Extending the Frontier of GIS Applications: Towards Evolving a Hybrid Tool for Sprawl Analysis

Y.A. Bununu[1] and A. Ahmed[2]
[1,2]Department of Urban and Regional Planning,
Ahmadu Bello University, Zaria-Nigeria

Abstract

The accurate mapping and analysis of urban sprawl has been a major challenge to urban planners. This has links to the shortcomings of known procedures and techniques of analysis that involve the use of the Shannon's entropy and the GIS and Remote Sensing techniques as standalone tools. The search for enhanced tools to confront these challenges has been long; but results have been slow in coming. This paper demonstrates the application of a unified frame of sprawl analysis based on the integration of GIS, remote sensing and the Shannon's entropy method. The results obtained showed advantages including the concurrent time series mapping and analysis of sprawl as well as the identification of sprawl implications. The results obtained confirm the potential of the tool in establishing the pattern and urban management implications of sprawl on multiple spatial and temporal scales. The primary benefit of the tool is that it provides urban planners and managers with an accurate, precise, flexible and cost effective means of determining and managing sprawl towards the sustainable growth and development of cities.

Background to the Study and Research Issue

Stand alone tools like the Shannon's entropy and the GIS have shortcomings in sprawl analysis that justify the search for new approaches (Yeh and Xia, 2001; Lata et al. 2001; Elkin et al. 1991; & Duany et al. 2000). Often ignored in this search is the potential of integrating the two tools; the argument being that the process will permit not only the mapping and statistical analysis of sprawl, but also the simulation of sprawl implications in a time series fashion and with precision. GIS and Remote Sensing are both spatial and temporal technologies that complement one another (Sudhira et al 2001). While Remote Sensing provides a reservoir of high quality digital data for GIS applications, it can be said that GIS compliments Remote Sensing by being probably the best means of utilizing the huge volumes of high quality data derived from it (Shekhar, 2006). Shannon's entropy on the other hand is acclaimed by researchers as a viable technique for quantifying the magnitude of sprawl using some measurable index (Yeh and Xia, 2001). Quantifying sprawl using the Shannon's entropy method almost always comes back to the issue of computing “area” and “density” which are then fed into some formula to enable the computation of a quantitative index of sprawl. This involves mapping relatively large areas and being able to compute measures of area and density accurately and quickly which is tedious and difficult to attain (Lata et al, 2001). Sprawl as a dynamic phenomenon requires timely data capture and retrieval and the ability to cross reference data across various time scales. The need for timeliness, accuracy, precision and cost effectiveness in the collection and analysis of sprawl related data therefore, is a consideration that new tools must meet which the integrated method attempts to provide. The logic in the integrated sprawl analysis tool is the dynamism it brings to the quantification of sprawl indices, sprawl pattern and the simulation of sprawl implications within one unified medium by utilizing data collected at varying spatial and temporal scales. The ability to manipulate spatial and attribute data in one medium is the second advantage offered. As shown in the literature, the Shannon's Entropy almost always falls short in sprawl pattern analysis and cannot be used in projecting sprawl implications (Yeh and Xia, 2001). The shortcomings of the techniques of GIS and remote sensing on the other hand lie with the lack of computation capacity to determine sprawl indices.

The development of an interface that brings the two tools together is the contribution made in this paper. How viable is the integrated framework in sprawl analysis? And how useful is it in measuring sprawl implications? The paper answers these two questions by reporting the results of the application of the tool in Kaduna metropolis in North-West Nigeria.

The Methods of Analyzing Sprawl

The Impervious Metric

This method aims to measure sprawl by calculating the change in the amount of built surface per capita, compares impervious change estimates derived from satellite imagery to population change data derived from census information (May et al. 2000). This approach is anchored on the assumption that urban sprawl is fundamentally defined as a relationship between population and the built-up environment (Booth and Jackson, 1997).

Human development typically converts native vegetation to impervious surfaces. Growth intended to minimize sprawl would limit the amount of impervious surface created with the influx of new residents to any given region. A principal challenge to this method is the difficulty in measuring impervious surfaces using Remote Sensing Techniques. The method is also limited because it is not suitable for pattern analysis (Booth, 2000).

The Neighbourhood Metric

This is another method that works on the principle of the population density at which mass transit becomes economically viable bearing in mind that sprawled districts are severely automobile dependent because they are characterized by rigidly separated residential and commercial areas rather than by neighborhoods with amenities in walking distance (Handy and Niemeier, 1997). It uses a variation on population density change analysis to assess the change in transit-friendly development as defined in the literature on public transit viability. A major challenge of this approach added to its shortcoming in pattern analysis is the data requirement for dasymetric mapping of population distribution and the utilization of the convolution kernel to assess density distribution at a map pixel scale (Newman and Kenworthy, 1989).

The Permit Metric

This works by way of evaluating the annual number of residential building permits for new construction. Specifically, it monitors the percentage of those occurring outside established urban growth boundaries as a way of gauging whether growth is leading to sprawl, or the infill of existing developed lands (Davis and Schaub, 2005). It evaluates the trends in permitted building activities in and outside of areas designated for development. Davis and Schaub (2005) further note that one key challenge of this approach is the non-availability of the data on building permits because even in the developed societies of the United States and Western Europe where the data is available, it is on record that obtaining and analyzing it is quite expensive. Like all the other techniques, this is also limited in the sense that it fails to take into account the spatial dynamics of sprawl as represented by resultant patterns.

Shannon's Entropy

Geographers study entropy levels in different population distributions and settlement patterns and use entropy-maximizing models to find the most probable pattern of spatial distribution in a system which is subject to restrictions. In the analysis of sprawl, Entropy works on the principle that naturally occurring virgin lands and landscapes are viewed as the normal and orderly state of things. Urbanization and human activity act to alter this naturally occurring state thereby creating disorder. A measure of this disorder is what the Shannon's Entropy represents. Shannon's entropy (Hn) can be used to measure the degree of spatial concentration and dispersion exhibited by a geographical variable (Burchell and Mukherji, 2003). This measure is based on the notion that landscape entropy or disorganisation increases with sprawl. Urban land uses are viewed as interrupting and fragmenting previously homogenous rural landscapes, thereby increasing landscape disorganisation. The dispersal of built-up areas from a city centre will lead to an increase in the entropy value. This gives a clear idea to recognise whether land development is towards a more dispersed or compact pattern.

The Shannon's Entropy of a variable is defined as:

$$Hn = \sum Pi\ (logn) \ldots\ldots\ldots\ldots\ldots 1$$

Where: Pi = proportion of the variable in the ith zone

n = Total number of zones under study

The value of entropy ranges from 0 to log n. If the distribution is very compact then the entropy value would be closer to 0 and when the distribution is dispersed the value will be closer to log n, large value of entropy indicates the occurrence of urban sprawl. Since entropy can be used to measure the distribution of a geographical phenomenon, the difference in entropy between two different periods of time can also be used to indicate the change in the degree of dispersal of land development or urban sprawl (Yeh and Xia, 2001). This is a more scientific and objective approach at quantifying sprawl.

GIS and Remote Sensing Techniques

Remote sensing and GIS can be used separately or in combination for application in studies of urban sprawl. When used separately, both remote sensing and GIS techniques will enable to some extent sprawl pattern recognition, mapping of patterns and spatial analysis. In the case of a combined application, an efficient, even though more complex approach is the integration of remote sensing data processing, GIS analyses, database manipulation and modeling into a single analyses system (Micheal and Gabriela, 1996 in Sudhira and Ramachandra 2001). Such an integrated analysis, monitoring and forecasting system based on GIS and database management system technologies requires an understanding of the nature of the phenomenon of urban sprawl and the application of available technologies. The integration of GIS and remote sensing with the aid of models and additional database management systems (DBMS) is the technically most advanced and applicable approach today. Remote sensing and GIS applications are growing very rapidly with the availability of high resolution data from state of the art satellites (LANDSAT, IRS-1C, Spot and Quickbird) and the advancement in computer hardware and software. These two technologies are however limited when it comes to the computation of the magnitude of sprawl or sprawl indices.

The Need for Robust Analytical Tools: Interfacing GIS, Remote Sensing and Shannon's Entropy

GIS and Remote Sensing are both spatial and temporal technologies that complement one another. While Remote Sensing provides a reservoir of high quality digital data for GIS applications, it can be said that GIS compliments Remote Sensing by being probably the only means of putting to good use the huge volumes of data derived from it. Shannon's Entropy on the other hand is acclaimed by researchers as a viable technique for quantifying the magnitude of sprawl using some measurable index (Sudhira and Ramachandra, 2001). Objective attempts at quantifying sprawl almost always come back to the issue of computing “area” and “density” which are then fed into some formula to enable the computation of a quantitative index of sprawl. This involves mapping relatively large areas and being able to compute measures of area and density accurately and quickly. Furthermore, if sprawl is to be analyzed following its nature as a dynamic phenomenon, then there is a need for data to be generated on a time-series basis. Standing alone, neither GIS and Remote Sensing nor Shannon's Entropy can fulfill all of the requirements mentioned above. However, the integration of the three can help overcome all the shortcomings mentioned and achieve the mapping and analyses of sprawl and its implications effectively and efficiently.

Urban Sprawl is a dynamic phenomenon. This dynamism therefore necessitates that any approach at studying it requires tools that are capable of providing insights into what the situation was in the past, establishing the present and simulating likely future trends. Secondly, any tools employed in the analysis of urban sprawl if they are to be effective must provide the capability to ensure timeliness, accuracy, precision and cost effectiveness in the collection and analysis of sprawl related data. Conventional mapping and data collection methods are slow, tedious and expensive, and therefore do not fit the description above. The current state of available technology is such that only the integration of Remote Sensing and GIS can ensure this supposed journey into the past through dated satellite imagery, a sojourn in the present through current satellite image scenes and a peep into the future with reasonable accuracy through scenario building and simulation using data collected on a time-series basis.

The Proposed Hybrid Tool for Integrated Sprawl Analysis: Methodology and Processes

The conceptual argument for integration of existing tools of sprawl analysis is with the need to ensure cost effective acquisition of time series spatial data, pattern analysis and simulation of the implications of sprawl including the computation of sprawl indices. The integrated tool that has emerged from this and shown in Fig. 1 involves five processes. The first is the use of remote sensing techniques and capabilities in the acquisition of digital spatial data (satellite images) at varying spatial and temporal scales. Stage two is the transmission to, and recording of the Remote Sensing data in a suitable GIS software environment. In this form, the Remote Sensing data is subjected to a series of pre-processing operations (which include geo-referencing, image extraction, geometric correction and image classification) preparatory to the mapping of different land cover (developed and undeveloped) categories. Computation of area coverage and development density statistics for the two digitized themes (i.e developed and undeveloped land) within the spatial unit of analysis (the urban area boundary as delineated into its constituent units) is the third component. This is permitted by the use of the 'measure area' and 'measure distance' modules common in most GIS software. The computation of sprawl indices (entropy) using the area and density statistics derived from the previous stage is the fourth component. The fifth and final stage of the integration is the exploration of scenarios using the mapped data in the GIS environment to simulate the implications of sprawl. This is permitted with accuracy, little effort and time spent using the modeling and measurement functionalities in the GIS.

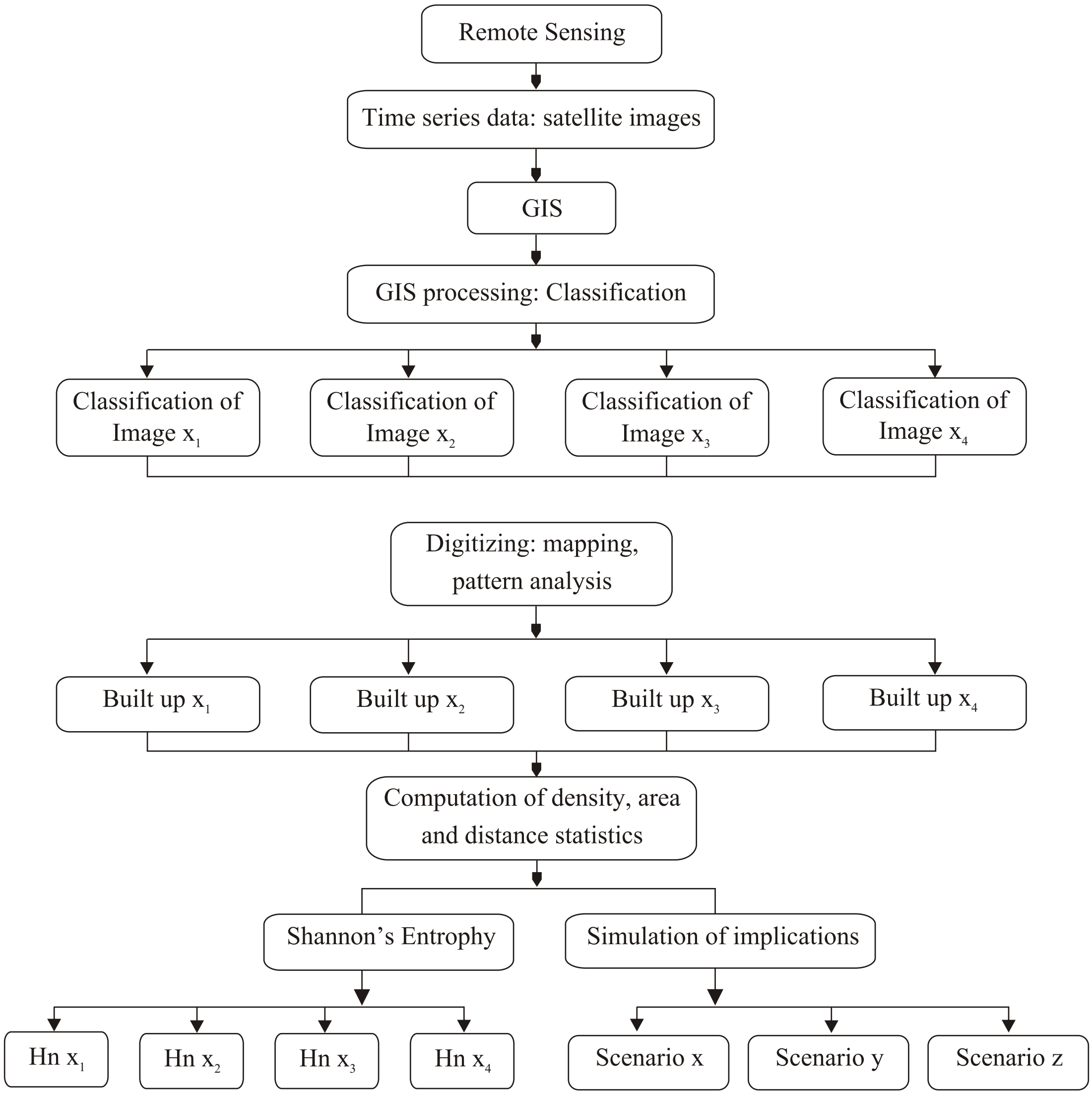

Figure. 1: *Framework and process of hybrid tool for integrated sprawl analysis*

Application of the Tool in Kaduna

The study sought to determine the urban sprawl pattern over the period of four decades (1973-2008). This is through the classification of satellite images of the city (over the four different time epochs: 1973, 1991, 2001 and 2008 as shown in fig. 2 below) and the mapping of the built extent of the city.

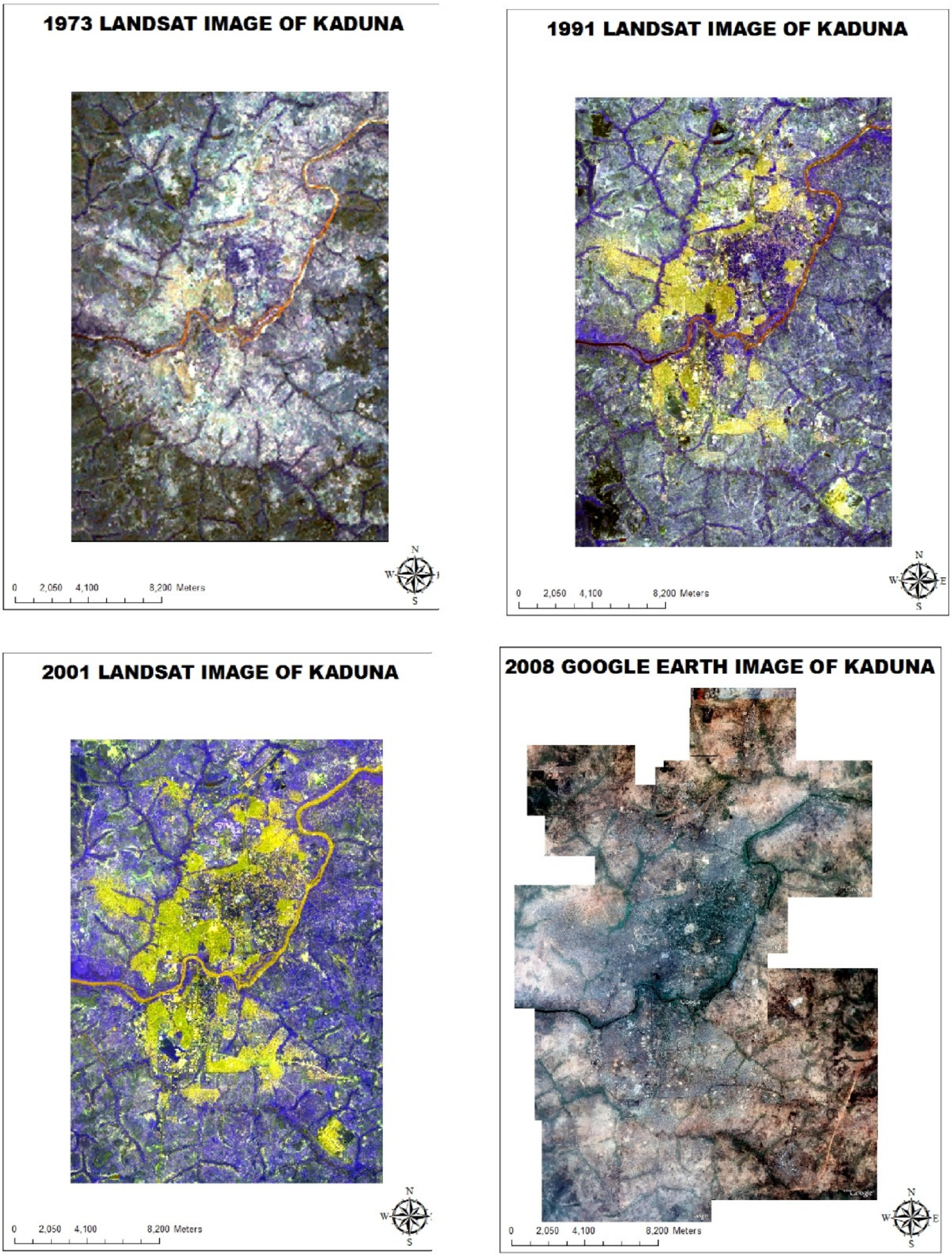

Figure 2: *Satellite images of Kaduna for 1973, 1991, 2001 and 2008*

The standard process for the analyses of satellite imagery such as extraction, restoration, classification and enhancement was applied. The maximum likelihood classifier (MLC) was further employed for the image classification. This was to enable the area under built-up theme to be recognized and digitized in the different satellite image scenes as a way of determining the extent of the urban area in each year. The next is the stage at which the spatial analysis capabilities of the GIS were utilized in computing the total area (in km^2) of all the built up themes for the different time epochs and the total area of the spatial units of analysis. Development densities for each time epoch were also computed using the results from the area computations. The urban sprawl indicator is then computed for each unit of analysis for the different time epochs using the entropy approach with the results of the area and density computations as input data. To simulate the urban management implications of sprawl in the city, the GIS was again utilized. This involved computing the total area of development outside approved layouts and development plans, and establishing the cost of servicing them. This also included the sprawled districts of Kaduna.

To obtain the value of Entropy, the area (in km^2) of the planning radius (40 km measured at the Leventis roundabout) of the city of Kaduna (which is the delimiting boundary of the officially designated Kaduna urban area) was computed using the "measure area" module in ArcGIS 9.2. The circle is then divided into quadrants. This is followed by the computation of the area (km^2) of the built-up theme for each quadrant at the four different time epochs as digitized from the classified satellite images. This was also achieved using the measure area module in ArcGIS 9.2. The development density (a measure of the proportion of what is built up compared to the total area of the planning radius) for each quadrant at each time epoch was then calculated and then substituted into the equation ***Hn = Pi log n, as Pi,*** with the value of log ***n*** (a constant) being equal to 0.6 , that is, the log of 4 (n in this case is the four quadrants). Repeating the procedure outlined above for every time epoch results in the computation of the magnitude of sprawl denoted by (Hn), that is the Entropy value. The result derived for the four time epochs enabled the analysis of the trend and intensity of sprawl at different periods in the evolution of Kaduna. By this, the quadrant with the highest or the lowest magnitude of entropy at any given epoch can be easily identified. The interpretation of the entropy values derived gave useful insights into the pattern of land development at different periods of time in the development of the city of Kaduna. The measure area module is again used to measure the area of the total built extent of the city at the four different time epochs and the area of the portions of the city categorized under Government approved layouts and DPs. This enabled easy computation of the proportion of the city's built extent that is within or outside Government approved development plans. Having all this data in an automated environment made possible scenario development, like simulating the cost of extending infrastructure and services to unserved locations; computing average transportation costs for trips within the city; annual rate of town growth; and revenue accruable from ground rent and other land and physical development related taxes and levies.

Results and Discussion

Sprawl Indices and Resultant Pattern

The entropy values obtained representing the pattern of sprawl in Kaduna is shown on table 1 and fig ii. As indicated, there are variations in the intensity of sprawl for the different quadrants at different periods, but an upward trend appears predominant. The North-East quadrant stands out with the highest values of Entropy at 0.13, 0.20, and 0.23 for 1973, 1991 and 2008 respectively. It however shows a drop to the South-West quadrant by 0.01 in 2001 with a reading of 0.19. This was the period characterized by very little outward growth and more of infill development. The second ranked is the South-West quadrant with entropy values of 0.06, 0.18, 0.20 and 0.21 for the four years under consideration. The last ranked quadrant in terms of sprawl intensity is the North-West quadrant which had Entropy values of 0.06, 0.12, 0.13 and 0.20 for the epochs 1973, 1991, 2001 and 2008. General picture obtained is that of growing entropy values from the base year suggesting sprawl.

***Table 1**: Entropy values for Kaduna 1973-2008*

Quarant	1973	1991	2001	2008
North-West	0.06	0.12	0.13	0.20
North-East	0.13	0.20	0.19	0.23
South-East	0.07	0.10	0.16	0.20
South-West	0.06	0.18	0.20	0.21

The sprawled pattern is attributable to population increases and the dispersed nature of urban growth as opposed to urban infilling. This is what accounts for the ribbon pattern of sprawl as the city is about 32km along its north-south axis and only 13km on its east-west axis (see fig 4).

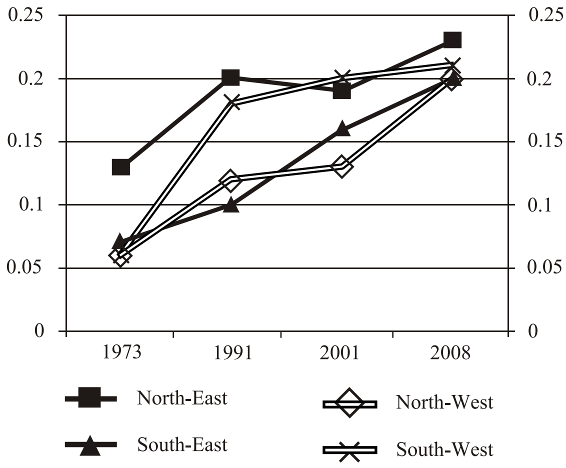

***Figure 3:** Entropy values for Kaduna by quadrants*

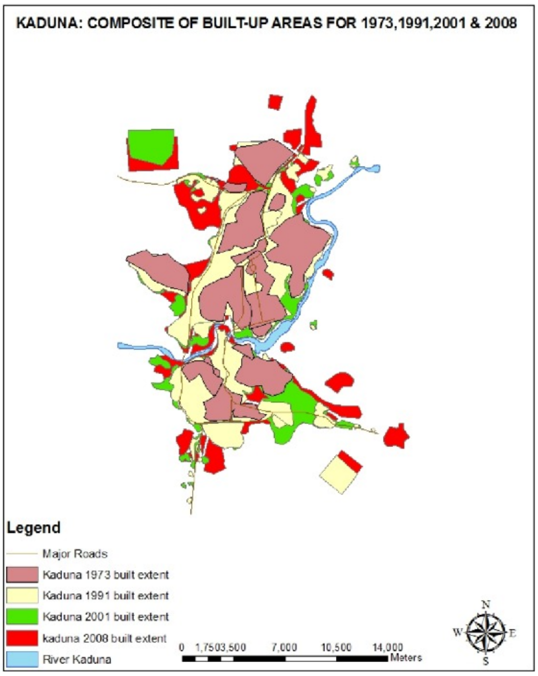

***Figure 4:** Overlay of built-up themes for 1973, 1991, 2001 & 2008*

Simulating Urban Management Implications

Establishing the urban management implications of sprawl using the tool was the second application attempted. Six issues were explored: cost of infrastructure delivery to the city, projecting land based revenues, establishing the quality of development control, computing urban growth rates, simulating traffic flow and congestion, and simulating transportation costs. First, cost of extending portable water (with distances taken as the crow flies) to three unserved outlying areas of the city was obtained and is shown in table 2 below. It indicates a cost of about Three Billion Naira to build distribution pipe networks for water supply to the sampled suburban districts. As shown by the statistics, sprawling districts pose problems of consumer diseconomies to a city as regards the extension of infrastructure and services to outlying developments. This is by increasing the cost per population served.

Table 2: *Cost of extending water distribution pipes to three peripheral locations*

S/N	Peripheral Area	Distance from Water works	Rate/500m of Piping in Naira	Total Amount in Naira
1.	Trade Fair Village Layout	19.70 km	35,696,700*	1,406,449,980
2.	Maraarraban Rido	11.61 km	35,696,700*	828,877,374
3.	Rigasa	12.87 km	35,696,700*	918,833,058
	Total			**3,154,160,412.00**

**Source: Kaduna State Water Board*

Using the tool, an attempt was next made to establish the areas that are planned and therefore taxable. The finding is that approximately 94.86 km^2 representing about 58% of the (164.00 km^2) of the total built fabric of Kaduna as at 2008 lies outside approved layouts and development plans. On ground rent alone therefore, the annual revenue loss was estimated at N4, 426,800,000.00 (Four Billion Four Hundred and Twenty Six Million Eight Hundred Thousand Naira Only). This is at the approved rate of approximately N70, 000 for a 1500m^2 lot. The loss of revenue is a strain on the city's financial base and a setback on the provision of basic infrastructure and services.

The application of the tool in computing the rate of urban growth for Kaduna was also attempted. This was done by employing the mapping, measure area and map calculator modules. The difference in area of the built extent between one epoch and another was computed, which showed an annual growth rate for Kaduna at 2.66 km^2. By using the tool, potential traffic flow pattern was also inferred. This was to estimate congestion and travel costs. The finding is that current sprawled form of the city (shown by the density statistics and entropy values) has created excessive separation of activity areas (work areas from residential areas) necessitating longer and regular journeys by residents. Vehicles Miles Travelled (VMT) therefore is high. With the absence of an efficient mass transit system, this has created heavy reliance on personal automobile, taxis and small buses for daily commuting. The low PCU of available transportation modes and the high Vehicle Miles Travelled raises concerns on environmental pollution, green house effects and global warming as a result of CO_2

emissions. The cost of transportation within the city resulting from this pattern was also established using the rate per kilometer as charged by commercial transport operators in the city. Using a hypothetical traveler between two points and then commercial rates chargeable, costs were established for various journeys. As an illustration, the route between Rigachikun and the Leventis roundabout in downtown Kaduna was used. With a distance of 17 km and at an average of N6 per kilometer, the cost of the trip is N100. The travel cost to work projected for the month at N6, 000 compares unfavorably with the minimum monthly wage of N18, 000 because it suggests that 1/3 of basic income is spent on transportation alone.

Conclusion

The results obtained generally supports the advancement of two arguments. The first is that the integrated sprawl analysis tool is viable. The second is that the mapping and analysis of sprawl in Kaduna has demonstrated that urban planners and managers alike can utilize the tool as a cost effective, convenient and accurate means of monitoring urban growth, analyzing varying resultant patterns and simulating the implications of any such resultant patterns. The tool generally offers tremendous opportunities for effective monitoring and management of development which is currently lacking in most urban centers of developing countries. This is because it offers solutions to the reported shortcomings of earlier tools of sprawl analysis (Booth, 2000; Handy and Niemeier, 1997; Newman and Kenworthy, 1989; Davis and Schaub, 2005; Yeh etal, 2001; Micheal and Gabriela, 1996 in Sudhira etal 2001).

Because of its reported versatility, it is recommended that urban planners and managers employ the hybrid tool of sprawl analysis in the mapping of urban growth, identifying and analyzing urban sprawl and the simulation of its implications. As shown from the study, not only will there be value from the precision of the tool but the savings in time facilitated by the tool allows for proactive response to urban development and management issues. To draw value from the methodology embodied in the tool, the basic constraints to its adoption need to be removed. In most planning offices, the equipment and personnel base to utilize the method is lacking. The constraint of lack of capacity can be removed through training and education. Secondly, there is an urgent need for government as represented by its agencies to improve mapping at suitable spatial scales and also improve the generation and archiving of other data types. This will facilitate effective research and formulation of robust urban management and development control strategies.

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