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Spatiotemporal dynamic study of lakes and development of mathematical prediction model using geoinformatic techniques

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Abstract Lake is the important part of the wetland and also the main source for agricultural irrigation, domestic water supply and industrial requirement. It maintains the aquatic ecosystem and also considered as the major place for biodiversity conservation. The lake area is getting reduced due to increase in siltation and eutrophication processes in the aquatic region. The dynamic changes of the lake create an adverse effect on the environment. The main objective of the present research is to study the spatial dynamic changes of the lake by GIS techniques and to develop the mathematical prediction model to understand the future trend of lake area. Multi-dated satellite image and topographical maps were used to generate the GIS-based thematic databases of the lake boundary for the period from 1954 to 2011. The result shows that the lake area decreased from 33.26 km^2 to 10.8 km^2 during 1954–2011. The decrease of the lake area is due to the natural and anthropogenic activities. In order to study the dynamic change and future trend of lakes, the spatial prediction model was developed for Thirukanchur Lake and was validated by a numerical prediction model with field based studies. The spatial model predicts that the lake area will be further reduced from 0.12 km^2 in 2011 to 0.045 km^2 in 2021. The above model can be applied to other lakes to predict future status of lake by adopting the required parameters.

Keywords Lakes · Geoinformatics · Spatiotemporal dynamics · Satellite image · Mathematical model · Prediction

Introduction

Lake is a fresh water body of relatively stable water with considerable size, which is surrounded by land. Inland lakes are natural or man-made, small or big and deep or shallow water bodies that receive water from its catchment area (Bao and Zhang 2011; Maeda et al. 2011). Ponds and lakes located in many regions and performed several essential functions such as storing rainwater, providing suitable aquatic habitats for flora and fauna and maintaining hydrological cycle. In the context of global climate change, these water bodies help to reduce the extremes of atmospheric temperature in many regions (Fragoso et al. 2011).

In recent years, rapid morphological changes are observed in many lakes due to the combination of the impact of climatic change and human activities (Du et al. 2011; Gong et al. 2010; Trolle et al. 2011). The increase in water temperature is leading to eutrophication with increase in algae growth (Malmaues 2004). Also, the rapid growth of population and urbanization is increasing the exchange of nitrogen and phosphorous between lands and surface water. This further increases the amount of nutrients in aquatic environments and contributes to accelerate the eutrophication process. In the catchment, basin raises runoff in volume and speed, causing greater soil carrying capacity leads to greater siltation in the lake area. The lake depth is reduced due to increase in siltation and eutrophication process. Despites, inland lakes are highly influenced by urban stress, such as industry and residences (Ruan et al. 2008).

The spatiotemporal changes of lakes and its impact on environment were studied from different literatures. Shuqing

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et al. (2003) analysed the dynamics of the marsh landscape structure of the Sanjiang Plain to observe the conversion in the past 20 years between marsh and other land use types. It was also observed that the reclaimed marsh had mainly converted to paddy field and dry land and influences natural environment and made suitable for further agricultural development (Shuqing et al. 2003; Bedford and Preston 1988). The water balance of inland lakes on the Tibetan Plateau was studied, and lake dynamic impact on hydrological processes was analysed (Lei et al. 2011, 2014; Zhang et al. 2011; Wan et al. 2014). Landsat satellite data were used to analyse the water quality parameters for Mosul Dam Lake, and derived result was compared with field observation data (Mohammed and Merkel 2014). Similarly, Jinling et al. (2014) studied the spatiotemporal changes using multi-temporal remote sensing data for multiple years in Beijing by adapting artificial neural network-based classification techniques. Song et al. (2013) analysed the lake water storage changes using multi-mission satellite data, and model was developed for Tibetan Plateau. Wu et al. (2009) studied the seasonal dynamics of water clarity to analyse the influence of water level, wind velocity and total precipitation on the dynamics in Lake Dahuchi, China. The analysed result shows that the lake was primarily controlled by suspended sediment, while the seasonal variation of water level induced different suspended sediment. It was also concluded that the water clarity seasonal dynamics of Lake Dahuchi was mainly regulated by seasonal variation of water levels (Wu et al. 2009; Nellis et al. 1998; Swift 2006). Hassanzadeh et al. (2012) developed a simulation model based on system dynamics method to identify the various factors for the Urmia Lake basin to estimate the lake's level.

Mushtaq and Pandey (2014) investigated the impacts of temporal changes in LULC and meteorological as well as hydrological parameters to evaluate the current status of Wular Lake environment using multi-sensor, multi-temporal satellite and field observation data. Guidoum et al. (2014) developed model of water erosion in northeastern Algeria using a seasonal multi-criteria approach and explain the impact of erosion on aquatic environment. Hereher (2015) delineated the extent and capacity of El-Rayan depression, Egypt, by the utilization digital elevation models (DEMs) along with five Landsat satellite images and also analysed

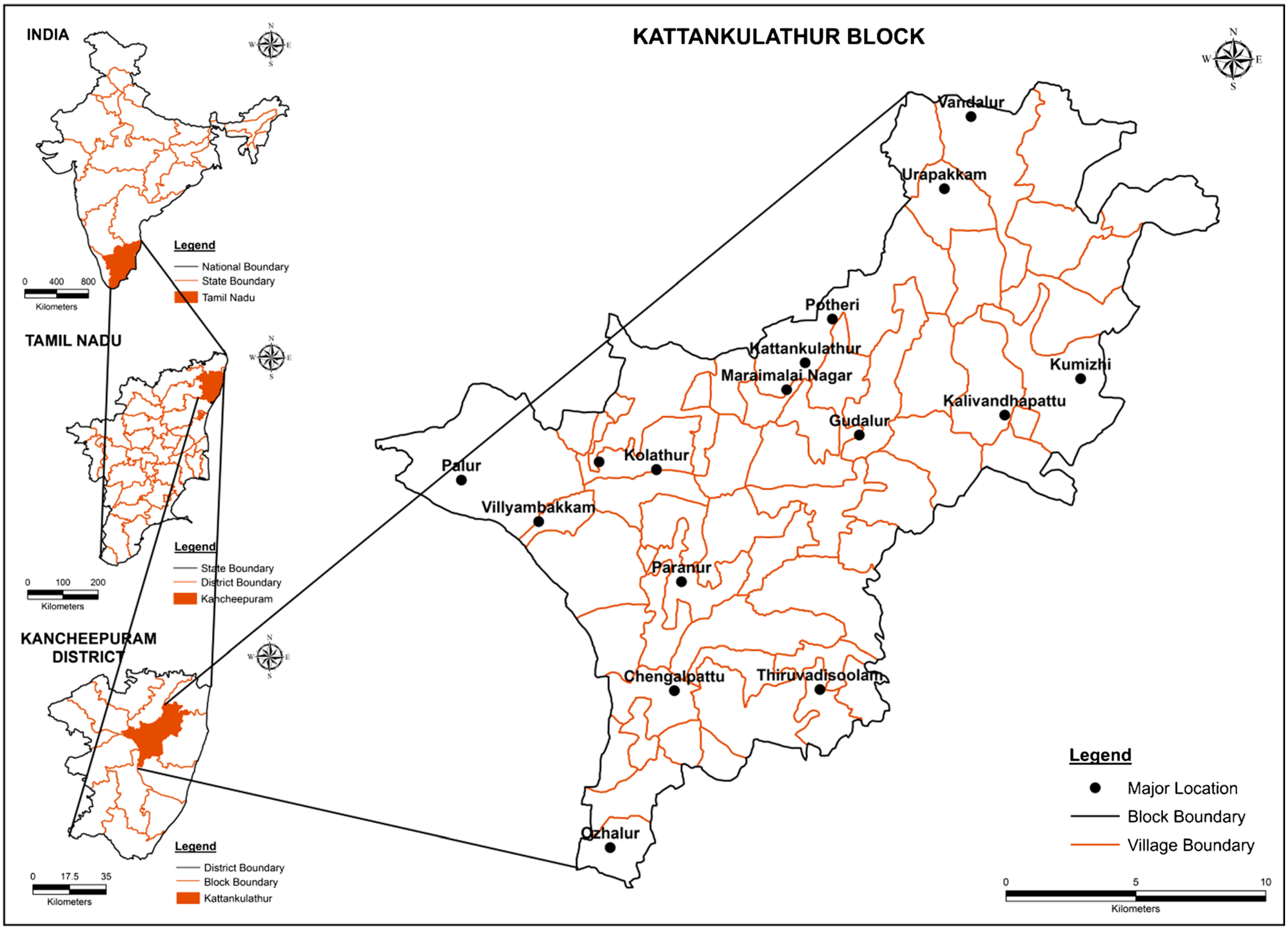


Fig. 1 Location map of study area

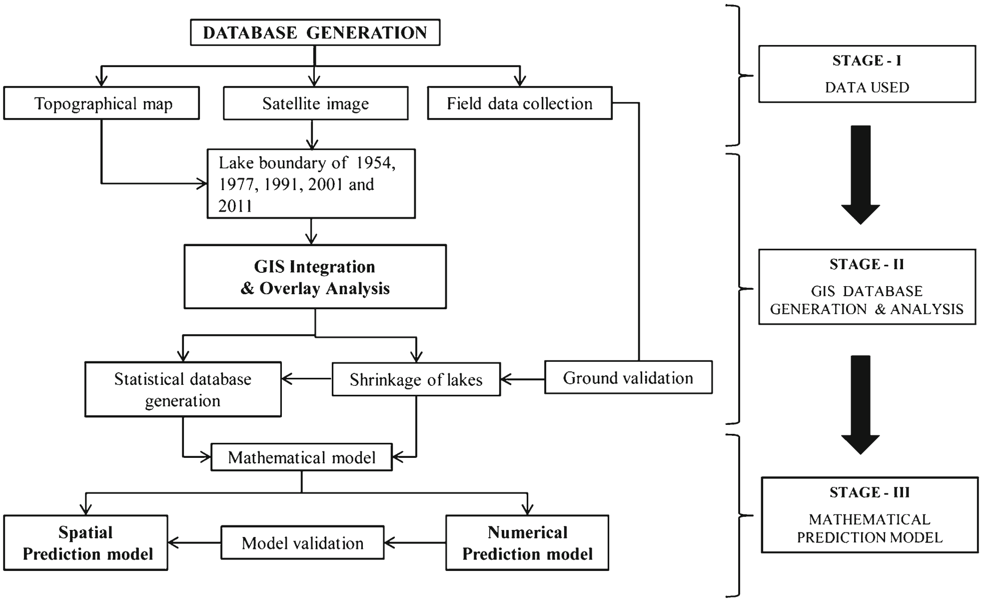


Fig. 2 Flowchart of methodology

the temporal changes of lakes using geoinformatics techniques. Donia (2013) explained the importance of remote sensing satellite imagery for lake dynamic analysis in watershed environment. The changes in lake morphology greatly affect the available freshwater resources leading to the consequent evolution of local and regional ecological environment (Huang et al. 2010; Klemas 2011). Multi-dated satellite was used to understand the land-use/cover change (LULC), and groundwater resources are important for land-use planning and natural resource management (Kelarestaghi and Jeloudar 2011). Determination of the causes and consequences of the changes of lakes is thus the precondition of solutions for their protection and restoration, and it is one of the main challenges in the present research. The impact of climatic change and human activities has been considered to be the most important factors in recent lake changes (Silva et al. 2011).

However, lake shrinkage is one of the main environmental problems in the recent year (Song et al. 2012; Wang et al. 2009). The rapid development of remote sensing and GIS technology provides a good technique to study various kinds of spatial information, especially the dynamic change of lakes. The remote sensing technique provides effective information sources for the dynamic change of resources and its assessment (Barducci et al. 2009). The satellite image is useful to analyse dynamic processes in aquatic environments. The algorithms were developed to process satellite images and to detect spectral reflectance of water bodies in the visible range (Shevyrnogov et al. 2002). Geographic Information System (GIS) has strong function of data acquisition, editing, analysis and developing statistics (Yanan et al. 2011) for such problems.

The present research focused to study the spatio dynamic status of lakes using topographical data and multi-dated satellite image of the years 1954, 1977, 1991, 2001 and 2011. The field observation was incorporated with the present study to identify the causes of change and anthropogenic activity. The mathematical prediction model is also developed using linear regression and coordinate geometric method to predict the future trend of lake area by integrating geoinformatic techniques.

Table 1 Sources of data

Data used	Year/month	Scale/resolution in meter/pixel (m/p)	Source of data
Topographical map	1954	1: 250,000	AMS Topographical map, University of Texas Libraries
Landsat 2–MSS image	1977, November	80 m/p	USGS Earth explorer
Landsat 5–TM image	1991, August	30 m/p	Global Land Cover Facility (GLCF)
Landsat 7–ETM$^+$ image	2001,October	30 m/p	Global Land Cover Facility (GLCF)
Landsat 7–ETM$^+$ image	2011, September	30 m/p	USGS Earth explorer
Resourcesat 1–LISS–III	2011, November	23 m/p	NRSC, India
QuickBird image	2011, September	8 m/p (available)	Google Earth satellite image

Study area

The study area is Kattankulathur Block, Kancheepuram District (A district of lakes), Tamil Nadu, India, and extends 12° 37′ 24″ N–12° 54′ 11″ N latitude and 79° 52′ 42″ E–80° 10′ 17″ E longitude (Fig. 1). It covers a total geographical area of 353.062 km^2. The average maximum and minimum temperature of study area is about 37 and 21 °C, respectively. The average annual precipitation is 1083 mm of which 48 % are through the North East monsoon and 32 % through the South West monsoon. The water resources potential of this area is entirely dependent on monsoon rain where monsoon failure leads acute water scarcity and severe drought. Palar is the major river flows through the western side of the study area. This river is connected by different tributaries and distributaries and is interconnected with inland lakes. Lakes are distributed over the lacustrine plain and the alluvial plain which is formed by

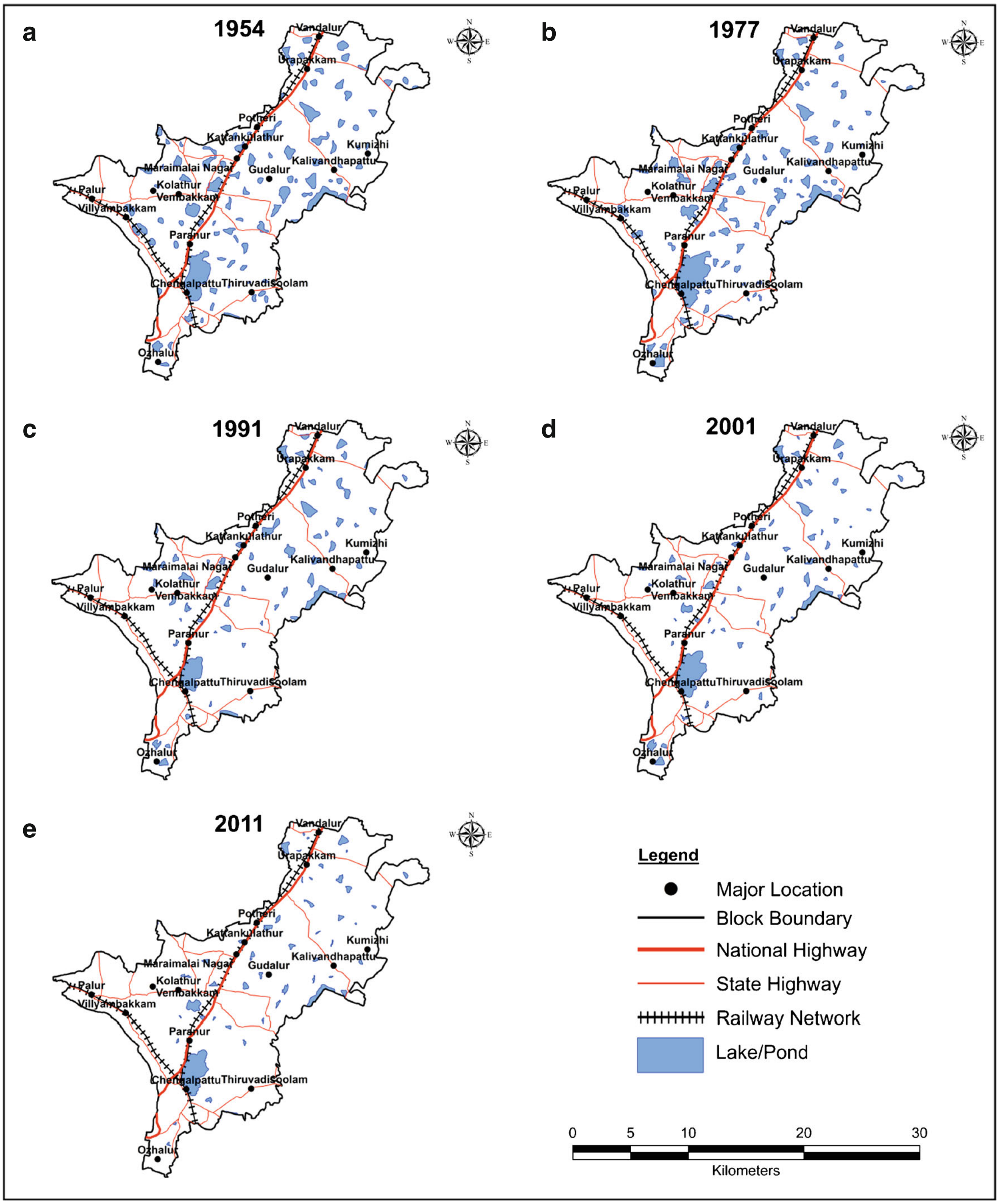


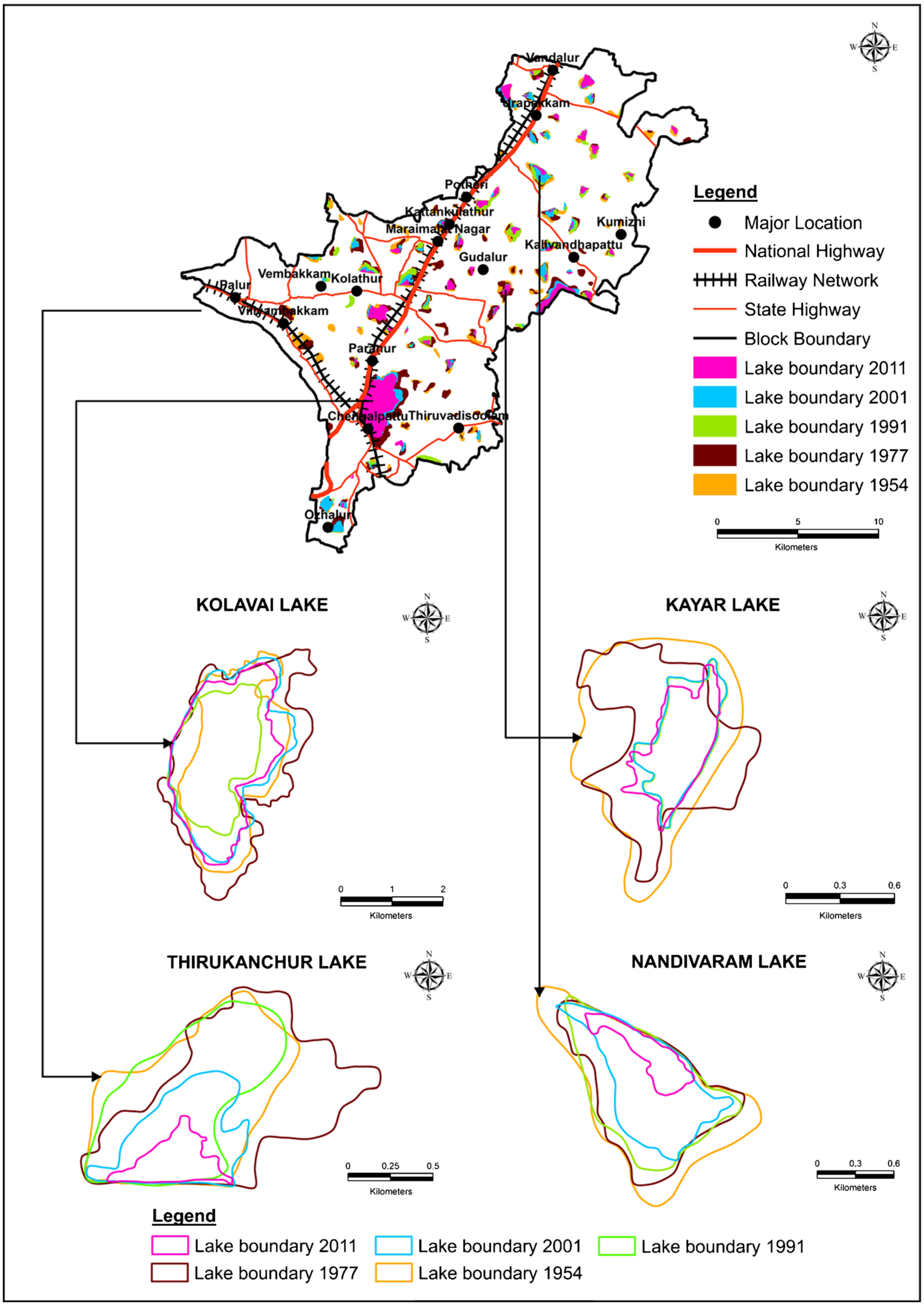
Fig. 3 Lake boundary map: **a** lake boundary of 1954, **b** lake boundary of 1977, **c** lake boundary of 1991, **d** lake boundary of 2001 and **e** lake boundary of 2011

the rivers and lake sediments. The area is covered by plain land with isolated residual hills, where maximum elevation is 220 m and minimum is 20 m. The slope varies from 1° in plain land to 40° in the residual hilly region. The very deep clayey soils with high organic matter are found in the lake environment. Major settlements in the study region are Kattankulathur, Maraimalai Nagar, Kolathur, Vandalur, Kumzhi, Palur, Paranur, Urapakkam, Ozhalur Chengalpattu, Thiruvadisoolam and Gudalur.

Materials and methods

The spatial and non-spatial data were collected from various sources. Lake boundary maps of multiple years were generated from the available maps and multi-dated satellite image using ArcGIS software for the study region. GIS spatial overlay analysis technique was used to study the shrinkage of lake area. A spatial prediction model was developed to predict the future trend of lakes using linear regression and coordinate

Fig. 4 Shrinkage of lake (1954–2011)



geometric method. Similarly, a numerical model was proposed for validating the present spatial model. The detailed methodology is given in the flowchart (Fig. 2).

Data used

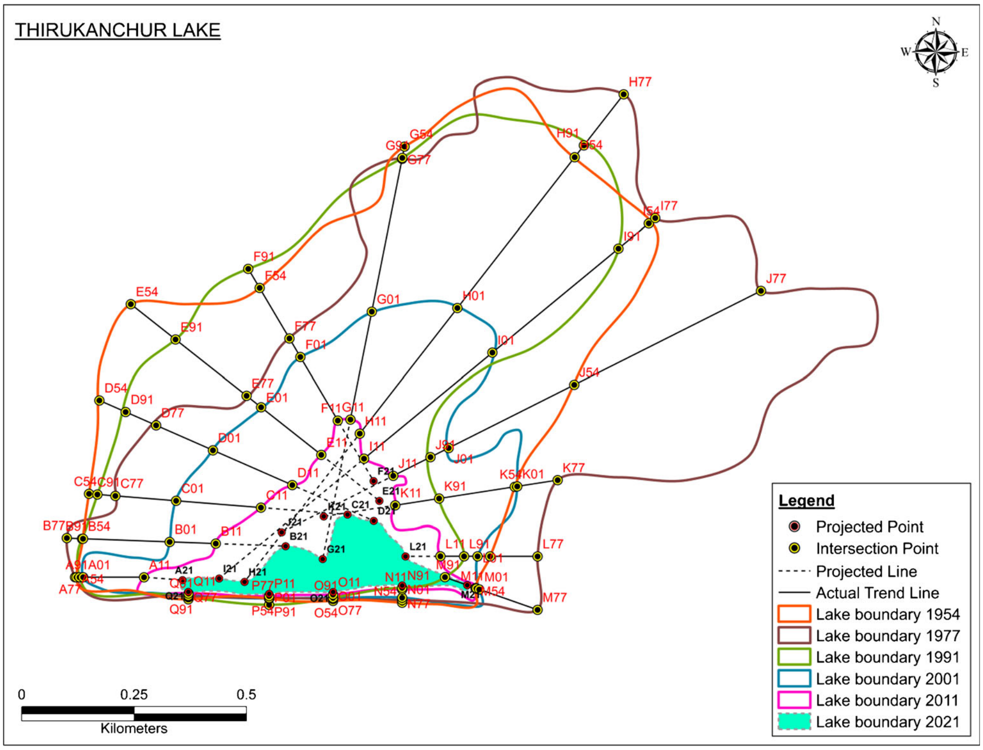
Topographical map of 1954 and multi-dated satellite images were collected to generate thematic databases to analyse the lake dynamics and its trend. Landsat MSS satellite image of 1977, TM image of 1991 and ETM+ image of 2001 and 2011 were collected from different sources to compare the lake boundary change during the study period. High-resolution QuickBird image and Resourcesat 1 LISS–III image of 2011 were also referred and used to study the spatial dynamics of the lake and to compare with the field collected information as ground truth. The sources of data and its details are given in Table 1.

GIS database generation and analysis

The GIS database is generated by the digitally processing satellite images followed by visual interpretation. The key elements of visual image interpretation are shape, size, pattern, tone and texture (Bhatta 2008). Lake boundary is easily identified from the satellite image on the basis of geometric form, spatial arrangement and relative brightness of the object in the image (Garg and Agarwal 2000). In the present study, the lake boundary maps for the five periods were prepared in ArcGIS platform as shown in the methodology and were consequently used to analyse the lake dynamics. The visual interpretation technique was adopted to extract qualitative and quantitative information from the image to study the morphological changes of lake. The simple digitization (vectorization) method is used to extract the lake boundary for multiple years by duly considering the ground control points from the spatial data and field observations. Lake status in 1954 was derived from published topographical map (Fig. 3a). The spatial lake status of 1977 was generated from MSS Landsat data (Fig. 3b). Similarly, the lake boundary status of 1991, 2001 and 2011 was also derived from Landsat TM, ETM$^+$, Resourcesat 1 LISS–III image and high-resolution QuickBird image, respectively (Fig. 3c–e).

The GIS-based overlay techniques are the method of superimposing the individual vector layer over each other to study the change and construct the overall suitability maps for each land use (Malczewski 2004). The GIS-based approaches of hand-drawn overlay techniques were used by American landscape architects in the late nineteenth and early twentieth century (Steinitz et al. 1976). In the present study, the GIS-based spatial data analysis, specifically digital overlay techniques, was used to study the lake area change detection for the period from 1954 to 2011. The shrinkage of lake area map was generated after superimposing the spatial layers of individual lake boundary of 1977, 1991, 2001 and 2011 using overlay analysis techniques (Fig. 4).

Fig. 5 Spatial prediction model



Mathematical prediction model

The mathematical prediction model was developed for predicting the future trend of lakes using present observation. The spatial model for lake was developed on the basis of coordinate geometry and linear regression method to predict the projected coordinates for showing the lake morphological change and trend in the future.

The spatial prediction model was applied to the Thirukanchur Lake to predict the spatial changes in future by comparing the morphological vector databases of 1954, 1977, 1991, 2001 and 2011. The linear lines were drawn with a specific interval on the GIS overlying map of selected lake, and it intersected the vector layers of multiple years covering the entire lake area. The intersection points were assigned by the individual point layers to get the coordinates of those points. The lake boundary was calculated for all successive years using Pythagorean formula.

To develop the spatial model, $A_{54}A_{11}$ was considered as a straight line which intersected A_{54} (lake boundary of 1954), A_{77} (lake boundary of 1977), A_{91} (lake boundary of 1991), A_{01} (lake boundary of 2001) and A_{11} (lake boundary of 2011) points (Fig. 5). The coordinates of all points assigned as $A_{54}(X_{A54},Y_{A54})$, $A_{77}(X_{A77},Y_{A77})$, $A_{91}(X_{A91},Y_{A91})$, $A_{01}(X_{A01},Y_{A01})$ and $A_{11}(X_{A11},Y_{A11})$, and the coordinate values were derived from point attribute table (Table 2). The lake boundary change (D_{A77}) during 1954–1977 along the straight line of $A_{54}A_{11}$ was computed with the help of A_{54} (X_{A54}, Y_{A54}) and A_{77} (X_{A77}, Y_{A77}) points using the following formula

$$D_{A77} = \pm\sqrt{(Y_{A77}-Y_{A54})^2 + (X_{A77}-X_{A54})^2} \tag{1}$$

Similarly, the lake boundary changes during 1977–1991, 1991–2001 and 2001–2011 were also computed with the help of (A_{77} and A_{91}), (A_{91} and A_{01}) and (A_{01} and A_{11}) points, respectively. In this purpose, the lake boundary of 1954 was considered as a base layer for all lines. If the lake boundary retreated from the previous year, the value was taken as negative (−) and vice versa. However, the lake boundary changes during the year 1954–1977, 1977–1991 and 1991–2011 are consequently calculated with the help of all respective selected points of different straight lines and summarized in Table 2 and also graphically shown in Fig. 6.

Now, lake boundary changes during 2011–2021 are predicted for all lines respectively, using linear regression methods on the basis of existing value (Eqs. 2 to 18), and summarized in Table 3. The following equations were generated from the proposed linear regression model for all selected lines.

For the line $A_{54}A_{21}$,

$$y = -1.683 \times \text{year} + 34.658 \tag{2}$$

Table 2 Selected points with respective coordinates and relevant changing distances between them

Location no.	Easting (m)	Northing (m)	Changing lake boundary (±m)
A_{54}–A_{11} line			
A_{54}	391332	1412090	0
A_{77}	391329	1412090	+3
A_{91}	391339	1412090	−10
A_{01}	391347	1412090	−8
A_{11}	391479	1412090	−132
B_{54}–B_{11} line			
B_{54}	391347	1412180	0
B_{77}	391311	1412180	+36
B_{91}	391344	1412180	−33
B_{01}	391535	1412170	−191.26
B_{11}	391635	1412170	−100
C_{54}–C_{11} line			
C_{54}	391360	1412280	0
C_{77}	391417	1412270	−57.87
C_{91}	391378	1412270	+39
C_{01}	391549	1412260	−171.29
C_{11}	391733	1412240	−185.08
D_{54}–D_{11} line			
D_{54}	391383	1412480	0
D_{77}	391506	1412430	−132.77
D_{91}	391440	1412460	+72.5
D_{01}	391630	1412370	−210.24
D_{11}	391802	1412290	−189
E_{54}–E_{11} line			
E_{54}	391452	1412700	0
E_{77}	391703	1412490	−327.26
E_{91}	391549	1412620	+201.53
E_{01}	391735	1412470	−238.95
E_{11}	391865	1412360	−170.22
F_{54}–F_{11} line			
F_{54}	391733	1412730	0
F_{77}	391797	1412620	−127.26
F_{91}	391708	1412770	+174.42
F_{01}	391820	1412580	−220.55
F_{11}	391901	1412440	−161.74
G_{54}–G_{11} line			
G_{54}	392048	1413040	0
G_{77}	392043	1413020	−20.62
G_{91}	392044	1413020	+1
G_{01}	391976	1412680	−346.73
G_{11}	391929	1412440	−244.56
H_{54}–H_{11} line			
H_{54}	392418	1413020	0
H_{77}	392525	1413160	−176.21
H_{91}	392438	1413040	+148.22
H_{01}	392162	1412680	−453.63

Table 2 (continued)

Location no.	Easting (m)	Northing (m)	Changing lake boundary (±m)
H_{11}	391949	1412410	−343.9
I_{54}–I_{11} line			
I_{54}	392579	1412870	0
I_{77}	392593	1412880	−17.2
I_{91}	392512	1412810	+107.06
I_{01}	392238	1412590	−351.39
I_{11}	391958	1412350	−368.78
J_{54}–J_{11} line			
J_{54}	392415	1412510	0
J_{77}	392822	1412720	+457.98
J_{91}	392102	1412350	−809.51
J_{01}	392142	1412370	−44.72
J_{11}	392021	1412310	−135.06
K_{54}–K_{11} line			
K_{54}	392285	1412290	0
K_{77}	392378	1412300	+93.54
K_{91}	392121	1412260	−260.09
K_{01}	392291	1412290	−172.3
K_{11}	392025	1412250	−268.99
L_{54}–L_{11} line			
L_{54}	392231	1412130	0
L_{77}	392334	1412130	+103
L_{91}	392174	1412130	−160
L_{01}	392204	1412130	−30
L_{11}	392123	1412140	−81.61
M_{54}–M_{11} line			
M_{54}	392199	1412060	0
M_{77}	392334	1412020	+140.8
M_{91}	392133	1412090	−212
M_{01}	392207	1412060	−79.8
M_{11}	392201	1412060	−6
N_{54}–N_{11} line			
N_{54}	392039	1412030	0
N_{77}	392039	1412040	−10
N_{91}	392040	1412070	+30.02
N_{01}	392039	1412040	−30.02
N_{11}	392040	1412060	−20.02
O_{54}–O_{11} line			
O_{54}	391889	1412040	0
O_{77}	391889	1412040	0
O_{91}	391889	1412040	0
O_{01}	391889	1412040	0
O_{11}	391889	1412050	−10
P_{54}–P_{11} line			
P_{54}	391750	1412040	0
P_{77}	391750	1412040	0
P_{91}	391750	1412030	+10
P_{01}	391750	1412040	−10
P_{11}	391750	1412050	−10
Q_{54}–Q_{11} line			
Q_{54}	391575	1412040	0
Q_{77}	391575	1412050	−10
Q_{91}	391575	1412050	0
Q_{01}	391575	1412050	0
Q_{11}	391575	1412050	0

For the line $B_{54}B_{21}$,

$$y = -2.784 \times \text{year} + 69.443 \tag{3}$$

For the line $C_{54}C_{21}$,

$$y = -3.130 \times \text{year} - 88.11 \tag{4}$$

For the line $D_{54}D_{21}$,

$$y = -2.981 \times \text{year} - 104.41 \tag{5}$$

For the line $E_{54}E_{21}$,

$$y = -1.731 \times \text{year} - 113.5 \tag{6}$$

For the line $F_{54}F_{21}$,

$$y = -2.517 \times \text{year} - 79.689 \tag{7}$$

For the line $G_{54}G_{21}$,

$$y = -5.431 \times \text{year} - 145.8 \tag{8}$$

For the line $H_{54}H_{21}$,

$$y = -8.710 \times \text{year} - 190.58 \tag{9}$$

For the line $I_{54}I_{21}$,

$$y = -7.604 \times \text{year} - 183.38 \tag{10}$$

For the line $J_{54}J_{21}$,

$$y = -5.388 \times \text{year} - 111.05 \tag{11}$$

For the line $K_{54}K_{21}$,

$$y = -3.067 \times \text{year} - 65.236 \tag{12}$$

For the line $L_{54}L_{21}$,

$$y = -1.628 \times \text{year} - 28.441 \tag{13}$$

For the line $M_{54}M_{21}$,

$$y = -0.652 \times \text{year} - 2.4129 \tag{14}$$

For the line $N_{54}N_{21}$,

$$y = -0.098 \times \text{year} - 6.2383 \tag{15}$$

For the line $O_{54}O_{21}$,

$$y = -0.069 \times \text{year} - 3.1948 \tag{16}$$

For the line $P_{54}P_{21}$,

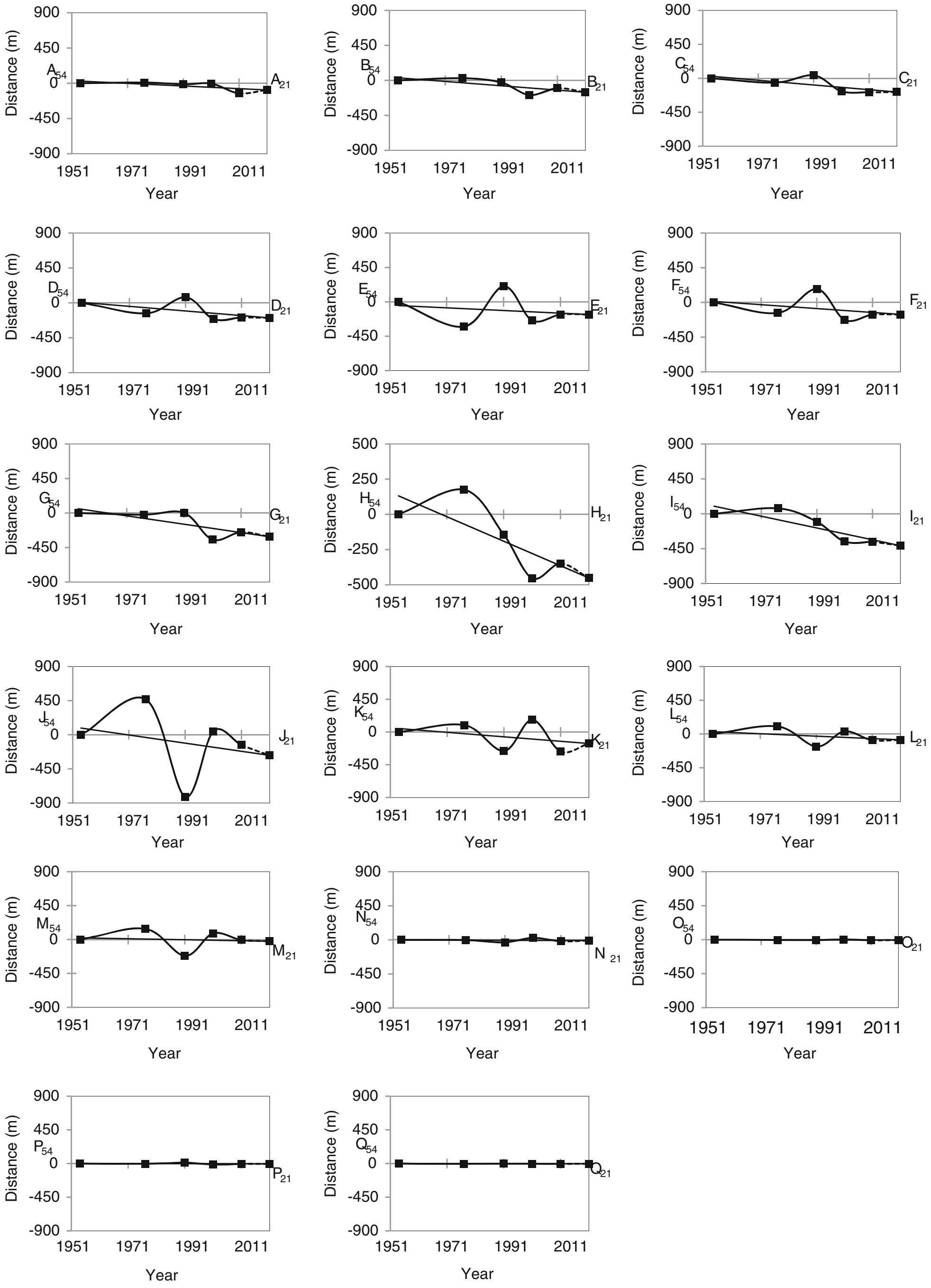
$$y = -0.103 \times \text{year} - 1.7235 \tag{17}$$

For the line $Q_{54}Q_{21}$,

$$y = -0.039 \times \text{year} - 2.2971 \tag{18}$$

Similarly, the projected coordinates for 2021 are derived for all individual lines and summarized in Table 3.

Fig. 6 Profile of trend line (*A*–*Q*) for 1954–2011



By considering $A_{21}(X_{A21},Y_{A21})$ point as a projected point of 2021 lake boundary along the extended straight line of $A_{54}A_{11}$, the lake boundary changes (D_{A21}) during 2011–2021 was calculated with the help of $A_{21}(X_{A21},Y_{A21})$ and $A_{11}(X_{A11},Y_{A11})$ points using the given formula as below

$$D_{A21} = \pm\sqrt{(Y_{A21}-Y_{A11})^2 + (X_{A21}-X_{A11})^2} \tag{19}$$

Now, the gradient (m_A) of the straight line $A_{54}A_{21}$ running between two points $A_{21}(X_{A21},Y_{A21})$ and $A_{54}(X_{A54},Y_{A54})$ is calculated using the following formula

$$m_A = \frac{Y_{A21}-Y_{A54}}{X_{A21}-X_{A54}} \tag{20}$$

The gradient between any points of a specific straight line will be the same. So, the gradient between another two points $A_{21}(X_{A21},Y_{A21})$ and $A_{11}(X_{A11},Y_{A11})$ of a same straight line $A_{54}A_{21}$ will be

$$m_A = \frac{Y_{A21}-Y_{A11}}{X_{A21}-X_{A11}} \tag{21}$$

Now, the equation of a straight line passing through three points $A_{54}(X_{A54},Y_{A54})$, $A_{11}(X_{A11},Y_{A11})$ and $A_{21}(X_{A21},Y_{A21})$ of a straight line $A_{54}A_{21}$ will be

$$\frac{Y_{A21}-Y_{A54}}{X_{A21}-X_{A54}} = \frac{Y_{A21}-Y_{A11}}{X_{A21}-X_{A11}} \tag{22}$$

The coordinate (X_{A21}, Y_{A21}) of A_{21} points along the straight line $A_{54}A_{21}$ is derived from above equations (Eq. (19) and (22)) to predict the lake boundary of 2021. In the same way, all the coordinates of projected points (B_{21}, C_{21}, D_{21}, E_{21}, F_{21},………Q_{21}) in the different selected straight lines of the lake boundary of 2021 are computed and listed in Table 3. Finally, the all projected points inserted on the map and predicted the lake boundary in 2021 by joining the points (Fig. 5).

Numerical prediction model was also developed by applying the least square linear regression method for validating the spatial model. The changing curve of the Thirukanchur lake area with respect to multiple year was plotted in the graph, and the linear trend line was fitted to estimate the future trend. The following new equation was developed from this model to predict the status of 2021 lake area (Eq. 23).

$$y = -0.0188 \times \text{year} + 0.6089 \tag{23}$$

Result and discussion

The spatial analysis of the multi-dated satellite data of the study area reveals that the significant changes occurred in the lake and its environment of the Kattankulathur block during 1954–2011. The GIS spatial overlay techniques were used to show the variation in lake morphology in the study area, and the statistical databases were generated in developing the model. The changes in the lake area are mainly due to the denudational and fluvial geomorphic processes leading to soil erosion in the catchment area. Further, it increases the rate of siltation in the lakes followed by eutrophication process. The anthropogenic activities are also inducing the lake area reduction. The consequences of cumulative effects are drastically reducing the lake area from 33.26 to 10.80 km^2 during 1954–2011.

Table 3 Estimation of changing lake boundary during 2011–2021and projected coordinates for generating vector lake boundary layer of 2021

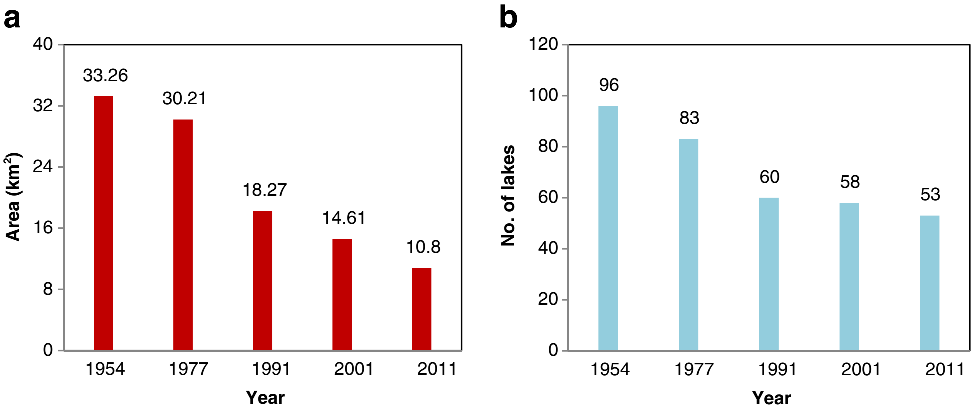
Projected location no.	Predicted changing lake boundary (2011–2021) (±m)	Projected coordinates for the points of 2021	
		Easting (m)	Northing (m)
A_{21}	−85.14	391562	1412084
B_{21}	−152.96	391787	1412159
C_{21}	−182.02	391921	1412228
D_{21}	−193.85	391978	1412214
E_{21}	−162.09	391991	1412258
F_{21}	−155.22	391978	1412302
G_{21}	−308.75	391867	1412130
H_{21}	−451.9	391697	1412080
I_{21}	−411.5	391642	1412088
J_{21}	−272.71	391778	1412190
K_{21}	−157.26	391870	1412224
L_{21}	−77.35	392047	1412135
M_{21}	−21.95	392181	1412071
N_{21}	−9.1	392040	1412071
O_{21}	+5.29	391889	1412057
P_{21}	−4.81	391750	1412053
Q_{21}	−3.48	391575	1412058

Spatial overlay analysis in GIS was adopted to understand and quantify the reduction of lake area by overlaying individual lake area of 1954, 1977, 1991, 2001 and 2011 (Fig. 4). The result shows that the lake area reduced in the site of Chengalpattu, Urapakkam, Kolathur and Gudalur. The

Table 4 Lake Status in Kttankulathur Block (1954–2011)

Year	Lakes area (km^2)	Lakes area (%)	No. of lakes
1954	33.26	9.42	96
1977	30.21	8.55	83
1991	18.27	5.17	60
2001	14.61	4.13	58
2011	10.8	3.05	53

Fig. 7 Status of lake during 1954–2011—a statistical review



maximum reduction was observed in Palur, Vembakkam, Kumizhi and Vandalur areas. The major lakes such as Kolavai Lake, Kayer Lake, Nandivaram Lake and Thirukanchur Lake were also showing a drastic change in the lake area, and spatial status is shown in Fig. 4.

The quantification of lake area for all the years is calculated and listed in Table 4. The analysis of the data shows an alarming rate of reduction in the lake area. In 1954, the lake area was 33.26 km^2 and it reduced to 30.21 km^2 in 1977. During 1977–1991 periods, the total lake area further reduced to 18.27 km^2. Similarly from 1991 to 2001, the total lake area decreased to 14.61 km^2. Also from 2001 to 2011, the total lake area also declined to 10.8 km^2, which was considerably higher than that in the previous two periods. The percentage of declination is also shown in the Table 4. Similarly, the number of lakes also reduced from 96 to 53 during the year 1954–2011 (Fig. 7, Table 4).

Area calculation is also done for major lakes in the study area and is shown in the Fig. 8 and Table 5. The lake area was continuously reduced from 1954 to 2011 due to the increasing rate of eutrophication and followed by the human encroachment. It is observed that during 1954–2011, Tirukanchur, Kayar and Nandivaram lake areas were reduced from 1.16, 0.83 and 1.28 km^2 to 0.12, 0.15 and 0.16 km^2, respectively. It is also observed that the areal change of Kolavai lake has very irregular pattern during the study period. The surface water resources in Kolavai Lake are controlled by the river systems and its tributaries in the catchment as well as rain water. The database shows that in 1954, it was 5.78 km^2 and it increased to 8.32 km^2 in 1977 due to severe flood in Tamil Nadu (De et al. 2005; Mulvany 2011). During 1977–1991, it is reduced to 3.71 km^2 due to deficit of rainfall and lack of river water supply. Similarly from 1991 to 2001, the lake area increased to 6.04 km^2 depending upon the availability of water in the river systems and its tributaries of Pennar Basin. Also from 2001 to 2011, the total lake area also reduced to 5.39 km^2 due to less water sources of stream water.

The field data was collected to compare the results of the model for validation. It is observed that many numbers of lakes were converted to other land-use type during the study period. The major reduction took place in various lakes namely Kolavai Lake, Thirukanchur Lake, Kayar Lake and Nandivaram Lake due to the increase in siltation, eutrophication process and conversion of lake area to other land use (Fig. 9). In recent years, the dynamic changes in many lakes were witnessed due to the combination of the impact of climatic change and human activities (Du et al. 2011; Gong et al. 2010; Trolle et al. 2011). The reduction of the water level due to natural cause leads to a more sensitive life of plant and animal in aquatic ecosystem (Fragoso et al. 2011). The soil erosion also can take place by surface runoff, different geomorphic agents such as wind and water, and different

Fig. 8 Shrinkage of major lake—a statistical review

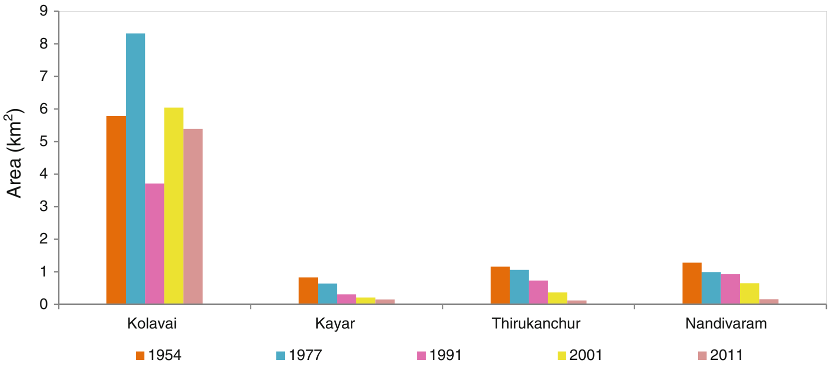


Table 5 Status of major lakes in Kattankulathur block (1954–2011)

Major Lakes	Area (km^2)				
	1954	1977	1991	2001	2011
Kolavai Lake	5.78	8.32	3.71	6.04	5.39
Kayar Lake	0.83	0.64	0.31	0.21	0.15
Thirukanchur Lake	1.16	1.06	0.73	0.37	0.12
Nandivaram Lake	1.28	0.99	0.93	0.65	0.16

geomorphic process such as weathering, denudation and fluvial action. The rapid soil erosion in the catchment area and abundant supply of nutrient into the lake leads to great siltation and reduction in depth of water.

The field observation data also show the massive urban expansion and industrial growth along with the increase in the rate of the exchange of polluted materials between land and surface water. Further, increasing amount of nutrients in aquatic environments accelerate the eutrophication process with an increase in algae growth. Also, it is observed that the lakes are highly influenced by the expansion of agricultural land, wasteland and rapid growth of human settlement in the lake environment. The lake morphological changes highly affect the quality of available freshwater resources (Huang et al. 2010; Klemas 2011). The maximum reduction in lake area was observed in Palur, Vembakkam, Kumizhi and Vandalur area due to urban expansion and industrial growth. Further anthropogenic activities have also stressed the lakes after dumping the waste materials inside or near the lakes. This phenomenon leads the reduction of water resources which creates a negative impact on increasing population growth.

The spatial prediction model was developed for Thirukanchur Lake and was validated by a numerical prediction model. The spatial model predicts that the lake area will be further reduced from 0.12 km^2 in 2011 to 0.045 km^2 in 2021 (Table 6, Fig. 10a). It was also estimated on the basis of statistical trend line analysis, and it shows that the area will be 0.044 km^2 in 2021 which almost coincides with spatial databases (Table 6, Fig. 10b). It can be also validated from the future satellite image and field observation data.

The available published data related to lakes, cloud free satellite and errorless data have been used to study the spatiotemporal changes of lakes. The selected satellite data sets were

Fig. 9 Field observation: **a** soil erosion in the catchment area, **b** siltation in the lake, **c** primary growth of aquatic plant in the lake environment (eutrophication process), **d** rapid growth of aquatic plant and aquatic scrub land, **e** land encroachment by anthropogenic activities (solid waste material in/near the lake) and **f** built-up new settlement in the lake environment

Table 6 Comparison between Spatial and numerical model

Selected lake for observation	Existing lake area (km^2)					Projected lake area	
	Spatial overlay analysis					Spatial model	Numerical model
	1954	1977	1991	2001	2011	2021	
Thirukanchur Lake	1.16	1.06	0.73	0.37	0.12	0.045 km^2/45000 m^2	0.044 km^2/44000 m^2

in between August to November month at least to avoid seasonal variation. In the proposed prediction model, the accuracy level can be increased by the use of least temporal resolution with fixed interval data. The seasonal variation of lake area study is also required to predict the future status of lake.

The concentration of lake water depends on the slope of the lake bottom. The water concentrates in the centre of the lake where the depression is more. The bottom slope can be changed due to high siltation in the lake leads to change the place of concentration of water. The irregular slope of the lake bottom divided the lakes into multiple patches. The field observation implies that the lake is also segregated from its original source by the anthropogenic activity. In this condition, the proposed model can be used with some modification of relevant parameters to predict lake dynamics. Even, it is also observed that the lake area is changing in irregular manner depending on the natural and anthropogenic parameters. For better accuracy in prediction can be achieved by decreasing the interval period of spatial database.

Conclusions

In the present study, remote sensing and GIS technique is used to extract information from available data to study the lake morphology. The quantitative databases depict the dynamic change of lake area in different periods. The lake dynamic study through geoinformatics clearly indicates that the lake area will be drastically reduced in the future, which can further accelerate the eutrophication process due to high nutrient contents in the lake. Consequently, aquatic environmental condition will be more vulnerable for the growth of aquatic flora and fauna which will directly affect the aquatic ecological environment. The field observation data also incorporated to study the topographic and anthropogenic impact on lake area change. It is observed that the main causes of lake area changes are due to soil erosion in the catchment area, increasing the rate of siltation followed by eutrophication process in the lakes and encroachment of lake water body by anthropogenic activities. The increasing build up land in the region significantly altered the natural landscape and resulted in the loss of natural vegetation, agricultural lands and water bodies. The proposed mathematical model predicts more vulnerable status of lakes in the future in the study area, and it can be concluded that if the same status continues, many numbers of lakes would further be disappeared within few decades. This phenomenon will also lead to the reduction of water resources which will further create an adverse effect on the hydrological cycle. However, it is important to conserve the lake and its aquatic environment to control the hydrological cycle and preserve fresh water in the lake by implementing lake restoration plan. The proposed prediction model can be applied to other lakes in the study area to predict the future status of lakes, and remedial measures can be taken before it disappears. It can be concluded that the geoinformatics-based spatial analysis and mathematical model can be best used to predict the dynamics of lakes and its future trend for restoration planning and management.

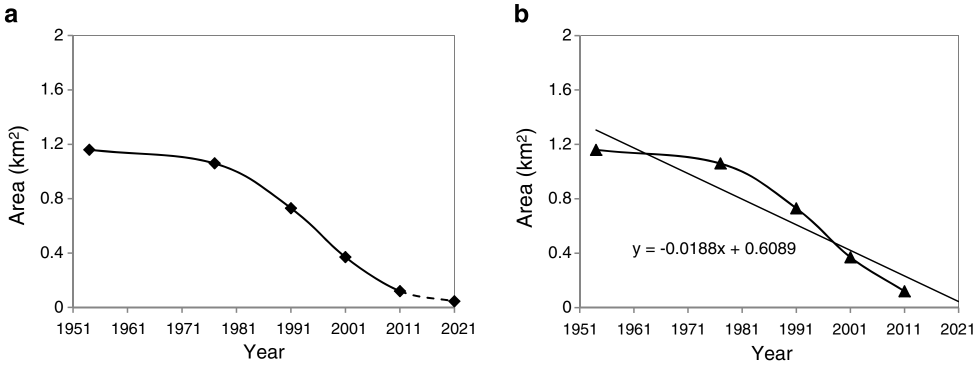


Fig. 10 **a** Graphical representation of spatial model. **b** Numerical prediction model

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