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Assessing Drought Pattern Through Satellite Based Observation in the Koshi River Basin, Nepal

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Abstract: Drought identification is crucial for different environmental and ecological consideration. This study observed the spatial and temporal variation of drought based on satellite-derived vegetation condition index (VCI) on different time scales i.e. Winter, Pre-monsoon and Annual compared with remotely sensed Land Surface Temperature (LST) and precipitation. MODIS NDVI product, LST and meteorological stations data for rainfall were used. VCI was used to classify drought. The Pearson correlation between VCI with LST and precipitation was conducted. The results shows that severe drought was detected in 2001 in winter and pre-monsoon season and also in 2006 during pre-monsoon season. No severe drought was detected on the annual time scale but normal droughts were found in several years. The VCI trends has increased at the rate of 1.29 yr-1, 1.52 yr-1 and 1.72 yr-1 for annual, winter and pre-monsoon respectively. Conversely, the LST decreased at the rate of 0.007 yr-1, 0.044 yr-1 and 0.028 yr-1 during annual, winter and pre-monsoon. These increased VCI and decreased LST indicates decreases in drought trends in an annual scale. The positively increased Anomaly of VCI (AVCI) indicates a better vegetation growth under moist soil condition. The VCI was also linked with precipitation showing positive correlation on annual and pre-monsoon time scale but negative correlation with winter season. The correlation between LST and VCI was negative in all time scales and more significant during pre-monsoon and winter season. This study helps to understand vegetation-based drought and its relation with temperature and precipitation in the Koshi basin in Nepal.

Keywords: Vegetation Condition Index; Land Surface Temperature; Precipitation; Drought; Koshi River Basin

1. Introduction

Drought is a natural hazard which occurs slowly on a considerable time period with greater impacts to environment. Generally, drought is categorized into four major types according to different types of water deficits which are: meteorological droughts, Agricultural droughts, hydrological droughts and ecological droughts [1]. Among these types, agricultural drought is simply characterized by the lack of moisture in soil that effects the crop yield as well as vegetation growth [2]. It is considered as natural disaster which plays a vital role in economics for agrarian countries like Nepal, India where 68% of people are totally dependent on agricultural production [3]. Different techniques have been developed to calculate indices for drought monitoring using different climatic parameters such as precipitation, temperature and evaporation [4]. Remote sensing is obviously a useful tool for monitoring drought. Normalized Difference Vegetation Index (NDVI)[5], Temperature Vegetation Drought Index (TDVI) [6], Vegetation Condition Index (VCI)[7], Vegetation Health Index (VHI), Absolute Normalized Difference Vegetation Index (ADVI), Standardized Vegetation Index (SVI) are RS-based vegetation drought indices. NDVI is the most popular index used across the world to determine the fluctuation in greenness of plant in a spatial and temporal scale throughout the time span [4]. VCI is the NDVI derived vegetation condition index [8].

The efficiency of remotely sensed derived VCI in assessing agricultural drought monitoring is shown by positive correlation between VCI and rain fed crops [9]. VCI can be used effectively for regional drought assessment [10]. Also, assessment of frequency trend analysis of regional drought can be performed using VCI [8]. Drought monitoring using VCI index has higher sensitivity than using NDVI and temperature vegetation drought index (TVDI) [11]. VCI is better indicator of moisture deficiency than NDVI because it separates short time climate signals from the long term ecological signals thus it is widely used to monitor and analyze drought around the world [12]. Therefore, VCI emerged as one of the best remote sensing techniques to monitor drought which obviously help to understand the economic loss caused by ecological and agricultural drought [4]. Climate change has influenced the rise in temperature all over the world. Global warming has become the main concern at today's time. Earth surface temperature has also risen than before which could give lead to drought. Since heat and water exchange with the atmosphere is controlled by earth, temperature that earth radiates is used to figure out land surface temperature [13]. LST is one of the important climatic variable that builds relation between earth's surface and atmosphere [14]. Higher LST is the indication of the scarce vegetation correlating with the drought depending upon types of vegetation. Ecological droughts are the events of deficit in water availability that ecosystems become more vulnerable, impacts ecosystem services, and natural and/or human systems get affected [15]. Assessment of ecological drought in Yellow River estuary of China tells that shortage of water and soil moisture resulted in severe ecological drought [16]. Increase in land surface temperature is the reciprocal of the vegetation growth, which is also one of influencing factors of ecological drought.

Nepal receives almost 80% of annual rainfall in monsoon months [17], while there is deficit on water in other months contributing only 3% of annual rainfall [18]. Summer monsoon is characterized by southeasterly monsoonal winds originated and coming from the Bay of Bengal and occasionally from the Arabian Sea with precipitation distributed over large area where as winter monsoon is described by westerly wind with localized precipitation [19]. Deficit in precipitation on different timescales brings meteorological drought. Mid and far western Nepal often faces more drought [20], especially during the winter and summer season [21] Therefore, they are regarded as drought prone areas. Central Nepal observed the worst widespread droughts in the year 2004, 2005, 2006, 2009 during summer and 2006, 2008 and 2009 during winter [4]. The lowlands and the western hills of Nepal are frequently dominated by drought where temperature is comparatively higher. Drought leads to economic losses as it directly affects crops and people of countries like Nepal who are mostly dependent on rain -fed agriculture for their livelihood.

In recent years, drought has emerged as a source of vulnerability in rain fed agriculture in Nepal particularly in hills and mountains [21]. There have been many studies related to drought monitoring but very few in Nepal and remote sensing-based drought studies which is needed to further exploration and linked to vegetation and ecology. Previously, studies were linked between atmospheric circulation and some climate indices with the spatial and temporal pattern of drought events based on Precipitation data calculating standard precipitation index (SPI) [18,20,21). For the spatial extent, stations must be in larger number. As in the case of Nepal, data gaps could be the major problem and fewer stations might not enough to cover the whole area. The commonly used index SPI creates the problem when precipitation contains a number of significant zero values (mostly in dry climates) [22]. Calculating SPI using limited station data to monitor drought could give unconvincing results. Satellite based research on understanding the temporal and spatial patterns of drought and its change is limited. A synoptic view of the land and measuring drought impacts on a spatial context through satellite remote sensing have proved to be a valuable source of timely, spatially continuous data with improved information on monitoring vegetation dynamics over large areas [23]. Moderate Resolution Imaging Spectroradiometer (MODIS) images are already calibrated and its noise effects are omitted. Therefore, it is reliable to use MODIS images for drought monitoring. Thus, this study has investigated VCI based drought possibility and its nexus with temperature and precipitation in the Koshi basin of Nepal. This study explores the new dimension of the vegetation-based drought which is directly related to the ecology and moisture availability. Using satellite-based drought pattern are very useful in the Himalaya country like Nepal where the meteorological stations are scare and difficult for frequent physical surveillance of the drought.

2. Materials and Methods

2.1. Study Area

The Koshi River basin is located between 850-890 E longitude and 250-290N latitude in the southern margin of the Tibetan Plateau. It extends 160 km North to South. The Koshi River is a trans-boundary river originating from the high Himalayas which cover 69,300 km2 area in which 45% of the land are located in the Nepal and the rest of other parts lie in Tibetan Plateau in the North and India in the South. The Koshi catchment receives 80 to 85% of the total rainfall from the southerly monsoons which starts from approximately end of May and continues until October. This basin is located at the eastern part of Nepal ranging between the altitudes of 77m at the South to 8796m at the North (**Figure 1**)

The forest is the dominant land use types which is followed by cropland in the Koshi river basin [24]. Temperature drastically changes in the region in response to elevation. A large part of the Koshi basin in Nepal which is located in the South of the Himalayan range receives an average annual precipitation of about 1,800 mm.

2.2. Data

This study is mostly based on remotely sensed MODIS data. Two MODIS products are used in this study namely MOD13Q1.006 Terra Vegetation Indices 16-Day Global 250m and MOD11A2.006 Terra Land Surface Temperature and Emissivity 8-Day Global 1km. The MOD13Q1 V6 NDVI product downloaded from https://lpdaacsvc.cr.usgs.gov/ appears during the period of 2001 to 2020, and it has 15 days temporal resolution and 1km spatial resolution. The semimonthly data was converted into monthly using maximum value composite method [25]. Additionally, MOD11A2 V6 product was used which provides an average 8-day land surface temperature (LST) and 1km resolution grid. Similarly, this data from 2001 to 2020 were taken for the study and processed in google earth engine and precipitation data of Meteorological stations situated at the basin during the same period were taken from Department of Hydrology and Meteorology (DHM), Government of Nepal. The auxiliary data such as DEM from SRTM site, LULC from ICIMOD, GIS layers data from Department of Survey were taken.

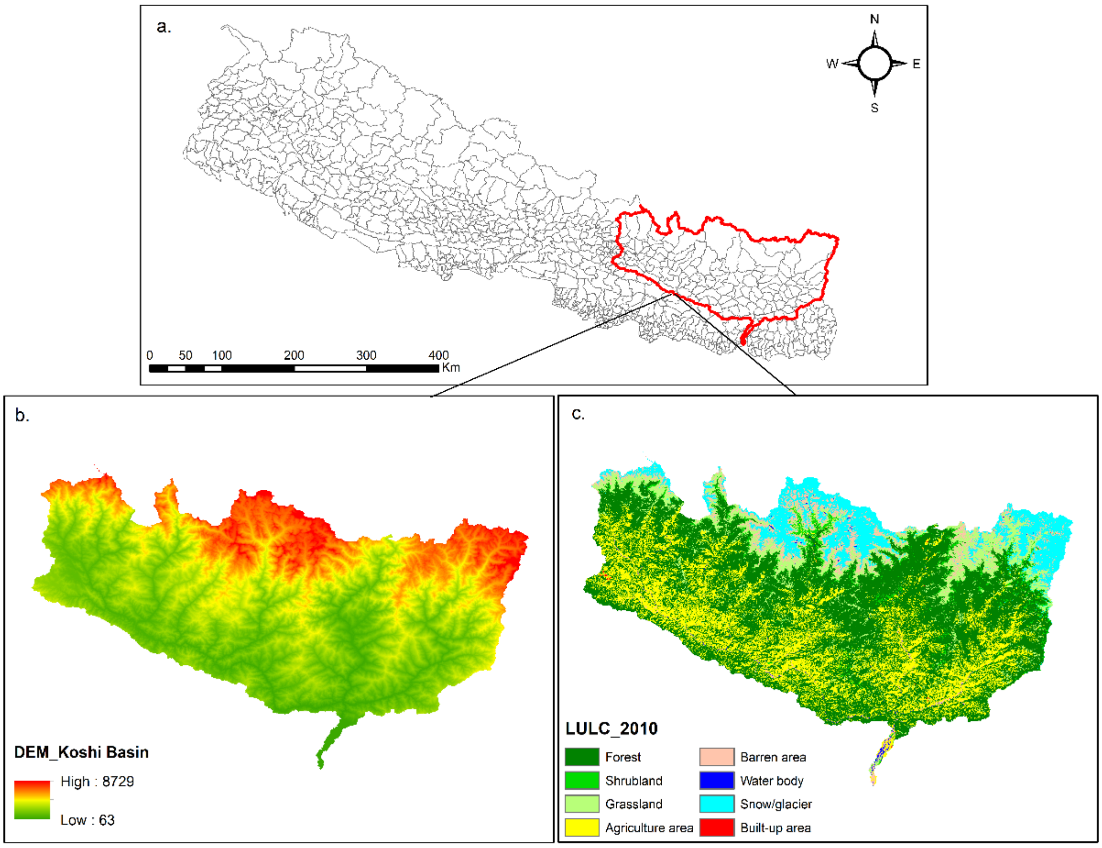

Figure 1: Study area; a) Koshi River basin in local unit map of Nepal; b) SRTM 30m DEM of Koshi Basin and c) Land Use Land Cover Map, 2010 [24]

2.3. Methods

2.3.1. NDVI Data Processing

Altogether 460 NDVI images from year 2001-2020 were collected along with 460-pixel reliability files. Most of the data are fine but the images during monsoon season were vague which needed to be masked in order to get better-and high-quality results. Along with this snow and ice covering pixels were made value zero because there is no use of ice and snow in calculating vegetation indices like VCI. Masking means to exclude the certain parts of the image for further analysis. Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs) ranging from -1 to +1 [26]. NDVI is calculated using formula of equation(1) [27].

$$NDVI = Red\text{-}Nir/Red+Nir \qquad (1)$$

Vegetation condition index (VCI) is derived from long term NDVI[28]. The VCI is expressed in % and gives an idea where the observed value is situated between the extreme values (minimum and maximum) in the previous years. Lower and higher values indicate bad and good vegetation state conditions, respectively. VCI is used to identify drought conditions and decide onset of drought areas where it frequently localized [29]. Mainly, it focuses on the impact of drought on vegetation and can provide information on severity of drought with the help of vegetation changes and comparing with historical values [30]. Kogan proposed a Vegetation Condition Index (VCI) based on the relative Normalized Difference Vegetation Index (NDVI) change with respect to minimum historical NDVI value. The VCI is calculated using equation (2) [28]

$$VCI_{ijk} = (VI_{ijk}-VI_{i,min})/(VI_{i,max}-VI_{i,min})*100 \quad (2)$$

where VCI_{ijk} is the VCI value for the pixel i during week/month/DOY j for year k VIijk is the weekly/monthly/DOYs VI value for pixel i in week/month/DOY j for year k whereby both the NDVI or EVI can utilized as VI, VIi,min and VIi,max are the multiyear minimum and maximum VI, respectively, for pixel i.

For the identification of drought using vegetation condition index VCI, three major types of drought grades was used which are based on VCI values developed for monitoring drought worldwide [28] as shown in **Table 1**.

Table 1: Drought grades defined by Vegetation Condition Index (VCI)

Grade	Types	VCI (%)
1	Normal	>50
2	Drought	35-50
3	Severe drought	<35

2.3.2. Land Surface Temperature Data Processing

These data were all processed in Google Earth Engine which is very useful and easiest platform for the students as well as researcher. It is known for its easy access. Using java script provided within GEE, altogether 920 images (MOD11A2 V6) were used to calculate LST on different timescales same as VCI.

2.3.3. Anomaly of Vegetation Condition Index

For the analysis historical changes of the VCI and the level of soil moisture conditions on annual and seasonal time scales, the anomaly of vegetation condition index (AVCI) was developed. The AVCI was calculated using Equation (3) [31]

$$AVCI = (VCI_i - VCI_{avg})/VCI_{avg} \quad (3)$$

Where, VCIi is the VCI value during a specific period, and VCIavg is the average VCI value during the studied period from 2000–2020. A positive AVCI indicates that soil moisture is relatively abundant and better than average vegetation conditions, while a negative AVCI indicates moisture deficient soil and worse than average vegetation condition.

2.3.4. Correlation Analysis

The Pearson correlation coefficient (r) between the VCI and climatic factor (i.e. Precipitation) on the annual, seasonal monsoon and pre-monsoon time scales was calculated to examine the relationship between drought and climatic factor [32]. The Pearson correlation analysis was conducted using the statistics package in R and the t-test [33] was performed for trend analysis significance. If the correlation coefficient between two variables is positive and the p-value is less than 0.05, it is believed that correlation is statistically significant.

As a whole, the descriptive process of the study is shown below in **Figure 2** as flowchart.

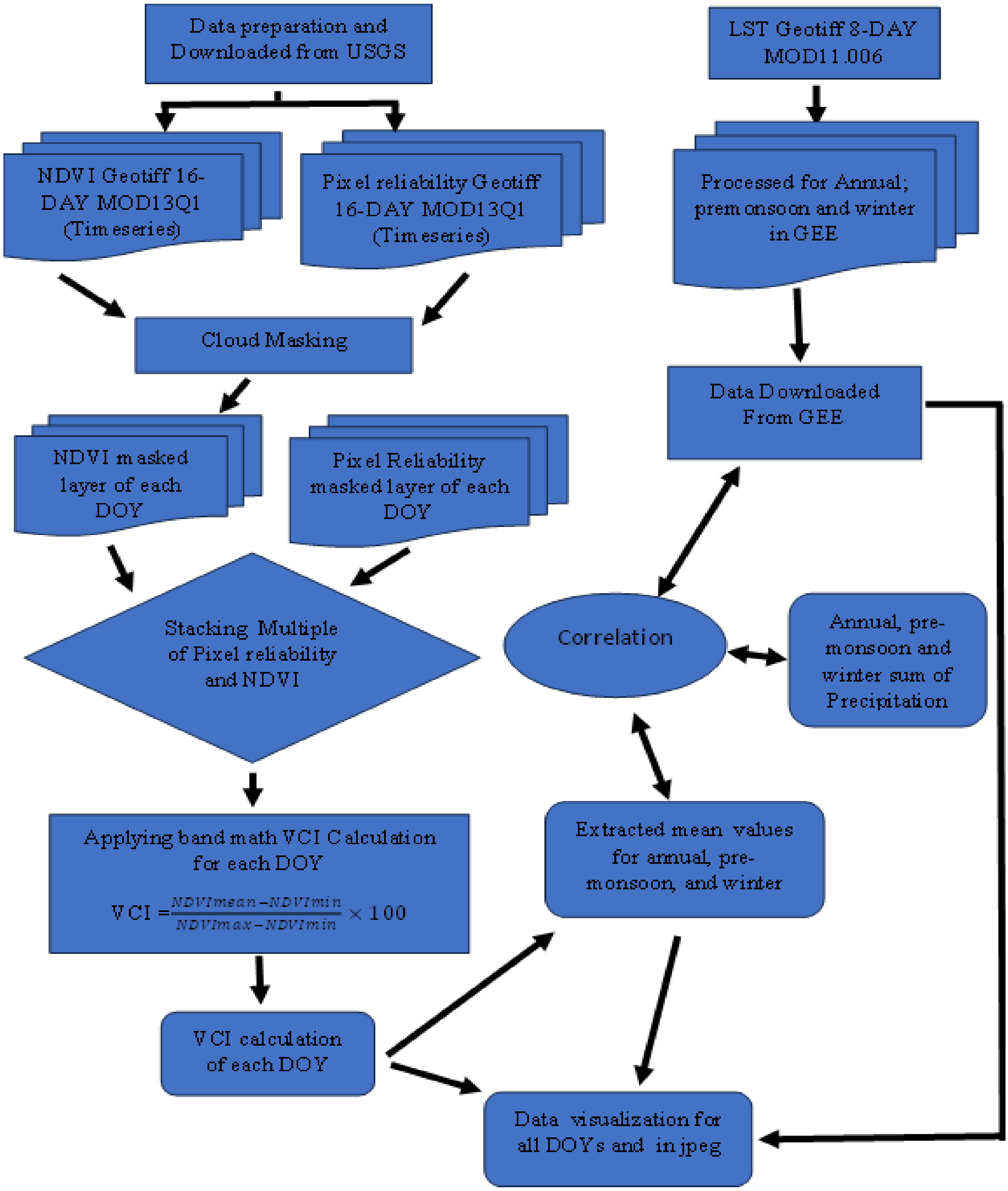

Figure 2: Flowchart of the data processing methods

3. Results

3.1. Temporal Variation of VCI

The average annual VCI for the year 2001 was 38.86% indicates moderate drought at the basin. The VCI values was also lower during winter and pre-monsoon season in 2021 which indicates that a year 2001 is a severely drought year. During 2009 and 2010, the VCI of the basin found 46.23 and 47.85% which indicates that the basin experienced moderate drought on that year. During 2020, VCI value reached 71.65% due to having a good vegetation and no drought was occurred. The severe drought was also identified later in 2006. Similarly, 2009 and 2013 was also identified as being in drought with VCI 40.1 and 42%, respectively. The overall VCI are lower in the basin however the annual, winter and pre-monsoon VCI trends was found positive in the basin during 2001-2021 (**Figure 3**).

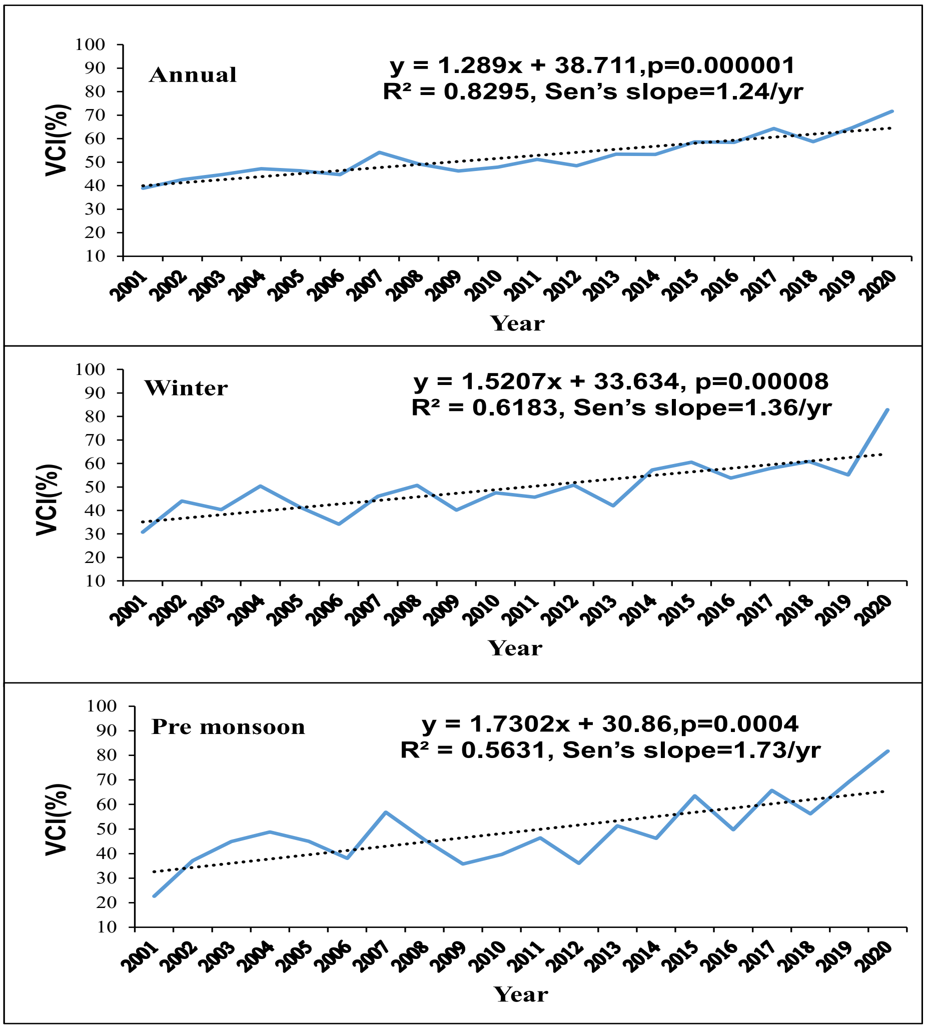

Figure 3: Temporal trend of vegetation condition index (VCI) for; Annual, winter, and Pre-monsoon season

Overall, the annual, winter and pre-monsoon VCI has increased at rate 1.29 yr-1, 1.52 yr-1 and 1.72 yr-1 respectively. However, majority of the years have average VCI of ranges from 38.86 to 60 % in all the season. In comparison to other season, the rate of positive VCI trends during pre-monsoon showed higher. The VCI was the lowest at the beginning but estimated to be increased and higher during the end of study period. Severe drought was notice in 2001 followed by 2009 having VCI value less than 36% indicating moisture deficiency. As shown in **Figure 4**, the spatial average annual, winter and pre-monsoon VCI during 2001-2021 were found 52.24%, 49.60%, 49.02%, respectively.

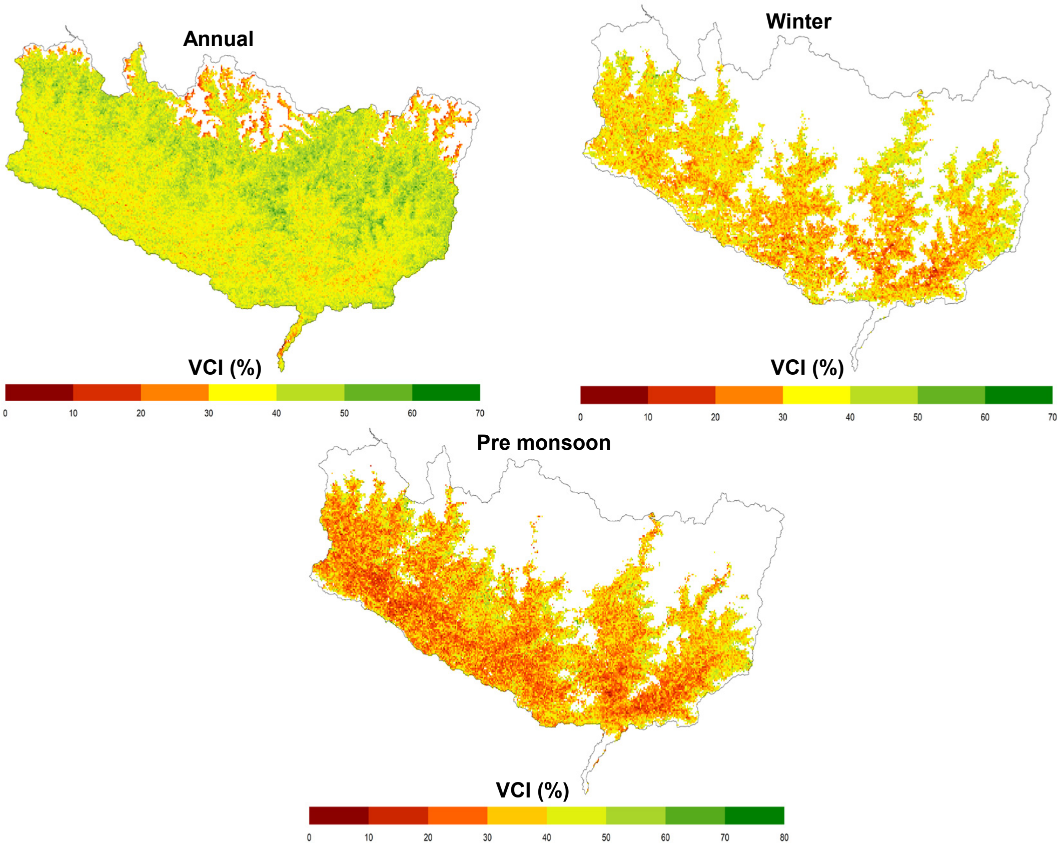

Figure 4: Spatial variation of the temporally averaged VCI; Annual, Winter and Pre- monsoon Vegetation Condition Index

3.2. Spatial Variation of VCI

Spatially, the basin experienced severe to moderate drought mainly during 2001-2006 but area covering Middle Mountain escaped from drought showing good vegetation. On a spatial extend of temporally averaged VCI during 2001-2021, moderate drought of VCI of 40-50% occurred in Terai (low land). Lower part of hilly region (middle land) was identified no drought whereas upper parts (high land) faced normal drought ranging between 50 and 70% VCI. Northern part was characterized by severe drought to few areas near Himalayas. During winter, eastern part was identified with lower VCI value in comparison to other parts of basin. Western parts of basin were noted to be in drought with VCI value ranging between 35% and 50%. The temporal averaged VCI was identified less during winter season in Terai region in compare to annual scale. Overall, the pre-monsoon drought in the basin were found higher in many regions followed by winter compared to the annual VCI in the basin (**Figure 4**)

The drought scales are varied in different geographical location in response to each year in the basin. The Terai (low land), hills (mid land) and Himalaya (high land) have found drought variability during 2001-2021. Terai region showed the presence of severe to moderate drought during 2001 to 2006 especially during 2001, the higher spatial coverage of the drought was observed. Almost whole Terai region experienced drought but western part of the study area was more concentrated with drought in 2001 whereas southeast part faced more drought in 2002, 2005 and 2006. Later in 2009 and 2010 basin was characterized by moderate drought in some part. During winter, most of the parts of the basin in year 2001, 2005 and 2009 were dominated by normal to severe droughts. In 2001, almost all parts of the basin experienced severe drought during pre-monsoon. Southwest region of the basin showed occurrence of drought in year 2009 whereas normal drought was occurred in southeast region in the year 2013.

3.3. Anomaly of Vegetation Condition Index.

The temporal variation of anomaly vegetation condition index trends on annual scale, winter season, and pre-monsoon were positively increased at the rate 0.024yr-1, 0.030yr-1 and 0.035yr-1 respectively which is good indication for growth of vegetation. However, the VCI anomaly are negative in the majority of the years until 2013 in all the three-time scales. All annual, winter and pre-monsoon AVCI indicated the moisture deficiencies in several years. During winter season, the maximum negative AVCI reached -0.38 on 2001 followed by 2006, 2009 and 2003. The maximum positive AVCI was noticed in 2020 followed by 2015 and 2018 (**Figure 5**)

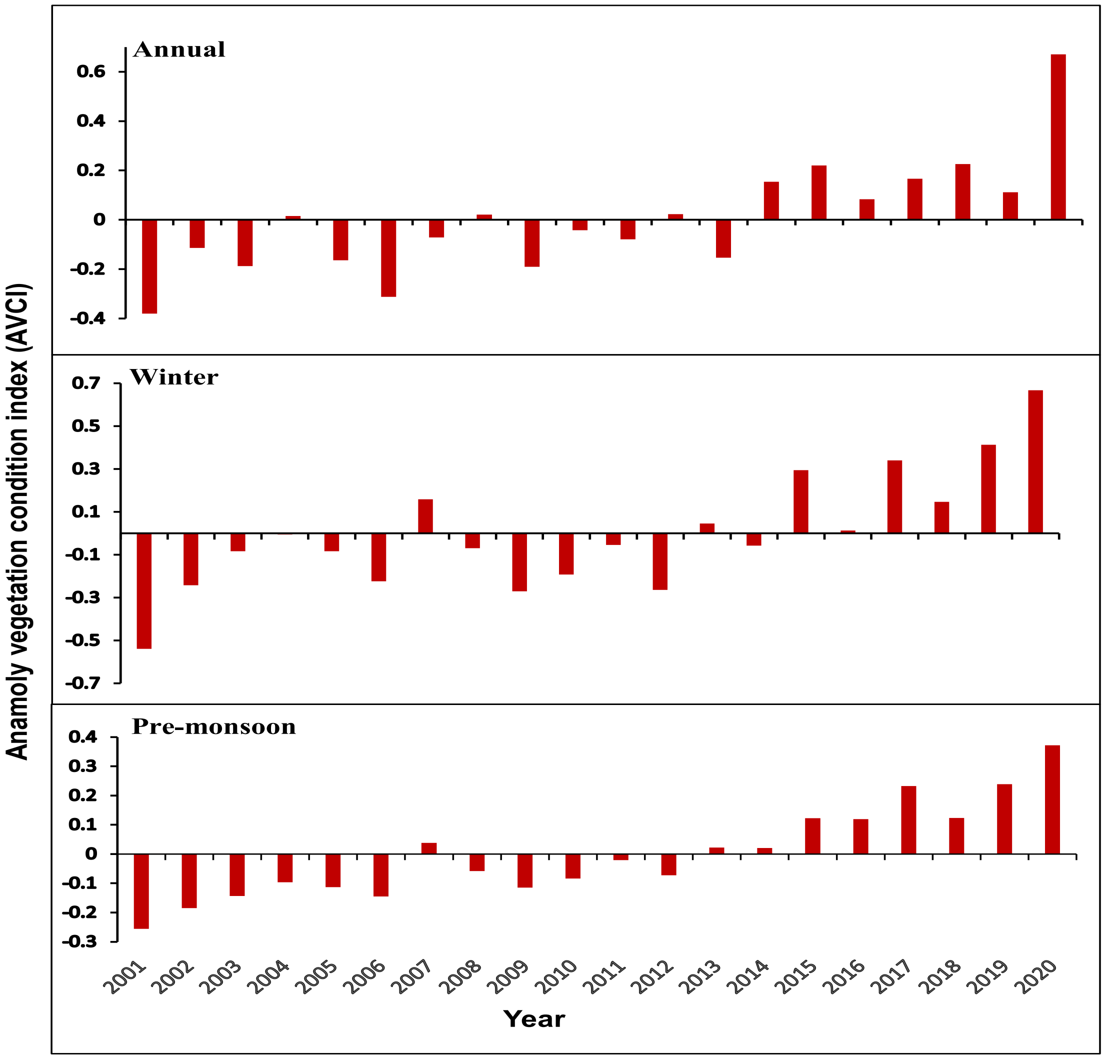

Figure 5: Anomaly of the vegetation condition index for Annual, Winter and Pre-monsoonal season from 2001–2020 in Koshi River Basin

After 2014, the AVCI was positive in all time scales. AVCI were negative from the beginning of the study period till 2013 excluding 2004, 2008 and 2012 which showed positive AVCI by small margin during winter season. But on annual scale, AVCI was positive in 2007 and 2013. Moisture deficiencies was observed during first five years of study period on annual scale. Overall, the soil moisture condition indicated by AVCI was relatively deficient before 2013 and get enriched after 2014 only. On the whole, the analysis showed positive increases in spatially averaged AVCI on all time scales but pre-monsoon has greater rate of increase. However, the average negative AVCI in many years indicates deficient moisture and drought year in the KRB.

3.4. Spatial Variation of LST

Spatially, the terai (low land) to hill (middle land) found higher surface temperature in all the time scales (**Figure 6**). Land surface temperature was identified higher up to 33°C to western parts of basin in comparison to eastern parts. The lower hills of mountain region were found lower LST than upper hills differ by 5 to 7°C. The maximum temperature reached up to 36°C during Pre-monsoon season in the basin. The Himalayan region has always lower surface temperature especially during winter season. In the Himalaya, the temperature is always negative as shown in **Figure 6.** The northeast and northern central area of basin were identified to have lower surface temperature than southwest area.

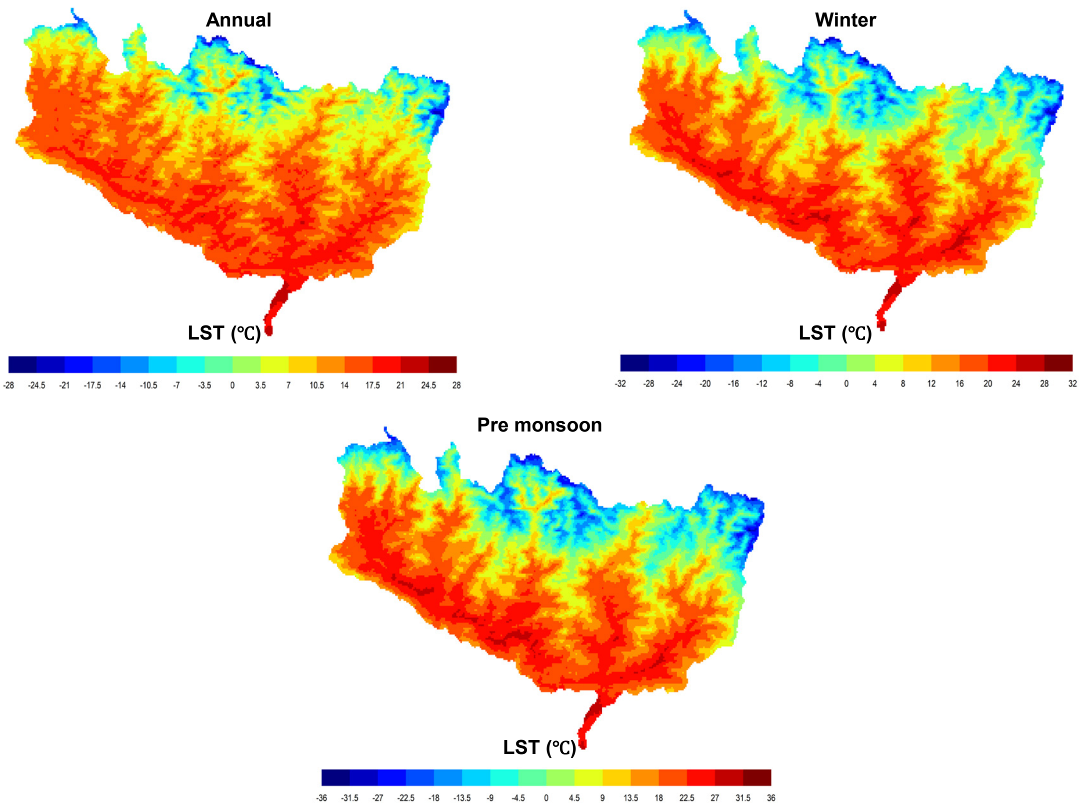

Figure 6: Spatial variation of the temporally averaged LST for different time scales; Annual LST, Winter LST and Pre-monsoon LST in Koshi River Basin from 2001-2020

The minimum LST was observed in 2020 on all time scales. And the precipitation in 2020 over the basin were all above the average precipitation. The maximum LST value was recorded in 2016 which is 17.02°C while the minimum LST was 15.15°C in 2020. The maximum winter LST was observed in 2006. Also, the precipitation during winter season was recorded one of the lowest in 2006. Similarly, there was low rainfall in study area during pre-monsoon in 2010 when the maximum LST was observed according to the result. So, the relation between LST and precipitation is inversely proportional to each other. More fluctuation was noticed on annual time scale.

3.5. Relation between VCI and Climates (LST and precipitation)

The Pearson correlation between the spatially averaged VCI and LST was negative in all time scales but more significant during winter (r = -0.54, p = 0.02) and pre-monsoon (r = - 0.57, p= 0.007) and less significant in annual time scale (r = -0.34). The correlation coefficient between spatial averaged VCI and LST on annual time scale is poor but it was noticed well during pre-monsoon and winter season. The correlation coefficient between VCI and LST indicates increase of mean LST decreases the mean VCI trend inviting drought events. Both LST and VCI is related to moisture as moisture deficiency results in the increase of surface temperature and decrease of healthy vegetation. This relation implies that increased land surface temperature supports in the decrease of vegetation and vice versa. Similarly, the Pearson correlation between the spatially averaged VCI and precipitation was positive in annual (r= 0.262) and pre-monsoon (r=0.05) timescale and negative during winter season (r= -0.104).

Table 2: Correlation between spatially averaged VCI with precipitation and Land surface temperature (LST)

Timescale	rp	p-value	rLST	p-value
Annual	0.262	0.26	-0.343	0.13
Pre-monsoon	0.05	0.816	-0.57	0.007
Winter	-0.104	0.67	-0.54	0.02

4. Discussion

This study has critically examined the drought years based on vegetation based VCI index and correlated with LST and precipitation in the Koshi River Basin mainly for annual (January–December), winter season (December–February) and pre-monsoon (March–May) time scales. The eastern part of Nepal receives less precipitation during winter season in compare to western part. Therefore, winter season was chosen for drought analysis. The discussions are mainly focused on the identification and spatiotemporal variation of VCI and its relation with LST from 2001–2020 in Koshi river basin.

4.1. Spatio-temporal Variation of VCI and Related Drought

Since Nepal has wide variation topographically, Koshi basin do have owns diverse bio-physical environment [4]. Therefore, temperatures, precipitation, wind velocity, humidity and sunshine hours were different. Likewise, VCI values were varied spatially. In this study, areas, ice and snow covered and cloud were removed. Therefore, the study excludes Himalayan part of study area. The foothills noted with no drought as the foothills are characterized by deciduous vegetation and sub alpine coniferous forest that results in larger VCI values. Lower Terai experienced normal drought which might be due to more agricultural practices [34]. Increased population [35] led to urbanization, deforestation and transformation of forest to agriculture and hence decreased VCI values. During winter, eastern part of the basin was noticed with low VCI value indicating drought which makes sense that winter precipitation is lowest over eastern lowlands (<20 mm) [36]. Similarly, during pre-monsoon western part faced moderate drought which means this part receives less precipitation in comparison to eastern region of the basin. In Nepal, precipitation trend was significantly negative during pre-monsoon, However, only 7.96% of annual rainfall was received in the pre-monsoon [37]. The spatially averaged VCI was greater than 50% on the annual time scale, but it was less than 50% for the winter and pre-monsoon seasons (**Figure 3**). Overall, the temporal trend of VCI drought index was positive in Koshi river basin. The spatially averaged VCI trends for all time scales was significantly increased indicating the decreasing trend of drought in the basin. At the beginning of the study period, the VCI trend showed steady increase till 2010 then increased and reached its highest value in 2020 in annual time scale. However, there was no significant change in winter and pre-monsoon seasons. Several drought years was observed in pre-monsoon period which was also noticed in a research of drought using tree ring [38] and VCI based identification of drought [4]. Similarly, moderate to severe drought years seen over the study area, was also detected in SPEI based drought variability study [39] and drought study using SPI [19]. Although, no severe drought was noticed on yearly time scale. This study analyzed the inter-annual variation of soil moisture using AVCI (**Figure 5**). The AVCI exhibited predominantly positive trends across all time scales, although there were some years with moisture deficiencies during the pre-monsoon which is similar to the study carried out by [4] and on annual and winter periods as well. During certain pre-monsoon years, the spatially averaged AVCI plummeted to as low as -0.58, signaling moisture deficiency and drought conditions in the Koshi river basin. But, after 2012, there was significantly increased of spatially averaged AVCI trends in all timescales illustrated enhanced soil moisture conditions. Soil moisture does not solely rely on the intensity and duration of rainfall, as a substantial amount of rainwater in Nepal flows directly into rivers instead of being retained as moisture [40]. Hence, employing AVCI can reveal soil moisture conditions that deviate from the optimal requirements for vegetation growth which also plays important role for vegetation in South Asian countries [41]. The VCI satellite index is a part of ecological drought in which the anomaly of VCI indicates the soil moisture condition as well, which is very important for agricultural management. The both temporal and spatial resolution of the different satellite products could be more effective in future. We have used MODIS VCI data sets of having 1km resolution, which was available after 2000. Instead of Landsat, it is fine resolute of 30m but not time series data product. Therefore, for the time series analysis, we have used MODIS satellite products. The results derived using this satellite based VCI and precipitation based index are coincided and similar in the Koshi basin. It shows that VCI can reflect drought in the basin.

4.2. Relationship between VCI with LST and Precipitation

In this study, how VCI values are related with the land surface temperature and precipitation were examined to relate it with drought that could be determined by VCI. Precipitation and temperature significantly influenced the variations in VCI across different locations and time periods. Types of drought that exits, are impossible to detect by VCI until they begin to impact on vegetation [42]. Hence, relation of VCI with climate is necessary. The correlation between spatially averaged VCI and spatially averaged LST was negative in all time scales. This relation declared that the VCI values are some where related to the temperature of surface where vegetation is present. As we know, surface temperature is needed for vegetation growth. Lower surface temperature is the indication of higher moisture but land surface temperature is also dependent to the weather and atmospheric temperature of the certain area. Positive correlation was established between LST and VCI on pre-monsoon and winter season but negative relation was observed in annual time scale. The significant correlation between VCI and LST means surface temperature has great role in vegetation growth. Hence, decrease in surface temperature increase the VCI index which means decrease of drought and vice-versa. Similarly, the correlation between spatially averaged VCI and precipitation were positive in annual and pre-monsoon season but negative in winter season. The negative correlation between VCI and precipitation during winter declared that the winter precipitation is not much effective to the vegetation growth. Beside this, weather condition, types of vegetation and moisture abundant could be the reason for healthy vegetation despite of less rainfall. During winter, vegetation was not healthy so the correlation is shown negative. Additionally, the positive but very poor correlation between VCI and precipitation during annual and pre-monsoon precipitation are responsible for the delayed response of vegetation to drought [4]. Numerous studies have suggested that VCI exhibits a delayed reaction to changes in moisture conditions, which is influenced by the previously accumulated soil water storage [42]. Global vegetation studies utilizing the GIMMS NDVI3g data from 1982 to 2008 revealed the presence of time lag effects between VCI and precipitation [43]. So, the vegetation in the Koshi basin also perform time lag effect to precipitation.

In the study of [44–46] on NDVI, rainfall, and evapotranspiration in Venezuelan and Colombian banana plantations found correlations similar to those in the Koshi Basin study, where VCI and precipitation showed a positive correlation, reinforcing the idea that rainfall is a critical factor in vegetation health [47]. Similarly, the Koshi River Basin study shows how moisture availability, indicated by VCI, affects vegetation health and drought severity. Both studies underline the importance of soil moisture in agricultural productivity and drought mitigation [48].

4.3. Uncertainty and Applicability of VCI-Based Drought

Uncertainties exist while using remote sensing data and selection vegetation index due to its course resolution and during the process of data acquisition, calibrated procedures and grid data interpolation. Cloud cover and other errors of the data may provide some limitation to the spatially averaged VCI. However, the data is widely used for the analysis of drought and its prediction. Research related to drought in Koshi River Basin is limited. In this study, MODIS 16-day composite NDVI dataset available from 2001 were used for calculating VCI. For the support of findings of the study, some previous research and precipitation records were used. **Table 3** listed the number of years having VCI ≤ 35% (considered as severe drought) and VCI 35% ≤ VCI ≤ 50% (considered as the normal drought).

Table 3: Spatially averaged VCI, severe drought years and normal drought years in the annual, pre monsoon and winter.

Timescales	VCI (%)	Severe drought years VCI%<35	Drought years 35≤VCI%≥50
Annual	52.24		2001,2002,2003,2004,2005,2006,2008, 2009,2010,2012
Pre-monsoon	49.02	2001	2002,2003,2004,2005,2006,2008,2009. 2010,2011,2012,2014,2016
Winter	49.06	2001, 2006	2002,2003,2005,2007,2008,2009,2010,2014

This study shows 10, 12, and 10 normal of drought years on annual, pre-monsoon and winter season, respectively in the Koshi basin. But severe drought was observed in the year of 2001 during pre-monsoon and in 2001, 2006 during winter season. Droughts have been recorded more frequently in Nepal since 2005 [33]. The CWSI value calculated during 2000-2014, indicated that Koshi River Basin is dominated by moderate drought [3] which supports our findings. Similarly, moderate drought was observed in 1992, 2008, 2009, 2015, and 2017 in hilly region [39] which give support to our result as 2008 and 2009 were identified to be normal drought year. Nepal experienced drought in 2010 [4] during annual, monsoon and pre-monsoon time scale which is another supportive study to our findings. 2 out of 2 severe drought years have lower rainfall than average winter rainfall which is 39.16mm from 2001-2020 during winter season. Similarly, 7 out of 12 normal drought years have lower rainfall than the average pre-monsoon rainfall (224.43mm) in Koshi basin from 2001-2020. On an annual timescale, precipitation was declined during 2009 and 2010 consequently drought was occurred according to our findings.

Conclusion

This study examined the spatial and temporal variation of droughts in the Koshi basin based on satellite derived VCI and its relation with Land Surface temperature during 2001 to 2020. Spatially average temporal VCI shows that severe drought was observed in 2001 during pre-monsoon and 2001, 2006 during winter season where the average annual rainfall was below normal. On annual time scale, moderate drought was observed during the years 2001, 2002, 2003, 2004, 2005, 2009 and 2012. Similarly, during winter, moderate drought was observed in several years as shown. In spite of some drought years, the spatially averaged temporal VCI has increased at the rate 1.29 yr-1, 1.52 yr-1 and 1.72 yr-1 annual, winter and pre-monsoon respectively. During the same time period, the land surface temperature has decreased at the rate -0.007 yr-1, -0.044 yr-1 and -0.028 yr-1 respectively. The positive trends of VCI and negative trend of surface temperature indicates lower risk of drought in the basin. The positively increased AVCI is the good sign for the vegetation growth and soil moisture abundant. The spatially averaged VCI was positively correlated on annual scale and winter season but negatively correlated on pre-monsoon season with precipitation. This study is very crucial to explore the risk of ecological drought in response to vegetation and its nexus with climates in small and large spatial-scales. Additionally, it can be applicable to drought managers and agriculture practitioners in Nepal. Further study using improved satellite data resolution and integrating socio-economic factors could be the future direction.

Author Contributions

Conceptualization, A.K. and M.S.; methodology, A.K, M.S.; investigation, A.K.; original draft preparation, A.K.; M.S.; B.B.; writing—review and editing, A.K.; M.S.; B.B.; X.L.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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