Geographical Information Systems (GIS) Innovations For Primary Health Care in Developing Countries

1 author:

Frank Tanser
University of Lincoln
394 PUBLICATIONS   **21,283** CITATIONS

Some of the authors of this publication are also working on these related projects:

masculinities View project

Emergency Medical Service Call Condition Clusters (EMSC3)/COVID-19: CCTV View project

Frank Tanser

Geographical Information Systems (GIS) Innovations For Primary Health Care in Developing Countries

Geographical information system (GIS) technology is increasingly being used in many areas of health care research and planning.[1] Applications range from the study of "classic" infectious diseases such as malaria, schistosomiasis, and tuberculosis, to cancers such as leukemia.[2]

One important area in which GIS is increasingly being applied is in the design and evaluation of health care programs.[3] This application is becoming more common not only in communities of industrialized countries, but in economically marginalized communities of developing countries as well.[4] The increasing availability of remotely sensed data sets and other digital databases, combined with declining hardware and software prices and improvements in global positioning system (GPS) accuracy, have encouraged more widespread use. The elevated disease burden in developing countries and proportion of that burden attributable to infectious diseases (often with well-defined and spatially varying covariates) make the inherent potential of GIS in developing countries considerable. In addition, due to infrastructure and cost constraints, many developing countries suffer from a lack of reliable statistics and disease reporting. GIS can help significantly in this area by filling the gaps with empirical disease modeling techniques. Public health practices need information to implement appropriate actions, and GIS is an innovative technology for generating this type of information. GIS is therefore considered an appropriate technology for developing countries, despite the fact that it appears to contradict the principles of appropriate technology (because it can require high costs and levels of expertise).[5]

Frank Tanser works as a spatial epidemiologist at the Africa Centre for Health and Population Studies, based in Mtubatuba, South Africa. His research has focused on the applications of GIS and remote sensing technologies to a diverse range of environmental and health problems. He was responsible for setting up and managing a comprehensive GIS within the Africa Centre's large population-based initiative that monitors and tracks vital events in a population of 85,000 in the surrounding area. He has worked for the South African Medical Research Council as a senior health GIS consultant and has undertaken numerous GIS related projects throughout Africa.
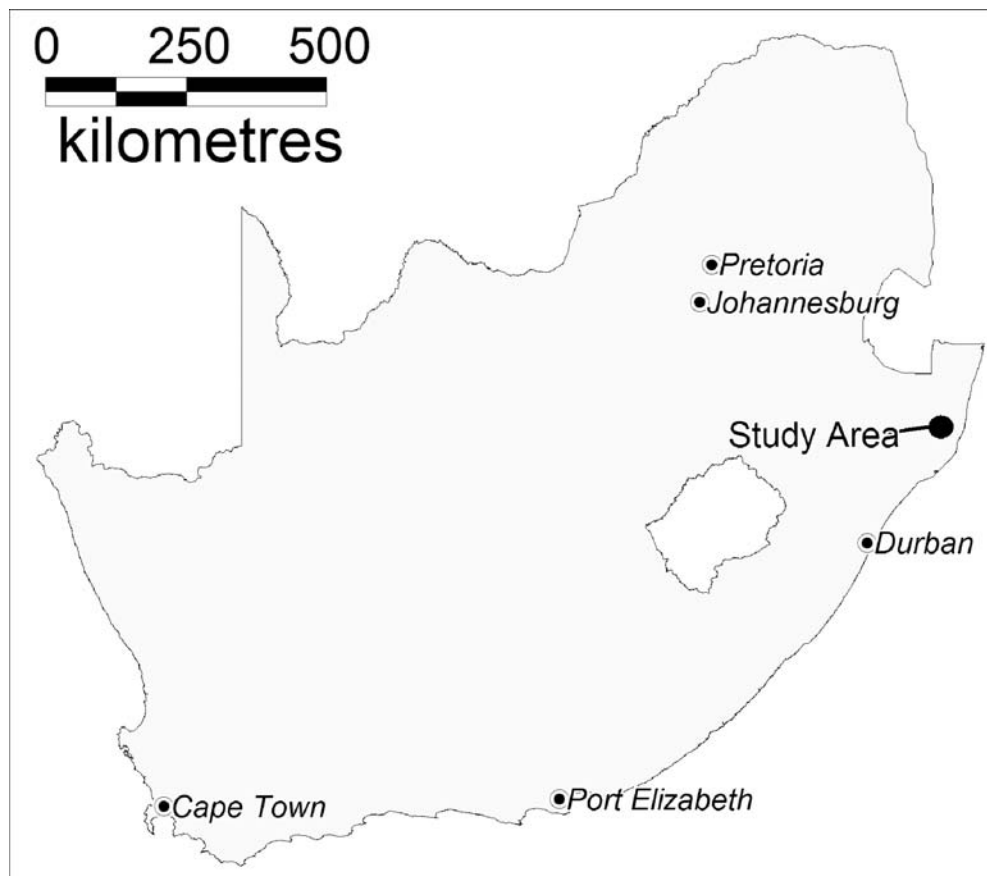
Figure 1. Location of the Hlabisa health subdistrict in South Africa.

Improved access to primary health care is required for the successful attainment of at least three of the United Nation's Millennium Development Goals (reduce child mortality; improve maternal health; and combat HIV/AIDS, malaria, and other diseases).[6] The effective delivery of health care in developing countries, and the development of systems to provide it, remain problematic. Malaria and tuberculosis are examples of diseases that thrive in the absence of effective health systems. Knowledge and understanding of health care usage and population distribution is vital for health resource allocation and planning. Good health system management depends on informed decisions regarding resource allocation. These decisions, however, often occur in the absence of data that allow the pattern of resource allocation to be assessed. This analysis of resource patterns is one area in which GIS can contribute significantly through its ability to "layer" multiple data sets from different data sources at different scales (using space as the unifying framework) to provide an evidence base from which to assist the decisionmaking process.

The use of GIS in health care research and management generally falls into one of three categories:
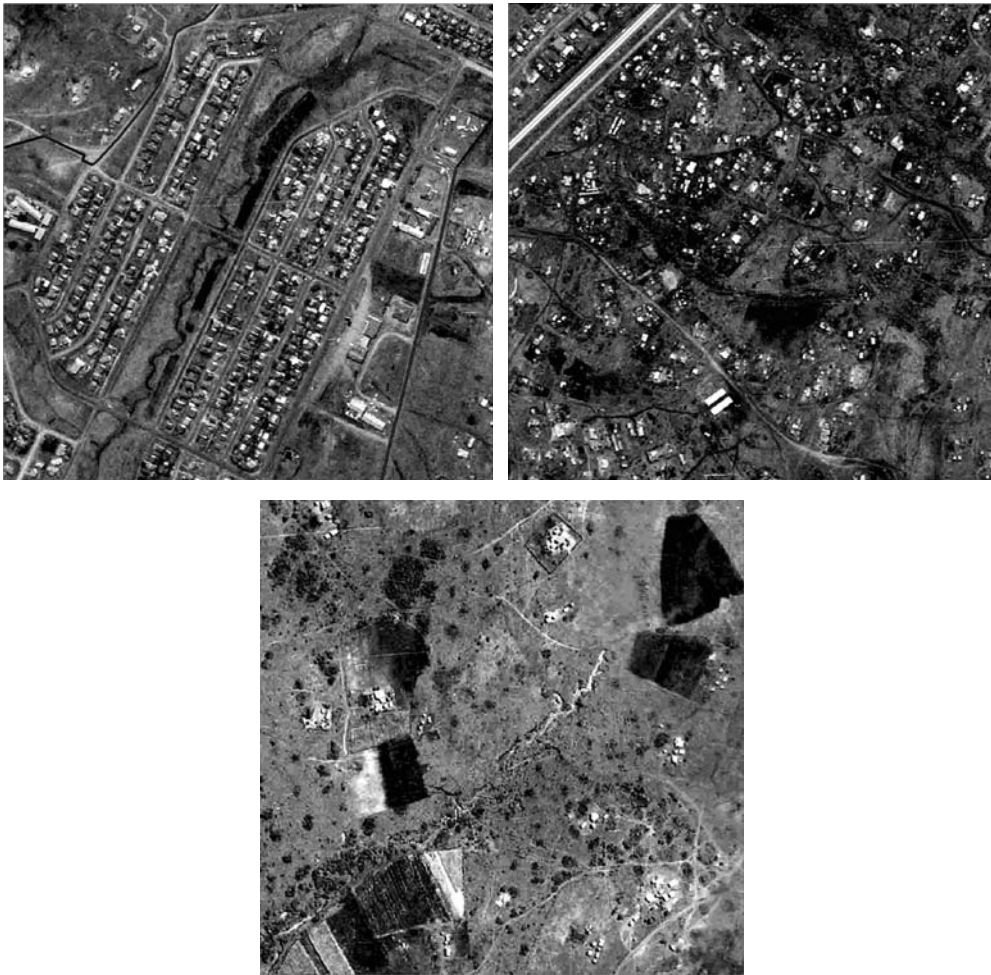
Figure 2. Aerial photographic comparison of urban (top left), peri-urban (top right), and rural (bottom) settings in the Hlabisa subdistrict.

- measuring access to and coverage of the health services;
- understanding the utilization patterns of the health services; and
- rational design and planning of the health services.

In this paper, I review work that we have done examining the uses of GIS for understanding health care services and needs in a rural health District in South Africa, and put those findings in the larger context of how GIS is now being used for management of health services in developing countries, especially those in Africa.

ANALYSIS

Study Area

Hlabisa health subdistrict is located within the rural district of Umkhanyakude in northern KwaZulu-Natal (Figure 1) and is 1,430-km^2 in size. The subdistrict is about 250 km north of the city of Durban (the third largest city in South Africa). The population consists of approximately 200,000 Zulu-speaking people, of which 3 percent are located in a formally designated urban township (KwaMsane), 20 percent live in peri-urban areas (informal settlements with a population density of more than 400 people per km^2), and the remaining 77 percent live in rural areas (Figure 2). The rural population live in scattered homesteads that are not concentrated in villages or compounds, as is the case in many other parts of Africa. The area is transected by a Hluluwe-Umfolozi game reserve and surrounded by hard boundaries in the form of large perennial rivers, nature reserves, forestry areas, and commercial farmland. Elevation ranges between 30 and 600 meters above sea level. The population distribution exhibits extreme heterogeneity—density ranges by two orders of magnitude (20–2,500 people per km^2). Median per capita expenditure is R125 (US$20) per month.[7] The community, like many others in the province of KwaZulu-Natal is in the throes of an unprecedented health crisis, with HIV prevalence close to 40 percent in women attending prenatal clinics.[8]

This subdistrict's health infrastructure is typical of many similar rural health systems in South Africa and functions as a semi-autonomous unit at the third tier of the national health system. A central community hospital and 13 fixed clinics provide the bulk of the primary health care in Hlabisa. The hospital has an adjacent clinic that dispenses primary health care to patients in the surrounding area. In addition, 30 mobile clinic points are visited twice monthly, and 130 community health workers are each expected to visit regularly a group of assigned homesteads.[9] To access primary health care, two-thirds of the population walk to clinics, while the remaining one-third use public transport. A negligible number (0.4 percent) use their own transport to access care.[10]

GIS data used

The analysis draws from GIS data maintained by the Africa Centre for Health and Population Studies comprising a series of geographical layers of the Hlabisa subdistrict—including magisterial and nature-reserve boundaries, roads, and rivers—and covers about 500 facilities (e.g. clinics, schools, shops) and 24,000 homesteads. All homesteads in the study area were positioned by 12 fieldworkers carrying hand-held GPS (Trimble Geoexplorer II) units that recorded to an accuracy of less than two meters. During this GPS survey, a key informant in each homestead was interviewed regarding usage of the health care clinics. Reported travel times to clinic were collected from residents for a random sample of 250 homesteads.[11] The reported times included walking time, time spent waiting for public transportation, and time spent on public transportation.
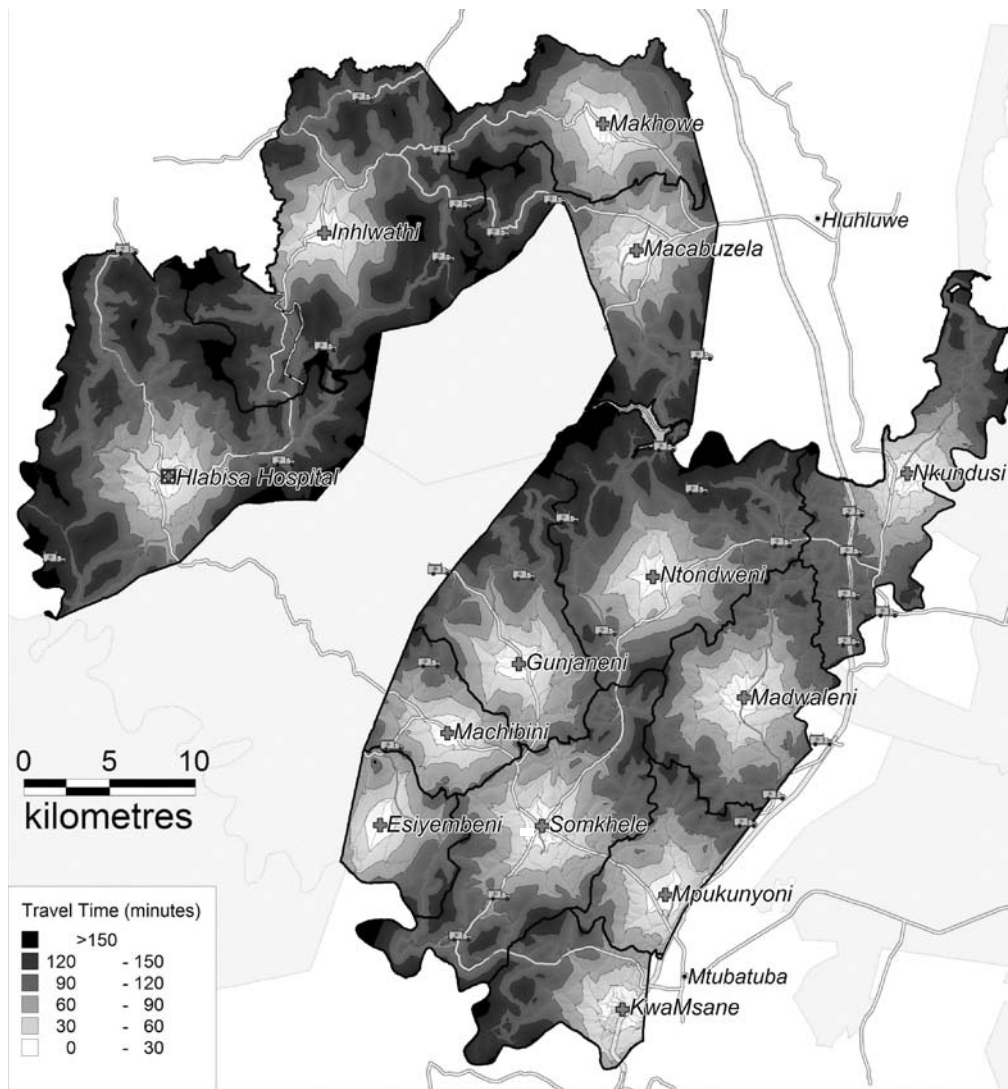
Figure 3a. Model of average travel time (in minutes) to clinic. The black boundaries represent the predicted clinic catchments; the main roads, fixed clinics, and mobile clinic points are superimposed. Striped areas indicate nature reserves.

Measuring Access to and Coverage of Health Services

Improving the performance of primary health care has been identified as a major global health priority.[12] Physical access to primary health care remains a key issue in most low income countries in which a large proportion of the population often resides in rural areas at considerable distances from basic health services. South Africa contains marked health care accessibility gradients, determined predominantly by race, socioeconomic status, and location.[13] Many studies show that physical access to health care is the most important determinant of the utilization of the heath care services. In addition, physical access to primary health care is corre-
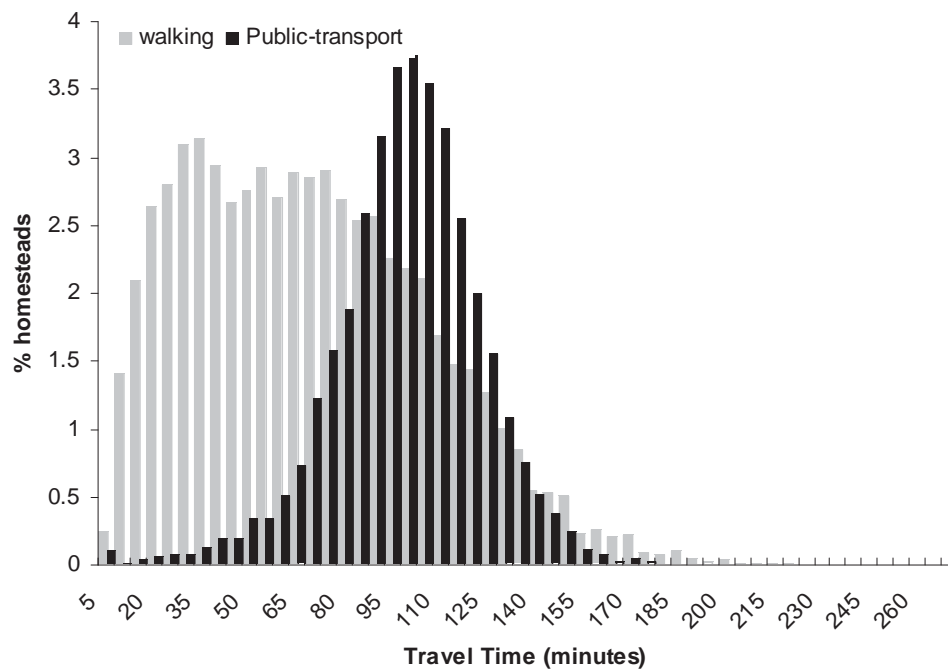
Figure 3b. Travel time histogram stratified by those walking (average = 67 minutes, 63.1 percent) and those using public transportation (average = 96 minutes, 36.9 percent) in the Hlabisa subdistrict. (Figure published in Soc Sci Med 2006; reprinted courtesy of Elsevier Science).

lated with many adverse health outcomes and likely affects adherence to demanding treatment regimens.

It is also essential to quantify access to care from the perspective of take-up of new interventions. In South Africa, an especially important issue is the take-up of and adherence to antiretroviral drugs for HIV therapy,[14] for which physical access to clinics is likely to be a crucial determinant. A good indicator of health service performance is therefore the population's proximity to primary health care. A key metric often used is the proportion of the population living within an hour of the nearest service. GIS is ideally suited to this type of contextual analysis—it can measure straight-line distances to care or utilize more sophisticated methods such as network analyses of travel time or monetary costs.[15]

To measure physical access to primary care in the Hlabisa subdistrict, we used GIS to estimate travel times to the nearest clinic and to derive clinic catchment boundaries (Figure 3a).[16] In the GIS analysis, we used friction values (corresponding to differing traveling speeds across differing surfaces) to compute travel times to the most accessible target clinic. The resulting travel times take into account the quality and distribution of the road network, natural barriers such as perennial rivers, and the proportion of the population likely to be using public transporta-

Setting	Travel time (minutes)		Adjusted odds ratio	
	Avg	Std. dev.	OR	95% CI
Urban	20.0	9.7	1[a]	
Peri-urban	55.7	31.8	28.2	19.2–41.3
Rural	83.9	29.3	18.0	12.5–26.0

[a] The urban category is used as the reference condition.

Table 1: Travel time to clinics and adjusted odds ratio of clinic usage between three population settings in the Hlabisa health subdistrict.

Source: Tanser, Gijsbertsen, and Herbst, "Modeling and understanding primary health care accessibility and utilization."

tion (as a function of walking time). As the distance to the nearest clinic increases, roads play more of a role in determining accessibility, because an increasing proportion of people make use of public transportation.[17] The resulting catchment boundaries constitute a line of equal travel time between neighboring clinics.

We then overlaid each of the homesteads in the subdistrict onto the travel time model to analyze the distribution of travel times to the clinics for all homesteads in the subdistrict (Figure 3b).[18] The model estimated the average travel time to the nearest clinic to be 77 minutes, and 65 percent of the population travel 1 or more hours to attend a clinic. The results show that many of the populations living in areas situated 1 or more hours from the nearest clinic are covered by the network of mobile clinics (Figure 3a). The estimated average travel time compared well with reported travel times in a sample of 250 homesteads (for which the average travel time was 73.6 minutes).[19] The model can be used to identify deficiencies in coverage and vulnerable populations with limited access to care. This information can then be used to inform the placement of new facilities and resource allocation in general.[20]

In the Hlabisa subdistrict, a significant socioeconomic gradient exists across the urban/rural continuum.[21] GIS can help analyze different population substrata by incorporating information from multiple sources (e.g., municipal demarcations, census tract). To analyze differences in access to the clinics in the subdistrict by populations in urban, peri-urban, and rural areas, we overlaid the homestead and municipal boundary data onto the travel time model. The results show that people in rural homesteads travel four times longer to access care than do their more affluent urban counterparts (Table 1).
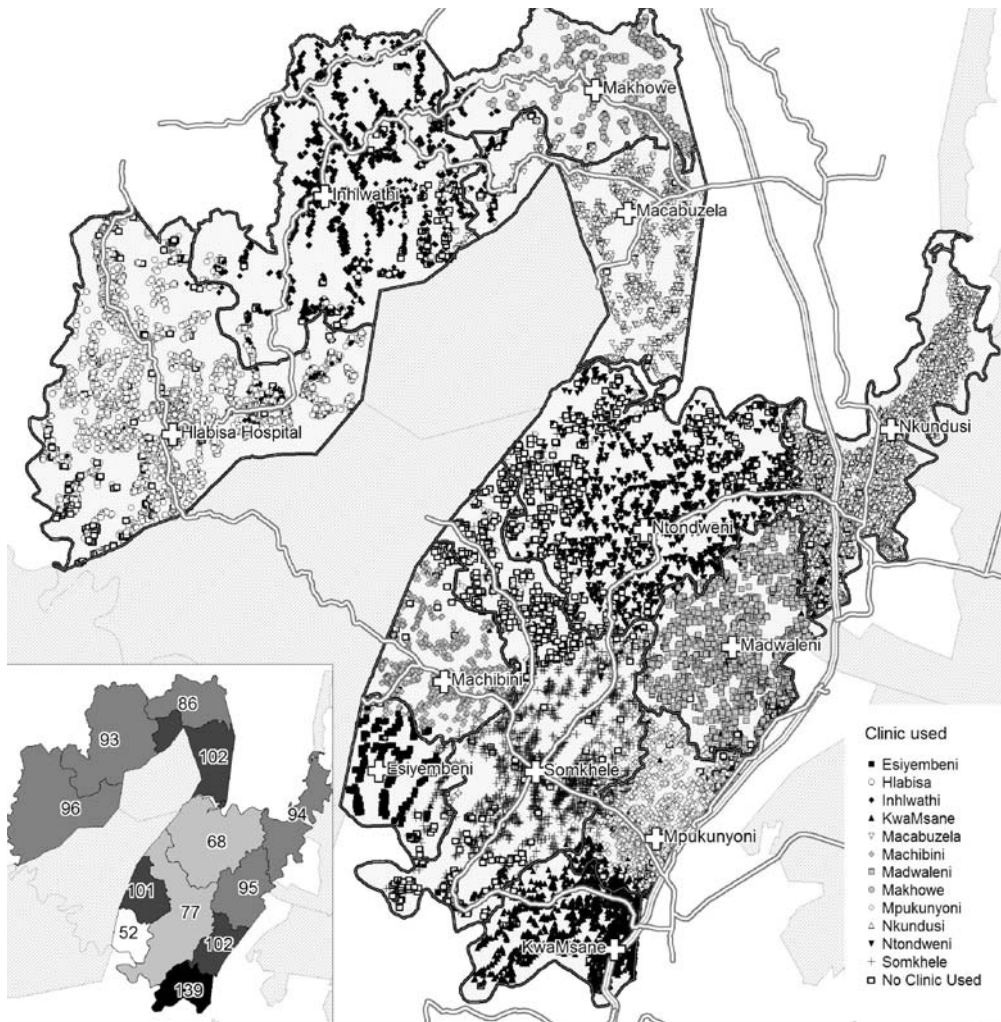
Figure 4: Comparison between reported clinic usage and predicted clinic catchments in Hlabisa health subdistrict. The black boundaries represent the predicted catchments, the symbols represent homesteads, coded by reported clinic usage, and the main roads are superimposed. The inset shows the distance usage index (DUI) for each clinic.

Understanding the Usage Patterns of Health Services

Managers of health care systems need to be able to quantitatively assess and understand the spatial usage patterns of the health facilities in a given area and be able to identify clinics that may be underperforming or offering reduced quality of service. It is also useful for managers to assess the extent to which patients use their nearest clinic, and the extent to which service quality and setting (rural, urban,

peri-urban) play a role in determining utilization. GIS can help answer these questions through the analysis of inter-clinic usage patterns relative to expectation.

We used GIS to analyze the deviations between observed and expected clinic usage by comparing homesteads' reported usage with the predicted catchments.[22],[23] The agreement between predicted and reported usage was 91% (Figure 4). We then used the differences between observed and expected usage to compute a distance usage index (DUI) for each clinic.[24] The DUI is a ratio of the total time traveled to a reported clinic divided by the expected total time traveled to that clinic, expressed as a percent. Expected total times traveled to clinics were calculated using all homesteads that fell within a clinic's predicted catchment. The index is an overall measure of inclusion, exclusion, and the strength of a patient's attraction to the clinic (using time traveled to attend clinic). Thus, a clinic that attracts a large number of patients from outside its predicted catchment and receives good attendance within its catchment will have a DUI of greater than 100 percent. Conversely, a clinic that only attracts patients from short distances and has poor attendance within its predicted catchment will have a DUI value of less than 100 percent.

> Physical access to primary health care remains a key issue in most low income countries in which a large proportion of the population often resides in rural areas at considerable distances from basic health services.

The DUI for each clinic in this study ranges from 52 to 139 percent, with an average DUI of 92 percent (Figure 4, inset). Many of the clinics have a DUI value that lies close to 100 percent. The average DUI value of 92 percent indicates that within the district overall, people generally utilize their closest (defined on the basis of travel time) clinic. However, the analysis reveals that one of the rural clinics (Esiyembeni) exhibits substantially less attraction and utilization than expected (DUI = 52 percent), while the only urban clinic (KwaMsane) exhibits substantially more attraction and utilization than expected (DUI = 139 percent). KwaMsane is the only one of the 13 clinics to be designated a Community Health Centre, offering a broader range of services than the other clinics and 24 hour service. Seventeen percent of its patients come from outside its predicted catchment, and many travel considerable distances to attend this clinic.

The ability to predict which clinic a homestead will use, with only a small margin of error, is useful for health care planning in rural South Africa. At a district level, health managers should strive towards DUI values close to 100 at all health facilities. This would indicate that the facilities are evenly distributed, patients are generally using their closest facility, and attendance is good. Clinics exhibiting low DUI values (lower than 70) should be investigated to determine whether quality of
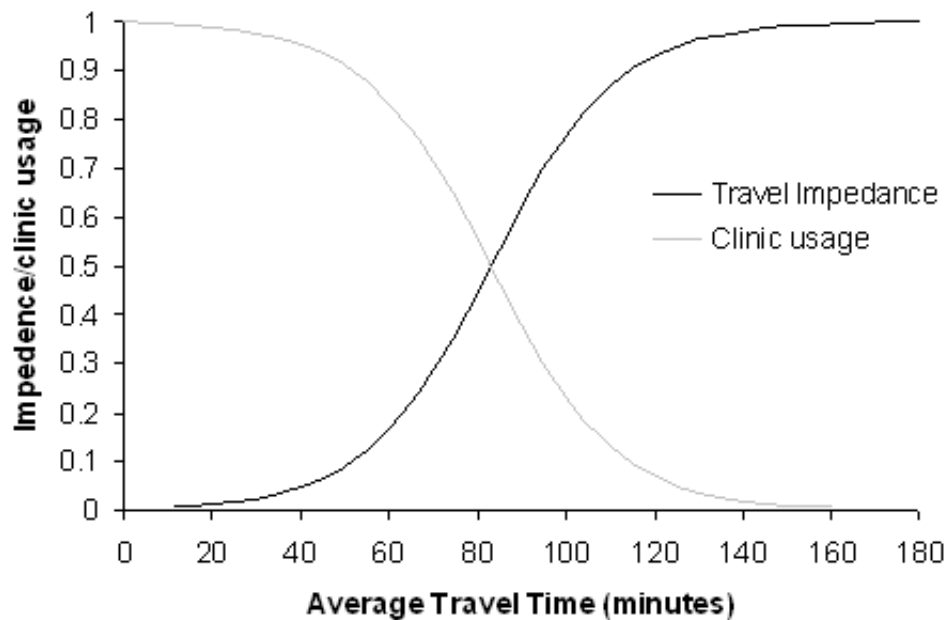
Figure 5: The relationship between travel time to clinic and (1) clinic usage (proportion of homesteads using a particular clinic) and (2) travel-impedance to clinic (1 - usage).

service is lower than other clinics. District managers do not need to conduct comprehensive, population-level surveys to calculate the DUIs and understand utilization patterns. Geographically stratified sampling techniques of small populations can be successfully employed to facilitate calculation of the indices. Calculation of DUIs is a good example of the manner in which GIS can distill information from a micro scale (clinic usage patterns of more than 23,000 homesteads measured at less than 2-m accuracy) and use it at a macro scale to extract meaning and facilitate better decisionmaking.

We used a logistic regression to analyze differences in utilization after adjusting for systematic differences in clinic access.[25] The adjusted odds of clinic usage by homesteads in peri-urban areas were nearly 30 times those of their urban counterparts (Table 1). The corresponding odds ratio for rural populations was 18. The disparity in usage of the clinics by urban/rural populations is a useful finding for health planners. The lower usage of the clinics by urban residents probably represents a higher usage of private medical practitioners. The slightly lower use of clinics by rural homesteads relative to peri-urban homesteads may reflect a greater use of traditional healers or reliance on the mobile clinics, but this difference in usage deserves further investigation. The results suggest that a weighting factor should be used in the planning of new facilities to estimate likely usage in rural versus urban areas. Failure to account for these disparities might result in an oversubscription of primary health care services to urban areas at the expense of their rural coun-
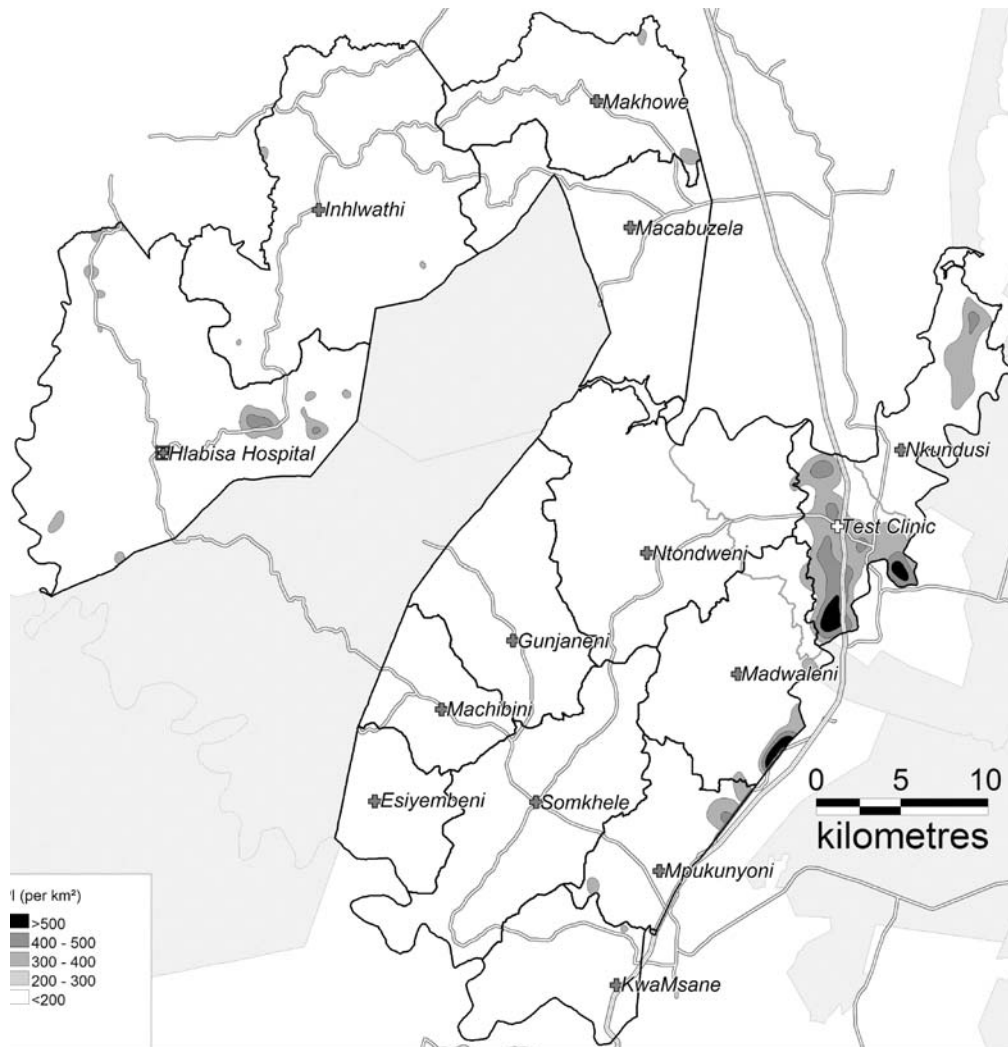
Figure 6: Person-impedance (PI) to clinic per km² Catchments of existing clinics are represented as black lines and the catchment of the "test" clinic is shown as grey lines.

terparts.

Rational Design and Planning of Health Services

GIS is increasingly being used in "location-allocation" problems to inform the optimal allocation of finite resources.[26] Health planners can identify potential locations for new primary health care facilities and evaluate each competing location for their effects on clinic access by using the power of GIS to incorporate information on the demand for care as well as the supply of that care. Poorer populations are more likely to exclusively use the nearest health care facility regardless of discrepancies in standard of care. This makes the optimal placement of health care

facilities in lower-income settings particularly important, and it is therefore vital to site facilities in such a way as to maximize access by the population.

I used GIS to identify the placement of a new clinic in the Hlabisa health sub-district so as to achieve the maximum population-level increase in accessibility to primary heath care.[27] Previous work in Hlabisa had shown a logistic relationship between decay in attendance of a specific clinic and travel time to that clinic.[28] I estimated impedance to care by using the reverse of this curve (1–usage; Figure 5).

At 50 minutes' travel time, usage of a particular clinic is still 91 percent but thereafter decays rapidly—at 81 minutes the use drops to 50 percent, and at 150 minutes, use is only 1 percent. The logistic relationship means that individuals encounter little impedance in accessing care if they live fewer than 50 minutes from a clinic, but thereafter impedance increases sharply until saturation starts to occur at about two hours' travel time.

> The ability to predict which clinic a homestead will use, with only a small margin of error, is useful for health care planning in rural South Africa.

The product of the impedance value and the number of residents for each homestead were superimposed onto a 30-m grid. I filtered the resulting image to calculate person-impedance per km^2.[29] The subsequent person-impedance map (Figure 6) delineates the areas where high levels of impedance to care correspond with high population concentrations, and where the placement of a clinic could greatly reduce the population's impedance (and therefore increase accessibility) to care. The potential site for the test clinic is shown on the map as "Test Clinic," with the resulting catchment superimposed. The test clinic would reduce person-impedance by 3.6 times the reduction achieved by the construction of the newest clinic in the subdistrict (Gunjaneni). The corresponding ratio for increasing clinic coverage (percent of the population within 60 minutes of care) would be 4.7.[30]

Through the GIS methodology, I identified an area for the placement of a new clinic where maximum increase in population accessibility can be achieved. The results constitute another example of the way in which GIS can distill information from multiple observations at a micro level to facilitate more macro-level decision-making. Deciding on how to allocate primary health care resources is difficult and can be based on many epidemiological, sociogeographical, and ethical criteria. The approach presented has focused on the spatial efficiency (defined as achieving the maximum population-level reduction in impedance to care) of clinic location and has not tried to address spatial equity (defined as achieving equal distribution of access to care among population sub-groups). There is a growing appreciation of the trade-off between equity and efficiency in delivery of health care.[31] Nevertheless, the effect of placement of potential clinics on population-level access to care can form an important part of the decisionmaking hierarchy.

DISCUSSION

Once thought of as a first-world research tool, GIS is being applied more often in developing countries to answer complex problems and inform optimal resource allocation. In the Hlabisa subdistrict, GIS has been used in other ways as well. GIS has been used to document the effect of community-based tuberculosis treatment on distance to treatment location,[32] to equitably distribute fieldworker workload in a large population-based survey,[33] and to investigate an ecological relationship between proximity to roads and HIV prevalence among women attending prenatal clinics.[34] In other areas of South Africa, GIS has been used to determine potential access to and allocation of public mental health resources in the province of KwaZulu-Natal,[35] to manage and monitor the impact and control of malaria,[36] to measure race-based inequalities in the ratio of population per hospital beds,[37] to analyze access to primary health care in a rural district,[38] and to analyze the geographical distribution of diagnostic medical and dental X-ray services at a national level.[39]

In addition, GIS is being used in other developing countries in public health management and allocation of resources. In Egypt for example, a GIS environmental risk model increased the accuracy of schistosomiasis control program decisions.[40] The project used coarse-resolution (1 km) satellite data to develop a regional risk model for the Nile delta and a local "village-scale" environmental risk model based on higher-resolution (30 m) satellite sensor data. A study in Chad aimed to design and implement a rapid and valid epidemiological assessment of helminths (internal parasites) among schoolchildren using GIS-derived ecological zones from satellite sensor data.[41] The prevalence of two helminth species showed marked geographical heterogeneity, and the observed patterns showed a close association with the defined ecological zones and significant relationships with environmental variables. The study concluded that GIS and remote sensing can play an important part in the rapid planning of helminth control programs where little information on disease burden is available. In Burkina Faso, the African Programme for Onchocerciasis Control used epidemiological data on the prevalence of onchocerciasis (river blindness) in conjunction with environmental data within a GIS model to delineate zones of differing levels of endemicity and facilitate targeted interventions.[42] In four districts in Kenya, GIS was used to measure disparities in inter-district access to primary health care in light of large-scale international and national efforts such as Roll Back Malaria.[43] The physical access estimates across the districts highlighted areas of poor access and large differences between urban and rural settings. The results of the study have important implications for the planning and equitable delivery of clinical services at national and international levels.

One of the biggest impediments to the implementation of GIS in a public health setting is skepticism that stems from the perception that GIS is merely a mapping tool. Although GIS output does commonly appear as a geographical presentation, the tool is far more powerful than its basic mapping abilities—it is

better described as a spatial analytical system.[44] Spatial analysis refers to the "ability to manipulate spatial data into different forms and extract additional meaning as a result."[45] Gattrell and Bailey[46] describe three general types of spatial analysis tasks: visualization, exploratory spatial analysis, and model building. Visualization includes production of thematic maps, basic map overlay operations, animation, and exploration of the results of traditional statistical analysis. Map overlay operations, for example, allow the analyst to derive new inferences for each location based on the attributes of multiple layers. Exploratory spatial analysis allows the analyst to sift meaningfully through spatial data, identify "unusual" spatial patterns, and formulate hypotheses to guide future research. Model building includes procedures for testing hypotheses about, for example, the causes of disease and the nature and processes of disease transmission.

It is unrealistic to expect managers at the district level of a developing country to have access to high-end GIS systems that will allow them to perform advanced spatial analytical procedures (which, in addition to expense require significant skills and training). However, low-end GIS systems can be used at the district level to display, overlay, and interact with basic health data concerning both health care facilities and disease patterns. Examples of such low-end software include the freely available HealthMapper, ArcExplore, and MapInfo Proviewer.[47] These systems permit rapid manipulation of spatial data and display of the results. Decisionmakers can then use the output for policy decisions. They can also take a further step to perform limited spatial queries and analyses such as buffering. More advanced GIS analysis and modeling from high-end systems can take place at a centralized level, and the results can feed into the district-level GIS systems, where local decisions can be made. The Mapping Malaria Risk in Africa (MARA) collaboration is a successful example of this type of approach.[48] The collaboration is embedding several of its GIS-devised research outputs[49] into the standalone MARAlite package for district-level malaria intervention planning.

Successful implementation and sustainability of GIS-based management in developing countries are associated with potential difficulties.[50] These include the paucity of qualified staff, limited (but improving) access to digital data sets, and relatively high cost (also improving) of commercial packages.[51] In settings where census data are not available (as is often the case in rural areas of developing countries), high-resolution satellite imagery (available at moderate cost) can accurately estimate and geolocate populations. The difficulties in accessing spatial data (which are fundamental to any GIS application) are not specific to health but to all sectors that utilize GIS. Similarities exist in the field requirements for GIS between forestry, ecology, archaeology, and epidemiology, and these disparate fields could substantially benefit from sharing experiences and pooling resources.[52] Inter-sectoral collaboration initiatives should therefore be encouraged and should receive funding priority. Development of such data sets is of paramount importance to ensure the growth of all sectors of GIS in developing countries.

Despite the many successful uses of GIS applications for health care research and planning, GIS remains a significantly powerful but under-utilized analytical

tool, particularly in developing countries. In this paper, I have reviewed work that we have undertaken in the Hlabisa subdistrict in rural South Africa: to estimate travel times to health care clinics, to understand primary health care usage patterns, to predict clinic used, to measure disparities in access to and usage of primary health care by setting (rural, urban, peri-urban), to evaluate clinic usage relative to expectation, and to optimally site a new facility such that it achieves the maximum population-level increase in access. The diversity of the problems tackled and the results obtained in this study and others mentioned in this paper demonstrates the considerable promise of GIS as a research and planning tool and as part of the rational design of programs and their evaluation. Considerable potential exists for GIS to play a key role in rational and cost-effective health service planning and resource allocation in South Africa and other developing nations.

Acknowledgements

1. See, for example, D.J. Briggs and P. Elliott, "The use of geographical information systems in studies on environment and health," World Health Statistics Quarterly Vol. 48, No.2 (1995), pp. 85–94; K.C. Clarke, S.L. McLafferty, and B.J. Tempalski, "On epidemiology and geographic information systems: a review and discussion of future directions," *Emerging Infectious Disease* Vol. 2, No. 2 (1996), pp. 85–92; D.A. Moore and T.E. Carpenter, "Spatial analytical methods and geographic information systems: use in health research and epidemiology," *Epidemiologic Reviews* Vol. 21, No. 2 (1999), pp.143–61; and M. Vine, "Geographic information systems: their use in environmental epidemiological research." *Journal of Environmental Health* Vol. 61, No. 3 (1998), pp. 7–10.
2. For GIS applications for malaria and schistosomiasis, see L.R. Leonardo, P.T. Rivera, B.A. Crisostomo, et al., "A study of the environmental determinants of malaria and schistosomiasis in the Philippines using remote sensing and geographic information systems," *Parassitologia* Vo. 47, No. 1 (2005), pp. 105–114. For applications for tuberculosis, see Z. Munch, S.W. Van Lill, C.N. Booysen, H.L. Zietsman, D.A. Enarson, and N. Beyers, et al. "Tuberculosis transmission patterns in a high-incidence area: a spatial analysis," *International Journal of Tuberculosis and Lung Disease* Vol.7, No. 3 (2003), pp. 271–277. For leukemia, see U. Hjalmars, M. Kulldorff, G. Gustafsson, and N. Nagarwalla, "Childhood leukemia in Sweden: using GIS and a spatial scan statistic for cluster detection," *Statistics in Medicine* Vol. 15, Nos. 7–9 (1996), pp. 707–715.
3. S.L. McLafferty, "GIS and health care," Annual Reviews of Public Health Vol. 24 (2003), pp. 25–42.
4. F.C. Tanser and D. le Sueur, "The application of geographical information systems to important public health problems in Africa," *International Journal of Health Geographics* Vol. 1, No. 4 (2002).
5. C. Dunn, P. Atkins, and J. Townsend, "GIS for development: a contradiction in terms?" Area Vol. 29, No. 2 (1997), pp. 151–159; L. Yapa, "Is GIS appropriate technology?" *International Journal of Geographical Information Science* Vol. 5, No. 1 (1991), pp. 41–58.
6. UNDP, Millennium Development Goals and Indicators, <http://www.undp.org/mdg/abcs.html>, accessed, 2005.
7. ACDIS, Household Socioeconomic Module 2, Africa Centre Demographic Information System (ACDIS), 2005. The South African rand (R) exchange is approximately R1 = US$0.16.
8. D. Wilkinson, C. Connolly, K. Rotchford, "Continued explosive rise in HIV prevalence among pregnant women in rural South Africa," *AIDS* Vol. 13, No. 6 (1999), p. 740.

9. F. Tanser, V. Hosegood, J. Benzler, and G. Solarsh, "New approaches to spatially analyze primary health care usage patterns in rural South Africa," *Tropical Medicine & International Health* Vol. 6, No. 10 (2001), pp. 826–838.

10. F. Tanser, B. Gijsbertsen, and A. Herbst, "Modeling and understanding primary health care accessibility and utilization in rural South Africa: an exploration using a geographical information system," *Social Science & Medicine* in press.

11. Tanser, Hosegood, Benzler, and Solarsh.

12. WHO, The World Health Report 2000—Health Systems: Improving performance (Geneva, Switzerland: World Health Organization, 2000).

13. F. Castro-Leal, The Impact of Public Health Spending on Poverty and Inequality in South Africa (Washington, D.C.: World Bank, Africa Region, 1999), p 35.

14. DOH, Operational Plan for Comprehensive HIV and AIDS Care, Management and Treatment for South Africa (Pretoria: Department of Health, 2003).

15. M.F. Guagliardo, "Spatial accessibility of primary care: concepts, methods and challenges," *International Journal of Health Geographics* Vol. 3, No. 1 (2004), p. 3.

16. For a detailed description of the construction of the travel time model, see Tanser, Gijsbertsen, and Herbst, "Modeling and understanding primary health care accessibility and utilization."

17. Tanser, Gijsbertsen, and Herbst.

18. Tanser, Gijsbertsen, and Herbst.

19. Tanser, Gijsbertsen, and Herbst.

20 A. Joseph and D. Phillips, *Accessibility and Utilization: Geographical Perspectives on Health Care Delivery* (New York: Harper and Row, 1984).

21. Africa Centre Demographic Information System, Household Socioeconomic Module 2.

22. For this component of the analysis, We restricted the calculation of the travel time model and associated catchments to clinics functioning at the time of the clinic usage survey.

23.Tanser, Gijsbertsen, and Herbst.

24. For an explanation of the distance usage index, see Tanser, Hosegood, Benzler, Solarsh, "New approaches to spatially analyse primary health care usage patterns."

25. Tanser, Gijsbertsen, and Herbst.

26. McLafferty, "GIS and health care."

27. F. Tanser, "A methodology for optimizing location of new primary health care facilities in rural communities: a case study in KwaZulu-Natal, South Africa." *Journal of Epidemiology and Community Health.* In press

28. Tanser, Gijsbertsen, and Herbst.

29. I used a 3 km x 3 km Gaussian filter to calculate person-impedance per km^2. The filter systematically moves across the subdistrict and calculates the weighted (according to a standard normal distribution) person-impedance per km^2 for each cell's unique 3 km x 3 km neighborhood. The greater the distance from the central cell, the less that area contributes to the person-impedance per km^2 estimate.

30. Tanser, "A methodology for optimizing location of new primary health care facilities"

31. L Gilson, "In defence and pursuit of equity," *Social Science & Medicine* Vol. 47, No. 12 (1998), pp. 1891-6.

32. F. Tanser and D. Wilkinson, "Spatial implications of the tuberculosis DOTS strategy in rural South Africa: a novel application of geographical information system and global positioning system technologies," *Tropical Medicine & International Health* Vol. 4, No. 10 (1999), pp. 634–638; D. Wilkinson and F. Tanser, "GIS/GPS to document increased access to community-based treatment for tuberculosis in Africa" Lancet Vol. 354, No. 9176 (1999), pp. 394–395.

33. F.C. Tanser, "The application of GIS technology to equitably distribute fieldworker workload in a large, rural South African health survey," Tropical Medicine & International Health Vol. 7, No.1 (2002), pp. 80–90.

34. F. Tanser, D. le Sueur, G. Solarsh, and D. Wilkinson, "HIV heterogeneity and proximity of homestead to roads in rural South Africa: an exploration using a geographical information system," *Tropical Medicine & International Health* Vol. 5, No. 1 (2000), pp. 40–46.

35. A. Bhana and Y.G. Pillay, "The use of the Geographical Information System (GIS) to determine potential access and allocation of public mental health resources in KwaZulu-Natal," South African *Journal of Psychology* Vol. 28, No. 4 (1998), pp. 222–233.

36. M. Booman, D.N. Durrheim, K. La Grange, et al., "Using a geographical information system to plan a malaria control programme in South Africa," *Bulletin of the World Health Organisation* Vol. 78, No. 12 (2000), pp. 1438–1444; C. Martin, B. Curtis, C. Fraser, and B. Sharp, "The use of a GIS-based malaria information system for malaria research and control in South Africa," Health & Place Vol. 8, No. 4 (2002), pp. 227–236.

37. M. Zwarenstein, D. Krige, and B. Wolff, "The use of a geographical information system for hospital catchment area research in Natal/KwaZulu," *South African Medical Journal* Vol. 80, No. 10 (1991), pp. 497–500.

38. J.M.. Tsoka and D. le Sueur, "Using GIS to measure geographical accessibility to primary health care in rural South Africa," *South African Journal of Science* Vol. 100, Nos. 7–8 (2004), pp. 329–330.

39. N.M. Walters, H.L. Zietsman, and N. Bhagwandin, "The geographical distribution of diagnostic medical and dental X-ray services in South Africa," *South African Medical Journal* Vol. 88, No. 3 (1998), pp. 383–389.

40. M.S. Abdel-Rahman, M.M. El-Bahy, J.B. Malone, R.A. Thompson, and N.M. El Bahy, "Geographic information systems as a tool for control program management for schistosomiasis in Egypt," *Acta Tropica* Vol. 79, No. 1 (2001), pp. 49–57.

41. S. Brooker, M. Beasley, M. Ndinaromtan, et al., "Use of remote sensing and a geographical information system in a national helminth control programme in Chad," *Bulletin of the World Health Organisation* Vol. 80, No. 10 (2002), pp. 783–789.

42. M. Noma, B.E. Nwoke, I. Nutall, et al., "Rapid epidemiological mapping of onchocerciasis (REMO): its application by the African Programme for Onchocerciasis Control (APOC)," *Annals of Tropical Medicine and Parasitology* Vol. 96, Suppl. 1 (2002), pp. S29–S39.

43. A.M. Noor, D. Zurovac, S.I. Hay, S.A. Ochola, and R.W. Snow, "Defining equity in physical access to clinical services using geographical information systems as part of malaria planning and monitoring in Kenya," *Tropical Medicine & International Health* Vol. 8, No. 10 (2003), pp. 917–926.

44. McLafferty, "GIS and health care."

45. T. Bailey, "A review of statistical spatial analysis in geographical information systems," in S. Fotheringham and P. Rogerson, eds., *Spatial analysis and GIS* (London, United Kingdom: Taylor and Francis, 1994), pp. 13–44.

46. A. Gatrell and T.Bailey, "Can GIS be made to sing and dance to an epidemiological tune?" International Symposium on Computer Mapping, 1995, Tampa, Fla.

47. HealthMapper was developed by the World Health Organization, Geneva, Switzerland; ArcExplore is produced by ESRI, Redlands, California; and MapInfo Proviewer is produced by MapInfo Corporation, Troy, New York.

48. M. Adjuik, M. Bagayoko, F. Blinka, et al., Towards an Atlas of Malaria Risk in Africa: First Technical Report of the MARA/ARMA Collaboration (Durban, South Africa: MARA/ARMA, 1998).

49. See, e.g., M.H. Craig, R.W. Snow, and D. le Sueur, "A climate-based distribution model of malaria transmission in sub- Saharan Africa," *Parasitology Today* Vol. 15, No. 3 (1999), pp. 105–111; F.C. Tanser, B. Sharp, and D. le Sueur, "Potential effect of climate change on malaria transmission in Africa," Lancet Vol. 362, No. 9398 (2003), pp. 1792–1798.

50. N.G. Sipe and P. Dale, "Challenges in using geographic information systems (GIS) to understand and control malaria in Indonesia," *Malaria Journal* Vol. 2, No. 1 (2003), p. 36.

51. Tanser and le Sueur, "The application of geographical information systems."

52. Clarke, McLafferty, and Tempalski, "On epidemiology and geographic information systems."