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Urban green-cover and the environmental performance of Chennai city

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Abstract Chennai city the capital of Tamil Nadu is located in southeastern India. Its average population growth rate is 25% per decade, which recurrently alters the city's land-cover particularly the receding green-cover distressed the city's self-renewal capacity, in terms of groundwater recharge, pollution sequestration and microclimatic amelioration. This has been appraised by means of a GIS model. This model was developed using three sets of green-cover associated parameters, namely air quality amelioration, hydrological process regulation and microclimatic amelioration. The outcome confirms the difference in the city's environmental performance between the 1997 and 2001. At some parts of the city, due to the green-cover change, the extent of modification was 38%, in terms of mean percent change in all three sets of parameters mentioned earlier. Through coefficient of correlation (r) method, relationship between green-cover change and environmental performance change are checked. It confirms positive relationship ($r = 1$) in all parts, except at few places.

Keywords Air quality · GIS model · Human well-being · Land cover · Runoff · Urban heat island

1 Introduction

The vanishing greeneries oversimplify many aspects of the environmental process and also triggered problems like urban heat island effect, more runoff, groundwater depletion pollution and so on (Setchell 1995; Alberti 1999; Whitford et al. 2001; Hamdi and Schayes 2008). As a consequence, the cities become enervated to keep up the well-being of its population (Cacciola et al. 2002; Nowak and Crane 1998; Norberg 1999; de Hollander and

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Staatsen 2003). The instantaneous change in the environment due to the green-cover loss is 'the rising air temperature', generally referred to as 'the urban heat island effect' (Oke 1982), which affects the health and economy of the people (Heisler 1986; Nowak et al. 1994; Kjelgren and Montague 1998; McPherson et al. 2002). For example, the study by Conti et al. (2005) in Italy during the summer of 2003 reported an increase of 15% in mortality due to the 'urban heat island effects' over the previous year (from 20,564 to 23,698 deaths). Further increase in urban temperature amplifies the space-cooling system's energy consumption and causes economic impact (Akbari et al. 1992, 1997).

On the other hand, degrading air quality emerges as today's prime health issue in many cities. For instance, Ahmad's (1990) research on urban air pollution and the occurrence of bronchitis in Kuala Lumpur between the years 1979 and 1985 calculated that the mean bronchitis prevalence rate for the whole city is 2.3 per 10,000 persons; and the annual trend indicating steady increase of 4.0 per 10,000 persons. In this context, the urban greeneries come in handy to ameliorate the urban air quality by means of sequestration, interception and filtration (Nowak 1993; Jo and McPherson Gregory 1995; Bolund and Hunhammar 1999; Akbari 2002; American forest www.americanforest.org). Furthermore, in an urban setting, the canopy interception of precipitation cuts down the storm water treatment and the flood control expenditures (Sanders 1986; Arnold and Gibbons 1996; Bolund and Hunhammar 1999; Pauleit and Duhme 2000; Taylor 2000; Xiao et al. 2000; Xiao and McPherson 2002).

These earlier studies reveal that the reduction in the amount of green-covered area could affect the city's environmental performance. Therefore, by taking Chennai city as the case study, a GIS model was developed to appraise the influence of the green-cover change on the city's environmental performance. Though, similar studies are done in other cities using the CITY green software, this study differs in two aspects. First, most of those studies are seldom analyzed beyond quantifying the benefits of the existing trees benefits. Second, this proposed study is an attempt to understand the spatial implication of the green-cover change on the city's environmental performance. (http://www.americanforests.org/productsandpubs/citygreen/).

The major limitation faced during this research is the lack of appropriate information, particularly the fact that there is no up-to-date and authoritative information on Chennai's past Green-covered areas. The availability of suitable time serial satellite data having submeter resolution was another shortcoming faced to obtain the leaf area index. Therefore, this research utilized the green pixels of the land-cover raster data, rather than using the leaf area index. The entire analysis was carried out in raster format. Finally, the association between the green-cover change and the environmental performance change was evaluated by the correlation assessment.

2 Background of the case study area

Chennai, widely known as Madras, is one among the four metropolitan cities of Indian subcontinent, which has a long history since 1639. Located in southern India, lies between 12° 09′, 80° 12′ NE and 13° 09′, 80° 19′ NE. It had grown from a small hamlet extending over an area of 6,800 Hectare with a population of 0.540 million to a metropolitan having 6.04 million populations extending in 17,047 Hectare. Its population is growing at an average of 25% per decade (http://www.cmdachennai.gov.in). The city is situated in a hot climatic zone, experiencing tropical maritime monsoons. The minimum temperature ranges from 21 to 24°C in the month of December to February, and the average daily maximum temperature is 37°C during the month of May. The minimum monthly rainfall ranges from 6 to 10 mm in the month of February, and a maximum rainfall of 320 mm has been recorded during the month of November. The city's terrain is more or less a flat plain with scattered hillocks, gently sloping toward the Bay of Bengal in the east. The soil type is broadly classified into red loamy soil (in the inland), sandy soil (along the coastal belt), clayey soil (along low lying areas) and lateritic soil (on some barren lands). The mean wind speed in the city is 4.055 m/s at a height of 15 m from the mean sea level.

After India's economic liberalization, Chennai city experienced rapid urbanization, particularly between the years 1997 and 2001 most of the natural spaces were converted to built-up areas, which distressed city's environmental processes, namely air quality, hydrological process and microclimate. Environmental modification between the years 1997 to 2001 were drastic compared to before and after this period. Therefore, to appraise Chennai's environmental performance change, this research has taken its study period between the years 1997 to 2001. Chennai, being a tropical coastal city, its atmospheric condition is fairly stable only during the spring season. Considering that, the analyses were carried out in spring season by collecting all relevant data for the same period.

3 Methodology

This research aims at achieving two basic objectives by means of appraising the relationship between the green-cover and the city's environmental performance. First, to understand the spatial implication of the green-cover reduction on the environment and second to develop a model to assess the influence of the green-cover change on the city's environmental performance. This research has evolved the GIS model by adopting Chennai city as the case study area. The GIS model is built based on the changes in three major green-cover services during the study period, namely (1) air purification service, (2) regulating the urban hydrological processes and (3) stay poised the urban microclimatic processes. The proposed GIS model consists of three steps. They are

- Acquiring the land-cover information.
- Building the GIS model.
- Appraisal of Chennai city's environmental performance change.

Each of these steps is elaborated below.

4 Acquiring the land-cover information

Chennai city's land-cover information for the years 1997 and 2001 was obtained from the IRS-1C and IRS 1D satellite data of the Indian Remote Sensing agency. The satellite images were acquired during the spring season, when sky is clear. The IRS 1C data was obtained on 17 Feb 1997, and the IRS 1D was acquired on 28 March 2001. Their spatial resolutions are 5.8 m. At the outset, the geometrical distortions of these satellite images are corrected before deriving the land-cover information, which is obtained by two steps. In the first step, groups of pixels, known as 'training sets', are selected to represent the various on-ground land-cover types. A total of nine training sets are selected in a supervised manner based on prior knowledge of Chennai's land-cover. In the second step, they are given as the representative key input variables to the image processing algorithm of the Erdas Imagine software (http://www.erdas.com/). According to the input, the algorithm assigned specific value to each pixel of the IRS 1C, and the IRS 1D satellite data and

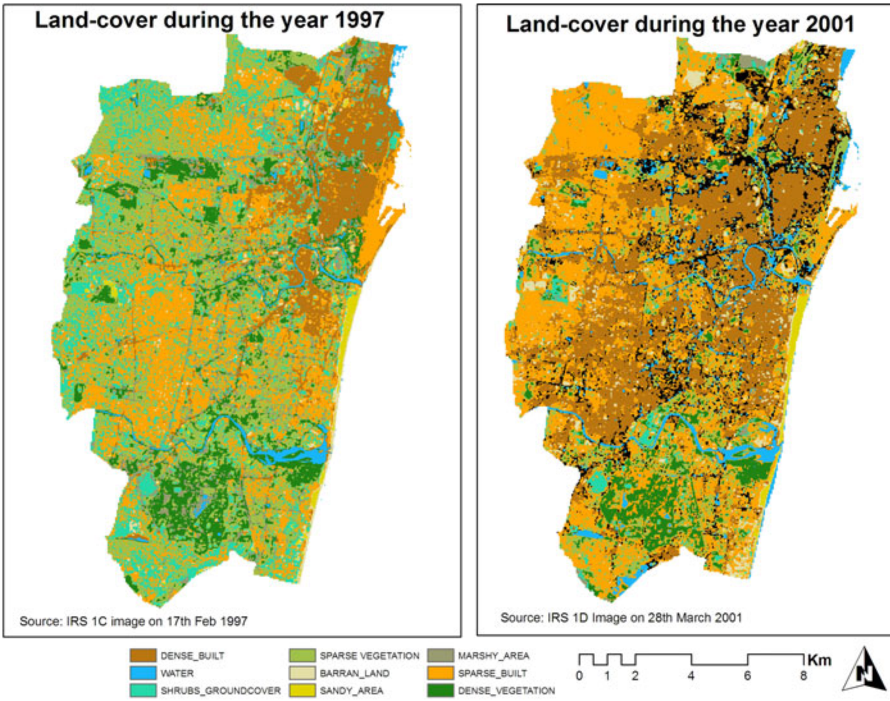

Fig. 1 Chennai city's land-cover during the years 1997 and 2001

subsequently grouped them into nine categories of land covers as shown in the Fig. 1. They are dense built-up areas, sparse built-up areas with vegetation, dense vegetation, inland water body, shrubs, ground covers, barren lands, marshy area and sandy area.

5 The GIS model for environmental performance

The environmental performance of a city can be defined as its capacity to support human health by means of providing fresh air, water and livable climatic conditions. The GIS model was built on the concept of Map Algebra (Tomlin 1994). This type of GIS analysis is generally known as raster analysis, and utilizes the raster data. Each cell of the raster data represents a location and their phenomena, which enables us to do the geographical analysis at the finer level, on a cell by cell basis. This aspect gives better results, while studying the phenomena that are spatially continuous rather than discrete in nature, like urban environmental issues. Therefore, this research has taken the pixels for analysis rather than the leaf area index. The proposed model is developed using three types of raster analysis, namely the local function, the focal function and the zonal function.

The environmental performance model was built utilizing the three green-cover services as variables. They are air quality amelioration service, microclimatic amelioration service and hydrological process regulation service. Using these as parameters, the GIS model was constructed in the model builder (Fig. 2). The following points are kept in mind while constructing the model,

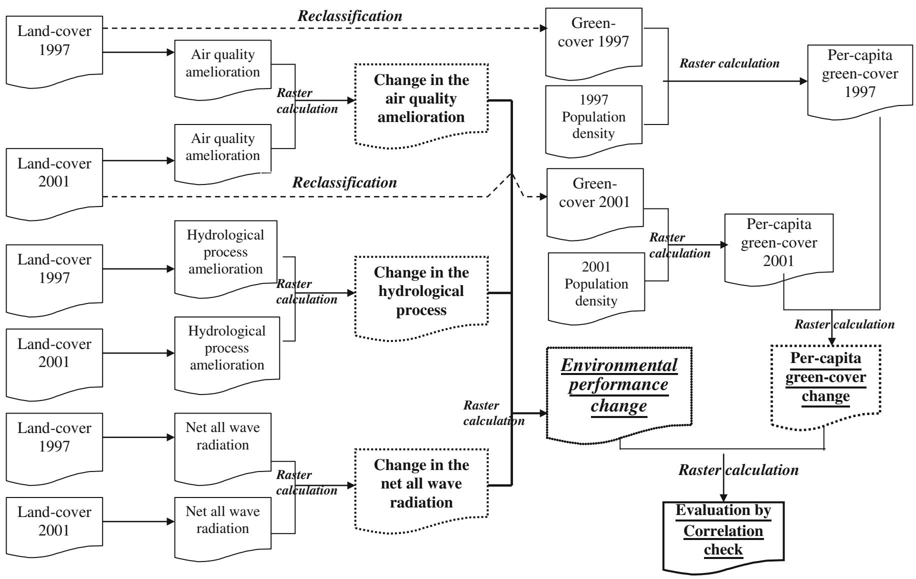

Fig. 2 Methodology

- The cell sizes of all the input and output raster layers are fixed as 5 m $\times$ 5 m, including the pollution data.
- The basic analyses are carried out at microlevel on a cell by cell basis in order to capture the finer details, i.e. change in all the three green-cover services are computed at cell level.
- The quantifications are done at the macrolevel, i.e. at the ward level (the smallest administrative unit), through summing up the cell values.
- For comparison purpose, all these value changes at the macrolevel are converted into a uniform relative scale.

6 Appraisal of environmental performance change

The proposed model appraised Chennai city's environmental performance in three steps. First, it calculated the modifications in the green-cover's services. Second, it evaluated the change in the city's environmental performance. Third, it appraised the correlation between the above two. Each of these steps is elaborated as follows:

6.1 Changes in Chennai city's green-cover service

The changes in the three types of green-cover services within Chennai city are assessed in the following manner.

6.1.1 Air quality amelioration service

Vegetation removes pollution from the air, both by stomatal absorption and by means of intercepting the pollutant's dry deposition (Boybeyi 2000). So far, numerous models have been developed to estimate the pollution removal capacity of the vegetation. Among Baldocchi et al. (1987) model on gaseous deposition on the surface of the vegetation is adopted to assess the air quality amelioration service of Chennai city's green-cover. This model estimates the deposition flux (F_d) by multiplying the deposition velocity (V_d) with the pollutant concentration (C).

$$F_d = V_d * C.$$

The deposition velocity is computed by totaling the inverse of all resistance that is confronted by a pollutant while deposition. They are, aerodynamic resistance (R_a), quasi-laminar (surface boundary layer) resistance (R_b), and canopy resistance (R_c). Therefore, the deposition velocity equals to

$$V_d = (R_a + R_b + R_c)^{-1}$$

Though this formula is generally used for calculating the deposition of gases, it is widely adapted to estimate the pollution's depositional velocity on urban trees (Nowak and Crane 1998).

SO2, NO2, SPM (<10 micron) are the three major pollutants of Chennai city. They mainly occur due to intensifying urbanization, increasing industrial activities and vehicular traffic. The pollution deposition velocity of Chennai city is assessed mainly by considering these three pollutants. The intensity of those three pollutants between the years 1992 and 2002 at various locations (Fig. 3) of Chennai city is taken from the National Ambient Air Quality Monitoring Series (NAAQMS, the annual report of the Central Pollution Control Board (CPCB) India). Using the ArcGIS Spatial Analyst, all these point pollution data are converted as pollution concentration (C) surfaces (raster format). Then, the average level of SO2, NO2, and SPM pollution across the city is calculated as a pollution concentration layer. Then the aerodynamic resistance (R_a) calculated by way of Killus et al. (1984); and the boundary layer resistance (R_b) computed based on Pederson et al. (1995); and the canopy resistance (R_c) assessed according to Baldocchi et al. (1987). The cuticular resistance is not relevant for SPM. Like this R_a, R_b, and R_c were derived individually for SO2, NO2 and SPM for the years 1997 and 2001. Subsequently the depositional velocity and depositional flux of SO2 and NO2 are computed for two periods.

Combining these depositional fluxes, the average pollution flux of Chennai city is derived for the years 1997 and 2001. The amount of pollution removed by the green-cover within the city for a particular year is quantified by multiplying the green-covered area with the net average pollutant flux of that year across the city. The quantity of pollutant removed by the green-cover in Chennai city during the years 1997 and 2001 is calculated separately at the microlevel and then summed up at the ward level. Then, by subtraction, the net change between the years 1997 and 2001 is identified at the ward level. During the study period, commercial and industrial activities are amplified at some wards and thus increased the vehicular traffic. As a result in those wards the air quality amelioration services are declined (Fig. 4a) drastically. In short the pollution removal capacity by natural means has gone down considerably across the city, at some wards to the extent of 68% dwindled.

6.1.2 Hydrological processes regulating services

The rapid conversions of permeable green-cover to impermeable paved surfaces have increased the city's surface runoff and have reduced the infiltration processes that have

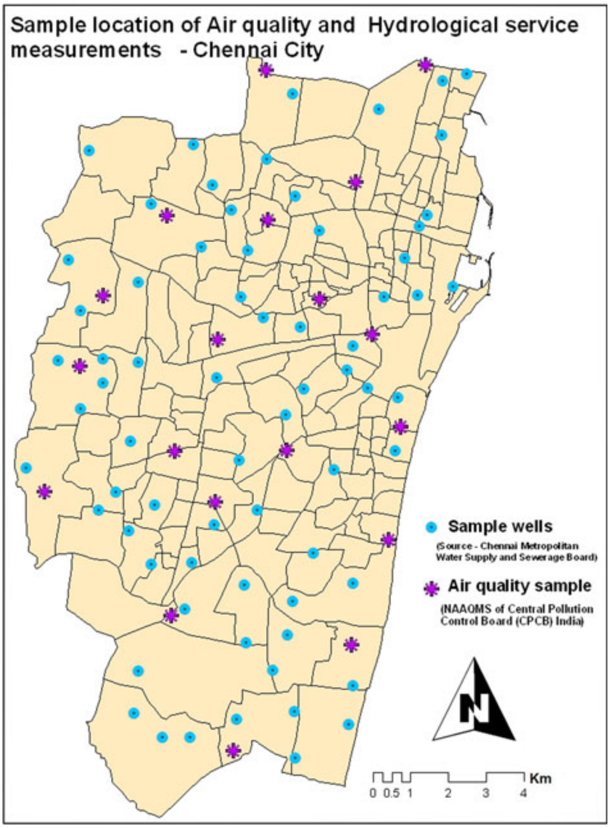

Fig. 3 Sample location of air quality and hydrological service measurement

invariably affected the city's groundwater level. The influence of green-cover change on the surface retention capacity and runoff volume is assessed using the Technical Release 55 (TR-55 1986) of US Soil Conservation Service (SCS).

First, the curve number raster layer (CN) for the years 1997 and 2001 is obtained from the SCS (1986) based on the soil type and land use of the city. From these curve number raster layers, the 'potential maximum retention after runoff begins' (S-raster) are computed for the study years 1997 and 2001. That is, $S = ((1000/CN) - 10)$. Following this, using the S-raster and 24-h maximum rainfall intensity (P), Chennai city's runoff 'Q' for the years 1997 and 2001 is derived.

$$Q = (P - 0.2 * S^2)/(P + 0.8\,S)$$

Between the years 1997 and 2001, some wards of the city almost lost 99% of the green-cover area to the non-vegetative developments. Because of this, the city's surface tumbled in its water-holding capacity**.** Particularly at the periphery and the northern part of the city the urbanization process multiplied during the study period, which increased the percentage of impermeable surfaces. As a result, the peak flow runoff amplified up to 89% in those wards (Fig. 4b). The raised surface runoff and reduced retention capacity of the land-cover almost stopped the groundwater recharging processes in the city. Hence, the city's groundwater level lowered up to 10 m (Fig. 4d) from the year 1997 to 2001 (source:

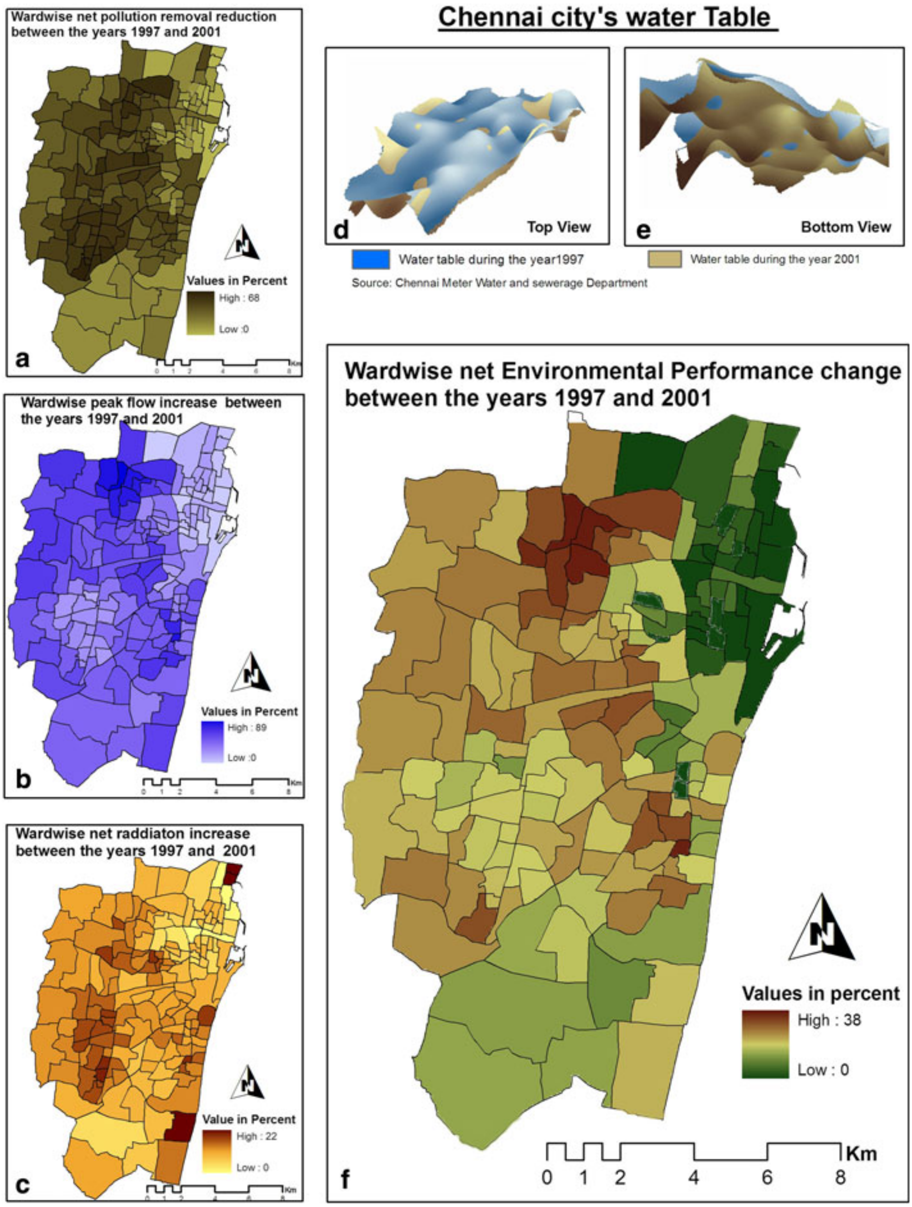

Fig. 4 Results of the Chennai city's environmental performance analysis

CMWSSB), which eventually affected the groundwater quality by raising the total dissolved solids (The Hindu 2004). During the study period, in some parts of the city the natural areas were not modified drastically, despite increase in built-up areas and traffic volumes. Those areas showed less change in the hydrological process compared to other two natural processes. For example, in the lower middle part of the city (Fig. 4b).

6.1.3 *Microclimate amelioration services*

Surface radiative fluxes are more critical to urban microclimate compared to direct solar radiation. The intensity of surface radiative fluxes governs by the characteristic of land-cover (Masson 2000). Particularly green-cover lessens the surface radiation by shading. For example, the green areas of Chennai city are experiencing 2 to 4°C less heat than the densely built-up areas (Sundersingh 1990). During the study period (1997–2001) it has been found that the non-vegetative land-cover was increased as much as 88% at some parts of the city. The corresponding change in the green-cover's microclimatic amelioration service is assessed by calculating the modification in the city's surface radiative fluxes between the study periods. The surface solar radiation (R_N) of the city has been calculated according to the concepts of PCRAMMET (1999). That is

$$R_N = (1 - r)R - I_N$$

where r is albedo, the numerical value of the solar irradiation property of the surfaces. R is the total incoming solar radiation, and I_N is the day tine net long wave radiation for the spring season calculated based on Holtslag and van Ulden (1983) and Offerle et al. (2003). In the above formula $(1 - r)\ R$ is the net short wave radiation. The value of albedo (r) for different land covers of the city are inferred from the study of Pielke and Avissar (1990).

Initially, Chennai city's albedo-cover for the years 1997 and 2001 is obtained by assigning the albedo value (r) to each land-cover type through re-classifying the land-cover raster data. The day time R_N for the years 1997 and 2001 is calculated for spring season at the microlevel using the ArcGIS Spatial Analysist. Next, using the zonal function the R_N for each year is summed up at the ward level. Finally, the change in the net wave radiation between the study periods, are calculated by simply subtracting the net wave radiation of the year 1997 from the year 2001. The wards in the periphery and central part of the Chennai city lost its green-cover to accommodate buildup area. Therefore, their micro-climate amelioration capacity drops down significantly, i.e. the net radiation has increased up to 22% (Fig. 4c).

6.2 The environmental performance change

At the outset the changes in three environmental services (air quality amelioration, hydrological process regulation, microclimate amelioration) between the years 1997 and 2001 were converted into uniform scale in terms percentage. Then the ward-wise environmental performance change of Chennai city is worked out by calculating the mean percent change of all the above mentioned environmental services of the green-cover. The outcome of this analysis (Fig. 4f) impeccably reveals the changes in the environmental performance across the city and in some parts has reduced to 38%. Chennai city's current environmental problems like water scarcity, drying of the groundwater table, flood during the monsoon and increasing local temperature are all clear evidences of its environmental performance change. Though, other factors also cause for this, green-cover destruction accelerates the environmental change and reduces city's self-rejuvenating capacity.

6.3 Evaluation

The degree of association between Chennai's green-cover change and its net environmental performance changes are evaluated using the coefficient of correlation (r) method.

Since the city's environmental quality is more influenced by its population density, the per capita vegetative cover has been taken for the correlation assessment. The per capita green-cover change is calculated at the ward level, by dividing the ward-level green-covered area by the population density. The correlation between the per capita green-cover change and environmental performance has been evaluated using the correlation factors (r) (Gujarati 1988) in the ArcGIS raster analysist. That is,

$$r = \frac{SS}{\sqrt{SS_{xx}SS_{yy}}}$$

where r is a measure of the strength of the linear relationship between the per capita green-cover (variable x) and the environmental performance (variable y). The outcome of this analysis shows a positive relationship (i.e. $r = +1$) in most of the wards, except in the lower and upper part where the value of the correlation coefficient, r, is negative. Those areas are reserved forests, water logging area and less urbanized areas (Fig. 5). This confirms the relationship between the per capita green-cover change and the environmental performance change of the city.

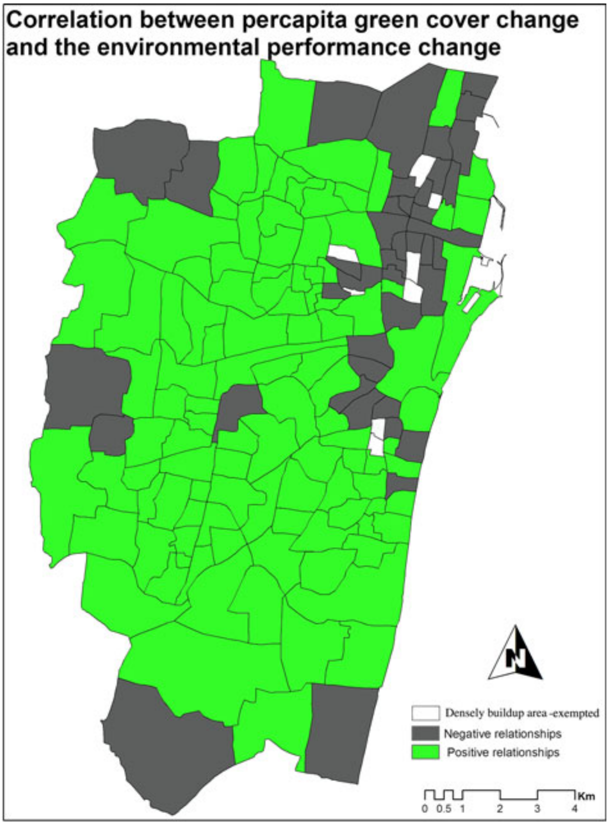

Fig. 5 Correlation between per capita green-cover change and environmental performance change

7 Discussion

The variations in the outcome are mainly because of the variation in the city's physical conditions. For instance, the northeast area of Chennai city is a historic part, characterized by wall-to-wall constructed, densely built multistorey buildings with little or no vegetation. The southwest part of the city is covered with reserved forests. The green-cover in both these places has not changed much between the years 1997 and 2001. Therefore, the outcome showed low environmental performance variation in these parts. From the ground observation, the northeast parts do not have any vegetation. Due to that the runoff, surface radiations are also more compared to other parts. Many of the institutional areas are located in the east part of the city along the coast. The green spaces of these institutional areas are modified fairly for their own growth. This has caused moderate change in the net environmental performance. The lower middle part of Chennai city has good amount of vegetation. Conversely, being an important commercial center, the increasing traffic and commercial activities have affected the quality of air and the hydrological process. The upper middle part of the city has a mixed residential area with a few industries. The population density here has intensified due to mixed economic opportunities, which has significantly shrunken the green spaces. Because of the constraints in all these areas, the population has naturally increased in the western and northwestern part of the city, which has brought down the green-cover area. As a result of these, the air quality, the hydrological process and local temperature are all heavily affected in these parts between the study periods. Nonetheless, this part still has a good amount of greenery; therefore, the surface runoff and surface radiation are minimum compared to the other parts. The correlation assessment shows a positive relationship in all parts, except at few places.

8 Conclusion

The environmental performance of a city can be broadly defined as its capacity to support human health, by providing quality air, water, livable climatic conditions and so on. These three components are maintained and refreshed continuously by the functions of the vegetative cover. The reduction of green-cover fundamentally affects the urban system's self-rejuvenating capacity. Hence, it has been suggested that monitoring the green-cover could help us maintain the well-being of human life. Therefore, to appraise the influence of the green-cover change on the city's environmental performance, a GIS model is proposed by adopting Chennai city as the case study area. The outcome of the model substantiates the positive relationship between the per capita green-cover change and the city's environmental performance change between the years 1997 and 2001, expect few areas that are either 100% built-up area or waterlogged area. This analysis also showed that green-cover can be one of the tangible indicators to monitor a city's environmental performance. Nevertheless, this research has been carried out to corroborate the relationship between the green-cover change and the city's environmental performance change rather than to quantify the impact. This is done as part of a bigger research effort, mainly to understand the critical areas, in order to make the appropriate interventions. As a matter of fact, in India there has hardly been any research carried out in the area of urban green-cover. In this context, this study can fill the existing void thereby providing suitable framework to carryout similar studies in other Indian cities. To conclude, this study emphasized that the role of the urban green-covers does not just end in the improvement of the physical environment; but also, it can be regarded as an answer to the well-being of people. On the other hand, some trees have been producing toxic gases, which are dangerous for human health, therefore avoiding such trees while selecting plants for urban areas would give better results.

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References

Ahmad, Azaharuddin. (1990). Urban air pollution and the occurrence of Bronchitis in Kuala Lumpur. *Energy and Buildings, 15–16*, 775–790.

Akbari, Hashem. (2002). Shade trees reduce building energy use and CO2 emissions from power plants. *Environmental Pollution, 116*(1), S119–S126.

Akbari, Hashem, Joe, Huang, Haider, Taha, & Susan, Davis. (1992). *Cooling our communities: A guidebook on tree planting and light-colored surfacing*. Washington, DC: US-EPA.

Akbari, Hashem, Kurn, D. M., Bretz, S. E., & Hanford, J. W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings, 25*, 139–148.

Alberti, Marina. (1999). Modeling the urban ecosystem: A conceptual framework. *Environment and Planning B: Planning and Design, 26*, 605–630.

Arnold, C. L., Jr, & Gibbons, C. J. (1996). Impervious surface coverage. The emergence of a key environmental indicator. *Journal of the American Planning Association, 62*(2), 243–257.

Baldocchi, D. D., Hicks, B. B., & Camara, P. (1987). A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. *Atmospheric Environment, 21*, 91–101.

Bolund, Per, & Hunhammar, Sven. (1999). Ecosystem services in the urban areas. *Ecological Economics, 29*, 293–301.

Boybeyi, Z. (Ed.). (2000). *Mesoscale atmospheric dispersion* (p. 424). Ashurt, Southhampton: Wessex Institute of Technology (WIT) Press.

Cacciola, R. R., Sarva, M., & Polosa, R. (2002). Adverse respiratory effects and allergic susceptibility in relation to particulate air pollution: flirting with disaster. Review article. *Allergy, 57*, 281–286.

Conti, Susanna, Meli, Paola, Minelli, Giada, Solimini, Renata, Toccaceli, Virgilia, Vichi, Monica, et al. (2005). Epidemiologic study of mortality during the summer 2003 heat wave in Italy. *Environmental Research, 98*(3), 390–399.

de Hollander, A. E. M., & Staatsen, B. A. M. (2003). Health, environment and quality of life: An epidemiological perspective on urban development. *Landscape and Urban Planning, 65*, 53–62.

Gujarati, D. N. (1988). *Basic econometrics* (3rd ed.). New York: McGraw-Hill Inc.

Hamdi, & Schayes, (2008). Sensitivity study of the urban heat island intensity to urban characteristics. *International Journal of Climatology, 28*, 973–982.

Heisler, M. G. (1986). Effects of individual trees on the solar radiation climate of small buildings. *Urban Ecology, 9*, 337–359.

Holtslag, A. A. M., & van Ulden, A. P. (1983). A simple scheme for daytime estimates of the surface fluxes from routine weather data. *Journal of Climate Applied Meteorology, 22*, 517–529.

Jo, Hyun-Kil, & McPherson, G. E. (1995). Carbon storage and flux in urban residential green space. *Journal of Environmental Management, 45*, 109–133.

Killus, J. P., Meyer, J. P., Durran, D. R., Anderson, G. E., Jerskey, T. N., Reynolds, S. D., et al. (1984). *Continued research in mesoscale air pollution simulation modeling. Volume V: Refinements in numerical analysis, transport, chemistry, and pollutant removal*. Publ. EPA/600/3-84/095a. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Kjelgren, Roger, & Montague, Thayne. (1998). Urban tree transpiration over turf and asphalt surfaces. *Atmospheric Environment, 32*(1), 35–41.

Masson, V. (2000). A physically based scheme for the urban energy budget in atmospheric models. *Boundary Layer Meteorology, 94*, 357–397.

McPherson, G. E., Simpson, J. R., Klaus, I. S. (2002). Actualizing Microclimate and air quality benefits with parking lot shade ordinances. USDA.

Norberg, Jon. (1999). Linking nature's services to ecosystems: some general ecological concepts. *Ecological Economics, 29*, 183–202.

Nowak, D. J. (1993). Atmospheric carbon reduction by urban trees. *Journal of Environmental Management, 37*, 207–217.

Nowak, D. J., Crane, D. E. (1998). The urban forest effects (UFORE) model, quantifying urban forest structure and functions. USDA forest services, integrated tools proceedings USA August, 16–20.

Nowak, D. J., McPherson, E. G., & Rowntree, R. A. (1994). *Urban forest structure: The state of Chicago's urban forest climate project*. US Department of Agriculture, Forest Service: General Technical Report.

Offerle, B., Grimmond, C. S. B, & Oke, T. R. (2003). Parameterization of net all-wave radiation for Urban areas. *Journal of Applied Meteorology, 42*, 1157–1173.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meterological Society, 108*, 1–24.

Pauleit, S., & Duhme, F. (2000). Assessing the environmental performance of land cover types for urban planning. *Landscape and Urban Planning, 52*(1), 1–20.

PCRAMMET. (1999). PCRAMMET user's guide of US environmental protection agency, URL: http://www.epa.gov/scram001/userg/relat/pcramtd.pdf. Accessed 25 Nov 2004.

Pederson, J. R., Massman, W. J., Mahrt, L., Delany, A., Oncley, S., den Hartog, G., et al. (1995). California ozone deposition experiment: Methods, results, and opportunities. *Atmospheric Environment, 29*(21), 3115–3132.

Pielke, R. A., & Avissar, R. (1990). Influence of landscape structure on local and regional climate. *Landscape and Ecology, 4*, 133–155.

Sanders, R. A. (1986). Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecology, 9*, 361–376.

Setchell, A. C. (1995). The growing environmental crisis in the world's mega cities. *Third World Planning Review, 17*, 1–18.

Sundersingh, D. S. (1990). Effect of heat island over urban Madras and measures for its mitigation. *Energy and Buildings, 15–16*, 245–252.

Taylor, J. (2000). The hydrological effects of urban forests with reference to the maritime Pacific Northwest, Technical Bulletin 6. landscape & Livable Environment. URL: www.sustainable-communities.agsci.ubc.ca. Accessed 20 Nov 2004.

The Hindu. (2004). The Hindu, national daily news paper.; Date: 28/02/2004 URL: http://www.thehindu.com/thehindu/pp/2004/02/28/stories/2004022800050100.htm. Accessed 20 Nov 2004.

Tomlin, C. D. (1994). Map algebra: one perspective. *Landscape and Urban Planning, 30*, 3–12.

TR-55 (Technical Release 55) (1986) United States Department of Agriculture (USDA), Urban Hydrology for Small Watersheds. Soil Conservation Service, Engineer.

Whitford, V., Ennos, A. R., & Handley, J. F. (2001). 'City form and natural process'- indicators for the ecological performance of urban areas and their application to Meyseyside, UK. *Landscape and Urban Planning, 57*, 91–103.

Xiao, Qingfu, & McPherson, G. E. (2002). Rainfall interception by Santa Monica's municipal urban forest. *Urban Ecosystems, 6*, 291–302.

Xiao, Qingfu, McPherson, G. E., Ustin, S. L., Grismer, M. E., & Simpson, J. R. (2000). Winter rainfall interception by two mature open-grown trees in Davis, California. *Hydrological Process, 14*, 763–784.