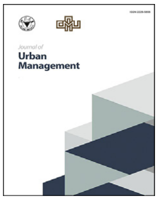
Journal of Urban Management 11 (2022) 310–320

Contents lists available at ScienceDirect

Journal of Urban Management

journal homepage: www.elsevier.com/locate/jum



Research Article

Quantification of green-blue ratios, impervious surface area and pace of urbanisation for sustainable management of urban lake – land zones in India -a case study from Bengaluru city

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A R T I C L E I N F O

Keywords:
Urban lakes
Urban sustainability
Green-blue ratio
Blue-built up area ratio
Green-built up area ratio
Impervious surface area

A B S T R A C T

Quantification of the ecosystem services of blue and green infrastructure in urban centres with the perspective of planning sustainable development is usually data-intensive, includes use of multi-platform datasets and adds to the complexities in deriving effective and reproducible metrics. The present study describes the creation of four simple metrics to estimate: 1. the ratio of 'green' vegetated areas to the 'blue' water spread areas, defined as the 'Green-blue ratio' (GBA); 2. The ratio of 'blue' water spread areas to 'built-up' ratio around the lakes, defined as the 'Blue to Built-up ratio' (BBA), 3. the percentage of impervious surface area (ISA) and 4. the pace of urbanisation in the dynamic zones (DZ) of urban lake environments. These new metrics were evaluated using landcover areas mapped from satellite imageries. Visual interpretation-based method was adopted to delineate the green, blue and built-up areas from Google Earth, which is suitable for wide range of users. The use of these metrics has been illustrated using available datasets for four representative lakes in Bengaluru city, India: Sankey tank, Ulsoor lake, Nagavarakere and Puttenahallikere. Significant spatio-temporal variations in the ratios of GBA and BBA as well as %ISA were observed and satisfactorily reflected the ecological status of these lakes in concurrence with earlier studies. Detailed analyses constrained a permissible rate of annual increase in the built-up area within the DZs to ~ 3% for sustainable development of the lakes. The present set of metrics can be recommended as useful tools for urban planners and citizen scientists for seasonal monitoring of urban lake environments.

1. Introduction

Impervious Surface Area (ISA) per person in India has been estimated to be about 76.7 m^2 and the nation has been classified as one with a high concentration of primary watersheds damaged by ISA, alongside several others including China, USA and Japan (Elvidge et al., 2007). Estimates of more than 3% watersheds, with 25–100% ISA, are found in parts of Karnataka, Tamil Nadu and Andhra Pradesh in South India. However, the need of the hour is to generate complete local and regional datasets on the ISA for such regions in India. e r. One of the key indicators of rapid urbanisation in a given region is the loss of water-spread regions and green coverage, which may be linked to the increased urban sprawl and a consequent increase in the impervious surfaces across the urban centres (e.g. Sudhira et al., 2007; Thippaiah, 2009, p. 118). From the previously reported studies, it is evident that growth of ISA is proportional to the reduction in the green spaces, which in turn affect the microclimatic characteristics of the watersheds (e.g. Zhu, Blum, Ferguson, Balke,

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https://doi.org/10.1016/j.jum.2022.03.001
Received 22 June 2020; Received in revised form 25 February 2021; Accepted 16 March 2022

& Bayer, 2011). It can also significantly add to the enhancement of the subsurface geothermal profile through the urban heat island effect (UHI; e.g. Bornstein, 1968).

Furthermore, in an urban environment, the increasing use of air coolers, air conditioners and inverters for achieving comfortable temperature limits can also trigger a finite increase in the local air temperature. Studies indicate ~1 °C rise in the urban atmospheric temperature in hot/dry cities due to the use of air conditioner during the night hours (Salamanca et al., 2014). Such atmospheric heating prompts more frequent use of the air conditioners, thereby increasing electricity demands irrespective of residential and commercial spaces (e.g. Hassid et al., 2000; Memon et al., 2008). Such interactions are quite complex and need closer investigations to ascertain the roles of lakes as blue-green infrastructure in regulating the UHI.

Further, urban lake ecosystems play a crucial role in maintaining the urban hydrological cycles as regulators of storm water drainage and preserving the ground water resources over long periods of time. As a result, lakes can serve as effective nature-based solutions (NBS) on their own, towards managing the unique blue-green infrastructures of urban landscapes (van den Bosch & Sang, 2017). Owing to the loss of the transitional green barrier zones surrounding urban lakes, the soil erosion increases and the direct discharge of grey-water and/or storm water into the waterbody is blocked or restricted. Subsequently, the ecological characteristics of lakes that are related to the run-off from storm events (Jarvie et al., 2008), are influenced as well, to a large extent.

Quantification of the nature and extent to which these ecosystem services are hindered due to the rise in the imperviousness are quite necessary to understand the ecological sensitivity and diversity of the lake-land interaction zones and the evolution of the urban land management scenarios across multiple temporal scales that are likely to impact end-uses. Hence the rate of urbanisation has the most profound effect in terms of increase in the imperviousness of the land surface (corresponding to a substantial reduction in the urban green cover), for which sustainable interventions are needed to preserve the local hydrological cycle. Subsequently, as the rate of surface evaporation increases, and the depth of the water column diminishes leading to long-term impacts on the overall ecosystem.

Local-level studies within dynamic zones (DZ) of interaction around the lakes of interest need to be undertaken to understand such transformations. A DZ is the immediate area surrounding the lakes where the lake-land interaction is found to be the most intensive under the influence of both natural as well as anthropogenic factors. Thus, it can serve as an accurate representation of the ecosystem services provided by lakes, based on the extent of internal and external forcings. The quantification of ISA at the local scale of a DZ is of pivotal importance to study the long-term urban sprawl and urban heat island characteristics (e.g. Sun et al., 2020, p. 102125). Recent studies have stressed upon the need for a basic set of simple and common environmental indicators to study the lakes (Servos et al., 2013), which impact the policy decisions for the urban infrastructure development. However, local data with adequate level of granularity is very scarcely available particularly for Indian urban lake ecosystems. Methodical identification of the ISA around the lakes in the city is quite important for practical implementation of the conservation and management techniques available in the literature so far, as well as, to design appropriate green spaces (e.g. Taylor and Hochuli, 2017).

Despite the availability of advanced technologies for synoptic coverage of land-use changes, the need for simple, yet robust indices which help to overcome the complexities of using multi-platform are essential for easy quantification of these changes. Models such as the Vegetation-Impervious surface-soil (VIS; Ridd, 1995) have shown the use of remotely-sensed datasets to study urban imperviousness at moderate resolutions (e,g. Ridd, 1995 for Salt Lake City, Utah, USA). However, many reports have highlighted the challenges in differentiating between the three biophysical parameters, which may be overcome by the use of advanced image processing techniques with/without spectral unmixing algorithms, such as Spectral mixture analysis (SMA; e.g. Phinn et al., 2002 for Brisbane), as well as, other advanced techniques for a variety of remotely-sensed datasets (e.g. Wu & Murray, 2003 for Columbus metropolitan area, USA). Recently, machine learning methods have been applied to pixel identification for differentiating urban vegetation and impervious surfaces (e.g. Walton, 2008). New indices, such as Normalised Difference Impervious Surface Index (NDISI), are data-driven decision-based advanced techniques which have been used for investigating the relationship between ISA with prominent urban microclimatic phenomenon, such as the heat island effect (e.g. Xu, 2010). Such studies are sparsely reported for Indian urban settings with lake environments.

Typically, all these methodologies involve complex geo-spatial and mathematical operations to derive the information, which may not be easy for urban managers and citizen scientists with less or no training in handling spatial datasets. Further, the access to suitable remotely-sensed imageries itself is a challenge especially for developing regions of the world, due to constraints on cost and availability. However, dynamic platforms such as Google Earth provide easy access to large number of spatio-temporal datasets at appropriate scales (high to medium resolutions), in the form of geo-referenced, rectified data. Due to the ease of operation, Google Earth can also be used as a functional mapping platform by urban analysts and/or managers with low software computing skillsets. Hence, use of such geospatial advancements in the urban planning would prove to be quite advantageous.

The present investigation extends this idea by generating simple metrics to provide a first-cut estimate of the 'state of imperviousness', aided by the data products available from the user-friendly Google Earth platform (on a public access mode). The present study is principally aimed at illustrating the use of simple and novel surface area ratios in assessment of the impact of rapid urbanization, using examples of four urban lake ecosystems in Bengaluru, India, whose ecology has been well reported for Indian conditions. The focus of the present study is towards classifying the lake DZs based on an index of their "blue-greenness", which would facilitate ease of monitoring any visible changes to the urban water spread area and the surrounding vegetative cover. The metrics are built on the assumption that the increase in the built-up area, accompanied by shrinkage in green cover, is directly linked to the increase in ISA within DZs. The usefulness of the derived metrics are validated using information from the ground survey for four urban lake ecosystems, located in Bengaluru city.

2. Methodology

2.1. Selection of study sites

For the present study, urban lakes system in Bengaluru city have been considered. The urban biodiversity of Bengaluru city is one of the best monitored in India; owing to the continued involvement of governmental, non-governmental and academic institutions over the past two decades (e.g. Ramachandra et al., 2017). Lakes and tanks that give rise to the unique cityscape, constitute a very significant part of the urban resources and are in the need of better administrative and managerial interventions in the modern era of rapid urban development (e.g. Unnikrishnan & Nagendra, 2015), as well as, unplanned urban beautification. Numerous scientific reports on the ecological and socio-economic aspects of the lake environments render ample usefulness towards monitoring the changing dynamics of the urban landscape over the years (e.g. Thippaiah, 2009, p. 118). However, there is still a wide scope to study the changes to the transitional zones around the lakes, the so-called ‘blue and green spaces’, as the indicators for the urbanisation and unsustainable development patterns of the city. Such investigations are pivotal to understand the importance of habitat characteristics of the urban flora and fauna, as proxies for hemerobiotic gradients in the anthropogenically-influenced environments (e.g. Battisti et al., 2017).

Numerous lakes situated within and around the Bengaluru city are mostly isolated holomictic systems that have uniform temperature and nutrient profiles, devoid of direct connections with any major rivers or channels. They had been created by the early settlers such as Kempegowda-I and the Wodeyar rulers, to function as inter-connected basins for rainwater harvesting during the monsoons (Thippaiah, 2016), and also to serve as large evaporative surfaces during summer. With the basins receiving mixed types of drainages from the different sources (e.g. direct precipitation, treated water, domestic grey water, storm water run-offs etc.), the relevance of the urban lakes turns out to be profound towards meeting the city's water quality targets. Studies of blue-green infrastructure development are thus quite relevant to Bengaluru city, which has slowly been transforming into a global metropolis. Considering the aforesaid contexts, the overall problem that needs to be addressed is the extent to which the blue-green infrastructure around Bengaluru lakes may be impacted by the changes in land uses that result in an increase in ISA. Thus, quantification of the blue, green and the built-up areas, as well as, the ISA using time-series datasets are quite essential.

A series of fact-finding missions starting from the 1985 Lakshman Rau Commission (Expert Committee report, 1986), followed by the 2006 A.T. Ramaswamy Commission (JLC report, 2006; JLC report, 2007; Interim report, 2007; 2011) etc. have identified the threats to the lake systems in Bangalore arising from the rapid urbanisation of the city (e.g. Deccan Herald report, 2018). However, the combined experiences from these studies need to be perceived and quantified in terms of the rapidly changing ISA.

Out of the four lakes in Bengaluru city selected for the present investigation (Fig. 1), two of them are located in the Northern part of the city (Sankey tank and Nagavarakere), another in the central part, which is also the oldest portion of the city (Ulsoor lake), and the last one is from a recently developed part of the city in the southern zone (Puttenahallikere, JP Nagar). The differences in the ecological profiles of these four lakes and their statuses in the present urban setting provide good cases to evaluate their relative contributions as

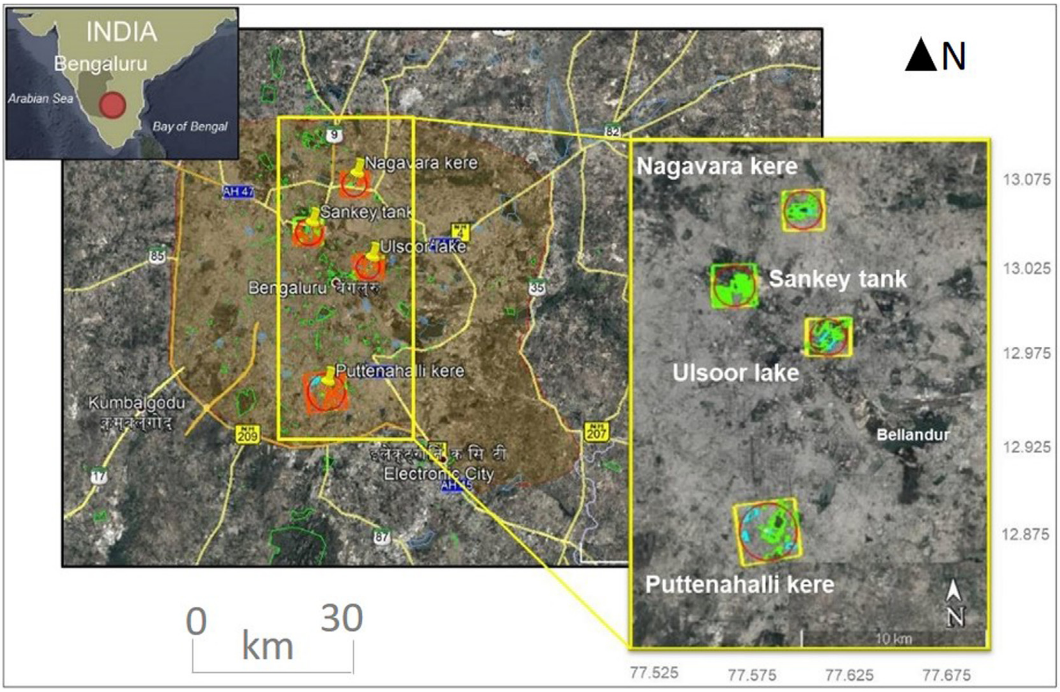

Fig. 1. Map showing the location of Bengaluru city and that of the four lake ecosystems investigated – Nagavarakere, Sankey tank, Ulsoor lake and Puttenahallikere.

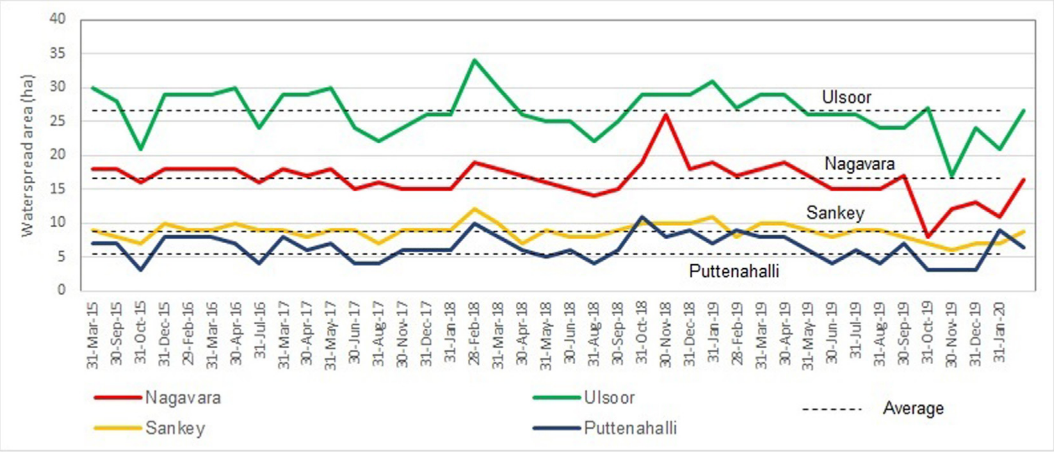

Fig. 2. Time series graph of water spread area using the data retrieved from the Water Body Information System at Bhuvan geoportal (https://bhuvan-wbis.nrsc.gov.in) for the four lakes Sankey, Nagavarakere, Ulsoor and Puttenahalli kere, Bengaluru city. The dashed lines represent the average water-spread area over the period March 2015 to January 2020.

drivers of blue-green infrastructure of the city. All of these lakes form the part of the old Kempegowda lake-chain model originally planned for multiple end-uses such as rainwater harvesting, fishing grounds and supply of water for domestic consumption, as well as, the irrigation of the lands (Thippaiah, 2016). However, the urban transformation and encroachments over the years rendered these lakes wholly or partially dysfunctional for the originally intended purposes (Thippaiah, 2009, p. 118; 2016) of irrigation and water storages interconnected through an efficient system of '*Rajakaluves*' or sub-surface canal systems which facilitated the exchange of water between the lakes in Bengaluru city (Rajeshuni et al., 2016).

Sankey tank, as well as, Ulsoor lake are situated in densely populated areas and both the lakes are significant in the context of environmental and cultural history of the respective regions; whereas, similar contexts of significance are not applicable to Nagavarakere and Puttenhallikere waterbodies. Being situated at a populated part of the city, surrounded by several high-rise building projects, as well as, the technology parks; the recent lease-out of the lake premises for development of a theme park on the shores of Nagavarakere is an additional end-use envisioned recently, which would likely place immense pressure on the natural eco-sustenance of the lake.

Similarly, Puttenahallikere is a lake that is situated in a recently urbanised and largely concretised environment with dense fringe population (PNLIT report, 2012). Hence, extended development along the shoreline of the lake is bound to affect the perviousness, which would subsequently affect the quality of the lake water. These chosen four lakes vary in terms of the water spread area, fringe vegetation cover and extents of built-up area, including densely concretisation in their immediate vicinity. Table 1 presents total built-up area, total green area and the percentage of impervious spaces around the lakes.

Evidently, the total vegetated area is the least for Puttenahallikere and the same is found to be the highest for Sankey tank. From Table 1, it is also evident that Ulsoor and Nagavarakere waterbodies witness large areas of built-up lands around them. The minor seasonal fluctuations observed indicate that the variations in the average water spread areas of four lakes over the past five-year period (i.e. March 2015 to January 2020) are negligible. Hence, in this study the values for the total 'blue' (water-spread) areas are assumed to remain unchanged for all the chosen lakes and constant values of blue areas are used in further calculations.

2.2. Estimation of the spatial extents of blue, green and built-up areas within dynamic zone (DZ)

In the present work, the '*dynamic zone*' around each lake is defined as the spatial extent of the lake shore area, with the lake at the centre, where, maximum diurnal, seasonal and annual changes due to human-lake interactions result in accelerated rate of urban growth; indicated by the loss in the green cover and substantial increase in the percentage of impermeable spaces. The extent of changes in the DZ are highly influenced by the presence of obstacles for natural storm water run-offs on the surface, as well as, for the ground water seepages in the subsurface. Within the DZ, features such as buildings, roads and influx of storm water and municipal sewage into the lakes, as well as, over land flow to adjacent aquatic systems pose challenges for the environmental quality of the urban lake systems.

Table 1
Total areas of blue, green and built-up regions around four lakes in Bengaluru – Sankey tank, Puttenahallikere, Nagavarakere and Ulsoor lake along with the extents of the dynamic zone (DZ).

Lake	Total blue (km^2)	Total built (km^2)	Total green (km^2)	Total area of DZ (km^2)
Sankey	0.15	2.85	2.99	5.99
Puttenahalli	0.07	8.63	1.44	10.14
Nagavara	0.38	3.48	0.74	4.61
Ulsoor	0.75	2.95	1.34	5.04

Based on the documented reports (Aithal & Ramachandra, 2015; Ramachandra & Mujumdar, 2009; Thippaiah, 2016), the DZ areas for the four lakes have been estimated as shown in Table 1.

The spatial extents of three essential parameters, viz. the water spread area, the extent of fringe vegetation cover and the extent of built-up area have been measured using available imageries from Google Earth. Upon selecting each DZ, measured from the centre of each lake, the following sub-zones are classified as: blue (water spread), green (vegetation cover) and yellow (built-up areas around these lakes) by digitisation of the respective extents and measuring the areas (Fig. 3).

The extents of coverage under each of these categories have been estimated by aggregating the areas of the fragments under each colour zone on the map, and the final value indicated the total area under each category as shown in Equation (1), for the annual data recorded over the different years. The classification of the 'blue', 'green', and 'built-up' areas was also verified through extensive ground-truth surveys during the period May 2018 to June 2019. The estimation of the areas under the above-mentioned categories are represented mathematically as follows:

$$\sum_{i,j=1}^{n,4} A = \sum_{i=1}^{x} B + \sum_{i=1}^{y} G + \sum_{i=1}^{z} C \tag{1}$$

where.

i = ranges from 1 to n, representing the number of observations,
j = ranges from 1 to 4 representing the chosen lake systems, respectively (as can be seen in Table 1),
A = total lake area within the DZ for the available 'n' number of datasets for each of the selected lake,
B = sum of areas for 'x' datasets of the water spread, within the DZ for each lake environment, as seen in Fig. 3,
G = sum of areas for 'y' datasets of the vegetation cover, within the DZ for each lake environment, as seen in Fig. 3,
C = sum of areas for 'z' datasets of the built-up zone, within the DZ for each lake environment, as seen in Fig. 3.

Logical reasoning based on field verification was used to classify the open spaces under 'green' or 'built-up' zone. In the context of the present study, if the open spaces around each lake system that are devoid of any adjacent vegetative cover are covered by the concretised

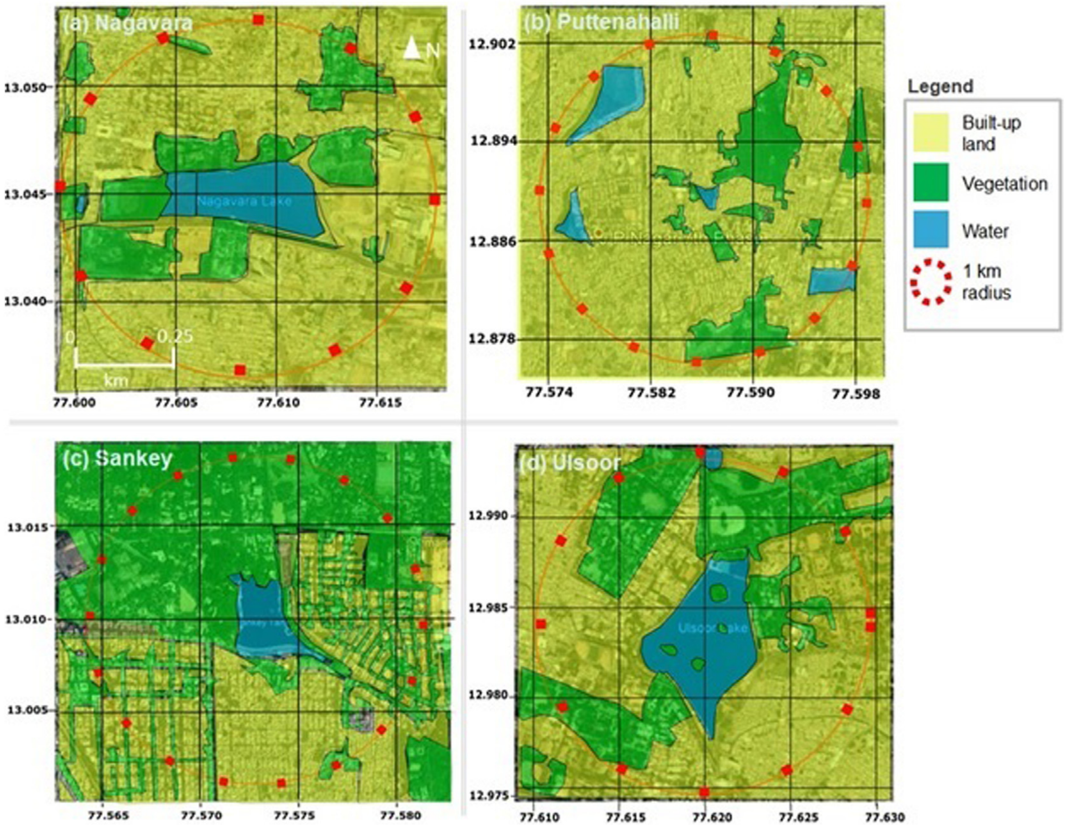

Fig. 3. Extents of water-spread area (Blue), vegetated lands (Green) and constructed lands (built-up area) in the DZs of the four lakes (a) Nagavarakere, (b) Puttenahallikere lake JP Nagar 6th Phase, (c) Sankey tank, and (d) Ulsoor lake during May 2018 to June 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

surfaces alone on all sides, they have been classified as 'built-up' since they would not be able to contribute significantly to subsurface seepage of rainwater. On the other hand, due to their likely ability to hold excess water, they might well contribute to the run-off of storm water. If the non-vegetated open spaces illustrate one or more active connections with either the water spread area or the surrounding vegetation, then they are categorised as 'green' fragments. In order to have a qualitative estimate of the lake environment, in terms of the defined categories of the landscapes, two novel qualitative indices, viz. Green Blue Ratio (GBR) and Blue to Built-up Area (BBA) ratio, are developed using the cumulative areas B, G and C (as defined in Equation (1)). The mathematical formulation for GBR is expressed as,

$$GBR = \frac{\sum_{i=1}^{y} G}{\sum_{i=1}^{x} B} \tag{2}$$

where, GBR represents the Green-blue ratio for each of the four lake systems; B and G bear the same meaning as in Equation (1). It is noteworthy that the reciprocal of GBR gives another useful metric Blue-green ratio (BGR) for all the four lake ecosystems. Further, the expression for BBA is written as,

$$BBA = \frac{\sum_{i=1}^{x} B}{\sum_{i=1}^{y} C} \tag{3}$$

where, BBA denotes Blue to built-up ratio for each of the four lake systems, B bears the and C bear the same meaning as in Equation (1). Green to built-up areas (GBA) can be obtained by multiplying the values of the two abovementioned metrics GBR and BBA, respectively.

The percentage of impervious spaces were calculated using Equation (4), from the data corresponding to the blue, green and built-up areas, as extracted from satellite imageries from Google Earth (Fig. 3).

$$I = \frac{\sum_{i=1}^{z} C}{\sum G + C} {*}100 \tag{4}$$

where, the percentage of impervious spaces within the DZ for each lake environment is represented by I; C and G bear the same meaning as in Equation (1).

Some important assumptions are as follows: (a) the built-up area devoid of vegetation around the lake represents the bulk of the impervious space for the present investigation; (b) In order to achieve an indicator of tolerable pace of urbanisation, a minimum acceptable value of GBA within the DZ around each lake is assumed. This critical value of GBA brings forth the highest tolerable value of the built-up area and it also furnishes the minimum acceptable value of the green cover.

Subsequently, the ratio of the minimum area of green cover to the maximum built-up area would help in deciding the future of urban planning, as well as, sustainable management of the blue-green infrastructure in the ecologically sensitive, fragmented urban lake environments. Furthermore, the critical value of GBA would also help in deciding the urban limit line (or urban growth boundary), as well as, in tracking the temporal modifications of the same (Web source: Urban Growth Boundaries; Greenbelt Alliance).

2.2.1. *Estimation of pace of urbanisation through green-to-built area ratio (GBA) for better land-use management*

Estimation of the rate of shrinkage of the green cover and the rate of increase in the built-up area in the dynamic or the sensitive ecological zones around the urban lakes is very important, as this would bring forth the changes in the values of GBA, indicating temporal changes in the acceleration of urban sprawl. For the estimation of the urban growth, it was assumed that blue areas for each candidate lake remains constant over a substantial period, as can also be seen in Fig. 2.

Let the green cover area and the built-up area within the DZ around an urban lake be G and BA km^2, respectively. Now, assuming a% reduction in the green cover and b% increase in the built-up area in total from the respective initial values, over a period of n years; the terminal values of the green cover and the built-up area turn out to be G(1-0.01*a) and BA(1 + 0.01*b) km^2, respectively. Let the yearly shrinkage rate of the green cover be r_a % and the rate of increase in the built-up area is r_b %. The following mathematical expressions can be used to calculate the values of the yearly rate of change,

$$\mathrm{G}(1 - 0.01{*}\mathrm{r_a})^{\mathrm{n}} = \mathrm{G}(1 - 0.01{*}\mathrm{a}) \tag{5}$$

$$\mathrm{BA}(1 + 0.01{*}\mathrm{r_b})^{\mathrm{n}} = \mathrm{BA}(1 + 0.01{*}\mathrm{b}) \tag{6}$$

In absence of any other competitive components, numerically r_a and r_b are of equal magnitude. Therefore, it can be written as,

$$\mathrm{r_a} = \mathrm{r_b} = \mathrm{r} \tag{7}$$

Now, in order to calculate the urban growth limit for a typical DZ, let us assume a critical minimum value of GBA as below,

$$\left(\frac{G}{BA}\right)_{min} = \left(\frac{G}{BA}\right)^{*} = k_1 \tag{8}$$

where, k_1 is chosen based on the temporal changes in the GBA values, i.e. the acceleration of the urbanization. In this study the value of k_1 is chosen to be 0.015. The choice of the representative value for the critical minimum GBA (k_1) is made upon looking at a very high urban fraction of ~0.98 in the densely built-up city centre of London (KCL site in central London) (Hertwig et al., 2020).

The present study pivots around the GBA values that have been derived from Google Earth images of the DZ maps available in 2018, and the GBA value calculated for each lake is essentially a constant. Therefore, the base value of GBA can be represented as,

$$\left(\frac{G}{BA}\right)_j^{2018} = Q_j (j = 1\text{to}4) \tag{9}$$

where, Q_j represent the constant values and index j represents the chosen lake systems as presented in Table 1.

From Equations (5)–(9), the expression relating the critical GBA with the base value of GBA can be formulated as below,

$$\left(\frac{G}{BA}\right)^* = \left(\frac{G}{BA}\right)_j^{2018} \left(\frac{1 - 0.01^*r}{1 + 0.01^*r}\right)^n \tag{10}$$

Upon calculating the yearly rate of change in the green and built-up areas from available urban land map data, the number of years (n) to reach the critical GBA can be estimated for each of the lakes as below,

$$n_j = \frac{\log_{10}\left(\frac{k_1}{Q_j}\right)}{\log_{10}\left(\frac{1-0.01^*r}{1+0.01^*r}\right)} (j = 1\text{to}4) \tag{11}$$

where, index j bears the same meaning as in Equation (9).

If the value of n is small, indicating that a particular DZ is dangerously close to the urban growth limit; then in order to estimate a sustainable pace of urban development, keeping mind the long-term urban planning, a larger value for the number of years needs to be considered. Considering the slowed down pace of urban growth through proper interventions, let the newly chosen number of years be n_1; before which the GBA value of a DZ of interest is not allowed to reach the critical level as defined by Equation (8).

The GBA values for the 2019 can be predicted from the following expression,

$$\left(\frac{G}{BA}\right)_j^{2019} = \left(\frac{G}{BA}\right)_j^{2018} \left(\frac{1 - 0.01^*r}{1 + 0.01^*r}\right) \tag{12}$$

Thereafter, the modified annual rate of increase in built-up area (or the shrinkage in green cover) (r_1) in each of the DZ can be calculated as below,

$$r_1 = \left(\frac{1 - k_3}{1 + k_3}\right) \tag{13}$$

where, $k_3 = \left(\frac{\left(G/_{BA}\right)^*}{\left(G/_{BA}\right)_j^{2019}}\right)^{1/n_1}$ and index j bears the same meaning as in Equation (9).

Fig. 4 depicts a conceptual flow diagram of data-driven framework summarising the data extraction, data interpretation and evaluation of the management strategies, based on the novel metrics suggested in this study.

3. Results and discussions

The defined metrics BBA, GBR and GBA, as well as, the percentage ISA for the four lake systems are discussed in detail in the following sections.

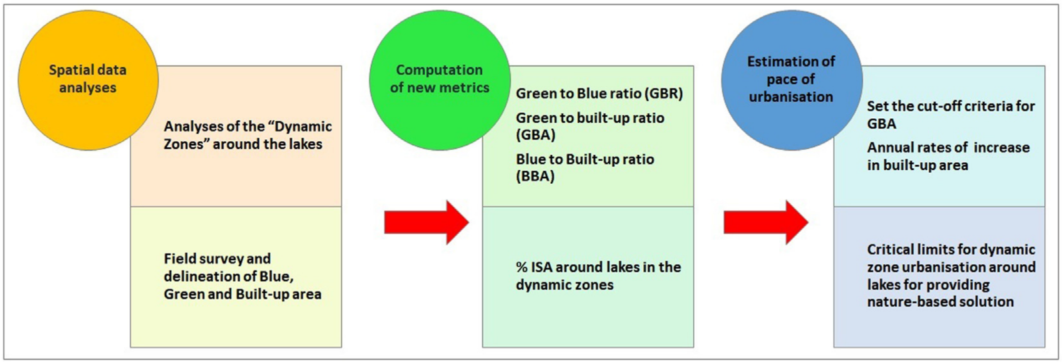

Fig. 4. Flowchart of data extraction, data interpretation and evaluation of the suggested metrics.

3.1. *Blue-green-built area ratios*

Fig. 3 depicts the expanse of the water (blue), vegetated lands (green) and built-up (built) areas within the DZ for each of the lakes, with the main water bodies being located approximately at the centre of the respective regions of interest. It is found that within the DZ around the representative lake systems, Sankey lake has the highest spread of vegetated land, whereas, Puttenahallikere has the least spread of vegetated land surrounding the main waterbody. Both Nagavarakere, as well as, Ulsoor have comparable stretches of vegetated lands, as well as, the built-up area as can be seen in Fig. 3. Corresponding to area estimates for the different zones as presented in Table 1, the percentage of impervious space for each of the lake systems is calculated using Equation (4). In the decreasing order of impervious space around the waterbody, the lake systems of interest can be arranged as: *Puttenhallikere* > *Nagavarakere* > *Ulsoor lake* > *Sankey lake*. Puttenahallikere having the highest percentage of impervious spaces (Fig. 5), is expected to have the lowest contribution towards the groundwater recharge potential, as reported and highlighted in a previous study by Ramachandra and Mujumdar (2009), in the context of Bengaluru city. Although the extents of built-up areas are comparable for Nagavarakere and Ulsoor lakes, the extent of green area around the Ulsoor lake is found to be almost double as compared to for the Nagavarakere (Table 1). Consequently, the percentage of the impervious space around the Nagavarakere is found to be quite higher than that in case of Ulsoor lake. Sankey lake has the least percentage of impervious space around it as compared to the other candidate lakes as can be concluded from Table 1, as well as, Fig. 5.

The insights achieved from the metrics suggested in this study estimates provide important implications for lake eco-sustainability management, when examined closely with respect to the land-uses as developing or developed thematic parks for commercial purposes, as described in previously reported prominent literature related to Nagavarakere by Unnikrishnan and Nagendra (2015). Table 2 shows the BGR calculated for the lakes. It is quite evident that Puttenahallikere has the lowest BBA ratio which illustrates that the lake water spread area is surrounded by a high percentage of constructed or built-up land and a low vegetation cover, which results in episodic volumes of high run-off into the lake, thereby impacting the water quality substantially (PNLIT report, 2012).

On the other hand, Sankey has the highest GBA ratio indicating a higher cover of vegetation surrounding the lake. Also, a low BBA ratio indicates that the area of the built-up land surrounding the lake is quite low. Both Nagavarakere and Ulsoor lake exhibit moderate BGR and GBA ratios, indicating that the area of constructed land is larger as compared to Sankey lake, but not to the extent observed in the vicinity of Puttenahallikere. Fig. 5 shows the ratios of blue areas (lakes and surface water bodies) to the green areas (vegetated soil), as well as, to the built-up surfaces (concretised surfaces and developed lands). It also exhibits the ratios of the green areas to the built-up surfaces (Table 2). As observed from Fig. 5, the BBA ratios are quite conservative as the extents of the concretised lake boundaries are well-defined. Therefore, these ratios can be good indicators of long-term as well as sudden, short-term changes in the water spread if computations are performed using Equation (3), on the monitored data recorded at regular intervals. GBA ratios indicate the relative amount of the green cover and provided a quick indication of pervious surfaces around these lakes. Along with the quantification of ISA, GBA ratios can be used to rapidly indicate the change in the ground perviousness in the critical zone around these lakes. This observation is discussed as follows.

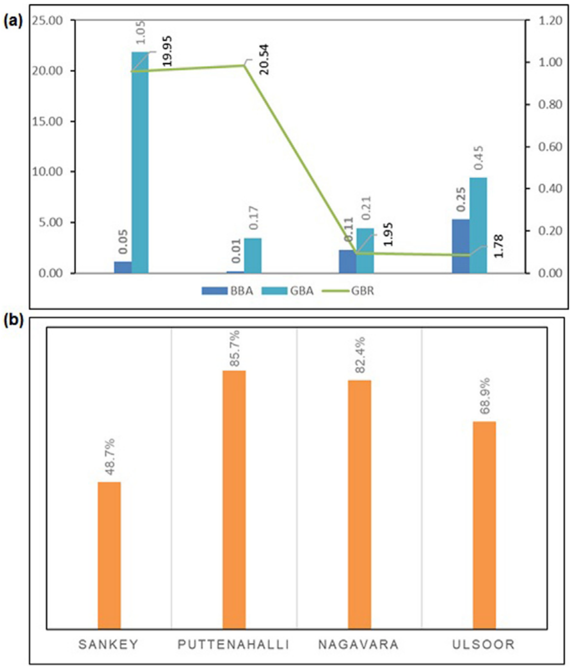

Fig. 5. (a) Ratios of green to blue area (GBR), blue to built area (BBA), green to built-area (GBA) and (b) percentage impervious area, estimated for four selected lakes in Bengaluru city – Nagavarakere, Puttenahallikere, Sankey tank and Ulsoor lake. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Ratios of Blue-Green (BGR), Blue-Built-up Area (BBA), Green-Blue (GBR) and Green-Built Area (GBA) calculated for four lakes – Nagavarakere, Puttenahallikere, Sankey tank and Ulsoor lake.

Ratios	Sankey	Puttenahalli	Nagavara	Ulsoor
BGR	0.05	0.05	0.51	0.56
BBA	0.05	0.01	0.11	0.25
GBR	19.95	20.54	1.95	1.78
GBA	1.05	0.17	0.21	0.45

Sankey tank has the least BBA as well as GBA amongst all the four lakes. High BGR and low GBA ratios indicate that the water body is surrounded by a lesser area of vegetated land, and a greater expanse of built-up area, which can increase the probability of higher surface run-off into the lakes during the months of precipitation. On the other hand, a high GBR accompanied by a high GBA value indicates a higher probability for infiltration of the surface run-off into the subsurface aquifers, since the vegetated spaces in DZs can provide permeable surfaces that can absorb the excess rainwater (Ramachandra & Mujumdar, 2009). Based on these ratios, Puttenahallikere lake is found to be quite susceptible to higher surface run-off events as compared to the other lakes, especially during the monsoon. Sankey tank, on the other hand, is found to exhibit the least susceptibility to run-off events, given the higher extent of vegetated areas surrounding the lake. From the values of the above-mentioned metrics, both Nagavarakere and Ulsoor lake are expected to exhibit moderate susceptibility to surface run-off.

From the foregoing discussion, it is evident that the percentage of ISA around the central waterbody of a lake system presents many challenges for sustainable urban development of Bengaluru. Accelerated urban sprawl and the subsequent developmental activities around the waterbodies increase the amount of paved surface around urban lake systems, which in turn causes the run-off water to carry excess amount of pollutants into the lakes. Additionally, as the natural boundaries become more impervious, it hinders the interaction between the lake waterbody and the immediate surrounding landscape. Consequently, the stagnation of the lake water system results in deterioration of the quality of the associated ecosystem. Owing to this degradation, important lake services, such the fisheries and the recreational, as well as, the social activities are hindered. Increase in the built-up area (yellow coloured region in Fig. 3) and decrease in the vegetation result in sudden and significant rise in the ambient temperature of the air (Bornstein, 1968).

3.2. *Evaluation of pace of urbanisation, and sustainable urban growth rate for the DZs of the selected lakes*

From a recent study conducted in the Greater Bengaluru region, it was found that the built-up area has increased by about 125% between 2010 and 2014 (Aithal & Ramachandra, 2015). During the same period the green cover was found to decrease by a high margin of ~62%. Using Equations (5) and (6) and $n = 4$, the annual rate of increase in built-up area (or the shrinkage in green cover) is calculated to be $r = 22.5\%$. Using the GBA values evaluated for 2018 from the satellite images and the abovementioned annual rate of change, GBA values have been predicted for 5 consecutive years (2019–2023) for the selected four lakes. Table 3 presents the GBA values, and for all the lakes the GBA is found to decrease substantially with the passage of each year, indicating continuous urban growth at the cost of reduced green belts.

Now, assuming the aforesaid annual urban growth rate of 22.5%, the number of years required for reaching the critical GBA value of 0.015 will be different for the four different DZs considered, as the present level of Blue, Green and the Built-up Areas are distinctly different in all the cases. The time required to reach the critical GBA (urban growth limit) from the levels recorded in 2018 is calculated for each lake ecosystem using Equation (11) and the values are presented in Table 4. It is evident that DZ around Puttenahalli lake is witnessing the fastest growth in the built-up spaces and at the present rate of urban growth it is left with shortest time (~5.27 years) before reaching the critical limit. On the other hand, the vicinity of the Sankey tank is witnessing a pace of urbanization which would cause the DZ to reach the critical urban growth limit by approximately 9.29 years.

In order to have a long term sustainable urban growth, it is essential to have a reasonably slow pace of shrinkage of the urban green cover and the growth in the built-up spaces needs to be less aggressive. For the demonstration of the usefulness of the developed metrics in guiding the long-term planning of urbanization, a representative long-term period of 30 years has been chosen. Using $n_1 = 30$, as well as, the GBA values predicted for 2019 (ref. Tables 2 and 3) in Equation (13), the modified annual rate of increase in built-up area (or the shrinkage in green cover) (r_1) for each of the DZs is calculated.

The DZs around Puttenahallikere and Nagavarakere are found to be very sensitive towards the pace of urbanization. From Table 4 it is found that the permissible annual urban growth rates are 3.24% and 3.66%, for the DZs in the vicinity of Puttenahallikere and Nagavarakere, respectively; for delaying the attainment of the critical urban growth limit by 30 years from the period starting at the end

Table 3

Predicted GBA values for 2019–2023 based on 2018 land maps and annual urban growth rate of $r = 22.5\%$.

Lake	2018 Total green (km^2)	2018 Total built (km^2)	GBA values evaluated from the 2018 map	1st year	2nd year	3rd year	4th year	5th year
				2019	2020	2021	2022	2023
Sankey	3.0	2.8	1.051	0.665	0.421	0.266	0.168	0.107
Puttenahallikere	1.4	8.6	0.167	0.105	0.067	0.042	0.027	0.017
Nagavarakere	0.7	3.5	0.213	0.135	0.085	0.054	0.034	0.022
Ulsoor	1.3	3.0	0.452	0.286	0.181	0.114	0.072	0.046

Table 4
Time required from 2018 (in years), for reaching GBA = 0.015 at r = 22.5% per year and revised urban growth rates for reaching GBA = 0.015 in 30 years.

Lake ecosystem	GBA values evaluated from 2018 maps	Time required from 2018, for reaching GBA = 0.015 (in years) at r = 22.5% per year	Annual Urban Growth Rate for reaching GBA = 0.015 in n_1 = 30 years (in %)
Sankey	1.051	9.29	6.31
Puttenahallikere	0.167	5.27	3.24
Nagavarakere	0.213	5.80	3.66
Ulsoor	0.452	7.45	4.91

of 2019. Although, a little higher rate of urbanization is found to be acceptable for the DZs surrounding Sankey tank (6.31%) and the Ulsoor lake (4.91%); however, the conservative estimate for the annual rate of urban growth for long-term sustainable urban development is found to be ~3%, for the assumed level of critical limit (GBA = 0.015).

4. Conclusions

The present investigation illustrated the use of a set of simple, visual interpretation-based novel metrics to relate the surface areas of water-spread, vegetation and built-up lands with the percentages of impervious surfaces surrounding four urban lakes in India (Bengaluru city). Quantification using the developed metric revealed that the impervious surfaces around these lakes range between 48.3 and 85.1% indicating less potential for groundwater recharge within DZ around central waterbody in each lake system. It is also quite evident from the ratios of blue to green area, that these lakes are susceptible to higher surface run-offs that can drastically affect the water quality. Because of the increase in ISA, the absence of wetlands surrounding the lakes has led to the reduction in the capacity of the land to absorb the excess green water. Calculations indicate that the DZ around the Puttenahallikere and Nagavarakere are very sensitive to the urban growth, and the temporal changes in GBA values signify that the annual rate of increase in the built-up areas must not exceed 3% for long-term sustainable urban development.

The present investigation provided an easy and novel technique for quantifying the changes to the lake ecosystems in terms of the changes in the value of GBA (Green-to-built up area ratio), within the DZs around the lakes, which corresponds to the critical region of human-environment interaction. These regions, which experience the maximum impacts for both the humans and the lake ecosystems, need to be sustainably engineered, while preserving the green cover; so that the ecosystem services and blue-green infrastructure of the surrounding areas can be enhanced.

The quantification of the percentages of the impervious surfaces provided an easy way to assess the impact of concretisation activities in close vicinity of the lakes. The useful indices presented in this study can facilitate rapid assessment of the statuses of the selected lakes, using accessible technology such as the Google Earth imageries, especially for city planners. The metrics described here can be extended to study the blue-green infrastructure around any urban lake situated within the premises of densely populated cities and towns of any developing country, facilitating a rapid assessment of the state of imperviousness and rate of urbanisation.

The most important conclusions emerging from the present investigation for formulating strong lake-shore development policies for urban lakes, especially for developing countries, are:

- Long-term monitoring of the blue, green and built-up urban lakes at variable spatial resolutions are essential for regulating the urban development around the ecosystems.
- The percentage imperviousness and pace of urbanisation of lake shore must be important factors incorporated in the land-use planning.
- If the metrics established in this work can be extended and standardized for other similar urban lake systems, then considerably better management of DZs can be achieved through a decreased pace of urban growth, while maintaining a reasonable vegetative cover (for example, GBA >0.03).

Such metrics can also aid in understanding the variation of urban ambient temperature with respect to the loss of vegetation around the water-spread area, thereby serving as a futuristic guideline towards the expansion in built infrastructure in a sustainable human habitat, keeping in mind the possible occurrence of UHI effects. Our investigation contributes to the global database of local-level case studies on assessing urbanisation in dense cities such as Bengaluru, which contribute to the understanding of sustainable urban development.

Declaration of competing interest

No conflict of interest.

Acknowledgement

HS is thankful to environmentalists Ms. Surbhi Sharma and Dr. Pranab Patar at Earthwatch Institute India; Ms. Usha Rajagopalan, Ms. Divya Shetty, Ms. Nupur Jain and Ms. Susheela at the Puttenahalli Neighbourhood Lake Improvement Trust (PNLIT) for many useful discussions on urban lake environments which had inspired this investigation. HS thanks Prof. Sudhakar Rao and Prof. Monto Mani, Centre for Sustainable Technologies (CST), Indian Institute of Science (IISc) Bangalore for sharing their insights on lake water quality and blue green infrastructure development. HS is also thankful to Dr. Lepakshi Raju, Postdoctoral fellow, CST, IISc Bangalore for many interesting discussions on the roles of advanced building materials and construction processes with respect to urban lakes. HS is thankful to Ms. Soundaryavalli Madhugiri and Dr. Surendar Varma, ANCF, Bangalore for sharing their unique perspectives on lake ecosystems. The temporal and spatial satellite imageries accessed through the Google Earth application in publicly accessible mode as well as the spatial mapping functions performed using the same are gratefully acknowledged. The data used to study the water spread areas for the four lakes retrieved from the public datasets through the Water Body Information System (WBIS) of Bhuvan geoportal is gratefully acknowledged.

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