

Monitoring Drought with the Combined Drought Index in Kenya

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1 INTRODUCTION

Drought is a climate characteristic with features such as unfavourable weather conditions that lead to scarcity of freshwater sources, high temperature and strong winds. It is generally recognised by the climate research community as an integral part of the environment as well as a recurrent feature of the climate (Gommes and Petrassi, 1994; Jones and Hulme, 1996; Lloyd-Hughes and Saunders, 2002; Herweijer and Seager, 2008). Although it is a common phenomenon of climate variability, its occurrence is often a devastating and complex natural hazard. In Africa, many countries have repeatedly been affected by droughts over the last decades, resulting in considerable environmental, social and economic damage as well as in worsening food security (Hulme, 1992; Prospero and Lamb, 2003). Climate change studies further indicate a trend towards increasing climate variability in the African continent, most likely resulting in more frequent drought events (Hansen and Lebedeff, 1987; Druyan and Hall, 1996; Dai, 2010). In the Horn of Africa, including Kenya, drought occurrence and its impacts have triggered actions at various political and management level (<http://www.economist.com/node/14506436>, accessed on 17 April 2010).

Numerous researches and the general opinion in the region agree that there is a need for adequate and up-to-date information on the occurrence and severity of drought episodes, probability of their duration, and their possible impacts (Moron, 1997; Mutai et al., 1998; Shanko and Camberlin, 1998). This is important for the design of appropriate mitigation and coping strategies for

¹Retired

drought. This need calls for a scientific approach for the development of a relevant drought monitoring framework that is appropriate for the region.

Droughts and their impacts have been studied for many decades in the Horn of Africa. Most of these studies have been largely based on one or two variables that are linked to the characterization of the climate such as rainfall, temperature, vegetation and soil moisture (Shanko and Camberlin, 1998; Ntale and Gan, 2003; Hastenrat et al., 2007). None of these approaches have been able to fully trace the drought footprints and offer reliable prediction in the Horn of Africa. This is particularly true because drought is a composite natural phenomenon whose monitoring methodology should be able to include at least six variables simultaneously, namely, rainfall deficit and its persistence, soil moisture deficit and its persistence, and temperature excess and its persistence. The objective of this study was to develop a drought monitoring methodology for Kenya and the Horn of Africa that is able to measure the natural components of drought by comparing the prevailing situation to the multiyear average situation at a given time in a year at a given place.

2 DROUGHT DEFINITIONS, TYPES AND ESTIMATION

Drought is a natural phenomenon that is triggered and sustained by inadequate availability of freshwater supplies for human and ecosystem's needs over an extended period of time. It has many facets in any single region: starting with the deficiency of precipitation and subsequently developing into drought conditions if the deficiency persists for a long time, depending on the requirements of the affected system. Besides rainfall, droughts are associated with a decline of soil moisture, stream flow and a drop of groundwater table. Unfortunately, the term drought is often used for food shortages, which are not necessarily caused or linked to drought in a true sense. Food shortage can be caused by many other factors, such as population pressure on the land, types of seeds used, overgrazing, plant disease, pest problems, armed conflicts or volatile market conditions, among others. These characteristics make the definition of drought quite complex. A universal definition of drought is therefore an unrealistic expectation. Nonetheless, there are some attempts in the literature, which can be broadly categorised as either conceptual or operational (Wilhite and Glantz, 1985). Conceptual definitions are of the 'dictionary' type, which generally define the boundaries of the concept of drought. They can be seen as generic descriptions of the drought phenomenon, for example, 'a long period with no rain, especially during a crop-growing season'.

Operational definitions attempt to identify the onset, severity, continuation and termination of drought episodes. They are often used in an 'operational' mode in many disciplines to analyse sectoral drought attributes such as frequency, severity and duration. Each discipline incorporates different physical, biological and/or socioeconomic factors in its definition of drought. As an example, an operational definition of agricultural drought might be one that compares daily or monthly precipitation to the corresponding

evapotranspiration rates for determining soil moisture depletion rate. The resultant comparison is then used to relate drought effects to the plant behaviour at various stages of drought development (WMO, 2010).

The following definition was developed by this study for drought monitoring purposes based on various drought definitions in the literature:

Drought is an extended period, during which, fresh water availability and accessibility for the ecosystem at a given time and place is below normal, due to unfavourable spatial and temporal distribution of rainfall, temperature, soil moisture and wind characteristics.

Different drought ‘types’ are effectively different stages of the same process. Thus, meteorologic droughts attempt to explain the primary causes, while agricultural and hydrologic droughts attempt to explain the secondary impacts of the meteorologic droughts. This is illustrated in Figure 1, based on and further developed from Wilhite and Glantz (1985).

The process of monitoring the evolution of the drought is complex. Ideally it should include measurement and evaluation of all variables incorporated in

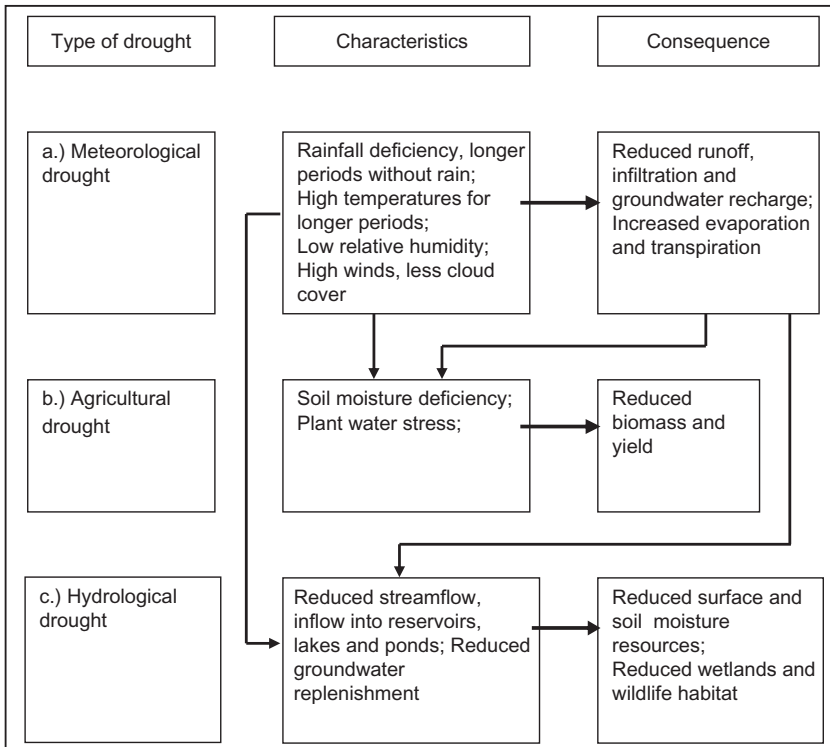


FIGURE 1 Schema for the relationship between drought types, characteristics and consequences. (Modified chart of Wilhite, 1993.)

the definition of drought in the preceding text. At present, there are many indices that have been developed to measure drought magnitudes, in different parts of the world (Szinell et al., 1998; Wu et al., 2001; Morid et al., 2006; Shakya and Yamaguchi, 2010). Although none of these indices is inherently superior to the rest in all circumstances, some indices are better suited than others for specific country/regional uses. These drought indices can be broadly put into two categories: (a) drought indices based on water balance calculation and (b) statistical drought indices based on time series analysis.

The water balance methodology requires application of several climatic and physical variables at a given time and space. Some of these variables might be calculated using some time series analysis, but all in all, their final goal is to determine the water deficit of the crop at a given time and space based on a distributed parameter model. Examples of these types of indices include the Palmer Drought Severity Index, the Palmer Hydrological Drought Index, the Palmer Z-Index, the Crop Moisture Index, the Surface Water Supply Index and the Reclamation Drought Index.

Most statistical indices are based on one or maximum two parameters, mostly rainfall and sometimes temperature deficiency/excess. To date, the most commonly used drought indices in this category include the Percent Normal Drought Index, the Standardised Precipitation Index, the Precipitation Decile Index and the Weighted Anomaly Standardised Precipitation.

The indices in the preceding text were analysed for suitability in practical monitoring of drought in Kenya.

3 METHODOLOGY FOR CALCULATING THE COMBINED DROUGHT INDEX

3.1 General Considerations and Data Used

Drought is conceived in this study as a combination of the following: a precipitation component, which considers rainfall deficits and dryness persistence; a vegetation component, which is used as a proxy for soil moisture deficit and which considers NDVI deficits and deficit persistence; and a temperature component, which considers temperature excesses and persistence of high temperatures. The drought index calculated using the precipitation component is referred to in the study as Precipitation Drought Index (PDI), while the index based on temperature is named as Temperature Drought Index (TDI) and that based on the vegetation component is named as Vegetation Drought Index (VDI). The drought index that combines the three drought components is named as Combined Drought Index (CDI).

Based on the considerations in the preceding text, the CDI was developed by Balint et al. (2011). The new index is a statistical index comparing the present hydrometeorological conditions with the long-term average characteristics in the same interest period within the year.

The index for the various components in simple words can be expressed as

$$\text{Drought Index} = \frac{\text{actual average for IP}}{\text{LTM for IP}} \cdot \sqrt{\frac{\text{actual length of continuous deficit/excess in the IP}}{\text{LTM length of continuous deficit/excess in the IP}}}$$

where IP is the interest period, LTM is the long-term mean, and deficit applies to rainfall or NDVI, while excess applies to temperature.

The following six different time series were used for the calculation of the drought indices in the preceding text:

- a. The dekadal (10-day) or monthly rainfall record.
- b. The time series of the rainfall run lengths ($RL^{(P)}$) for the specific interest period (IP).
- c. The dekadal (10-day) or monthly temperature record.
- d. The time series of the temperature run lengths ($RL^{(T)}$) for the specific IP.
- e. The dekadal (10-day) or monthly NDVI record.
- f. The time series of the NDVI run lengths ($RL^{(NDVI)}$) for the specific IP.

The run length in these time series characterises the persistence of the unfavourable weather conditions, during which the uninterrupted drought pressure exists. In the case of PDI and VDI, the run length is the period within the IP, in which the rainfall or NDVI is continuously below the long-term mean value. In the case of TDI, run length is the time period within the IP, in which the temperature is continuously above the long-term mean value characteristic for the same time unit (e.g. month).

The time series in the preceding text can be grouped in two categories. In group A, small values of the data indicate dry conditions and larger values indicate wet conditions. Rainfall and NDVI data fall into this group. In group B, large values in the time series indicate conditions that can contribute to drought, while the small values indicate better than drought conditions. Temperature data fall into this category.

Since the application of the drought indices in the preceding text invariably involves the comparison of actual drought conditions with the long-term average conditions, some sort of input data standardisation may be inevitable for homogeneous mathematical interpretation. In this study, this was done by moving the x -axis to the level of $(T_{\max} + 1)$ for temperature, $(RL_{\max} + 1)$ for run length and $(NDVI_{\min} - 0.01)$ for NDVI, where T_{\max} is the maximum temperature, RL_{\max} is the longest run length in the whole dataset used and $NDVI_{\min}$ is the minimum NDVI for the station under consideration. Adding 1.0 to the highest temperature and run-length values and subtracting 0.01 from the minimum NDVI serves the purpose of avoiding division by 0. The x -axis shift results into modified data series as given in Equation (1). This modification only serves to ease the calculation process. We found that the modification does not change the nature of the data series and that of the results in any way:

$$\begin{aligned}
 T^* &= (T_{\max} + 1) - T \\
 \text{RL}^* &= (\text{RL}_{\max} + 1) - \text{RL} \\
 \text{NDVI}^* &= \text{NDVI} - (\text{NDVI}_{\min} - 0.01)
 \end{aligned}
 \tag{1}$$

We found it advisable working with modified rainfall data specifically in countries that have distinct, long dry seasons without any rain. In these cases, a whole period is characterised by exclusively zero values, including the LTM, which can result into unrealistically large values when dividing by very small values close to zero. Shifting the x -axis of the coordinate system by 1 mm tended to solve such problems. In countries where some rainfall can be expected any time throughout the year, and the original data series work well, we still recommend using modified precipitation data as shown in Equation (2):

$$P^* = P + 1 \tag{2}$$

where P is the precipitation amount.

3.2 Calculation of PDI, TDI and VDI

The equations for calculating the PDI, the VDI and the TDI for year i and time unit (dekad/month) m are given in Equations (3–5):

$$\text{PDI}_{i,m} = \frac{\frac{1}{\text{IP}} \sum_{j=0}^{\text{IP}-1} P_{i,(m-j)}^*}{\left[\frac{1}{(n * \text{IP})} \sum_{k=1}^n \left[\sum_{j=0}^{\text{IP}-1} P_{(m-j),k}^* \right] \right]} * \sqrt{\left(\frac{\text{RL}_{m,i}^{(P^*)}}{\frac{1}{n} \sum_{k=1}^n \text{RL}_{m,k}^{(P^*)}} \right)} \tag{3}$$

$$\text{VDI}_{i,m} = \frac{\frac{1}{\text{IP}} \sum_{j=0}^{\text{IP}-1} \text{NDVI}_{i,(m-j)}^*}{\left[\frac{1}{(n * \text{IP})} \sum_{k=1}^n \left[\sum_{j=0}^{\text{IP}-1} \text{NDVI}_{(m-j),k}^* \right] \right]} * \sqrt{\left(\frac{\text{RL}_{m,i}^{(\text{NDVI}^*)}}{\frac{1}{n} \sum_{k=1}^n \text{RL}_{m,k}^{(\text{NDVI}^*)}} \right)} \tag{4}$$

$$\text{TDI}_{i,m} = \frac{\frac{1}{\text{IP}} \sum_{j=0}^{\text{IP}-1} [T_{i,(m-j)}^*]}{\left[\frac{1}{(n * \text{IP})} \sum_{k=1}^n \left[\sum_{j=0}^{\text{IP}-1} T_{(m-j),k}^* \right] \right]} * \sqrt{\left(\frac{\text{RL}_{m,i}^{(T^*)}}{\frac{1}{n} \sum_{k=1}^n \text{RL}_{m,k}^{(T^*)}} \right)} \tag{5}$$

where IP is the interest period (e.g. 3, 4, 5, ... dekad/months), $\text{RL}^{(P)}$ (run length) is the maximum number of successive dekad/months below long-term average rainfall in the IP, $\text{RL}^{(T)}$ is the maximum number of successive dekad/months above long-term average temperature, $\text{RL}^{(\text{NDVI})}$ is the maximum number of successive dekad/months below long-term average NDVI in the IP, n is the number of years where relevant data are available,

j is the summation running parameter covering the IP and k is the summation parameter covering the years where relevant data are available.

Equations (3)–(5) are separately dimensionless and measure the drought severity in a given IP. The first term is the ratio of average modified rainfall, modified NDVI or modified temperature during the IP to the long-term mean of the same parameters during the same IP. The numerator is a high-frequency component that measures the current conditions, while the denominator is a low-frequency term that measures the long-term average. The second term is a measure of persistence of dryness whose square root is intended to scale down the variability of the second term (i.e. to decrease its impact on the final value of the drought index). In this study, it was assumed that the effect of the first and second terms is multiplicative. The low values in Equations (3)–(5) indicate strong drought conditions and vice versa. In using the equations, the actual drought index represents the severity of drought for the IP ending in time unit m . For example, if the IP = 3 months, then the drought index (say PDI) of 0.35 for January 2006 implies actual drought for November and December 2006 and January 2006.

3.3 Calculation of the CDI

The CDI is computed as the weighted average of the VDI and the 2-dekad lagged PDI and TDI, as shown for decadal calculation on Equation (6):

$$CDI_{i,m} = w_{PDI} * PDI_{i,m-2} + w_{TDI} * TDI_{i,m-2} + w_{VDI} * VDI_{i,m} \quad (6)$$

The lags on the PDI and TDI demonstrate that the effects of rainfall and temperature on vegetation are slightly delayed. In general, the present-day rainfall or temperature in a given area is likely to affect the vegetation of the area in about two-dekad time. It is important to note that this lagging is not necessarily valid for time units of the order of 1 month. For larger time units, Equation (6) becomes

$$CDI_{i,m} = w_{PDI} * PDI_{i,m} + w_{TDI} * TDI_{i,m} + w_{VDI} * VDI_{i,m} \quad (7)$$

where w are the weights that are 50% for w_{PDI} and $w_{TDI} = w_{VDI} = 25-25\%$. Where either temperature or NDVI data are missing, w_{PDI} is assigned a weight of 67% and the others assigned 33%.

It is important to note that the CDI does not measure the physical parameters of either the vegetation or the soil. It does not attempt to simulate either the physical phenomena or the water balance. It is an index that measures how much the present conditions deviate from the reference level, which is the multiyear long-term average as characterised by the time interval.

3.4 Interpretation of the Results

The severity (scale) of the drought is measured by the value of the CDI.

If the computed drought index:

- equals 1.00, then conditions in the actual time unit can be considered ‘normal’;
- is greater than 1.00, then they can be considered better than the ‘normal’; and
- is less than 1.00, then they can be considered worse than the ‘normal’.

An initial classification of drought categories based on the value of the CDI was set up below.

CDI Value	Drought Severity
>1.0	No drought
1.0–0.8	Mild drought
0.8–0.6	Moderate drought
0.6–0.4	Severe drought
<0.4	Extreme drought

The classification earlier can be modified, based on socioeconomic analysis or geographic considerations and experience. The impact of the drought depends on a number of factors: on the crop type, soil type, climatic zone, availability of groundwater, vulnerability of the ecosystem, etc. Therefore, the methodology gives the researcher the flexibility to analyse various lengths of drought duration, starting from a few dekads (10-day periods) to several months, seasons or even years. The basic period of analysis is called the ‘interest period’. If the plants are sensitive even to a few weeks of drought conditions, dekadal data can be used with an IP of at least 3 dekads. As the CDI is calculated similarly to a moving average, in this case, the CDI values will characterise always the 3 dekads immediately before the selected date. In a more general situation, monthly data are recommended with an IP of 3–6 months; however, as seen in the succeeding text, sometimes the 12-month IP reflects best the longer-term characteristics of the drought. The shorter the IP, the more oscillation is shown in the graphs and the longer the IP the smoother are the graphs, reflecting longer-term trends but loosening short-term drought characteristics.

Besides all the features in the preceding text, the calculations later also clearly demonstrate that the drier the area, the more volatile the CDI values become, reflecting more abrupt changes in the behaviour of the climate there.

4 DROUGHTS IN KENYA, MEASURED BY THE CDI

4.1 Calculation CDI for Measuring Drought Severity

Monthly rainfall, temperature and NDVI data have been collected and used to calculate the CDI at the following stations.

	Name	Climate Zone
1	Dagoretti	Semi-arid
2	Embu	Semi-arid
3	Lodwar	Arid
4	Wajir	Arid
6	Kakamega	Subhumid

The results of the CDI calculations with monthly data and a 3-month IP are shown in Figure 2, and they clearly reflect the theoretical considerations in Section 3. There are two stations in semi-arid, one in subhumid and two in arid climatic zones. Figure 3 is a comparison between dekadal and monthly calculation at the Embu station. The oscillation of the CDI values is the most intensive with the 5-dekad analysis and much smoother with the 3-month analysis. Short-term droughts are detected well by the 5-dekad analysis;

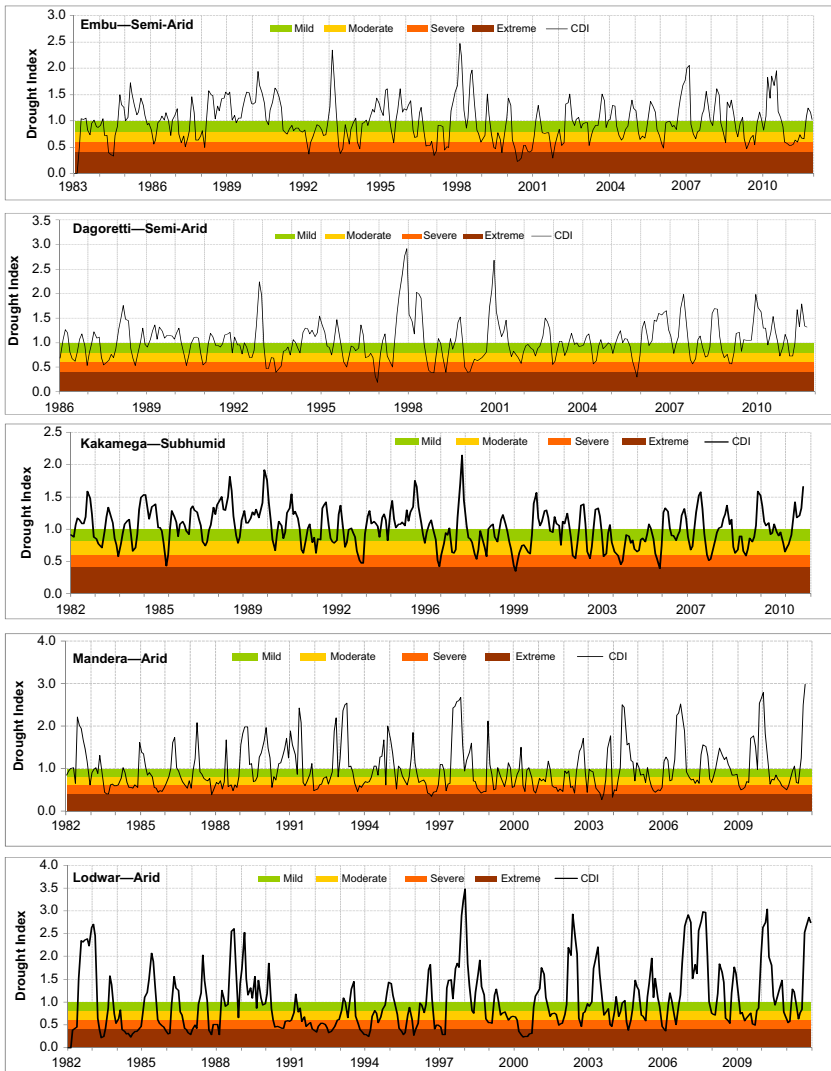


FIGURE 2 CDI calculations with monthly input data and a 3-month interest period.

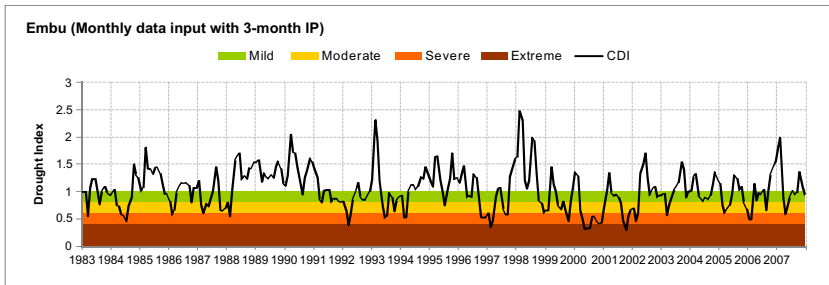
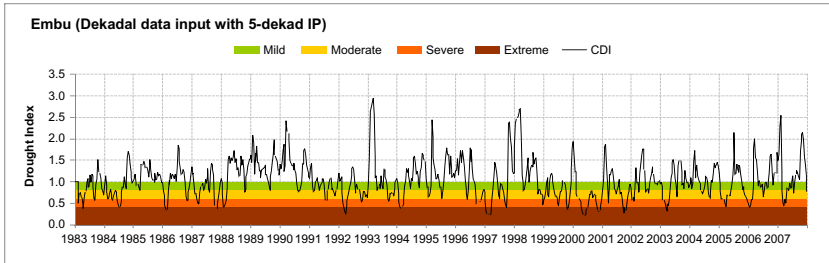


FIGURE 3 Comparison of decadal and monthly CDI calculation with 3-month/5-dekad interest periods.

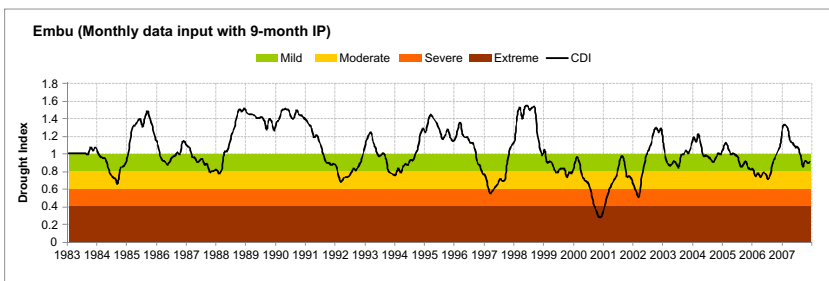


FIGURE 4 Example for a 9-month analysis for detecting longer droughts.

however, the more severe droughts causing wider-ranging impacts and national catastrophes are better shown with the 9-month analysis in [Figure 4](#).

4.2 Comparison of CDI Calculations with Drought Reports

‘Verification’ of the CDI results is not easy, because there are no exact, objective, detailed reports about the impacts of droughts in various years. Drought obviously starts in different months in different parts of the country, and national disaster is declared when its impact exceeds a certain extent. Some

regions might not experience drought at all, while in other regions, the severity of drought might be exaggerated purely on political grounds. However, analysing CDI results together with drought reports, we found that they reinforce each other and paint a more detailed and more realistic picture about temporal and spatial development of the drought.

As shown in [Table 1](#), there is evidence of drought impacts in Kenya emphasising the country's vulnerability to climate variability and the limitations of adaptive capacity. The table shows the drought events that the government declared as disasters from 1980 to 2011. During the 1980s, there were two major nationwide drought events in 1983/1984 and 1987; this has been well captured by the CDI as seen on [Figure 2](#) for all stations. 1992–1994 and 1999/2000 also witnessed severe droughts in many parts of the country as shown in [Tables 1 and 2](#) as well as the CDI graphs. The last decade has seen an increased number of drought occurrences. Devastating droughts during that period include that of 2001, 2002, 2004, 2006 and the most recent and much publicised one in 2010/2011. This again has been well captured by the CDI calculations.

TABLE 1 Recent History of Drought Incidences in Kenya (1980–2011)

Year	Region	Remark
1980	Widespread	40,000 People affected
1983/1984	Central, Rift Valley, eastern and northeastern	Severe food shortages in eastern province and less in central
1987	Eastern and central provinces	4.7 Million people dependent on relief power and water rationing
1991/1992	Northeastern, Rift Valley, eastern and coast provinces	1.5 Million people affected
1993/1994	Northern, central and eastern provinces	
1995/1996	Widespread	1.41 Million people affected
1997	Northern parts of Kenya	2 Million people affected
1999/2000	Countrywide except west and coast provinces	4.4 Million people affected (worst drought in 37 years)
2004	Widespread	2.3 Million people affected
2005	Northern parts of Kenya	2.5 Million people affected
2010/2011	Widespread	3.5 Million people affected

Sources: Republic of Kenya (2004), Republic of Kenya (2011).

TABLE 2 CDI Trend from the End of 1999–2000

Year	Month	Mandera	Lodwar	Embu	Dagoretti	Kakamega
1999	Oct	0.7	0.61	0.39	0.87	1.22
1999	Nov	0.58	0.67	0.73	1.06	1.08
1999	Dec	0.78	0.68	1.05	1.41	0.96
2000	Jan	1.14	0.67	1.44	1.52	0.8
2000	Feb	1.02	0.60	1.30	1.05	0.69
2000	Mar	0.56	0.36	0.63	0.50	0.43
2000	Apr	0.58	0.27	0.48	0.41	0.35
2000	May	0.86	0.23	0.23	0.41	0.49
2000	Jun	0.96	0.24	0.25	0.55	0.63
2000	Jul	1.51	0.25	0.29	0.66	0.74
2000	Aug	0.6	0.3	0.53	0.63	0.75
2000	Sep	0.47	0.31	0.54	0.66	0.71
2000	Oct	0.97	0.90	0.42	0.69	0.64
2000	Nov	1.02	1.13	0.41	0.75	0.62
2000	Dec	0.79	1.23	0.43	0.81	0.91

Drought severity legend					
Category	No Drought	Mild	Moderate	Severe	Extreme
colour code					
CDI	>1.0	1.0–0.8	0.8–0.6	0.6–0.4	<0.4

5 LONG-TERM TRENDS OF DROUGHT EVENTS IN KENYA

Is severity of drought increasing in Kenya? Is it going to cause more harm than in the previous years? Is the frequency of drought events growing? These are all questions that are important to answer in the course of preparing any drought management plan. FAO-SWALIM took the first steps in trying to answer these questions. Simple statistical analysis on various characteristics of the CDI graphs was performed for selected stations in Kenya with the following questions:

- Is there a general, increasing trend in severity of drought?
- Is the number of extreme/severe droughts increasing within a decade?

Results of the analysis are shown in [Figure 5](#) and [Table 3](#), and the summary conclusions are as follows:

1. To answer the first question, the complete time series were divided into three decades: years 1980–1989, 1990–1999 and 2000–2009 ([Figure 5](#)). The averages of the CDI values of less than 1.0 (mild to extreme

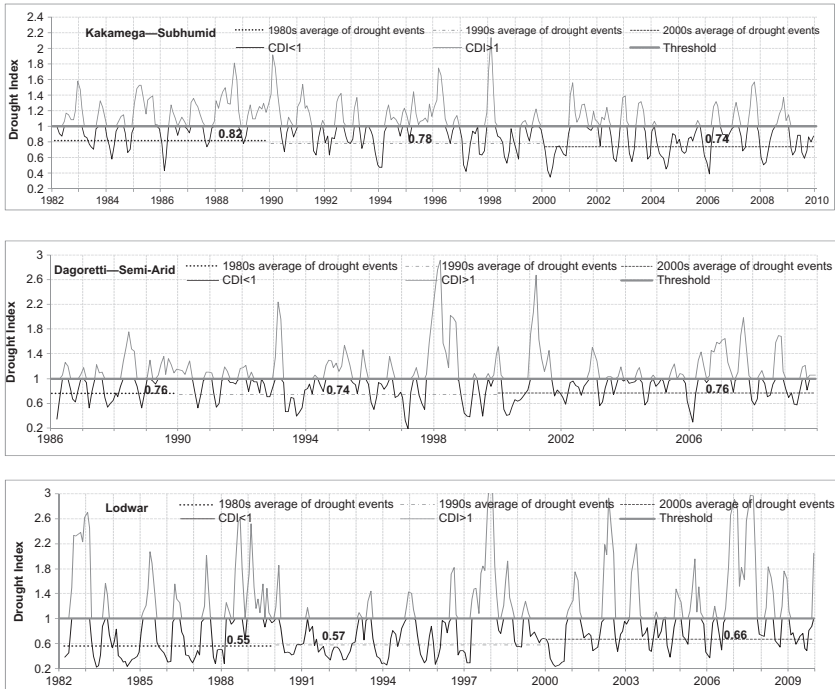


FIGURE 5 Decadal linear trends of below average CDI values at three Kenyan stations ($CDI < 1.0$).

TABLE 3 Number of Moderate to Extreme Drought Occurrences Per Decade ($CDI < 0.8$)

Station	1980	1990	2000
Dagoretti	23	67	71
Lodwar	54	86	75
Mandera	66	67	91
Kakamega	31	57	85
Embu	35	76	88

droughts) calculated for the periods in the preceding text show a shift towards more severe droughts from the 1980s to 2000s in most stations, while a few of them showed an improvement in drought severity in the 2000s.

- Table 3** speaks for itself. The number of the severe/extreme droughts per decade is increasing in all stations.

3. While the drought severity is not necessarily getting worse in all stations, there is evidence of an increasing trend of the frequency of drought occurrences in the country.

Note: The ones in the preceding text are just some examples of many more possible statistical analyses that can be performed by the researchers according to the particular questions.

6 SHORT-TERM FORECAST OF DROUGHT BY THE CDI

First attempts have been made in this study to perform ‘what-if’ analysis, a simplified ensemble forecast for the evolution of the drought until the end of the season. The calculation is performed on a monthly basis. CDI values are calculated at the end of each month, and three scenarios are assumed about the future development of the climatic conditions in the remaining months of the season.

The assumed input scenarios are

1. future rainfall conditions 25% better than normal with normal temperature and NDVI,
2. future conditions around normal,
3. future rainfall conditions 25% worse than normal with normal temperature and NDVI.

The results are calculated, and hypothetical series of future CDI values can help decision-makers evaluate the anticipated drought situation at the end of the season.

To test the early warning methodology, a simulation example for Embu for 2007 is presented in [Figure 6](#).

Short-term early warning is given for the three scenarios and compared with the actual situation in 2007. The example shows quite clearly that the 25% below average rainfall assumption captured very closely the actual situation in the first 6 months of the year.

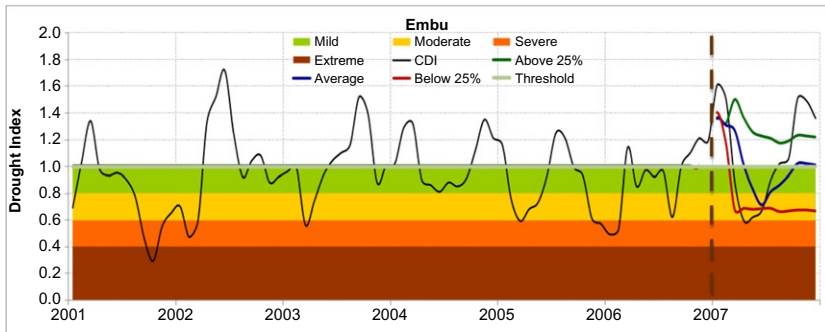


FIGURE 6 Short-term forecast (simulation) of the drought in 2007 at the Embu station.

7 CONCLUSIONS

This chapter uses a statistical approach that combines different parameters to an index herein represented as the CDI. This index:

1. Can clearly trace the footprints of droughts in Kenya.
2. Has the potential to give short-term early warning up to the end of the season.
3. Has the potential for use in climate trends and climate change analysis.
4. The results are supported with drought reports in the country.
5. The authors recommend that the CDI should be tested worldwide.

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