infiltration and runoff, temporal definition of evaporative demand and due to number of soil layers considered in the model.

An attempt has been made by National Institute of Hydrology (1986) to discuss a simple approach for development of a soil water budgeting model to simulate daily soil moisture in dry lands using historical rainfall and climatic data and moisture characteristics of the soil. The severity of drought for a given crop can be studied by defining different levels of drought definition (i.e. different levels of soil moisture content corresponding to different soil water deficits).

DROUGHT MANAGEMENT STRATEGIES

Drought frequently affects the nation and causes substantial economic losses, especially in agriculture sector. The recent widespread drought has resulted in severe adverse effects on food and agriculture production in many parts of the world leading to high market prices, a depressed economy, and population displacement. The response to drought aims at making available timely and accurate data and information to enable government authorities to take remedial decisions. These data and information include not only climatological information, but also information of the hydrological, social and economic impacts. A systematic description of important problem areas and the potential solution is necessary for effective and frugal government response in order to avoid over or under reactions. In India extensive work has been done in order to identify the drought. Work is also needed to have integrated response of various private, public and governmental bodies, and maintain proper channels of communication and responsibility as the drought identifies.

The drought response system normally developed with the view that it would avoid past problems, reflect needs that are pertinent to the current and expected conditions and ensure effective management of drought response in the long run. The system does not only incorporate the lessons learned and capability to take definitive action, but it is also be flexible enough to adjust quickly to newer unexpected impacts.

In order to deal with the complexities of emergency drought conditions, there are two systems normally adopted, one the assessment system and the other is response system. The assessment system is composed of representatives of concerned agencies comprising a number of task forces. This system depends on the variety of data and information from a broad range of sources. The assessment system works for drought monitoring, drought identification and impacts assessment. The response system is responsible for any action to be taken to solve the particular drought problem. This includes decisions to make media announcements, funding and co-ordination of effort and resources, etc.

The criteria of drought identification and plan activation and methods for assessment of drought impacts have been formulated and implemented. In India the relief measures are being taken for drought management. There is a need for the development of drought response plan which could provide an idea of organizational structure to co-ordinate assessment and response activities of central and state government.

REMOTE SENSING OF HYDROLOGIC INDICATORS

Remote sensing of hydrological indicators of drought are in various stages of operational status. In the succeeding sections review of current and potential remote sensing capabilities in regard to surface storage, groundwater storages and soil moisture is presented. In this respect a remote sensing based National Agricultural Drought Assessment and Monitoring System for country wide monitoring in India has been developed and used for operational monitoring through the kharif season of 1989. An integrated National Agricultural Drought Assessment and Monitoring System has been proposed beyond 1989 to combine the large area repetitive objective view of satellite with the detailed ground observations.

The occurrence of drought leads to reduction in streamflow and consequent reduction in reservoir and tank levels and depletion of soil moisture and decreased ground water storage. The subsequent paragraphs deal briefly with remote sensing capabilities in regard to the various hydrologic indicators of drought.

Remote Sensing of Surface Storage: Low streamflow and reduced storage in reservoirs, lakes and tanks are indicative of drought conditions, and in general reflect the precipitation deficiency over the basin. The coarse resolution of National Oceanic and Atmospheric Administration (NOAA) AVHRR data makes it difficult to identify surface water other than in large reservoirs and river systems. Reductions in streamflow exhibited by the decrease in river width are in general not identifiable on the meteorological NOAA satellite data. Even in the case of higher resolution early resources satellite data such as Landsat Multispectral Scanner (80 m) or Thematic Mapper (30 m) or SPOT HRV (10 m or 20 m) or the scheduled IRS LISS-I and II (73 m and 36.5 m) data marginal decrease in river water width are not accurately distinguishable. However, severe precipitation deficiencies leading to drastic decreases in streamflow may be discernable on large river systems. Decreased water width and intermittent versus continuous flow may be indicative of drought conditions in such situations.

Significant reductions in storage in large reservoirs may be observable on NOAA imagery with 1.1 km resolution at nadir. Landsat/IRS/SPOT data with much higher spatial resolution help in delineating the surface water fluctuations in almost all water bodies from reservoirs in small tanks. The use of such data however will be opportunistic due to the high probability of cloud cover at the time of satellite over-passes during the agricultural season. Comparison between surface water storages on comparable dates in different years provides information on drought occurrence and relative severity (Chakraborty et.al. 1982). Thiruvengadachari, 1982; Kumar, 1983; Sreenivas, 1986; Kishan, 1987). In another study covering Prakasam district of Andhra Pradesh state in which the surface water storages in irrigation tanks at different times during the kharif season on 1984 to 1987 have been compared to evaluate the potential of such information to indicate drought conditions and severity level (Thiruvengadachari 1989).

Remote Sensing of Soil Moisture Deficit: Remote sensing of soil moisture employs in general two approaches: indirect estimation of soil moisture availability versus demand through observation of canopy temperature, and direct estimation of soil moisture. The relationship between plant and soil temperatures and the evapotranspiration rates is evident from the land-atmosphere energy balance. As long as the soil and plant are well watered and not stressed, they are able to maintain relatively cooler surface temperatures since the absorbed solar radiation is mainly used to evaporate water. As moisture gets deficient, the surface warms up indicating soil moisture deficit. When plants are stressed the normal transpiration rates are generally not maintained and, as a result, heat up. Thermal infrared measurements have been used to monitor daily plant canopy temperatures for use in various indices as indicators of plant water stress (Ajay and Sahai, 1986).

Varying time periods of plant stress due to soil moisture deficit are common to all natural plants as well as to agricultural crops. Since the temperature of a stressed plant is higher than that of unstressed plant, it is possible to develop a stress index to supplement the greenness index. Recent efforts have been made to examine the potential of combining the greenness (vegetation) index using visible and near infrared data, and the temperature (stress) index using thermal infrared data. Strong negative relationships between vegetation index and thermal infrared measurements have been observed at scales ranging from field measurements to Advanced Very High Resolution Radiometer (AVHRR) data. A Global Vegetation Monitoring System can perhaps be developed integrating these two indexes.

Direct estimation of soil moisture through remote sensing techniques involves measurement of reflected or emitted electromagnetic energy from the soil surface. The variation in intensity of this radiation with soil moisture depends on either the dielectric properties or soil temperature or both.

Field measurements have substantiated that the amplitude of the diurnal range is a good measure of moisture content in the surface soil strata. However, this technique is not applicable to areas with vegetative canopy. In such areas the canopy temperature should be considered as indicative of soil moisture status in the root zone.

The strong physical relationship between the microwave response and soil moisture, with the capability of microwave sensors to penetrate clouds, most precipitation and herbaceous vegetation, makes them very attractive as soil moisture sensors. However, noise factors such as vegetation and surface roughness affect the sensor response and hence need to be accounted for.

Direct measurement/estimation of soil moisture will not be feasible in near future in an operational context in view of paucity of Indian experience. Even in regard to indirect estimation of soil moisture deficit through canopy temperature measurements the operationalization will be long term, in view of technique development efforts needed and improvement in supplementary ground measurements both in regard to time and space. The emphasis for country wide drought monitoring will have to be placed on various indexes to drought occurrence and severity in different areas call for sustained and large scale efforts, if it is to be calibrated based on ground truth regarding agricultural conditions. Airborne SLAR/SAC studies are under way in which microwave data in X/C band is proposed to be used for soil moisture mapping. Availability of microwave data from ERS-1 and Radar satellites will provide the input for use of such data in drought surveillance.

Remote Sensing of Ground Water Deficit Very few studies have attempted to assess the impact of drought on groundwater in a scientific way. Remote sensing of ground water deficits during drought years will have to be indirect in terms of reduction in groundwater irrigated cropped areas. Some studies have indicated promise in the delineation of groundwater irrigated areas, where such area is continuous and not mixed with other irrigation sources such as canal and tank (Thiruvengadachari, 1982). However, in other areas delineation of areas irrigated solely by groundwater may not be possible. But during drought situation both reservoir and tank storages are likely to be affected, similar to groundwater storage, and hence should result in reduction in irrigated crop areas. However, reliable estimation of reduction in irrigated copped area is likely to be obtained during severe drought years rather than during light-to-moderate drought situations.

Assessment of fluctuations in surface water storages will be possible only from high resolution earth resources satellites, but only in an opportunistic basis due to cloud cover conditions. Hence operational dependence on such data for country wide monitoring will not be possible. Assessment of deficient groundwater storages also requiring similar limitations and has the major constraint of technique development as well as establishing technical feasibility.

GAPS AND SUGGESTIONS

The studies on hydrological aspects of droughts are less attempted as compared to the meteorological and agricultural aspects of droughts in India. In drought studies, it is not sufficient to go by analysing the variability of total rainfall amount alone but also to analyse water, soil moisture and groundwater as well as demand patterns to understand drought in a better perspective. In this connection the hydrological drought indices are to be developed. The proper management of water resources is the back in the development of drought prone areas. The management includes both surface water and ground water. The ground water management for both dynamic and stotic storage is required. The indices are required for dynamic ground water storage. A suitable water distribution policy for different water uses (such as drinking purpose, fodder and crop production and industrial use in order to priority) linked with anticipated or current deficiencies in water supplies both surface and ground water has to be evolved for drought prone areas.

Needs for water conservation is important in delineating the effect of drought. The water conservation is need at all possible sources and places of utilisation such as insurface water, ground water and in uses such as domestic, agriculture, industrial and other uses. The conservation by water harvesting, lining of canals, irrigation methods interlinking the basins by long transfer of water can be few practices to conserve the water to meet the needs of drought.

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