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Desertification vulnerability assessment through geospatial techniques in Bahawalpur division of Punjab, Pakistan

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Abstract The purpose of this study is to evaluate the desertification vulnerability and the future trends of desertification expansion in the Bahawalpur division of Punjab, Pakistan. This aim is achieved by analyzing Landsat data between the years 1990 and 2019. The biophysical index and socio-economic index were used to identify the Desertification Vulnerability Index (DVI) and its changes which have taken place over the study period between the years 1990 and 2019. The findings indicated that there was a decrease in the rate of desertification vulnerability from 1990 to 2019. In addition, the central and southern part of the Bahawalpur division is classified as a highly vulnerable zone in comparison to the other part of the region. The overall results show that the barren land and the desert area have been showing a decreasing trend, accompanied by substantial growth in vegetation from 1990 to 2019. The findings of the DVI analysis indicate that the Highly Vulnerable Area has decreased spatially from 61.12 in 1990 to 55.3% in 2019, while the Moderately Vulnerable Area and the Least Vulnerable Area have grown from 25.59% and 17.2% in 1990 to 28.56 and 19.53% in 2019, respectively. The decreasing trend demonstrates the effectiveness of efforts to combat desertification and the government could develop the best strategies for rehabilitation works and control the land degradation process in the most vulnerable areas in the Bahawalpur division of Punjab, Pakistan.

Keywords Desertification · Vulnerability · Bare land · GIS · Cholistan · Bahawalpur · Pakistan

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Introduction

One of the most serious environmental issues facing the entire world is desertification, a natural phenomenon which threatens around one-third of the planet (Xue & Su, 2017). Desertification is a land degradation process in arid, semi-arid, and dry sub-humid areas due to various factors, including both climatic variations and human intrusions (Mirzabaev et al., 2019; UNCCD, 1994; Yang et al., 2005). According to the World Atlas of Desertification, which was released by the European Commission, more than 75% of Earth's land area has already degraded and more than 90% of it potentially faces depletion by 2050. Around the world, humans are accelerating the conversion of drylands into deserts on an unprecedented scale, ultimately leading to negative effects.

There are more than 100 countries that are at risk of desertification, striking some of the most vulnerable and poorest populations the hardest, as subsistence farming is widespread in many of the impacted areas (Adger et al., 2000). There are more than one billion people who are in potential danger due to this environmental crisis, and this problem affects about 250 million people (Kundu & Dutta, 2011). In a decertified zone, which encompasses a total area of between 6 and 12 million square kilometres worldwide, between 1 and 6% of the population resides (Xu et al., 2019). According to research by Damberg and AghaKouchak (2014), parts of South Asia have undergone drying during the past thirty years (UNEP-GEF, 2008). Rural populations in developing nations, particularly in South Asia, continue to be the most vulnerable to the whims of extreme climate events (IPCC, 2014; Hasnat et al., 2018). Furthermore, the risk of desertification in the drylands is anticipated to increase due to climate change. Currently, South Asia is home to around half of the worlds dryland population (IPCC, 2019; Mazhar et al., 2021). Water shortage continues to be a problem throughout South Asia (Zheng et al., 2018), as 12% of the total population in the area lives in extreme poverty (IPCC (2019). The rural population of Pakistan, according to Deressa et al. (2009), is particularly vulnerable to the consequences of climate change. According to Fahad and Wang (2018), Pakistan as a whole is also one of the nations that is most vulnerable to extreme climatic disasters.

In Pakistan, desertification is a result of both social and environmental factors (Irshad et al., 2007; Lal, 2018), such as unrestrained water use, agricultural land exploitation, unrestrained grazing practices during urbanization, population growth, as well as the pressures that come with it. Deforestation, water depletion, soil erosion, and salinization also pose large issues and further exacerbate the environmental crisis which Pakistan is facing (Abdi et al., 2013; D'Odorico et al., 2013; Martello, 2004; Mazhar & Shirazi, 2020). Climatic variations, decreasing soil fertility (Mohamed, 2013), overgrazing (Mazhar et al., 2018), increasing population (Ziboon et al., 2015) and poor cultivation methods (Sepehr et al., 2007) are the primary causes of desertification, contributing significantly to land degradation in Pakistan (Shah et al., 2011). The leading cause of Pakistan's growing aridity is climate change, and several arid and drought-prone areas may be found in Southern Punjab and Sindh (Haider & Adnan, 2014). Moreover, desertification endangers the sustainability of the land. Since Pakistan's economy is largely agrarian and nearly 68% of its land receives less than 250mm of annual rainfall, the country's aridity is also exacerbated (Fazal, 2016; Siddiqui & Javid, 2019). Thus, the vulnerability to natural disasters is increased by desertification. In those regions, dust storms and flash floods intensify. Due to dust storms and air pollution, respiratory disorders are widespread in desert regions (Anjum et al., 2010). The issue of desertification affects several countries, including Pakistan where 80 per cent of the land is dry or semi-arid (Türkeş et al., 2020; UNCCD, 1994). The lack of knowledge about the causes of desertification has been cited as one factor for the unsuccessful execution of UNCCD's efforts to prevent it (Giest, 2005).

Ecosystem services are also negatively impacted by desertification, particularly those related to the production of food and fodder (Williams, 2011). Additionally, desertification has contributed to the over-extraction of groundwater, reduced crop yields from sandblasting, frequent dust storms, and reservoir siltation. Moreover, it has also increased, multifaceted forms of poverty, migration, loss of biodiversity, food insecurity, malnutrition, decreased solar panel efficiency and cardiovascular and respiratory diseases (IPCC, 2019). As a result of land desertification, recurring droughts have also become commonplace in affected regions (Karmaoui, 2019). Desertification is a problem that impacts the stability, resource development, and human population of the area, as well as results in issues such as soil loss, which can further intensify factors leading to poverty such as crop failure and food shortages. Furthermore, the rising process of desertification in any location also affects the development of land management plans. Climate change, land vulnerability, and pressure from human land usage have all been used to gauge the extent of desertification. A prolonged drought is caused by short-term changes in atmospheric circulation. The sandy soil in these places has higher rates of water infiltration, increased salt, and quick oxidation (Chauhan, 2003). Vegetation, soil quality, water quality and quantity, economic development, and living condition of any area is directly affected by the desertification process (Xu et al., 2019). The human societies that live in drylands are the ones that suffer from desertification the most because their livelihoods rely on the productivity of the land, even though human-induced pressure, such as increased grazing density and changes in land use, intensifies the effects of climate change and accelerates desertification (Karmaoui, 2019; Mazhar & Shirazi, 2023).

To develop policies to stop the process of desertification, policymakers need to identify the areas which are most vulnerable to its development and intensification. Desertification is the result of the interaction of socioeconomic and biophysical factors, such as human pressure climate, soil, land use change, and climate change (Dharumarajan et al., 2018). To identify places at risk of desertification, a multidisciplinary approach based on socioeconomic and biophysical aspects is necessary. In remote places where human-based evaluation is challenging, GIS and RS approaches are highly beneficial for monitoring the desertification process (Mazhar et al., 2018; Nasar-u-Minallah, 2018). RS and GIS can work together to quickly and precisely detect areas of land degradation or desertification and connect them to the physiographic setting (Van Lynden & Mantel, 2001). The monitoring of long-term trends and the geographic distribution of land degradation or desertification are made possible by multitemporal remote sensing data (Salvati & Bajocco, 2011). Several methods may be employed to identify and monitor desertification in different regions. For instance, time series analysis was utilized by Petta et al. (2005) to identify the progress of desertification in Brazilian through land set data. To measure and map desertification, aerial images and Moderate Resolution Imaging Spectroradiometer (MODIS) images are valuable and trustworthy data sources (Orare, 2000). Artificial Neural Networks (ANN) and genetic programming techniques were utilised by Rampone and Valente (2019) to evaluate the vulnerability of land degradation in the Italian Sannio region. In Egypt, Shalaby et al. (2004) used the Cross tabulation method, the Maximum Likelihood methodology, and other GIS modules to analyze the effects of desertification on changes in land cover. Liu et al. (2018) used MODIS images from several periods between 2000 and 2015 to keep track of modifications to the Magnolia Plateau's desertification process. Ghebrezgabher et al. (2019) employed GIS tools and RS data to track the process of land deterioration. Mazhar et al. (2018) assessed the South Punjab, Pakistan region's vulnerability to desertification using the temporal datasets from three MODIS sensors.

Although there is a substantial amount of literature devoted to the evaluation of desertification vulnerability and its assessment, and the field of vulnerability assessment has a growing body of research (Antwi-Agyei et al., 2013; Huynh and Stringer, 2018; Nazari Nooghabi et al., 2020; Rajesh et al., 2018), some researchers have attempted to spatially portray their findings. This research fills up these gaps and expands the application of spatial mapping to desertification vulnerability analysis. The study was carried out with the aim of the assessment of the Bahawalpur Division's vulnerability to desertification between 1990 and 2019 and calculating the future trends of the desertification expansion in the study area for the next 30 years. The calculated model used in this study is novel and based on the combination of different geospatial indices. The specific objective of this study was to investigate the areas which are more vulnerable to desertification and its severity level and to increase awareness about desertification and also help combat the desertification process and for human welfare. The government could develop and use this model to form the best strategies for rehabilitation works and control the land degradation process in the most vulnerable areas in the Bahawalpur division of Punjab, Pakistan.

Materials and methods

Study area

The Bahawalpur division is the focus research area (Fig. 1). The study area for this research is comprised of three districts in South Punjab, Bahawalnagar, Bahawalpur, and Rahim Yar Khan (Fig. 1), all of which are located in the drylands zone (Saifullah et al., 2018). The Bahawalpur division is located at the Southern tip of Pakistan's Punjab province. The Bahawalpur division has a total area of 45,588 km^2 (GOP, 2018). The dry, hot part of Punjab Province is the research area. The land is virtually flat and uninhabited. Sand makes up about 81% of the desert, while the remaining 19% is made up of tiny dunes and alluvial flats. The Bahawalpur Division's soil has a very small amount of organic matter. As a result, it qualifies as poor soil. These districts extend as a

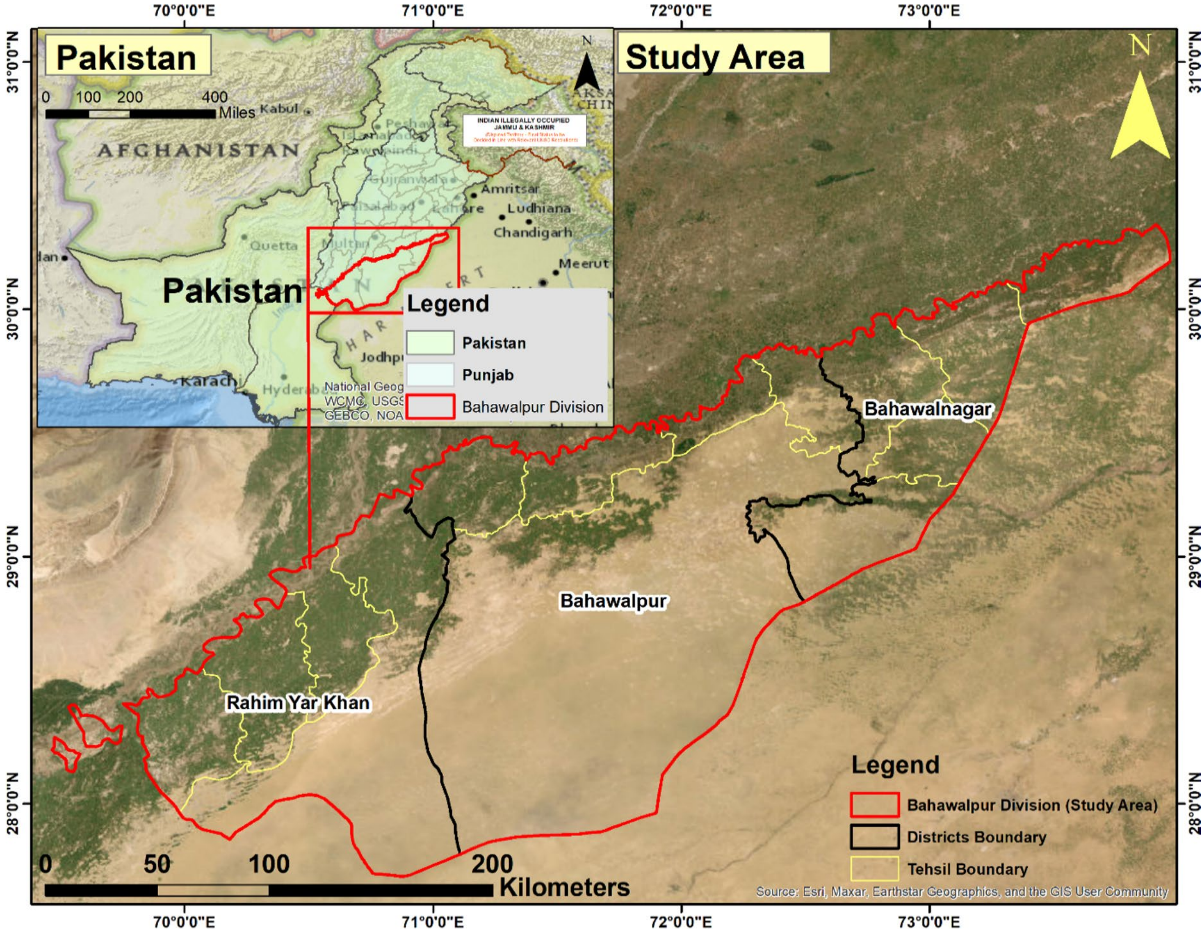


Fig. 1 Area under study (Bahawalpur division) geographical location

drylands region in Pakistan's Punjab province, where the Bahawalpur division's estimated population is 11,464,031 and from 1998 to 2017, there was a 3.19% yearly growth (GOP, 2017). The area had a 58.5% literacy rate and a population density of 251 people per square kilometre (GOP, 2017; Hussain et al., 2020). Each district has a population that is more than 65% rural, and the residents of these districts are heavily dependent on agriculture and livestock herding. This large number of rural residents confirms that the majority of the district's population depends heavily on agriculture. Thus, the region's extensive desertification will only worsen the living conditions of this largely agrarian populace (Mazhar & Shirazi, 2020).

The subtropical, arid, hot, and hotter climate is influenced by the seasonal monsoons. Annual and even daily temperature varies greatly. The average highest temperature varies between 35 and 50 °C from May to June and the lowest temperature varies between 15 and 20 °C from December to February (Hussain et al., 2020). The mean annual rainfall of Bahawalnagar was 110.2 mm, Bahawalpur 112.2 mm, and Rahim Yar Khan 112.13 mm in the year 2016, while the aridity index for the same year for the three districts under study was 0.04, 0.04 and 0.07 respectively (Javid, 2017). The area receives less rainfall; the Average annual rainfall ranges from 100 to 250 mm which is mostly

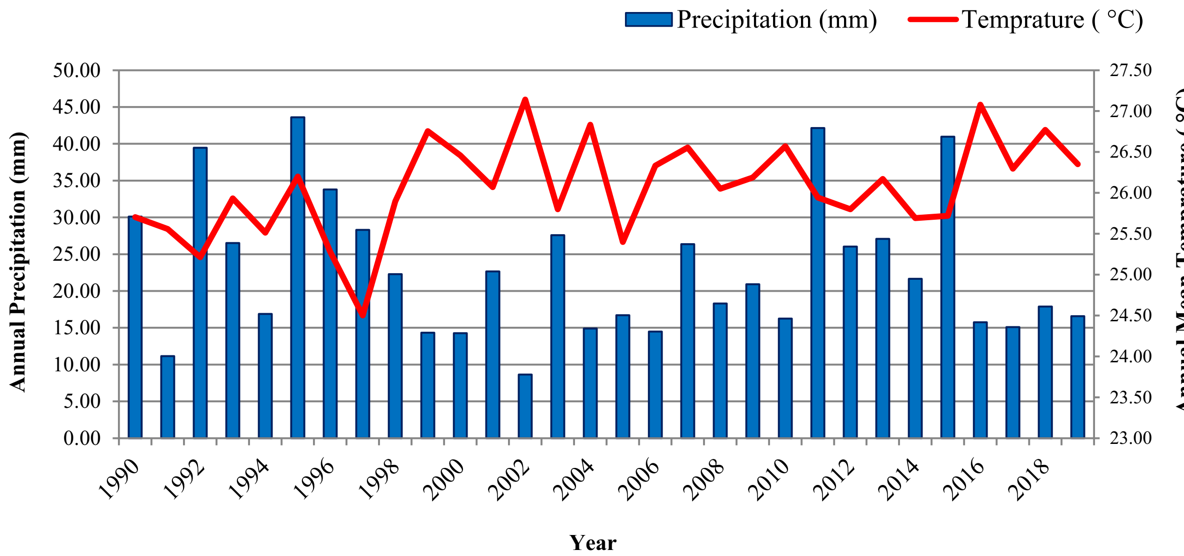


Fig. 2 Annual mean temperature and precipitation of Bahawalpur division

Table 1 Details of landsat and meteorological data are used in the study

Acquisition Date	Satellite and Data	Sensor	Resolution	Path/Row
26-05-1990	Landsat 5	TM	30 m	149/39,149/40,150/39,150/40,150/41,151/40,151/41
26-05-2019	Landsat 8	OLI_TIRs	30 m	149/39,149/40,150/39,150/40,150/41,151/40,151/41
1990–2019	Temperature	–	–	Bahawalnagar and Bahawalpur (Met station)
1990–2019	Precipitation	–	–	Bahawalnagar and Bahawalpur (Met station)
2002–2019	Temperature and Precipitation			Raheem Yar Khan (Met station)

controlled by the summer monsoon. Maximum rainfall from July to September during monsoons and January to March during winters (Arshad et al., 2006). Figure 2 reveals the long-term rainfall and temperature of the study area.

Data

The baseline period for the current study is from 1990 to 2019 (Table 1). Landsat-5 TM for 1990 and Landsat-8 TIRS/OLI for 2019 satellite images were used in this study, and they were both publicly available for download through the USGS's Earth Explorer (https://earthexplorer.usgs.gov/). To assess the Bahawalpur division's vulnerability to desertification, cloudless satellite imagery is used. The Pakistan Meteorological Department (PMD) Lahore provided monthly average climate data between 1990 and 2019 at three meteorological stations, while Raheem Yar Khan met station data available from 2002. To determine the climate index, meteorological data is used. In the course of desertification, human causes also play a vital role. To establish the socio-economic index, the Statistical Bureau of Pakistan was consulted for information on area, population, population density, illiteracy and unemployment.

Methodological approach

The flow diagram in Fig. 3 provides an overview of Landsat satellite data as well as the methodological approach used for this investigation.

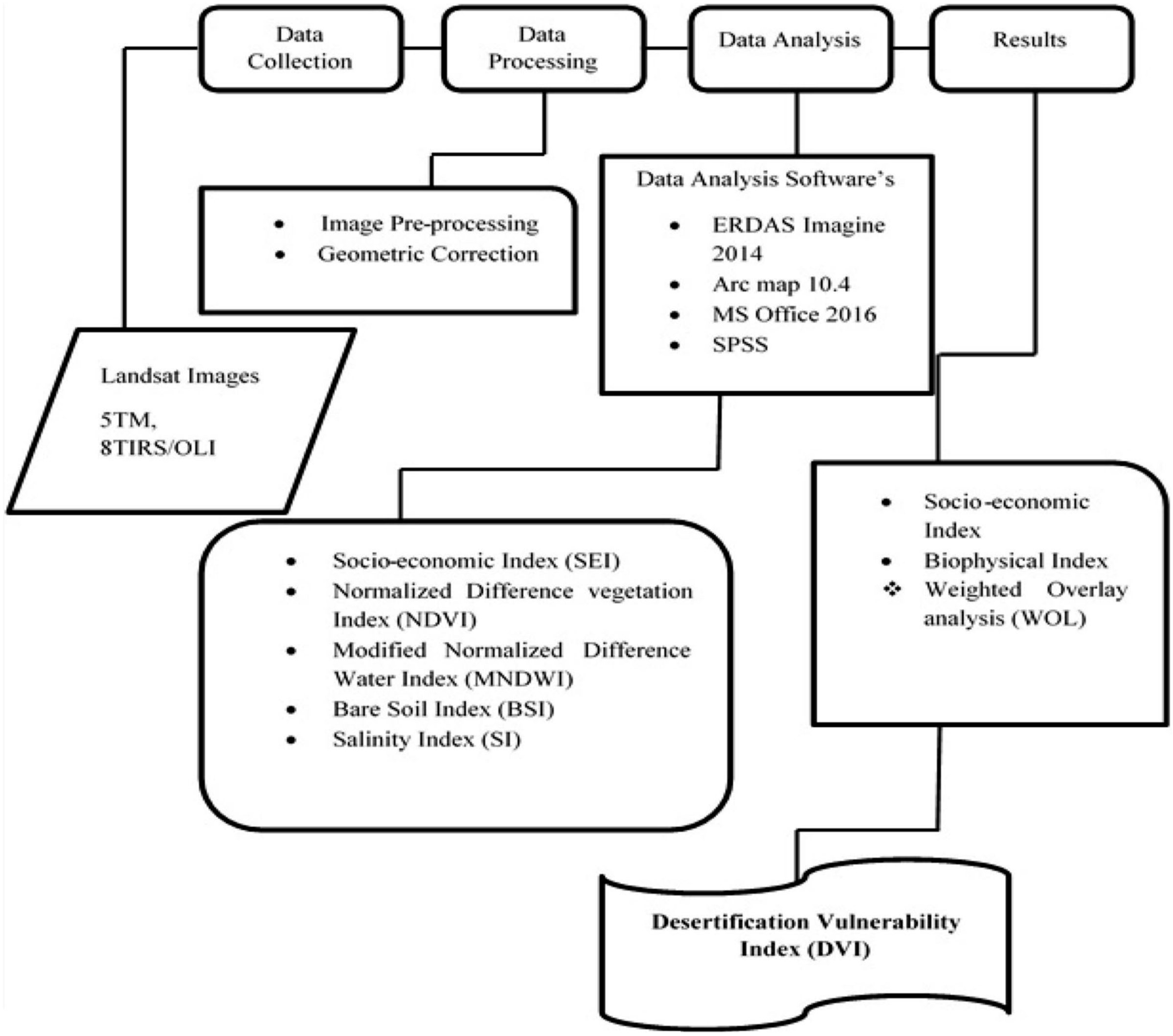


Fig. 3 The Conceptual framework of the study

Pre-processing and image analysis

The first and most important stage in image analysis is image pre-processing. All satellite images were radiometrically and geometrically adjusted by the USGS and formed level one terrain corrected (L1T) data of Landsat satellite. This study examined two separate sets of satellite data: Landsat 5 TM which contains seven spectral bands, while Landsat 8 includes 11 spectral bands. The satellite images were subsequently examined in ArcGIS and ERDAS Imagine software. The layer stack tool was used to combine all the layers into a single multispectral image in ERDAS Imagine 14 and the study area's subset in ArcGIS 10.4 (Fatima et al., 2023). The greatest results are always obtained when cloud contamination is removed. The clouds from satellite images were removed from this study using ERDAS Imagine Haze Reduction analysis. All the images were cropped in the study area using boundaries through the "Extract by mask tool" of ArcGIS10.4. To detect land usage and cover, the False Colours Composite (FCC) band combination was employed (Nasar-u-Minallah et al., 2021).

Desertification vulnerability index (DVI)

The Desertification Vulnerability Index (DVI) was used to calculate the assessment of the vulnerability to desertification. The Desertification Vulnerability Index (DVI), was calculated by combining various indices from Landsat images, including SEI, NDVI, NDWI, BSI, and SI. To create a composite Biophysical Index, all the indices—SEI, NDVI, NDWI, BSI, and SI—have been combined with ERDAS Imagine and ArcGIS. The following provides a detailed explanation of the computation process for each index:

Socio-economic index (SEI)

Land degradation occurs due to different physical and man-made factors (Mohamed, 2013). Therefore Socioeconomic index is used to identify the effect of human influence on land degradation (Sastry et al., 2017). Three main factors, population density, unemployed population, and illiteracy, are used to calculate the socioeconomic index. These factors have a positive and negative impact on land degradation and land management (Prakash et al., 2016). The socioeconomic Index (SEI) was calculated using Eq. 1 (Sastry et al., 2017) to evaluate the effects of humans' interference on land degradation.

$$\text{SEI} = (\text{Population Density} * \text{Un} - \text{Employed Population} * \text{Literacy})^{1/3} \quad (1)$$

Biophysical index

A composite Biophysical Index has been created by combining all of the indices below with the GIS environment.

Normalized difference vegetation index (NDVI) The NDVI is one of the most commonly used indices to monitor the proportion of vegetation cover and classify the decertified land (Ghebrezgabher et al., 2019; Gull et al., 2021; Nasar-u-Minallah, 2020). NDVI is the difference between the reflectance of NIR and R band combinations divided by the sum of both band combinations (Kundu et al., 2014, 2015; Mazhar et al., 2018; Nasar-u-Minallah et al., 2023). The NDVI value ranges from − 1.0 to + 1.0, where higher positive values indicate healthy vegetation (Bhalli et al., 2013; Sahoo et al., 2015; Hanif et al., 2022). Because the healthy vegetation reflects NIR radiation and chlorophyll absorbs a large amount of red VIS radiation. This process becomes reversed in the case of unhealthy vegetation (Dutta et al., 2013; Zia et al., 2022a, 2022b).

$$\text{NDVI} = (\text{NIR - R})/(\text{NIR + R}) \quad (2)$$

Normalized difference water index (NDWI) NDWI was used to identify the canopy-level water content. High values of NDWI showed the batter canopy water content and healthy vegetation (Allah, et al., 2017; Kundu et al., 2014). NDWI is calculated by using the following formula;

$$\text{NDWI} = (\text{NIR} - \text{SWIR})/(\text{NIR} + \text{SWIR}) \quad (3)$$

Modified normalized difference water index (MNDWI) In the MNDWI, open water bodies will have more positive results than the NDWI. The value ranges between − 1 and + 1 and the value of water bodies is greater than 0.5. Soil, built-up land, and vegetation will have still negative value. This modified index will show more accurate results (Xu, 2006).

$$\text{MNDWI} = (\text{Green} - \text{SWIR})/(\text{Green} - \text{SWIR}) \quad (4)$$

Salinity index (SI) The Soil Salinity Index has been used to detect areas with low vegetation density and highly crusted soil (Pashaei et al., 2017). The spectral radiance of salt-affected areas is much higher in the Red and Green bands of Landsat images than in other bands (Azabdaftari & Sunarb, 2016; Wang et al., 2013). The following Formula is used to detect Saline Soil (Othman et al., 2014).

$$\text{SI} = (\text{Green} + \text{Red})^{/2} \quad (5)$$

Bare soil index (BSI) A bare soil index (BI) is used to detect the bareness of soil in a region. It is calculated using the reflectance values of the blue, near-infrared, red, and short-wave infrared bands (Azabdaftari & Sunarb, 2016). Values vary from + 1 to -1, and larger values correspond to increased chances on bare soil (Diek et al., 2017). The following Formula

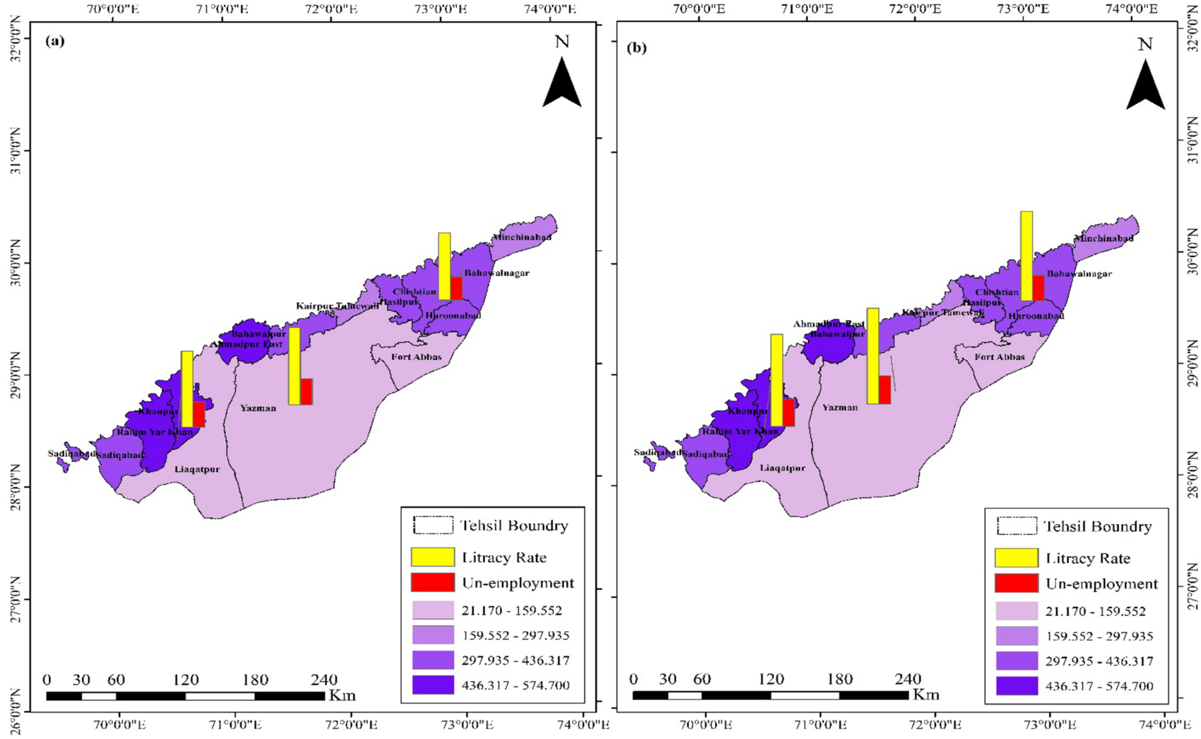


Fig. 4 Population density of Bahawalpur according to 1998 (**a**) and 2017 (**b**) population censuses

is used to detect the Bare Soil Index (Azabdaftari & Sunarb, 2016).

$$BSI = ((Red + SWIR) - (NIR + Blue))/((Red + SWIR)+(NIR + Blue)) \quad (6)$$

Weighted overlay analysis The Analytical Hierarchy Process (AHP) method was used to determine the weights in this investigation. Analytical Hierarchy Process (AHP), is a multi-criteria decision-making technique created by Thoms in 1990 (Dutta et al., 2015). Weighted overlay analysis is a technique in

Table 2 Matrix of pairwise comparison

	SEI	NDVI	NDWI	BSI	SI	DVI	sum	nth Root	PV	% weight
SEI	1.00	2.00	3.00	4.00	5.00	6.00	21.00	4.2000	0.34	34.34
NDVI	0.50	1.00	2.00	3.00	4.00	5.00	15.50	3.1000	0.25	25.35
NDWI	0.33	0.50	1.00	2.00	3.00	4.00	10.83	2.1667	0.18	17.72
BSI	0.25	0.33	0.50	1.00	2.00	3.00	7.08	1.4167	0.12	11.58
SI	0.20	0.25	0.33	0.50	1.00	2.00	4.28	0.8560	0.07	7.00
DVI	0.17	0.20	0.25	0.33	0.50	1.00	2.45	0.4900	0.04	4.01
sum	2.45	4.28	7.08	10.83	15.50	21.00	61.15	12.2293	1	
sum*pv	0.841	1.0857	1.2543	1.254951	1.08493	0.841419	6.3629			

Table 3 Random index (RI)

1	2	3	4	5	6	7	8	9	10
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

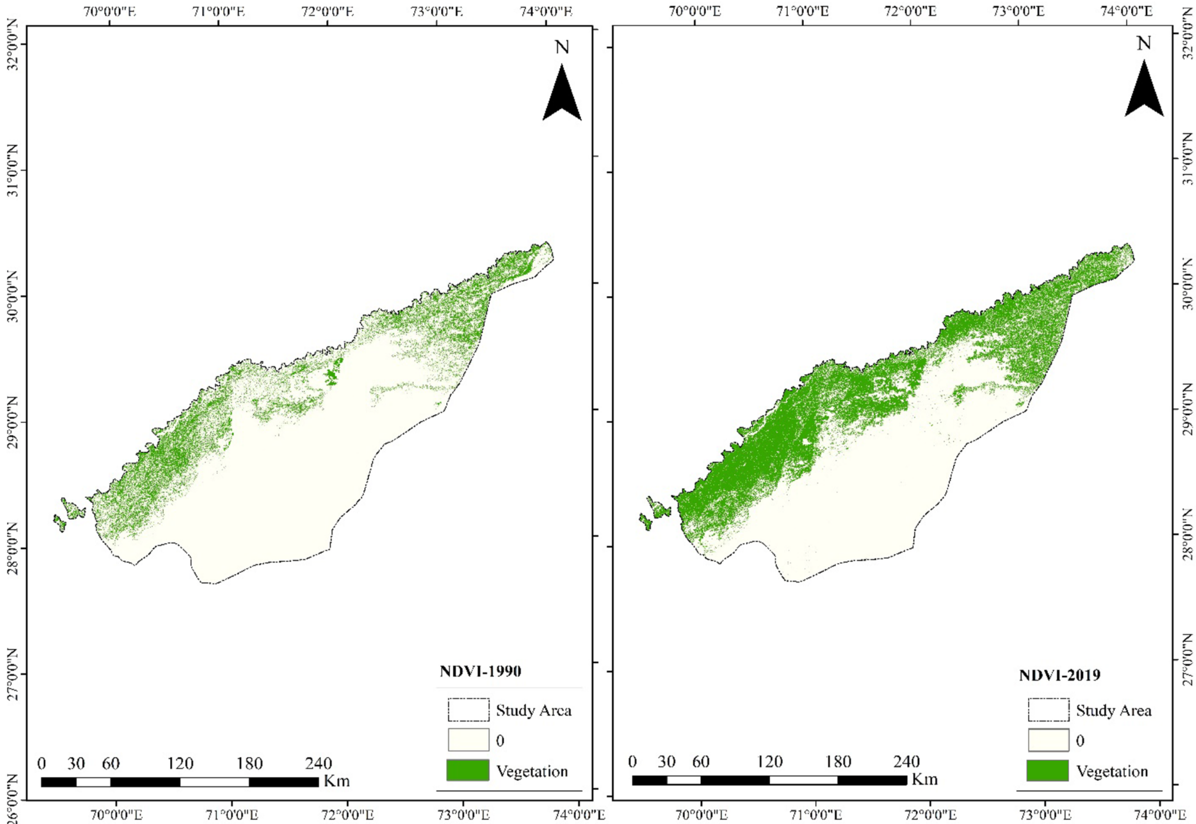


Fig. 5 NDVI maps of the Bahawalpur division between 1990 and 2019

which different parameters for desertification vulnerability are grouped into various classes and assigned a weight to each class according to its importance. The weights are assigned with the preferences of previous research that allow the user to create an index of vulnerability. Previous research (Alves et al., 2009; Conti, 2005; Souza et al., 2004) has highlighted anthropogenic activities and climate variations as key factors initiating and exacerbating land degradation. Likewise, research studies (Araújo, 2002; Becerril-Piña et al., 2015; Khire & Agarwadkar, 2014; Matallo Junior, 2001; Nascimento, 2014; Rocha, 1997; Rodrigues, 2006; Sampaio et al., 2003; Sobrinho, 1978) has been undertaken to enhance the depth of analysis concerning land degradation, with a focus on incorporating socioeconomic indicators rather biophysical indicators. Therefore, for the Bahawalpur Division, a weighted overlay of the SEI, NDVI, NDWI, BSI, SI, and DVI was extracted based on previous preferences mentioned in the literature.

The cumulative suitability index (CSI) of all the parameters, which is an expression of the total weightage, was calculated after computing the weightage for each parameter using the multiplicative approach. The formulation matrix (max A XX=), where (A) is a paired matrix and (X) is an eigenvector of weights, is used to construct the consistency check CI from Table 2 s data. Equation number 7 is used to obtain the CI from the max answer:

$$CI = (6.3629 - n)/(n - 1) = 0.07 \quad (7)$$

where n is the deciding factor and n = 6.

Finally, Eq. 8 is used to determine the consistency ratio from the random index (RI), which is displayed in Table 3.

$$CR = CI/1.24 = 0.056 \quad (8)$$

The resultant CR is 0.05, which is smaller than the 0.1 cutoff value and indicates strong

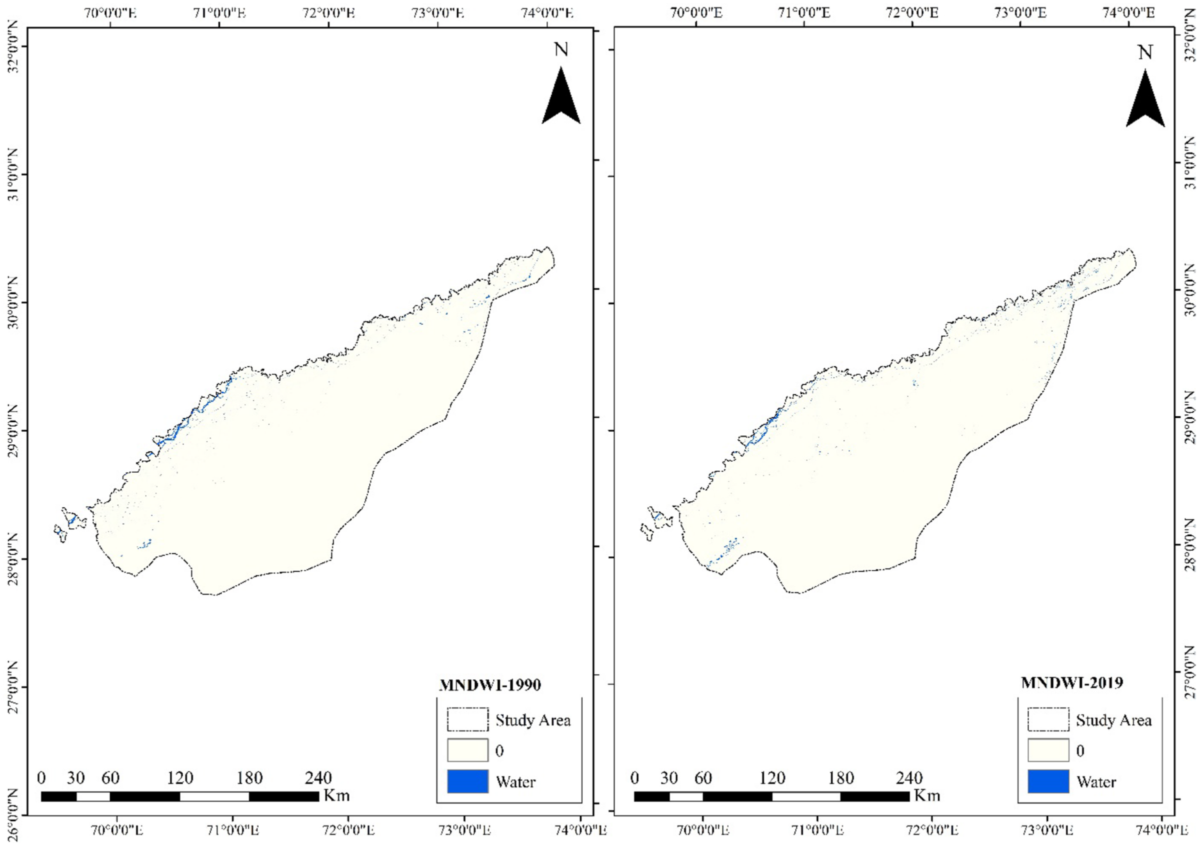


Fig. 6 Modified normalized difference index maps of Bahawalpur between 1990 and 2019. (Color figure online)

consistency in the paired judgments, leading to the conclusion that the estimated weights are appropriate.

Result

Socioeconomic index (SEI)

Physical processes and human-induced activities are interconnected, and their interaction results in various types of land degradation. The literacy rates in Bahawalpur, Bahawalnagar, and Rahim Yar Khan grew while the unemployment rate decreased in the study area between the years 1998 and 2017 according to census statistics (Fig. 4). The findings of the study show that the highly vulnerable areas of Fort Abbas, Yazman, and Liaqatpur have less population density in both years.

Biophysical index (BPI)

Normalized difference vegetation index (NDVI)

Figure 5 shows the level of vegetation cover in the research area, which is coloured green. Reclassify both images into the vegetation and non-vegetated (0) categories after computing the NDVI. When comparing the two images, it can be seen that the vegetation has significantly improved from 1990 to 2019.

Modified normalized difference water index (MNDWI)

The region's water bodies can be found using the Water Index. Figure 6 shows the water condition of the study area between the years 1990 and 2019. Reclassify both images into the categories of water

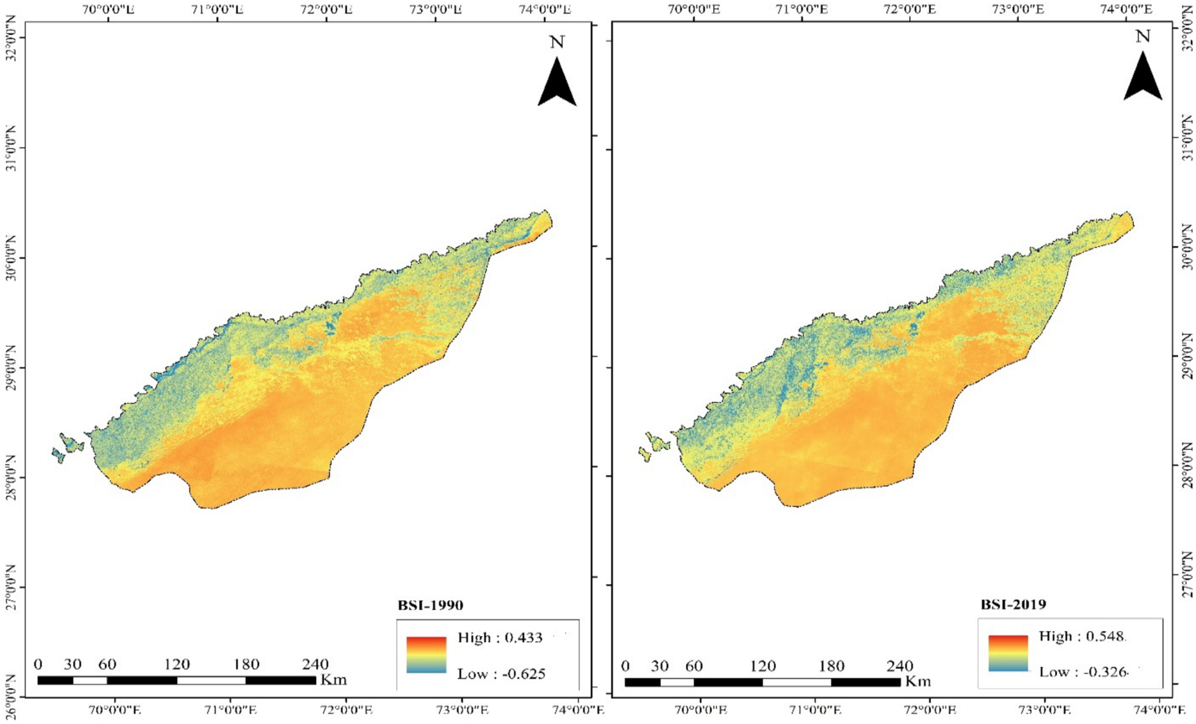


Fig. 7 Bare soil index maps of Bahawalpur division between 1990 and 2019

and non-water areas (0) after computing the MNDWI. The aforementioned two classes are depicted in Fig. 6 in blue and white, respectively. In the study region, the water bodies have undergone notable alterations. The obvious cause is that there are fewer water resources in this area. According to the study's findings, the Water area's percentage was 1.25% in 1990 but fell throughout the years to 0.77% in 2019.

Bare soil index (BSI)

This indicator serves as a valuable tool for monitoring and mapping changes in bare soil and sparse vegetation within the study area over the period spanning from 1990 to 2019. As depicted in Fig. 7, higher values of this index effectively capture the notable increase in bareness, particularly in the southeastern region of Bahawalpur. Notably, the upper limit of the Bare Soil Index (BSI) exhibited an increase from 0.433 to 0.548 during this timeframe, indicative of more pronounced bare soil conditions. Additionally, the lower limit of the BSI experienced a substantial increase, rising from − 0.6 to − 0.3, which is particularly evident in the northwestern side of the study area. These notable shifts in BSI values are visually represented in Fig. 7, highlighting significant changes in the extent of bare soil and sparse vegetation across the landscape.

Salinity index (SI)

Salinity index maps for the topsoil were created through an analysis of Landsat satellite imagery for the years 1990 and 2019 Fig. 8. These maps provide a more comprehensive understanding of how soil conditions were changed across the study areas in a decade, shedding light on the dynamics of soil salinity. The research area map of 2019 as compared to 1990 depicts salt patches in a very brilliant tone due to the high spectral reflectance in the visible and near-infrared spectral bands (Fig. 8). Notably, the salinity index indicates that salt patches have increased drastically in the northern side (Fig. 9).

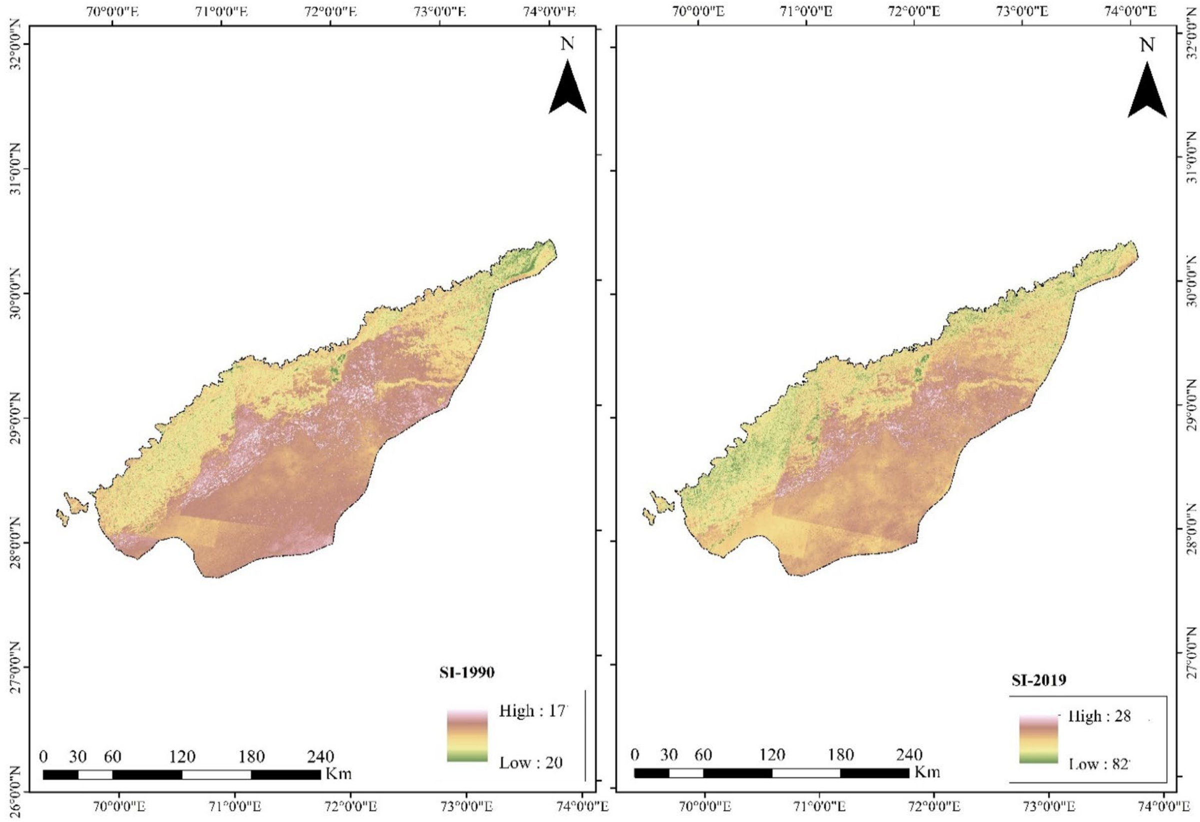


Fig. 8 Salinity index maps of Bahawalpur division between 1990 and 2019

Desertification vulnerability index (DVI)

In this research, the NDVI, BSI, SI and MNDWI for both years were used to calculate the Desertification Vulnerability Index. According to the vulnerability level in the study region, DVI was divided into three classes: Highly Vulnerable, Moderately Vulnerable, and Least Vulnerable. In the study region, there was an evident shift in each class of the Desertification Vulnerability Index from 1990 to 2019. The Least Vulnerable Area was 17.2% in 1990 and 19.53% in 2019. Additionally, it is seen that Moderately Vulnerable increases by roughly 25.59% and 28.56%, respectively. Since then, the Highly Vulnerable area has decreased by over 5.92%, reaching 61.12% in 1990 and 55.3% in 2019. Figure 10 depicts the progressive slowing down of desertification over the past 30 years (1990–2019). The amount of vegetation has greatly grown and the amount of bare land has reduced between 1990 and 2019.

In Fort Abbas Tehsil, a noticeable change was noticed. The southwest side of that region is where that change is spatially distributed. In Yazman Tehsil, where the arid terrain is turning into flora and farmland, the tendency of desertification is also declining. Desertification vulnerability decreased in the Liaqatpur Tehsil, close to Yazman. The Sutlej Valley Project and SCARP established deep water tube wells and a canal irrigation system in this area to address the problem of soil salinity and desertification. A salinity control and reclamation project (SCARP) was launched in the division of Bahawalpur in 1997. With the help of irrigation water and soil salinity reduction, this initiative aimed to increase agricultural output (Mahboob, 2016). The research area's southeast and centre sides continue to be in a zone that is extremely sensitive to desertification.

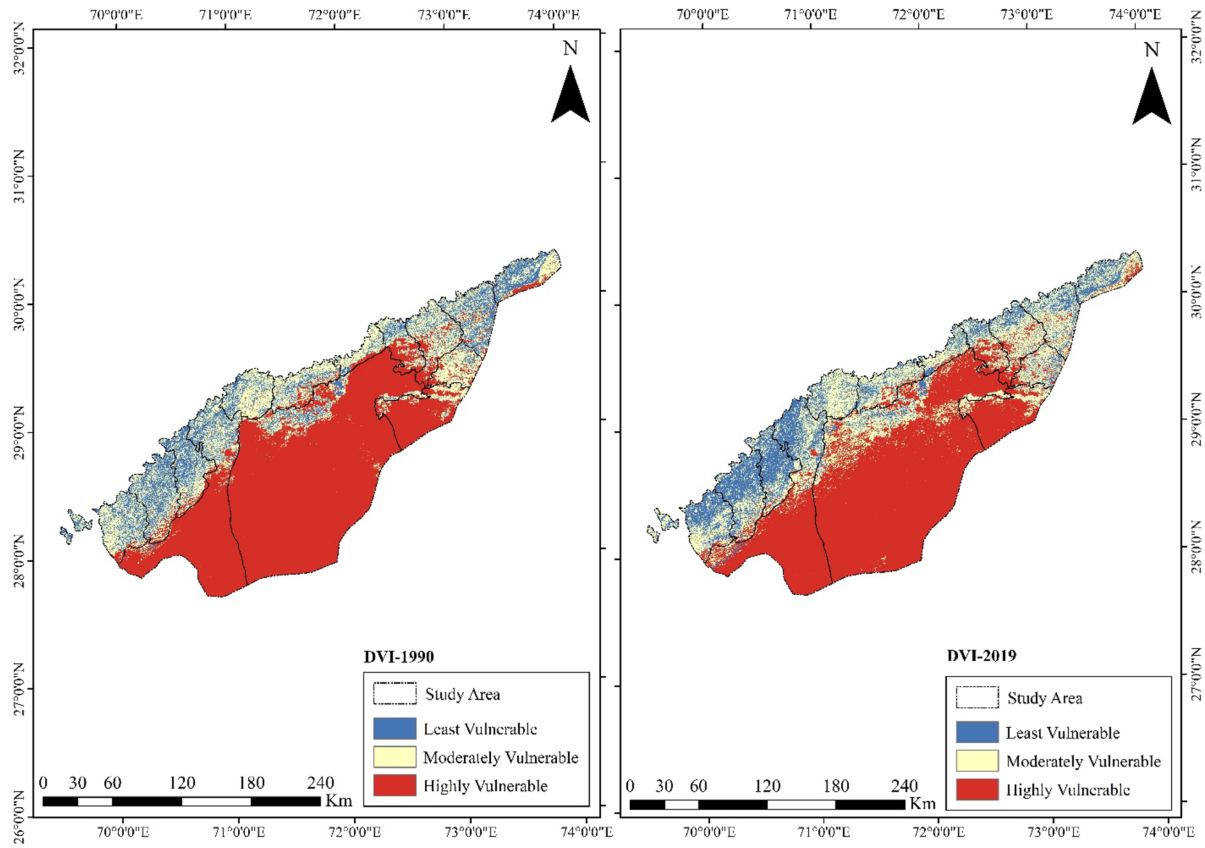
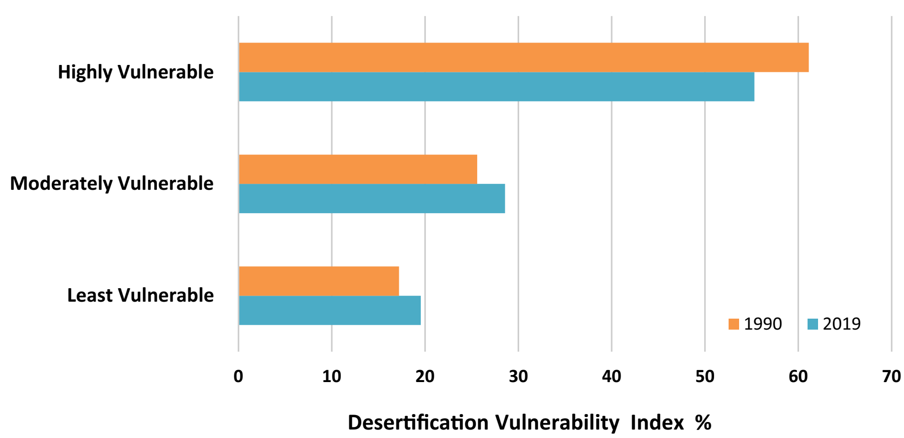


Fig. 9 Desertification vulnerability index maps of Bahawalpur division between 1990 and 2019

Fig. 10 Temporal change detection in desertification vulnerability of Bahawalpur division



Future scenario

Time series or future forecasting analysis is used to predict future observations by using historical data. Future forecasting analysis has been used to show the future trend of desertification for the next thirty years in the Bahawalpur division. According to Fig. 11, the highly vulnerable area will be decreased in upcoming years.

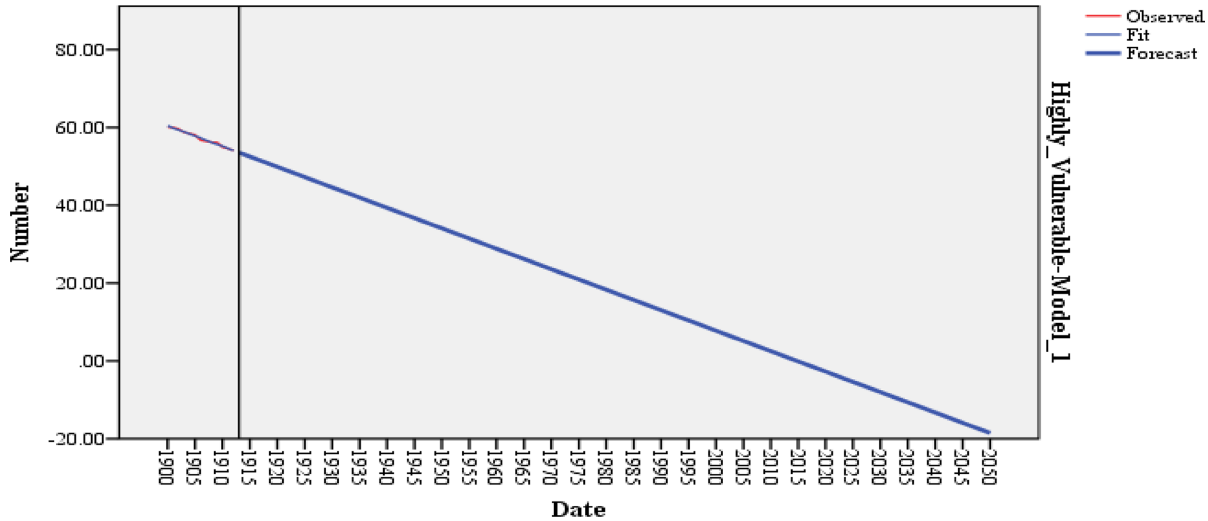


Fig. 11 Future trend of desertification vulnerability in study area

Discussion

This study considers multiple variables to assess land degradation influenced by human activities. To begin with, the socioeconomic index reveals an increase in literacy rates and a decrease in unemployment rates in Bahawalpur, Bahawalnagar, and Rahim Yar Khan. Notably, the study underscores that highly vulnerable areas like Fort Abbas, Yazman, and Liaqatpur had consistently low population densities during the selected study period. This finding contradicts the conclusion made by Vu et al. (2014), which suggests a strong positive correlation between population growth and the level of land degradation.

Furthermore, some biophysical Indices (BPI) are utilized to assess land conditions in the research area. The Normalized Difference Vegetation Index (NDVI) revealed a significant increase in vegetation cover from 1990 to 2019, aligning with findings from earlier studies. Like Mahboob (2016) and Mazhar et al. (2018), vegetation cover grew during the period while non-vegetated or bare land coverage decreased. The MNDWI indicated a decrease in water bodies, with water areas shrinking from 1.25% in 1990 to 0.77% in 2019. In line with the findings, a research study by (Mehmood et al., 2022) also revealed that the water body has shrunk over time. The Bare Soil Index (BSI) was used to identify sparse vegetation, while the Salinity Index (SI) highlighted areas with high salinity, impacting plant growth further.

The Desertification Vulnerability Index (DVI) incorporated these indices, showing a reduction in highly vulnerable areas (61.12% to 53.3%) and an increase in moderately vulnerable areas. These findings align with previous research by Aslam et al. (2017) and Dharumarajan et al. (2018). Notable changes were observed in Fort Abbas, Yazman, and Liaqatpur Tehsils, with reduced desertification vulnerability. Initiatives like the SCARP and Sutlej Valley Project played a role in addressing soil salinity and desertification, particularly in Cholistan and Bahawalpur divisions. However, the southeast and central regions of the research area remained highly sensitive to desertification over the past 30 years.

Conclusion

In this work, the Biophysical Index and Socio-Economic Index were combined and geospatially derived to produce a desertification vulnerability assessment. Several indices, including BSI NDVI, SI, and MNDWI have been used to generate the Desertification Vulnerability Index. The NDVI data demonstrates that between 1990 and 2019, the vegetation cover significantly increased. The MNDWI result demonstrates the decline in surface water in the research area from 1990 to 2019 as a result of the Sutlej River's decreased flow, as well as the absence of rainfall in the studied area. Between 1990 and 2019, the results of SI and BSI demonstrate a significant change in the amount of saline soil and desert land. Although there may be an increase in values in specific areas of the research region, overall values are declining. The built-up area has grown significantly as a result of the population's rapid growth. The highly vulnerable area has shrunk spatially, according to DVI anlysis, from 61.12% in 1990 to 55.3% in 2019, whereas the moderately and least vulnerable areas have grown, from 25.59% and 17.1% in 1990 to 28.56% and 19.53%, respectively, in 2019. This may be related to a rise in the amount of agricultural land and the accessibility of water, which reduced the research area's sensitivity to desertification. It is possible to link the SCARP to the rising trend in vegetation cover. Waterlogging and salt levels were significantly reduced because of the installation of small-capacity tube wells in SCARP zones. Following research on future forecasts, it is seen that the study area's sensitivity to desertification has significantly decreased. The model utilized in this study can be used to examine the desertification process in other land-degraded areas of the country and other comparable regions/countries in any part of the world. To develop thorough planning to mitigate desertification, it also helps to swiftly update maps every 10 or 20 years. For the study area's sustainable development and to halt the process of desertification, the government should construct other initiatives similar to SCARP and Roshan Energy Solar.

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Author contributions The study's inception and design involved input from all of the authors. JS prepared the material, collected the data, and conducted the analysis. JS and MN initially drafted the paper with comprehensive input and feedback from the entire authorship team for both the primary draft and subsequent revisions. Conceptualization and Methodology, review and editing by NP. Write AHP methodology, review and editing by SZ. The final manuscript was read and approved by all authors.

Declarations

Conflict of interest The authors reported no potential conflict of interest.

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