Research

Assessment of environmental degradation of lakes of Nainital district: an ecohydrological perspective

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Received: 31 May 2023 / Accepted: 8 September 2023
Published online: 23 September 2023

Abstract

Human activities have degraded lakes in Uttarakhand, endangering their vital role in urban sustainability, which includes providing essential services like water supply, flood mitigation, agriculture support, and biodiversity conservation in the Himalayan region. This study focused on Nainital district lakes, utilizing remote sensing and GIS techniques to assess their condition. Time series Landsat 8 satellite imageries acquire by USGS earth explorer from 2017 and 2022 were captured, pre-processed, and subjected to spectral-based classification algorithms in ArcGIS software to calculate Normalised Difference Vegetation Index (NDVI), Normalised Difference Water Index (NDWI), and Normalised Difference Built-up Index (NDBI) indices to assess changes in vegetation, water bodies, and build-up area in and around the lakes respectively. The results indicate a decrease in built-up areas for Nainital district lakes from 2017 to 2022: Naini Lake (1.42%), Bhimtal Lake (1.83%), Naukuchiatal Lake (1.45%), Sattal Lake (2.18%), Khurpatal Lake (2.25%), and Sariyatal Lake (1.3%). Additionally, Bhimtal, Naukuchiatal, and Khurpatal lakes exhibited reductions in shrub and grass vegetation by approximately 12%, 16%, and 0% over the five-year period. Notably, Sattal and Khurapatal lakes demonstrated significant decreases in built-up areas, likely attributed to restoration efforts or landslides. Findings emphasize the need for conservation, sustainable land-use practices, and effective management to protect lake ecosystems.

Article highlights

- Built-up areas decreased: Uttarakhand lakes saw reduced built-up areas from 2017 to 2022.
- Vegetation changes: Shrubs and grass declined in Bhimtal, Naukuchiatal, and Khurpatal lakes.
- Restoration efforts: Sattal and Khurapatal lakes showed significant improvement due to restoration.

Keywords Nainital lakes · GIS techniques · Eco-hydrology · Himalayan lakes · Band ratioing indices · Uttarakhand

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1 Introduction

Lakes are crucial for maintaining biodiversity because they provide homes for a wide variety of species, promote the cycling of nutrients, and provide water for many ecological processes [1]. However, due to increased pollution, sedimentation, encroachment, and disruption of hydrological regimes because of rapid speed of urbanization, industrialization, and agricultural intensification, once-pristine ecosystems are today dealing with problems like eutrophication, biodiversity loss, habitat degradation, and degraded water quality [2–4].

The Nainital district, widely known as India's lake district, and located amid Uttarakhand's picturesque landscapes, is home to six beautiful lakes namely Naini Lake, Bhimtal Lake, Sattal Lake, Sariyatal Lake, Khurpatal Lake, and Naukuchiatal Lake [5–7]. However, these lakes have been inflicted by encroachments, illegal development in the catchment areas surrounding the lakes, population growth, increased tourism, eutrophication, and contamination due to pollution because of the quick expansion of homes and hotels [8, 9]. These issues are made worse by silt deposition, solid waste disposal, and untreated wastewater discharge. Consequently, it is imperative to thoroughly examine the present state of the lakes in the Nainital district and present a comprehensive overview to the relevant authorities for appropriate action [10–14].

For comprehending lake issues and creating successful conservation strategies, ecohydrology blends ecology and hydrology. By facilitating effective decision-making and the evaluation of ecological repercussions, remote sensing and GIS technology has revolutionised lake management [15–19]. GIS-based technologies have recently started to be used to assess the condition of the lakes. It has been used for aquaculture site suitability, landslide susceptibility, and water quality assessment of the lakes of the Nainital district [20–23]. The water of Nainital, Bhimtal, Naukuchiatal, and Sattal lakes were found to be unsuitable

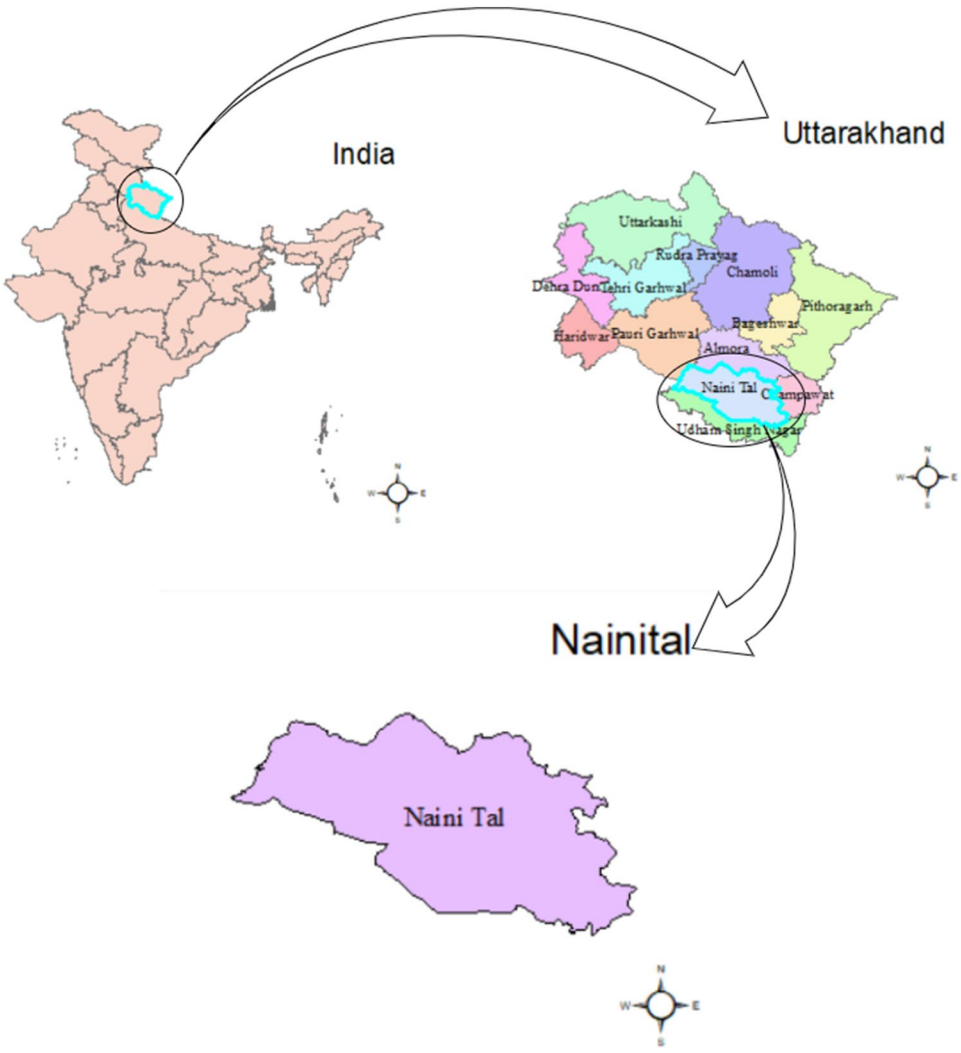

Fig. 1 Location of study area (using ArcGIS software)

Fig. 2 Satellite images of Nainital's Six Lakes dated 1 February 2023 (*Source* United States Geological Survey)

for drinking [21]. The same has been employed for determining the land use/ land cover change dynamics in the Bhimtal Lake catchment area using a multi-criteria evaluation approach, the results of which showed an increase in the settlement and agricultural area and a decrease in the forest area of the region [24]. Water spread areas of Bhimtal, Sattal, and Naukuchiatal lakes from 2001 to 2018 have also been calculated based on the band rationing indices revealing a significant increasing trend in the water surface area of Sattal Lake and Naukuchiatal Lake [25].

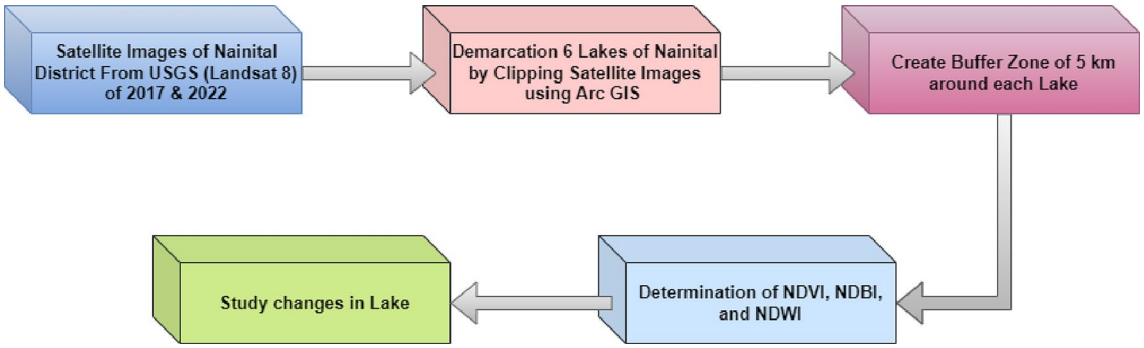

Fig. 3 Flowchart of the methodology adopted

Much of the research work focused on the Nainital Lake and least on the other five lakes of the Nainital district. Moreover, the current condition of the lakes needs to be assessed and addressed. The potential for using GIS technologies to assess lake environmental degradation in the Nainital District is enormous. Thus, using remote sensing and GIS techniques, the current study aims:

- To assess the condition of Nainital district lakes namely Nainital Lake, Bhimtal Lake, Sattal Lake, Khurpatal Lake, Naukuchiatal Lake, and Sariyatal Lake in Uttarakhand using remote sensing and GIS techniques.
- To analyze and quantify the changes in vegetation, water bodies, and built-up areas in the lakes from 2017 to 2022 using satellite imagery and spectral-based classification indices.
- To investigate the factors contributing to the observed changes such as restoration efforts or landslides and emphasise the value of conservation, environmentally responsible land use, and efficient management techniques for protecting lake ecosystems.
- To add to the body of knowledge on lake conservation and management by merging remote sensing, GIS, and an eco-hydrological perspective.

The present study made use of maps from the Survey of India that are scaled to 1:50,000 as well as Landsat 8 satellite imageries acquired by USGS earth explorer from 2017 and 2022. These satellite images were then analyzed by using ArcGIS software to calculate spectral-based classification indices namely Normalised Difference Vegetation Index (NDVI), Normalised Difference Water Index (NDWI), and Normalised Difference Built-up Index (NDBI) indices to assess changes in vegetation, water bodies, and build-up area in and around the lakes respectively. For assessing these indices, a 5 km buffer zone around the lakes was taken in ArcGIS. The buffer zone enables the inclusion of the lake's immediate surroundings, which might have an impact on the lake ecosystems and their biological dynamics, allowing for a more accurate assessment of the ecological integrity of the lakes. The results of the study enhance understanding of lake degradation and provide valuable information to policymakers, stakeholders, and communities for informed decisions and sustainable practices, safeguarding ecosystems for future generations.

The article is divided into several sections: Sect. 2 describes the data and methods used in the study; Sect. 3 presents the results in detail; and Sect. 4 brings the discussion of the results; and Sect. 5 closes the article by summarising the main conclusions and their implications.

2 Data and methods

The lakes in the Nainital District in Uttarakhand, India, are the subject of this study, which aims to comprehend its ecohydrological perspectives. Six well-known lakes—Nainital Lake, Bhimtal Lake, Sattal Lake, Sariyatal Lake, Khurpatal Lake, and Naukuchiatal Lake—are the subjects of the evaluation. Nainital district in Uttarakhand, India, enjoys a moderate climate with temperatures ranging from 14 to 30 °C (57–86°F) in summer and 3–15 °C (37–59°F) in winter. It receives an average annual rainfall of 1500–2000 mm (59–79 inches), with the majority occurring from July to September. Humidity is higher in summer and monsoon seasons. As shown in Fig. 2, the location map of the lakes in the Nainital District was created using ArcGIS software to help visualize their spatial distribution within the research area. Figure 1 displays the location of the study area and Fig. 2 shows the satellite images of the six lakes under study.

Table 1 Band rationing indices used in the study

S. No	Band rationing index	Description	Expression
1	Normalised Difference Vegetation Index (NDVI)	Used to track vegetation changes, calculate biomass, and spot deforestation or stressed vegetation Values range from − 1 to + 1 [26] Higher NDVI values indicate denser and healthier vegetation Negative NDVI areas are unvegetated or covered in water Positive NDVI values describe regions with active vegetation	$NDVI = \frac{Band5-Band4}{Band5+Band4}$ where, Band 5 corresponds to electromagnetic spectrum's near-infrared range (NIR) of frequency and Band 4 corresponds to the red frequency range [26]
2	Normalised Difference Built-up Index (NDBI)	Used to locate populated or urban areas, analysis of urban growth, land use planning, and the observation of urbanization processes Higher NDBI values indicate urbanized or built-up areas Lower values indicate underdeveloped areas [27, 28]	$NDBI = \frac{Band6-Band5}{Band6+Band5}$ where, Band 6 corresponds to shortwave infrared (SWIR) range of frequency and Band 5 corresponds to a near-infrared range of frequency [26]
3	Normalised Difference Water Index (NDWI)	Used to analyze changes in water extent over time [27, 28] Lower values signify non-water areas like land or plants, whereas higher values denote the presence of water	$NDWI = \frac{(Band3-Band5)}{(Band3+Band5)}$ where, Band 3 corresponds to the green frequency range and Band 5 corresponds to a near-infrared range of frequency [26]

USGS Earth Explorer was used to gather Landsat-8 satellite raster images of the six lakes from 2017 to 2022. The satellite images of 1 September 2017 and 1 July 2022 were taken for different lakes for 2017 and 2022 respectively. For analyzing Landsat imagery, "ArcGIS" software has been used. Figure 3 gives the flowchart of the methodology adopted in the present study.

The six lakes under study were delineated using ArcGIS software. To do this, image clipping technique was used to extract the precise regions belonging to each lake. The regions of interest were then highlighted by segmenting the satellite pictures. A 5 km-radius buffer zone was created around each lake to examine the lake's extent and spatial impact. Buffering enables to examine the areas close to the lakes facilitating the evaluation of their ecological and hydrological consequences. Buffering is followed by the determination of band rationing indices viz. NDWI, NDBI, and NDVI with the help of ArcGIS software. These indices provide key information on lake health, vegetation, built-up areas, and water bodies. They help analyze lake changes and environmental degradation by measuring variations in these indices. Satellite imagery's spectral bands are used in band ratio calculations to obtain specific Earth surface information. Table 1 gives the summary of the band rationing indices.

Figures 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,17, 18, 19, 20, 21 shows the images of Nainital lake, Bhimtal lake, Naukuchiatal lake, Sattal lake, Khurpatal lake, and Sariyatal lake analyzed for NDVI, NDBI, and NDWI by ArcGIS software after buffering. Finally, a thorough evaluation of the environmental deterioration was carried out by examining the alterations seen in the lakes by the application of the band rationing indices.

3 Results

Table 2 displays the findings of the investigation into changes in built-up areas, vegetation and water indices near five lakes in the Nainital region. Three parameters—the Normalised Difference Vegetation Index (NDVI), the Normalised Difference Water Index (NDWI), and the Normalised Difference Built-up Index (NDBI)—were the subject of the analysis. Data for the years 2017 and 2022 were compared to determine the change percentages. The areas were measured as a percentage of a 5-km buffer around each lake.

For Lake Nainital, the NDVI values pointed an overall positive trend, with an increase in the area covered by shrubs and grass (7% change), sparse vegetation (20% change), and dense vegetation (3.88% change). The NDWI implied a significant increase in the water area, with a

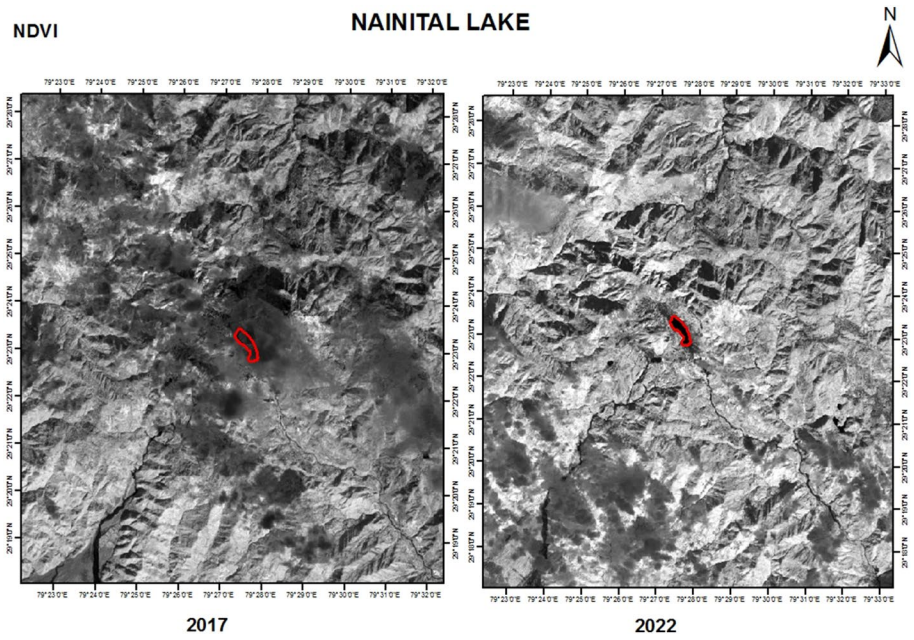

Fig. 4 Analyzed image of Nainital lake for NDVI

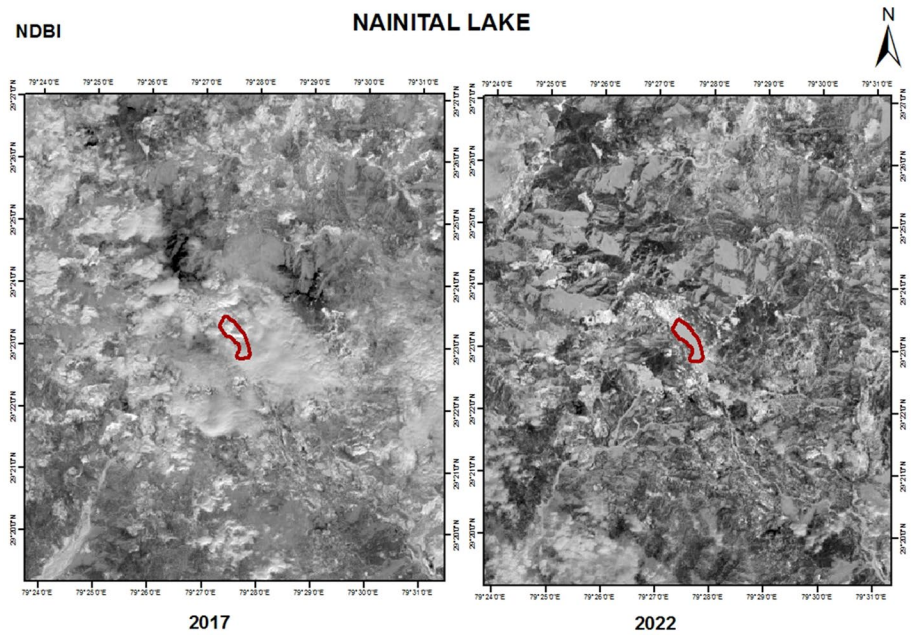

Fig. 5 Analyzed image of Nainital lake for NDBI

change of 7.29%. However, the NDBI showed a decrease in built-up areas by 1.42%.

The NDVI measurements for Lake Bhimtal showed that the area covered by shrubs and grass decreased (-12% change), whilst the area covered by sparse vegetation increased (19% change). Along with growth, the dense vegetation changed by 4.49%. The NDWI showed a 2.37% increase in water areas, whereas the NDBI showed a 1.83% decrease in built-up areas.

The NDVI readings for Lake Naukuchiatal showed a notable decline in the area covered by shrubs and grass (-16% change). However, there was an increase in the sparse vegetation (13.44% change), whereas the lush vegetation only slightly increased (3.91% change). While the

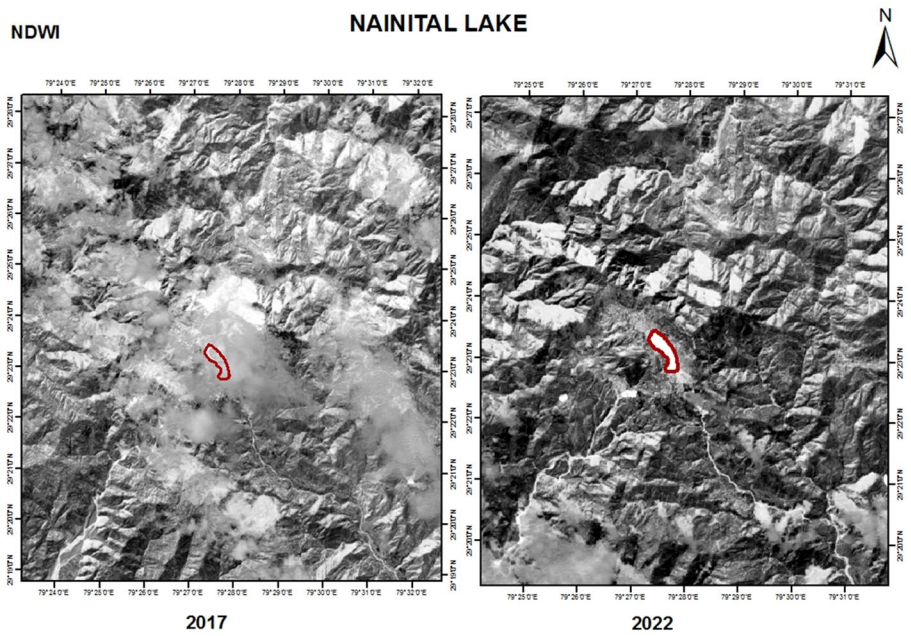

Fig. 6 Analyzed image of Nainital lake for NDWI

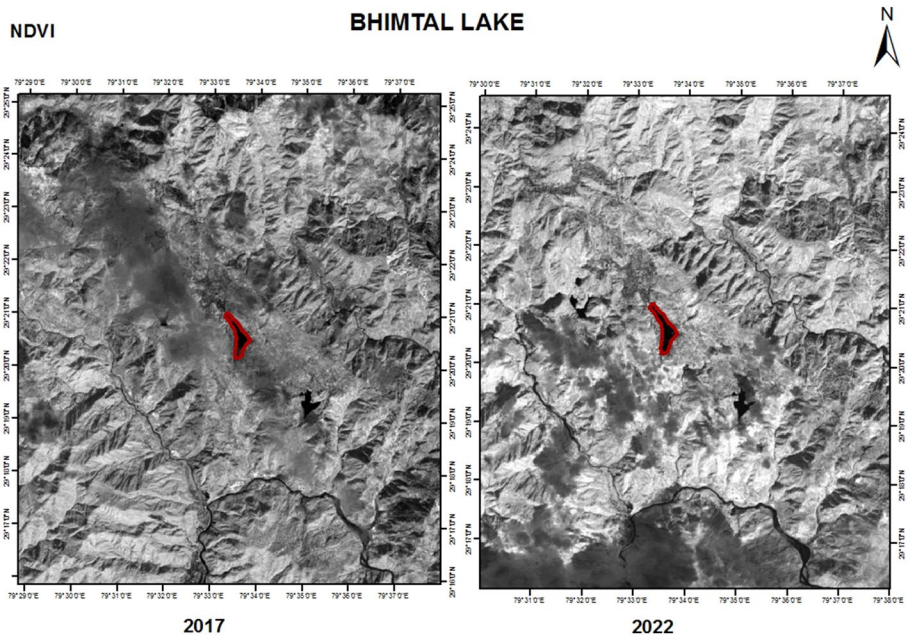

Fig. 7 Analyzed image of Bhimtal Lake for NDVI

NDBI showed a drop in built-up areas of 1.45%, the NDWI showed a considerable increase in water areas of 4.06%.

In the case of Lake Sattal, the NDVI values showed a decrease in the area covered by shrubs and grass (– 7% change). The change in the sparse vegetation was significant (18.6% change), while the change in the dense vegetation was minimal (3.94% change). The NDWI showed a 2.59% increase in water areas, whereas the NDBI showed a 2.18% decrease in built-up areas.

For Lake Khurpatal, the NDVI values showed no substantial change in the area covered by shrubs and grass (0% change). The amount of sparse vegetation increased (13.6% change), whereas the amount of dense vegetation only slightly increased (5.36% change). The NDWI showed a 5.1% rise in water areas, whereas the NDBI showed a 2.25% decrease in built-up areas.

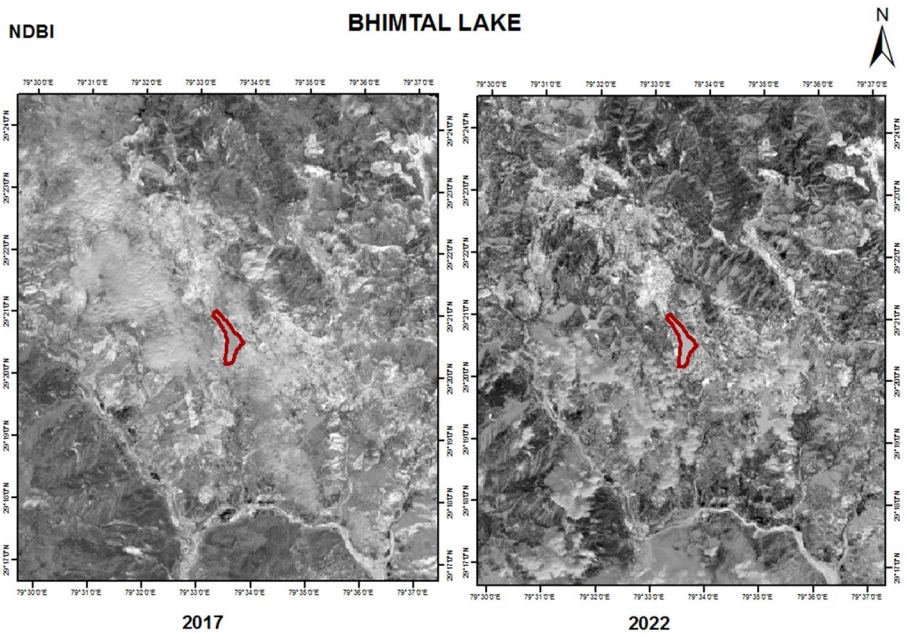

Fig. 8 Analyzed image of Bhimtal Lake for NDBI

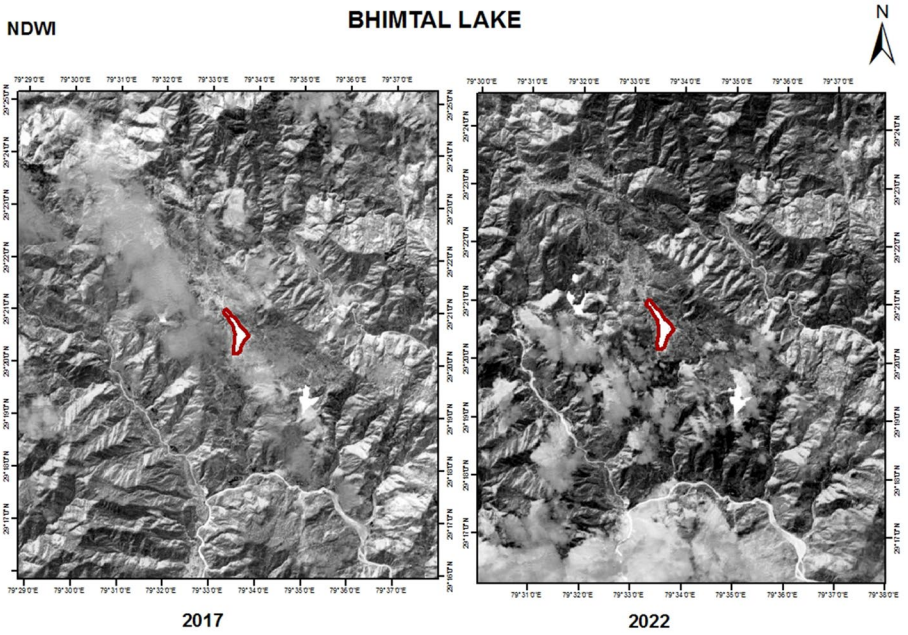

Fig. 9 Analyzed image of Bhimtal Lake for NDWI

Lastly, the NDVI values for Lake Sariyatal showed a small increase (3% change) in the area covered by shrubs and grass. Both the sparse vegetation (17.8% change) and the dense vegetation (5.88% change) experienced significant growth. While the NDBI showed a decrease in built-up areas of 1.3%, the NDWI showed a large increase in water areas of 7.44%.

4 Discussions

Figure 22 shows how the NDVI values for shrubs and grass, sparse vegetation, and dense vegetation changed across various lakes in the Nainital region between 2017 and 2022.

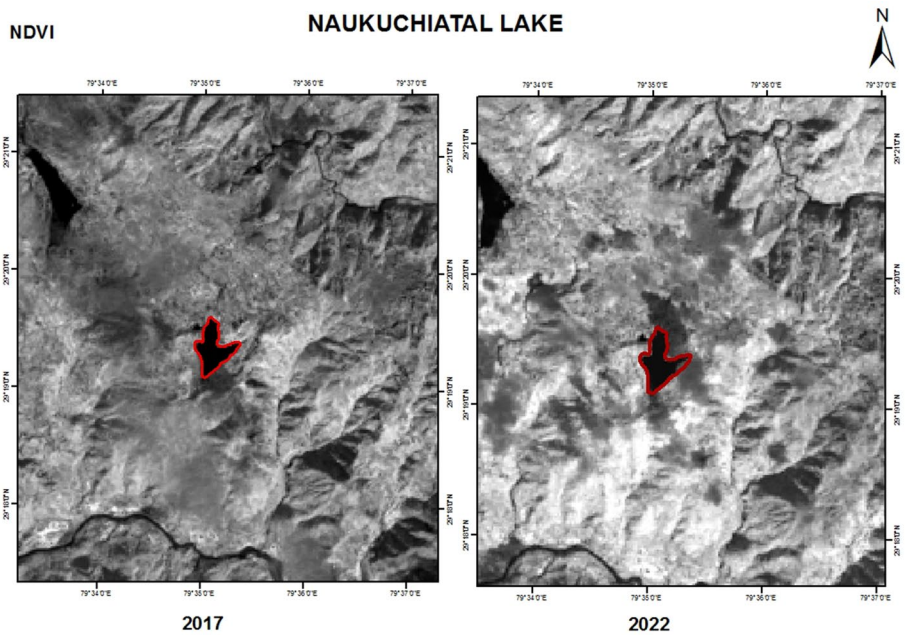

Fig. 10 Analyzed image of Naukuchiatal Lake for NDVI

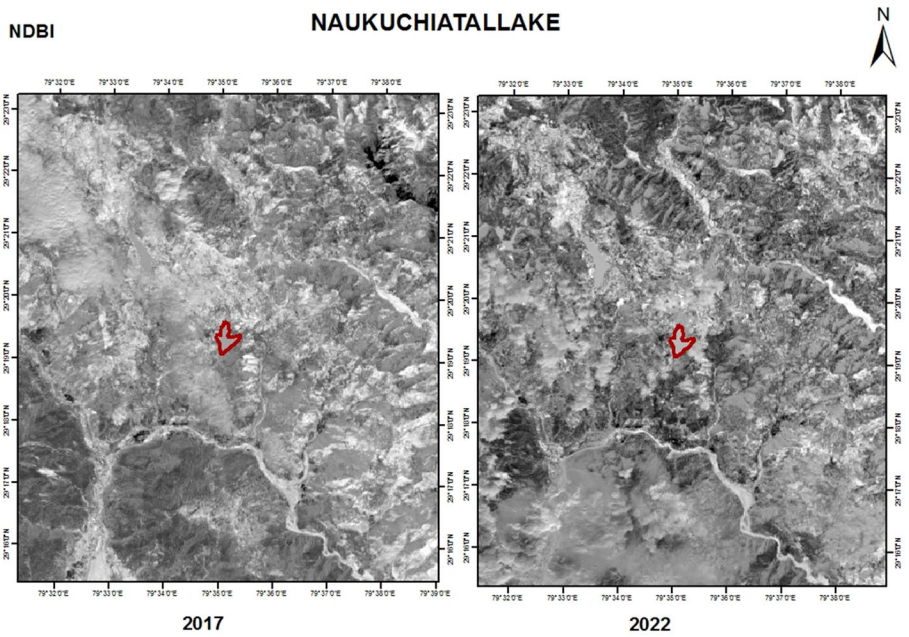

Fig. 11 Analyzed image of Naukuchiatal Lake for NDBI

Sattal, which had a modest reduction of -7%, was found to have the highest overall NDVI value of 35, followed by Bhimtal, indicating a generally healthier and denser vegetation cover in all categories. Bhimtal nevertheless stood out in terms of overall vegetation density even if the vegetation cover area showed a drop of -12%. This contrasts with the study conducted by Deoli V. et al. [25] which reported 14.77% and 7.77% increase in the NDVI of Sattal and Bhimtal lakes respectively. The reduction in the vegetation can be attributed to the increase in tourism activity and expansion of infrastructure in and around the two lakes.

Nainital displayed moderate NDVI readings, which indicated a rather healthy amount of vegetation. It saw

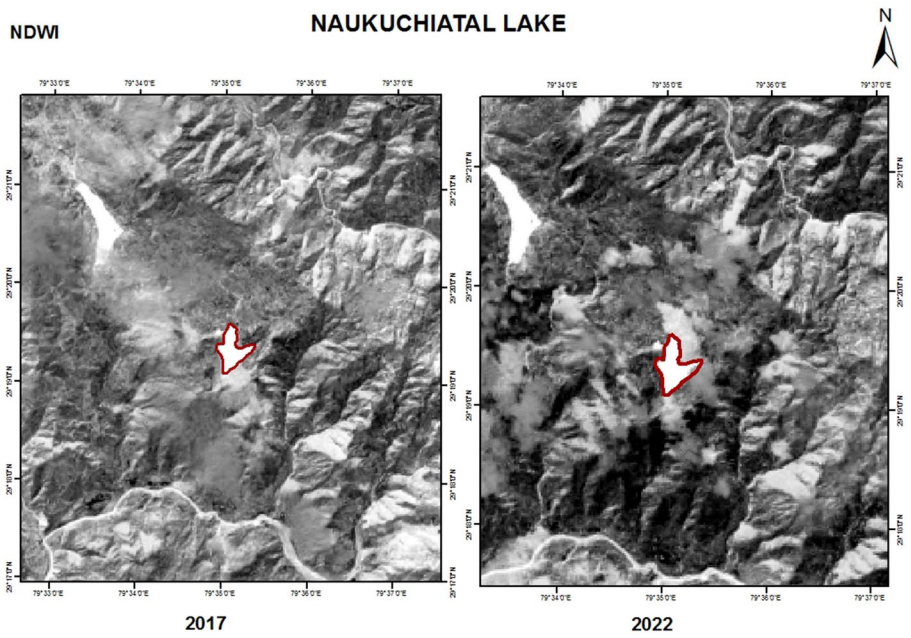

Fig. 12 Analyzed image of Naukuchiatal Lake for NDWI

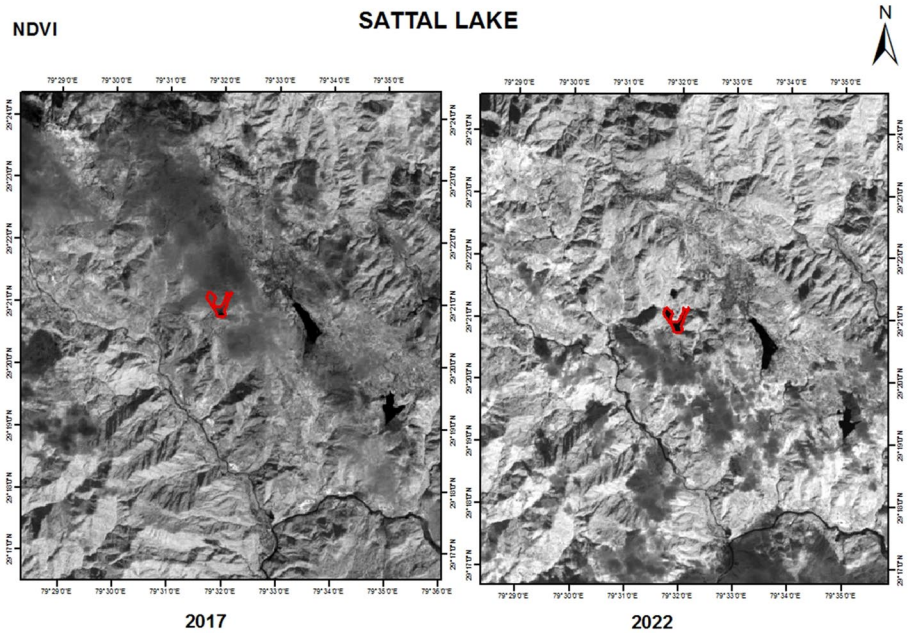

Fig. 13 Analyzed image of Sattal Lake for NDVI

an improvement in the vegetation cover overall, with a 7% rise. Similar NDVI values were seen in Sariyatal, Naukuchiatal, and Khurpatal, indicating similar vegetation densities. Overall vegetation cover varied between Sariyatal and Naukuchiatal, increasing somewhat in Sariyatal by 3% and significantly in Naukuchiatal by − 16%. With no change in percent area, Khurpatal showed a rather steady vegetation cover area. The study conduted by Deoli V. et al. [25] projected a growth in vegetation of the Naukuchiatal lake by 4.58%. 16% reduction in the vegetation cover in Naukuchiatal lake can be attributed to the heavy infrastructure construction to promote tourism in the region.

With a notable increase of 19% in the area covered by vegetation, Bhimtal showed the highest NDVI value,

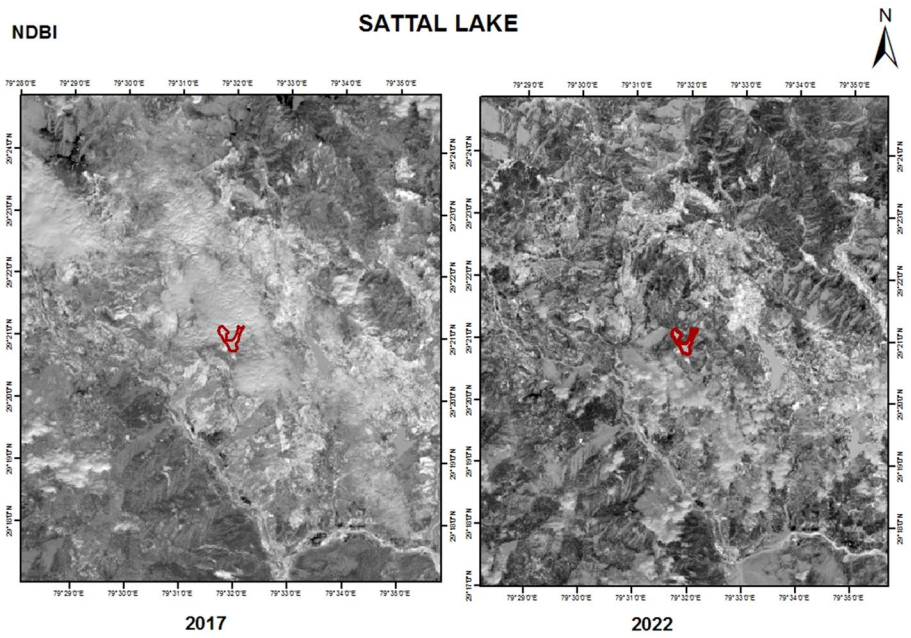

Fig. 14 Analyzed image of Sattal Lake for NDBI

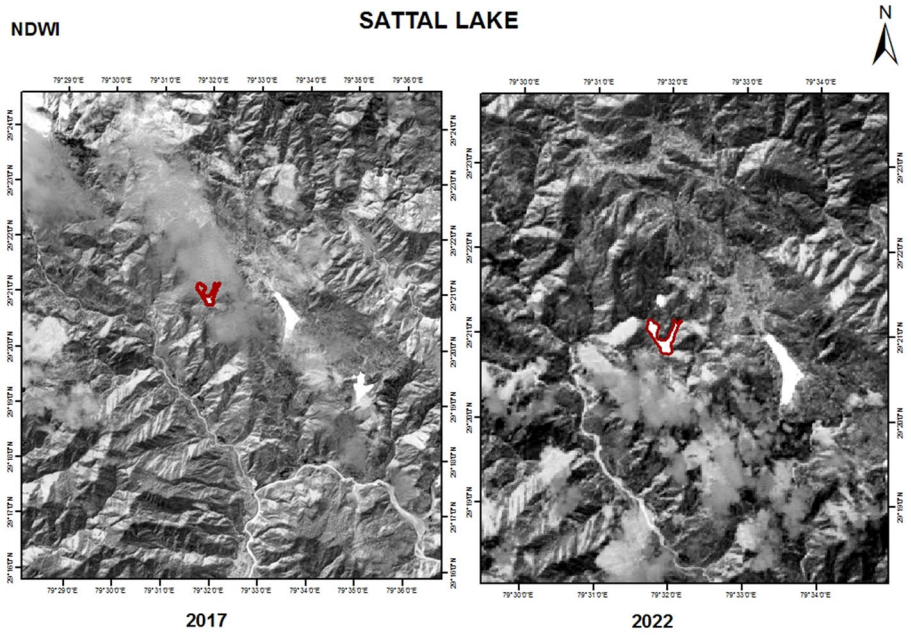

Fig. 15 Analyzed image of Sattal Lake for NDWI

indicating a healthier and denser sparse vegetation cover. Significant increases in the amount of sparse vegetation were seen in Nainital, Sattal, Naukuchiatal, Khurpatal, and Sariyatal, with increases ranging from 13.44 to 17.8%. Sattal exhibited the greatest NDVI value for dense vegetation, indicating a generally healthy and dense vegetation cover. The area covered by vegetation increased somewhat, by 3.94%. Similar NDVI values were seen at Bhimtal, Nainital, Naukuchiatal, Khurpatal, and Sariyatal, indicating similarly dense vegetation density. Between 3.88 and 5.88%, the dense vegetation cover around these lakes showed substantial expansions. Higher NDVI values, which indicate comparatively healthier and denser vegetation coverings, were particularly noticeable in Sattal and Bhimtal.

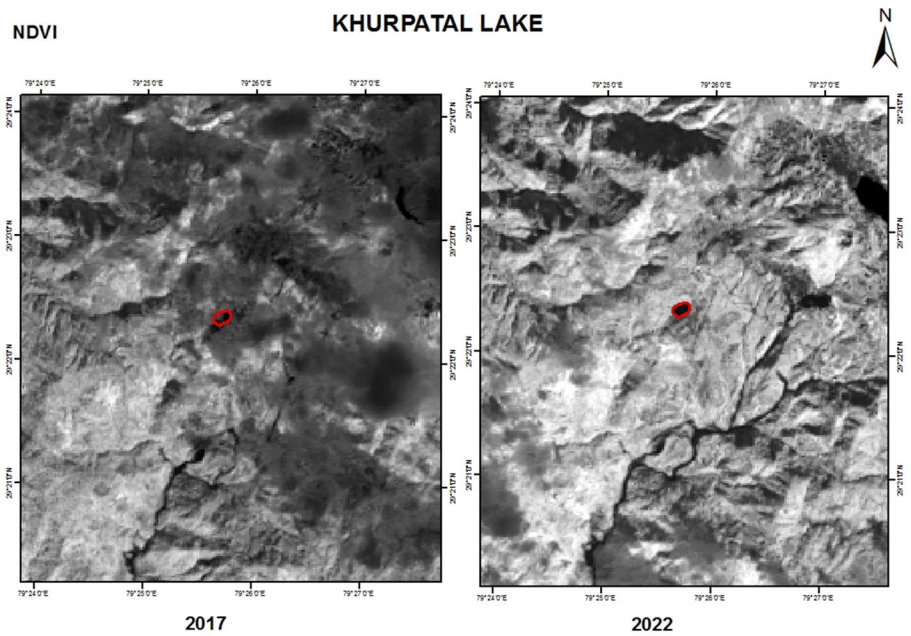

Fig. 16 Analyzed image of Khurpatal Lake for NDVI

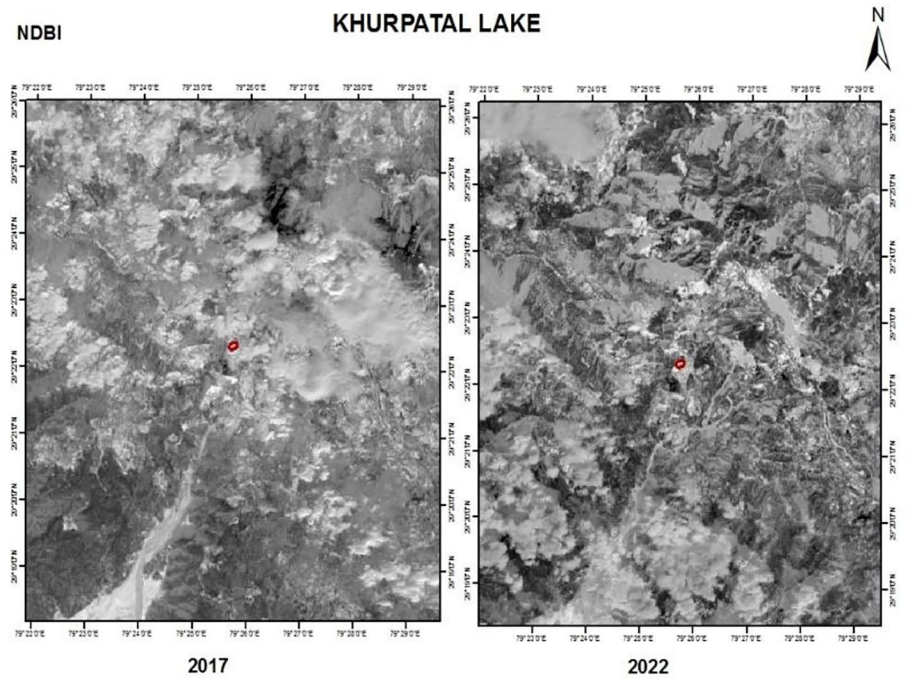

Fig. 17 Analyzed image of Khurpatal Lake for NDBI

The variation in NDBI values for 2017 and 2022 across several lakes in the Nainital region is shown in Fig. 23. In comparison to the other lakes, Khurpatal lake has the lowest NDBI value (2.35), indicating a significantly smaller concentration of built-up areas and urban growth. Among all the lakes, it showed the greatest decline in the NDBI value, with a decrease of 2.25%.

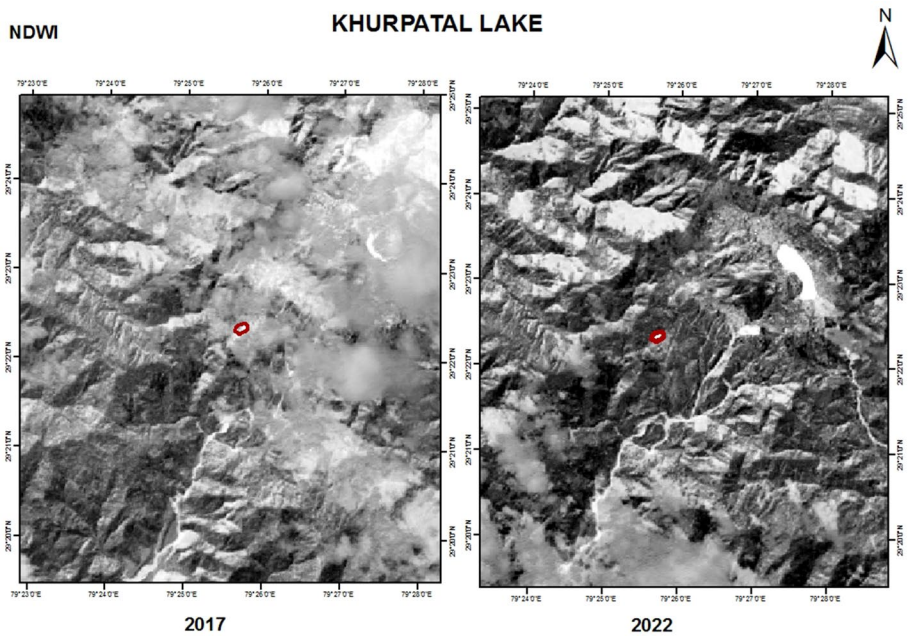

Fig. 18 Analyzed image of Khurpatal Lake for NDWI

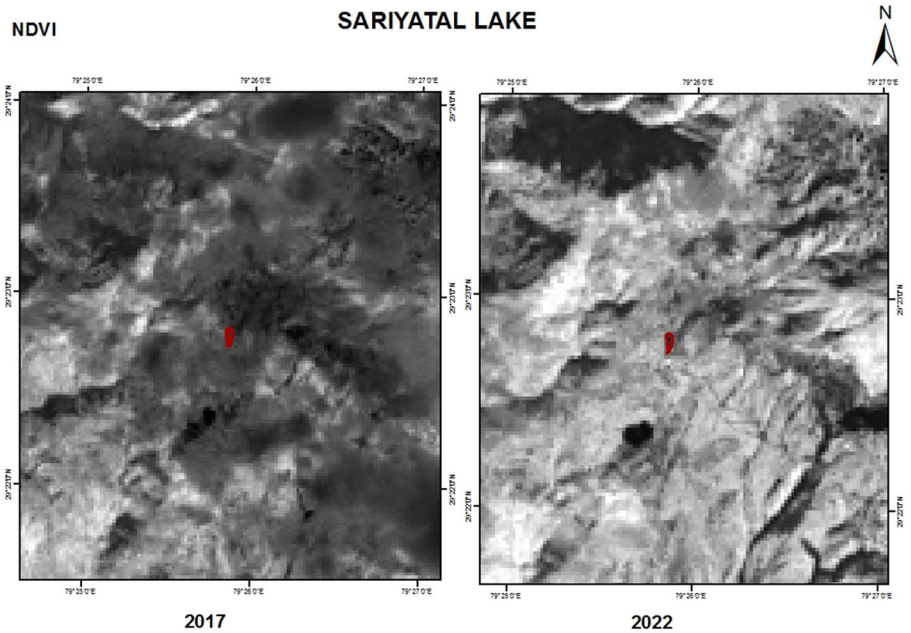

Fig. 19 Analyzed image of Sariyatal Lake for NDVI

This shows that Khurpatal's built-up areas have significantly decreased. Following Khurpatal, Nainital Lake had an NDBI rating of 2.44, indicating a little larger proportion of built-up areas than Khurpatal. In Nainital's built-up regions, the NDBI figure shows a decline of 1.42%. In comparison to Khurpatal and Nainital, Bhimtal Lake showed an NDBI value of 3.43, indicating a more prominent concentration of built-up areas and urbanisation. In the populated areas, it decreased by 1.83%. Compared to Khurpatal and Nainital, Lake Naukuchiatal displayed an NDBI value of 3.42, indicating a larger concentration of built-up areas. For Naukuchiatal, the NDBI value predicts a 1.45% decline in the built-up areas. The NDBI value for Sattal Lake was 3.16, which indicates that there are somewhat less built-up areas there than in Naukuchiatal but a larger concentration of built-up areas than in Khurpatal and Nainital. With a fall of 2.18%, it witnessed the second-largest decrease in the NDBI value among all the lakes. This decrease in all the lakes is a result of government regulations and restrictions on construction activities or a move towards more environmentally friendly development methods. The decrease

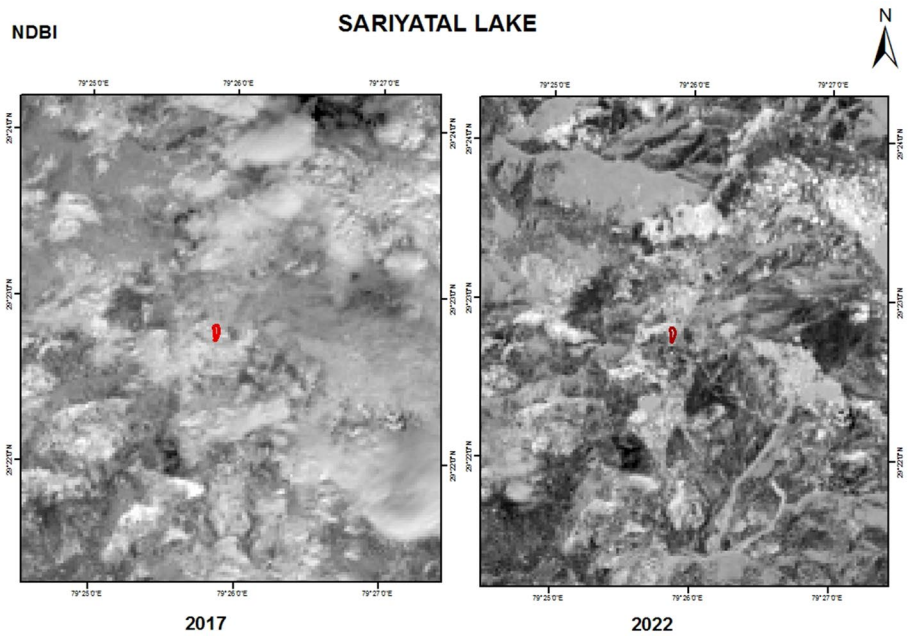

Fig. 20 Analyzed image of Sariyatal Lake for NDBI

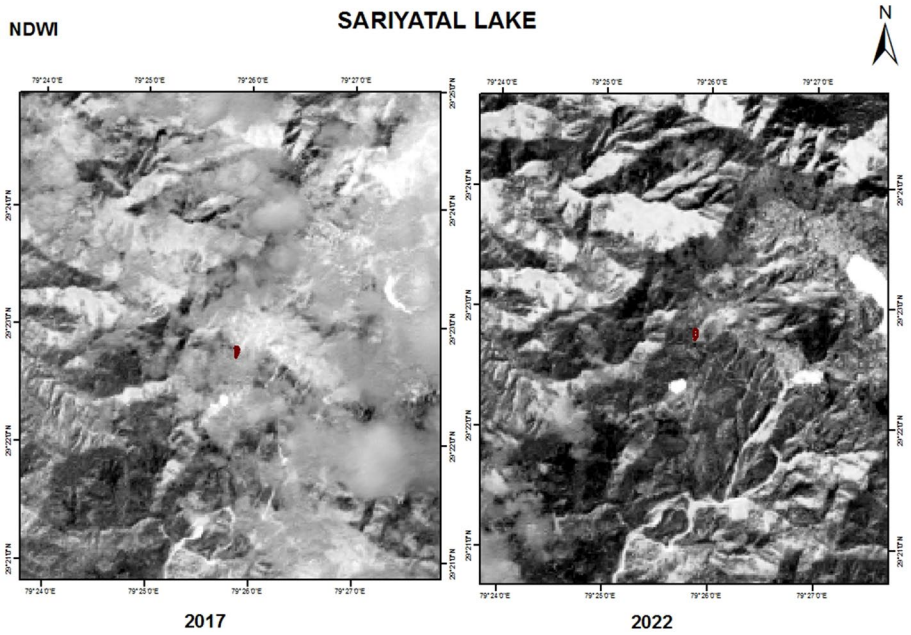

Fig. 21 Analyzed image of Sariyatal Lake for NDWI

in built-up area can also be contributed to the landslides in the vicinity of the lakes.

The variance of NDWI (Normalised Difference Water Index) values for several lakes in the research area are shown in Fig. 24.

Sariyatal Lake had the highest NDWI value of 8.3, which contrasted significantly with the other lakes and indicated a significant increase in water areas. With a gain of almost 7.44%, it showed the area's biggest percentage change. This means that Sariyatal's water bodies will significantly expand. Nainital Lake came in second with an NDWI value of 8, indicating a significant expansion of water areas. It showed a percentage shift of almost 7.29%, showing a significant increase in the number of water bodies in Nainital.

The NDWI values for Khurpatal and Naukuchiatal lakes were 5.5 and 4.63, respectively, indicating a significant increase in water areas relative to the baseline conditions. They observed changes in percentage of roughly 5.1% and 4.06%, respectively, which shows a significant rise in the number of water bodies. The rise in NDWI is in sync with the study conducted by Deoli V. et al. [25] which also

Table 2 NDVI, NDWI, AND NDBI area changes in percentage

Lake	Parameter	Subcategory	Area in % of 5 km buffer		
			2017	2022	Change %
Nainital	NDVI	Shrubs and grass	26	33	7
		Sparse	5	25	20
		Dense	0.12	4	3.88
	NDWI	–	0.71	8	7.29
	NDBI	–	3.86	2.44	– 1.42
Bhimtal	NDVI	Shrubs and grass	44	32	– 12
		Sparse	9	28	19
		Dense	0.11	4.6	4.49
	NDWI	–	0.43	2.8	2.37
	NDBI	–	5.26	3.43	– 1.83
Naukuchiatal	NDVI	Shrubs and grass	47	31	– 16
		Sparse	9.56	23	13.44
		Dense	0.09	4	3.91
	NDWI	–	0.57	4.63	4.06
	NDBI	–	4.87	3.42	– 1.45
Sattal	NDVI	Shrubs and grass	42	35	– 7
		Sparse	9.4	28	18.6
		Dense	0.06	4	3.94
	NDWI	–	0.11	2.7	2.59
	NDBI	–	5.34	3.16	– 2.18
Khurpatal	NDVI	Shrubs and grass	31	31	0
		Sparse	10	23.6	13.6
		Dense	0.14	5.5	5.36
	NDWI	–	0.4	5.5	5.1
	NDBI	–	4.6	2.35	– 2.25
Sariyatal	NDVI	Shrubs and grass	28	31	3
		Sparse	7.2	25	17.8
		Dense	0.12	6	5.88
	NDWI	–	0.86	8.3	7.44
	NDBI	–	4.3	3	– 1.3

projected an increase of around 4.76% in the water coverage area of Naukuchiatal lake.

Compared to the initial conditions, Bhimtal Lake's NDWI score of 2.8 showed a moderate increase in water areas. It changed by a percentage of roughly 2.37%, indicating a very minor increase in Bhimtal's water bodies. The lowest NDWI value was recorded in Sattal Lake (2.7), which was due to a modest expansion of the water area. This contrasts with the study conducted by Deoli V. et al. [25] which projected a very high increase of 18.56% and 6.93% in the water coverage of Sattal lake and Bhimtal lake. This variation can be attributed to the decrease rainfall in the area in 2022 as compared to 2018. A change in percentage of roughly 2.59% was observed, indicating a moderate expansion of water bodies in Sattal. This significant increase in all the lakes is possibly as a result of ongoing monitoring and conservation initiatives to protect the lake's water resources and preserve a thriving aquatic ecology.

Inferring significant water body expansion, Sariyatal and Nainital had the highest NDWI readings and the largest percentage increases in the water area. While Sattal showed a relatively lesser expansion, the water areas in Khurpatal, Naukuchiatal, and Bhimtal all showed considerable increases. These results demonstrate the range of water area changes across the research area's lakes as well as variances in water body dynamics.

5 Conclusions

The present study investigated the variation of band rationing indices viz. NDVI, NDBI, and NDWI for six lakes of the Nainital district. The results highlight the dynamic nature of the lakes' ecosystems and provide valuable insights into their ecological health.

- The analysis revealed an overall positive trend in NDVI values for Lake Nainital, indicating increases in the area covered by shrubs and grass, sparse vegetation, and dense vegetation. This suggests a generally healthier and denser vegetation cover in the lake.
- The NDBI values indicated variations in built-up areas among the lakes, with Lake Khurpatal showing the lowest value and the largest decrease. This suggests a relatively smaller concentration of built-up areas and urban growth around Khurpatal.
- The NDWI values revealed changes in water areas, with Lake Sariyatal exhibiting the highest value and the largest percentage increase. Nainital, Khurpatal, Naukuchiatal, and Bhimtal also displayed notable changes in water areas.

According to the study's conclusions, it is advised to give conservation efforts the top priority through responsible land management and habitat preservation. It's essential to strike a balance between urbanization and environmental protection, as well as to put effective water resource management strategies into action. For each lake, specific conservation strategies should be created, and long-term monitoring programmes should be set up to observe trends and assess conservation efforts. These suggestions are meant to safeguard the lakes' long-term sustainability as well as preserve and

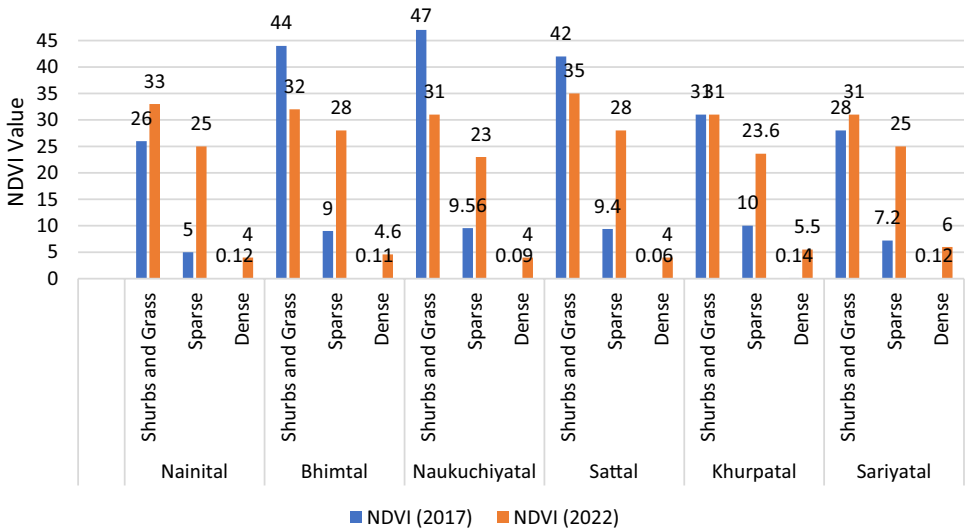

Fig. 22 Graphical representation of NDVI of different lakes

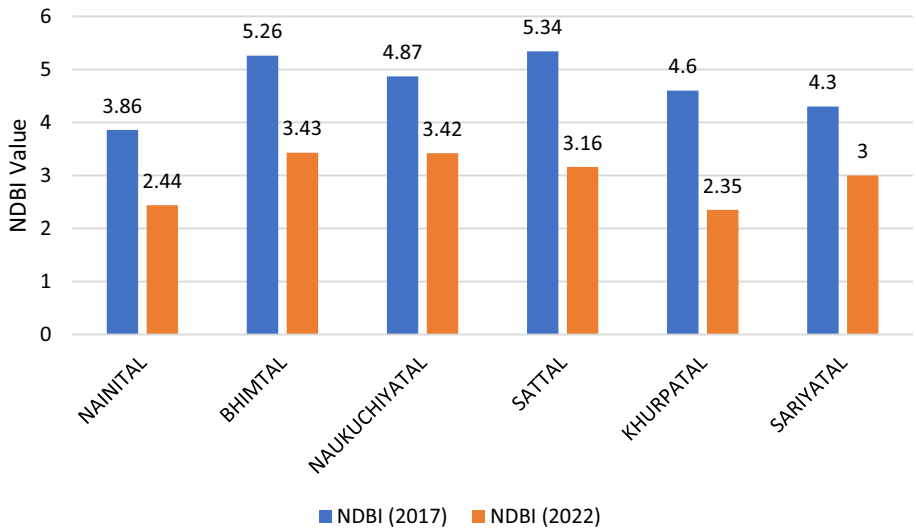

Fig. 23 Graphical representation of NDBI of different lakes

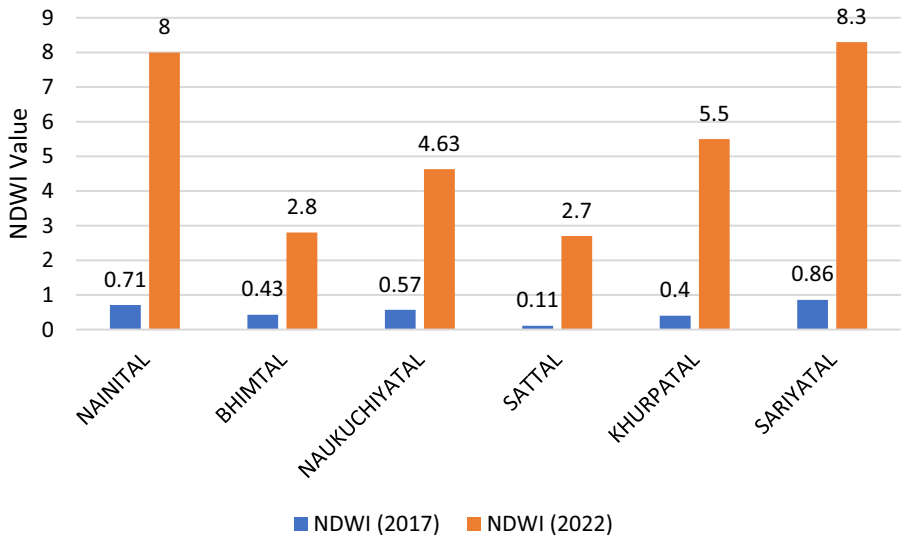

Fig. 24 Graphical representation of NDWI of different lakes

improve their natural health. These recommendations can be put into practice by all parties involved in order to guarantee the sustainable management and preservation of the lakes in the Nainital region, preserving their ecological integrity and fostering the welfare of the environment as well as the local communities.

Author contributions Conceptualization, Divyanjali, ; methodology, Gaurav Thakur and Priyanka, .; formal analysis, Gaurav Thakur; investigation, Neeraj Priyadarshi .; resources, Bhekisipho Twala.; data curation, Rajesh Singh.; writing—original draft preparation, Divyanjali,.; writing—review and editing, Anita Gehlot.G.; visualization, Shaik Vaseem Akram.

Funding The APC was funded by Tshwane University of Technology, South Africa.

Data availability Data will be available on basis of request.

Declarations

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose.

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