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Assessment of Combined Drought Index and Mapping of Drought Vulnerability in Jordan

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ABSTRACT
Many indictors and data sources have been used for the purpose of drought mapping in areas with water shortage problems. This study aimed to assess the combined drought index (CDI) and the standardized precipitation index (SPI) in terms of their correlation with crop production and yield in Jordan. Also, the study mapped the spatial extent of drought vulnerability at different administration levels (subdistrict, district and governorate). The CDI was based on monthly data of climate and remote sensing data of the normalized difference vegetation index (NDVI), while SPI was derived from monthly precipitation data. Assessment of both indicators was based on their degree of correlation with yield and production of rainfed crops in five governorates for the period 1994-2016. Vulnerability mapping was based on the use of different data related to sensitivity and adaptive capacity. Results showed that CDI had higher correlations with crop yield than SPI, with variations in the coefficient of determination (R^2)among the different governorates and for different periods for which the CDI was calculated. Results indicated that the use of 6-months CDI (November-April) for the purpose of drought assessment would be more convenient than the use of annual CDI or CDI for periods of 3 months. Results of drought vulnerability mapping showed that the high rainfall zones in Jordan are the most vulnerable areas in terms of drought. The governorates of Irbid, Jarash and Ajloun showed severe levels of drought vulnerability resulting from their high sensitivity and exposure and the relatively low adaptive capacity, particularly the available water resources in relation to the total population.

Keywords–CDI, Drought, GIS, Jordan, Remote sensing.

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I. INTRODUCTION

Drought is defined as a lack of water over a span of time that impacts some activities, groups, or environmental sectors [1]. It is described from a climatological perspective by prevailing unfavorable conditions that led to water deficit as high temperature and low and erratic rainfall [2]. This natural threat is considered to be disastrous to the main aspects of life on earth, especially in regions with water scarcity and food insecurity. In addition, it has negative impacts on economy, environment, and social life [3]. Therefore, understanding the causes and consequences of droughts is very crucial for food production and planning and management of water resources. This in turn requires management and action plans that include drought monitoring and assessment to minimize the negative impacts of drought on the different sectors.

Jordan is a water scarce country that suffers from frequent droughts that contribute to water shortage problems in the country. Historically, drought has been recognized since the late 1950's [4]. The worst drought event that was documented in Jordan was that of the 1999/2000 season which had 30 percent of the long-term average rainfall and resulted in 60% reduction in yield and production of rainfed crops, as well as in extremely low water amounts harvested in the main reservoir [5]. Drought continued to worsen with time and the last two decades showed to be the worst periods in terms of rainfall reduction and impacts on water resources, rainfed agriculture and livestock sector [6,7,8,9]. Therefore, drought monitoring and assessment is highly important and crucial for planning and management of water and land resources in the country.

Monitoring of drought requires the use of frequent and periodic data that reflect the spatial and temporal dimension of drought. The most commonly used data to monitor and assess drought is the rainfall data that is transferred into the Standardized Precipitation Index (SPI) [10]. The accuracy of SPI and meteorological indices, however, is highly affected by the spatial distribution of weather stations and the errors encountered by data collection [11]. Subsequently, many researchers proposed the use of remote sensing data to map and monitor drought, particularly the Normalized Difference Vegetation Index (NDVI) which showed to be highly correlated with rainfall [12]. Both of meteorological and remote sensing data can be utilized to map drought through the use of a combined drought index (CDI) [13, 14].

In Jordan, drought monitoring is based on the use of the NDVI from high temporal resolution data [11,15]. The use of CDI was proposed for the National Drought Committee (NDC), led by the Ministry of Water and Irrigation (MWI) Also, drought vulnerability maps were also needed by the NDC to identify areas with high priorities for proactive actions needed in the case of drought occurrence [16]. The advantage of CDI over the use of SPI or NDVI is the inclusion of the combined information from rainfall, vegetation, in addition to air temperature. However, the use of CDI requires validation for its correlation with crop yield and productivity to assess the contribution of NDVI over SPI. In addition to CDI validation, mapping of drought vulnerability in Jordan is needed at different administrative levels.

This study aims to assess the correlation between CDI and crop yield and production in different areas in Jordan. Also, it includes mapping of drought vulnerability at different administrative level. The approach of drought vulnerability mapping is based on considering sensitivity and adaptive capacity that are derived from biophysical and socioeconomic data. The down-scaled approach for these levels (Governorate, district and sub-district) will provide different options for drought response planned by decision –makers in the country. These maps are important in the light of predictions of climate change and drought occurrence, which showed negative trends of climate change [17] that would result in reduction of agricultural production [18,19].

II. METHODOLOGY

2.1 Study Areas

The study of CDI assessment covered five governorates (Irbid, Ajloun, Jarash, Madaba and Karak) where most of rainfed crops are cultivated (Fig. 1), while mapping of vulnerability covered the whole country at the levels of governorate, district and subdistrict. The study included the data of 29 stations operated by Jordan Meteorological Department (JMD). The governorates with data for CDI assessment has differences in their Mediterranean climate, as well as terrain. Elevations are in the range of 600-800m In Irbid, Jarash and Madaba, while the governorates of Ajloun and Karak has high elevation (900-1100m) and colder climate than the other governorates.

Rainfed cultivation in the five governorates and in the rainfed areas in Jordan starts in October and ends by May and June. Some farmers practice the late sowing which starts in December. The five governorates have a wide range of soil types. However, cultivation is mainly carried out in heavy clayey soils that have high storage for rainfall water [19]. Rainfall gradient is sharp in the five governorates, except in Ajloun. Rainfall decreases from west to east, north to south and from high to low altitudes. These trends characterize rainfall of Jordan as well (Fig. 1).

In terms of drought vulnerability, Jordan as a whole was considered in the mapping approach. The climate of the country can be described as arid in the west to hyper arid in the east. Areas with rainfall that exceed 400mm have semiarid climates. Generally, the country has a Mediterranean climate with cold winters and hot summers. Spring and fall are short transitional seasons; i.e. spring extendsin March and April and fall during September and October.

2.2 Assessment of the CDI

Drought indices are mathematical expressions based on empirical and/or physical approaches to study drought either quantitatively or qualitatively, which can be more effective than the direct use of raw climatic and crop data [10,20]. However, these indices require validation and assessment before being used for drought monitoring. The CDI is among the indices that were developed and adopted for drought monitoring in different countries [21].

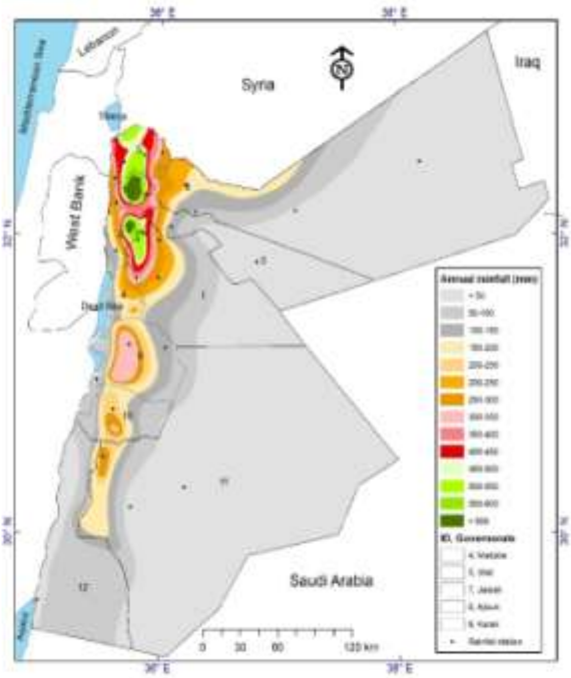

Figure 1: Location of the study areas and JMD weather stations in Jordan.

The CDI is based on four datasets that can obtained from remote sensing and climatic data at different spatial resolutions. These are the precipitation, soil moisture, the NDVI and soil surface temperature. This form of CDI was used by the United States Drought Monitor(USDM), (http://droughtmonitor.unl.edu) to generate drought maps with 5-km resolution for the entire US. Another version of CDI is the numerical CDI that was developed by the Food and Agriculture Organization of the United Nations [22]. This numerical CDI, which uses the data of precipitation, NDVI and air temperature, was assessed in this study to evaluate its ability to reflect drought conditions in rainfed areas in Jordan.

The numerical CDI was derived using the monthly data of rainfall and air temperature from JMD stations, the monthly NDVI from the National Oceanic and Atmospheric Administration - Advanced Very High-Resolution Radiometer (NOAA-AVHRR)at 5-km resolution. The CDI was calculated as following [22]:

$$CDI_{i,m},=(W_{PDI}*PDI_{i,m}) + (W_{TDI}*TDI_{i,m}) + (W_{VDI}*VDI_{i,m}) \quad (1)$$

Where,

- $CDI_{i,m}$ is the CDI for interest period (i) ending in time unit m.
- PDI, TDI and VDI arethe monthly precipitation temperature and vegetation (NDVI) indices, respectively.
- W is the weight of CDI components (0.50 for PDI, 0.25 for NDVI and 0.25 for PDI).

The calculation of the drought index (DI) in simple words can be expressed as:

$$DI = \frac{\text{Actual average for IP}}{\text{LTM for IP}} \times \sqrt{\frac{\text{Actual length of continuous deficit / excess in IP}}{\text{LTM length of continuous deficit or excess in IP}}} \quad (2)$$

WhereIP is the interest period (months),LTM is the long term average. The deficit applies to rainfall and NDVI, and excess applies to temperature.Interpretation of CDI values and their corresponding classification is as follows: No drought for CDI value >1.0; Mild drought for CDI range of 0.8-1.0; Moderate drought for CDI range of 0.6-0.8; Severe drought for CDI range of 0.4-0.6; Extreme drought for CDI<0.4.

The equations and detailed steps of calculating the CDI components are included in the manual of the software used to derive CDI components [22]. The CDI was calculated for the 29 JMD stations for different IP that covered 3 months (CDI_3) for different intervals during October-March, 6 months (CDI_6) for the rainy season October-March and 12 months (CDI_{12}or annual CDI) for January-December.

Outputs from calculations were CDI values for the 29 stations for the period 1994-2016. The data was transferred to point layers in the geographic information system (GIS) environment. The layers were then transferred into maps using the spatial interpolation method of the Inverse Distance Weighted (IDW) that gave higher weights to distance. The CDI was extracted for the governorate level using GIS spatial analysis tools. This was carried out to harmonize the data of CDI with the crop yield data which was obtained for the five governorates.

The numerical CDI data at governorate level were assessed by comparing the CDI at governorate level with the data of production and yield for rainfed crops for the period 1994-2016. This data was originally collected by the Department of Statistics (DOS) on annual basis and it was downloaded from the website of DOS (http://dosweb.dos.gov.jo/). Linear regression was carried out between CDI and crop production and the average yield (ton/ha). The comparisons were carried out for CDI_{12} $CDI_6$and CDI_3. The same comparisons were also carried out for SPI which was derived for 12 (annual), 6 and 3 months [23].

2.3 Mapping of drought vulnerability

Mapping drought vulnerability was based on the use of data from DOS and MWI, in addition to GIS maps of land use [18]. The approach of vulnerability mapping wasadapted from the concept and guidelines for standardisedvulnerability assessments as following [24]:

$$V = \frac{P}{Ia} = \frac{(E \times Is)}{Ia} \quad (3)$$

Where, V is the vulnerability, Ia is the adaptive capacity, P is the potential for drought, E is the exposure and I_s is the sensitivity.

The indicators represented natural factors related to exposure and a combination of natural and human-driven factors for the sensitivity [25]. Adaptive capacity, on the other hand, was based on the availability of water and financial resources that were implied in the poverty levels. Sensitivity and adaptive capacity were summed for the selected indicators, which were given equal weights. Subsequently, sensitivity was calculated using the following formula:

$$I_s = \sum a_i S_i \quad (4)$$

Where S_i is the indicator or data point of the target's sensitivity and a_i is the weighting factor of the sensitivity indicator S_i.

Similarly, adaptive capacity was calculated as follows:

$$I_a = \sum b_i C_i \quad (5)$$

Where$C_i$is the indicator or data point of the target's adaptive capacity and bi is the weighting factor of the sensitivity indicator C_i.

Each component of equation 3 was calculated by averaging the indicators for sensitivity and adaptive capacity. Therefore, data from DOS was tabulated and arranged for the three administration levels that included 12 governorates, 51 districts and 89 subdistricts.

The approach has the strength of scaling or normalizing the components of vulnerability from zero to one as the general formula for each indicator (data point) is calculated as follows [24]:

$$X_{i,0\ to\ 1} = \frac{(Xi - X_{min})}{(X_{Max} - X_{min})} \quad (6)$$

WhereX_i represents the individual data point to be transformed,$X_{Min}$is the lowest value for that indicator,$X_{Max}$is the highest value for that indicatorand$X_{i,0\ to1}$is the new value to calculate, i.e. the normalised data point within the range of 0 to 1.

The individual data point represented each indicator included in exposure, sensitivity and adaptive capacity. Equations for calculating vulnerability were applied in spreadsheets. Results were appended as attributes to the GIS layers of the three administrative levels. The output maps were classified based on the average and the standard deviation. Classes of vulnerability were based equal intervals(Table 1).

Table 1: Classification of vulnerability classes.

Value	Vulnerability class
< 0.20	No vulnerability
0.20-0.40	Low vulnerability
0.40-0.60	Moderate Vulnerability
0.60-0.80	High vulnerability
> 0.80	Extreme vulnerability

A summary of the criteria and the data used for mapping drought vulnerability is summarized in Table 2. The same criteria for drought vulnerability mapping was also applied after including the number of Syrian refugees in the data of total population and poverty. This was carried out based on requests of decision-makers (MWI) to prioritize plans and actions for those areas. The data on refugees population was obtained from official sources [25,26] for subdistrict level.

Table 2: Summary for criteria used in mapping drought vulnerability.

Component	Criteria	Steps
Exposure	Drought occurrence	1- CDI calculated and GIS maps prepared. 2- Count (Value) for years with CDI <0.6 was summed for each administration level. 3- Apply equation 6.
Sensitivity	1- Population 2-Agriculture 3-Livestock 4-Forestsand reserves	Equation 4 applied on the following indicators: 1- Population of administrative unit relative to the total population. 2- Agricultural area in relation to the area of administrative unit. 3- Livestock in relation to area of rangelands and agricultural area (rainfed and 0.20 of irrigated). 4- Area of forest or natural reserve.
Adaptive capacity	1- Poverty 2- Municipal Water 3- Irrigation water	1- Poverty as percent for each subdistrict was used for sensitivity by normalizing equation 6. 2- Per capita of Municipal water calculated using supply and population. 3- Maps of groundwater wells were used to derive available water per irrigated area.

III. RESULTS AND DISCUSSION

3.1 Assessment of the CDI

Coefficient of determination between CDI and crop production and yield is summarized Table 3. Results showed variations the degree of correlation among CDI, SPI and crop yield and production. Generally, weak correlation was observed between the crop production and CDI_{12} (Annual CDI). However, correlations between CDI_{12} and crop yield and production were better than those obtained for annual SPI. The same trend was also observed for most of the correlations for the 3 and 6 months CDI. Results showed that CDI_{12} was significantly correlated with wheat production in three governorates and production of barley and all rainfed crops in two governorates. The degree of correlation improved for the data of yield (ton/ha), except in the governorate of Madaba. For most governorates, production and yield were not significantly correlated with SPI_{12}. This could indicate that annual CDI_{12} was better than annual SPI_{12} in assessing the overall drought conditions at the governorate and country level. The coherency of CDI as an indicator that would reflect the variation incereal crop yields during a drought period was also indicated in Europe [21].

The CDI_6 for the rainfall season October-April showed better correlations with production and yield for wheat and barley than the annual CDI did. The maximum correlations were obtained for the data of Karak, with an R^2 value that reached 0.65 for barley yield with CDI_6, compared with a value of 0.35 for the annual CDI vs barley yield (Fig. 2). Comparing the CDI_6 showed better correlations with production and yield than the SPI6, with exceptions for Madaba. This could indicate that the use of 6 months CDI during October-March would be convenient for assessing agricultural drought and for assessing drought impacts on rainfed agriculture in Jordan.

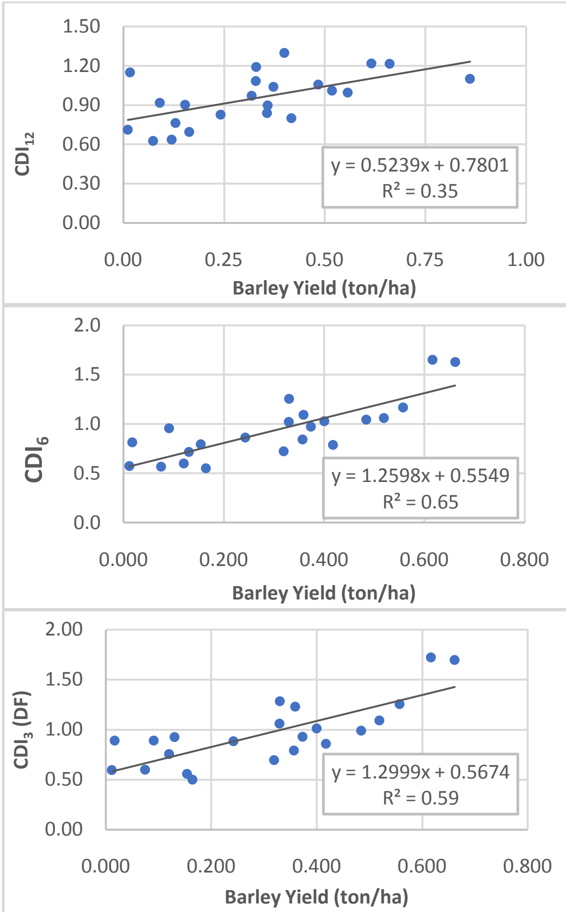

Figure 2: Relationships between barley yield and CDI_{12} (Top) CDI_6 (Middle) and CDI_3 (Bottom) in Karak governorate.

Table 3: Coefficient of determination (R2) between rainfed crop production and yield with CDI and SPI for the period 1994-2016.

Relationship*	Irbid	Ajloun	Jarash	Madaba	Karak
Production and yield vs CDI_{12}					
TP vs. CDI_{12}	ns**	ns	0.35	ns	0.37
WP vs. CDI_{12}	0.29	ns	0.38	ns	0.35
WY vs. CDI_{12}	0.27	0.35	0.56	ns	0.37
BP vs. CDI_{12}	ns	ns	ns	0.32	0.32
BY vs. CDI_{12}	0.29	0.22	0.22	0.19	0.35
Production and yield vs SPI_{12}					
TP vs. SPI_{12}	0.19	ns	ns	ns	0.19
WP vs. SPI_{12}	ns	ns	ns	ns	ns
WY vs. SPI_{12}	ns	ns	ns	ns	ns
BP vs. SPI_{12}	0.31	ns	ns	ns	0.23
BY vs. SPI_{12}	ns	ns	ns	ns	ns
Production and yield vs CDI_6					
TP vs. CDI_6	ns	ns	0.48	0.21	0.54
WP vs. CDI_6	0.34	ns	0.40	ns	0.50
WY vs. CDI_6	0.47	0.34	0.46	ns	0.45
BP vs. CDI_6	ns	ns	0.47	0.42	0.43
BY vs. CDI_6	0.26	0.26	0.30	0.18	0.65
Production and yield vs SPI_6					

TP vs. SPI_6	ns	ns	0.38	0.30	0.52
WP vs. SPI_6	0.31	ns	0.30	0.21	0.47
WY vs. SPI_6	0.34	0.34	0.32	ns	0.41
BP vs. SPI_6	ns	ns	0.38	0.38	0.44
BY vs. SPI_6	0.25	0.22	0.30	0.22	0.57
Production and yield vs CDI_3					
TP vs. CDI_3***	ns	ns	0.36 NJ	0.22NJ	0.47 DF
WP vs. CDI_3	0.30 NJ	ns	0.38 DF	ns	0.42 DF
WY vs. CDI_3	0.47 NJ	0.30 DF	0.36 NJ	ns	0.38 JM
BP vs. CDI_3	ns	ns	0.24 NJ	0.47NJ	0.40 DF
BY vs. CDI_3	ns	0.23 DF	0.23 NJ	0.24NJ	0.59 DF
Production and yield vs SPI_3					
TP vs. SPI_3***	ns	ns	0.25 NJ	0.27 NJ	0.43 DF
WP vs. SPI_3	0.26 DF	0.19 JM	0.33 NJ	ns	0.40 NJ
WY vs. SPI_3	0.35 NJ	0.25 JM	0.20 NJ	ns	0.32 JM
BP vs. SPI_3	ns	ns	ns	0.42 NJ	0.40 DF
BY vs. SPI_3	ns	ns	ns	0.23 NJ	0.54 NJ

* TP: Total production, WP: Wheat production, WY: Wheat yield, BP: Barley production, BY: Barley yield.
** ns: not significant at $P < 0.05$
*** Maximum significant correlation is shown with the abbreviations OD: Oct-Dec; NJ: Nov-Jan; DM: Dec-Mar.

Results for the 3-months CDI explained important factors related to drought and production of rainfed crops. In terms of correlation with production and yield, the CDI_3 showed slightly lower correlations with production and yield than the CDI_6 in some governorates and better correlations in others. Both of CDI_3 and CDI_6, however, showed better correlations with production and yield than the annual CDI. These findings agreed with the studies that recommended the use of indicators for shorter interest periods than using the annual indicators for drought assessment [21,28,29].

Similar to CDI_{12} and CDI_6,the CDI_3 showed slightly higher values of R^2 for the correlations with yield and production than the SPI_3. The important findings from the results obtained for CDI_3 and SPI_3 were the periods for which the index was derived. These were different among the governorates and reflected the character of each area. For example, the period of December-February was the important period that had significant impacts on yield and production of rainfed wheat and barley in Karak. In other governorates, the period of November-January was more important than the periods December-February and January-March. These results could indicate the positive impact of early rainfall on crop production and yield. Oppositely, the high correlations for the periodJanuary-March in Karak and Ajloun could be attributed to the impact of temperature as a component of CDI_3, as both areas had colder climates than Jarash, Irbid and Madaba. Subsequently, rainfall during January-March would significantly contribute to crop yield in both governorates.

The variations in correlations between CDI and crop production and yield among the governorates could be also attributed to the agricultural management practices and the land use/cover of each governorate. For example, the governorates of Ajloun and Madaba showed weak correlations or insignificant correlations among crop production and yield with CDI which could be explained by the presence of forests in Ajloun and the presence of irrigated areas in Madaba. Expansion of urbanized areas in Irbid and Madaba, on the other hand, would also contribute to the variations in CDI and changes in crop production during 1994-2016.

3.2 Drought Vulnerability

Maps of drought vulnerability showed that the potential of drought (Fig. 3) was high for many parts of the country, particularly the high rainfall zones in the north and northwest of Jordan where exposure and sensitivity were high and adaptive capacity (Fig. 4) was low. As a result, these subdistricts were highly vulnerable to drought (Fig. 5). Although the subdistricts in low rainfall zones had low adaptive capacity, however, their sensitivity to drought was low due to the high aridity in these areas and the low numbers of population.

The degree of vulnerability was different among the administration levels (governorate, district and subdistrict), with consistent results for the northwest areas of Jordan (Fig. 6, Fig. 7 and Fig. 8). This was mainly attributed to the high potential for droughtin these areasresulting from the high percent of rainfed areas and the presence of forests that form important ecosystems in the country. In addition, the northwestern areas had been subjected to severe droughts in the last three decades, as revealed by the CDI and SPI analysis which showed that the probability of drought occurrence reached 25% (Once every 4 years). Therefore, results indicated that the most vulnerable areas to agricultural drought were rainfed croplands and forest, located in areas with a very high probability of drought occurrence. Under these conditions soil moisture deficiency would be high [30].

Differences in the map of vulnerability for subdistrict were observed when the data of Syrian refugees was included in the mapping (Fig. 6) when compared with the map without considering this data (Fig. 5). The result of these changes in vulnerability is increase in vulnerability level for the already vulnerable subdistricts in the northwest of Jordan (Irbid, Ajloun, Jarash) and in Mafraq and Zarqa governorates. This could be explained by the fact that these areas host the larger number of refugees than other areas in Jordan. The impacts of refugees on the populationwas also related to reduction in water share. The political dimension of the war and political conflict in Syria deprived Jordan's share from transboundary water coming from Yarmouk River, as indicated by previous studies [31] that indicated the deterioration of the water resources that would lead to more drought vulnerability.

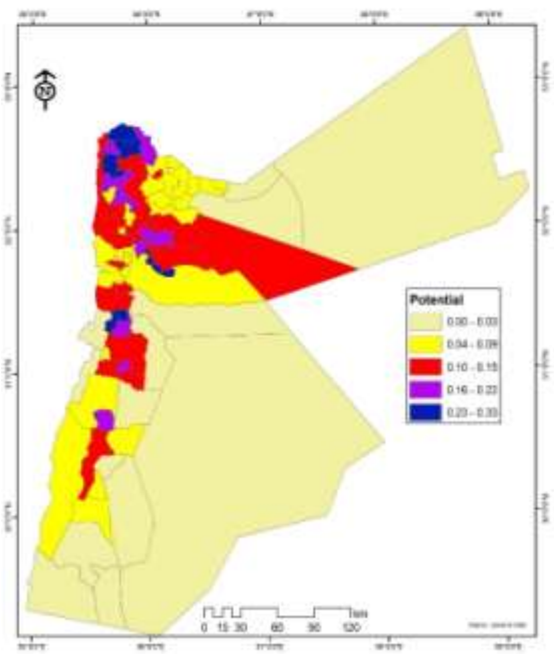

Figure 3: Drought potential based on exposure and sensitivity for subdistrict level.

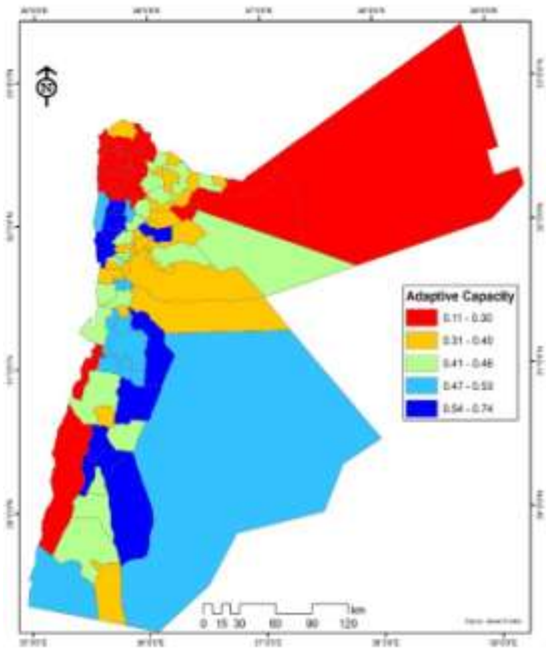

Figure 4: Adaptive capacity for drought at subdistrict level.

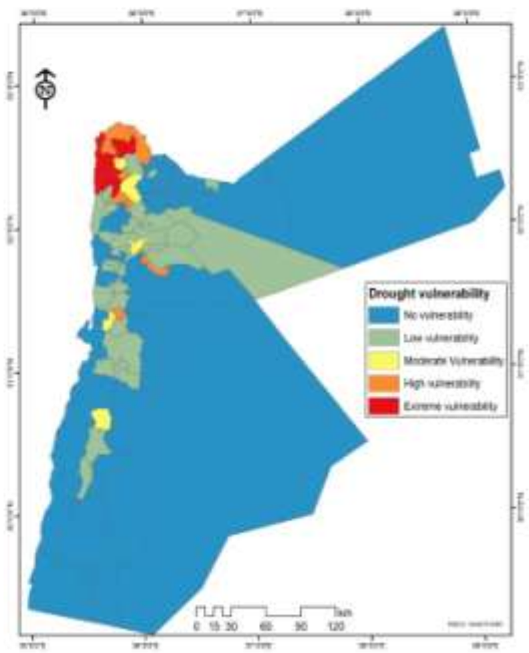

Figure 5: Map of drought vulnerabilityfor the subdistrict level in Jordan.

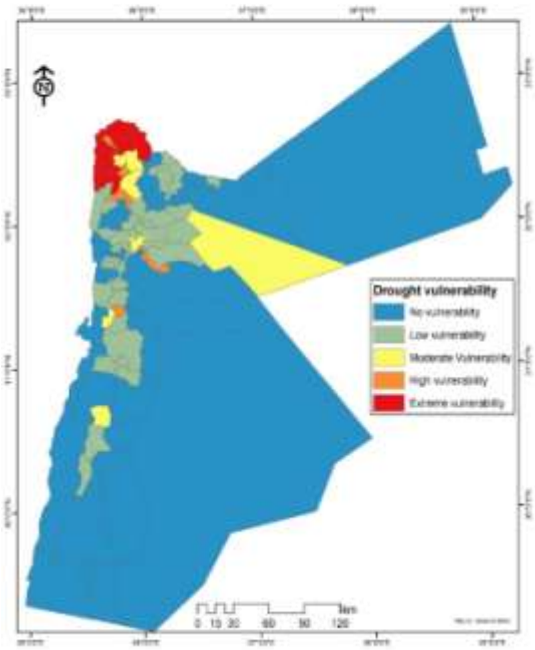

Figure 6: Map of drought vulnerabilityfor the subdistrict level in Jordan after including the number of refugees.

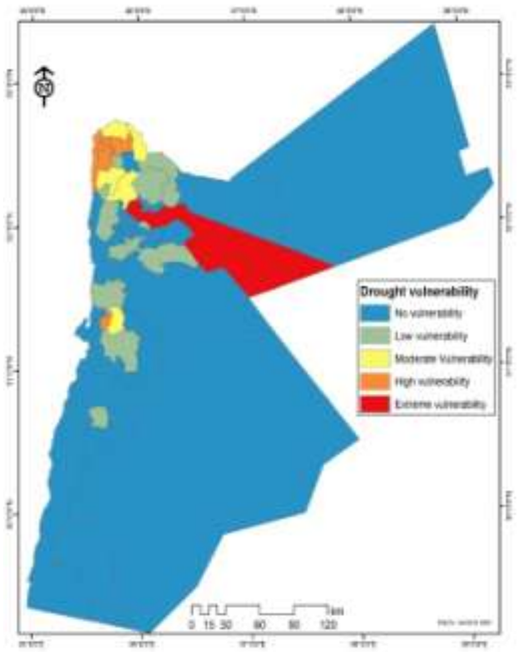

Figure 7: Map of drought vulnerabilityfor the district level in Jordan.

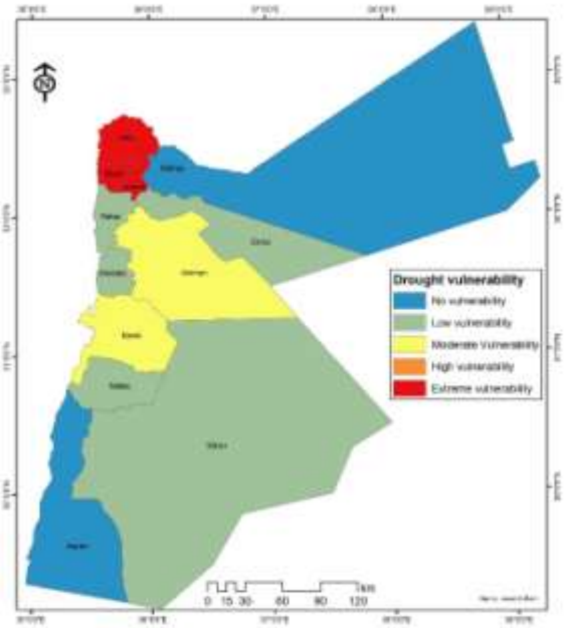

Figure 8: Map of drought vulnerabilityfor governorate level in Jordan.

Results of vulnerability showed that aggregating data from subdistrict to district and to governorate levels resulted in changing the vulnerability level. This would show the strength of the approach followed for vulnerability mapping as it reflected the main factors leading to drought vulnerability. The factors were a combination of environmental and socioeconomic conditions that were also indicated as the main rivers for drought risk and vulnerability [32,33].

Finally, thechanges in vulnerability maps according to administrative level would reveal possible solutions to decision-makers by proposing means for improving adaptive capacity. Since water scarcity is the main challenge for drought mitigation, augmentation of water supply shall be considered with possible actions that include inter-basin water conveyance. Also, master plans for water and land use shall be consider for the highly vulnerable areas.

IV. CONCLUSIONS

Results indicated the suitability of CDI for mapping and monitoring of drought severity in Jordan. The use of CDI would be better than the use of the single indicator (SPI) for this purpose. The use of the 3 and 6 months CDI would be recommended over the annual CDI fro drought monitoring and assessment. Considering the characteristic of each zone, it could be concluded that CDI_3 would change in terms of the calculation depending on the interest period. Results from this study would recommend the use of November-January period for warm areas and January-March for cold rainfed areas. In terms of improvement for the CDI, it would be important to validate the weights of CDI components, although the default weights used in this study were convenient and responded tochanges in production and yield, particularly for wheat and barley.

In terms of drought vulnerability, the study represented the first attempt in Jordan to map spatial distribution of drought. Results showed that areas with relatively high rainfall zones in the north and northwest of Jordan were the most vulnerable areas.The approach of vulnerability mapping identified these areas at the level of subdistrict. The combination of high sensitivity and low adaptive capacity, in addition to the regional conflict and immigration, made these areas highly vulnerable to drought. As such, the problem of water scarcity under prolonged droughts in the future would add more challenges to water management in Jordan. Therefore, plans for strengthening adaptation in these areas are urgently needed.

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