Drought is not a rare or random event, but a normal recurrent feature of climate. Persisting over months and years, drought can affect large areas and cause tremendous social hardship, environmental damage and economic loss. Since drought affects many social and economic sectors, a multitude of definitions have been developed by a range of disciplines. Drought occurs with differing frequencies throughout the world and affects all types of economies, developed and developing alike. Approaches to define drought reflect regional and ideological differences. These factors make any universal attempt at definition unrealistic (Wilhite 1993). For practical purposes, however, drought can be classed as meteorological, agricultural, groundwater or surface (van Lanen and Peters 2000).

Based on a disciplinary perspective can be found in Dracup et al.(1980), where droughts are related to precipitation (meteorological), streamflow (hydrological), soil moisture (agricultural) or any combination of the three. A similar classification can be found in Wilhite & Glantz (1985), where four categories are identified:

- **Meteorological drought**: Usually expressions of precipitation’s departure from normal over some period of time. Reflects one of the primary causes of a drought.
- **Hydrological drought**: Usually expressions of deficiencies in surface and subsurface water supplies. Reflects effects and impacts of droughts.
- **Agricultural drought**: Usually expressed in terms of needed soil moisture of a particular crop at a particular time.
- **Socio-economic drought**: Definitions associating droughts with supply of and demand for an economic good.

A drought event is caused by a certain meteorological situation, for instance a persisting anticyclone/high pressure system. Associated with the prevailing dry and warm weather, a meteorological drought with a rainfall deficit develops. The rainfall deficit and the high evapotranspiration reduce the soil water content, which might cause an agricultural drought if occurring during the growing season. Due to the precipitation deficit in the catchments, stream flow decreases until it is only fed by groundwater and finally the groundwater reservoirs will also deplete. Consequently, hydrological droughts lag the occurrence of atmospheric droughts and depending on the season and the crop also the occurrence of agricultural drought. Water in hydrological storage systems such as surface and groundwater reservoirs is often used for multiple and competing purposes, e.g. flood control, irrigation, recreation, hydropower, navigation or wildlife habitat, further complicating the sequence and quantification of impacts (Wilhite, 2000). When the demand exceeds the supply, a socio-economic drought occurs. It is the rising demand on surface water resources (compare Chapter 1), which calls for a better prediction of the natural water supply and thus a better understanding and prediction of the characteristics of hydrological drought.
Hydrological drought can be defined in many different ways. Tate and Gustard (2000) reviewed climatological, agro-meteorological, streamflow, groundwater, and operational drought definitions from a hydrological perspective. Water balance indices constructed from different hydrometeorological variables govern the climatological and agro-meteorological definitions while extreme values and runs below a threshold usually define drought in streamflow time series.

![Fig.1 Propagation of drought through the hydrological cycle (modified after NDMC, 2001)](image)

**Event definition**

**The threshold level method**

Hydrological drought events derived from streamflow time series are most frequently defined by the threshold level concept: a drought event starts, when the flow falls below the threshold and ends either when the threshold is exceeded or when the water deficit volume below the threshold has been replenished.

The most important decision for drought definition is the choice of the threshold level. Basically, a threshold can be constant or varying over the year, depending on how one wants to define the 'abnormal’ situation. If particular seasons are treated separately, a different constant value can be chosen for instance to study summer and winter droughts.
(Figure 3.2a). If the 'normal' situation is considered to be a typical annual regime, the threshold should be varying at a monthly or daily resolution (Figure 3.2b/c). Such a varying threshold determines relative streamflow deficits during both, the high and low flow seasons. However, flow which is less than usual during a particular season but not absolutely low is commonly not considered a drought. Hence, events defined with the varying threshold level should be called streamflow deficiency or streamflow anomaly rather than streamflow drought.

A general decision to make is how to derive the actual threshold level value. This value can be a certain streamflow, e.g. necessary to fill a reservoir or to guarantee an ecological habitat in the river, or a certain water level required for navigation.

The varying threshold level method determines periods below an annual threshold cycle, which consists of a specified exceedance probability, p, of daily flow duration curves. Since daily discharge values are used in the study, the varying threshold should also have a daily resolution. Normally, fdcs are based on calendar units (year, month, day) (Figure 3.5a). For a short time period like Period 1 (1962-90), a daily fdc would be constructed of 29 values only. To increase the sample size, a daily flow duration curve was obtained from a moving window sample also including the streamflow values of the preceding and following days (Figure 3.5b). This procedure allows the construction of a smooth fdc for each day of the year.

Under Indian conditions, a commonly used index for drought analysis is to compare the runoff depth or volume for given duration i.e. month or a year with an along term mean or standard period normal value for the given duration. It is considered that if during any year the runoff is found to be less than 75% of the normal runoff, the year would be considered as drought year and if it occurs in 25% or more than 25% of years, the area would be considered to be drought prone. (CWC, 1982).

Based on this definition, available stream flow data on yearly basis was considered for various stations and analysis was performed. The following table summarises the information of selected gauging stations on sub basin name, data available period, no. of drought years and classification of station for hydrological drought based on the above definition.
Flow Duration curve for every day. The varying threshold level approach applied to the a) daily flow duration curves from a 21-day moving window b) the resulting annual exceedance cycles.

Comparison of annual flows with average and 75% of average flows for Vijayawada is shown in Fig 4.

Low flow analysis:

Another parameter for consideration of hydrological drought analysis is low flow index. 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 flow duration curves are used to define low flow index (LFI) as the 10 days average flow which is exceeded by 95% of the time of duration of the series. Flow duration curves for various periods for chosen sites using the available data were constructed.

Daily flow frequency distribution of moving average (7 day basis) values observed at Arjunwad station (Sub Basin K1) is shown in the following Fig 5.

Similarly, the information was generated for moving day on 10 day, 15 day, 30 days basis for stations which have got more 20 years of data. Further, frequency distribution curves were generated utilizing on daily discharges and on moving day average basis for 7 day, 10 day, 15 day, 30 days also. This info is useful for understanding the low flows that were experienced during the past years.
Table 1: Categorisation of selected gauge stations for hydrological drought analysis based on CWC criteria

<table>
<thead>
<tr>
<th>Sub basin name</th>
<th>Station name</th>
<th>Drought/Non drought</th>
<th>No. of drought years</th>
<th>No. of years of data availability</th>
<th>Start and end of data available years</th>
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<td>39</td>
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</tr>
<tr>
<td>K5</td>
<td>Sarathi</td>
<td>Drought</td>
<td>13</td>
<td>39</td>
<td>1965 2003:</td>
</tr>
<tr>
<td>K5</td>
<td>Wadakbal</td>
<td>Drought</td>
<td>18</td>
<td>39</td>
<td>1965 2003:</td>
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<td>K7</td>
<td>Vijayawada</td>
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<td>39</td>
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<td>K7</td>
<td>Wadepally</td>
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</table>
Hydrological drought analysis (Deficit, duration and intensity analysis)

In order to understand the hydrological drought in terms of duration, deficiency of flow and intensity, one needs to assess the observed flow against the flows at different probability levels. Considering that the monsoon is limited to South West monsoon to a larger extent, deficiency or duration of deficit flow with reference to average flow value of a season annual basis for a particular season may lead to erroneous conclusions. In order to overcome this difficulty, flow duration curves for each day of year were constructed considering flows on a particular day for each station. Stations with more than 20 years of data were only considered for this analysis.

A sample output of variable discharge for each day at different probabilities is given below (Fig 6).

In order to estimate the drought duration and deficit volume, difference between observed discharge and probable flows was estimated on a daily basis. Maximum duration (continuous days) of negative flows i.e (negative difference between actual flow and probable flow at different probabilities) was cumulated and maximum duration and deficit volume was estimated in every year. Observed flow against probable flows for different probabilities is shown in the following Fig 7.
In order to estimate the drought duration and deficit volume, difference between observed discharge and flows at different probabilities was estimated on daily basis. Maximum duration (continuous days) of deficit flows i.e (negative difference between actual flow and probable flow at different probabilities) was accumulated thus estimating maximum duration and corresponding deficit volume for every year. Observed flow against probable flows for different probabilities is shown in the following Fig 7.

Estimated maximum duration of drought spell and it’s deficit volume in every year at different probabilities shown in the following Table. Hydrological drought can be based on maximum duration or maximum deficit. In this exercise, drought intensity analysis was carried out based on (a) maximum duration and corresponding deficit volume and (b) maximum deficit volume and corresponding duration. Accordingly, drought intensity was estimates were compared for both maximum deficit and maximum duration basis on yearly basis for each of the stations. An example of drought intensity estimations is given in following Table 2 for drought intensity analysis based on discharge, Table 3 for drought intensity analysis based on duration and Table 4 for drought intensity comparison based on maximum duration and discharge for station Arjunwad.

Analysis of hydrological drought intensity for identified stations (Fig 8) based on stream flow indicate that the intensity is higher at Vijayawada, Wadepally, Bavapuram and Narsinghpur stations located in K-7, K-7, K-8 and K-5 sub basins respectively. In case of Vijayawada and Wadepally gauging stations, the hydrological drought intensity is consistently higher from 1990 onwards and is comparable with severity of intensities experienced during 1985-86 and 1986-87.
Table 2 Maximum duration of drought spell and its deficit volume in every year at different probabilities based on discharge at Arjunwad

<table>
<thead>
<tr>
<th>Year</th>
<th>10%</th>
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<th>75%</th>
<th>90%</th>
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Table 3: Maximum duration of drought spell and its deficit volume in every year at different probabilities based on duration at Arjunwad.
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</table>

**Fig 19 Hydrological drought Intensity analysis -Time series data**

![Graph showing hydrological drought intensity analysis](image)

**Summary**

A procedure for estimation of hydrological drought at sub basin level is presented. An application of the same for selected sub basins in Krishna basin were discussed.