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Evaluation of Drought in Gandaki River Basin, Nepal

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Abstract

Drought is often considered a silent disaster, leading to food and water shortages, displacement, and even conflict. Although evidence of ongoing climate change has been observed, limited research is carried out on drought conditions in the Gandaki River Basin of Nepal. This study analyzed four indices i.e., Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Land Surface Temperature (LST) and Normalized Difference Drought Index (NDDI) for January and November between 1991 and 2021 by using Geographic Information System (GIS) and remote sensing data. NDVI showed that dense vegetation decreased by 93.26% and built-up area increased by 96.88% in January compared between 1991 and 2021. Compared between 1991 and 2021, NDWI showed that the high water stressed area increased by 49.5% in January. NDDI showed an increase in abnormally drought area in January (164.03%) compared between 1991 and 2021. Both climate change and human activities significantly contributes increasing trend of drought over the 30-year period in Gandaki River Basin. The study suggests exploring the potential of modern tools such as GIS and Remote Sensing for prediction of drought and monitoring its impact on ecosystems and human. This will be beneficial for policy makers for developing a strategy for combating drought and climate change.

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Introduction

Drought, although among the most intricate of natural disasters, remains one of the least comprehended, impacting a larger population than any other disaster (Hagman et al., 1984; Mehta & Yadav, 2023). The term “drought” commonly denotes an extended duration, spanning months or even years, during which a specific area experiences an inadequate supply of surface water or groundwater, leading to a disruption in its hydrological equilibrium (Hisdal et al., 2000; Jonathan & Suvarna Raju, 2017; Natarajan & Vasudevan, 2020). There are different types of droughts (meteorological, hydrological, ecological, agricultural, and socioeconomic) with their own unique characteristics and impacts (Khan et al., 2020; Liu et al., 2022). According to prior studies, insufficient rainfall is the main reason for drought (Chen et al., 2015; Haile, 1988; Liu et al., 2015; Natarajan et al., 2023; Zolotokrylin, 2010). However, severity and duration of drought recurrences are further exacerbated by human interferences such as deforestation (Vaglietti et al., 2022), unsustainable grazing (Jordaan et al., 2019), and over cultivation, increasing demands and consumption of water (Khan et al., 2020) and rising temperature trends and shifting weather patterns (Bernstein et al., 2008). Drought exerts a substantial influence on primary production (Ciais et al., 2005), the surface water flow (Lotfirad et al., 2022; Radmanesh et al., 2022), groundwater availability, hydropower production (Vliet et al., 2016), and heightened vulnerability to wildfires (Natarajan et al., 2023). Furthermore, droughts amplify water scarcity, which can have negative impacts on people’s health and overall productivity (Turral et al., 2011).

Droughts have substantial, pervasive, and frequently underestimated consequences for people, ecosystems, and economies, and only a fraction of the damage is officially documented (GAR, 2021; UNDRR, 2021). Each year, droughts are expected to directly affect 55 million people worldwide, making them the greatest threat to agricultural products (crops and livestock) in almost every region of the world (Eckstein et al., 2021). More than 10 million people have lost their lives as a consequence of significant drought occurrences over the past century, resulting in hundreds of billions of dollars in economic losses around the world, and the figures are rising (Guha-Sapir et al., 2017; Haitham et al., 2021). Every year, approximately 12 million hectares of land are lost due to the combined effects of drought and desertification, and there has been a more than two-fold increase in the proportion of plants suffering from drought damage over the past four decades (FAO, 2017). Drought-caused wildfires are threatening 84% of all terrestrial ecosystems and 14% of all wetlands crucial for migratory species are located in drought-prone areas (WWF, 2019). UNCCD (2022) has projected that as many as 700 million people might be compelled to leave their homes as a result of drought by 2030. Similarly, there will be between 4.8 and 5.7 billion people living in drought affected places by the year 2050, up from 3.6 billion at present (UN-Water, 2021). South Asia is regarded as a hotspot for hazards-prone regions, where the danger of climatic extremes like drought has increased due to a warming climate (IPCC, 2023). Future predictions indicate that climate change is expected to have significant impacts on South Asia including Nepal, India and Pakistan (Miyan, 2015) in the middle of the 21st century (Aadhar & Mishra, 2020). Nepal is vulnerable to climate change impacts. It has experienced more pronounced warming in recent years compared to the global average (Ghimire, 2019; Mehta et al., 2012; MOHA, 2009). Nepal ranks among the top 10 most affected countries by climate change in 2020 as per the long-term Climate Risk Index (Eckstein et al., 2021). Nepal is also experiencing rising temperatures and a shortening of the monsoon season with high-intensity rains (Tripathi et al., 2020). Such circumstances have resulted in drought, particularly in the rain-dependent hill farming system, where people rely on rains for substantial agricultural production (Adhikari, 2018; Bista et al., 2021). The issue, however, had got worse due to a lack of research on an appropriate index, inconsistent precipitation and rainfall patterns, a lack of real-time monitoring systems, etc., and therefore calls for prompt assessment of drought occurrences for decision-making (Bista et al., 2021).

Remote sensing techniques and Geographic Information Systems (GIS) combined together is very useful for drought assessment as it can monitor drought conditions continuously and consistently and make spatial data available for regional and global drought analysis, especially in places where spatial data is few or non-existent (Tang et al., 2009), especially in mountainous countries like Nepal (Sharma et al., 2020). Drought severity is a quantitative measure of the intensity of the drought event and indices are used to provide quantitative assessment of the severity of the drought (WMO and GWP, 2016). There exists a wide array of indices used for assessing various aspects of drought, including the Palmer Drought Severity Index (PDSI) developed by Palmer (Palmer, 1968), the Normalized Difference Vegetation Index (NDVI) introduced by Rouse (Rouse et al., 1974), the Standard Precipitation Evapo-transpiration Index (SPEI) by Vicente (Vicente-Serrano et al., 2010), the Standardized Precipitation Index (SPI) formulated by McKee et al., (1993), the Normalized Difference Water Index (NDWI) by Gao, (1996), and the Normalized Difference Drought Index (NDDI) proposed by Gu et al., (2007), etc., that can be used to assess drought severity. Due to the complex nature of drought, Diego et al., (2010) as well as Ndayiragije & Li (2022) suggested a cross-combination of various drought indices for more accurate assessment of drought. Therefore, in this study, the NDVI, NDDI and NDWI based on Land Surface Temperature (LST) were adopted among other indices for drought severity assessment because of their cost effectiveness (Gulácsi & Kovács, 2018), reliability, wide availability and easiness to use in remote sensing and GIS. These indices are also well-established in the scientific literature and have been used in numerous studies (Bashit et al., 2022; Gu et al., 2007; Nepal et al., 2021; Paniagua et al., 2020; Tavazohi & Nadoushan, 2018) to monitor and assess the impacts of drought.

The Gandaki River Basin (GRB) of Nepal's climate has been changing (Sigdel et al., 2022), but there aren't enough researches available to analyze the drought in light of potential future climatic scenarios (Mallick et al., 2019; Shrestha et al., 2018). Furthermore, certain studies have noted instances of drought events occurring in Nepal, with variations observed both in terms of location and timing (Adhikari, 2018; Dahal et al., 2016; Hamal et al., 2020; Sigdel et al., 2010). In particular, available studies and research (Baidya et al., 2008; Bajracharya et al., 2011; Gautam & Regmi, 2013; Gurung & Bhandari, 2009; Chaulagain et al., 2006; Shrestha et al., 1999) in the GRB have primarily focused on temperature and precipitation patterns. However, there is limited research on drought conditions in the GRB (Shrestha et al., 2020). Therefore, to fill this research gap, this study aimed at assessing drought in the GRB of Nepal using GIS and remotely sensed data.

Material and Methods

1. Study Area

GRB (Figure 1) is a cross-border basin spanning three distinct nations: China, Nepal, and India (Dandekhya et al., 2017). It is situated in the central region of Nepal, characterized by coordinates ranging from 25.6° to 29.4° N latitude and 82.8° to 85.82° E longitude (Panthi et al., 2015). It is the second-largest among Nepal's three major river basins (Panthi et al., 2015). Emerging from the southernmost point of the Tibetan Plateau, this basin meanders its way through Nepal and into India, ultimately merging with the Ganges River (Pant et al., 2018). The elevation within the basin varies significantly, ranging from 60 meters in the southern region to over 8000 meters north (Shrestha et al., 2011). GRB encompasses 46,300 square kilometers of catchment area, with a significant portion, approximately 35,000 square kilometers, situated in Nepal, covering all of its agro-ecological zones (Panthi et al., 2015). The prevailing climate in this region is predominantly influenced by the summer monsoon system of India, with roughly 80% of the annual rainfall occurring between June and September (Panthi et al., 2015; Zhang & Fang, 2020).

The GRB can be categorized into five distinct physiographic regions: Terai, Siwalik (Sub-Himalaya), Lesser Himalaya (Middle Mountains), Higher Himalaya, and Trans-Himalaya (Shrestha et al., 2011). Consequently, the GRB showcases a spectrum of topographical, climatic, ecological, and socio-economic variations along Nepal's elevation gradient (Panthi et al., 2015). This basin is notably susceptible to water-related hazards, such as floods and landslides, during the monsoon season, as well as forest fires, often ignited by dry season winds (Dandekhya et al., 2017). In Nepal, the GRB spans 19 districts (Maharjan et al., 2020) and 12 of these districts are totally inside the river basin, while seven are partially within it (Regmi et al., 2016). The total population residing either partially or entirely within the basin is approximately 40 million people, with 5 million of them accounted for in Nepal according (CBS, 2011).

2. Data Collection

United States Geological Survey (USGS) archives (1991 and 2021) were used to obtain the Operational Land Imager (OLI), Thermal Infrared Sensor (TIRS) and LANDSAT-8 images. Images having cloud cover < 5% were selected. The images were collected for the post-monsoon (November) and winter season (January) for the year 1991 and 2021.

3. Data Analysis

3.1 Drought Severity Map

The drought severity map was created by classifying the Normalized Difference Drought Index (NDDI) map. The NDDI was computed from the LANDSAT-8, OLI/TIRS images using ArcGIS 10.8. Normalized Difference Vegetation Index (NDVI) was obtained using Equation 1 (Rouse et al., 1974).

$$\mathrm{NDVI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \rho\mathrm{Red}} \quad (1)$$

Where,

NIR is the reflectance corresponding to Near Infrared Reflectance band and Red is the reflectance corresponding to red band. The Normalized Difference Water Index

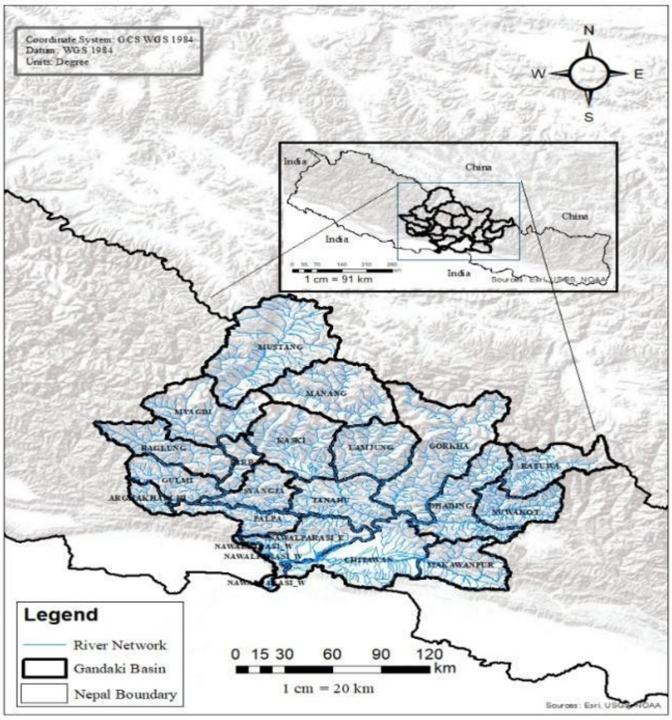

Fig 1. Study area showing Gandaki River Basin

(NDWI) results show a faster reaction to drought circumstances. It was calculated using Equation 2 (McFeeters, 1996).

$$\mathrm{NDWI} = \frac{\rho\mathrm{Green} - \rho\mathrm{NIR}}{\rho\mathrm{Green} + \rho\mathrm{NIR}} \qquad (2)$$

Where,
Green is reflectance corresponding to green band and Red is reflectance corresponding to red band.
The Land Surface Temperature (LST) is used as an indicator for evaluating vegetation water stress, evapotranspiration, and soil moisture. It was calculated using Equation 3 (Orimoloye et al., 2018).

$$\mathrm{LST} = \frac{\mathrm{Tb}}{1 + (\lambda * \mathrm{Tb}(\rho)\mathrm{In}\varepsilon}. \qquad (3)$$

Where,
Tb: Brightness Temperature,
λ: wavelength of emitted radiance,
ρ: h × c/σ; h is Planck's constant ($6.26 \times 10–^{34}$ J s); c is the velocity of light (2.998×10^{8} m/s); σ is Stefan Boltzmann's constant ($1.38 \times 10 - {}^{23}\mathrm{J\,K}^{-1}$)
ε: land surface emissivity.
Both the NDWI and NDVI data generated from LANDSAT bands were used for calculating the NDDI. It was estimated using Equation 4 (Gu et al., 2007).

$$\mathrm{NDDI} = \frac{\mathrm{NDVI} - \mathrm{NDWI}}{\mathrm{NDVI} + \mathrm{NDWI}} \qquad (4)$$

Discussion

1. Normalized Difference Vegetation Index (NDVI)

The NDVI classes were classified into five NDVI categories (ANNEX 1.1). Dense[1] vegetation decreased by 93.26% in January between the year 1991 and 2021 (Figure 2 and Table 1). However, dense vegetation increased by 222.37% in November when compared between the

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[1] The trees and other plants in a large densely wooded area

year 1991 and 2021. Sparse[1] vegetation decreased by 12.14% in January when compared between the year 1991 and 2021. However, the sparse vegetation area increased by 163.42% in November when compared between the year 1991 and 2021. The shrub and grassland were found to be increased by 49.45% and 14.5 % in January and November respectively when compared between the year 1991 and 2021. The barren land was observed to increase by 102.73% in January when compared between the year 1991 and 2021. Though, decline of barren land by 5.02% was observed in November when compared between the year 1991 and 2021. The built-up area increased by 96.88% in January when compared to the year 1991 and 2021. However, the built up area was decreased by 14.61% in November when compared to the year 1991 and 2021. The water body decreased by 56.15% and 14.61% in January and November respectively when compared between the year 1991 and 2021.

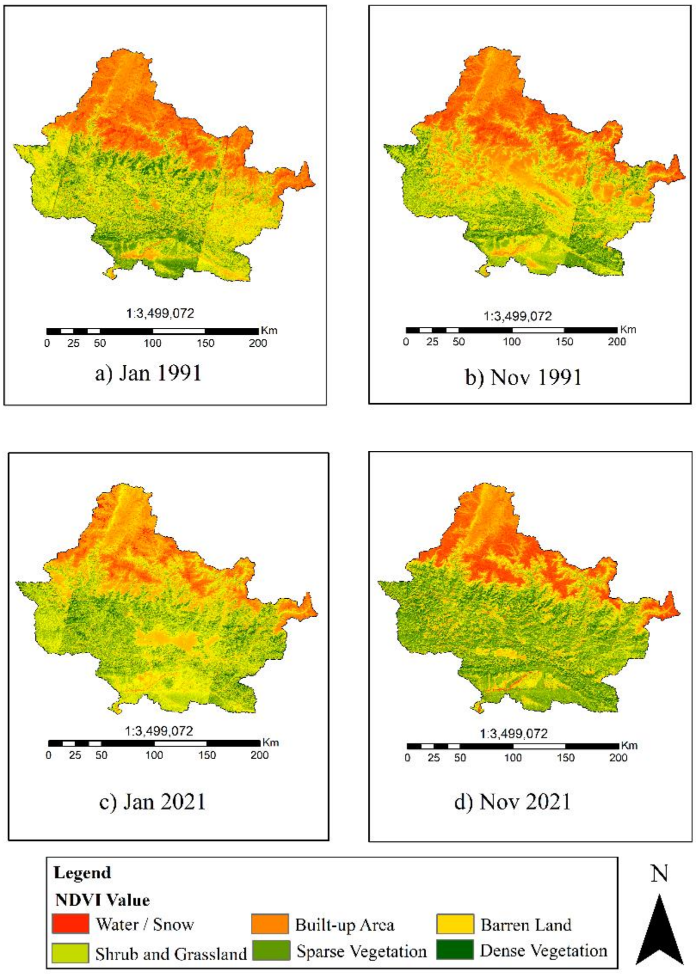
a) Jan 1991
b) Nov 1991
c) Jan 2021
d) Nov 2021

Fig 2. NDVI map of GRB

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[1] Limited or very little vegetation, as in things on the forest floor, due to lack of sun

Table 1. Area in percentage of different vegetation

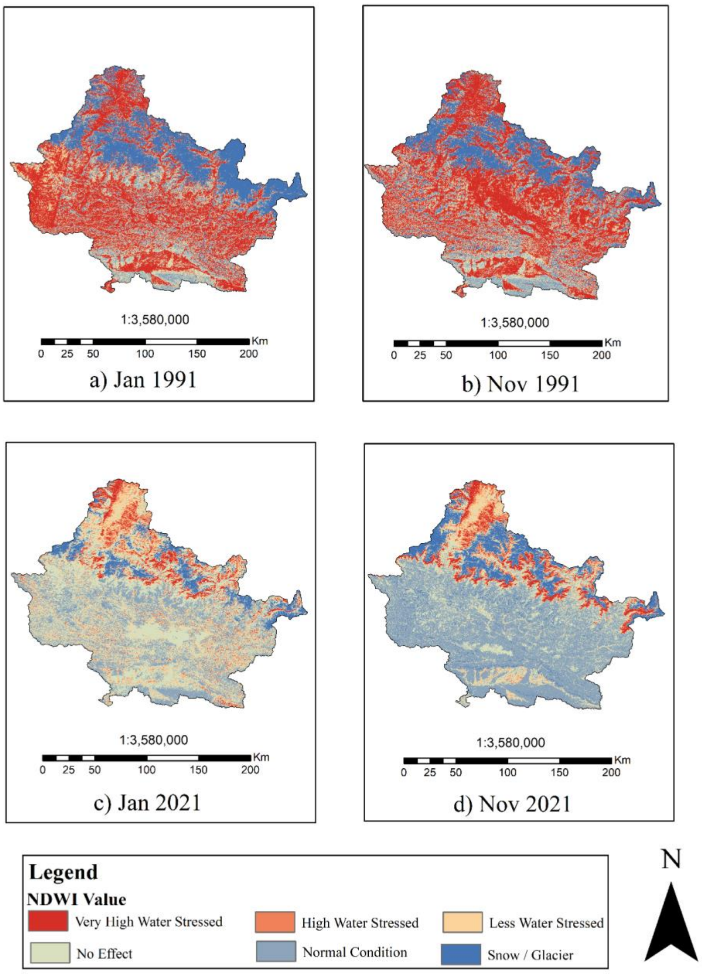
Vegetation	**Area in percentage**			
	Jan 1991	**Nov 1991**	**Jan 2021**	**Nov 2021**
Water	34.3	39.5	15.0	16.1
Built-up Area	18.5	23.9	36.5	20.4
Barren Land	7.6	7.3	15.4	7.0
Shrub and Grassland	15.0	15.6	22.3	17.9
Sparse Vegetation	11.2	9.2	9.8	24.3
Dense Vegetation	13.5	4.5	0.9	14.4
Total	100	100	100	100

As NDVI serves as a robust indicator of drought-affected vegetation, it was computed and cartographically represented using ArcGIS (Joshi & Dongol, 2018). The study found a considerable increased in barren land and a decline in dense vegetation during January when compared between the year 1991 and 2021 (Table 1). The idea that drought-induced stress slows down photosynthesis (Hossain & Li, 2021), increases mortality, and reduces plant recruitment and seedling establishment is supported by the declining vegetation, which may possibly be a result of increased drought intensity and frequency (Das et al., 2023). Shrub and grassland areas, on the other hand, increased during January and November (Table 1), indicating a possible shifting cultivation and biotic pressure (Sangita & Dulal, 2021). The NDVI analysis unveiled a noteworthy reduction in the extent of water bodies, attributable to the influence of climate change and amplified human activities within the basin (Table 1) (Bajracharya et al., 2011; Mirza, 2003; Paudel et al., 2021). The study conducted in Bangladesh's northwest, found the increasing impact of drought on the country's existing waterways (such as rivers and canals) (Das et al., 2023; Seto, 2011). Furthermore, ecosystem functioning was also observed declining (Das et al., 2023; Sultana et al., 2021). Conversion of natural areas into built-up land is another crucial factor in declining water bodies (Ramachandraiah & Prasad, 2004). However, the number of emerging cities and megacities has increased in built-up areas (Nagendra et al., 2014). Our study's findings are comparable with several recent studies conducted in the northern part of Bangladesh (Ahmed et al., 2020; Das et al., 2023; Rai et al., 2017), which show a declining tendency of water bodies and a rising trend of settlement and built-up land. Overall, the NDVI experienced increasing trends which is parallel with the findings of several studies in Nepal (Baniya et al., 2018) and the Northern Hemisphere (Chen et al., 2014; Mishra & Mainali, 2017; Wang et al., 2017; Xu et al., 2014; Zhong et al., 2010). Research findings have shown a rise in NDVI levels in regions such as Russia, Europe, and northern China characterized by northern mid and high latitudes, as well as in equatorial regions like Africa and Southeastern Asia, with the exception of South America. This observation was documented in studies conducted by Kawabata et al., (2001) and Ichii et al., (2002). The increase in NDVI between November 1991 and 2021 in our study might be due to the afforestation program carried out in the degraded land and conservation initiatives led by the government which is comparative to the study in the North Western region of Bangladesh (Das et al., 2023; Kafy et al., 2020). However, the NDVI had declined in the Southern Hemisphere i.e., Argentina, and Australia (Ichii et al., 2002; Kawabata et al., 2001). Furthermore, the study found a negative trend in the NDVI value due to the increase in drought events from 1990 to 2020 (Das et al., 2023; Isbell et al., 2015). This can be due to the combined effects of deforestation, climate change, and migration in the basin (Nepal et al., 2021; Regmi et al., 2016; Wassie, 2020; Yang et al., 2023). It might also be feasible to utilize NDVI projection methods based on rainfall patterns, as demonstrated in the work of (Brown et al., 2005), to offer advance alerts for early drought situations.

2. Normalized Difference Water Index (NDWI)

The NDWI classes were classified into six NDWI categories (ANNEX 1.2). The very high water stressed area decreased by 85.45% and 85.26% in January and November respectively when compared between the year 1991 and 2021 (Figure 3 and Table 2). The high water stressed area increased by 49.5% in January when compared between the year 1991 and 2021. However, the high water stressed area decreased by 21.27% in November when compared between the year 1991 and 2021. The less water stressed area increased by 94% and 1.77% in January and November respectively when compared between the year 1991 and 2021. The no effect area was increased by 205.97% and 67.41% in January and November respectively when compared between the year 1991 and 2021. The normal conditions increased by 93.67% and 244.73% in January and November respectively when compared between the year 1991 and 2021. The snow/glacier area decreased by 69.76 % and 30.43 % in January and November respectively when compared between the year 1991 and 2021.

Nepal ranks 40th for overall water stress around the world and lies in the high water stress category (Hofste et al., 2019). In GRB, the very high water stressed area decreased from 1991 to 2021 (Table 2). Adaptation practices like modern agriculture practices, rain water harvesting, conservation ponds, etc., practiced in the basin may be the possible cause (Regmi et al., 2016). High water stressed area was increased in January between the year 1991 and 2021 (Table 2) due to more soil moisture loss, low precipitation, climate change, and increase in temperature than in November (Dhakal et al., 2010). The study in Bangladesh's northwest between 2004 and 2013 revealed a decrease in annual average precipitation, which also supports drought in the region (Das et al., 2023; Rahaman et al., 2016). Drip irrigation and water uplifting might have contributed in the increment of less water stress area and no effect area along with normal condition class (Dhakal et al., 2010). Snow, glaciers and mountains are the primary sources of water in the South Asian countries (Cui & Graf, 2009). They shifted greatly from 1991 to 2021, with reductions of areas in November (Figure 3 and Table 2) due to climate change and human action (Cui & Graf, 2009). The snow decreased due to an increase in temperature and changing precipitation pattern which is analogous with the record of Rebetez (1996) in six different locations of Switzerland. Rising temperatures have contributed to the melting of snow and glaciers across the world i.e., India (Mastny, 2000; Vohra, 1981), China (Mool et al., 2004; Tang et al., 2013), Bhutan (Ageta et al., 2003), and GRB in recent years (Rai et al., 2018). The stress in water availability has serious impact on climate change (Figure



a) Jan 1991 b) Nov 1991 c) Jan 2021 d) Nov 2021

Fig 3. NDWI Map of GRB

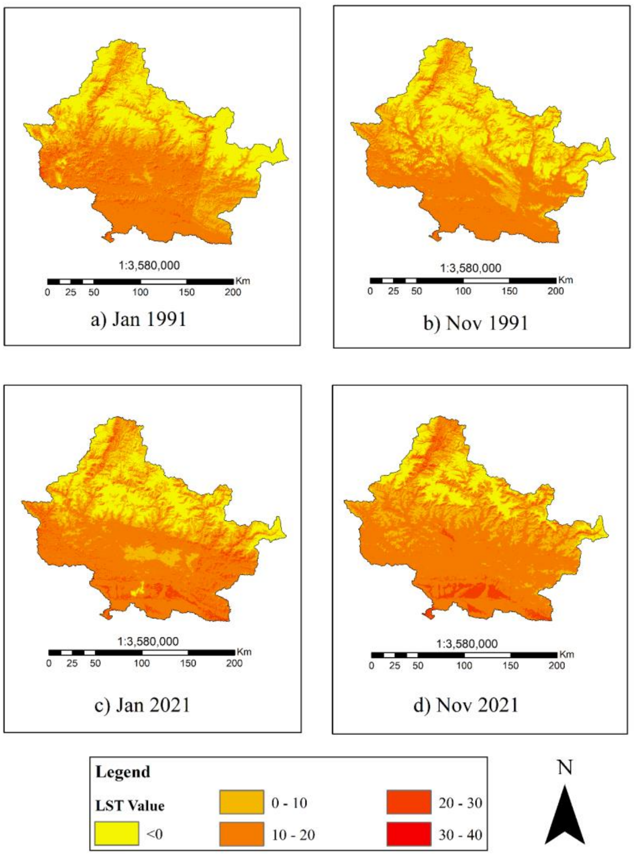
Table 2. Area in percentage of different water stress level

Water Stress Level	**Area in percentage**			
	Jan 1991	**Nov 1991**	**Jan 2021**	**Nov 2021**
Very High Water Stressed	41.2	44.6	6.0	6.6
High Water Stressed	4.6	5.2	6.9	4.1
Less Water Stressed	7.8	7.2	15.1	7.3
No Effect	13.5	13.1	41.2	21.9
Normal Condition	12.7	14.3	24.7	49.2
Snow / Glacier	20.1	15.7	6.1	10.9
Total	100	100	100	100

3). A further sign of climate change is the decline in water supplies (groundwater recharge decreases) especially in downstream areas (Nagendra et al., 2013) which is correlate with the result of Park et al., (2016) in the north-western areas of Bangladesh.

3. Land Surface Temperature (LST)

The LST classes were classified into five categories based on temperature (i.e., <10^{0}C, 10^{0}C -20^{0}C, 20^{0}C -30^{0}C, 30^{0}C <). Land area with temperature less than 0^{0}C was decreased in both the months by 23.97% and 55.56 % in January and November when compared between the year 1991 and 2021 (Figure 4 and Table 3). Land area with temperature between 0-10^{0}C decreased by 7.59% in January, and 21.04 % in November when compared between the year 1991 and 2021. Land area with temperature between 10-20^{0}C increased by 12.78% in January and 36.23% in November when compared between the year 1991 and 2021. Land area with a temperature between 20-30^{0}C increased by 62.08% (3.56% to 5.78%) in January and 544.73% (0.16% to 6.19%) in November when compared between the year 1991 and 2021. Land area with temperature more than 30^{0}C decreased by 44.32% in January however, it increased in November when compared between the year 1991 and 2021.



a) Jan 1991

b) Nov 1991

c) Jan 2021

d) Nov 2021

Fig 4. LST map of GRB

Table 3. Area in percentage of different land surface temperature

Temperature (Degree Celcius)	Area in Percentage			
	Jan 1991	Nov 1991	Jan 2021	Nov 2021
Less than 0	26.12	28.39	19.86	12.62
0 - 10	24.20	26.29	22.36	20.75
10-20	46.10	44.36	52.00	60.44
20-30	3.56	0.96	5.78	6.19
More than 30	0.01	0.00	0.01	0.01
Total	100	100	100	100

Temperature was found to be increasing in GRB between the years 1991 and 2021 (Figure 4 and Table 3). The increase in temperature in GRB is parallel to the results of Qin et al., (2009) and Ouyang et al., (2019), in the neighboring area of the Tibetan Plateau and Mao et al., (2017) in the South Asia region. The land area with temperature <10^{0}C was decreased (Table 3), which might be due to the melting of Himalayan glaciers and low rainfall/ snow in the region (global warming phenomenon) (Luintel et al., 2019). The land area with temperature 10-30^0 C is increasing (Figure 4) due to urbanization, deforestation (Maillard et al., 2022), air pollution (Kahya et al., 2016) and land use change (Kafy et al., 2020) which results in increasing drought in the GRB. Negative relation between NDVI and temperature was discovered in our study, indicating that the rising temperature in GRB had an adverse effect on vegetation (Figure 3 and Figure 4) which is parallel with the study of Das et al., (2023), in Bangladesh. The inverse correlation observed between vegetation NDVI and LST (Figure 3 and 4) may be attributed to decreased vegetation resistance and resilience, possibly resulting from the lasting impacts of drought (Das et al., 2023; Hossain et al., 2022; Hossain & Li, 2021; Isbell et al., 2015). The increasing LST has resulted in drought-induced stresses in GRB and led to climate-induced disturbances (Das et al., 2023).

4. Accuracy Assessment

Accuracy assessment of NDVI was carried out were overall accuracy was achieved more than 70% with kappa coefficient more than 65% (Table 4).

Table 4. Accuracy Assessment of NDVI for the months Jan and Feb of the year 1991 and 2021.

S. N.	Vegetation (Jan,1991)	Water	Built-up Area	Barren Land	Shrub and Grassland	Sparse Vegetation	Dense Vegetation	Total	User Accuracy	Kappa
1	Water	149	0	13	2	4	3	171	0.87	0
2	Builtup Area	0	54	25	4	4	6	93	0.58	0
3	Barren Land	0	0	25	2	7	4	38	0.66	0
4	Shrub and Grassland	0	0	8	57	5	5	75	0.76	0
5	Sparse Vegetation	0	0	0	2	46	8	56	0.82	0
6	Dense Vegetation	0	0	3	3	11	50	67	0.75	0
	Total	149	54	74	70	77	76	500	0	0
	P_Accuracy	1	1	0.33784	0.814286	0.597403	0.657895	0	**0.762**	0
	Kappa	0	0	0	0	0	0	0	0	**0.705**
S. N.	**Vegetation (Nov,1991)**	**Water**	**Built up Area**	**Barren Land**	**Shrub and Grassland**	**Sparse Vegetation**	**Dense Vegetation**	**Total**	**User Accuracy**	**Kappa**
1	Water	177	0	13	2	3	2	197	0.90	0
2	Builtup Area	0	75	25	8	6	6	120	0.63	0
3	Barren Land	0	5	28	1	1	2	37	0.76	0
4	Shrub and Grassland	0	0	3	54	9	12	78	0.69	0
5	Sparse Vegetation	0	0	1	3	33	9	46	0.72	0
6	Dense Vegetation	0	0	1	1	2	18	22	0.82	0
	Total	177	80	71	69	54	49	**500**	0	0
	P_Accuracy	1.00	0.94	0.39	0.78	0.61	0.37	0	**0.77**	0
	Kappa	0	0	0	0	0	0	0	0	**0.77**

Continue of Table 4. Accuracy Assessment of NDVI for the months Jan and Feb of the year 1991 and 2021.

S. N.	Vegetation (Jan,2021)	Water	Builtup Area	Barren Land	Shrub and Grassland	Sparse Vegetation	Dense Vegetation	Total	User Accuracy	Kappa
1	Water	73	0	2	0	0	0	75	0.97	0
2	Builtup Area	2	112	55	9	4	0	182	0.62	0
3	Barren Land	0	9	59	8	1	1	78	0.76	0
4	Shrub and Grassland	0	2	4	29	6	8	49	0.59	0
5	Sparse Vegetation	0	1	3	6	93	9	112	0.83	0
6	Dense Vegetation	0	0	3	1	1	5	10	0.50	0
	Total	75	124	126	53	105	23	**506**	0	0
	P_Accuracy	0.97	0.90	0.47	0.55	0.89	0.22	0	**0.742**	0
	Kappa	0	0	0	0	0	0	0	0	**0.742**

S. N.	Vegetation (Nov,2021)	Water	Builtup Area	Barren Land	Shrub and Grassland	Sparse Vegetation	Dense Vegetation	Total	User Accuracy	Kappa
1	Water	77	0	3	0	0	0	80	0.96	0
2	Builtup Area	5	44	38	5	4	6	102	0.43	0
3	Barren Land	0	0	19	8	4	4	35	0.54	0
4	Shrub and Grassland	1	2	4	60	6	16	89	0.67	0
5	Sparse Vegetation	0	0	1	6	105	10	122	0.86	0
6	Dense Vegetation	0	1	2	3	9	57	72	0.79	0
	Total	83	47	67	82	128	93	**500**	0	0
	P_Accuracy	0.93	0.94	0.28	0.73	0.82	0.61	0	**0.724**	0
	Kappa	0	0	0	0	0	0	0	0	**0.724**

5. Normalized Difference Drought Index (NDDI) as Drought Severity Map

The NDDI classes were classified into six NDDI categories (ANNEX 1.3). The abnormally drought area increased by 164.03% in January when compared between the year 1991 and 2021 (Figure 5 and Table 5). However, abnormally drought area declined by 40.5% in November when compared between the year 1991 and 2021. Moderately drought area increased by 34.58% and 44.36% in January and November respectively when compared between the year 1991 and 2021. Severe drought area decreased by 67.81% in January when compared between the year 1991 and 2021 (Table 5). Though severe drought area increased by 39.49% in November when compared between the year 1991 and 2021. Extreme drought area decreased by 96.37% in January when compared between the year 1991 and 2021. However, the extreme drought area increased by 216.37% in November when compared between the year 1991 and 2021. Exceptional drought area decreased by 99.1% in January when compared between the year 1991 and 2021, though, increased by 984.66% in November when compared between the year 1991 and 2021 (Table 5). The water body/snow decreased by 45.91% and 47.91% in January and November respectively when compared between the year 1991 and 2021.

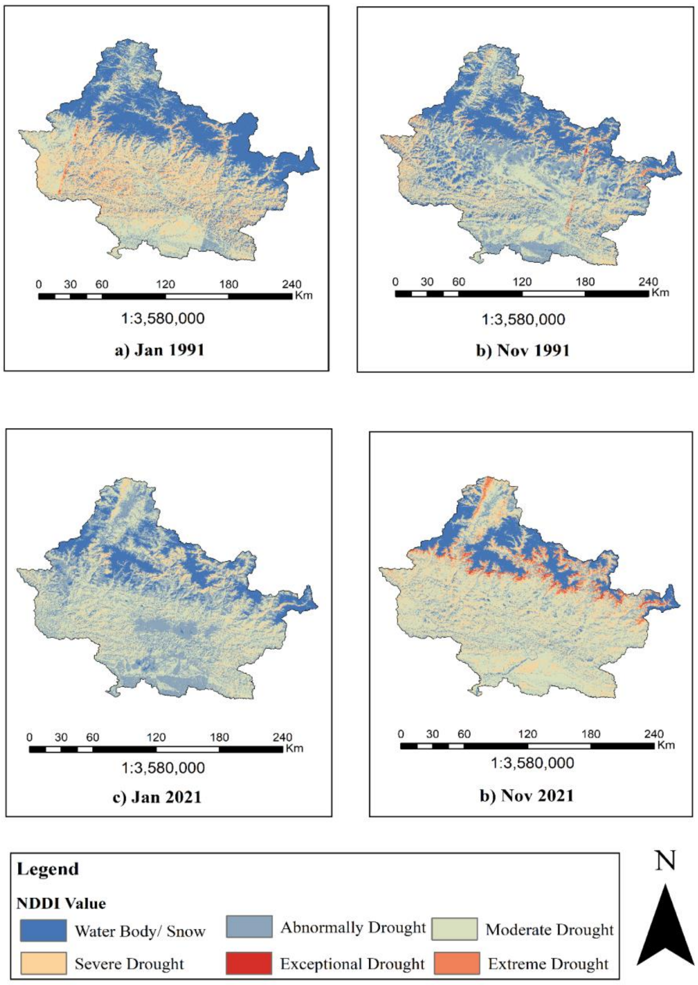


Fig 5. Drought map of GRB

Table 5. Area in percentage of different drought level

Drought Level	Area in Percentage			
	Jan 1991	Nov 1991	Jan 2021	Nov 2021
No Drought (Water/ Snow)	30.9	27.6	16.7	14.4
Abnormally Drought	13.8	25.1	36.3	14.9
Moderate Drought	29.0	32.5	39.1	47.0
Severe Drought	24.3	13.4	7.8	18.7
Extreme Drought	2.0	1.3	0.1	4.1
Exceptional Drought	0.0	0.1	0.0	0.9
Total	100	100	100	100

NDDI is recommended for measuring drought because it is a more recent and sensitive indicator and can provide a more accurate response in relation to the drought rates (Tavazohi & Nadoushan, 2018). Our study found higher NDDI during the dry season of the year which is in full accord with the results of several studies

(Mongkolsawatu et al., 2009; Torres et al., 2010; Tavazohi & Nadoushan, 2018). Higher NDDI during the dry season is also similar to the study in Northeastern Thailand (Mongkolsawatu et al., 2009; Torres et al., 2010). In summer, NDDI was proven as an effective index in measuring drought (Gu et al., 2007). Considering the area of the GRB, study in Mongolia also concluded about the NDDI capacity to measure drought on a large scale (Erdenetuya et al., 2010). The abnormally drought, moderately drought and severe drought area were increased in January when compared between the year 1991 and 2021 whereas Moderate Drought area also increased in November (Table 5), which might be due to change in rainfall patterns (Tavazohi & Nadoushan, 2018), overpopulation (Young, 1995), climate change (Sayari et al., 2013), and anthropogenic activities (AghaKouchak et al., 2021). A study by Khatiwada & Pandey (2019) also recorded an increase in drought events in the Karnali river basin of Nepal. An escalation in drought conditions could have far-reaching consequences, impacting water availability, crop yields, and posing significant challenges across the environmental, economic, and social domains (Khatiwada & Pandey, 2019).

Nepal witnessed consecutive and worsening drought conditions during 2005–2006 which was among the most difficult for Nepal's mountainous country's agriculture practices and water resource management (Bagale et al., 2021). Similar study shows the western and central region of Nepal as a highly affected drought area than eastern region. However, the abnormal drought area and severe drought area decreased in GRB due to the change in local weather patterns (Sayari et al., 2013). Drought has a direct impact on crops, resulting in financial losses and jeopardizing the livelihoods of the people. Nations like Nepal, where a significant portion of the population depends heavily on rain-based agriculture for their sustenance, are especially susceptible to the adverse effects of drought (Gentle & Maraseni, 2012). Previous research indicated that Ethiopia experienced its worst extended droughts between 2002 and 2003, affecting the Awash River Basin. This finding aligns with our analysis of the drought tendency in the GRB between 1991 and 2021 (Getahun et al., 2023; Bayissa 2018; Mohammed et al., 2018; Suryabhagavan, 2017; Yadeta et al., 2020). Studies conducted around the world revealed that the current drought caused by climate change has increased in intensity, severity, and frequency over the past few decades (Band et al., 2022; Getahun et al., 2023; Sahana et al., 2021; Shamshirband et al., 2020). According to previous research (Fensholt et al., 2015; Nicholson et al., 1998), drought is an important factor in land degradation processes all over the world. GRB may be more susceptible to extreme dryness if drought persists, which could have a significant impact on local people and ecosystems (Leng et al., 2015). Similar findings were reported by the study of Orimoloye et al., (2019) in South Africa. Therefore, impact assessment studies of drought events are essential (Bagale et al., 2021).

It is evident that the basin is confronted with significant hurdles pertaining to the utilization of water resources, degradation in upstream areas, the vagaries of weather patterns, and a deficiency in public awareness, as highlighted in the work of Chhetri et al., (2020). Moreover, the absence of comprehensive data on actual water availability within the basin compounds the challenges faced in formulating effective drought mitigation strategies. Consequently, it is imperative to conduct a comprehensive study in regions affected by drought to accurately assess water availability in the basin and address both present and future water demands and mitigate the impact of drought.

Conclusion

In conclusion, this study sheds light on the often underestimated and silent catastrophe of drought, with its far-reaching consequences including food and water shortages, displacement, and even the potential for conflict. Amidst the evident signs of ongoing climate change, there has been a notable lack of research focused on drought conditions within the GRB of Nepal. Through the rigorous analysis of four key indices NDVI, NDWI, LST, and NDDI in the period 1991 and 2021, and employing the power of GIS and remote sensing data, this study provides valuable insights into drought occurring in GRB. The findings are both compelling and concerning. They reveal a stark 93.26% decrease in dense vegetation and a striking 96.88% increase in built-up areas in the month of January, when comparing the years 1991 and 2021. Equally alarming is the 49.5% growth in high water-stressed areas observed in the same month. The NDDI further underscores the gravity of the situation, with an astounding 164.03% expansion in abnormally drought-affected areas in January over the three-decade span from 1991 to 2021.

What becomes unmistakably evident is that the increasing trend of drought in the GRB is not merely a product of natural climate variability but is significantly exacerbated by human activities. This necessitates urgent attention from policymakers and the wider community. In light of these findings, this study advocates for the exploration and utilization of modern tools such as GIS and Remote Sensing for the prediction of drought and the continuous monitoring of its impact on both ecosystems and human populations. Such an approach offers a valuable resource for policymakers and stakeholders as they work to develop effective strategies for combatting the growing threats of drought and climate change. By harnessing the power of these technologies, we can better prepare, respond, and adapt to the evolving challenges posed by drought, ultimately fostering resilience and sustainability in the GRB and similar regions facing similar crises.

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7. ANNEXES

ANNEX 1.1. NDVI Threshold

NDVI Threshold

S.N.	Vegetation Level	Range
1	No Vegetation	-1 to -0.2
2	Low to Medium	-0.19 to 0.23
3	Medium	0.24 to 0.36
4	Medium to Dense	0.37 to 0.45
5	Very Dense	0.46 to 1

ANNEX 1.2. NDWI Threshold

NDWI Threshold

S.N.	Water Stress Class	Range
1	Very High Water Stressed	-1 to -0.084
2	High Water Stressed	-0.084 to -0.05
3	Less Water Stressed	-0.05 to 0
4	No Effect	0 to 0.106
5	Normal Condition	0.106 to 0.24
6	Snow I Glacier	0.24 to 1

ANNEX 1.3. NDDI Threshold

NDDI Threshold

S.N.	Drought Category	Range
1	Water Body I No Drought	-1 to -0
2	Abnormally Dry	0 to 0.1
3	Moderate Dry	0.1 to 0.2
4	Severe Drought	0.2 to 0.3
5	Extreme Drought	0.3 to 0.4
6	Exceptional Drought	0.4-1