Lake water volume calculation using time series LANDSAT satellite data: a geospatial analysis of Deepor Beel Lake, Guwahati

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Abstract

Purpose – Deepor Beel is one of the Ramsar Site and a wetland of great biodiversity, situated in the south-western part of Guwahati, Assam. With urban development at its forefront city of Guwahati, Deepor Beel is under constant threat. The study aims to calculate the lake water volume from the water surface area and the underwater terrain data using a triangulated irregular network (TIN) volume model.

Design/methodology/approach – The lake water surface boundaries for each year were combined with field-observed water level data to generate a description of the underwater terrain. Time series LANDSAT images of 2001, 2011 and 2019 were used to extract the modified normalized difference water index (MNDWI) in GIS domain.

Findings – The MNDWI was 0.462 in 2001 which reduced to 0.240 in 2019. This shows that the lake water storage capacity shrank in the last 2 decades. This leads to a major problem, i.e. the storage capacity of the lake has been declining gradually from 20.95 million m^3 in 2001 to 16.73 million m^3 in 2011 and further declined to

15.35 million m³ in 2019. The fast decline in lake water volume is a serious concern in the age of rapid urbanization of big cities like Guwahati.

Originality/value – None of the studies have been done previously to analyze the decline in the volume of Deepor Beel lake. Therefore, this study will provide useful insights in the water resource management and the conservation of Deepor Beel lake.

Keywords Lake water volume, Deepor Beel lake, Modified normalized difference water index, Landsat satellite data, Surface water mapping, GIS technique

Paper type Research paper

1. Introduction

Lakes provide a wide range of ecosystem, socio-cultural as well as ecological services to humankind and nature (Sterner *et al.*, 2020; Adrian *et al.*, 2016). Optimal management of lakes entails a proper understanding of anthropogenic impacts both on the lake ecosystems and on the services, they provide for society (Lu *et al.*, 2013). The specific structural and functional properties of lake morphology, hydrography, biogeochemical cycles and food-web structure are all directly related to their size and other lake characteristics (Tilahun and Kifle, 2020; Winslow *et al.*, 2015). In this regard, the volume of water and its variations over time are fundamental properties of a lake as they affect the physical, chemical and biological processes of its ecosystems (Crétaux *et al.*, 2016). Also, the water area at a given site or suite of sites determines the vegetation structure as well as the wildlife habitat and therefore strongly influences the interactions of nutrients, pesticides and other contaminants between lake sediments and its water column (Lane and D'Amico, 2010). Water volumes in lakes and rivers also reflect the equilibrium between rainfall and evaporation and interactions between surface and groundwater systems (Taubenböck *et al.*, 2011; Medina *et al.*, 2010).

Lakes all around the world are experiencing threats to its sustainability, including encroachment and anthropogenic alterations to the region's hydrology (Talukdar *et al.*, 2021; Mishra and Griffin, 2010). Anthropogenic activities such as intensive extraction of fisheries resources, reclamation of land from marshes of wetlands, pollution discharge and development of water conservancy and have had a significant impact on lake ecosystems (Wang and Ma, 2016). Moreover, lakes located in urban areas all around the world are undergoing drastic changes in relation to both volume and area (Mallick, 2017; Shahjahan and Ahmed, 2016). Municipal wastewater discharges, failing septic systems and sewage overflows may contribute to create sanitary and environmental problems in urban lakes (Yang *et al.*, 2020). Increasing population contributes to small as well as large scale land use land cover (LULC) changes, especially from the perception of demand for built-up area, industrial and agricultural activities (Panwar, 2017; Rahman *et al.*, 2012). With the increase in urban population and expansion of big cities presents the severe problem between urban expansion and lake protection (Seto *et al.*, 2012). It is noticed in India that since the land is limited so lakes are eaten up by being filled up with solid waste and mud and then buildings come up on such lands (Rashid and Aneaus, 2020; Mundoli *et al.*, 2014). Moreover, urbanization and deforestation and will continuously have negative impacts on the nature of a water body and its ecosystem (Ghosh, 2019; Adugna *et al.*, 2018).

The spatial as well as temporal changes in the volume of water bodies can be calculated by several methods depending on the availability of morphometric and areal data. Water volume, water area and water level are three key parameters of lake dynamics (Kumar *et al.*, 2020). A long term and continuous water volume data can directly reflect the regional water supply and deficit (Geng *et al.*, 2021). Moreover, our attention typically focuses on large lakes, following the oversight of small lentic water bodies when analyzing global-scale systems (Messager *et al.*, 2016). Several studies exhibited the importance of small lakes for processes ranging from evaporation to sediment trapping, greenhouse gas emissions, catchment interactions, lake mixing, diagenetic reactions or aquatic habitat conservation (Holgerson and Raymond, 2016;

Downing *et al.*, 2008). Large lakes might dominate processes driven by volume or surface area due to their prevalence at a global scale, but small lakes contribute more to the total aquatic-terrestrial interface than large lakes (Winslow *et al.*, 2015).

In the last 20 years, multi-spectral remote-sensing images have been widely used for surface water monitoring. Many mapping methods have been proposed according to the characteristics of the water bodies' responsiveness to different spectral ranges. The normalized difference water index (NDWI) is used to delineate open water bodies with reflective near-infrared radiation and visible green light (McFeeters, 1996) and the improved version of NDWI by using short-wave infrared radiation and is renamed as modified normalized difference water index (MNDWI) are used continuously in the field of remote sensing to detect water bodies in small as well as large scale level (Xu, 2006). Landsat TM, ETM+ and OLI/TIRS, Moderate Resolution Imaging Spectroradiometer (MODIS), SPOT (Système Pour l'Observation de la Terre), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite images have been widely used to map the urban surface water (Sivanpillai and Miller, 2010; Bastawesy *et al.*, 2008).

The Deepor Beel lake is one such small water body located in the Guwahati Metropolitan Area, Assam. The mapping of this urban lake is significant because it is a typical water-land eco-fragile zone that has been strongly affected by anthropogenic activities in recent decades. In particular, the problem of dumping municipal wastes, which accelerated the shrinking of water bodies and significantly altered the land cover state in the Deepor Beel area, and this process has been accompanied by many discussions about its environmental impacts (Mozumder and Tripathi, 2014). The main objective of the present study is to calculate changing dynamic of the water volume of the Deepor Beel. This study also explored the spatial and temporal patterns in and around the Deepor Beel during 2001–2019.
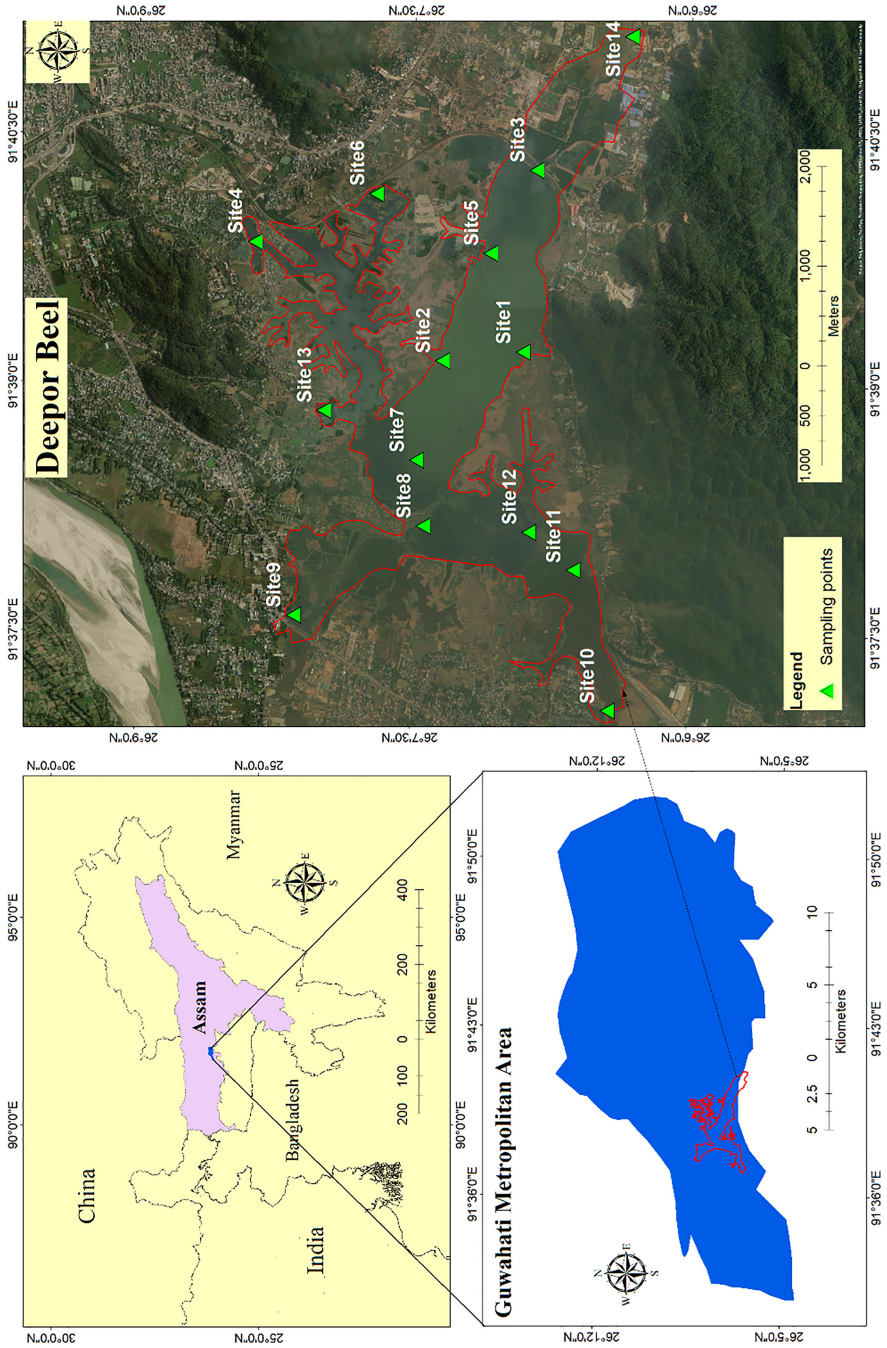
2. Study area
The Deepor Beel is a permanent, freshwater lake in a former channel of the Brahmaputra River sited in the south of the river in Kamrup Metropolitan district, 10 km southwest of Guwahati City, Assam. It is located between 26°06' N and 26°09' N latitude and 91°36' E and 91°41' E longitude with an altitude varies between 50 and 57 m amsl covering an area of about 40 km^2 (Figure 1). The Beel is a large natural wetland having great biological and environmental importance besides being the only major stormwater storage basin for the Guwahati city (Goswami *et al.*, 1999). It is of international importance under the Ramsar Convention been chosen as a Ramsar Site (No. 1207) in November 2002 for providing a framework for national action and international cooperation for the conservation and judicious use of wetlands and their resources (Deb *et al.*, 2019).

Over time, the Beel has been facing numerous problems because of the accumulation of municipal solid wastes that are increasingly finding their way into the core area of the lake. The dumping of the solid wastes in its proximity at Boragaon by the Guwahati Municipal Corporation (GMC) has pushed the lake's pollution to alarming levels. The lake is shrinking rapidly since the last 2 decades due to rapid urbanization and this has led to jeopardy in the biodiversity of the lake and presently the degradation of the water body has reached a critical state.

3. Data base and methodology
3.1 Data base
Landsat 7 TM/ETM+ (Thematic Mapper/Enhanced Thematic Mapper Plus) and Landsat 8 (OLI/TIRS) satellite data of 2001, 2011 and 2019 were downloaded from (https://earthexplorer.usgs.gov/), is used for driving the various indices, LU/LC pattern and transformation.

Figure 1.
Locational aspect and
distribution of
sampling points of
study area

Toposheet obtained from Survey of India at a scale of 1:50,000 has been used to extract the map of the Kamrup Metropolitan district. Long-term water level data are collected from the Principal Chief Conservator of Forest and Head of Forest Force office, Guwahati, Assam. The distribution of the sampling points in the Deepor Beel has been shown in Figure 1 and the details of all the data sets used in the study have been shown in Table 1.

3.2 Methods
3.2.1 Land use/land cover. Five LULC groups were defined and categorized for 2001, 2011 and 2019 based on the spectral characteristics of satellite imagery and existing knowledge of land use in the study area. The classes viz. built up, vegetation, water bodies, rangeland and open land were identified in the study area based on National Remote Sensing Centre (NRSC), India LULC classification scheme (NRSA, 1995). Further, the accuracy of the classified maps was analyzed using Kappa coefficient. The results of accuracy assessment show an overall accuracy level of 85.55%, 87.75% and 89.42% for 2001, 2011 and 2019, respectively and the corresponding Kappa statistics was 0.835, 0.887 and 0.891, respectively.

3.2.2 Surface water mapping. To correctly extract the water features, Xu (2006) proposed the MNDWI which is calculated using the Green and SWIR bands (equ. 1). The value of MNDWI ranges from the value of −1 to +1. Finally, the higher reflectance of built-up and lower reflectance of water in the SWIR band result in negative values of built-up and positive values of water features in the MNDWI-derived image.

$$\text{MNDWI} = \frac{\rho Green - \rho SWIR}{\rho Green + \rho SWIR} \tag{1}$$

Where, $\rho Green$ is the green band and $\rho SWIR$ is the short-wave infrared band

Finally, the MNDWI-derived water surface images and LULC images (unsupervised classification) are compared and analyzed to obtain the trends and patterns of change in the surface area of Deepor Beel.

3.2.3 Underwater topographic modeling. Triangulated irregular network (TIN) model is considered as one of the superior methods for underwater topography simulation (Mi *et al.*, 2007). TIN was chosen to simulate the underwater topography of the lake along with the morphology of the lake area with all the vector water level contours and DEM data. For the crisscrossing contours of the identical water level at different times, a blend of these was used. Lastly, the underwater terrain as well as the surrounding of the lake was modeled almost as a set of non-overlapping triangles. Individually, every triangle node has the coordinates *x*, *y*

S. No.	Data source				Year	Extractable information
1.		Google earth			2019	City map, Deepor Beel map
2.	Satellite Data (USGS Earth Explorer)	Landsat 7 (TM and ETM+)	Path 137	row 42	2001 and 2011	Optical and Thermal Data (Land use/cover, Vegetation, Temperature etc.)
3.		Landsat 8 (OLI + TIRS)	137	42	2019	Optical and Thermal Data (Land use/cover, Vegetation, Temperature etc.)
4.	Wildlife Division of Guwahati, Assam				2001, 2011 and 2019	Hydrological data of Deepor Beel (water level data)

Table 1.
Details of data sets used

and elevation value (depth of water, z), and each triangle surface has a certain slope angle. The sum of triangles in different areas depends on the actual topography. In flat areas, a fairly small number of triangles was generated and vice versa (Yin-Xi *et al.*, 2016).

3.2.4 Lake water volume calculation. The volume of the lake water was calculated with the help of area and volume statistics module in ArcMap 10.3 3D Analyst Tool, in which the physical model of the given water body was formed with the intersection of the underwater terrain obtained from TIN and water surface data. The physical model created was then divided into several triangular prisms by projecting each triangle vertex to the water surface (see Figure 2). The volume of water was then calculated by adding the volumes of each triangular prism based on Mi *et al.* (2007) equation (2).

$$V = \sum_{i=1}^{n} S_i \frac{(h_i + h_{i+1} + h_{i+2})}{3} \tag{2}$$

Where,

volt is the total volume (m^3),

S_i is the projection area (m^2) of the underwater terrain triangle surface on the water surface, h_i, h_{i+1} and h_{i+2} are the distance (m) of the underwater triangle vertexes to the water surface, and n is the number of triangular grids.

3.2.5 Mann–Kendall test. The Mann–Kendall statistical test has been frequently utilized to quantify the significance of trends in hydro-meteorological time series (Tabari, 2019; Silva *et al.*, 2015; Duhan and Pandey 2013). The Mann–Kendall (Mann 1945; Kendall 1957) is calculated as:
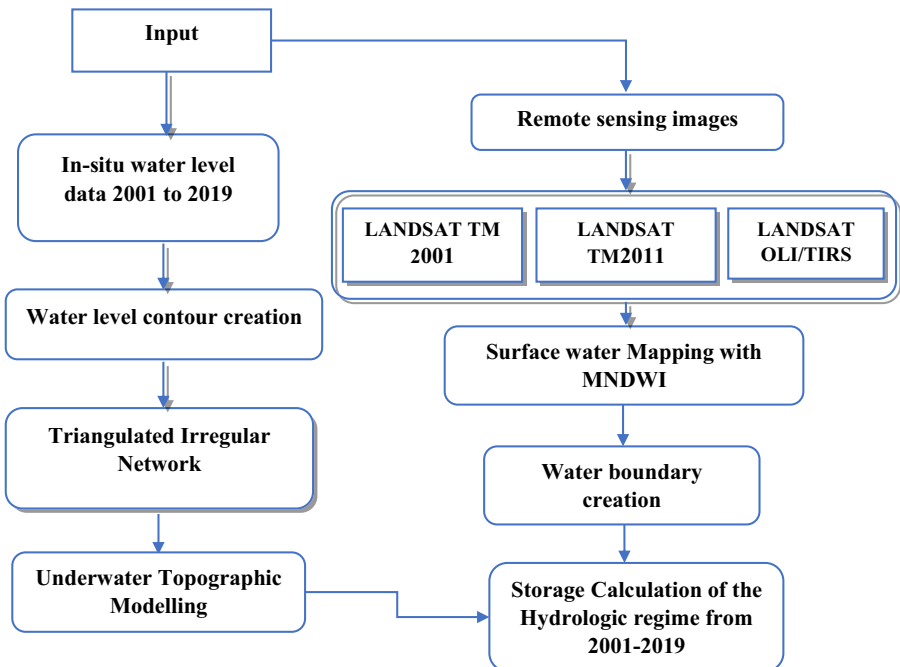

Figure 2.
Methodology for storage calculation (Volume) of water body

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \tag{3}$$

where n is the number of data points, x_i and x_j are the data values in the time series i and j $(j > i)$, respectively, and sgn $(x_j - x_i)$ is the sign function as:

$$\text{sgn } (x_j - x_i) = \begin{cases} +1 & \text{if} & x_j - x_i > 0 \\ 0 & \text{if} & x_j - x_i = 0 \\ -1 & \text{if} & x_j - x_i < 0 \end{cases} \tag{4}$$

The variance is computed as:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{P} t_i \, (t_i - 1)(2t_i + 5)}{18} \tag{5}$$

where n is the number of data points, P is the number of tied groups, the summary sign (Σ) indicates the summation over all tied groups, and t_i is the number of data values in the Pth group. If there are not any tied groups, this summary process can be ignored (Ay and Kisi, 2015).

A tied group is a set of sample data having the same value. In cases where the sample size $n > 30$, the standard normal test statistic z_s is computed using Eq. (6):

$$Z_S = \begin{cases} \dfrac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \tag{6}$$

Positive values of Z_S indicate increasing trends whereas negative Z_S values show decreasing trends. Testing trends is done at the exact significance level. When $|Z_S| > Z_{1-\alpha/2}$, the null hypothesis is rejected and a significant trend exists in the time series. $Z_{1-\alpha/2}$ is obtained from the standard normal distribution table. In this study, significance level $a = 0.05$ is used. At the 5 % significance level, the null hypothesis of no trend is rejected if $|Z_S| > 1.96$ and vice versa.

3.2.6 Sen's slope estimator. Sen (1968) developed a nonparametric procedure for estimating the slope of trend in a sample of n pairs of data. The Sen's method uses a linear model to estimate the slope of the trend, and the variance of the residuals should be constant in time calculated as:

$$Q_i = \frac{X_j - X_k}{j - K} \quad \text{for } i = 1, \ldots, n \tag{7}$$

where X_j and X_k are the data values at times j and k $(j > k)$, respectively. If there is only one datum in each time period, then $N = n \, (n-1)/2$, where n is the number of time periods. If there are multiple observations in one or more time periods, then $N n \, (n-1)/2$. The n values of Q_i are ranked from smallest to largest, and the median of slope or Sen's slope estimator is computed as:

$$Q_{med} = \begin{cases} Q_{\left[\frac{n+1}{2}\right]} & \text{if } n \text{ is odd} \\ \dfrac{Q_{\left[\frac{n}{2}\right]} + Q_{[(n+2)/2]}}{2} \end{cases}$$

if n is even

3.2.7 Statistical analysis. Also, a correlation matrix of the three main parameters of a water body namely, water level, surface water area and water volume were constructed for the urban lake. The correlation coefficient was in the present study to calculate and understand the relationship between the area and water volume as well as water level/depth and water volume of Deepor Beel. The linear correlation coefficient represented by r measures the direction and strength of a linear relationship between two variables. The linear correlation coefficient is calculated with equation (8):

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n\left(\sum_x 2\right) - \left(\sum_x 2\right)}\sqrt{n\left(\sum_y 2\right) - \left(\sum_y 2\right)}}. \tag{8}$$

where n is the number of pairs of data

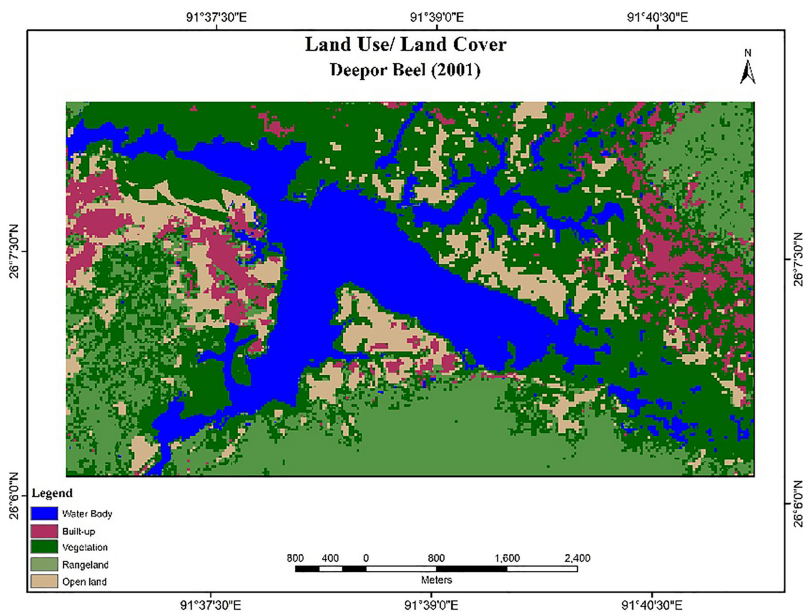The value of r is such that $-1 \leq r \leq +1$.

4. Results

4.1 Spatio-temporal changes of Deepor Beel Lake

Rapid social and economic development has led to increased LULC changes in the urban areas all over the globe, which affect the surface energy balance and hydrological processes (Elmahdy *et al.*, 2020). The result of the study shows a significant change in LULC around the Deepor Beel lake during 2001–2019. It is evident from Table 2 that the overall Deepor Beel Lake area shows a decrease over the past 2 decades. In 2001, the built-up areas were mostly concentrated in the east along with small patches in the northern and western parts of the lake (Figure 3a). But in 2011, most of the northern and central parts have been concretized (Figure 3b). In 2019, built-up areas could be seen all around the lake area replacing vegetative regions and open spaces (Figure 3c). Moreover, in 2001, the water extent of the Deepor Beel was from south-east to north-west spread over an area of 657.068 ha which decreased to 495.085 ha in the year 2019. The area of rangeland and vegetation have also significantly declined during the study period, especially in northern, eastern and western parts of the lake. Overall the maximum increase has been noticed in the built-up area (248.47%) and the maximum decrease has been observed in vegetation (−40.57%) followed by water bodies
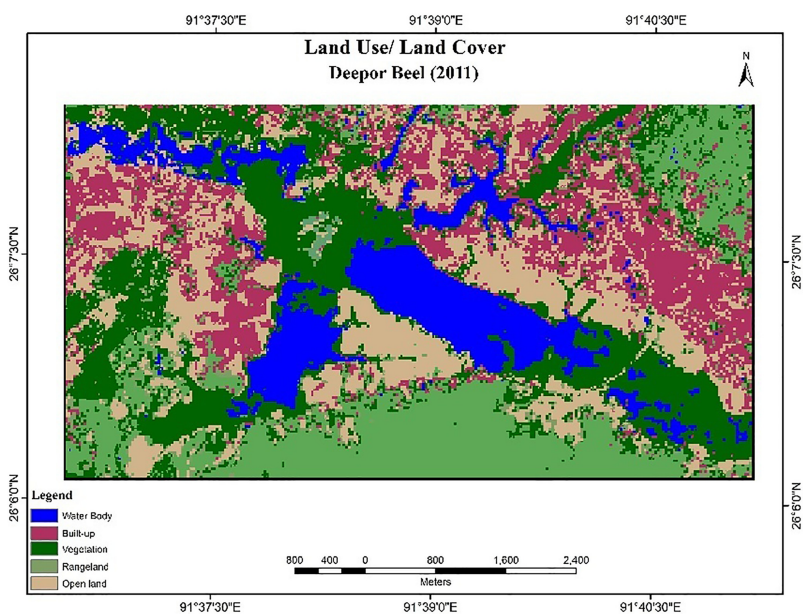
S. No.	LU/LC Classes	Area (2001)		Area (2011)		Area (2019)	
		hectares	%	hectares	%	hectares	%
1.	Water bodies	657.07	20.08	558.71	16.23	495.08	15.62
2.	Built-up	246.87	7.56	685.71	19.92	833.74	26.3
3.	Vegetation	1304.22	39.87	809	23.50	775.01	24.45
4.	Rangeland	704.49	21.54	683.05	19.84	660.85	20.84
5.	Open land	358.45	10.95	706.70	20.51	405.52	12.79
Total		3171.1	100.00	3171.17	100.00	3170.2	100.00

Table 2.
Land use/land cover change of Deepor Beel (2001–2019)

Figure 3.
Land use/land cover (a)
2001; (b) 2011 and
(c) 2019

Figure 3.

Land Use/ Land Cover
Deepor Beel (2019)

Legend
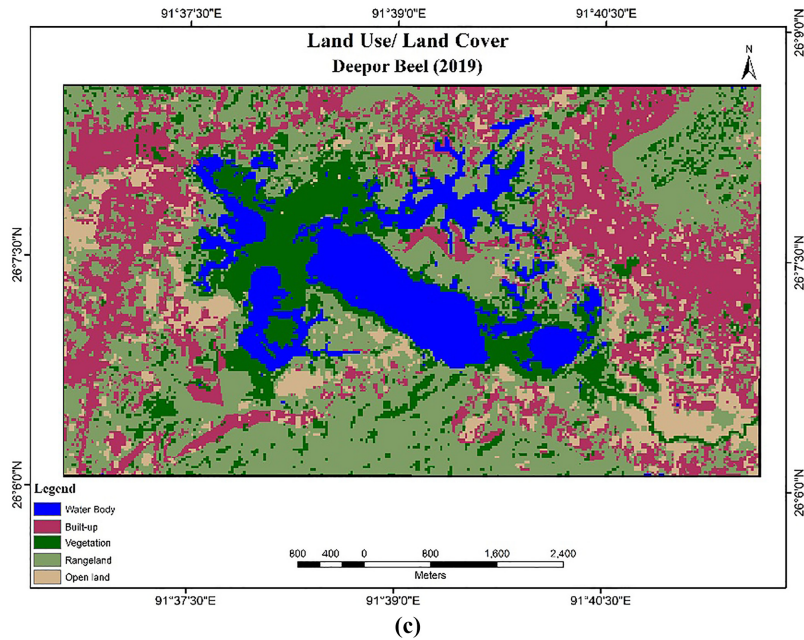- Water Body
- Built-up
- Vegetation
- Rangeland
- Open land

(c)

(−24.65%). Various researches has showed change of water bodies as a result of urbanization and LULC change. These changes are mainly attributed to the human activities, especially land reclamation and aquaculture activities along the lakeshore (Liu *et al.*, 2020; Wada *et al.*, 2016; Song *et al.*, 2013).

4.2 Spatio-temporal variation of surface water in Deepor Beel
The MNDWI in the Deepor Beel area is maximum in 2001 (Figure 4a–c), whereas 2011 and 2019 are highly concretized as validated with the LULC results (Table 2). Therefore, 2011 and 2019 have the least MNDWI values. In 2001, water bodies and vegetation are visible along with rangelands. Further in 2019, the dense amalgamation of apartments and buildings, where the tree cover along the roads, highways and open land around the Deepor Beel has become more dominating than the water body itself.

The lake water area was extracted using spectral water indexing. The analysis clearly shows that the shoreline of the Deepor Beel shrunk in the past eighteen years. Table 3 shows that the variations in the water surface area of Deepor Beel extracted from the LULC and MNDWI are quite similar. According to the MNDWI, between 2001 and 2019 there were drastic changes in the lake water area. The results reveal that the surface area of Deepor Beel lake in 2001 was approximately 659.05 ha (Table 3). By 2011, the surface area had decreased by approximately 101.12 ha. From 2001 to 2019, the lake lost about one-fourth of its surface area. However, from 2011 to 2019, the lake lost about one-tenth of its surface area (Table 3). According to the result given in Figure 4, the highest rate of water area change was observed in the south eastern and western part of the lake. Large-scale encroachment in the government as well as private-owned low-lying area of the Deepor Beel Ramsar site for various purposes such as settlements, institutions and business shops are causing tremendous threats to the water surface area of the lake. Figure 4 (a–c) clearly shows the change in the surface water boundary of Deepor Beel from 2001 to 2019.
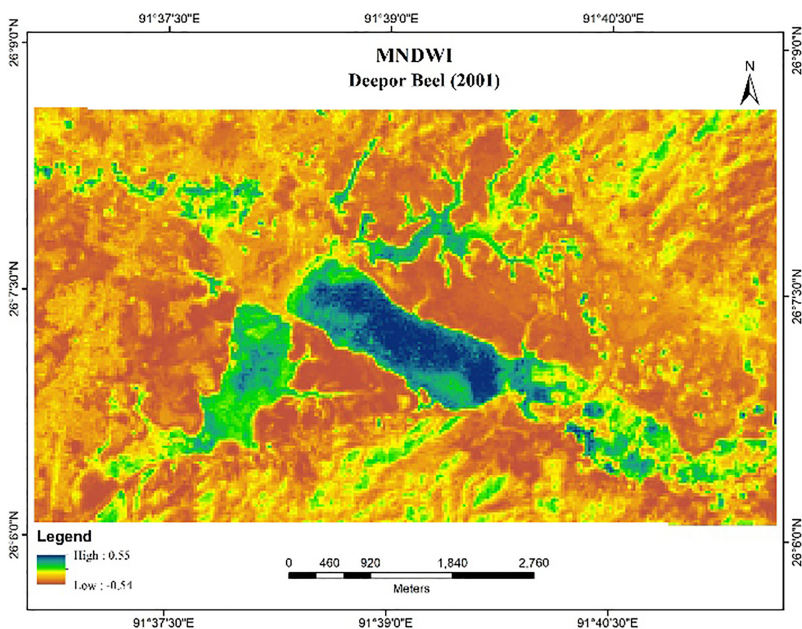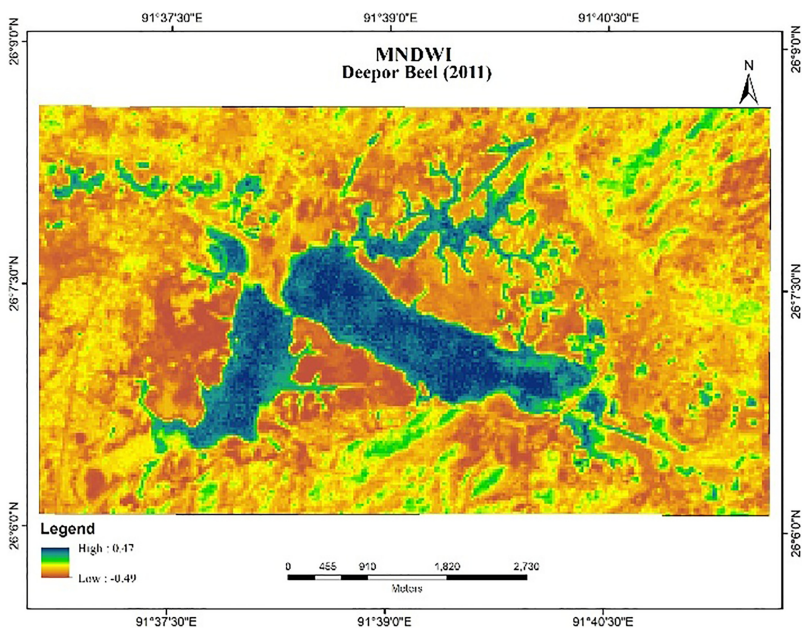
Figure 4.
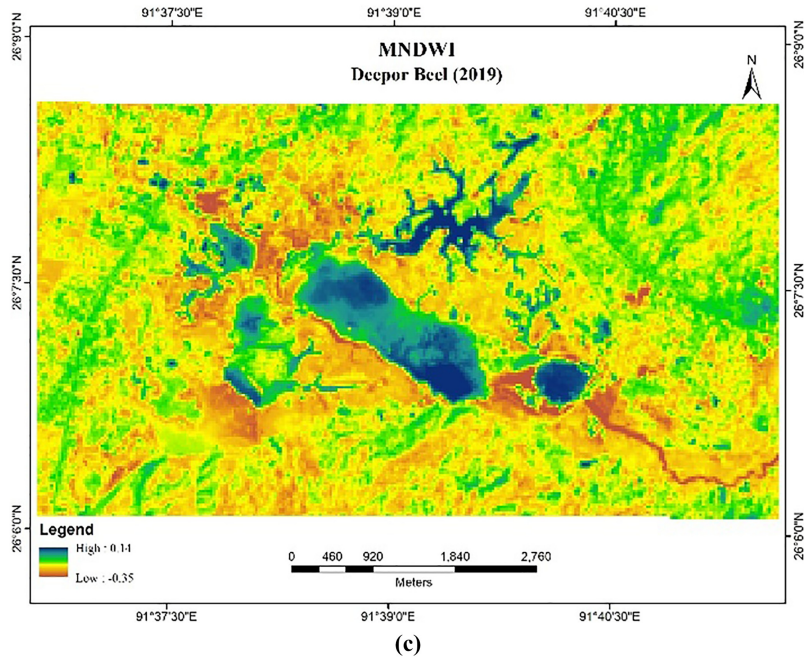MNDWI of Deepor Beel
(a) 2001; (b) 2011 and
(c) 2019

Figure 4.

(c)

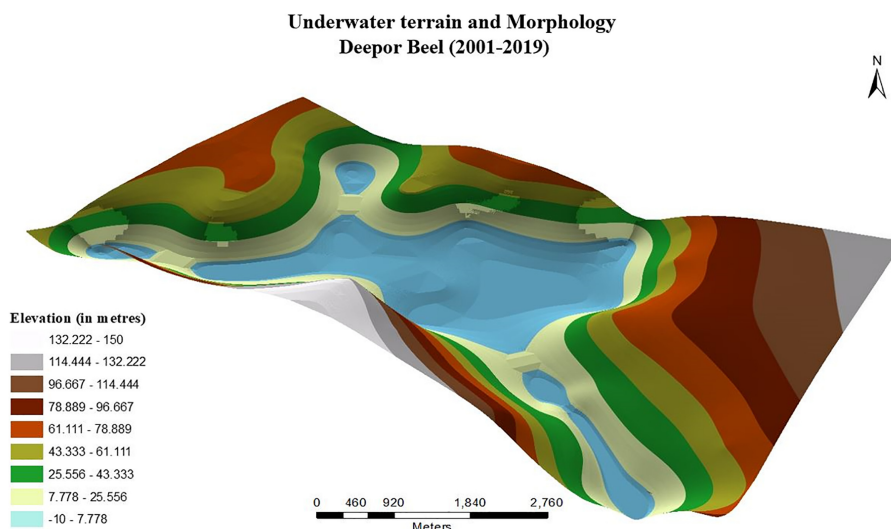| S. No.	Years	Surface water area using MNDWI (hectares)	Surface water area using unsupervised classification (hectares)
1.	2001	659.05	657.07
2.	2011	557.93	558.71
3.	2019	500.34	495.08

Table 3.
Variation in Deepor Beel surface water area using MNDWI and Unsupervised classification

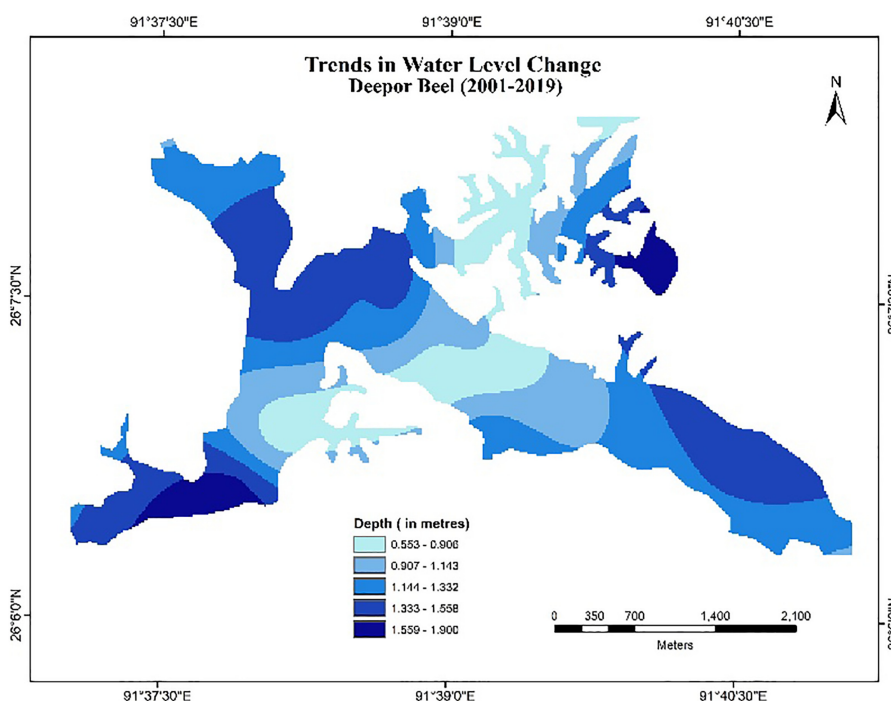### 4.3 Underwater terrain and morphology of Deepor Beel

It is evident from Figure 5 that the basin bottom of the lake is relatively undulating and its flanks are steep, with slopes ranging from 0 to 2 degrees. The results indicate that the water level of Deepor Beel lake decreased over the past eighteen years. The interpolation map of the lake during the study period shows that the maximum water depth was 1.9 m whereas the lowest depth was 0.5 m (Figure 6). The water level shows a slight decrease in a total of 0.8 m from 2001 to 2019 (Table 4). The water depth profile clearly shows that the depth slowly increases from the centre of the lake (1.32–2.38 m) toward the shoreline in the south (Figure 6). Furthermore, the depth of the lake suddenly drops in the frontal terminus, then reach a depth of 1.32–1.67 m. The lake boundary of different years from vector data was also created to show the spatio-temporal changes (Figure 7a–c).

The northern and the eastern flanks of the lake are quite shallow as compared to the rest of the lake. This is mainly due to the active National Highway 37 which passes beside the eastern and northern side of the Beel, leading to the establishment of built-up patches and shops (vendors). Moreover, changes in the underwater terrain of the Deepor Beel are mainly caused by human activities, mainly urbanization leading to illegal sewage dumping. The western part is deeper in comparison to the rest of the lake. The western margins of the lake

**Underwater terrain and Morphology
Deepor Beel (2001-2019)**

Elevation (in metres)

- 132.222 - 150
- 114.444 - 132.222
- 96.667 - 114.444
- 78.889 - 96.667
- 61.111 - 78.889
- 43.333 - 61.111
- 25.556 - 43.333
- 7.778 - 25.556
- -10 - 7.778

0   460   920   1,840   2,760
Meters

Figure 5.
Underwater terrain
and morphological
modeling of Deepor
Beel and its
surroundings
2001–2019

**Trends in Water Level Change
Deepor Beel (2001-2019)**

Depth (in metres)

- 0.553 - 0.906
- 0.907 - 1.143
- 1.144 - 1.332
- 1.333 - 1.558
- 1.559 - 1.900

0   350   700   1,400   2,100
Meters

Figure 6.
Trend and pattern of
water level of Deepor
Beel lake from 2001
to 2019

are still a bit scarce on built up as compared to the other three sides. The southern part of the lake is the shallowest mainly because of the railway line constructed by the Northeast Frontier Railway around the Deepor Beel area (Figure 7). Since the 1960s, people living along

urban lakes have been using land near the lakeshore for farming and aquaculture (Dash *et al.*, 2019). As a result, the area and water level of the lake has decreased sharply, and some natural shorelines have also disappeared.

4.4 Volume of the Deepor Beel Lake
During the study period, the proposed method calculated the volumes from 2001 to 2019 ranging from 20.95 to 15.35 million m^3 from the underwater topographic modeling and water level, with a mean of 10.568 million m^3. In 2001, the calculated water volumes were quite higher than in 2011 and 2019. The volume of the Deepor Beel has been declining very rapidly. The largest decrease in the volume of Deepor Beel occurred in the year 2019 (Table 5), possibly caused by wetland vegetation cover and haphazard establishment of settlements in the surrounding area. The storage capacity of the lake indicates a gradual decline during the study period, and the trend is statistically significant at the 5% significance based on the Mann–Kendall test (Table 6). The trend slope based on Sen's method exhibited that the decadal volume of the lake showed a significant decrease at the rate −2.8 million m^3/decade over the last 18 years.

Along with volume, it's related aspectsi.e area ($Z = −1.880$) and depth ($Z = −5.947$) also depicts a clear negative trend. The water level has decreased at a rate of 0.05 m/year (Table 6). Dumping of untreated waste has led to blockage of the natural drainage pattern of the lake causing an imbalance in the water level leading to a decline in the storage capacity of the lake. The water volume of a lake is a function of water level and surface water area, and a critical variable in the water mass budget of a lake catchment (Geng *et al.*, 2021). Figure 8 shows a high correlation between the water volume and water surface area of Deepor Beel with a graphical representation from 2001 to 2019.

The adjacent forest areas around the lake are being cleared to supply timber for the sawmills, leading to heavy erosion, which in turn is causing rapid siltation in the Beel, further declining the storage capacity (Deb *et al.*, 2019). Furthermore, brick factories and widespread soil cutting within the Beel ecosystem properly threatens the volume of the Beel (Islam and Gnauck, 2008). Urban lakes all over the globe are facing similar problems of declining volume, water area and level (Cai *et al.*, 2020; Wufu *et al.*, 2020). Such deterioration of quality of urban lakes are majorly caused due to anthropogenic activities (Wufu *et al.*, 2020; Talukdar and Pal, 2019; Lu *et al.*, 2013).

4.5 Validation and auxiliary data
The validation of the *in situ* water level data and the calculated storage capacity of Deepor Beel is done with a correlation matrix which is shown in Table 7.

The main aim to study the volume of water bodies is to develop a mathematical equations relating area and volume to depth and water level using morphometric data. While validating the calculated storage capacity there are obvious discrepancies within the measured values. By comparing the values of correlation coefficient (r) it was clear that the water level has a direct positive relationship with the volume of the lake (Table 7). Additionally, the surface water area also shows a strong positive significance with water volume ($r = 0.951$). After

Table 4.
Average, maximum and minimum water surface level of Deepor Beel (2001, 2011 and 2019)

S. No.	Years	Mean (m)	Maximum (m)	Minimum (m)
1.	2001	1.77	1.82	1.25
2.	2011	1.27	1.89	0.75
3.	2019	0.97	1.59	0.45
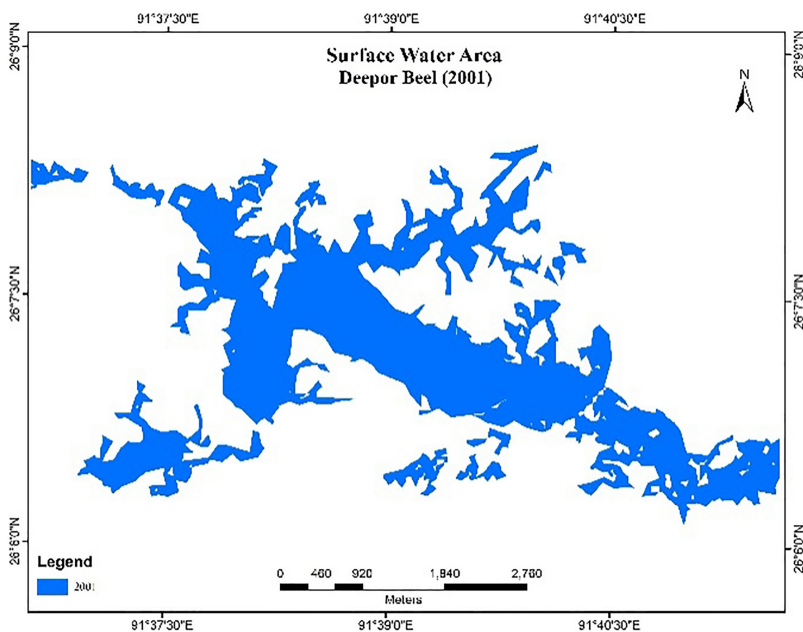
(a)

(b)

Surface Water Area
Deepor Beel (2019)

Legend
2019

0 460 920 1,840 2,760
Meters
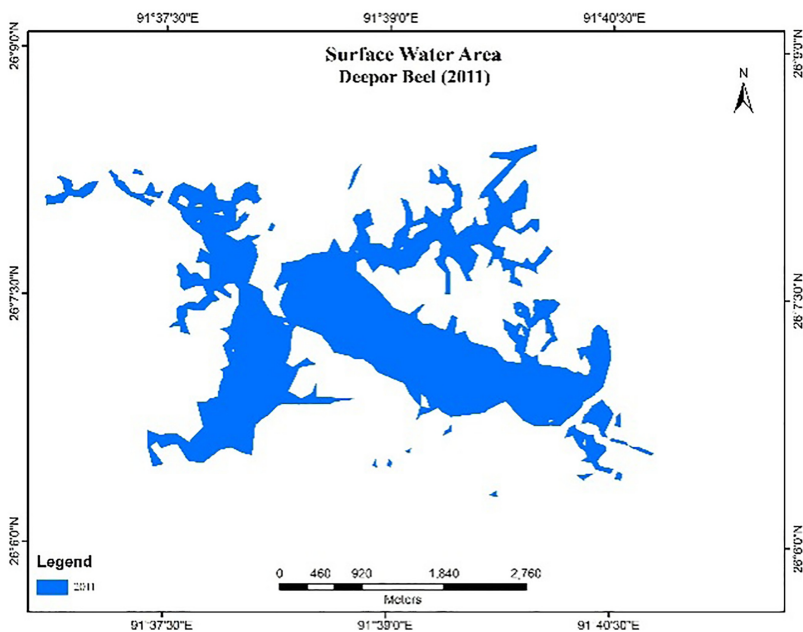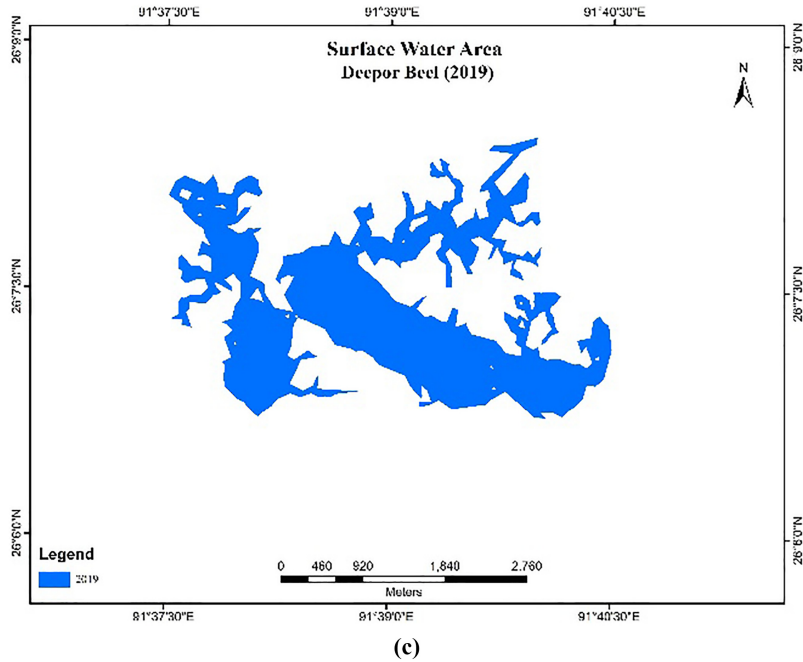
Figure 7.

S. No.	Years	Volume (million m^3)	Area (km^2)
1.	2001	20.95	29.88
2.	2011	16.73	25.24
3.	2019	15.35	23.65

Table 5.
Calculated volume of water and area of the Deepor Beel

	Mann–Kendall Z value	Mann- Kendall statistics (S)	Kendall's Tau (τ)	Sen's slope estimator (Q_i)
Water volume	−1.045	1.00	0.018	−2.8
Water surface area	−1.880	1.02	0.052	−3.51
Water level	−5.947	−171	−1	−0.005

Table 6.
Mann–Kendall trend test and Sen's slope test of water volume, water surface area and water level of Deepor Beel

developing the correlation coefficient matrix, scatter diagrams were constructed and shown in Figure 9a–d, respectively. The linear models thus obtained shows that the correlation coefficient between water volume, area and water level (average, maximum and minimum) demonstrates a statistically significant decline over time. In both cases, i.e. correlation coefficient and linear model, the objective is to establish a relation between water level-volume as well as area-volume (Zhang *et al.*, 2019; Arabsahebi *et al.*, 2019). Besides, the *in situ*
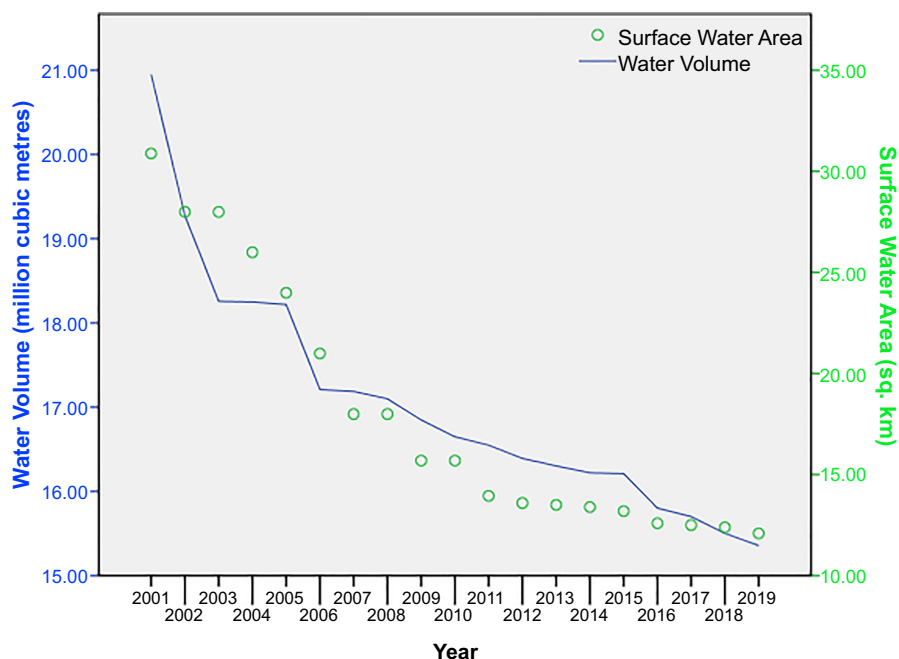
Figure 8.
Changes in the volume
and area of Deepor Beel
lake from 2001 to 2019

| Correlation Coefficient(r)		Water surface area	Water level (mean)	Water level (max.)	Water level (min.)
Water volume	Pearson correlation	0.951[**]	0.809[**]	0.810[**]	0.810[**]
	Sig. (2-tailed)	0.000	0.000	0.000	0.000

Note(s): [**]Correlation is significant at the 0.01 level (2-tailed)
[*]Correlation is significant at the 0.05 level (2-tailed)

Table 7.
Correlation coefficient
between water volume,
water surface area and
water level of
Deepor Beel

water level data along with the calculated storage capacity and surface water area clearly shows decline in different years from vector data of the lake boundary.

5. Discussion

The LULC derived images of the Deepor Beel shows a variation in the land use patterns around the lake from 2001 to 2019. The LULC maps of three observation periods (Figure 3a–c), clearly shows that the surface water area of the Deepor Beel lake (657.07 ha in 2001, 558.71 ha in 2011; 495.08 ha in 2019) is continuously decreasing whereas area coverage by built-up (246.87 ha in 2001, 685.71 ha in 2011; 833.74 ha in 2019) around the Beel is continuously increasing from 2001 to 2019. The establishment of the Gopinath Bordoloi International Airport, the National Highway no. 37, and the railway line constructed by the Northeast Frontier Railway are the key aspects that play a major role in the land use pattern around the Deepor Beel area. The greenery in and around the lake area is no more to be seen (Mozumder *et al.*, 2014). Due to the migration of population in search of livelihood into the city,
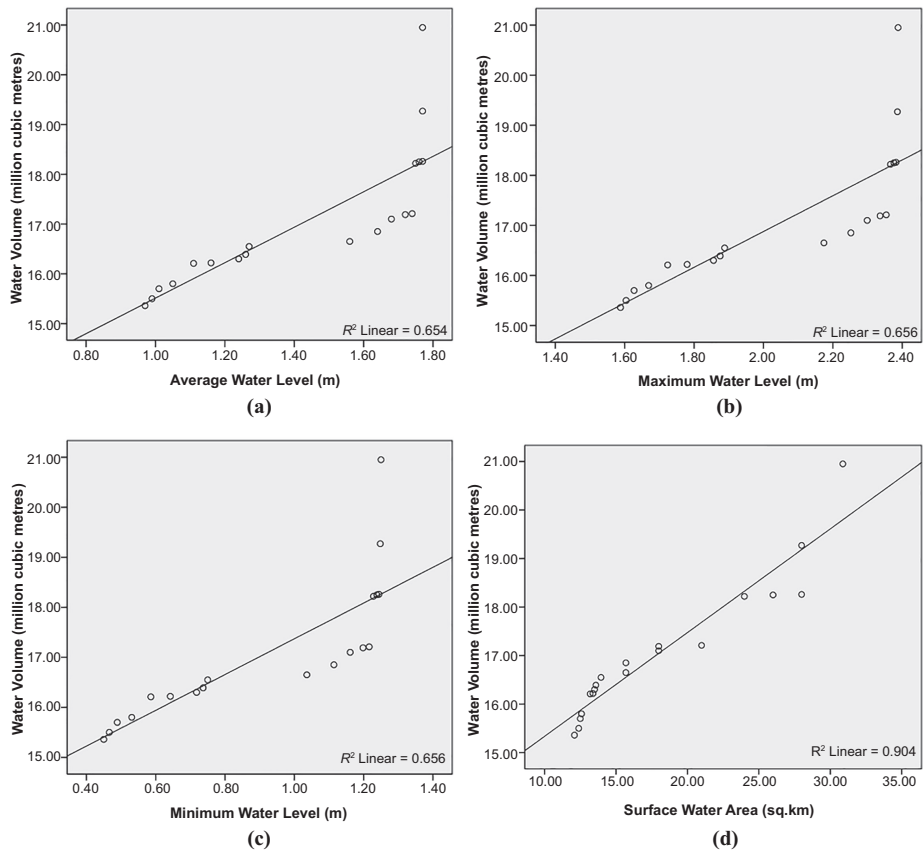
Figure 9.
Scatter plot for average, maximum and minimum water level with water volume and surface water area

the suburb areas including the Deepor Beel wetland areas around the Guwahati city are rapidly filling up for residential, educational, industrial purposes which severely affected the wetland ecosystem. Such scenarios are quite common in the 21st century urban water bodies all over the globe (Cai *et al.*, 2020; Yan *et al.*, 2019; Talukdar and Pal, 2019; Ganaie *et al.*, 2017). The natural drainage pattern of the lake is mostly blocked causing an imbalance in the water level. Dumping of industrial and untreated domestic waste by the GMC at the municipal garbage dumping site at Paschim Boragaon near Deepor Beel cause enormous water and land pollution which in turn resulted into the destruction of numerous species of flora and fauna in the surrounding area (Dash *et al.*, 2019). Besides, during the monsoon season, the surface runoff usually sweeps away the waste materials from the dumping site then mixing of this into the lake water deteriorating the water quality (Wu *et al.*, 2017).

Furthermore, the modified normalized water index proved itself to be the most accurate method to detect, measure and monitor the urban surface water bodies because they can easily differentiate dry land and water bodies (Saha *et al.*, 2020). With the assumption that LULC as constant with time may not give reliable outputs or results and may deviate from observed and simulated results in hydrological modeling. The surface area of the Deepor Beel was extracted from both the MNDWI and LULC results. Thus, accurate classification of features plays important roles in modeling of hydrological system. In this study, both the outputs showed identical values. Also, the result of MNDWI shows that in the last eighteen

years, the urban aquatic ecosystem of Deepor Beel has been decreasing more than 150 ha. Guwahati city, especially, the outskirts are experiencing massive urban development such as housing and residence in which many forests areas and open spaces such as field and swamps are converted (Pawe and Saikia, 2017). As a result, the urban water body is getting smaller and smaller because water bodies or vegetation area are mostly converted to built-up areas (Cai et al., 2020; Modi et al., 2019; Wu et al., 2017). The MNDWI method is very effective as it can suppress information about land built effectively by highlighting water information and accurately extracting information from water bodies (Xu, 2006) in the study area. The results show that MNDWI can improve water bodies and suppress built-up capabilities very efficiently, thus extracting the area of the water bodies.

Furthermore, the underwater terrain and morphology modeling with the help of the field-observed water level data, DEM and triangulated irregular network (TIN) clearly shows changes in the basin morphology (Lu et al., 2013) of the Deepor Beel lake. The TIN based method has broad implications for water storage change monitoring in lakes with annual variations in water level (Yao et al., 2012). The volume of the Deepor Beel lake has been decreasing in the three proposed timed period from 20.95 million m^3 in 2001 to 16.73 million m^3 in 2011 to 15.35 million m^3 in 2019. A rapid urban expansion has been identified around the Deepor Beel which endangers the green environment in and around the urban lake (Mozumder and Tripathi, 2014). This has led to human mismanagement to intensify pollution and loss of habitat for birds and fish in the lake area (Modi et al., 2019). Moreover, construction of broad-gauge railway line connecting Guwahati with Bongaigaon through the south bank of the Brahmaputra river with a bridge at Jogighopa cuts across the lake and wastewater from different parts of the city and the adjoining areas (Goswami, 2012) and Pamohi as well as Paschim Boragaon garbage dumping site adjoining the Deepor Beel are the major anthropogenic causes for the deterioration of the storage capacity of the lake.

Our analysis similar to several previous studies, also depicts that the surface area and water level are important factors in determining the storage capacity (Zhang et al., 2017; Arabsahebi et al., 2019). The surface area of the Deepor Beel lake has been declining along with decline in water level from 2001 to 2019. When all the water parameters are treated independently for the calculation of contribution to the decrease or increase of storage capacity, validation with the help of the correlation matrix revealed that that water volume is affected by both water surface area ($r = 0.951$) and water level ($r = 0.809$). This condition is further proceeded with the linear model function. The coefficient correlation along with the linear model function validates that the Deepor Beel lake demonstrates a statistically significant declining trend of volume, area and water level over time.

The Preservation and Conservation Act, 2008 has been put in place to stop illegal construction activities in and around Assam's lone Ramsar site, Deepor Beel. In particular, the Guwahati Metropolitan Development Authority started clearing illegal newly occupied areas, and illegal occupation was curbed (Joshi and Solanki, 2019). However, many areas around the lake are still used for reclamation and aquaculture that have not been cleared (Dash et al., 2019; Goswami, 2012). In addition to the reduction in water area and storage capacity, disorderly farming and aquaculture can affect the water quality of lakes (Cai et al., 2020) like Deepor Beel (Bhattacharyya and Kapil, 2010). Moreover, in March 2015, it was reported that the Kamrup (Metropolitan) district administration has ordered the GMC to shift its garbage disposal project from Deepor Beel (Joshi and Solanki, 2019). Therefore, the work of construction, farming and aquaculture areas to lake area should continue to be strictly carried out around Deepor Beel, and the monitoring and management of the lake should also be maintained.

6. Conclusion
The present study clearly shows that the LULC changes around the Deepor Beel was significant during the period from 2001 to 2019. Also, from 2001 to 2019, the lake lost about

one-fourth of its surface area and from 2011 to 2019, the lake lost about one-tenth of its surface area. Moreover, the inland urban lake of Deepor Beel is shrinking with declining storage capacity mostly due to the inflow of wastewater from Guwahati city to this Beel which has also reportedly degraded the water quality. The lake volume has decreased from 20.95 million m^3 in 2001 to 15.35 million m^3 in 2019. Besides, unprecedented urban growth and permanent agriculture are steadily encroaching on the lake area reducing the extent of the marsh vegetation rapidly. Furthermore, when all the water parameters are treated independently for the calculation of contribution to the decrease or increase of storage capacity, validation with the help of the correlation matrix revealed that that water volume is affected by both water surface area ($r = 0.951$) and water level ($r = 0.809$). Therefore, what matters more at this hour are the well-planned conservative measures to be undertaken to stem these distressing problems suffered by such urban lakes. Deepor Beel is the only Ramsar site located in Assam and it's natural feature benefits the surrounding regions. But disorderly development along the lake may reduce its capability of water storage and flood regulation.

Although, the Government had proposed a sewage treatment plant as well as the shifting of the garbage dump. These plans need to be executed at the earliest as at this point, it is also necessary to create a sustainable balance in the restoration of the Beel as well as sustaining the livelihood of the fishermen. In this regard, aquaculture and sustainable methods of fishing could be employed; or alternate livelihood could be taught to the villages that depend on fishing. Even though Deepor Beel has been stripped of its glory in the past decades, proper implementation and coordination of the various administrative, social and legal frameworks together should be capable of restoring the Beel and prevent further degradation. Although, the task is an uphill one, but with an appropriate policy and effective management, Assam's lone Ramsar site can still be restored.

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