CHAPTER 2

STUDIES ON DROUGHTS – A REVIEW

2.1 GENERAL

Review of literature will always help one to have information and to perceive significance of the present status of the problem to be dealt with. It will throw light on the state of the art of knowledge and enlighten the future course of study. An attempt in this direction of thought would certainly help one to understand the natural process of drought for further work.

Drought is a weather-related natural disaster. It affects vast regions for months or years. It is a recurrent feature of the climate and occurs in virtually all-climatic zones. Its characteristics vary significantly in different regions.

Drought is related to deficiency of precipitation over an extended period of time, usually for a season or more. This deficiency results in a water shortage for some activity, group or environmental sector. Drought is also related to the timing of precipitation. Other climatic factors such as high temperature, high wind and low relative humidity are often associated with drought.

Drought is more than a physical phenomenon or a natural event. Its impact results from the relation between a natural event and demands on the water supply and it is often exacerbated by human activities. The experience
from droughts has underscored the vulnerability of human societies to this natural hazard.

2.2 DEFINITIONS

A drought may mean different things to different people. Drought definitions are of two types viz., (i) conceptual; and (ii) Operational.

Conceptual definitions help to understand the meaning of drought and its effects. For example, drought is a protracted period of deficient precipitation, which causes extensive damage to crops, resulting in loss of yield. These definitions are normally vague, do not provide quantitative answers to “when”, “how long”, “how severe” a drought is and are often used as a startup in scientific papers and reports. Some sources (National Drought Mitigation Center, Nebraska, USA) refer to them as Conceptual definitions and differentiate between conceptual and operational definitions.

Operational definitions help to identify the drought's beginning, end and degree of severity. To determine the beginning of drought, operational definitions specify the degree of departure from the precipitation average over some time period. This is usually accomplished by comparing the current situation with the historical average. The threshold identified as the beginning of a drought (e.g., 75% of average precipitation over a specified time period) is usually taken.

An operational definition for agriculture may compare daily precipitation to evapotranspiration to determine the rate of soil-moisture depletion and express these relationships in terms of drought effects on plant behavior. These definitions are used to analyze drought frequency, severity, and duration for a given historical period. Such definitions, however, require
weather related data on hourly, daily, monthly or other time scales and possibly impact data (e.g., crop yield). Drought for a given region provides a greater understanding of its characteristics and the probability of recurrence at various levels of severity. Information of this type is beneficial in the formulation of mitigation strategies. Operational definitions are formulated in terms of drought indices.

2.3 CLASSIFICATION OF DROUGHT DEFINITIONS

Depending upon the influential factor considered for defining the drought, the definitions are grouped as below:

(i) Precipitation based drought definitions;
(ii) Evapotranspiration based drought definitions;
(iii) Streamflow based drought definitions;
(iv) Soil moisture based drought definitions; and
(v) Vegetation based drought definitions.

Relevant definitions available under each category are listed and the implications of each of them are discussed with respect to their physical representation of the drought assessment.

2.3.1 Precipitation Based Drought Definitions

Hoyt (1938) defined the drought in humid and semi-arid areas with an annual precipitation deficiency of 15 percent. Blumenstock (1942) defined the drought as a period in which the precipitation is less than 0.1 inch in 48 hours. Condra (1944) defined the drought as a period of strong wind, low precipitation, high temperature and unusually low relative humidity.
Ramdas and Malik (1948) suggested a week of drought as a period in which the actual rainfall is equal to half the normal rainfall or less. Ramdass (1960) defined the drought when the actual seasonal rainfall is less by twice the standard deviation from the standard long term mean rainfall.

Palmer (1965) defined drought as a situation when the actual rainfall is less than the rainfall which is climatically appropriate for the existing conditions. Herbst et al (1966) defined the absolute drought as the period of at least 15 consecutive days without 0.01 inch of rain on any one day and the partial drought as the period of 29 consecutive days, the mean rainfall of which does not exceed 0.01 inch per day.

Yevjevich (1967) discussed the droughts as the deficiency of rainfall about the mean (truncation level). National Commission on Agriculture (1976) classified the meteorological drought as a situation when there is significant (more than 25%) decrease from the normal period of four consecutive weeks in the period from middle of May to middle of October.

Gadgil and Yadamuni (1987) defined drought as a period having less than 10% probability of occurrence of rainfall. Jorge Morban (1988) defined drought as the rainfall amount over a specified period of time that is less than its corresponding normal amount. The India Meteorological Department (IMD) is assessing the droughts based on the percentage departure of rainfall from the long term mean rainfall.

From the above, it can be seen that the drought assessment period is varying from person to person and country to country ranging from hours, days, weeks, months, a season and a year. Hence, the literature does not lead one to a definite understanding as to how exactly a meteorological drought can be assessed. Further, small periods such as hours, days and weeks may be
insignificant in the context of drought whose influence is felt over a longer period. Hence, all of the above definitions which are based on an amount of precipitation alone may not be effective for practical purposes.

2.3.2 Evapotranspiration Based Drought Definitions

Evapotranspiration has been considered in a limited way for defining the drought as compared to the precipitation. Thornthwaite (1948) has used this factor. He defined the drought as a condition in which the amount of water needed for transpiration and direct evaporation exceeds the available soil moisture. Potential evapotranspiration depends upon the climatic and vegetative factors. Actual evapotranspiration depends on the availability of soil moisture which in turn depends on the amount of precipitation and soil characteristics. The concept of evapotranspiration is relevant only during the periods when vegetation is growing actively. Hence, the consideration of evapotranspiration for defining the drought may be an indirect way and it might not truly reflect the reality unless the supply and demand pattern of the cropping activities are taken into account for defining the drought.

2.3.3 Streamflow Based Drought Definitions

Hoyt (1938) defined the drought as the period in which the actual flow of a natural stream in a selected number of days has a small probability of occurrence. The drought is also identified as the deficiency of streamflow with respect to the long term mean streamflow as truncation level (Yevjevich 1967). Dracup (1980) defined it as the deficiency of streamflow from a level which could be the median of long term streamflows.
Joseph (1970) defined the drought as a period with lowest mean discharge at a specified measuring point in a streamflow for 14 consecutive days during a climatic year beginning April 1. Thambiannan (1990) quoted the drought as three weeks to three months runoff deficit during the period of germination of vegetation.

Based on the above, it is clear that any deficiency in streamflow compared to its long term mean or an arbitrary value is taken as the criteria for demarcating the period of non-availability of water and hence the drought. Considering only the availability of streamflow without taking into account to other forms of water availability and demand may be insufficient for the analysis of drought. The streamflow data collected from the particular gauging point may not truly represent the water availability in a particular administrative region or boundary.

2.3.4 Soil Moisture Based Drought Definitions

Agricultural drought is generally defined as the deficiency of soil moisture to meet the crop water requirement. Van Bavel and Verlinden (1956) defined the drought as a day on which the available soil moisture was depleted to some small percentage of available capacity. Shantz (1970) defined the drought as a situation when the available soil moisture diminishes so that the vegetation can no longer absorb water from the soil rapidly enough to meet the transpiration requirements.

Warrick (1975) defined the drought as a condition of moisture deficit sufficient to have an adverse effect on vegetation, animals and human beings over a sizable area. World Meteorological Organisation (1975) defined the drought as the deficiency of soil moisture with respect to the plant behaviour, perhaps for a specific crop.
National Commission on Agriculture (1976) defined the drought as the period when the soil moisture is inadequate during crop season to support healthy crop growth. Smith (1978) defined the drought as a condition under which plant fails to develop and mature properly because of insufficient moisture. Rama Prasad (1990) proposed the drought as the period when the soil moisture value is less than that which is necessary to ensure the crop water demand to be fully met in the growing season.

It is seen that all the above definitions are pointing to the deficiency of soil moisture in meeting the crop water requirements. The computations are based on rainfall without taking into account the irrigation with surface or groundwater. Hence, these are applicable only to rainfed areas and will not form part of a sole limiting factor to assess the drought.

### 2.3.5 Vegetation Based Drought Definitions

Thiruvengadachari (1988) assessed the drought for two weekly periods for taluks on the analysis based on vegetation index map, greenness map and vegetation index statistics. The assessment of drought from the status of vegetation was performed for bimonthly periods for each taluk. The satellite based drought assessment and monitoring was developed based on the relation between the two consecutive years Normalized Difference Vegetation Index (NDVI). It is to be observed here that all the vegetal cover in an area may not be productive and some vegetation may not reflect the water availability in that area.

### 2.3.6 Need for Grouping of Definitions

A drought may mean different things to different people. For example, for a meteorologist, it is a deviation from normal precipitation; for a
hydrologist, a fall in stream flow, lake level or groundwater level; for an agricultural scientist, lack of soil moisture to sustain crop growth; for an economist, a famine condition; and for an urbanite, shortage of tap water supply. There is a lack of a precise and objective definition of drought and that can lead to indecision and inaction on the part of managers, policy makers and others (Wilhite et al 1986).

Developing countries, like India, are now looking for research which is socially acceptable rather than that of academic interest. The approaches should be operational so that these can be utilized by the Federal Governments to give effective fillip for monitoring/management of droughts. The various definitions are highlighting the drought based only on a few factors and analyzing only a part of the whole problem. But these works had not developed further in giving a deterministic procedure in the quantification of water deficiency i.e., drought severity. It is clear from the above that there is a need for grouping the definitions and developing an integrated drought definition. In other words, the droughts in meteorological, hydrological and agricultural contexts should be combined to give an overall view and integrate the drought situation in an area.

National Commission on Agriculture (1976), broadly classified droughts into the following three types:

(i) **Meteorological drought:** Meteorological drought is a situation when the actual rainfall is significantly lower than the climatologically expected rainfall over a wide area.

(ii) **Hydrological drought:** Hydrological drought is associated with marked depletion of surface water and consequent drying up of lakes, rivers reservoirs etc. Hydrological
drought results if meteorological drought is sufficiently prolonged.

(iii) **Agricultural drought:** Agricultural drought is a condition in which there is insufficient soil moisture available to a crop resulting in reduction of yield. Agricultural drought is the end effect of meteorological and hydrological drought. Many researchers related Agricultural drought as an inadequate amount of soil water available during the critical crop growth periods.

Apart from the drought defined by National Agricultural Commission, socioeconomic drought is also defined. Socioeconomic drought occurs when physical water shortages start to affect the health, well being, and quality of life of the people, or when the drought starts to affect the supply and demand of an economic product.

### 2.4 DROUGHT ASSESSMENT

Drought assessment involves analysis of spatial and temporal water related data. Several methods were developed to assess the drought quantitatively. Basically, droughts are assessed with reference to (i) Nature of water deficit (ii) Averaging period (iii) Truncation level and (iv) Regionalization approach (Dracup et al 1980). Over the years, various indices have been developed to detect and monitor droughts and there is extensive literature on modeling of droughts using these indices. A drought index integrates various water related parameters like rainfall, evapotranspiration, runoff, etc. into a single number and gives a comprehensive quantitative assessment for decision making.
The effects of drought often accumulate slowly over a considerable period of time; they may linger for several years after the drought period ends. As a result, the onset and end of a drought are difficult to determine precisely and that is why a drought is often referred to as a creeping phenomenon (Mishra et al 2007).

After the various definitions of drought and their groupings to confine the problem, many researchers have attempted to assess drought severity. The following section reviews such studies, which give a definite direction for the study to be conducted to add additional knowledge in mitigating the effects of drought.

2.4.1 Meteorological Drought Assessment

Meteorological drought is a situation when there is a significant decrease in precipitation from the normal over an area. However, many definitions are available based on different truncation levels and base periods to delineate the rainfall deficiency and drought periods.

In Bali, any period of 6 days or more without rain is considered as a drought, while in Libya, droughts are recognized only after 2 consecutive years without rain (Dracup et al 1980).

Subramanyam (1964) developed a concept of drought classification with the help of Aridity index (Ia). The aridity index is the percentage ratio of annual water deficiency to annual water need or annual potential evapotranspiration.

Palmer (1965) developed an elaborate and comprehensive technique for identifying drought. He applied water balance technique and
incorporated current and antecedent rainfall, evapotranspiration and soil moisture in his index. Instead of using the normal precipitation, he coined a term CAFEC precipitation. This term represents Climatically Appropriate For Existing Conditions. This technique found its application in many countries. This method enables identification of the period of drought including those in non-rainy months and their intensity.

George et al (1973) applied Palmer’s methodology to various subdivisions of India and delineated periods and intensity of drought based on data for 71 years. A great lacuna in this method is that it cannot be applied uniformly over all agro climatic zones. In humid zones, it represents more of agricultural drought whereas in semi arid and arid zones it represents hydrological drought (Shewale 2001).

Appa Rao (1981) made extensive analysis in classification of droughts using the aridity index. Appa Rao (1987) presented meteorological subdivisions of India affected by moderate and severe droughts during the period from 1875 to 1980. These research works have not presented any specific method to assess the drought severity of an area.

The rainfall criterion is useful for continuous monitoring of the monsoon season. The sum of the season’s rainfall forms the basis in describing a region under moderate or severe drought. When more than 50% of the area in the country is under moderate or severe drought, the country is described as severely affected by drought and when the affected area is 26-50% of the country, it is described as an incidence of moderate drought (Singh 2000).

According to the Task Force on Drought Prone Area Programme (DPAP 1973), the areas which received less than 750 mm of rainfall per
annum are classified as drought prone and those between 750 mm to 800 mm as vulnerable to drought.

The Meteorological Department of the Government of India has defined an area as drought hit when annual rainfall is less than 75% of the normal, (i.e., the rainfall deficit is 25% to 50%) and severe drought when deficiency is above 50%. The Irrigation Commission assumed that the area is drought hit if the irrigated area falls short by 70% of the irrigable area. So, when the irrigated area is less than 30% of the irrigable area, the areas are to be called as drought prone.

McKee et al (1993) developed the Standardized Precipitation Index (SPI) to quantify the precipitation deficit for multiple time scales, reflecting the impact of precipitation deficiency on the availability of various water supplies.

Kulandaivelu and Jayachandran (1994) reported that in Tamilnadu, 85% of the total area benefits from the northeast monsoon; only 15% benefits from the southwest monsoon and the mean annual rainfall is 945mm, with 45 rainy days. Tamil Nadu has been classified into a drought-prone area, based on precipitation, potential evaporation and soil type.

Ravikumar (1997) developed the land use based Integrated Drought Severity Index(IDSI) to identify the drought prone areas in Dharmapuri District, Tamil Nadu. IDSI integrates the effect of meteorological, hydrological and agricultural factors using land use criterion as basis.

Singh (2000) reported that a drought prone area is one in which the probability of a drought year is greater than 20%. A chronic drought-prone area is one in which the probability of a drought year is greater than 40%.
A drought year occurs when less than 75% of the “Normal” rainfall is received.

Sinha Ray and Shewale (2001) reported that the probability of drought exceeds 20% over Gujarat, West Rajasthan and Jammu & Kashmir. In other words, a drought can be expected in these areas once in 4 to 5 years. The probability of drought occurrence is between 16-20 % over Haryana, Punjab, Himachal Pradesh, East Rajasthan and Rayalaseema, whereas in the hills of West Uttar Pradesh (now Uttarakhand), Marathwada and Telangana, it could be between 11 to 15%. The probability of drought occurrence is 10 % or less in rest of India.

IMD (2002) reported that when the rainfall for the monsoon season of June to September for the country as a whole is within 10% of its long period average, then it is categorized as a normal monsoon. When the monsoon rainfall deficiency exceeds 10%, it is categorized as an all-India drought year. In the year 2002, the Southwest monsoon rainfall for the country as a whole was 19% below normal, making 2002 an all - India drought year.

The following methods are widely used for meteorological drought assessment:

(i) Indian Meteorological Department (IMD);
(ii) Herbst’s method;
(iii) Aridity Index; and
(iv) Palmer’s Drought Severity Index.

Among the above methods, the IMD method is a simple and widely used one which will give a preliminary idea about the drought condition of an
area. In this method, drought is assessed on the basis of percentage deviation of rainfall from the long term annual mean rainfall.

Herbst et al (1966) developed a technique for evaluating droughts by using monthly precipitation. The technique determines duration and intensity of droughts as well as the month of their onset and termination.

The Aridity Index (Subramanyam 1964) is the percentage ratio of annual water deficiency to annual water need or annual potential evapotranspiration.

Palmer (1965) developed drought index known as Palmer Index. Based on the water budget of the soil, Palmer used the difference between actual precipitation and required precipitation under conditions of average climate in an area to evaluate drought severity in space and time. It takes into account precipitation, potential evapotranspiration, antecedent soil moisture and runoff.

2.4.2 Hydrological Drought Assessment

The meteorological drought, if prolonged, results in hydrological drought with marked depletion of surface water and consequent drying up of inland water bodies such as lakes, reservoirs, streams and rivers as well as fall in the level of water table. Hydrological drought is associated with the effects of periods of precipitation shortfalls on surface or subsurface water sources.

The hydrological aspects of drought are in general less attempted and poorly understood. Hydrological drought is understood with respect to low streamflow or water availability. Literature is available for the stochastic characterization of droughts using streamflow data; Gumbel (1959),

Chow (1964) suggested that analysis of low stream flows is a suitable way of quantifying droughts. He found that during the periods of deficient precipitation, the deviation from normal conditions is greater for stream flow than for rainfall. He also suggested that low flow data must be specified in terms of magnitude of flow. He used this analysis for monitoring droughts.

Herbst et al (1966) developed a method to assess the meteorological drought severity using rainfall data, which was applied by Mohan and Rangacharya (1991) for the stream flow data. The effective available water \( Q_e \) of a particular month is calculated by adding the actual available water \( Q \) with the excess or deficit of previous month’s available water from long term mean monthly available water. While doing this carry-over, a weighting factor \( W \) is included. The frequency and severity of hydrological drought is defined on a watershed or river basin scale. This method provides information on onset, termination and severity of drought.

Dracup et al (1980) proposed a method by using the concept of long term mean streamflow as the truncation level. There are three deterministic approaches which are based on different truncation levels to demarcate the drought periods using the streamflow data.

2.4.3 Agricultural Drought Assessment

Agricultural drought occurs when soil moisture and rainfall are inadequate to support crop growth to maturity and cause extreme crop stress
leading to the loss of yield. Meteorological and hydrological droughts are concerned with rainfall, surface water and groundwater components of the hydrologic cycle, i.e. they are only supply oriented ones, whereas agricultural drought is concerned with the availability of water to meet the crop water requirements. Agricultural drought severity can be estimated by a conventional method whereby supply-demand estimates are made to find out any deficiency.

Many previous works in agricultural drought severity assessment focus their attention mainly on micro-implications of agronomy of crops and not in quantification of water deficiency during agricultural drought. Stochastic analysis of agricultural droughts were reported by Prajapati et al (1977).

National Remote Sensing Agency of India (Thiruvengadachary, 1988) has assessed the drought based on the analysis of vegetation index map and the greenness map as well as vegetation index statistics for bimonthly periods for each taluk. The satellite based drought assessment and monitoring methodology was developed based on the relationship obtained between previous years Normalized Difference Vegetation Index (NDVI) profiles with the corresponding agricultural performance available at district level and their relative difference in the current year. The National Agricultural Drought Assessment and Monitoring System (NADAMS) in a view of the whole country coverage, envisages the use of data from NOAA satellites with 1.1 km resolution, for generation of weekly composited Normalized Difference Vegetation Index (NDVI) maps of country. The NDVI is a transformation of reflected radiation in the visible and near infrared bands of NOAA AVHRR and is a function of green leaf and biomass.
The various approaches presented above have not tried to quantify the water deficiency during an agricultural drought, which is relevant from the water resources engineering point of view. Rama Prasad (1990) tried to quantify the water deficiency during an agricultural drought and the method considers the soil moisture in the form of an Antecedent Precipitation Index (API).

2.4.4 Drought Studies Using Remote Sensing and GIS

Krishnaveni (1993) reported that in case of drought assessment, the important parameters that may be influencing drought are rainfall, groundwater levels, stream flows, soils, land use etc. These parameters possess temporal and spatial characteristics. Geographic Information System software provides tools to incorporate spatial and temporal variations. Therefore, GIS can be advantageously used for the analysis of drought.

Tiruvengadachari et al (1987) in their case study in Tadipatri taluk of Anantapur District in Andhra Pradesh, India, reported that the NDVI response over the taluk was compared between two years, supported by ground reports on agricultural conditions. NDVI comparisons over specific sites around rain gauges and anomalous areas provided an improved understanding of the NDVI response specially as applied to taluk level drought assessment. It is suggested that in addition to total vegetated area, the NDVI response averaged over the total geographic area of the taluk or the product of vegetated area and NDVI response could be significantly used as drought indicators. They were found to be more effective than the mean NDVI response over vegetated areas.

Chanzetal (1998) developed the procedure to form the image to express the unavailability of water during periods of drought for a selected
drainage basin. Based on the method of truncation level, truncated values of precipitation and stream flows were estimated at each gauging station. These truncation levels were used to reflect the levels of drought severity. The stream flow image from precipitation was subtracted to obtain drought severity at each level. These were done on a cell by cell basis to create new attribute values for the new image to represent the unavailability of water at each level of drought severity.

Park (1999) discusses the future perspective of the applications of GIS technology for agricultural resources management. Land use suitability analysis is carried out as a part of the study and land use classification is given. The drought mitigation and management and spatial variation of drought conditions are explained. It offers in-depth analyses of regional drought conditions.

MongKolsawat and Thirangom (2000) modeled the drought risk area with a set of themes using remotely sensed data and GIS. The underlining concept of the paper is that the severity of drought can be considered as being a function of rainfall, hydrology and physical aspect of landscape. Each theme of the drought consists of a set of logically related geographic features and attributes are used as data input for analysis. The matrix overlay operation of the drought risk layers was performed. They are then classified into 4 drought classes of drought risk: very mild, mild, moderate and severe.

Nagarajan and Subrata Mahapatra (2000) developed the Land Based Information System for drought to store information of past, compared it with the current data and to assess the vulnerability of an area using orbital temporal remotely sensed and ancillary data in understanding the situation and decided on the mitigation planning. This study provides an overall
picture about drought information requirement for decision makers. This study highlights the land information based system developed for this purpose for the drought prone Marathwada region.

Wilhelmi et al (2002) explains the agro-climatological factors of vulnerability to agricultural drought. Evapotranspiration (ET) values were estimated based on the relationship between ET, water use efficiency and crop yield. Probability values were assigned by spatial interpolation and classified using GIS. The classifications included low, moderate, high and very high probability of seasonal crop moisture deficiency. The results of this study formed the basis for a comprehensive, GIS-based agricultural drought vulnerability assessment for Nebraska.

2.5 DROUGHT INDICES

A drought index value is a single number, useful for decision-making. There are several indices that measure how much precipitation for a given period of time has deviated from historically established norms. Although none of the major indices is inherently superior to the rest in all circumstances, some indices like Palmer Drought Severity Index (PDSI), Percent of Normal, Standardized Precipitation Index (SPI), Crop Moisture Index (CMI), Surface Water Supply Index (SWSI), Deciles etc., are better suited than others for certain uses.

2.5.1 Review of Drought Indices

Drought indices are normally continuous functions of rainfall and/or temperature, river discharge or other measurable variable. Rainfall data are widely used to calculate drought indices, because long-term rainfall records are often available. Rainfall data alone may not reflect the spectrum of
drought related conditions, but they can serve as a pragmatic solution in data-poor regions. Some of the well-known and less-well-known indices used in drought studies, monitoring and management are briefly reviewed below.

2.5.2 Percent of Normal

Analyses using the percent of normal are very effective when used for a single region or a single season. Percent of normal is also easily misunderstood and gives different indications of conditions, depending on the location and season. It is calculated by dividing actual precipitation by normal precipitation typically considered to be a 30-year mean and multiplying by 100. This can be calculated for a variety of time scales. Usually these time scales range from a single month to a group of months representing a particular season, to an annual or water year.

One of the disadvantages of using the percent of normal precipitation is that the mean or average precipitation is often not the same as the median precipitation, which is the value exceeded by 50% of the precipitation occurrences in a long-term climate record. The reason for this is that precipitation on monthly or seasonal scales does not have a normal distribution. Use of the percent of normal comparison implies a normal distribution where the mean and median are considered to be the same.

2.5.3 Palmer Drought Severity Index (PDSI)

Palmer (1965) developed a soil moisture algorithm (a model), which uses precipitation, temperature data and local available water content. Palmer based his index on the supply-demand concept of the water balance equation, taking into account of the precipitation deficit at specific locations.
2.5.4 Standardized Precipitation Index (SPI)

McKee et al (1993) developed the Standardized Precipitation Index (SPI) to quantify the precipitation deficit for multiple time scales, reflecting the impact of precipitation deficiency on the availability of various water supplies. They calculated the SPI for 3, 6, 12, 24 and 48 month scales to reflect the temporal behavior of the impact. To calculate the SPI, a long-term precipitation record at the desired station is first fitted to a probability distribution (e.g. gamma distribution), which is then transformed into a normal distribution so that the mean SPI is zero (Steinemann 2003).

2.5.5 Aridity Index ($I_a$)

Subramanyam (1964) developed a concept of drought classification with the help of Aridity index ($I_a$). The aridity index is the percentage ratio of annual water deficient to annual water need or annual potential evapotranspiration.

\[
I_a = \frac{\text{Water deficit}}{\text{Water need}} = \frac{\text{Potential evapotranspiration} - \text{Actual evapotranspiration}}{\text{Potential evapotranspiration}}
\]

For computing the water deficit, the climate water balance using the book-keeping procedure of Thornthwaite and Mater (1955) has been used. The values of Aridity Index are used to calculate the arithmetic mean and standard deviation ($\sigma$) for the number of years of calculation. The climatic drought classification is given below in Table 2.1.
Table 2.1 Climatic drought classifications (Aridity Index Method)

<table>
<thead>
<tr>
<th>Departure of $I_a$ from normal</th>
<th>Drought severity</th>
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<tbody>
<tr>
<td>Less than $\sigma/2$</td>
<td>No drought</td>
</tr>
<tr>
<td>$\sigma/2$ to $\sigma$</td>
<td>Moderate drought</td>
</tr>
<tr>
<td>$\sigma$ To $2\sigma$</td>
<td>Large drought</td>
</tr>
<tr>
<td>Greater than $2\sigma$</td>
<td>Disastrous drought</td>
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</tbody>
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Note: ‘$\sigma$’ is the standard deviation of $I_a$ values.

2.5.6 Deciles

“Deciles” was used by Gibbs and Maher (1967) to avoid some of the weaknesses within the “percent of normal” approach. The technique they developed divided the distribution of occurrences over a long-term precipitation record into tenths of the distribution. They called each of these categories a decile. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications. One disadvantage of the decile system is that a long climatological record is needed to calculate the deciles accurately.
2.5.7 Crop Moisture Index

The Crop Moisture Index (CMI) is an index that uses a meteorological approach to monitor week-to-week crop conditions. It was developed by Palmer (1965) from procedures within the calculation of the Palmer Drought Severity Index (PDSI). While the PDSI monitors long-term meteorological wet and dry spells, the CMI was designed to evaluate short-term moisture conditions across major crop producing regions. Since CMI is designed to monitor short-term moisture conditions impinging a developing crop, it is not a good long-term drought-monitoring tool.

2.5.8 Aggregate Drought Index (ADI)

ADI a multivariate drought index developed by Keyantash and Dracup (2004) that considers the bulk quantity of water across the meteorological, hydrological and agricultural regimes of drought. The domain of the ADI is a region of climatic uniformity, such as a National Climatic Data Center (NCDC) climate division, which has its water-related resources aggregately assessed through Principal Component Analysis (PCA) of monthly hydrologic data.

2.5.9 Water Availability and Water Stress Indices

The Water Availability Index (WAI) is a global measure of water available for socio-economic development and agricultural production. It represents the accessible water diverted from the runoff cycle in a give country, region or drainage basin, expressed as volume per person per year. Water stress is commonly evaluated by comparing the volume of renewable water resources per capita at a national level. Critical values of the water stress index (WSI) identify various ranges of water scarcity.
Smakhtin and Hughes (2004) reviewed the existing drought indices and analysed for their applicability for drought prediction and management in the specific context of South Asia. A software package was developed for automated estimation, display and analysis of various drought indices. They observed that Standardized Precipitation Index is being used in Southwest Asia than other drought indices due to its limited input data requirements, flexibility and simplicity of calculations.

2.6 DROUGHT FORECASTING

The basic requirement of mitigating the detrimental effects of droughts is the ability to forecast drought conditions in advance. Accurate drought forecasts would enable the decision makers for optimal operation of irrigations systems. Traditionally, statistical models have been used for hydrologic drought forecasting based on time series methods. However, they are basically linear models assuming that the data are stationery and have a limited ability to capture non-stationarities and nonlinearities in hydrologic series. Hydrological variables such as monthly and annual rainfall and stream flows have been extensively modeled by ARMA models during the past several decades. However, it is necessary for hydrologists to consider alternative models when nonlinearity and non-stationarity play a significant role in the forecasting.

In the field of water resources engineering, there are numerous examples of variability and uncertainty. Variability and uncertainty are explicitly considered in some studies and in other cases they are more subtly incorporated into the analysis while in many cases they are completely ignored. Hydrologic analysis generally includes an explicit representation of variability/uncertainty and there is some ambiguity as to the exact meaning and difference between variability and uncertainty
(Grayman 2005). Vose (2000) provides a good distinction between these terms. Variability is the effect of chance and is a function of the system. Uncertainty is the assessor’s lack of knowledge/level of ignorance about the parameters that characterize the physical system that is being modeled. He adds that total uncertainty is the combination of uncertainty and variability and that these two components act together to erode our ability to be able to predict what the future holds. In the case of droughts, it is observed that there are vagueness in definition, imprecision in discrete measurements and parameter uncertainty over space and time. Fuzzy set theory introduced by Zadeh (1965) is especially well suited for handling vague data. Overlap of fuzzy rules smooths out measurement error and noise in the data. In addition, derivation of the fuzzy rules from the historical record establishes an inherent consistency between the model and the hydrologic behavior observed in the basin. Finally, as mentioned above, the transparency of the fuzzy rules provides explicit qualitative and quantitative insights into the physical behavior of the system.

Yevjevich (1967) investigated the properties of droughts using the geometric probability distribution, defining a drought of $k$ consecutive years when there were not adequate water resources. Saldariaga and Yevjevich (1970) used the run theory for predicting the drought occurrence. Rao and Padmanaban (1984) used stochastic models to forecast and simulate yearly and monthly Palmer’s drought Index.

Yevjevich (1967) suggested that the ARMA models are the best overall models in predicting short and long-term persistence. They used ARMA models for streamflow as well as annual precipitation series. They also suggested simple seasonal and multiplicative ARIMA models for modeling monthly precipitation series. They also used this model for forecasting.
Winstanley (1973) and Bunting et al (1975) used ARMA model for modeling the seasonal precipitation. They also used the model for analyzing droughts and for seasonal forecasting over Sahel area. ARMA models were also used for modeling series of decade mean rainfall for Southeast England for drought analysis.

Dyer (1977) adopted the one step ahead forecasts for forecasting precipitation and streamflows in South Africa. Rodda et al (1978) used ARMA model for modeling 51 years of winter rainfall of England and Wales. They used frequency analysis for identifying droughts on the generated series.

Zekai Sen (1980, 1989) abstracted a drought generating mechanism by simple analytical formulation of the probabilistic behaviour of extreme droughts by making use of extremes of random number of random variables combined with the theory of runs. He also applied this mechanism for annual streamflow sequences of Rhine, Danube, Mississippi and Missouri rivers.

Rao (1983) fitted an ARMA model for monthly precipitation series of Chikmagalur rain gauge station and attempted real time forecasting with the model.

Venkataraman and Bhaskar Reddy (1987) attempted frequency analysis on rainfall data for studying meteorological droughts. Log Pearson type III distribution was fitted to predict the occurrences of meteorological droughts. This study was conducted for the Rayalaseema region of Andhra Pradesh state.

Beersma and Buishand (2007) studied the distribution of annual maximum precipitation deficit for six districts within the Netherlands and applied the time series model based on nearest-neighbourhood resampling.
Moreira et al (2008) developed SPI based drought category prediction using loglinear models. Loglinear modeling for 3-dimensional contingency tables were used with data from 14 rainfall stations located in Alentejo and Algarve region, Southern Portugal, for short term prediction of drought severity classes. Loglinear models were fitted to drought class transitions derived from Standardized Precipitation Index (SPI) time series computed in a 12-month time scale. Odds and respective confidence intervals were calculated in order to understand the drought evolution and to estimate the drought class transition probabilities. The validation of the predictions was performed for the 2004-2006 droughts.

2.7 APPLICATION OF ANN TO WATER RESOURCES

Artificial Neural Network (ANN) was utilized in several hydrological forecasting models motivated by its nonlinear modeling capabilities (Olason et al 1997). The ANN approach has proven to be effective in modeling the river flow process in situations where explicit knowledge of the internal hydrologic sub-process is not available (Subramanian et al 1999). Literature survey showed that ANN models were successfully applied to problems involving river watershed and weather prediction. Moreover, several types and architectures of ANN were investigated in the field of water resources management especially for river flow forecasting.

In recent decades, ANNs have shown great ability in modeling and forecasting nonlinear and nonstationary time series in hydrology and water resources engineering due to their innate nonlinear property and flexibility for modeling. In general, the advantages of ANNs over other statistical models are that the application of ANNs does not require a prior knowledge of the process because ANNs have black-box properties.
Morid et al (2007) described an approach for drought forecasting, which makes use of Artificial Neural Networks (ANN) and predicts quantitative values of drought indices – continuous functions of rainfall which measure the degree of dryness of any time period. The indices used are the Effective Drought Index (EDI) and the Standard Precipitation Index (SPI). The forecasts are attempted using different combinations of past rainfall, the above two drought indices in preceding months and climate indices like Southern Oscillation Index (SOI) and North Atlantic Oscillation (NAO) index. A number of different ANN models for both EDI and SPI with the lead times of 1 to 12 months have been tested at several rainfall stations in the Tehran Province of Iran.

Kim and Valdes (2003) proposed a nonlinear model for drought forecasting based on a conjunction of wavelet transforms and neural networks. The model was applied to forecast the droughts in the Conchos river basin in Mexico.

Mishra et al (2007) used a hybrid model, combining linear stochastic model and a nonlinear ANN model for forecasting droughts in the Kanabati River basin in India using SPI as a drought index.

2.8 APPLICATION OF FUZZY LOGIC TO DROUGHT FORECASTING

Fuzzy Logic (FL) provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy or missing input information. FL incorporates a simple, rule-based IF X AND Y THEN Z approach to solve a control problem rather than attempting to model a system mathematically. The FL model is empirically based, relying on an operator's experience rather than their technical understanding of the system. FL
requires some numerical parameters in order to operate such as what is considered to be a significant error and a significant rate-of-change-of-error, but exact values of these numbers are usually not critical unless very responsive performance is required in which case empirical tuning would determine them. It uses an imprecise but very descriptive language to deal with input data more like a human operator.

The main concept in FL is to simulate the operating system with both fuzzy logic programming and fixed rules. The key idea about FL is that it allows for something to be partly this and partly that, rather than having the same to be either all this or all that; and that the degree of 'belongingness' to a set or category can be described numerically by a membership number between 0 and 1.

For a fuzzy problem, the fuzzy objective and constraints are characterized by their membership functions. Since the satisfaction (optimization) of the objective and the constraints are needed, a decision or selection of a set of design variables in a fuzzy environment can be made assuming that the constraints are non-interactive and that the logical ‘AND’ corresponds to intersection. The decision in fuzzy environment can be viewed as the intersection of the fuzzy constraint and the fuzzy objective function. An important feature of fuzzy set theory is the symmetry between the objective function and constraints.

Fuzzy set theory provides a means for representing uncertainties. Historically, probability theory has been the primary tool for representing uncertainty in mathematical models. Because of this, all uncertainty was assumed to follow the characteristics of random uncertainty. It could be argued that the overwhelming amount of uncertainty associated with complex systems and issues, which humans address on a daily basis, is non-random in
nature. Fuzzy set theory is a tool for modeling the kind of uncertainty associated with vagueness, impression and/or with a lack of information regarding particular element of the problem in hand (Ross 1997).

Fuzzy set theory has also been examined in hydrological modeling such as rainfall forecasting, inflow prediction and reservoir operation. Several reservoir operation techniques based on fuzzy systems and fuzzy control systems for reservoir operations can be found in the literature along with the use of Genetic Algorithms. These models include fuzzy optimization techniques, fuzzy rule based systems and hybrid fuzzy systems. In these models, fuzzy rules were created using expert knowledge or observed data.

Apparently, neural networks and fuzzy models are suitable alternatives for modeling nonlinear and non-stationery problems in water resources engineering compared to conventional modeling approaches especially in situations where the problem has ambiguity in definition itself such as droughts.

Geza Pesti et al (1996) proposed a methodology for predicting regional droughts from atmospheric pressure patterns. Drought characteristics are strongly related to general circulation patterns (CP). The link between the large-scale CPs and regional scale droughts is modeled using fuzzy rule-based approach. The rules are derived from a training set which includes a daily time series of CP classes and a corresponding monthly sequence of Palmer Drought Severity Indices. These rules are applied to predict droughts in terms of atmospheric circulation patterns.

Pongracz et al (1999) developed a fuzzy rule based approach to predict droughts at the U.S. Great Plains from large scale climate information, namely daily atmospheric circulation patterns (CPs) and the El Nino/Southern
Oscillation (ENSO) phenomena represented by the commonly used SO Index (SOI). Palmer Modified Drought Index (PMDI) time series for the state of Nebraska and eight climate divisions in the region were used as response variables of the fuzzy rule based model. Two, three and five triangular fuzzy numbers are defined on each premise. The fuzzy rule based model using the weighted counting algorithm results in accurate statistical information on drought conditions in different regions of Nebraska.

Pongracz et al (1999) proposed a fuzzy rule model to predict the regional droughts (characterised by PMDI) using two forcing inputs, ENSO and CPs in a typical Great Plains State of Nebraska. In all its eight climate divisions and Nebraska itself, the fuzzy rule based technique using the joint forcing of CP and SOI, is able to learn the high variability and persistence of PMDI and results in reproduction of the empirical frequency distributions.

Bogardi et al (2000) presented the experiences with fuzzy rule-based modeling of hydrological extremes. They presented the results of fuzzy rule based modeling linking CP and ENSO to local climatic factors for long-term forecasting.

2.9 SUMMARY

The different classifications, definitions and the various methodologies for meteorological, hydrological, agricultural drought assessments and forecasting were reviewed. The above review has given a much greater understanding of the drought and its characteristics. It also helped to have information and to perceive importance of the present scenario of the drought problem to be analysed in detail. Existing methods of drought analysis either have qualitative assessments or use only a few drought causing parameters and data intensive. Hence, it is proposed to develop a
methodology for meteorological (Controlling factor for rainfed crops) and agricultural drought (Other cropped areas) assessment.

From literature review, it is understood that statistical models have been used for hydrologic drought forecasting based on time series methods. It is necessary for hydrologists to consider alternative models when nonlinearity and non-stationarity play a significant role in the forecasting.

Drought time series are rarely linear and mostly seasonal. Fuzzy Logic can be used to forecast droughts. Combining a time series model with Fuzzy Logic might characterize the droughts more accurately. The use of GIS (Geographic Information System) techniques might also enhance the spatial analysis of drought distribution across the study area. Understanding the degree of imprecision or vagueness involved and the non-random occurrence of a drought event, it is proposed to develop a forecasting methodology for drought using Fuzzy logic. The proposed methodologies are presented in Chapter 4 and demonstrated in Chapter 5.