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A REVIEW OF FUNDAMENTAL DROUGHT CONCEPTS, IMPACTS AND ANALYSES OF INDICES IN ASIAN CONTINENT

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Abstract: Drought characterization is essential for drought risk and sustainable water resources management. Therefore, it is important to have a timely review of fundamental concepts of droughts, classification, types of drought indices and historical droughts. The impact of drought has increased on water availability at different scales all over the world. It is also important to correlate trends of drought as influenced by the climate variability of the present times. Drought frequency, duration and intensity in the major river basins have been increasing. The influencing hydro-meteorological parameters and their interaction are necessary in developing measures for mitigating impacts of droughts. The existing indices for each category of meteorological, hydrological, agricultural are reviewed and the current state of development is described in this study. Out of this review, this article draws conclusions where gaps for more focused research to be conducted in future.

Keywords: Submission; paper sample; JUEE; instruction

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INTRODUCTION

Droughts are common throughout the globe with a devastating damage potential on agriculture, economy, and society. It is estimated that 4 billion people – one half of the world's population will live under conditions of severe water crisis by year 2025, with conditions particularly severe in Africa, Middle east and South Asia (Diwan, 2002). In monetary values, causing an average of $6–$8 billion in global annually. In a span of a century from 1900 to 2004, more than ten million people have died (Wilhite 2000; Below *et al.*, 2007). California in 2015, was in its fourth year of drought, staggering through its worst dry spell in twelve hundred years; farmers have sold their herds, and some have abandoned crops. According to the UK-based organization Wateraid, water shortages are responsible for more deaths in Nigeria. There are places in India where hospitals have trouble finding the water required to sterilize surgical tools (Michael, 2015). North Korea has been hit by what it describes as its worst drought in a century, while in Pakistan, a heat wave has killed more than 1,000 people in Karachi (Naveen, 2015).

India's current heatwave – which has claimed as many as 2,500 lives – is the second deadliest that the country has experienced and the fifth deadliest in its history. Last year, poor monsoon rains led to drought in parts of India. Over 65 per cent of agricultural production in India is dependent on rainfall, so another drought year will pose significant risks to monsoon-dependent crops.

In Thailand, the monsoon season has begun but 22 out of 76 provinces are still contending with drought conditions, affecting around 7.45 million hectares of rice farm land. The weather bureau in Manila said 23 provinces continue to experience extreme heat or drought while 31 others are hit by a dry spell, in 2015. The Japan Meteorological Agency said that there will be lower rains in the year of 2015 in Southeast Asia and India (Naveen, 2015). For Malaysia, it tends to experience dry weather early in the year. A series of drought conditions have repeatedly occurred and becoming more frequent in recent years. The condition may have triggered by environmental event such as El Nino event in 1997–1998 and 2014 time period when longer drought duration is experienced especially in the urban area of the south-western region (Wahida *et al.*, 2014).

Drought situation in Malaysia often forced the authorities to ration the water supply to residential and business areas for several months, resulting in disruption of daily activities. The frequency of drought occurrences has increased in recent years, this may imply clues of possible changes in global rainfall pattern (Ahmad & Low, 2003; Ahmad & Hashim, 2010).

Drought differs from other natural hazards in several ways. Many consider it as a "creeping phenomenon," making its onset and end difficult to determine. The effects of drought build up slowly over a significant period of time, and its effect may remain for years after the termination of the event. At the same time, due to the multi-discipline character of this natural hazard, a single, unique definition of a drought does not exist, but is subject to the domain of interest of the observer (Wilhite &Glantz, 1985; Maracchi, 2000; Tate & Gustard, 2000). Drought indices essentially face the same problem. As there is no single and uniquely accepted definition of a drought, there is no single and universal drought index, either. The absence of a precise and universally accepted definition of drought adds to the uncertainty about whether or not drought exists and, if it does, its severity. Drought impacts and damages are less observable and spread over a large geographical area than are damages that result from other natural hazards. Since drought seldom results in structural damage, it is more difficult to prepare for relief, unlike other forms of natural disasters (Wilhite, 1993). Globally, drought has become more frequent and severe due to climate variability with different regions experiencing droughts at varying scales and times. Consequently, global impacts of drought on environmental, agricultural and socio-economic aspects need to be studied.

At present, most of major river basins in Malaysia have limited or lack of adequate quantifiable information of drought occurrence, frequency and severity. In addition, there is lack of sufficient and appropriate drought assessment and forecasting methods. To prepare for effective mitigation of drought risks in Malaysia, evaluation of drought conditions is vital. Thus, this research primarily reviews drought assessment methods and provides the fundamental concepts based on which drought indices have been developed. The main objective of this study is to review available information and literature and conduct a detailed search to build a continental, regional and country level perspective.

FUNDAMENTAL DROUGHT CONCEPTS

Definition & types

Drought is an insidious natural hazard which was defined by Steila (1972) as "A period of deficient rainfall that is seriously injurious to vegetation" and hydrological drought defined by Linsely *et al.* (1975) as "a period during which stream flows are inadequate to supply established uses under a given water management system". Agricultural drought could be defined as a period of dryness caused by rainfall shortfall during crop growth that caused a great reduction of its yield. As we can see from the definitions of drought there are different types of droughts, like the meteorological, the hydrological, and the agricultural and socio-economic drought.

Meteorological drought is usually defined by the measure of the departure of precipitation from the normal and the duration of the dry period. Some definitions identify drought based on the number of days an area goes with precipitation that is lower than a specified level. Famine, on the other hand, is caused by a decline in availability of and/or access to food often caused by one of the three kinds of drought. Where there is insufficient water to produce a staple crop, for example, or where there is insufficient fertilizer to produce the standard yield for a crop, drought may lead to and certainly cause famine. Yet, it is not necessarily the drought that causes a famine. The propagation of hydrological and agricultural drought originates from meteorological droughts which develop from changing phenomena within the hydrological cycle (**Fig. 1**). To measure the metrological drought there are different indices that define the type, for example, standardization precipitation index (SPI), Normal precipitation index (PI) and Decile index. The hydrological drought refers to deficiencies in surface and subsurface water supplies. It is measured as stream flow and as lake, reservoir and groundwater levels. Since there is a lag time between rainfall and the collection of water in streams, lakes and reservoirs, hydrological measurements cannot be used as the most basic indicator of drought. Low flow analysis is considered as a way of hydrological drought indication. Truncation level method can add a clearer picture about this type of drought, since it determines the starting and ending date of drought as well as magnitude and severity.

On the other hand, high temperatures lead to changes in wind characteristics, low relative humidity, cloud cover and increased evapotranspiration. Agricultural droughts impact negatively on farming systems whenever they occur. Their impacts are normally twofold; environmental and economic impacts. The agricultural drought is a type associated with low agricultural production, decline in output from agro-processing industries and unemployment incidents in the agricultural sector. Apart from these, socioeconomic drought is also defined as 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. Varied definitions, depending upon the influential factor used, of droughts are seen in the literature which can be grouped as: (i) Precipitation based, (ii) Evapotranspiration based, (iii) Streamflow based, (iv) Soil moisture based, and (v) Vegetation based drought definitions.

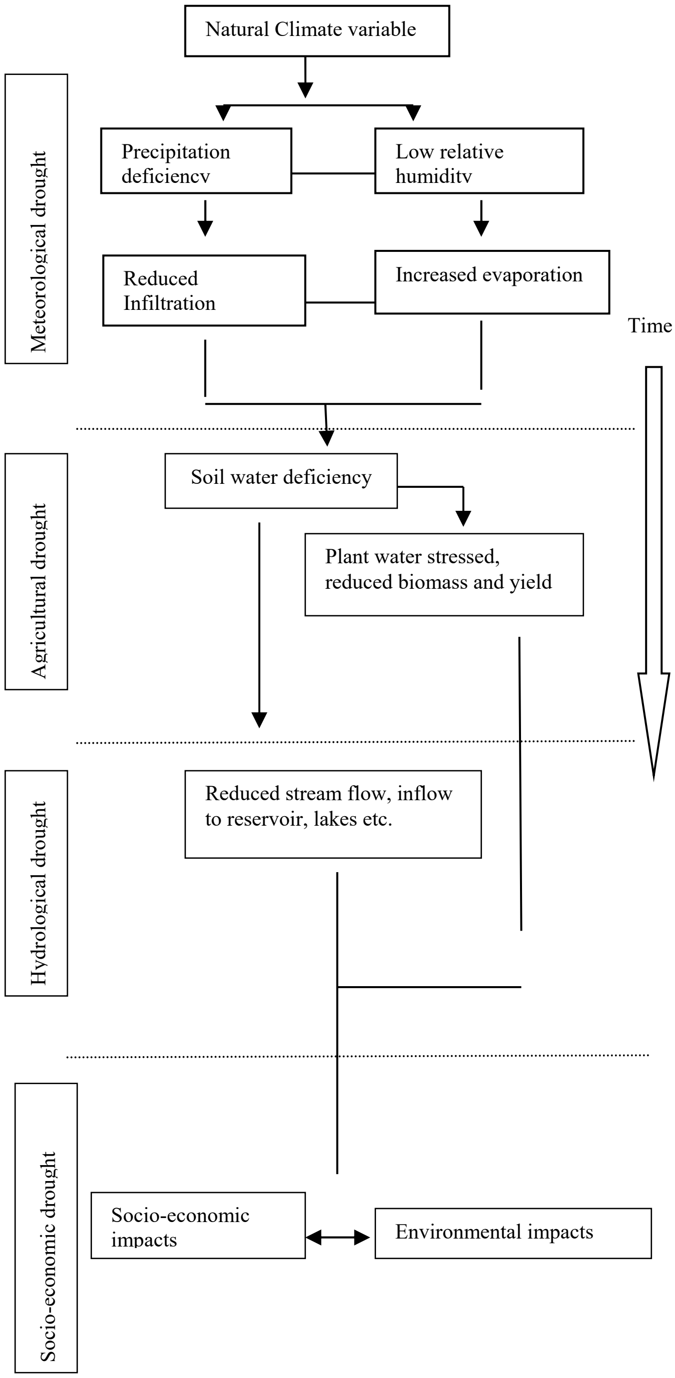

Fig. 1: Sequence for the occurrence of drought types (Modified from: http:\\www.nrl.unl.edu, Hayes, 2006).

Characteristics of drought

Hoyt (1983) defined the drought in humid and semi-humid areas with an annual precipitation deficiency of 15 percent. Blumenstock (1942) defined the drought as a period in which the precipitation is less than some small amount such as 0.1 inch (25.4mm) in 48 hours. Ramdas & Malik (1948) suggested a week of drought as a period in which the actual rainfall is equal to half the normal rainfall or less. Condra (1944) defined the drought as a period of strong wind, low precipitation, high temperature and unusually low relative humidity. Ramdas (1960) defined the drought when the actual seasonal rainfall is less by more than twice the mean deviation. Palmer (1965) defined the drought as a situation when the actual rainfall is less than the rainfall which is climatically appropriate for the existing conditions. Herbest *et al.* (1966) defined the absolute drought as the period of at least 15 consecutive days without 0.01 inch (0.254mm) 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 (0.254mm) per day. Yevjevich (1967) discussed the droughts as the deficiency of rainfall about the mean (truncation level). Gadgil & Yadamani (1987) defined the drought with a period having less than 10% probability of occurrence of rainfall.

As seen above, the period of drought and deficiency level by which the assessment is made vary from researcher to researcher and on geographical location. The literature here does not lead one to a definite understanding as to how exactly a meteorological drought can be assessed, both in duration as well in its level. Also, small periods such as hours, days and weeks may be insignificant and irrelevant in the context of drought whose influence is felt over a longer period. Many studies show that the temporal distribution of rainfall is more important than the total rainfall in a season or even over a month. Thiruvengadachari (1988) confirmed that the rainfall use efficiency varies both over time and space thus limiting the use of rainfall as a sole drought indicator. Evapotranspiration has been considered in a limited way for defining drought as compared to the precipitation. Thronthwaite (1948) has used this factor and defined drought as a condition in which the amount of water needed for transpiration and direct evaporation exceeds the available soil moisture. Potential evaporation 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.

Droughts are fundamentally characterized in three dimensions: severity, duration, and spatial distribution. Additional characteristics include: frequency, magnitude (cumulated deficit), predictability, rate of onset, and timing. Unfortunately, usage of the terms severity, intensity, and magnitude is not universal, and sometimes their meanings are switched. For example, Yevjevich (1967) uses the vocabulary of run-sum, run-length, and run intensity for the associated terms of severity, duration, and magnitude used by Dracup *et al.* (1980). Here, we use the widely adopted terminology of

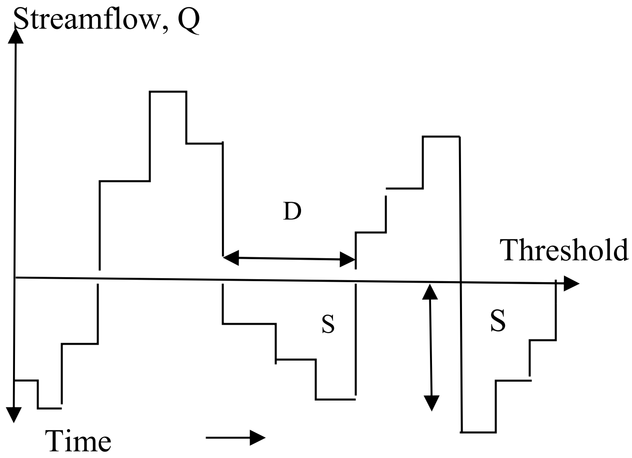

Fig. 2 Basic drought characteristics.

Salas (1993): Duration- depending on the region, drought's duration can vary between a week up to a few years. Because of drought's dynamic nature, a region can experience wet and dry spells simultaneously when considering various timescales. As such, in shorter durations the region experiences dryness or wetness, while in longer-term, it experiences the opposite (NCDC, 2010). Magnitude- the accumulated deficit of water (e.g., precipitation, soil moisture, or runoff) below some threshold during a drought period (**Fig. 2**). Intensity- the ratio of drought magnitude to its duration. Severity- two usages are provided for drought severity: the degree of the precipitation deficit (i.e., magnitude), or the degree of impacts resultant from the deficit (Wilhite, 2004). Geographical extent- the areal coverage of the drought which is variable during the event. Frequency (return period)- the frequency or return period of a drought is defined as the average time between drought events that have a severity that is equal to or greater than a threshold.

HISTORICAL DROUGHTS AND IMPACTS IN ASIA

The impacts of drought are diverse and often ripple through the economy. Thus, impacts are often referred to as either direct or indirect. A loss of yield resulting from drought is a direct or first-order impact of drought. However, the consequences of that impact (for example, loss of income, farm foreclosures, and government relief programs) are secondary or even tertiary impacts. A recent global review on droughts and aridity by Dai (2011) indicated that large-scale droughts have frequently occurred during the past 1000 years.

The article reported a few of these severe and multiyear droughts in North America, China and Africa, but did not provide the detailed review of the historic droughts across the world. Mishra & Singh (2010) conducted a comprehensive review on drought concepts and a critical evaluation of the most widely used indicators for drought assessment which only briefly mentions few of them with their main impacts. The review remains limited in terms of description of the historic droughts especially on Asian content. Asia is a drought-hit area. A severe drought hit much of South-West Asia between 1999 and 2003, including Afghanistan, Kyrgyzstan, Islamic Republic of Iran, Iraq, Pakistan, Tajikistan, Turkmenistan, Uzbekistan and parts of Kazakhstan (Waple & Lawrimore, 2003; Levinson & Waple, 2004).

The persistent multi-year drought in Central and South-West Asia has affected close to 60 million people. Agriculture, animal husbandry, water resources, and public health have been particularly stressed throughout the region. Preliminary analysis suggests that the drought is related to large-scale variations in the climate across the Indian and Pacific Oceans, including the "La Niña" in the Eastern Pacific. In 2006, a severe drought in a region of Southern China has left 520,000 people short of drinking water and damaged crops. The drought affected areas throughout the poor, mountainous Guangxi region on China's southern coast. Nearly 102,000 hectares (254,000 acres) of crops were damaged, causing losses of more than 400 million RMB Yuan (US$50 million). China's South-Western city of Chongqing, located along the upper reaches of the Yangtze River, suffered from its worst drought in half a century.

In the 75 days from June 1 to August 14 of 2006, Chongqing and neighboring Sichuan province measured an average rainfall of no more than 287.1 millimeters, about 103 millimeters less than the median rate. And in the 35 days from July 10 to August 13, there were 25 days when the city's temperature climbed above 40 degrees Celsius—about 13 days more than normal, setting another record in modern history. The 2006 drought caused Chongqing financial losses of nearly 8.04 billion RMB Yuan (US$1.04 billion). Nearly 8 million local residents had difficulty accessing drinkable water, and some 2.07 million hectares of farmland have been affected. Droughts in areas across China that summer left 18 million people short of drinking water. Chongqing drought raised climate change worries, some experts believe the unusual drought in Chongqing and Sichuan in the summer of 2006 was just one of the many footnotes to indicate an increase in abnormal climatic occurrences related to global warming. The available estimates on drought impacts suggest that, during the period 1900–2015, there were 662 drought events reported across the world resulting in a huge toll to humanity, killing about 12 million people and affecting over 2 billion (EM-DAT, 2015). The total economic damages are estimated at USD135.5 billion (**Table 1**). From the same data source it was found out

Table 1. Overview of number of droughts and their impacts across the world during 1900-2015

Continent	N. of events	Total deaths	Total affected	Damage (× 10^3 USD)
Africa	297	867,143	37,1035,501	2,984,593
America	142	77	104,090,026	57,771,139
Asia	159	9,663,389	1,744,562,029	37,956,865
Europe	42	1,200,002	15,488,769	25,481,309
Oceania	22	660	8,034,019	11,526,000
Total	662	11,731 ,271	2,243,210,344	135,719,906

Source: EM-DAT: the International Disaster Database. Centre for Research on the Epidemiology of Disasters-CRED; http://www.emdat.be/database

Table 2. Top ten droughts worldwide (1900-2015)

Country	Date	Total affected
India	00-07-2002	300,000,000
India	00-05-1987	300,000,000
India	00--1972	200,000,000
India	00--1965	100,000,000
India	00-06-1982	100,000,000
China P Rep	00-01-1994	82,000,000
China P Rep	00-04-2002	60,000,000
China P Rep	00-10-2009	60,000,000
India	00-04-2000	50,000,000
China P Rep	00-06-1988	49,000,000

Source: EM-DAT: the International Disaster Database. Centre for Research on the Epidemiology of Disasters-CRED; http://www.emdat.be/database

that based on total affected people, all the top ten droughts took place in the Asian continent (**Table 2**). Drought remains a major disaster causing huge damages to humanity, the environment and the economy, despite making considerable progress on monitoring, forecasting and mitigation of droughts across the world. The lack of desired level of success could be attributed to many reasons.

Impacts by regions in ASIA

South-East Asia

Drought conditions currently exist in many parts of South-East Asia, particularly in Indochina (Myanmar, Cambodia, Lao People's Democratic Republic, Thailand and Viet Nam). The drought has stressed rice, coffee, sugar and other crops in the region, and sharply lowered the supply of water for drinking and irrigation. In 2004 the wet season ended about a month ahead of schedule, and drought conditions quickly developed across an area that stretched from Central China to Southern Thailand to Luzon, Philippines. The Thai government announced that 70 of its 76 provinces had been hit by drought that year, affecting more than 9 million farmers and almost a million hectares of paddy fields. The 2004/05 rice crop was estimated at 17.0 million tons, down 1.0 million from 2003 (USDA, March estimate), and trade sources expected the sugar crop to drop by about 30 per cent in 2004/05.

North-East Asia

Drought often occurs in North-East Asia. Chinese agriculture sources estimated that the national heat crop to dropped nearly eight per cent, to 105 million tons from 113 million tons, in large part due to the drought in 2000. Prolonged drought persisted in China's northern plains, with wheat one of the crops worst affected. In the northern province of Shaanxi of China, the drought affected some 667,000 hectares, 40 per cent of the province's farmland. The mighty Yellow River, tapped by factories and Farmers along its 3,000-mile (5,000 km) course, is reduced to an intermittent stream by the time it reaches its mouth in Shandong Province. In Beijing, the water table and key reservoirs are at their lowest levels since the early 1980s. Water resources per capita are 300 cubic meters just 3.3 per cent of the world average in the capital city. Reduced plantings and a serious drought have led to a sharp reduction in wheat production. The drought has led to much more frequent sand and dust storms in Northern China. In 2000 and 2001, Beijing was struck by about 15 sandstorms which primarily originated from the arid and semi-arid deserts in the North-West. Severe drought spread from the mainland's north and threatened the southern provinces.

South Asia

From early 2000 onwards, severe drought affected vast areas of South Asia, including Western India, Southern and Central Pakistan. In India, a large numbers of people were affected by the drought. Some 7,500 villages spread over 145 blocks in 15 districts were severely affected during year 2000. In Pakistan, government officials estimate that nearly 3 million people - mostly villagers faced starvation in 2000. More than 100 people died as a result of the drought, most because of dehydration.

South-West and Central Asia

This sub region represented the largest region of persistent drought from 1999 to 2001 in the world. A persistent multi-year drought in Central and South-West Asia has affected close to 60 million people as of November 2001. In Afghanistan, the worst drought in 30 years spread across the broken country and almost half of its 20 million people were affected. Chronic political instability in many parts of this region and the recent military action in Afghanistan have further complicated the situation. Most parts of the Islamic Republic of Iran recently experienced an exceptional drought that lasted more than 2 years (1998–2000). In some areas, drought has also extended into winter 2001. The 1998-2000 droughts inflicted $3.5 billion in damages, killing 800,000 head of livestock and drying up major reservoirs and internal lakes (Pagano *et al.*, 2001).

Climatic extremes over ASIA

Severe weather events are called extremes. Examples are cyclones, tornadoes, dust storms, sandstorms, blizzards, thunderstorms, droughts, heat waves and cold waves. Climate variability is the change in patterns of climate elements such as rainfall and temperature distributions and magnitudes. The number of natural catastrophes in Asia has risen from under 100 in 1980 to over 300 in 2010. The largest growth is in hydrological events e.g. flooding and mass movement. Between 1980 and 2010 Asia experienced 4,950 weather related catastrophes, more than any other continent over the same period (Catherine et el, 2012). Between 1980 and 2010 Asia has suffered 51% of the world's reported fatalities from natural catastrophes (1.16 million people). **Figure 3** below shows the average monthly temperature and rainfall for Asia from last century.

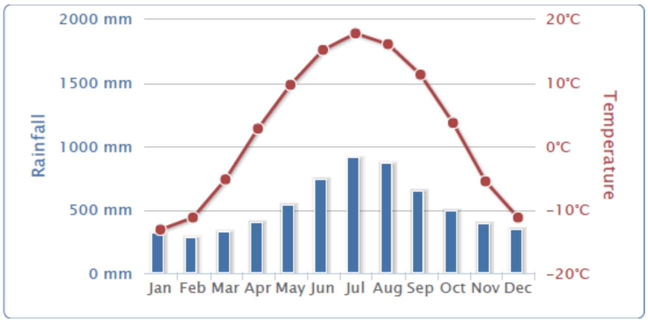

Fig. 3 Average monthly temperature & rainfall for Asia (1900-2012). Source: Climate Change Knowledge portal, The World Bank Group- sdwebx.worldbank.org/climateportal

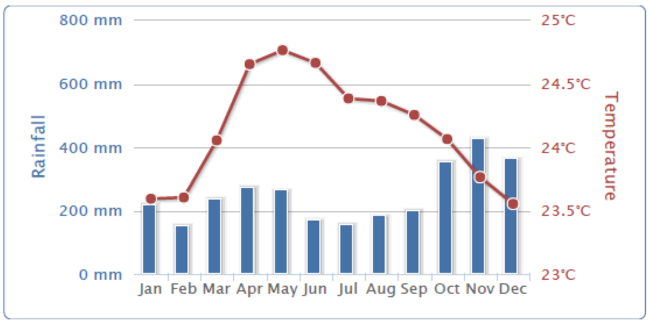

Fig. 4 Average monthly temperature & rainfall for Malaysia (1900-2012). Source: Climate Change Knowledge portal-http\\sdwebx.worldbank.org/climateportal

In a year, maximum monthly rainfall amounts just below 1000mm and temperature at 180C. For Malaysia, a tropical country, it was observed as maximum monthly rainfall amounts just above 400mm and temperature at 250C (**Fig. 4**). The Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) pointed out that the global surface temperature increase reaches 0.85°C (0.65°C −1.06°C) (based on existing 3 independent data sets) from 1880 to 2012. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.780 C [0.72 to 0.850 C], based on the single longest data set available (IPCC, 2013).

Recent three ten years are the warmest than that of any other ten years since 1850.all over the world almost experienced heating process. Water cycle factors will be redistributed in time and space caused by global climate change, extreme weather events will become more frequent, more intense, wider range induced by climate change with global warming characterized. (IPCC Fifth Assessment Report: Climate Change 2014). **Table 3** below shows the observed changes in precipitation & temperature extremes since the 1950s over Asian continent. It also provides scientific information on what can be expected from changes in weather and climate extremes in various regions and sub-regions of Asia.

DROUGHT ASSESSMENTS & FORECASTING USING DROUGHT INDICES

There are several methods that have been used in the past as drought assessment tools such as measurement of lack of rainfall, shortage of stream flow, Drought Indices (DIs) among others. However, traditionally the estimation of future dry conditions (or drought forecasting) has been conducted using DIs as the most common drought assessment tools. This is because the DI is expressed by a number which is believed to be far more functional than raw data during decision making (Hayes, 2003). Drought indices are essential tools for the characterization and the monitoring of drought, since they simplify the complex climatic functions and can quantify climatic anomalies as for their severity, duration and frequency. They are also very useful as they can communicate to the wider audience easily comprehensible information regarding the severity of drought episodes (Tsakiris *et al.*, 2007). The DI in general is a function of several hydro-meteorological variables such as rainfall, temperature, and stream flow and storage reservoir volume. In defining DIs, some researchers and professionals argue that drought is just deficiency in rainfall and can be defined with the rainfall as the single variable. Based on this concept, majority of the available DIs including Percent of Normal (PN) (Hayes, 2003), Deciles (Gibbs & Maher, 1967) and many others were developed with rainfall as the only variable. This rainfall based Dis are widely

Table 3. Observed Changes in precipitation & temperature extremes since the 1950s over ASIA (Modified from Catherine C., 2012)

Region and Sub-region	Trends in maximum temperature (warm and cold days)	Trends in minimum temperature (warm and cold nights)	Trends in heavy precipitation (rain, snow)	Trends in dryness and drought
North Asia	Likely increase in warm days (decrease cold days	Likely increase in warm nights (decrease cold nights)	Increase in some regions, but spatial variation	Spatially varying trends
Central Asia	Likely increase in warm days (decrease cold days	Likely increase in warm nights (decrease cold nights)	Spatially varying	Spatially varying
East Asia	Likely increase in warm days (decrease cold days)	Increase in warm nights (decrease cold nights)	Spatially varying	Tendency for increased dryness
South east Asia	Likely increase in warm days (decrease cold Days. Insufficient evidence for Malay Archipelago	Likely increase in warm nights (decrease cold nights). Insufficient evidence for Malay Archipelago	Spatially varying trends, partial lack of evidence	Spatially varying trends
South Asia	Increase in warm days (decrease warm days	Increase in warm nights (decrease in cold nights)	Mixed signal in India	Inconsistent signal for different studies and indices
West Asia	Very likely increase in warm days (decrease in cold days more likely than not)	Likely increase in warm nights (decrease in cold nights)	Decrease in heavy precipitation events	Lack of studies, mixed results

used than other DIs due to their less input data requirements, flexibility and simplicity of calculations (Smakhtin and Hughes, 2004). However, other drought researchers and professionals believe that rainfall based DIs do not encompasses drought conditions of all categories of droughts, since they can be used only for defining meteorological droughts (Keyantash & Dracup, 2004; Smakhtin & Hughes, 2004). Smakhtin & Hughes (2004) also stated that the definition of droughts should consider significant components of the water cycle (such as rainfall, stream flow and storage reservoir volume), because the drought depends on numerous factors, such as water supplies and demands, hydrological and political boundaries, and antecedent conditions (Steinemann, 2003).

It should also be noted that most of the DIs that had been developed were regionally based and some DIs are better suited than others for specific uses (Redmond, 2002; Hayes, 2003; Mishra & Singh, 2010). Therefore, a review of the existing DIs is necessary before adapting any of the existing DIs, for use in areas/catchments outside those areas for which they were originally developed. These DIs were used to trigger drought relief programs and to quantify deficits in water resources to assess the drought severity. By identifying the patterns of drought incidence it is possible to highlight the challenging nature of drought management in the country and the needs for well-coordinated water resources planning and drought preparedness, as well as effective and efficient emergency responses during drought events.

Meteorological drought assessment

Meteorological drought, in general, implies the deficiency of rainfall of such magnitude which would seriously affect the normal living of the society. However, many definitions are available based on different truncation levels and base periods to delineate the rainfall deficiency and drought periods. The development and implementation of a drought index heavily depends on data availability (Steinemann *et al.* 2005). Earlier drought indices used meteorological data readily available from synoptic meteorological stations (Niemeyer, 2008). **Table 4** shows notable meteorological droughts indices.

Hydrological drought assessment

Hydrological drought is understood with respect to low streamflows or water availability. Hydrological drought indices were based largely on streamflow, as this variable summarizes and is the by-product of essentially every hydro-meteorological process taking place in watersheds and river basins (Heim, 2002). Vast literature is available for the stochastic characterisation

Table 4. Notable Meteorological drought indices

Drought Index (DI)	Reference	Input Type	Special Notes
SPI	(McKee *et al.* 1993)	Rainfall	Uses only precipitation, loosely connected to ground conditions. As SPI is adaptable for the analysis of drought at variable time scales; it can be used for monitoring agricultural and hydrological
PDSI	(Palmer 1965)	Rainfall, temperature	More comprehensive than precipitation only indices; evapotranspiration and soil moisture are also considered
Keetch-Byram Drought Index (KBDI)	Keetch & Byram (1968)	Rainfall, temperature	Analyzes P and SM in the water budget model; used by fire control managers to monitor forest fires
Effective Drought Index (EDI) Byun and Wilhite (1999)	Byun & Wilhite (1999)	Rainfall	Developed in response to weaknesses in then-available drought indices, weaknesses include imprecision in the drought beginning, ending and accumulated stress
Rainfall Anomaly Index (RAI)	Rooy (1965)	Rainfall	r compared to arbitrary value of +3 and -3, which is assigned to the mean of ten extreme + and - anomalies of r.
Bhalme and Mooly Drought Index (BMDI;	Bhalme & Mooley 1980)	Rainfall	Percent departure of r from the long term mean.
Rainfall Deciles (RD)	Gibbs & Maher 1967	Rainfall/ Rainfall	Provides a statistical measure of precipitation; performed well in limited tests Requires long-term precipitation data; no consideration of evaporation
Reconnaissance Drought Index (RDI)	Tsakiris *et al.* (2007)	Rainfall Evapotranspiration	Essentially, it relates precipitation to the potential evapotranspiration at a location, and can be considered as an extension of the SPI. By standardization and normalization it receives the same drought severity classes as the SPI.

Table 5. Notable Hydrological drought indices

Drought Index (DI)	Refe-rence	Input Type	Special Notes
Palmer Hydrological Drought Index (PHDI)	McKee *et al.* 1993)	Rainfall Streamflow Temperature	Computed using the same Palmer model as for the PDSI, but with a more stringent criterion for the termination of the drought or wet spell
Surface Water Supply Index (SWSI)	Shafer & Dezman (1982)	Rainfall, Snowpack streamflow	Developed in response to PDSI's limitations for mountain snow hydrology; calculates the weighted average of the standardized anomalies for P, ReS, SP, and runoff, the four primary features in the surface water budget; used for river basins in western USA
Regional Streamflow Deficiency Index (RDI)	Stahl (2001)	Streamflow	To detect regional drought events from timeseries of measured discharge data. And only if a substantial number of stations show a similar pattern of low flows, a regional drought event is detected
Reclama-tion Drought Index (RDI))	Weghorst (1996)	Rainfall, Streamflow Temperature	Similar to SWSI, however incorporates temperature-variable demand and duration into the index; calculated basin-wise.
Total water deficit (S)	Dracup *et al.* (1980)	Rainfall/ Stremflow	Simple calculation. No sub-basin information, no standard drought classification

Table 6. Notable Agricultural drought indices

Drought Index (DI)	Reference	Input Type	Special Notes
Crop Moisture Index (CMI)	Palmer (1968)	Rainfall Temperature	Analyzes precipitation and temperature in a water balance model
Crop Specific Drought Index (CSDI)	Meyer *et al.* (1993)	Precipitation, Temperature Evapotranspiration	Requires soil and crop phenology information in addition to climatological data; estimates soil water availability for different zones and soil layers by daily intervals.
Soil Moisture Index (SMI)	Hunt *et al.* (2009)	Evapotranspiration Soil Water	This method is based on the assumption that evapotranspiration becomes limited below the midpoint between field capacity and wilting point, or at 50% of total available water. No reduction in ET occurs until soil water falls below 50% of field capacity
Crop Drought Index (CDI)	Allen *et al.* (1998).	Evapotranspiration	It indicates the reduction of evapotranspiration in relation to potential evapotranspiration due to soil water deficit
Crop Water Stress Index (CWSI)	Idso *et al.* (1981); Jackson *et al.* (1981)	PET	Applied for irrigation scheduling
Soil Moisture Drought Index (SMDI;	Hollinger *et al.*, 1993	Soil Moisture	Summation of daily sm for a year.

of droughts using streamflow data; Gumbel (1959), Chow (1964), Huff (1964), Yevjevich (1967), Milan & Yevjevich (1970), Dyer (1977), Rodda *et al.* (1978), Whipple (1996), Zekai Sen (1980) and Chang (1990). Chow (1964) suggested that analysis of low streamflow is a suitable way of quantifying droughts. He found that during the periods of deficient precipitation, the deviation from normal conditions is greater for streamflow than for rainfall. He also suggested that low flow data must be specified in terms of magnitude of flow. This group of indices aims at providing a comprehensive characterization of delayed hydrologic impacts of drought. Earlier, the sophisticated PHDI (Palmer, 1965) model considered precipitation, evapotranspiration, runoff, recharge, and soil moisture.

Agricultural drought assessment

Agricultural drought occurs when soil moisture and rainfall are inadequate during the growing season to support healthy crop growth to maturity and cause extreme crop stress and wilt. Meteorological and Hydrological droughts are concerned with rainall, 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. 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 with respect to agricultural demand (Krishnan, 1979); Choudhury, 1987); Schmugge *et al.*, 1986); Wang & Choudhury, 1985). Stochastic analysis of agricultural droughts were reported by Prajapati *et al.* (1977). Approaches to characterize agricultural drought mainly evolve around monitoring soil water balance and the subsequent deficit in the event of a drought. **Tables 5–6** below shows notable hydrological and agricultural drought indices used by researchers.

DROUGHT INDICES COMMONLY USED IN ASIAN COUNTRIES AND LIMITATIONS

A few indices which are currently in use for drought monitoring in some Asian countries are briefly described in this section. The three indices commonly used in China are the Standardized Precipitation Index (SPI, McKee *et al.* 1993), which is solely based on a precipitation record, the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano *et al.* 2010), which integrates temperature into SPI for the calculation of potential evapotranspiration, and the Palmer Drought Severity Index (PDSI, Palmer, 1965), which derives the total moisture status of a region by a two-layer soil water balance model based on precipitation and temperature for estimating moisture supply and demand. Another type of PDSI used is the self-calibrating PDSI (SC-PDSI) by Wells *et al.* (2004), which adopts the dynamically calculated weighting factors but not the empirical constants, enabling more credible comparisons of drought severity for different locations. For drought monitoring in India, rainfall departure is used for meteorological drought. In this regard, SPI, being developed and tested, could also be proved to be a good index. For monitoring and assessing agricultural drought - Aridity anomaly index is used. Besides, remote sensing applications could also be very effective in assessing drought severity, their impacts on sectors like agriculture, and related policy decisions. In Pakistan, for assessment & characterization of drought events and drought affected areas PMD (Pakistan Meteorological Department) has been using Percent Normal Method, Aridity Index and Standardized Precipitation Index (SPI). In Bangladesh and Nepal no standard method was used earlier. Recently SPI is being tried in these countries. In Malaysia, SPI, agricultural rainfall index (ARI), SWSI and KBDI are being used for monitoring drought, assessing its severity and taking relevant policy decisions (Polpanich, 2010). In Thailand- NDVI, SPI, PDSI being used. In Philippines- monitoring in rice production (SPI, PDSI, SMI) and for Cambodia- SMI but very less number of researches have done it. In Indonesia- SPI, vegitation condition index, thermal condition index, Vegitation health index being used. In Vietnam- SPI (for meteorological drought) and SWSI for hydrological drought (Polpanich, 2010). The indices used in Iran include deciles index (DI), percent of normal (PN), standard precipitation index (SPI), China-Z index (CZI), modified CZI (MCZI), Z-Score and effective drought index (EDI) and Soil Moisture Index (SMI) (Morid *et. al*., 2006).

To date SPI is finding more applications in Asian countries than other drought indices due to its limited data requirements, flexibility and simplicity of calculations. For PDSI drought index, the major problem associated using is its computational which is complex and require substantial input of meteorological data. Its application in Asia where observational networks are scarce is therefore limited. Another index EDI has not received much attention in Asian regions, it is, in principle, applicable to drought monitoring over large areas and it is based on daily precipitation data – these data although readily available in nature are much less readily available from the government agencies in Asian regions. In SWSI index, it is difficult to maintain a homogeneous time series, in addition, extreme event may cause a problem- if they have not recorded previously, a frequency distribution of a relevant component needs to be revisited. This may be serious limitation for use of SWSI in Asian regions which hosts a variety of climates from the monsoon dominated areas to arid zones with limited lengths of historical hydro-meteorological time series. For the Deciles DI, relatively simple to calculate, requires only precipitation data and fewer assumptions than major comprehensive indices , may be more appropriate for conditions in Asia specially south Asia, south east/west Asia.

PROBLEMS OF CURRENT COMMONLY USED DROUGHT INDICES

Most current drought indices use longer time period (i.e. monthy) as a unit than using a daily unit. The daily unit should be used because an affected drought region can return to normal condition with only a day's rainfall.

Furthermore, it is important that the drought intensity be re-evaluated frequently and be presented at any time. This would allow the general public to prepare against the risks. Drought occurs with the deficiency of fresh water resources from the climatological mean. Important is that it is not only the deficiency at a specific time, but the consecutive occurrence of a deficiency. Therefore, when water deficit period began and how long it has lasted is very important. But most of current indices only assess the deficiency of water from the climatological mean on some duration which is predefined.

After rainfall events happened, soil moisture diminishes day by day as a function of a runoff and evapotranspiration ratio. One day's diminishing of water is not small enough to simply be ignored. Therefore, because simple summation of the precipitation cannot provide good results, a time dependent reduction function is needed to estimate the current water deficiency. However, almost all current drought indices use simple summation of precipitation. Damages from drought can be categorized into two kinds of causes. One is damage from lack of soil moisture; another is from lack of reserved water. Soil dryness is influenced by a short term deficiency of precipitation, and water resources deficit in reservoirs or other sources are resulted by much longer term precipitation totals. It is not easy to imagine other drought damages which are not associated with these two categories. So, categorizing these two separately is better method to assess drought. But it is very hard to find available drought indices which divide the two stated above.

Another important aspect is drought forecasting which plays an important role in the mitigation of impacts of drought on water resources systems. Traditionally, statistical models have been used for hydrologic drought forecasting based on time series methods. Simple/multiple regression and autoregressive moving average (ARMA) models are typical models for statistical time series methods for forecasting. However, they are basically linear models assuming that data are stationary, and have a limited ability to capture non-stationarities and nonlinearities in data. Hydrologic variables of interest such as annual and monthly streamflow and precipitation have been extensively modeled by ARMA models, which have been generally accepted by practitioners during the past several decades. However, it is necessary for hydrologists and engineers to consider alternative models when nonlinearity and non-stationarity play a significant role in the forecasting.

SUMMARY AND CONCLUDING REMARKS

Water never technically disappears. When it leaves one place, it goes somewhere else, and the amount of freshwater on earth has not changed significantly for millions of years. But the number of people on the planet has grown exponentially; in just the past century, the population has tripled, and water use has grown six fold. More than that, we have polluted much of what remains readily available and climate change has made it significantly more difficult to plan for floods and droughts. Firstly, because there are going to be profound changes in the water cycle due to climate change. Feeding a planet with nine billion residents will require at least fifty per cent more water in 2050 than we use today. It is hard to see where that water will come from. Half of the planet already lives in urban areas, and that number will increase along with the pressure to supply clean water. There are ways to replace oil, gas, and coal, though we would not do that unless economic necessity demands it. But there is not tidy and synthetic invention to replace water. Conservation would help immensely, as would a more rational use of agricultural land—irrigation today consumes seventy per cent of all freshwater.

Drought characterization is essential for drought management operations. Using drought indices is a pragmatic way to assimilate large amounts of data into quantitative information that can be used in applications such as drought forecasting, declaring drought levels, contingency planning and impact assessment. With regard to the recent developments of agricultural drought indices it can be deduced that practitioners like to get hands on indices that are simple to apply and as specific as possible to their crops. This tendency will probably be influenced by the increasing establishment of drought management plans in almost all parts of the world, mainly on the basis of hydrological catchment regions. Here, specific drought indices are required in order to define indicators, thresholds, and triggers for practical management of water resources in case of drought. These indices have to describe best the local and regional conditions of the hydrological cycle, and have to comply with the already available data that are measured routinely. On the other hand, drought observatories on the continental scale will aim at applying drought indicators that produce a consistent image of the hydric state of the land surface over the entire area, and that use a consistent set of input data such as from remote sensing. Both continental and local applications do not exclude each other, but will be complementary and will provide valuable insight into the phenomenon of droughts from different perspectives. All newly developed drought indices is the issue of validation. Often, the new indices are compared to old, already established indices with good agreement, although the initial idea was to develop an index with a better performance. Furthermore, the validation exercise is mostly restricted to a few test cases in specific regions and time periods. While there is clearly a need for targeted drought indices as mentioned before, it is equally important that the boundary conditions and limitations under which a new index has been developed and tested, are explicitly described. Frequently, the criteria to evaluate the performance of the drought index, which are certainly application dependent, are omitted or marginalized. For an external user, however, it is often more important to know about these boundary conditions of a new drought index than the choice of the index itself.

When this paper is being compiled it was very interesting and striking that certain acronyms of drought indices were already occupied twice or even three-times for different indices i.e. RDI. While the confusion created by the different meanings of the same abbreviation might be still minor to the expert community, it might be an indication that the "market of drought indices" is slowly saturating, and that it will be increasingly difficult to maintain a good overview. Instead of developing more new single drought indices, the combination into more comprehensive and integrative drought monitoring and detection tools seems to be the more promising way. Most progress is made in the field of exploiting novel remote sensing information, as data of new sensors become available. Not only the derivation of drought indices from single new sensors, but also the combination of different sensors will surely remain a wide area for research in this domain. Besides precipitation, current drought indices are calculated from the data of soil moisture, inflow and outflow by waterways, evaporation and evapotranspiration etc. But most of the parameters are not observed but have to be estimated from some meteorological data. During the estimation, unreasonable simplification is inevitable because these parameters are strongly dependent on the nature of the soil and topography, which may vary widely. In addition, the important fact that the origin of water source included in these parameters is nothing but the rainfall itself, may be disregarded.

The overview of drought indices given in this paper indicates the directions in which future developments will point to. Building awareness of the importance of improved drought management today and investing in preparedness planning, mitigation, improved monitoring and early warning systems and better forecasts will pay vast dividends now and in the future all over the world.

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