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Research Article

Monitoring Urban Sprawl Dynamics Through Spatiotemporal Analysis Using Normalized Difference Built-up Index in Mardan City, Pakistan

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Abstract: The assessment of spatial distrubution and expansion-driven urban sprawl is cruical for effective urban planning and ensuring sustainable resource management. This study presents a spatiotemporal assessemnt of urban expansion dynamics in Mardan City, Pakistan, by employing the Normalized Difference Built-up Index in the ArcGIS 10.7 environment using Landsat satellite images data. For this purpose, the Landsat 4-5 Thematic Mapper for 1998, Landsat 7 Enhanced Thematic Mapper Plus for 2005, and Landsat 8-9 Operational Land Imager for 2017 and 2022 were used to determine spatial changes in the urbanized area of the city. The data indicates a marginal expansion in the built-up area of Mardan City, which rose from 25.12 km^2 in 1998 to 25.88 km^2 in 2005, reflecting a slow rate of urbanization during this timeframe. However, a considerable growth was observed from 27 km^2 to 33 km^2, between 2017 and 2022, reflecting rapid growth of urbanization. Prospectively, the proposed study could play a crucial role in supporting decision-making and policy formulation regarding urban growth. Moreover, the present approach can provide valuable guidelines for urban planners, policymakers, and researchers to address the challenges and opportunities associated with urbanization in this region.

Keywords: Urban Sprawl, NDBI, Landsat, Spatiotemporal Analysis, RS, GIS.

1. INTRODUCTION

Urban area retains small portion of the global landmass. However, these areas have dense population with relatively high resource consumption [1]; hence, required improvement in resource management practices [2, 3]. Pertaining to this, understanding the spatiotemporal based distribution and expansion of urban areas, as well as mapping built-up areas is one of the major and considerable tasks, Wang *et al.* [4] and Pham *et al*. [5]. Several studies have been carried out with a focus on different related aspects and factors of urban dynamics [6] particularly focusing on its impact on the economy, society, and environment, as well as for effective land use planning and achieving sustainable development. The main factors influencing urban expansion are determined to be population increase and economic development, Jenberu and Admasu [7], Filion *et al.* [8], and Rahman *et al.* [9]. The access to free and advance satellite data has help the recent approach towards precise mapping of the expansion-based determination of small and large cities over the many regions of world Angel *et al.* [10] and Forget *et al.* [11]. Moreover, studies show that application of remote sensing with integration of advanced satellites-data for spatiotemporal based assessment

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of cities is significant for promotion of sustainable urban development Xi *et al.* [12].

Traditional mapping techniques, including ground surveying and aerial photography, needs a significant number of resources while mapping of built-up regions in a precise timely manner is relatively challenging due to fast urban growth [13-15]. For this purpose, a recently developed technique may be divided into two general groups. The first approach is based on the classification of input images, besides both pixel and object-based classification methods [16, 17]; while the second is based on the direct image segmentation using spectral indices Zha *et al.* [18] and Xu [19]. In previous related studies, usually coarse-resolution satellite images, for instance, moderate resolution imaging spectro-radiometer (MODIS) Schneider *et al*. [20] and Sharma *et al.* [21], Numerous satellite imagery has been used, besides the defense metrological program and operational line-scan system (DMSP/OLS) Su *et al*. [22], medium to high resolution imagery such as, Landsat, Sentential-2, Worldview and Quick Bird. In earlier studies, Landsat images acquired since the early 1980s, have the ability to give an old information for mapping the built-up area. It has been widely used in urban studies for extracting built-up areas. It is more efficient for mapping built-up area due to its widespread coverage, 30 m spatial resolution, with a long historical record, and free of coast obtainability [23].

For extracting built-up areas from satellite images, various indices have been created. Spectral characteristics of built-up areas and other characteristics related to the wavelength regions of the electromagnetic spectrum through absorption or reflection form a learning basis for development in indices. Various regions of a satellite images represent different regions or wavelength regions of the electromagnetic spectrum. Thus, it is possible to create indices through a distinct combination of picture-focused regions. To improve and develop various indices for detecting exact land cover features, it is crucial to analyze their spectral characteristics. In previous studies, numerous spectral indices have been utilized to advance the Normalized Difference Built-up index (NDBI), including Index-based built-up index (IBI), Urban Index (UI), Normalized Difference Bareness Index (NDBaI), and Normalized Built-up Index (NDBI). Currently, numerous spectral indices have been developed for built-up and urban area extraction, such as, the Normalized Built-up Area Index (NBAI), Built-up Area Band Ratio for Built-up Area recognition (BRBA), New Built-up Index (NBI), Built- up Index (BUI), Bare Soil Index (BSI), Enhanced Built-up and Bareness Index (EBBI), and Built-up Area Extraction Method [24-29]. The emergence of the geo-informatics field has enabled the provision of spatiotemporal satellite images that can be applied to monitor and determine changes on the land surface while the use of remotely sensed images can be beneficial for determining the transition of agricultural land to other developed land cover [17, 23, 30] From the point of view of geospatial technology, methods relative to the maximum likelihood classification algorithm, the NDBI can be regarded as a promising substitute to rapidly and objectively extract built-up land. It is important to note that no built-up index in existence is ideal to use Landsat 8 OLI (Operational Land Imager) images to automatically distinguish between built-up and barren regions. Over the last twenty four years (1998 to 2022), agriculture has been rapidly replaced by urban areas. Since significant land use changes have been reported at the city boundry in the rural area of District Mardan , no relevent research has been carried in this critically significant area.

Recent geoinformatics-based study emphasizes a disturbing rate of spatial change across the Khyber Pakhtunkhwa region, with Mardan developing as a serious case study due to its rapid expansion. Kamran *et al*. [31] led a complete spatiotemporal assessments of Mardan from 1990 to 2021, showing a notable growth of the built-up area by 408%. This deep variation within local context is not only a measurable change in land use but it also serves as the main driver for succeeding environmental degradation. Based on this indication, Sultan *et al*. [32] stated that the built-up area expended from 165.47 km^2 in 2002 to 266.70 km^2 in 2022, and this development caused in a substantial increase in land surface temperature. This proposes that the replacement of bare land with impervious urban surfaces is basically changing the local micro-climate and making localised urban heat islands. In addition, outside these environmental influences, previous studies presented a critical socio-spatial layer by representing that the city's remaining green areas are not spread equally. Their diverse-methods

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assessment shows that as the city increases, access to high-quality green spaces remains limited to affluent zones, hence; creating a green divide. Subsequently, the thickly populated and newly expanded areas recognised by Kamran *et al*. [31] disturbed from a total lack of public green structure. Together, these findings underline a worsening urban ecosystem where rapid horizontal sprawl without integrated green planning is bargaining both environmental flexibility and social justice in Mardan.

The present study aims to analyze changes in the urban land use pattern in and around Mardan city, which is experiencing fast expansion with substantial consequences for peri-urban agriculture. Hence, using GIS and remote sensing methods, the proposed NDBI was used in the ArcGIS 10.7 environment to a time series of Landsat satellite images from 1998, 2005, 2017, and 2022 to evaluate changes in the city land use pattern.

2. MATERIALS AND METHODS

2.1. Study Area

The city of Mardan (Figure 1) has an area of 32 km^2. It located between 34° 05'-34° 32'' North latitude and 71° 48'-72° 25' East longitude. It is situated 148 km west of Islamabad (the federal capital) and 64 km from Peshawar, the provincial capital of Khyber Pakhtunkhwa (KP). It is the second-largest fastest-growing metropolis city in KP province. The city peri-urban agricultural region has seen tremendous urban expansion over the last few decades. As a result, in recent decades, significant developments with increasing number of people has settled close to its urban area. Consequently, as the metropolitan area has grown on the periphery, prime farmland and waste land have been lost. In addition, Mardan city is distinguished by intricate peri-urban and urban landscapes that combine variety of land uses at different spatial scales. In

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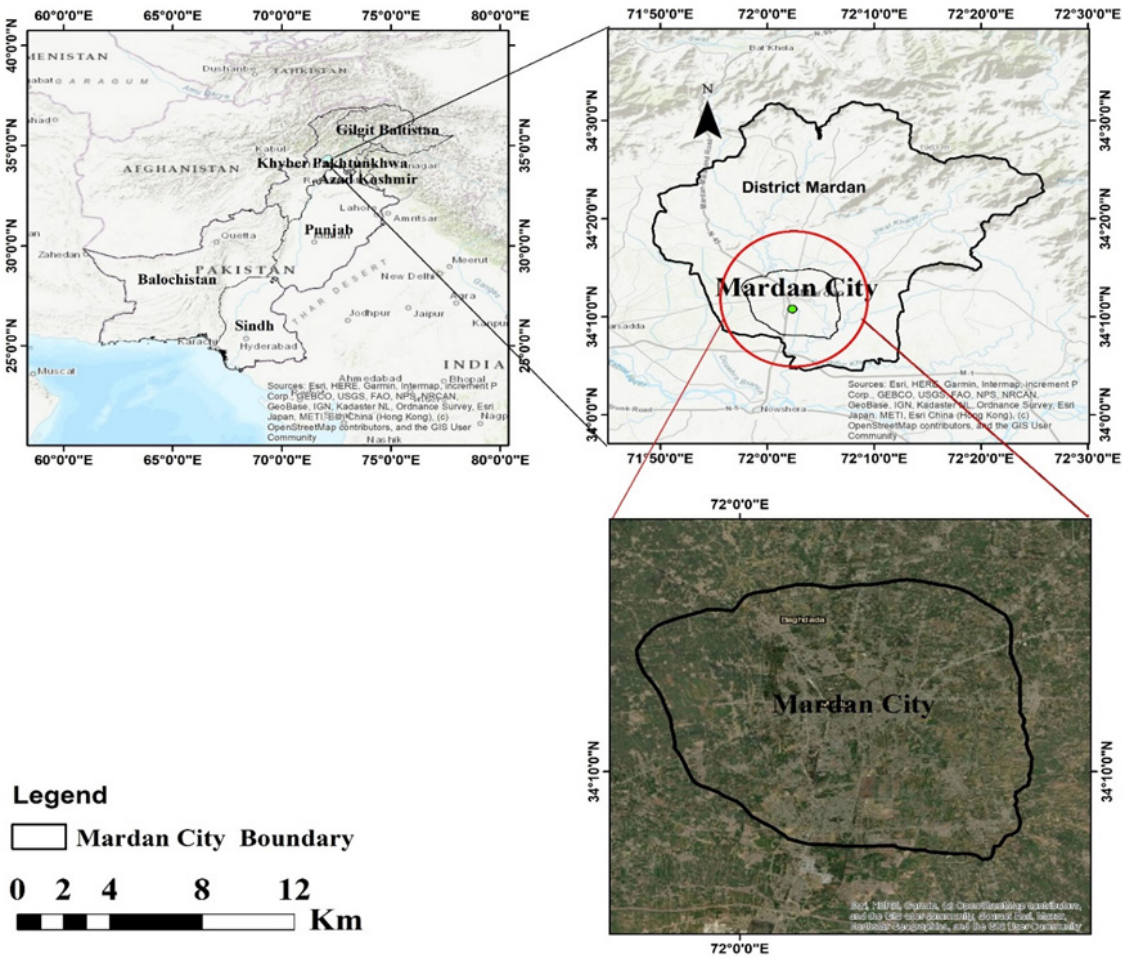

Fig. 1. Study area map.

its urban area, about 246,000 populations was estimated in 1998 which at the current pace of growth was projected to reach 402391 in 2015 and 512,778 till 2030, respectively [33].

2.2. Data and Processing

The Landsat TM and OLI satellite imageries (with 30-meter resolution and <10 percent cloud cover) were acquired from USGS (https://earthexplorer.usgs.gov/). For further image processing and analysis, we used ArcGIS 10.7 software. In ArcGIS environment, a technique developed for this approach may be divided into two general groups. The first method is based on the classification of input imagery, which includes both pixel-based and object-based classification approach, while the next one is based on the direct image segmentation using indices mentioned in related studies [34-38]. For this purpose, we analyzed data from 1998, 2005, 2017 and 2022 and made a comparative analysis to determine change in urban area over the years. Furthermore, NDBI was used as a better alternative for prompt and particularly mapping built-up areas [39, 40]. Table 1. Shows the details of the dataset.

2.2.1. Normalized difference built-up index

Numerous indices are available for the assessment of built-up areas. Most popular indices for assessing built-up regions are Enhanced Built-up and Bareness Index (EBBI), Index-based Built-up Index (IBI), Built-up Index (BU), Urban Index (UI), and NDBI. Each of these indices has its own computation process and formula.The Built-up Index (BU) can be utilized for improved results. The index used to analyze urban pattern using NDVI and NDBI is called the Build-up Index, Zha *et al*. [18], Macarof and Statescu [41], Tin and Muttitanon [24]. The binary image known as the "built-up index" permits BU, since, only higher positive values represent both built-up and barren areas.

The process of classifying images using supervised and unsupervised methods is time-consuming and intricate. For the end results, composite band and application of numbers of operations are needed. The image analyst and the methodology determine how accurate the image categorization process is. Nonetheless, NDBI computation is straightforward and easy to derive. The NDBI may be determined by applying formula given below.

$$NDBI = \frac{SWIR-NIR}{SWIR+NIR} \quad (1)$$

Where NDBI for Landsat 4-5 TM, the math band is clearly NDBI = (Band 5 – Band 4)/(Band 5 + Band 4) for the Landsat 7 ETM+, the similar band composite is used as TM. For Landsat 8-9 OLI/TIRS data, NDBI = (Band 6 – Band 5)/(Band 6 + Band 5). The Landsat 4-5 TM wavelength Band 5 SWIR is (1.55 - 1.75 µm) and Band 4 is (0.76 - 0.90 µm) while for Landsat 8-9, Band 5 NIR (0.851 - 0.879 µm) Band 6 SWIR1 the wavelength is (1.566 - 1.651 µm). Furthermore, the value of Normalize Difference Build-up Index ranges from -1 to +1. Water bodies are shown by an NDBI value that is negative, and built-up regions by a number that is greater while the NDBI value of vegetation is low.

3. RESULTS AND DISCUSSION

In Figure 2, July 26, 1998, the higher value of NDBI calculated was 0.659091, while lowest values was -0.156863, resulting in a difference of 0.502228. The high spatial values (in color-ramp) of NDBI reflects built-up area while the low values depicts vegetation in the city or water bodies. While comparing the built-up cover with the August 06, 2005, built-up cover the high value for NDBI is 0.202073 and lowest value was -0.584416,

Table 1. Landsat satellite images details used in this study.

Date Acquired	Satellite/Sensors	Spatial Resolution (m)	Path/Row
26/07/1998	Landsat 4-5 (TM)	30	150/36
6/08/2005	Landsat 7 (ETM+)	30	150/36
15/08/2017	Landsat 8 (ETM)	30	150/36
13/08/2022	Landsat 8-9 (OLI/TIRS)	30	150/36

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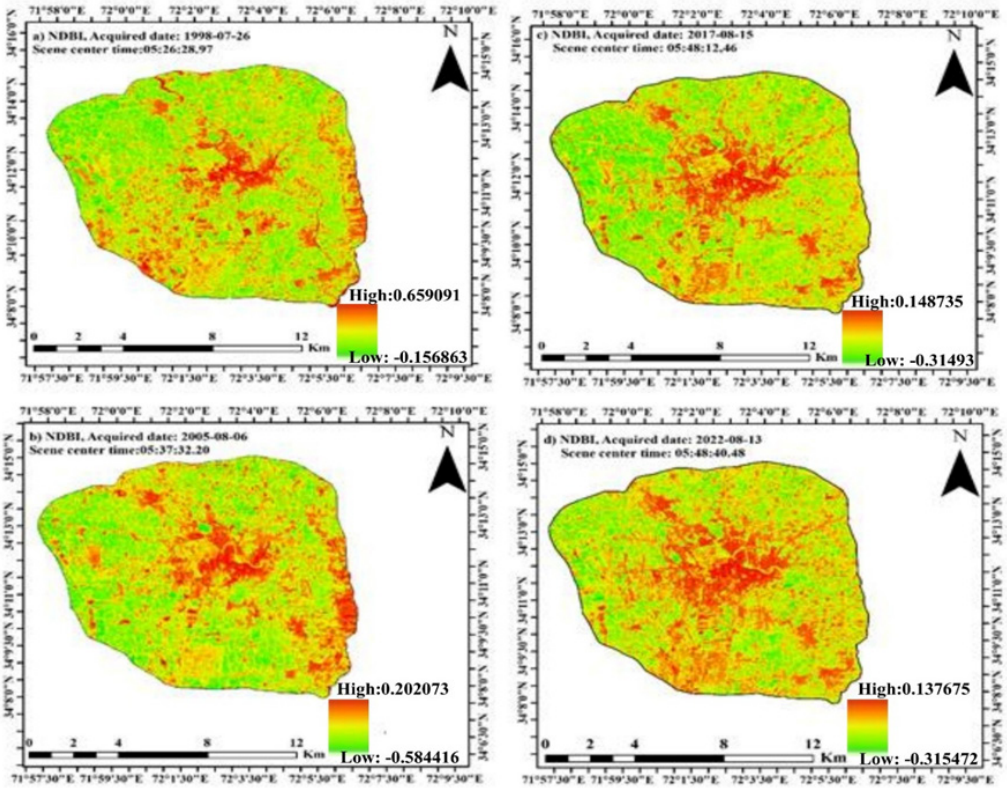

Fig. 2. Spatiotemporal change in NDBI (a) 1998, (b) 2005, (c) 2017, and (d) 2022.

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resulting in a difference of 0.382343. The total area covered by built-up cover was 25.88 km^2. In the study area, only slight change of 0.76 km^2 has occurred in the built-up over 8 years. On August 15, 2017, the highest value of NDBI was calculated as 0.148735 while the lowest value was -0.31493, resulting in a differnces -0.166195. However, in 2022, the hghest values of NDBI was calculated as 0.137675 and lowest value was -0.319472, resulting in a difference of -0.181797. Higher positive values in the color ramp represent built-up area due to high SWIR reflectance relative to NIR. Lower or negative values represent vegetation and water bodies. The results of this study present robust contact on the main patterns of land changes in Mardan, while vary in the exact impact they qualify. Moreover, the previous studies for Mardan and Charsadda [42, 43], and for Islamabad [44] reported a significant increase in built-up areas together with decline vegetation and agriculture, conforming rapid urban sprawl over time. Qasim and Gul [45] results were in line these studies by showing similar spatial urban sprawl trends, their results focused the role of population stress and migration as noticeable drivers of this expansion. Table 2. Shows high and low vales in NDBI.

Table 2. Showing temporal changes in high and low NDBI values.

Data	NDBI High Value	NDBI Low Value	Changes
26/07/1998	0.659091	-0.156863	0.502228
6/08/2005	0.202073	-0.584416	-0.382343
15/08/2017	0.148735	-0.31493	-0.166195
13/08/2022	0.137675	-0.319472	-0.181797

Figure 3 shows the temporal extraction of built-up area through four selected years 1998, 2005, 2017 and 2022. The analysis shows that the standard spatial extent of the NDBI was firstly low in 1998, a slow increase occurred in 2005, followed by a continued increase trend in 2017, finally a rapid expansion was detected in 2022.

Bar graph showing the temporal increase in built-up area in km^2 over study period, as illustrated in Figure 4. A clear difference was noticed comparing our findings with previous studies. In the present study, the built-up area was noted at 25.12 km^2 in 1998, 25.88 km^2 in 2005, 27 km^2 in 2017, and 33 km^2, showing a steady increase in Figure 5. In contrasts, Sultan *et al.* [32] described a substantially larger built-up area which increased from 165.47 km^2 in 2002 to 266.70 km^2 by 2022. These differences can be ascribed to numerous factors. First, the disparity in the spatial extent of the study area: Sultan *et al.* [32] studied a larger administrative boundary of Mardan district, where the current study is limited to Mardan City. Second, differences in classification methodology and satellite data processing may have affected the result. The previous study may have comprised peri-urban area and rural built-up area, although the current study applies a more rigorous definition built on high-density impervious surfaces using NDBI. Consequently, both studies ratify a similar increasing tendency in urban expansion, the total values vary due to differences in the demarcation of the study area and classification approach.

Nasar-u-Minallah *et al*. [46], focused on Lahore, produced comparable results in terms of rapid urban sprawl and spatiotemporal analysis of urban growth pattern, but exclusively adds analytical outcomes, showing consistent expansion in the future. Resultantly, all studies find on the

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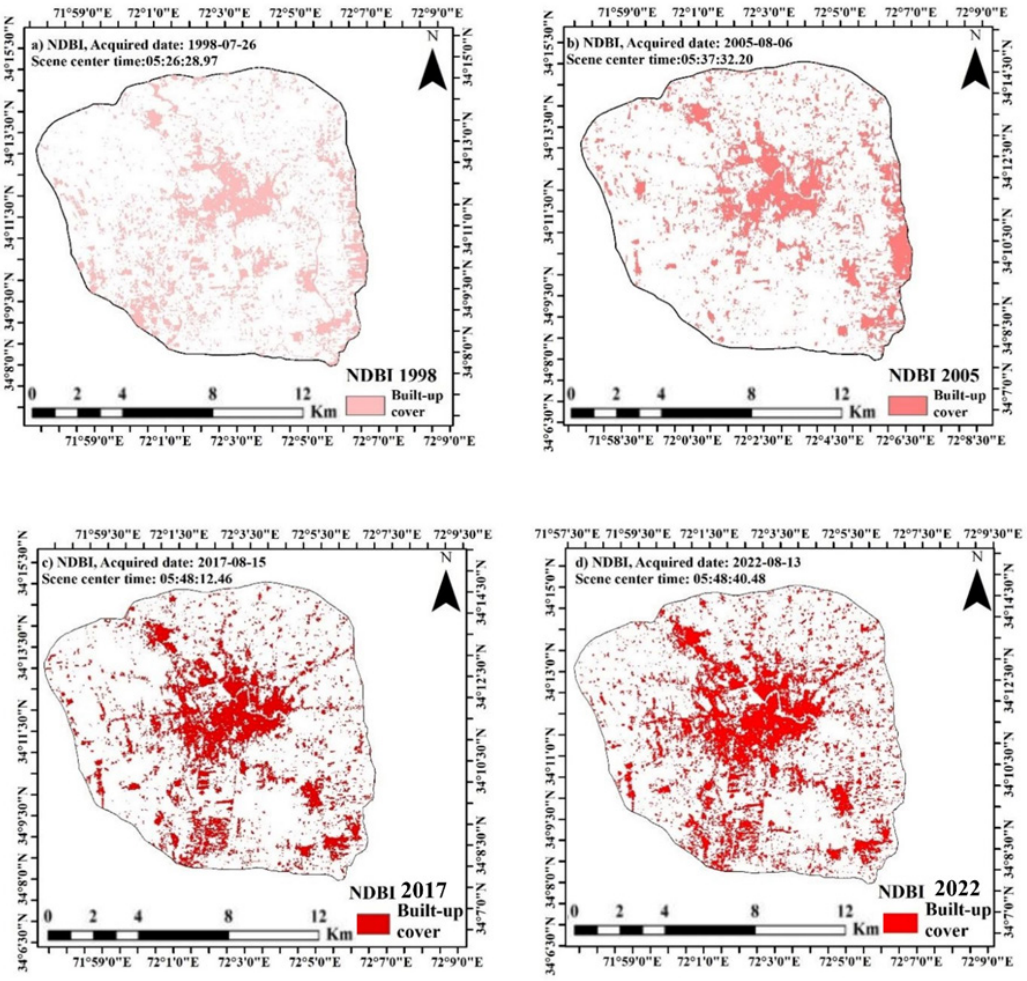

Fig. 3. Extracted layers of NBDI: (a) 1998, (b) 2005, (c) 2017, and (d) 2022.

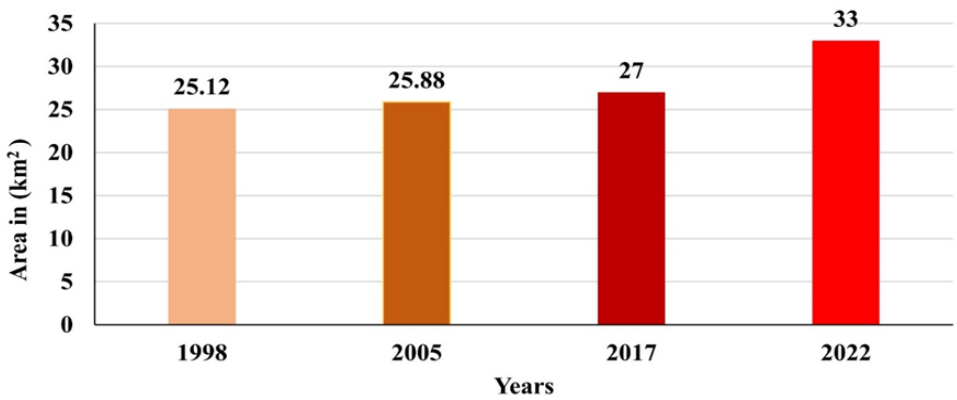

Fig. 4. Visualizing spatiotemporal change in built-up area in km^2.

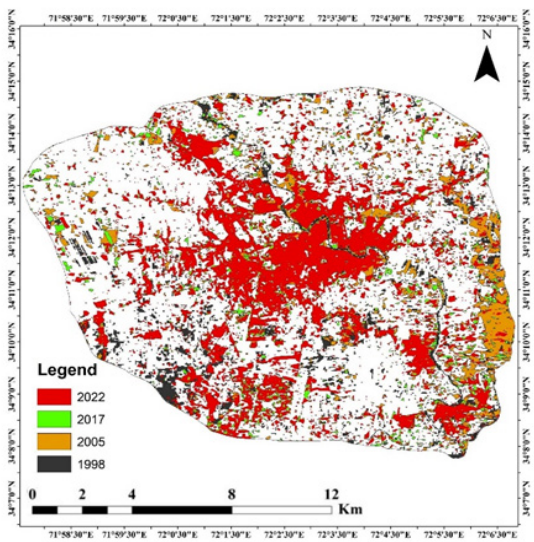

Fig. 5. Spatiotemporal change in built-up area over the years 1998, 2005, 2017 and 2022.

leading trend of increasing urbanization and decreasing barren land, they vary in the exact results they focused temperature rise, groundwater depletion, future growth, they combined shows different extent of urban expansion impacts.

The aim of this study was to analyze the spatiotemporal changes and expansion of Mardan city over more than two decades using Normalized Difference Built-up index (NDBI) a geospatial approach. On basis of findings, the overall discussion is given as follows.

3.1. Urban Growth Trends and its Influencing Factors in Mardan City

The findings depicts that built-up area of Mardan city had considerable modifications across the study time periods. The built-up area has grown from 25.12 km^2 in 1998 to 25.88 km^2 in 2005 which reflects a moderate growth rate over this time. The built-up area shows significant expansion from 27 km^2 in 2017 to 33 km^2 in 2022. This pace of rapid growth relates to the larger urbanization patterns which is generalized in many developing countries and correlates with a substantial change in the urban landscape. Moreover, behind apparent urban growth of the study area, other related variables include changes in land use regulations, a rise in economic activity, better infrastructure, and population expansion. However, these factors were not included in the present study which can prospectively help in a more comprehensive picture to examine the precise drivers urbanization in this area. Kamran *et al.* [31], Qasim and Gul [45] found that rapid population growth from rural to urban migration is the main reason of urban expansion. Their findings were strengthened by Shahid *et al.* [42] who verified a sustained decadal growth in built-up areas at the cost of agricultural and vegetation, a tendency also matched with the wide urban sprawl and future growth patterns modeled by Nasar-u-Minallah *et al*. [46] for Lahore. Sultan *et al.* [32] also proposed that Mardan follows national scale urbanization dynamics.

3.2. Implications for Urban Planning and Environmental Sustainability

Due to the fast urbanization observed between 2017 and 2022, there will be a number of related effects on urban planning and sustainability. Eventually, it will put more burden on the services and infrastructure, hence, will probably lead to more strain on daily need-based resources including electricity, water, and transportation. In addition, demand for homes and commercial spaces will rise with urban expansion which might cause an impact on land

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values and housing affordability. Since expansion into regions that were not previously cultivated may cause habitat fragmentation, agricultural land-loss, and deforestation. Hence, significance of sustainable urban design and demand for balanced growth are more considerable. Sultan *et al.* [32] and Khan *et al.* [43] revealed a strong relationship between the growth of built-up areas and the increase in land surface temperature, showing an increase of the urban heat island effect. While Yar [47] exclusively highlighted groundwater depletion as a serious consequence of reduced infiltration and expose significant variations in the supply and availability of green spaces, especially affecting low earning population.

3.3. Present Approach Applications and Prospective Insight

This study approach of NDBI and GIS technology demonstrates its significance for montioring and possibility towards the mitigation of urban expansion. For purpose of making well-informed choices on the infrastructure development, the smart use of land and resources distribution, municipal officials and urban planners can benefit greatly from the capacity to monitor variations in built-up areas. To maintain sustainable urban expansion and resolve potential problems, ongoing observation is crucial. Present study has given important insights into urban evolution of the Mardan City. However, there are number of research directions that might be further pursued including thorough studies of the particular factors causing urbanization, the socioeconomic effects of population expansion, as well as the creation of all-encompassing urban planning plans that strike a balance between the demands of inhabitatnts and environment.

4. CONCLUSIONS

In this study, RS satellite data and GIS techniques based Normalized Difference Built-up Index (NDBI) was applied to analyze the urban growth and dynamics in the built-up area of Mardan city, Pakistan, focusing on two distinct periods from 1998 to 2005 and from 2017 to 2022 . Through this approach, prospective ascpets of the changing urban landscape of Mardan city were obtained. Overall findings showed that urban landscape of city has undergone a substantial transition with discernible variations in the pace of urban growth throughout the course of study periods. Particularly in the study period, (between 2017 and 2022), the built-up area has shown a rapid increment of about 6 km^2 (from 27 to 33 km^2) showing a tendency toward fast urbanization which is consistent with larger trends observed in many developing areas. Although this study did not specifically address the driving mechanisms behind urban growth of area, however; it has attributed a insightful base for pointing out its potential factors including land use rules, infrastructural development, economic activity, and population increase as significant contributors. Hence, for a better assessment of the dynamics of urbanization in the region and this area in particular, these drivers needs to be studied further. Such urban growth has a variety of ramifications for current infrastructure and other daily life resources, as well as potentially impact the land values and housing affordability due to higher demand for residential and commercial real estate. Additionally, the negative effects of urbanization on the environment highlight the necessity of sustainable urban design. The use of geospatial technology and NDBI index application emphasizes its scope for assessment and green check on urban expansion. Suggestively, additional research may focus on identification of the precise factors which drives this urban expansion, evaluate its socioeconomic effects, and create comprehensive urban planning plans that consider sustainability and the welfare of the city as a first priority. From overall spatial results of this study, the detrermined changes in built-up area highlight necessity of taking proactive steps to manage urbanization responsibly. Moreover, it will make ensure that the city expansion is balanced and sustainable, satisfying the needs of its inhabitants while protecting local ecosystem. In this regard, environmental impact assessments should also be incorporated into urban planning procedures. With conclusive suggestion, urban expansion should be monitored on spatiotemporal basis with satellite images and GIS based real-time databases to support well-informed decision-making, as well as to expedite management and planning procedures. Prospectively, it will help formulating plans and policies necessary to address shifting conditions and shifting urbanization patterns.

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6. ETHICAL STATEMENT

This work does not involve any studies with human or animal subjects; therefore, ethical approval was not required.

7. CONFLICT OF INTEREST

All authors decleared no clonflict of interest.

8. FUNDING

No funding was received for conducting this research.

9. AUTHORSHIP CONTRIBUTION STATEMENT

Abdur Raziq: writing methodology, original draft writing, and investigation of data analysis;: supervision; writing-review and editing; Ihsan Ullah: resources and English correction, proofreading; Muhammad Alamgir Khan: original draft extensive editing and finalizing; Tariq Sardar: writing, methodology, review of the manuscript, and editing; Izhar Ullah: review and rewriting of the manuscript.

10. DECLARATION

The authors approve that the result and finding existing in this research are original, have not been published elsewhere, and are not under consideration by any other journal. All Authors have reviewed and approved the final version of the manuscript and consent to its submission. All data, result and figures comprised in this research are original and created by authors. Therefore, no copyright approvals were needed. Upon acceptance of this manuscript for publication, the authors agree to transfer the copyright of the manuscript to the Pakistan Academy of sciences.

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