Conservation of wetlands to mitigate urban floods

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Abstract

Floods in an urbanised landscape refer to the partial or complete inundation from the rapid accumulation or run-off resulting in the damage to property and loss of biotic elements (including humans). Urban flooding is a consequence of increased impermeable catchments resulting in higher catchment yield in a shorter duration and flood peaks sometimes reach up to three times. Thus, flooding occurs quickly due to faster flow times (in a matter of minutes). Causal factors include combinations of loss of pervious area in urbanising landscapes, inadequate drainage systems, blockade due to indiscriminate disposal of solid waste and building debris, encroachment of storm water drains, housing in floodplains and natural drainage and loss of natural flood-storages sites. Flood mitigation in urban landscape entails integrated ecological approaches combining the watershed land-use planning with the regional development planning. This includes engineering measures and flood preparedness with the understanding of ecological and hydrological functions of the landscape.

Bangalore is experiencing unprecedented urbanisation and sprawl in recent times due to concentrated developmental activities with impetus on industrialisation for the economic development of the region. This concentrated growth has resulted in the increase in population and consequent pressure on infrastructure, natural resources and ultimately giving rise to a plethora of serious challenges such as climate change, enhanced green-house gases emissions, lack of appropriate infrastructure, traffic congestion, and lack of basic amenities (electricity, water, and sanitation) in many localities, etc. This study shows

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that there has been a growth of 632% in urban areas of Greater Bangalore across 38 years (1973 to 2010). Urban heat island phenomenon is evident from large number of localities with higher local temperatures. The study unravels the pattern of growth in Greater Bangalore and its implication on local climate (an increase of ~2 to 2.5 °C during the last decade) and also on the natural resources (76% decline in vegetation cover and 79% decline in water bodies), necessitating appropriate strategies for the sustainable management. The study reveals that frequent flooding (since 2000, even during normal rainfall) in Bangalore is a consequence of the increase in impervious area with the high-density urban development in the catchment and loss of wetlands and vegetation. This is coupled with lack of drainage upgrade works with the changes in enhanced run-offs, the encroachment and filling in the floodplain on the waterways, obstruction by the sewer pipes and manholes and relevant structures, deposits of building materials and solid wastes with subsequent blockage of the system and also flow restrictions from under capacity road crossings (bridge and culverts). The lack of planning and enforcement has resulted in significant narrowing of the waterways and filling in of the floodplain by illegal developments.

Keywords: Urban Floods, Wetlands, Heat Island, Mitigation, Remote Sensing, Gradient Analysis

Introduction

Wetlands constitute vital components of the regional hydrological cycle. They are highly productive, support exceptionally large biological diversity, and provide a wide range of ecosystem services such as food, fibre, waste assimilation, water purification, flood mitigation, erosion control, groundwater recharge, microclimate regulation, enhance the aesthetics of the landscape, and support many significant recreational, social and cultural activities, aside from being a part of our cultural heritage. It was acknowledged that most urban wetlands are seriously threatened by conversion to non-wetland purposes, encroachment of drainage through landfilling, pollution (discharge of domestic and industrial effluents, disposal of solid wastes), hydrological alterations (water withdrawal and inflow changes), and over-exploitation of their natural resources. This results in loss of biodiversity and disruption in goods and services provided by wetlands (Ramachandra, 2009). Last section of this communication addresses the strategies considering the current trends in aquatic ecosystem conservation, restoration, and management including the hydrological and the biophysical aspects, peoples' participation and the role of non-governmental, educational, and governmental organisations and future research needs for the restoration, conservation, and management.

Urbanisation is a form of metropolitan growth that is a response to often-bewildering sets of economic, social, and political forces and to the physical geography of an area. It is the increase in the population of cities in proportion to the region's rural population. The 20th century is witnessing "the rapid urbanisation of the world's population", as the global proportion of urban population rose dramatically from 13% (220 million) in 1900, to 29% (732 million) in 1950, to 49% (3.2 billion) in 2005 and is projected to rise to 60% (4.9 billion) by 2030 (UN, 2005). Urban ecosystems are the consequence of the intrinsic nature of humans as social beings to live together (Sudhira *et al.*, 2003; Ramachandra and Kumar, 2008). The process of urbanisation contributed by infrastructure initiatives, consequent population growth and migration results in the growth of villages into towns, towns into cities and cities into metros. Urbanisation and urban sprawl have posed serious challenges to the decision makers in the city planning and management process involving plethora of issues like infrastructure development, traffic congestion, and basic amenities (electricity, water, and sanitation), etc. (Kulkarni and Ramachandra, 2006). Apart from this, major implications of urbanisation are:

- **Loss of wetlands and green spaces:** Urbanisation has telling influences on the natural resources such as decline in green spaces (vegetation) including wetlands and / or depleting groundwater table.
- **Floods:** Common consequences of urban development are increased peak discharge and an increased frequency of floods as land that was converted from fields or woodlands to roads and parking lots loses its ability to absorb rainfall. Conversion of water bodies to residential layouts has compounded the problem by removing the interconnectivities in an undulating terrain. Encroachment of natural drains, alteration of topography involving the construction of high-rise buildings, removal of vegetative cover, reclamation of wetlands are the prime reasons for frequent flooding even during normal rainfall post 2000.
- **Decline in groundwater table:** Studies reveal the removal of water bodies has led to the decline in water table. Water table has declined to 300 m from 28 m over a period of 20 years after the reclamation of lake with its catchment for commercial activities. In addition, groundwater table in intensely urbanized area such as Whitefield, etc. has now dropped to 400 to 500m.
- **Heat island:** Surface and atmospheric temperatures are increased by anthropogenic heat discharge due to energy consumption, increased land surface coverage by artificial

materials having high heat capacities and conductivities, and the associated decreases in vegetation and water pervious surfaces, which reduce surface temperature through evapotranspiration.

- **Increased carbon footprint**: Due to the adoption of inappropriate building architecture, the consumption of electricity has increased in certain corporation wards drastically. The building design conducive to tropical climate would have reduced the dependence on electricity. Higher energy consumption, enhanced pollution levels due to the increase of private vehicles, traffic bottlenecks have contributed to carbon emissions significantly. Apart from these, mismanagement of solid and liquid wastes has aggravated the situation.

Unplanned urbanisation has drastically altered the drainage characteristics of natural catchments, or drainage areas, by increasing the volume and rate of surface runoff. Drainage systems are unable to cope with the increased volume of water, and are often blocked due to indiscriminate disposal of solid wastes. Encroachment of wetlands, floodplains, etc. obstructs flood-ways causing loss of natural flood storage.

Studies on the phenomenon of Urban Heat Island (UHI) using satellite-derived Land Surface Temperature (LST) measurements have been conducted using various satellite data products acquired in thermal region of the electromagnetic spectrum. Currently available satellite thermal infrared sensors provide different spatial resolution and temporal coverage data, which can be used to estimate LST. The Geostationary Operational Environmental Satellite (GOES) has a 4-km resolution in the thermal infrared, while the NOAA-Advanced Very High Resolution Radiometer (AVHRR) and the Terra and Aqua-MODIS have 1-km spatial resolutions. Significantly, high-resolution data come from the Terra-Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), which has a 90-m pixel resolution, the Landsat-5 Thematic Mapper (TM), which has a 120-m resolution, and Landsat-7 Enhanced Thematic Mapper (ETM) that has a 60-m resolution. However, these instruments have a repeat cycle of 16 days (Li *et. al.,* 2004; Ramachandra and Uttam Kumar, 2009). Weng (2001, 2003) examined LST pattern and its relationship with land cover (LC) in Guangzhou and in the urban clusters in the Zhujiang Delta, China. Nikolakopopulos *et al.*, (2003) have used Landsat-5 TM and Landsat-7 ETM+ data for creating the temperature profile of Alfios River Basin. Stathopoulou and Cartalis (2007) have used Landsat ETM+ data to identify daytime urban heat island using Corine LC data for major cities in Greece. Using a Landsat ETM+ imagery of City of Indianapolis, IN, USA, Weng *et al.,* (2004) examined the surface temperature UHI in the city. They derived the LST, analysed their spatial variations using Landsat ETM+ thermal measurements with the urban vegetation abundance, and investigated their relationship. UHI studies have traditionally been conducted for isolated locations and with in situ measurements of air temperatures. The advent of satellite remote sensing technology has made it possible to study UHI both remotely and on continental or global scales (Streutker, 2002). In this work, Landsat data of 1973 (of 79 m spatial resolution), 1992 and 2000 (30 m), IRS LISS-III data of 1999 and 2006 (23.5 m) and MODIS data of 2002 and 2007 (with 250 m to 500 m spatial resolution) are used with supervised pattern classifiers based on maximum likelihood (ML) estimation. In addition, attempts to map land surface temperatures across various LC types were made in order to understand heat island effect.

Study Area

Greater Bangalore (77°37'19.54" E and 12°59'09.76" N), is the principal administrative, cultural, commercial, industrial, and knowledge capital of the state of Karnataka. With an area of 741 sq. km., Bangalore's city administrative jurisdiction was widened in 2006 by merging the existing area of Bangalore city spatial limits with 8 neighbouring Urban Local Bodies (ULBs), and 111 Villages of Bangalore Urban District (Ramachandra and Kumar, 2008; Sudhira *et al.*, 2007). Thus, Bangalore has grown spatially more than ten times since 1949 (69 square kilometres) and is a part of both the Bangalore urban and rural districts (figure 1.1). The mean annual total rainfall is about 880 mm with about 60 rainy days a year over the last ten years. The summer temperature ranges from 18° C – 38° C, while the winter temperature ranges from 12° C – 25° C. Thus, Bangalore enjoys a salubrious climate all-round the year. Bangalore is located at an altitude of 920 meters above mean sea level, delineating three watersheds, viz. Hebbal, Koramangala-Challaghatta and Vrishabhavathi watersheds (Figure 1.2). The undulating terrain in the region has facilitated creation of a large number of tanks providing for the traditional uses of irrigation, drinking, fishing, and washing. Bangalore had the distinction of having hundreds of water bodies through the centuries. Even in early second half of 20th century, in 1961, the number of lakes and tanks in the city stood at 262 (and spatial extent of Bangalore was 112 sq. km). However, number of lakes and tanks in 1985 was 81 (and spatial extent of Bangalore was 161 sq. km). This forms important drainage courses for the interconnected lake system (Figure 1.2), which carries storm water beyond the city limits. Bangalore, being a part of peninsular India, had the tradition of harvesting water through surface water bodies to meet the domestic water requirements in a decentralised way. After independence, the source of water for domestic and industrial purpose in Bangalore is mainly from the Cauvery River and ground water. Untreated sewage is let into the storm water drains, which progressively converge at the water bodies. Now, Bangalore is the fifth largest metropolis in India currently with a population of about 8.72 million as per the latest population census (figure 2). Population has increased from 410,987 (1941) to 4,130,288 (1991), 5,655,844 (2001) and 8,719,939 (2011). Spatial extent of the city has increased from 69 (1941) to 161 (1981), 226 (2001) and 745 (2011) sq.km. Due to the changes in the spatial extent of the city, the population density varies from 5956 (1941) to 18147 (1981), 25653 (1991), 25025 (2001) and 11704 (2011) persons per sq.km.

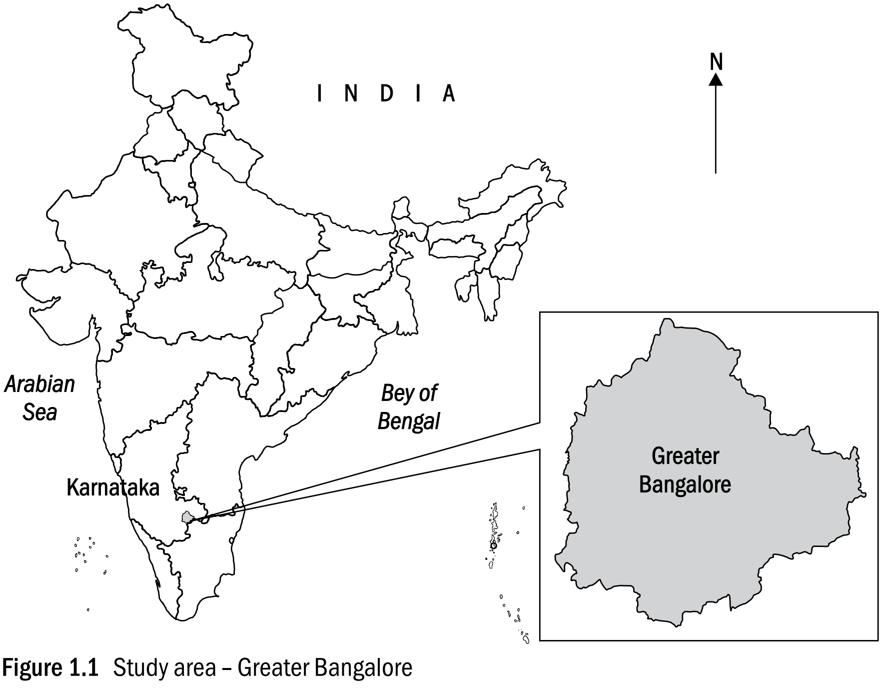


Figure 1.1 Study area – Greater Bangalore

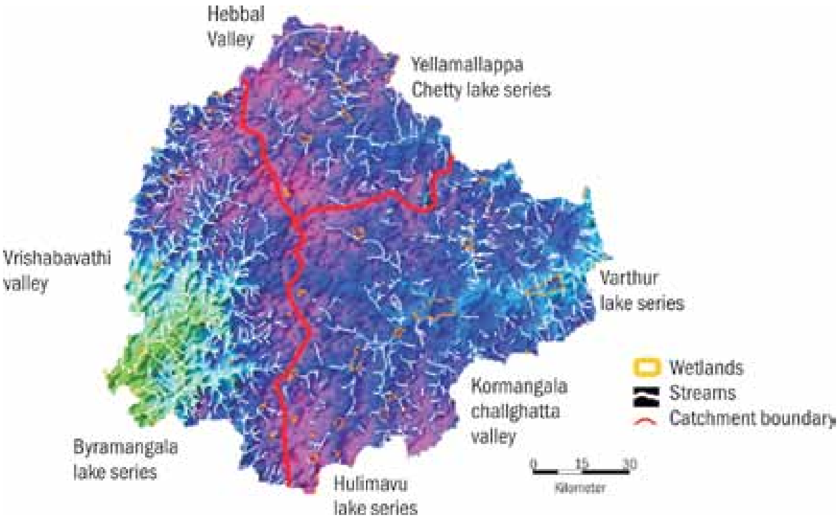


Figure 1.2 Watersheds (drainage with water bodies) of Greater Bangalore

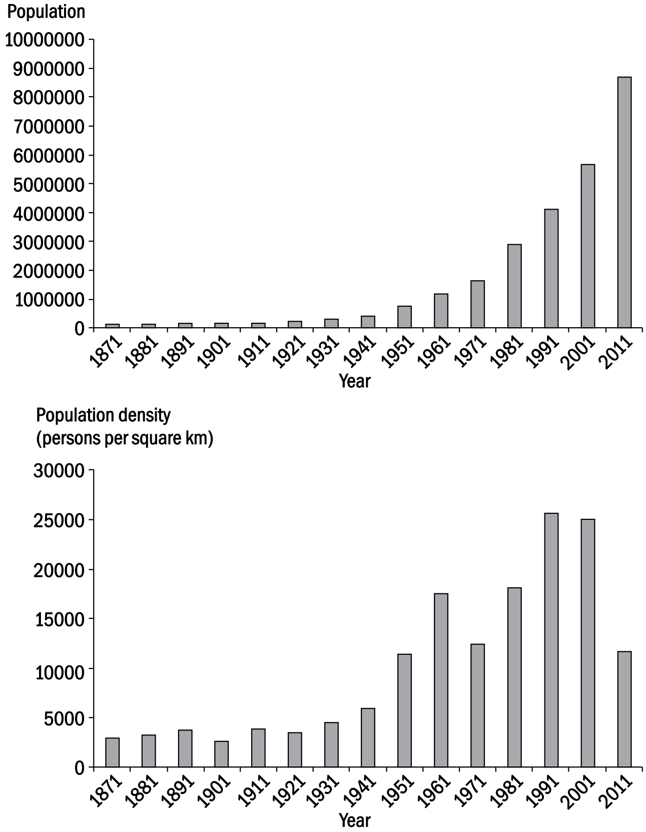


Figure 2 Population growth and population density

Materials and Methods

Data: Survey of India (SOI) toposheets of 1:50000 and 1:250000 scales were used to generate base layers. Field data was collected with a handheld GPS. The time series remote sensing data acquired from Landsat Series Multispectral sensor (57.5m) and Thematic mapper (28.5m) sensors for the period 1973 to 2010 and Landsat ETM+ (2000 and 2009) were downloaded from public domain (http://glcf.umiacs.umd.edu/data). MODIS (Moderate Resolution Imaging Spectroradiometer) Surface Reflectance 7 bands product [downloaded from http://edcdaac.usgs.gov/main.asp] of 2002, MODIS Land Surface Temperature/Emissivity 8-Day L3 Global and Daily L3 Global (V004 product) [http://lpdaac.usgs.gov/modis/dataproducts.asp#mod11]. Google Earth data (http://earth.google.com) served in pre and post classification process and validation of the results. Latest data for 2010 (IRS – Indian remote Sensing) was procured from the National remote Sensing Centre (http://www.nrsc.gov.in), Hyderabad. The methods adopted in the analysis involved:

Pre-processing of data: The remote sensing data were geo-referenced, rectified, and cropped pertaining to the study area. Geo-registration of remote sensing data (Landsat data) was done using ground control points collected from the field using pre calibrated GPS (Global Positioning System) and also from known points (such as road intersections, etc.) collected from geo-referenced topographic maps published by the Survey of India. Geo-referencing of acquired remote sensing data to latitude-longitude coordinate system with Evrst 56 datum: Landsat bands, IRS LISS-III MSS bands, MODIS bands 1 and 2 (spatial resolution 250 m) and bands 3 to 7 (spatial resolution 500 m) were geo-corrected with the known ground control points (GCP's) and projected to Polyconic with Evrst 1956 as the datum, followed by masking and cropping of the study area. The Landsat satellite 1973 images have a spatial resolution of 57.5 m x 57.5 m (nominal resolution) were resampled to 28.5m comparable to the 1989 - 2010 data that are 28.5 m x 28.5 m (nominal resolution). Landsat ETM+ bands of 2010 were corrected for the SLC-off by using image enhancement techniques, followed by nearest-neighbour interpolation. As the accuracy of the classified output of LANDSAT ETM+ was relatively low, the analysis for 2010 was repeated with IRS (LISS III) data procured from NRSC coinciding with the dates of field data collection.

Land use analysis: The analyses of land use were carried out using supervised pattern classifier - Gaussian maximum likelihood classifier (GMLC) for Landsat and IRS data, and Bayesian Classifier (MODIS data). The method involves: i) generation of False Colour Composite (FCC) of remote sensing data (bands – green, red and NIR). This helped in locating heterogeneous patches in the landscape ii) selection of training polygons (these correspond to heterogeneous patches in FCC) covering 15% of the study area and uniformly distributed over the entire study area, iii) loading these training polygons co-ordinates into pre-calibrated GPS, vi) collection of the corresponding attribute data (land use types) for these polygons from the field. GPS helped in locating respective training polygons in the field, iv) supplementing this information with Google Earth (latest as well as archived data), v) 60% of the training data has been used for classification, while the balance is used for validation or accuracy assessment.

Recent remote sensing data (2010) was classified using the collected training samples. Statistical assessment of classifier performance based on the performance of spectral classification considering reference pixels is done which include computation of kappa (κ) statistics and overall (producer's and user's) accuracies. For earlier time data, training polygon along with attribute details were compiled from the historical published topographic maps, vegetation maps, revenue maps, etc.

Normalised Difference Vegetation index (NDVI) was computed to understand the changes in the vegetation cover during the study period.

NDVI is the most common measurement used for measuring vegetation cover. It ranges from values -1 to +1. Very low values of NDVI (-0.1 and below) correspond to soil or barren areas of rock, sand, or urban built-up. Zero indicates the water cover (Ramachandra and Kumar, 2009). Moderate values represent low-density vegetation (0.1 to 0.3), while high values indicate thick canopy vegetation (0.6 to 0.8).

Density Gradient Analysis: Urbanisation pattern has not been uniform in all directions. To understand the pattern of growth vis a vis agents, the region has been divided into 4 zones based on directions - Northwest (NW), Northeast (NE), Southwest (SW), and Southeast (SE) respectively based on the Central pixel (Central Business district). Further, each zone was divided into concentric circle of incrementing radius of 1 km radius from the centre of the city that would help in visualizing and understanding the agents responsible for changes at local level. These regions are comparable to the administrative wards ranging from 67 to 1935 hectares. The growth of the urban areas in respective zones was monitored through the computation of urban density for different periods.

Derivation of Land Surface Temperature (LST)

LST from Landsat TM: The TIR band 6 of Landsat-5 TM was used to calculate the surface temperature of the area. The digital number (DN) was first converted into radiance L_{TM} using (Artis and Carnhan, 1982; Ramachandra and Kumar, 2009):

$$L_{TM} = 0.124 + 0.00563 * DN \quad \text{...(1)}$$

The radiance was converted to equivalent blackbody temperature $T_{TMSurface}$ at the satellite using

$$T_{TMSurface} = K_2 / (K_1 - \ln L_{TM}) - 273 \quad \text{...(2)}$$

The coefficients K_1 and K_2 depend on the range of blackbody temperatures. In the blackbody temperature range 260-300K the default values (Singh, S. M., 1988) for Landsat TM are $K_1 = 4.127$ and $K_2 = 1274.7$. Brightness temperature is the temperature that a blackbody would obtain in order to produce the same radiance at the same wavelength (λ = 11.5 μm). Therefore, additional correction for spectral emissivity (ε) is required to account for the non-uniform emissivity of the land surface. Spectral emissivity for all objects are very close to 1, yet for more accurate temperature derivation emissivity of each LC class is considered separately. Emissivity correction is carried out using surface emissivity for the specified LC (table 1) derived from the methodology described in Snyder *et al.*, (1998) and Stathopoulou *et al.* (2006).

The procedure involves combining surface emissivity maps obtained from the Normalized Difference Vegetation Index Thresholds Method ($NDVI^{THM}$) (Sobrino and Raissouni, 2000) with LC information. The emissivity corrected land surface temperature (Ts) were finally computed as follows (Artis and Carnhan, 1982)

$$T_s = \frac{T_B}{1 + (\lambda \times T_B / \rho) \ln \varepsilon} \quad \text{...(3)}$$

Where λ is the wavelength of emitted radiance for which the peak response and the average of the limiting wavelengths (λ = 11.5 μm) were used, $\rho = h \times c / \sigma$ (1.438×10^{-2} mK), σ = Stefan Boltzmann's constant (5.67×10^{-8} $Wm^{-2}K^{-4} = 1.38 \times 10^{-23}$ J/K), h = Planck's constant (6.626×10^{-34} Jsec), c = velocity of light (2.998×10^{8} m/sec), and ε is spectral emissivity.

Table 1 Surface emissivity values by LC type

LC type	Emissivity
Densely urban	0.946
Mixed urban (Medium Built)	0.964
Vegetation	0.985
Water body	0.990
Others	0.950

LST from Landsat ETM+: The TIR image (band 6) was converted to a surface temperature map according to the following procedure (Weng *et al.*, 2004). The DN of Landsat ETM+ was first converted into spectral radiance L_{ETM} using equation 4, and then converted to at-satellite brightness temperature (i.e., black body temperature, $T_{ETMSurface}$), under the assumption of uniform emissivity ($\varepsilon \approx 1$) using equation 5 (Landsat Project Science Office, 2002):

$$L_{ETM} = 0.0370588 \times DN + 3.2 \qquad \text{...(4)}$$

$$T_{ETMSurface} = K2/\ln (K_1 / L_{ETM} + 1) \qquad \text{...(5)}$$

Where, $T_{ETMSurface}$ is the effective at-satellite temperature in Kelvin, L_{ETM} is spectral radiance in watts/ (meters squared x ster x µm); and K_2 and K_2 are pre-launch calibration constants. For Landsat-7 ETM+, K_2 = 1282.71 K and K_1 = 666.09 $mWcm^{-2}sr^{-1}\mu m^{-1}$ were used (http: //ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_htmls/chapter11/chapter11. html). The emissivity corrected land surface temperatures Ts were finally computed by equation 3.

Results and Discussion

Land use analysis for the period 1973 to 2010 has been done using Gaussian maximum likelihood classifier and the temporal land use details are given in table 2. Figure 3.1 provides the land use in the region during the study period. Overall accuracy of the classification was 72% (1973), 75% (1992), 71% (1999), 80% (2002), 73% (2006), and 86% (2010) respectively. Land use analysis was done using the open source programs (i.gensig, i.class, and i.maxlik) of Geographic Resources Analysis Support System (http://wgbis.ces.iisc.ernet.in/ grass). From the classified raster maps, urban class was extracted and converted to vector representation for computation of precise area in hectares. There has been a 632% increase in built up area from 1973 to 2009 leading to a sharp decline of 79% area in water bodies in Greater Bangalore mostly attributing to intense urbanisation process. Analyses of the temporal data reveals an increase in urban built up area of 342.83% (during 1973 to 1992), 129.56% (during 1992 to 1999), 106.7% (1999 to 2002), 114.51% (2002 to 2006) and 126.19% (2006 to 2010). Figure 3.3 illustrates the zone-wise temporal land use changes at local levels. This aids in the identification the agents responsible for land use changes. Figure 4 shows Greater Bangalore with 207 water bodies (in 1973), which declined to 93 (in 2010). The rapid development of urban sprawl has many potentially detrimental effects including the loss of valuable agricultural and eco-sensitive (e.g. wetlands, forests) lands, enhanced energy consumption and greenhouse gas emissions from increasing private vehicle use (Ramachandra and Shwetmala, 2009). Vegetation has decreased by 32% (during 1973 to 1992), 38% (1992 to 2002) and 63% (2002 to 2010.

Disappearance of water bodies or sharp decline in the number of water bodies in

Table 2 Greater Bangalore LC statistics

Class →	Urban		Vegetation		Water		Others	
Year ↓	Ha	%	Ha	%	Ha	%	Ha	%
1973	5448	7.97	46639	68.27	2324	3.40	13903	20.35
1992	18650	27.30	31579	46.22	1790	2.60	16303	23.86
1999	24163	35.37	31272	45.77	1542	2.26	11346	16.61
2002	25782	37.75	26453	38.72	1263	1.84	14825	21.69
2006	29535	43.23	19696	28.83	1073	1.57	18017	26.37
2010	37266	54.42	16031	23.41	617	0.90	14565	21.27

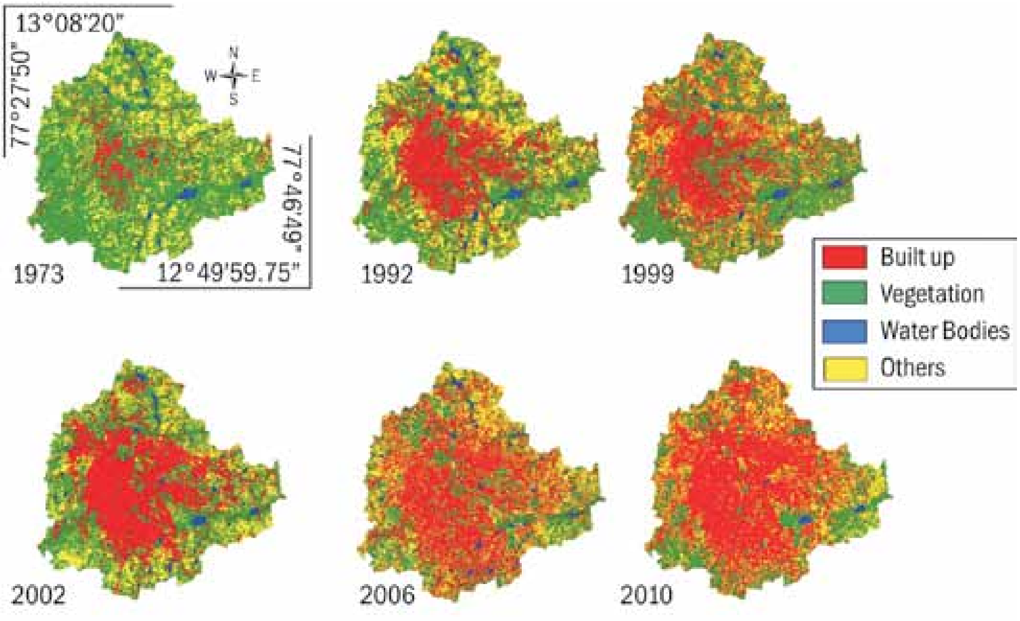


Figure 3.1 Greater Bangalore in 1973, 1992, 1999, 2002, 2006, and 2010

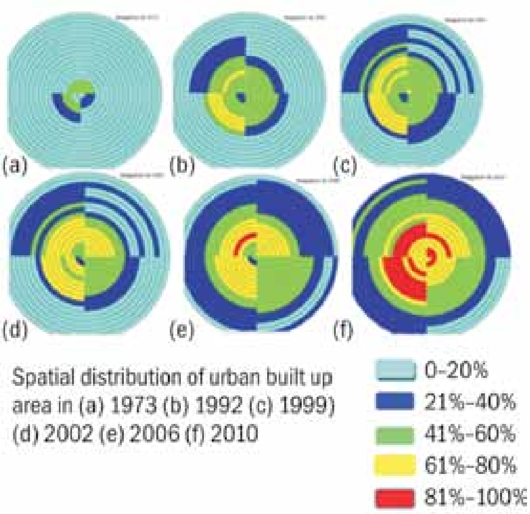


Figure 3.2 Gradient analysis of Greater Bangalore- Built-up density circle wise & zone wise from 1973 to 2010

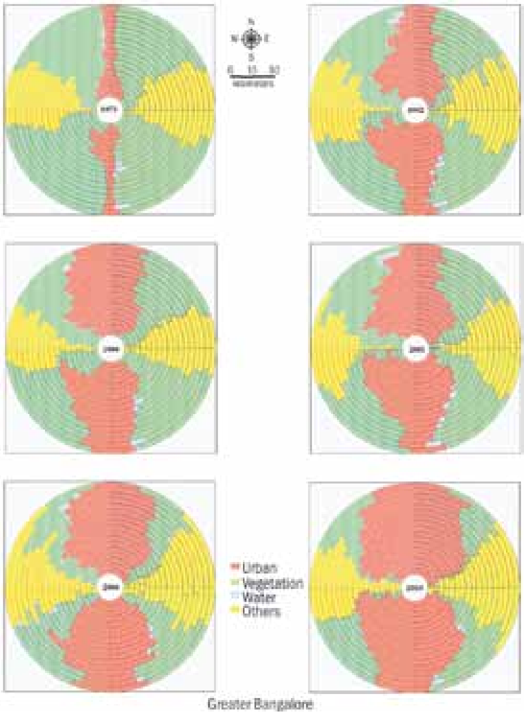


Figure 3.3 Zone-wise and Gradient-wise temporal land use

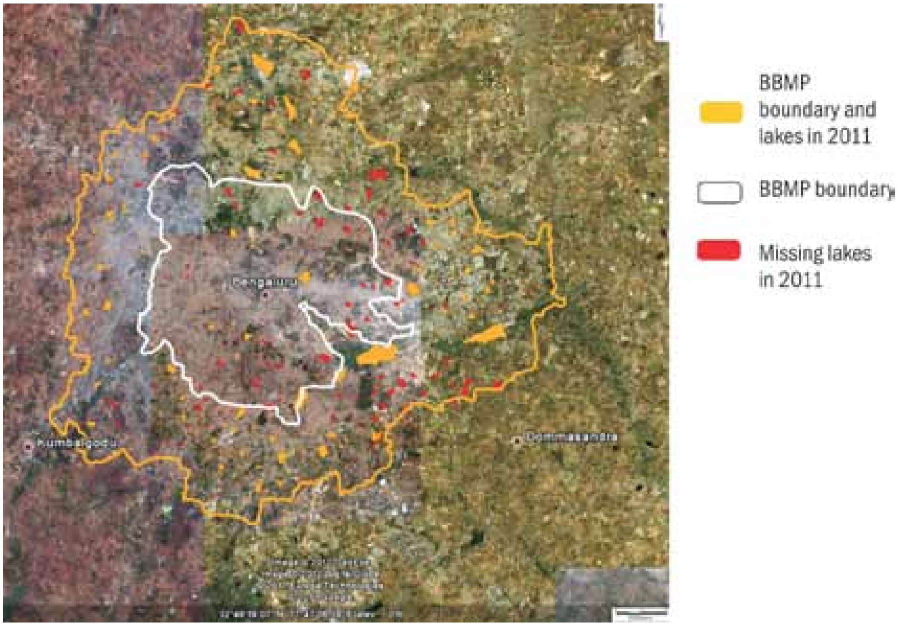


Figure 4 Greater Bangalore with 207 water bodies (1973), 93 water bodies (2010)
Erstwhile Bangalore city 58 water bodies (1973), 10 water bodies (2010)
Note BMP Bangalore Mahanagara Palike; BBMP Bruhat Bangalore (Greater Bangalore) Mahanagara Palike

Bangalore is mainly due to intense urbanisation and urban sprawl. Many lakes (54%) were encroached for illegal buildings. Field survey of all lakes (in 2007) shows that nearly 66% of lakes are sewage fed, 14% surrounded by slums and 72% showed loss of catchment area. In addition, lake catchments were used as dumping yards for either municipal solid waste or building debris (Ramachandra, 2009a). The surrounding of these lakes have illegal constructions of buildings and most of the times, slum dwellers occupy the adjoining areas. At many sites, water is used for washing and household activities and even fishing was observed at one of these sites. Multi-storied buildings have come up on some lake beds that have totally intervene the natural catchment flow leading to sharp decline and deteriorating quality of water bodies. This is correlated with the increase in built up area from the concentrated growth model focusing on Bangalore, adopted by the state machinery, affecting severely open spaces and in particular water bodies. Some of the lakes have been restored by the city corporation and the concerned authorities in recent times.

Study area was divided into concentric incrementing circles of 1 km radius (with respect to centroid or central business district) in each zone as shown in Figure 3.2. This illustrates radial pattern of urbanization for the period 1973 to 2010. In 1973, the growth was concentrated closer to the central business district and was minimal. In 1992, Bangalore grew intensely in the NW and SW zones. This growth can be attributed to the policy of industrialization consequent to the globalization during early 90's. Consequent to this, the industrial layouts came up in these areas specially in the NW and SW intensified the urban growth and as a result land was also acquired for housing and urban sprawl was noticed in others parts of the Bangalore. These phenomena intensified during post 2000 as the SE and NE Bangalore saw intense growth for development of IT and BT sectors. Subsequent to this, relaxation of FAR (Floor area ratio) in mid-2005, lead to the spurt in residential sectors, paved way for large scale conversion of land leading to intense urbanization in these localities. This also led to the compact growth at central core areas of Bangalore and sprawl at outskirts that are deprived of basic amenities. The gradient analysis showed that Bangalore grew radially from 1973 to 2010 indicating that the urbanization is intensifying from the city centre and has reached the periphery of the Greater Bangalore.

LST were computed from Landsat TM and ETM thermal bands. The minimum and maximum temperature from Landsat TM data of 1992 was 12 and 21 with a mean of 16.5±2.5 while for ETM+ data was 13.49 and 26.32 with a mean of 21.75±2.3. MODIS Land Surface Temperature/Emissivity (LST/E) data with 1 km spatial resolution with a data type of 16-bit unsigned integer were multiplied by a scale factor of 0.02 (http://lpdaac.usgs.gov/modis/dataproducts.asp#mod11). The corresponding temperatures for all data were converted to degree Celsius. Figure 5 shows the LST map and NDVI of Greater Bangalore in 1992, 2000, and 2007. The minimum (min) and maximum (max) temperatures were computed as 20.23, 28.29 and 23.79, 34.29 with a mean of 23.71±1.26, 28.86± 1.60 for 2000 and 2007 respectively. Data were calibrated with in-situ measurements. NDVI was computed to study its relationship with LST. The Landsat TM NDVI had a mean of 0.04±0.4543, ETM+ data had a mean of 0.0252±0.5369, and MODIS had a mean of -0.0917±0.5131.

The correlation between NDVI and temperature of 1992 TM data was 0.88, 0.72 for MODIS 2000 and 0.65 for MODIS 2007 data respectively, suggesting that the extent of LC with vegetation plays a significant role in the regional LST. Respective NDVI and LST for different land uses is given in table 3 and further analysis was carried out to understand the role of respective land uses in the regional LST's.

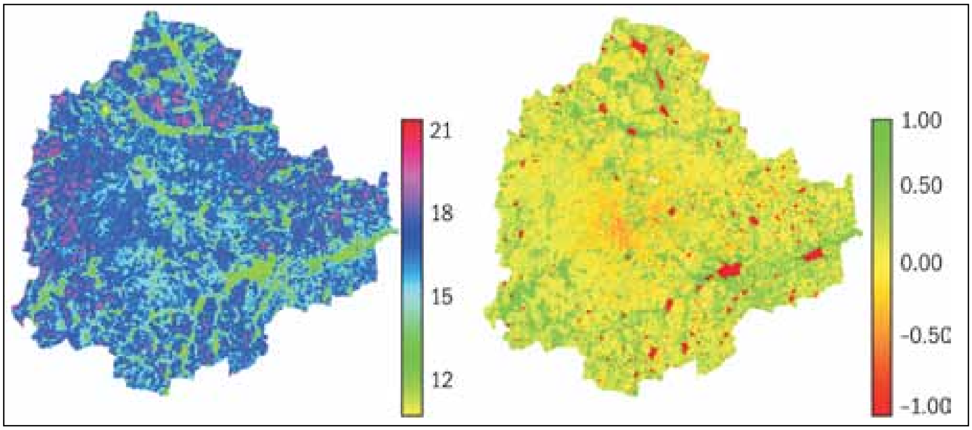


Figure 5 LST and NDVI from Landsat TM (1992)

Table 3 LST (°C) and NDVI for various land uses

	1992 (TM)				2000 (MODIS)				2007 (MODIS)			
Land use	LST	± SD	NDVI	±SD	LST	± SD	NDVI	± SD	LST	± SD	NDVI	± SD
Built-up	19.03	±1.47	-0.162	±0.096	26.57	±1.25	-0.614	±0.359	31.24	±2.21	-0.607	±0.261
Vegetation	15.51	±1.05	0.467	±0.201	22.21	±1.49	0.626	±0.27	25.79	±0.44	0.348	±0.42
Water bodies	12.82	±0.62	-0.954	±0.055	21.27	±1.03	-0.881	±0.045	24.20	±0.27	-0.81	±0.27
Open ground	17.66	±2.46	-0.106	±0.281	24.73	±1.56	-0.016	±0.283	28.85	±1.54	-0.097	±0.18

It is clear that urban areas that include commercial, industrial, and residential land exhibited the highest temperature followed by open ground. The lowest temperature was observed in water bodies across all years and vegetation. Spatial variation of NDVI is subject to not only the influence of vegetation amount, but also to topography, slope, solar radiation availability, and other factors (Walsh *et al.*, 1997). Table 4 lists the relationship between LST and NDVI, which was investigated for each LC type through the Pearson's correlation coefficient at a pixel level. The significance of each correlation coefficient was determined using a one-tail Student's t-test. It is apparent that values tend to correlate negatively with NDVI for all LC types. NDVI values for built up ranges from -0.05 to -0.6. Temporal increase in temperature with the increase in the number of urban pixels during 1992 to 2009 (113%) is confirmed with the increase in 'r' values for the respective years. The NDVI for vegetation ranges from 0.15 to 0.6. Temporal analyses of the vegetation show a decline of 65%, with a consequent increase in the temperature.

A closer look at the values of NDVI by LULC category (table 3) indicates that the relationship between LST and NDVI may not be linear. Clearly, it is necessary to examine the relationship between existing LST and vegetation-abundance using fraction (proportion of land use in a pixel) as an indicator. The fraction of land use in a pixel is estimated by linear un-mixing technique. Abundance is computed using linear un-mixing from ETM+ bands were further analysed to see their contribution to the UHI by separating the pixels that contains 0-20%, 20-40%, 40-60%, 60-80% and 80-100% of urban pixels. Table 5 gives the average LST for various land use classes.

Table 4 Correlation coefficients between LST and NDVI by LC type (p=0.05)

Land use	1992	2000	2007
Built up	-0.7188	-0.7745	-0.7900
Vegetation	-0.8720	-0.6211	-0.6071
Open ground	-0.6817	-0.5837	-0.6004
Water bodies	-0.4152	-0.4182	-0.4999

8 transacts were laid across the city in different directions (north [N], north-east [NE], east [E], south-east [SE], south [S], south-west [SW], west [W] and north-west [NW]) and LST was analysed as shown in figure 6, to understand the temperature dynamics.

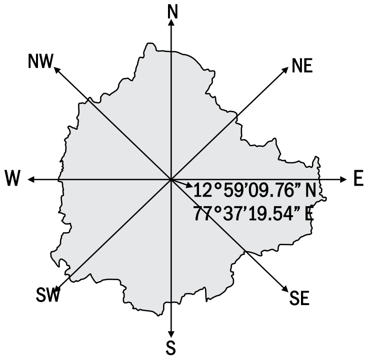
The temperature profile was analysed by overlaying the LST map on the land use classified map to visualise the effect of vegetation, built-up, water bodies and open ground. The temperature profile plot fell below the mean when a vegetation patch or water body was encountered on the transact beginning from the centre of the city and moving outwards along the transact. The corresponding graphs are shown in figure 7. The major natural green area and water bodies responsible for temperature decline are marked with circle. The spatial location of these green areas and water bodies are shown in figure 8.

Urban Floods

Frequent flooding since 2000 (even during normal rainfall) is a consequence of the increase

Table 5 Mean LST for various land use classes for different abundances

Class → Abundance ↓	Mean Temperature± SD of dense urban	Mean Temperature± SD of mixed urban	Mean Temperature± SD of vegetation
0-20%	21.99±2.37	21.57±2.36	17.91±2.19
20-40%	22.06±2.15	21.58±2.36	17.39±1.37
40-60%	22.27±2.00	21.67±2.41	17.22±0.89
60-80%	22.33 ±2.22	22.28±2.02	17.13±0.85
80-100%	22.47±1.96	22.37±2.17	17.12±0.91



Direction	Mean LST±SD
N	21.30±2.39
NE	22.15±2.22
E	21.01±2.47
SE	21.34±2.30
S	21.71±2.07
SW	22.19±1.92
W	22.97±1.72
NW	22.07±2.25

Figure 6 Transect lines superimposed on Greater Bangalore boundary along with LST in various directions.

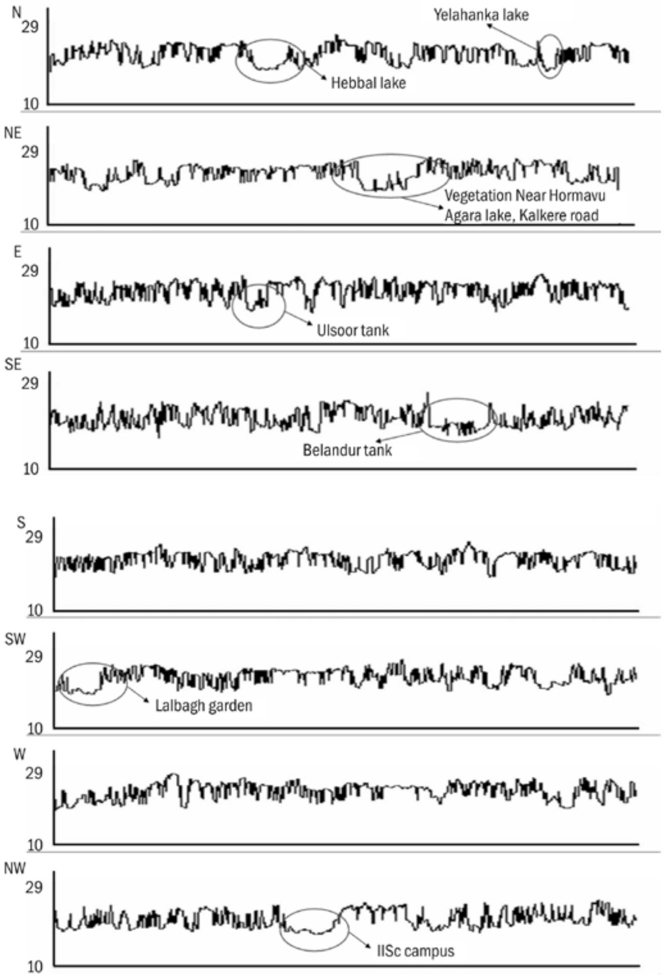
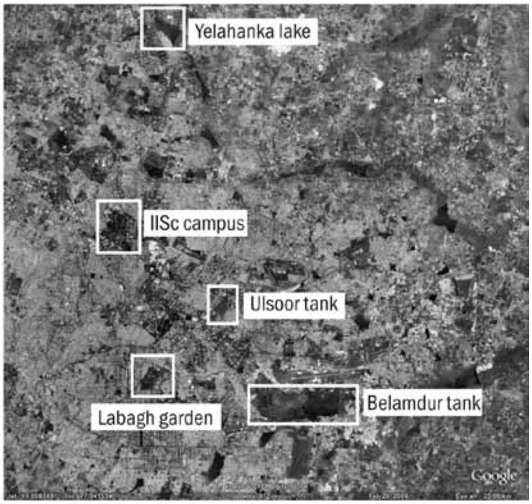


Figure 7 Temperature profile in various directions. X axis – Movement along the transacts from the city centre, Y-axis - Temperature (°C).



Fgure 8 Google Earth image showing the low temperature areas (refer figure 7).
Source http://earth.google.com/

in impervious area due to land use changes in the catchment from open space to impervious surfaces with the high-density urban developments. This is coupled with lack of drainage upgrade works with the changes in enhanced run-offs, the encroachment and filling in the floodplain on the waterways, obstruction by the sewer pipes and manholes and relevant structures, deposits of building materials and solid wastes with subsequent blockage of the system and also flow restrictions from under capacity road crossings (bridge and culverts). The lack of planning and enforcement has resulted in significant narrowing of the waterways and filling in of the floodplain by illegal developments. This has subsequently caused flooding to other properties that have not previously been flooded, new properties in the flood plain built below the high flood marks (designated flood levels), these being frequently flooded, and restrictions of options for future flood mitigation including widening of waterways.

Reclamation of lakes for various developmental activities has resulted in the loss of interconnectivity in Bangalore district leading to higher instances of floods even during the normal rainfall. Analyses of Bellandur and Ulsoor drainage network (figure 9.1) showed that the network is lost due to conversion of Chelgatta tank into a golf course. Similarly, the drainage network between Madivala and Bellandur revealed of encroachment and conversion that has resulted in the loss of connectivity between Yelchenhalli kere and Madivala (figure 9.2).

Increased peak discharge and higher frequency of floods are the consequences of urbanization due to lack of provisions for infiltration. As land use changes from vegetation and wetlands to impervious layer (built-up, roads, etc.), it loses its ability to infiltrate/absorb rainfall. Urbanization has increased run off three to six times over what

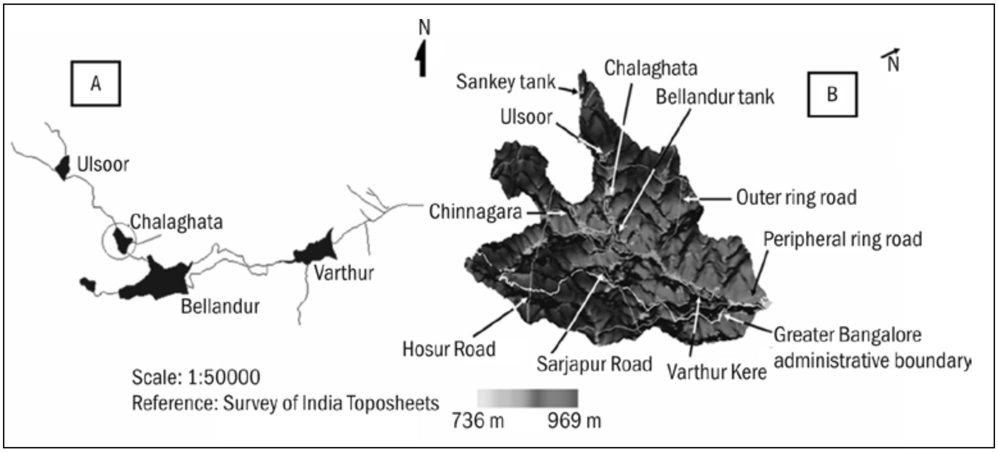


Figure 9.1 Ulsoor–Bellandur–Varthur (a) drainage network (b) lakes overlaid on 10 m DEM showing their missing interconnectivity

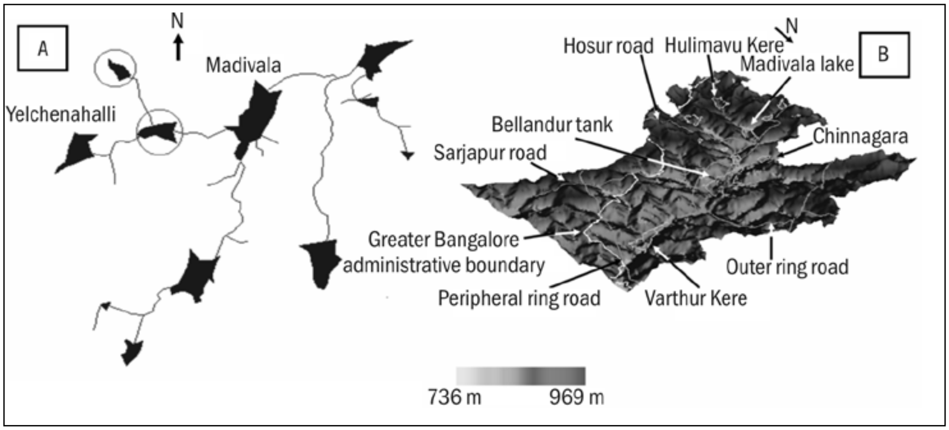


Figure 9.2 Madivala–Bellandur–Varthur (A) drainage network (B) lakes overlaid on 10 m DEM showing their missing interconnectivity

would occur on natural terrain in some pockets of Bangalore (Ramachandra and Mujumdar, 2009). During periods of urban flooding, streets become swift moving rivers, while low-lying residential areas and basements become death traps as they fill with water. Conversion of water bodies to residential layouts and encroachment of storm water drains have further exaggerated the problem.

Ulsoor–Belandur catchment: This catchment has six lakes – Sankey, Ulsoor, Chalghata, Chinnagara, and Varthur and was classified into three major land use types – built up, vegetation and others (comprising open land, wasteland etc.). The total rainfall yield in this catchment is 240 Mm^3, percolated water is 90 Mm^{3,} and water overflow is 150 Mm^3. The SRTM DEM data were resampled to 10 m resolution and the volume of each lake was computed assuming the depth to be 1 m and the mean annual rainfall to be 850 mm. The total volume of all the six lakes in this catchment is 73 Mm^3. Hence there is surplus overland flow of 77 Mm^3, which cannot flow to downstream due to disruption of natural drainage (removal of lakes and blockage of storm water drains) resulting in flooding (even during normal rainfall).

Madivala–Varthur catchment: Similar analysis was done for Madivala catchment which has 14 lakes – Venkatapura, Yellakunte, Bandepalya, Begur Doddakere, Madivala, Hulimavu, Marenahalli, Govindanaikana kere, Tank north of Doresanipalya, Gittigere and Vaddarpalya. The total rainfall yield is 247 Mm^3; percolated water is 97 Mm^3 and the remaining 150 Mm^3 water flows as overland flow and storage in lakes. The total volumes of all the lakes considering 1 m depth is 110 Mm^3 resulting in the excess of 40 Mm^3 from the catchment leading to artificial floods. In addition to rainfall, Belandur-Varthur watershed receives untreated municipal sewage to the order of 500MLD.

Flooding in urban areas has caused large damage at buildings and other public and private infrastructure (evident during 1997, 2002, and 2007). Besides, street flooding can limit or completely hinder the functioning of traffic systems and has indirect consequences such as loss of business and opportunity. The expected total damage; direct and indirect monetary damage costs as well as possible social consequences is related to the physical properties of the flood, i.e. the water level above ground level, the extent of flooding in terms of water volume escaping from or not being entering the drainage system, and the duration of flooding. Table 6 summarises the causal factors for poor drainage system and remedial measures to be undertaken to improve the condition.

Table 6 Causal factors and key impacts

Causal factors	Key Impacts and remedial actions
Unplanned urbanisation	
Increase of impervious surfaces and non-upgradation of drains to handle enhanced runoff Encroachment of drains	Causes increased volume and rate of surface run-off from developed lands, which leads to more flash flooding and increased extent, height, and frequency of flooding. ✓ Prevention of alteration of topography in the catchment. Upgradation of drains from top of catchment to catchment outlet for handling increases in run-off
Sediment and erosion from median strips and verges, spills from construction vehicles (e.g. concreting, earthmoving)	Reduced capacity, ✓ Improved catchment management practices
Development in flood-prone areas	
Encroachment and alteration of floodplain	Restricts flow and increases flooding on unfilled lands ✓ Control filling to overall valley
	Reduces flood storage capacity, increasing downstream flooding ✓ Undertake whole of catchment planning for drainage
Inadequate provision for main drains in development plans	Causes gradual reduction in waterway capacity due to encroachments ✓ enforce compliance ✓ Incorporate drainage reserves
Development below flood level	Creates high flood damage, lowers standard of housing and reduces property values ✓ Prepare flood level plans to a datum and use them to control building floors and other development
Cross drainage (and services in drains)	
Lack of capacity of cross drainage works	Causes localised and widespread flooding ✓ Reconstruct to a standard equal to the future drain requirements
Construction of services (water, telecommunication, power etc.) above invert and below flood level	Obstructs flow and aggravates flooding ✓ Relocate services, coordinate works and agree on service locations
Sewerage system in drains	
Reduction in storm water system capacity	Increases flooding significantly ✓ Lower manholes and reconstruct sewers below drain invert
Obstruction and redistribution of storm water flow, generally poorly constructed sections	Causes bank and bed erosion; flooding in the waterways ✓ Reconstruct and improve future designs
Solid waste disposal	
Dumping of solid waste and building site waste in the drainage channel	Causes blockage and pollution in the drainage system ✓ Implement solid waste strategy plan
Unstable and degraded waterways	
Weed infestation, encroachment, vegetation loss, and eroded and unstable riparian zones	Causes siltation of downstream waterways ✓ Treat erosion sites and develop guidelines for silt control during construction

Conservation and Management of Wetlands: The loss of ecologically sensitive wetlands is due to the uncoordinated pattern of urban growth happening in Greater Bangalore. This could be attributed to a lack of good governance and decentralized administration evident from lack of coordination among many Para-state agencies, which has led to unsustainable use of the land and other resources. Failure to deal with water as a finite resource is leading to the unnecessary destruction of lakes and marshes that provide us with water. This failure in turn is threatening all options for the survival and security of plants, animals, humans, etc. There is an urgent need for:

- **Restoring and conserving the actual source of water -** the water cycle and the natural ecosystems that support it - are the basis for sustainable water management
- **Reducing the environmental degradation that is preventing us from reaching goals** of good public health, food security, and better livelihoods world-wide
- **Improving the human quality of life** that can be achieved in ways while maintaining and enhancing environmental quality
- **Reducing greenhouse gases to avoid the dangerous effects of climate change** is an integral part of protecting freshwater resources and ecosystems.

A comprehensive approach to water resource management is needed to address the myriad water quality problems that exist today from non-point and point sources as well as from catchment degradation. Watershed-based planning and resource management is a strategy for more effective protection and restoration of aquatic ecosystems and for protection of human health. The watershed approach emphasizes all aspects of water quality, including chemical water quality (e.g., toxins and conventional pollutants), physical water quality (e.g., temperature, flow, and circulation), habitat quality (e.g., stream channel morphology, substrate composition, riparian zone characteristics, catchment land cover), and biological health and biodiversity (e.g., species abundance, diversity, and range).

The suggestions for conserving and managing wetlands to mitigate frequent floods were as per the recommendations of Lake 2010: Wetlands, Biodiversity and Climate Change (22-24 December 2010) organized at the Satish Dhawan Auditorium, Indian Institute of Science, and Brainstorming session for evolving the strategies for the conservation and management of lakes (26th Sept 2009) at the Centre for Infrastructure, Sustainable Transport and Urban Planning [CiSTUP], Indian Institute of Science. Lake 2010 forum discussed the recommendations of Lake Symposiums (Lake 2008, Lake 2006, Lake 2004, Lake 2002, LimGIS 2001, Lake 2000, 1998 symposium) and Brainstorming Session (Ramachandra, 2009 a, b) apart from discussing the draft notification of the Regulatory Framework for Wetlands Conservation of The Ministry of Environment and Forests, Government of India. Policy interventions required in order to conserve fragile ecosystems – wetlands are:

1 **Carrying capacity studies for all macro cities:** to adopt holistic approaches in regional planning considering all components (ecology, economic, social aspects) in rapidly urbanizing macro cities such as Greater Bangalore, etc.

2 **Demarcation of the boundary of water bodies:** The existing regulations pertaining to boundary demarcations within different states need to be reviewed according to updated norms and based on geomorphology and other scientific aspects pertaining to individual water bodies. Maximum Water Level mark should form the boundary line of the water body. The buffer zone should be treated as inviolable in the long-term interests of the water body and its biodiversity. This requires

  - Declare and maintain floodplains and valley zones of lakes as no activity regions

- Remove all encroachments – free flood plains, valley zones, storm water drains, etc. of encroachments of any kind.
- Ban conversion of lake, lakebed for any other purposes.
- Urban wetlands, mostly lakes, have to be regulated from any type of encroachments.
- Regulate the activity which interferes with the normal run-off and related ecological processes – in the buffer zone (200 m from lake boundary / flood plains is to be considered as buffer zone)

3 **Mapping of water-bodies:** The mapping of water bodies should also include smaller wetlands, springs etc. The neglect of these hydrological systems could cause considerable impoverishment of water flow in the river systems as well as turn out to be threats to rare kinds of biodiversity.

4 **Holistic and Integrated Approaches – Conservation and Management:** Integration of the activities with the common jurisdiction boundaries of Government Para-state Agencies for effective implementation of activities related to management, restoration, sustainable utilization, and conservation. This necessitates common jurisdictional boundary for all Para-state agencies. To minimise the confusion of ownership – assign the ownership of all natural resources (lakes, forests, etc.) to a single agency – **Lake Protection and Management Authority** (or Karnataka Forest Department). This agency shall be responsible for protection, development, and sustainable management of water bodies). There is a need to maintain catchment integrity to ensure lakes are perennial and maintain at least 33% land cover should be under natural Vegetation.

5 **Documentation of biodiversity:** The biodiversity of every water body should form part of the School, College, People's Biodiversity Registers (SBR, CBR, and PBR). The local Biodiversity Management Committees (BMC) should be given necessary financial support and scientific assistance in documentation of diversity. The presence of endemic, rare, endangered, or threatened species and economically important ones should be highlighted. A locally implementable conservation plan has to be prepared for such species.

6 **Mitigation of Floods**: This entails maintenance of open spaces (vegetation, water bodies). Mitigation necessitates restoration of wetlands, removal of blockages in the drainage network, removal of encroachments (storm water drains, wetlands), prevention of indiscriminate disposal of solid waste (including building debris) in storm water drains, lake beds, catchment of wetlands and restoration of the connectivity of lakes

7 **Preparation of management plans for individual water bodies:** Most large water bodies have unique individual characteristics. Therefore, it is necessary to prepare separate management plans for individual water bodies.

8 **Implementation of sanitation facilities:** It was noted with concern that the water bodies in most of India are badly polluted with sewage, coliform bacteria, and various other pathogens.

9 **Restoration of lakes:** The goals for restoration of aquatic ecosystems need to be realistic, and should be based on the concept of expected conditions for individual eco-regions. Further development of project selection and evaluation technology based on eco-region definitions and description should be encouraged and supported by the national and state government agencies.

10 **Protection of riparian and buffer zone vegetation:** Any clearances of riparian vegetation (alongside lakes) and buffer zone vegetation (around lakes) have to be prohibited.

11 **Restoration of linkages between water bodies:** The process of urbanization and neglect caused disruption of linkages between water bodies such as ancient lake systems of many cities. Wherever such disruptions have taken place, alternative arrangements should be provided to establish the lost linkages.

12 **Rainwater harvesting:** Intensive and comprehensive implementation of rainwater harvesting techniques can reduce taxation of water bodies and minimize electricity requirements. The country needs in principle a holistic rainwater harvesting policy aimed at directing water literally from "roof-tops to lakes" after catering to the domestic needs.

13 **Environment Education**: Lake Associations and citizen monitoring groups have proved helpful in educating the public. Effort should be made to ensure that such groups have accurate information about the causes of lake degradation and various restoration methods.

14 **Adopt Inter-disciplinary Approach**: Aquatic ecosystem conservation and management requires collaborated research involving natural, social, and inter-disciplinary study aimed at understanding various components, such as monitoring of water quality, socio-economic dependency, biodiversity and other activities, as an indispensable tool for formulating long-term conservation strategies. This requires multidisciplinary-trained professionals who can spread the understanding of ecosystem's importance at local schools, colleges, and research institutions by initiating educational programmes aimed at raising the levels of public awareness of aquatic ecosystems' restoration, goals, and methods. Actively participating schools and colleges near the water bodies may value the opportunity to provide hands-on environmental education, which could entail setting up of laboratory facilities at the site. Regular monitoring of water bodies (with permanent laboratory facilities) would provide vital inputs for conservation and management.

Conclusion

Urbanisation and the consequent loss of lakes has led to decrease in catchment yield, water storage capacity, wetland area, number of migratory birds, flora and fauna diversity and ground water table. As land is converted, it loses its ability to absorb rainfall. The relationship between LST and NDVI investigated through the Pearson's correlation coefficient at a pixel level and the significance tested through one-tail Student's t-test, confirms the relationship for all LC types. In addition, increased urbanisation has resulted in higher population densities in certain wards, which incidentally have higher LST due to high level of anthropogenic activities. The growth poles are towards N, NE, S and SE of the city indicating the intense urbanization process due to growth agents like setting up of IT corridors, industrial units, etc. Newly built-up areas in these regions consisted of maximum number of small-scale industries, IT companies, multi-storied building, and private houses that came up in the last one decade. The growth in northern direction can be attributed to the new International Airport, encouraging other commercial and residential hubs. The southern part of the city is experiencing new residential and commercial layouts and the northwestern part of the city outgrowth corresponds to the Peenya industrial belt along with the Bangalore-Pune National Highway 4.

Temporal land use analysis reveal that there has been a 632% increase in built up area from 1973 to 2009 leading to a sharp decline of 79% area in water bodies in Greater Bangalore mostly attributing to intense urbanisation process. The increase in urban built up area ranges from 342.83% (during 1973 to 1992), 129.56% (during 1992 to 1999), 106.7% (1999 to 2002), 114.51% (2002 to 2006) to 126.19% (2006 to 2010). Number of wetlands has declined from 207 (1973) to 93 (2010). The gradient analysis showed that Bangalore grew radially from 1973 to 2010 indicating that the urbanization is intensifying from the city centre and has reached the periphery of the Greater Bangalore.

The temperature profile analysis by overlaying the LST on the land use reveal of higher temperatures in urban area while vegetation and water bodies aided in moderating temperature at local levels (evident from at least 2 to 2.5 °C lower temperature compared to urban pockets).

Frequent flooding in the city is a consequence of the drastic increase in impervious area (of 632% in 4 decades) with the high-density urban developments. This is coupled with lack of drainage upgrade works with the changes in enhanced run-offs, the encroachment and filling in the floodplain on the waterways, obstruction by the sewer pipes and manholes and relevant structures, deposits of building materials and solid wastes with subsequent blockage of the system and also flow restrictions from under capacity road crossings (bridge and culverts). Increased peak discharge and higher frequency of floods are frequent at pockets with the intense urbanization, loss of lakes' interconnectivity, encroachment of storm water drains. The uncoordinated pattern of urban growth could be attributed to a lack of good governance and decentralized administration, which was evident from the lack of coordination among many Para-state agencies, which has led to unsustainable use of the land and other resources. The mitigation of frequent floods and the associated loss of human life and properties entail the restoration of interconnectivity among wetlands, restoration of wetlands (removal of encroachments), conservation, and sustainable management of wetlands

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