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Bi-hazard assessment for timely and effective disaster management: Free State disaster area 2015

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ABSTRACT

Drought is actually the most obstinate, insidious and pernicious of all natural hazards that nature can ever conjure up. With its slow-on-set *creeping* nature, at its most severe levels it can last longer and extent across large areas generating secondary hazards such as dust bowls, land degradation, destruction of terrestrial and aquatic wildlife habitats and widespread wildfires. Therefore thereis no universal definition of drought, therefore *"Operational definitions can also be used to analyze drought frequency, severity, and duration for a given historical period. Such definitions, however, require weather data on hourly, daily, monthly, or other time scales and, possibly, impact data (e.g., crop yield), depending on the nature of the definition being applied. Developing climatology of drought for a region provides a greater understanding of its characteristics and the probability of recurrence at various levels of severity. Information of this type is extremely beneficial in the development of response and mitigation strategies and preparedness plans"*. Following the declaration of the Free State province on the 10th September 2015 being drought disaster area, the current study aims to assess drought and fire hazards from regional operational indices in order to help disaster managers and political authorities facilitate resource allocation mobilization in response to the present situation. The study collected January 2014 to October 2015 precipitation, wind speed, temperature, and relative humidity data from a web-based source. A modified water balance method in conjunction with the works of Iyengar and Sudashan were used in constructing a composite drought index. This analysis which was conducted in three dimensions, severity, frequency and spatial extent, revealed the Free State province generally experiencing the same magnitude of frequencies and severity, although, rankings of spatial extent show a descending trend from the northern to the north-eastern parts of the province and lastly the southern parts. The same spatial extent was revealed by a Swedish Angstrom index for fire dangers.

Key words : *Disaster, Drought, Vulnerability index, Swedish Angstrom index*

Introduction

Drought is defined as time period of drier- than-normal conditions and when rainfall is less than normal for several weeks, months and years which leads to water related problems (Nagarajan, 2009). There is however, no specific definition of drought but can be categorized in four main types. *Meteorological drought* refers to the degree of dryness compared to the normal conditions and this is variable over time and specific region (National Drought Mitigation Center (NDMC), 2012). *Hydrological drought* refers to rainfall deficit able to cause serious reduction in run-off streamflow, inflow into storage reservoirs and recharge of groundwater (Whitmore, 2000). *Agricultural drought* refers to insufficient soil

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moisture to sustain plants and livestock resulting in impaired growth and reduced yields (FAO, 2008).

Socio-economic drought refers to when human activities are adversely affected by reduced water availability and precipitation (FAO, 2013). Figure 1 below depicts the interrelationship of the types of drought.

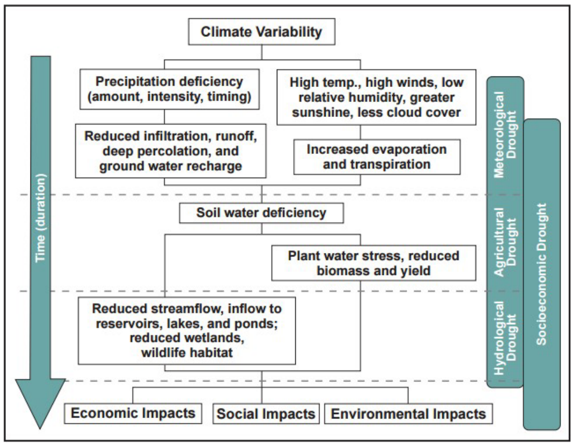


Fig. 1. Sequence of drought types occurrence and their impacts
Source: National Drought Mitigation Center, (2012)

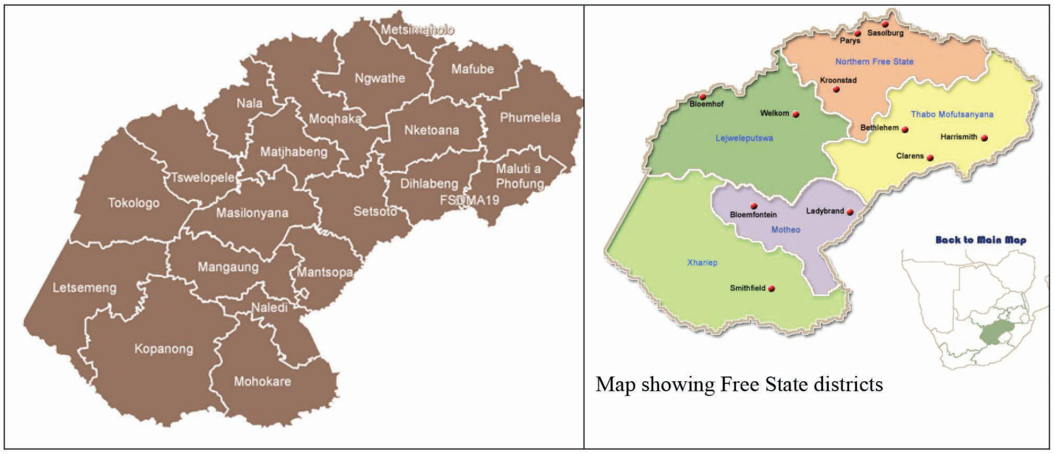
In 2014, South Africa proposed to celebrate World Day to Combat Desertification (WDCD) through the Department of Environmental Affairs in Collaboration with the Department of Agriculture, Forestry and Fisheries. This celebration was proposed to be held in the Free State Province at Thabo Mofutsanyana mainly because Free State was one of the provinces that was severely affected by the impacts of land degradation, desertification and drought that have negative effects on rural communities (Department of Environmental Affairs, 2014). In September 2015, the Free State Premier Ace Magashule officially declared this province in drought disaster (Coleman, 2015). The chief researcher at Council for Scientific and Industrial Research (CSIR) Mr Willem Landman made a mention that Strong El Niño will definitely add stress to systems already feeling the warming planet impacts and therefore long-term predictions on rainfall will be hard to make given twice the global average rise in temperature across Africa (Kings, 2015). On the 18th November 2015 the MEC of Agriculture and his Department went to Conerlia in the northern Free State to help out since this place has been declared agriculture village. On Monday 16th November that week, 300 bags of feed and Lucerne were handed over to farmers in Delpotrus in Welkom (Chabalala, 2015). In response to this prevailing drought disaster, the department of Agriculture has committed R30 million to assist emerging farmers in the whole province. However there is still a need for an additional R22 million for boreholes (Chabalala, 2015). Given the above proposed response efforts and the fact that Free State is known as the "bread basket" of South Africa, with over 90% of the land under crop production (South African Government, 2012), it is therefore imperative that drought assessment is done to facilitate resource allocations.

Both drought monitoring and early warning are very important measures in building community resilience against adverse impacts of drought (Bachmair *et al*., 2015; Valipour, 2013; Valipour, 2013a; Valipour, 2013b; Valipour, 2013c). On the contrary an accurate drought monitoring has always been a great challenge because drought slow-onset nature, its severity varying with precipitation deficits making it difficult to compare one drought to another (Peters *et al*., 2002; Valipour, 2014: Valipour, 2015). In the reduction of drought impacts, it is crucial thatsystems that accurately disseminate information in timely manners are developed (Anon, 2014; Valipour, 2016: Ambarwulan *et al*., 2016). However these systems are sub-divided into two categories, those measuring the current situations and those meant for prediction. Drought information requirement vary both temporally and spatially, for this reason some decision makers need daily, weekly and monthly information for their decision making particularly during drought periods (She *et al.*, 2016; Ye *et al*., 2017). Drought indices are of great help in aiding this process; however the majority of these

indices are computed over long time scales thereby limiting their usage during drought periods (Carbone *et al*., 2008; Tong *et al*., 2017). The current study aims to provide disaster managers and political authorities with the current drought situation in the Free State province to facilitate the resource allocation. The study therefore chose the available appropriate variables in computing the operational drought index.

Study area

Figure 2 below shows the geographic location of the Free Province with its municipalities. This figure first indicates where South Africa is located in the



Map showing Free State districts

Fig. 2. Study area, Free state province showing municipalities Source: http://bgis.sanbi.org/municipalities/choose-muni.asp?prov=FS

Southern Africa, then the Free State province with municipalities from right to the left.

Materials and Methods

Data processing

A web-based data collection method was employed over 9 weather stations across the Free State province from January 2014 to October 2015 (22 months). Three variables were selected to quantification of current drought situation. These variables were; precipitation, temperature, humidity and wind speed. A modified water balance method was used together with the works of

Iyengar and Sudashan (1982) who computed a composite index from multivariate data. Since the three variables bear different units, a normalization process was conducted with the aid Microsoft Excel. The functional relationship with drought was considered since the three selected variables have differing effects on drought. Table 1 shows the selected input variables and their functional relationships with drought.

The normalization process was conducted from the following equations; Variables with decreasing functional relationship,

$$y_{ij} = \frac{\underset{i}{Max}\{X_{ij}\} - X_{ij}}{\underset{i}{Max}\{X_{ij}\} - Min\{X_{ij}\}} \quad .. (1)$$

Where yij is the normalized value at i^{th} month at j^{th} station and Max (Xij) and Min (Xij) are

$$x_{ij} = \frac{X_{ij} - \underset{i}{Min}\{X_{ij}\}}{\underset{i}{Max}\{X_{ij}\} - \underset{i}{Min}\{X_{ij}\}}$$

maximum and minimum values respectively over the study period. Similarly for variables with increasing functional relationships were computed from;

$$x_{ij} = \frac{X_{ij} - \underset{i}{Min}\{X_{ij}\}}{\underset{i}{Max}\{X_{ij}\} - \underset{i}{Min}\{X_{ij}\}} \quad .. (2)$$

After normalization of the variables' values whose values range from [0, 1], all the three variables values were aggregated for a composite index per month per weather station. A suitable probability distribution was chosen and in this case, a beta

Table 1. Selected variables and their functional relationships

Input variables	Functional relationship with drought
Total monthly Precipitation/rainfall (mm)	↓
Monthly average Temperature (^{o}C)	↑
Average relative Humidity (%)	↓
Monthly average wind speed (Km/h)	↑

distribution was fit for this situation since it takes values from [0,1] and it is skewed. In their work, Iyengar and Sudashan (1982) proposed a suitable and meaningful fractile classification from beta probability distribution. Table 2 below shows this classification;

Table 2. A modified Iyengar and Sudashan fractile classfication

Description	class
Less dry/wet	0.0 < Index < 0.2
Moderately dry/wet	0.2 < Index < 0.4
dry	0.4 < Index < 0.6
Highly dry	0.6 < Index < 0.8
Very Highly/Severely dry	0.8 < Index < 1.0

Source: http://danida.vnu.edu.vn/cpis/files/Papers_on_CC/Vulnerability/Quantitative%20assessment%20of%20Vulnerability% 20to%20 Climate% 20Change.pdf

All the computed monthly indices for each station were classified according to Table 2. All those whose values fell between [0.4 – 1.0] were identified for further analysis since their indices showed dryness. The collected data was analyzed in three dimensions; severity, frequency and spatial extent.

Severity was calculated from the following equation

$$S_e = \left| \sum_{j=1}^{m} Index_j \right|_e \qquad ..\ (3)$$

$$F_s = \frac{n_s}{N_s} \times 100\%$$

Where Se is the absolute value of all indices in the range [0.4 – 1.0] of "m" months. Drought frequency (Fs) was used to analyse the drought liability during the study period.

$$F_s = \frac{n_s}{N_s} \times 100\% \qquad ..\ (4)$$

Where nsand Ns denote the number of moths whose indices fall in the interval [0.4 – 1.0] and the total months during the study respectively. Drought station proportion (*Pj*) is the ratio of number of drought stations to total number of stations. It indicates the spatial extent of drought occurrence in a region. It is calculated by:

$$P_j = \frac{n_j}{N_j} \times 100\% \qquad ..\ (5)$$

where *j* is a month, *nj* is number of drought stations (when 0.4 < drought index < 1.0) in month *j*, and *Nj* is total number of stations used.

Validity and reliability

Secondary to drought evolution is the fire dangers, to validate the calculated operational drought indices; a fire danger index (Swedish Angstrom index) was computed monthly mean temperature and relative humidity from the following equation;

$$\mathbf{I} = \frac{\mathbf{R}}{\mathbf{20}} + \frac{\mathbf{(27-T)}}{\mathbf{10}} \qquad ..\ (6)$$

Where:
R = relative humidity (%)
T = air temperature (°C)
The values for **I** translate into fire risk as follow:

Swedish Angstrom index	Description
I>4.0	fire occurrence unlikely
4.0<I<3.0	fire occurrence unfavourable
3.0<I<2.5	fire conditions favourable
2.5<I<2.0	fire conditions more favourable
I<2.0	fire occurrence very likely

Source: Skvarenina *et al.* 2003

Results and Discussion

Table 3 above shows a full drought characterization over the Free State Province. The northern part of this province seems to experience the highest hardships depicted by the severity levels as shown in Table 3 above. This severity levels are observed to move in the direction south-eastern parts of the province. This observation is consistent with the efforts undertaken by the MEC of Agriculture on the 18th November 2015, in helping out farmers in Delpotrus in Welkom and Conerlia in the northern parts of the province. The leading stations also experienced more frequent dry periods during the study period (Jan 2014 to Oct 2015). Table 4 shows districts, municipalities and weather stations ranked according to drought severities.

Each selected weather station was linked with the municipality and the district it is found in, or a nearby municipality for further characterization. The leading district with severe drought impacts is

Fezile Dabi followed by Lejwelephutswa and lastly Thabo Mofutsanyana. Due to lack of meteorological data availability in the areas adjacent to two municipalities in Xhariep district; Letsemeng and Kopanong, these two municipalities were hardly linked to Zastron station due their spatial distance from Zastron. However, the available data in this station was incomplete and the gaps were filled with average values from the previous months

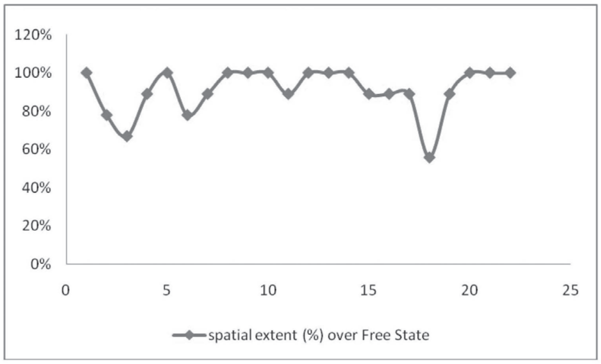


Fig. 3. Spatial extent progression (%) over Free State (Jan 2014-Oct 2015)

The spatial extent was tracked from January 2014 to October 2015 and the graph below shows this characteristic being almost constant with a100% coverage over the entire province. It is from this graph and table 3 that the current study reveals that this province has generally suffered the same impacts of drought with little variations.

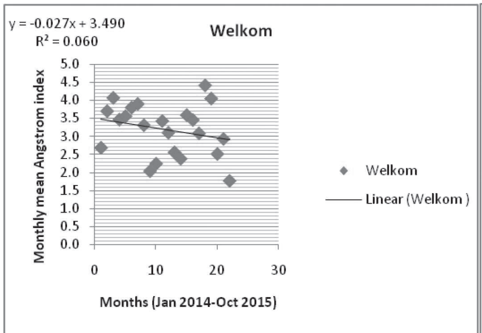
From Figure 4 below, an interesting feature is ob-

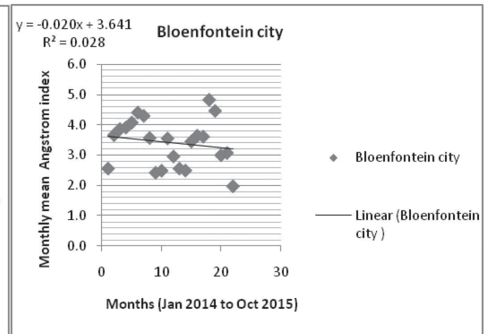
Table 3. Severity and frequency levels computed from (Jan 2014-Oct 2015)

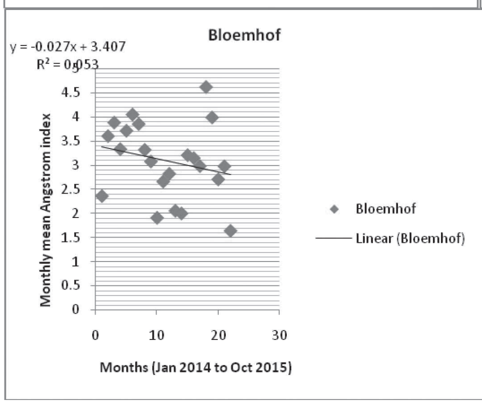
Weather station	Station number	latitude	Longitude	Altitude	Severity (Se)	Frequency
Bloemhof	683430	-27.65	25.61	1128	14.08084660	95%
Frankfort	683620	-27.26	28.5	1499	13.71802245	100%
Bethlehem Airport	684610	-28.25	28.33	1686	12.63932941	100%
Kronstad	683550	-27.63	27.23	1432	12.46724421	91%
Bloenfontein city	684430	-29.11	26.18	1406	12.16679277	91%
Welkom	683450	-28	26.66	13.42	11.85576890	86%
Excelsior	687190	-32.95	19.43	945	11.60335575	77%
Zastron	689390	-30.3	27.11	1300	10.85698143	95%
Fickburg	684490	-28.81	27.9	1614	10.23044146	82%

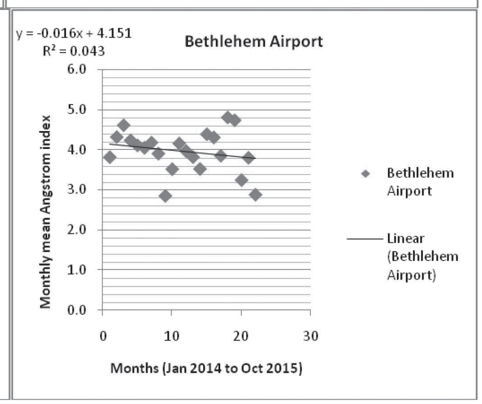
Table 4. Selected weather stations linked to nearby municipalities

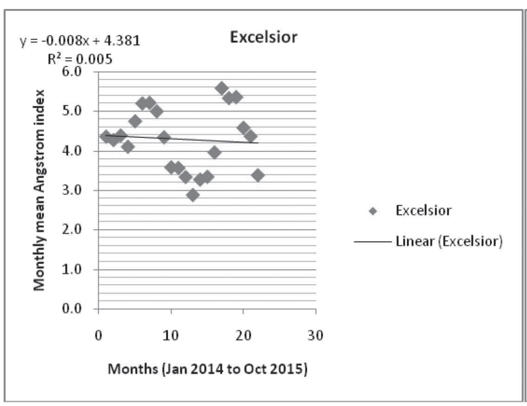
District	Municipality	Nearby selected weather station	Station number	Average Severity level	District ranking
Motheo	Mangaung metropolitan	Bloemfontein city	684430	12.16679277	3
Lejwelephutswa	Nala	Bloemhof	683430		
	Tokologo				
	Tswelopele				
	Masilonyana	Welkom	683450	12.96830775	2
	matjhabeng				
Xhariep	Naledi	Zastron			
	Mohokare				
	Letsemeng		689390	10.23044146	5
	Kopanong				
Fezile Dabi	Moqhaka	Kronstad	683550		
	Ngwathe			13.092633325	1
	Metsimaholo	Frankfort	683620		
	Mafube				
Thabo Mofutsanyana	Mantsopa	Excelsior			
	Setsoto	Ficksburg	684490		
	Dihlabeng			11.4336804733	4
	Maluti-a-phofung	Bethlehem airport	6846210		
	Nketoana				
	Phumelela				

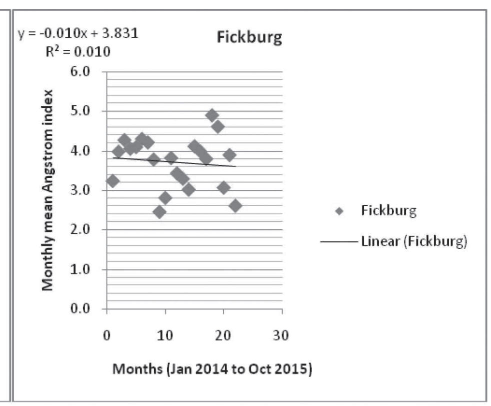

y = -0.027x + 3.490
R² = 0.060
Welkom
Monthly mean Angstrom index
Months (Jan 2014-Oct 2015)
Welkom
Linear (Welkom)

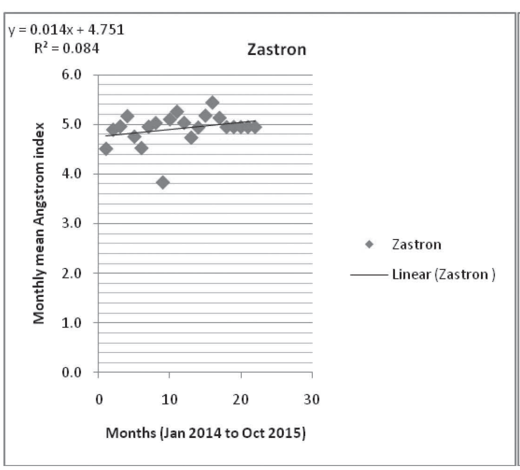

y = -0.020x + 3.641
R² = 0.028
Bloenfontein city
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Bloenfontein city
Linear (Bloenfontein city)

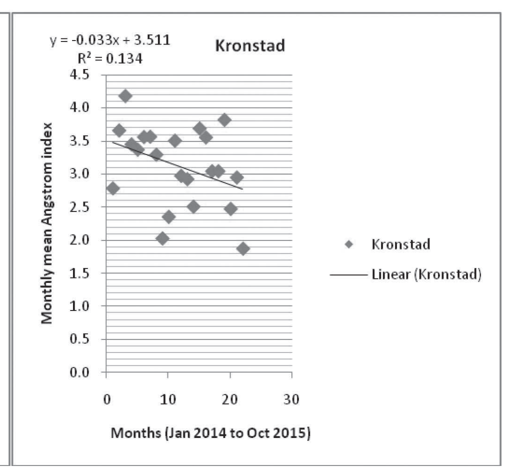

y = -0.027x + 3.407
R² = 0.053
Bloemhof
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Bloemhof
Linear (Bloemhof)


y = -0.016x + 4.151
R² = 0.043
Bethlehem Airport
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Bethlehem Airport
Linear (Bethlehem Airport)


y = -0.008x + 4.381
R² = 0.005
Excelsior
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Excelsior
Linear (Excelsior)


y = -0.010x + 3.831
R² = 0.010
Fickburg
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Fickburg
Linear (Fickburg)


y = 0.014x + 4.751
R² = 0.084
Zastron
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Zastron
Linear (Zastron)


y = -0.033x + 3.511
R² = 0.134
Kronstad
Monthly mean Angstrom index
Months (Jan 2014 to Oct 2015)
Kronstad
Linear (Kronstad)

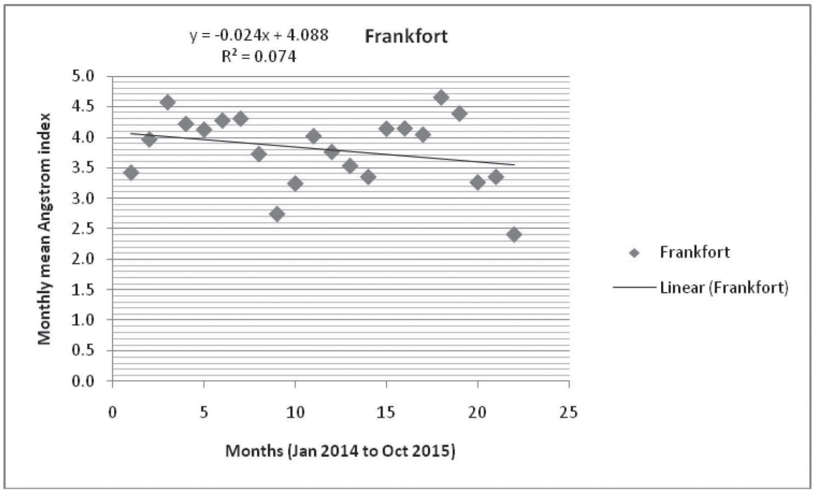


Fig. 4. Fire danger index (Swedish Angstrom index) trend analysis

served where a Swedish Angstrom index was computed to complement the calculated operational drought index, all the gradients in all stations are negative showing a decreasing nature of the Angstrom index thereby moving towards lower values that show high likelihood fire dangers given the current drought conditions. Konstad, Welkom and Bloemhof stations in the northern part of the province again show the steepest slopes showing increased fire danger possibilities in the next months given the current conditions or worst. Only Zastron shows a decrease in fire danger levels, this could be brought about incomplete data records.

Conclusion

In conclusion,the study used two indices operational drought index and Swedish Angstrom index to quantify both drought and fire danger. The two indices concur leading the researcher to a conclusion that the calculated drought index was valid and reliable. Free State province seems to experience a generally uniform drought stress slightly moving from the northern parts of the province down to north eastern parts. The spatial extent was further plotted against time in months from January 2014 to October 2015 and results showed a constant spatial extent over the study region. Local municipalities were then linked to the nearby weather station to give a picture of the drought severity levels for disaster mangers and political leaders. For a complete picture of the disaster risk levels, these results must be coupled with municipalities' individual vulnerabilities. The government is therefore urged to address drought response from socio-economicviewpoint.

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