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A GEOGRAPHIC INFORMATION SYSTEM APPLIED TO A MALARIA FIELD STUDY IN WESTERN KENYA

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Abstract. This paper describes use of the global positioning system (GPS) in differential mode (DGPS) to obtain highly accurate longitudes, latitudes, and altitudes of 1,169 houses, 15 schools, 40 churches, four health care centers, 48 major mosquito breeding sites, 10 borehole wells, seven shopping areas, major roads, streams, the shore of Lake Victoria, and other geographic features of interest associated with a longitudinal study of malaria in 15 villages in western Kenya. The area mapped encompassed approximately 70 km^2 and included 42.0 km of roads, 54.3 km of streams, and 15.0 km of lake shore. Location data were entered into a geographic information system for map production and linkage with various databases for spatial analyses. Spatial analyses using parasitologic and entomologic data are presented as examples. Background information on DGPS is presented along with estimates of effort and expense to produce the map information.

Analysis of spatial relationships is fundamental to epidemiologic research. Although affordable geographic information system (GIS) software has simplified this effort, an accurate base map is required for any spatial analysis. Lack of such maps is a substantial obstacle for researchers wishing to perform geographic analysis in tropical disease research since studies are often conducted in areas where existing maps are inaccurate, insufficiently detailed, or outdated. Various methods, each applicable to particular circumstances, can be used for base map production. Performance of a geographic survey requires special skills beyond the reach of those not professionally trained in these methods. Sketch maps are normally created for operational purposes. They are inaccurate and lack a coordinate system needed for spatial analysis. Satellite images and remotely sensed data are useful when finely detailed spatial analysis is not required .[1–4] Aerial photography is expensive if archived aerial photographs are not available to the researcher.[5] Furthermore, security concerns can make access difficult. Use of the global positioning systems (GPS) can provide an accurate, detailed map of any tropical site. As previously used, GPS has provided adequate, but not extraordinarily accurate maps.[6,7] We describe here how a simple modification of GPS known as differential GPS (DGPS) can be used to produce a highly accurate base map in a tropical area, and then illustrate the map's usefulness by performing some simple spatial analyses.

A collaborative study between the Kenya Medical Research Institute (KEMRI) and the Centers for Disease Control and Prevention (CDC) of the development of natural immunity to malaria in western Kenya provided the framework for this effort. This longitudinal study of malaria in young children was carried out in a 70-km^2 area in Siaya district in western Kenya.[8] Clinical, hematologic, parasitologic, immunologic, entomologic, and demographic data were regularly collected for each participating family in 15 villages. The entomologic data consisted of weekly trap collections for each study households. Clinical data were collected biweekly. Blood samples were obtained monthly or whenever any fever was reported. Blood samples were used to measure parasitemia, hemoglobin levels, and on certain subsamples, immunologic parameters. Since all of these data were collected with household identifiers, opportunities for examining spatial hypotheses exist in many disciplines if a map of study households, health care centers, mosquito larval habitat, bodies of water (rivers, lakes), roads, and other features of interest could be produced in a computer-readable format and linked to the various study databases through GIS and other statistical software. Existing maps and aerial photography were either unavailable, inaccurate or too outdated to be useful for mapping households and many of the other features of interest.[9] This paper describes the DGPS methodology used to produce a map with highly accurate locational information for all of the geographic features of interest, and follows the process through to the final output: spatial analysis.

METHODS

The global positioning system. Twenty-four satellites (21 for navigational purposes and three active reserves) orbiting at an altitude of approximately 10,900 miles form the the global positioning satellite network.[10] The GPS satellites continuously broadcast the time, and their orbital path to provide the information used by a terrestrial GPS unit to compute the longitude, latitutude, and altitude (also called a position fix). Data received from four satellites allow the GPS unit to calculate latitude, longitude, and altitude, while data from three satellites allow calculation of latitude and longitude only. The exact methodology for how position fixes are computed is described in detail elsewhere.[11]

Global positioning system errors. The computations of a GPS position fix are subject to error from several uncontrolled factors: clock errors, atmospheric conditions, GPS receiver noise, and reflectance of satellite signals.[12] The largest error component, selective availability (SA), is the intentional error component added for security purposes at each satellite. Because SA error varies with time and from one satellite to the next, when a GPS unit changes the group of satellites it is using to compute a position fix, the different SA error term results in a sudden change in the computed location. A single reading on a standard GPS unit has accuracies of 100 m horizontally, and 156 m vertically. Approximately 55 m of the horizontal error is due to SA.[12]

Accuracy is defined as two standard deviations of measurement error. The position dilution of precision (PDOP) is a measurement of the possible position error that is related to the geometric configuration of the satellites used to compute a position fix.[10, 12] The PDOP is minimized when three satellites are high and one is near the horizon. Accuracy is inversely proportional to the PDOP.

Differential GPS. Errors of 100 m for horizontal measurements (latititude and longitude) and 150 m for vertical accuracy are far too large to make simple GPS use practical for mapping the locations of objects that are relatively close together, such as households within villages. Such large errors will result in gross distortion of the true spatial relationships between the measured points. Such spatial inaccuracies would be make a map produced with simple GPS readings very confusing to use for operational purposes.

Differential GPS circumvents the effects of SA and environmental errors to produce a highly accurate position fix. Several different approaches to DGPS exist, but each uses the principle of having two GPS units simultaneously taking readings from the same set of satellites. One GPS unit is located at a fixed control site, preferably a known location, and the others become the roving field units. As a result, the position fixes for both GPS units are subject to the same SA and clock error terms. If the units are relatively near to each other (less than 50 km), the precisely timed GPS signals travel through similar ionospheric and tropospheric conditions.[12] For both units, each position fix is stored to a computer file, along with the exact time of the reading and the set of satellites used to compute the location. The matching files for the two GPS units are then downloaded to a computer. Software is used to pair or synchronize readings that were taken at exactly the same time. Three methods exist for comparing the paired readings from the GPS units: double-differenced pseudorange differential, carrier-phase, and mobile-point processing. For each of these methods, the location of the remote GPS unit is computed by adding the distance between the two GPS units to the known location of the control GPS unit. In our application, this involved simultaneous creation of computer files on control and remote GPS units, followed by copying these files to a computer and running software to compute calibrated positions.

Pseudorange differential GPS takes the computed distances between a particular satellite and the two GPS units (called pseudoranges), after discarding readings that do not match up with units with respect to time and satellites. This method of computing location requires 3–5 min of data collected at a rate of one fix per second (200–300 position fixes) to reduce errors to the 2–5 m range on a horizontal basis and 3–7 m range on a vertical basis.[12] Since GPS satellite orbits are known precisely, planning software can predict the optimal sets of satellites to use at any time or place on earth. Such software is useful for locating alternative satellites when the signal from a preferred set is blocked by a tree, building, or other object.

Another method of differential processing, carrier phase processing has the ability to reduce errors to the submeter range. The data collection sessions must be longer to be able to detect changes in satellite locations. Recent improvements in GPS technology have reduced the necessary time requirements to 7–10 min.[12]

Linear features such as roads, streams, and lake shores are mapped using mobile point differential positioning. The control unit is stationary, but the remote unit is moving during data collection. The antenna of the remote GPS unit was placed outside of a moving vehicle to map roads. Rivers and streams were mapped by a person walking by the bank, holding the remote GPS unit. To map the shore of Lake Victoria, a fishing boat was chartered to be rowed near the shoreline, while field staff operated the GPS unit. This procedure did not have a measurable accuracy because the location of the remote GPS unit was continually changing, preventing the calculation of the mean position and its standard deviation.

Differential GPS applied to the Asembo Bay malaria cohort study. We established a control GPS location near a primary school soccer field in a centrally located village. This was a flat, relatively open area with few obstacles that might block satellite signals. A 2.5-m antenna extension allowed us to check the reception of the GPS unit without obstructing the satellite signals. The exact location of the control GPS unit was unknown, so several readings were taken over a one-day period and averaged to provide an estimate of the true location. Because this position was used as a correction factor for all remote sessions, any error associated with estimating the control location was consistent across all remote points, having the effect of moving the entire map in one direction or another. To maximize the area covered by the original control point, three radios in relay were used synchronize operations between the remote and control units. However, villages in the northeastern and northwestern parts of the study area were located beyond even this extended range, so two additional control points were established. The latitude, longitude, and altitude of these points were estimated by taking the average of 3–4 GPS sessions calibrated to the original control point to maximize consistency. The entire 70-km^2 study area was mapped using a total of three control points.

Equipment and personnel. We used two Magellan (Magellan System Corp., San Dimas, CA) Pro Mark V GPS units with 2.5-m tripod antenna extensions, three battery powered hand held radios, a compass, and six AA alkaline batteries per day per GPS unit or two sets of shorter lived but more economical rechargeable alkaline batteries per day per unit. Total equipment and software costs were approximately $12,500 for the GPS equipment and GIS software. Three people were involved in field operations, one at the control unit and two in the field. The additional person with the field unit was a local worker who knew where to find the features to be mapped. Each point resulted in two 150-Kb files being created for later processing. A computer specialist, working part-time on this project, was responsible for GPS to personal computer (PC) data communications, using the DOS-based post-processing software to compute the calibrated positions, and any data entry on a 486/66 computer. Approximately 1 hr of computer work was necessary to process six hours of GPS field data , generally between six and eight megabytes of data representing 25–35 positions. Approximately four person months of effort were required for the field work, post-processing, and data entry.

Logistics. Planning software was used to print out the four best satellite sets for each 15-min time period throughout the day. A list of the identification numbers of the households or compounds to be visited was also produced. After moving to the field site by vehicle, the field team then set up the control GPS unit and antenna. One staff member remained at the control site with a printout of the planning software, a GPS unit mounted on a tripod, a compass, and a walkie-talkie. The field team with the same equipment then proceeded to a point to be mapped. The antenna for both sites was set at a height of 2.5 m, which is adjusted for by the post-processing software. The remote team then set up the GPS antenna, noting the distance and direction of the antenna's position from each point to be mapped. In most cases, the antenna was placed 5 m in front of houses to be mapped. After setup of the GPS antenna, the planning printout was reviewed for the recommended satellites to be used. The GPS unit provided information on the azimuth and the elevation of each satellite. This information, combined with use of a compass, allowed us to approximately locate the satellites in the sky and to determine if their signals would be obstructed by trees or a building. Approximately 5 min of overlapping data from the same set of four satellites must be recorded on both remote and control units. The walkie-talkie was used to coordinate initiation of data collection and proper choice of alternative satellites, if necessary. Losing the signal of one of the satellites during a session requires the session be repeated, so signal strength was checked during the 5-min session at both sites. Since optimal satellite geometry calls for one of the satellites to be near the horizon, this loss of signal happened in approximately 10% of sessions. All sessions that had PDOPs >7.5 were repeated.

At the end of the day, the GPS units were returned to the computer center at the field station, where their files were downloaded and GPS memories were cleared for the next day's use. The control and remote GPS files for each point to be mapped were then matched and analyzed using the post-processing software to compute a calibrated longitude, latitude, and altitude. This information was entered into a database file, along with the ID number of the point, an attribute descriptor (household, mosquito larval habitat, and so on) and a brief description, if necessary. Mobile sessions files were processed in a slightly different fashion. As with the point files, the remote and control files were analyzed with the post-processing software. This resulted in a file of corrected positions, which was imported into AutoCad (Autodesk, Inc., San Rafael, CA), in which the points were replaced with a smoothed line, computed with a spline function.[13] The AutoCad export file for the resulting line was then converted to the proper format for the GIS software.

Geographic information system. Atlas GIS and SAS (SAS Institute, Inc.,Cary, NC) were used for all spatial analyses. Location information was linked to parasitology and entomology databases through common identifiers.[14, 15] The database file of locations and types was used to create a multilayered GIS map. Separate layers were generated for households, shops, hospitals, clinics, mosquito breeding sites, roads, streams, and the lake shore, which allows customized map production. In this project, there were entomologic, immunologic, epidemiologic, meteorologic, demographic, and parasitologic information that could be linked to each household's location on the map.

Automated, or batch computing of distances between one group of points to another, is a feature that is not available in the popular entry-level GIS programs unless supplemental programming tools are purchased. An SAS program has been developed that computes all possible distances from one group of points to another, chooses the smallest distance from each point in the first group to any point in the second group, and then creates an output database with household identifiers and the desired distances. The second group of points may be a collection of points, lines, or regions. The accuracy of the program has been checked by comparing its results with distances computed interactively using the GIS software. The distance computations account for the curvature of the earth by computing arc length instead of linear distance and are the basis for spatial analyses.[16] As a result, GIS software is not necessary for conducting many spatial analyses, once positional information is obtained via GPS or some other source.

Quality assessment. The performance of the GPS units and the post-processing software, as well as correct usage by the operators, was checked by placing the two units next to each other, designating one as the control unit, collecting positional information for 20 sessions of 5 min each, and computing the calibrated location of the remote unit. The mean and standard deviations of the calibrated longitudes, latitudes, and altitudes of the remote units were then computed.

One-hundred sixty-five data files that were being created by the control GPS unit for calibrating the readings of the remote GPS were used to examine the distribution of the uncalibrated positions for the control point. These 5-min data files contained an average of 275 positions, were taken over a period of a month, and when averaged, gave an estimate of the true longitude, latitude, and altitude of the control point, as well as the standard deviations (accuracies) of the uncalibrated 5-min sessions.

Maps of each of the 15 villages were produced and distributed to village monitors, who assessed their accuracy and completeness. Special opportunities often arose for external validation. Many households were near roads, so they were checked to verify that the map showed them on the proper side of the road and at the correct approximate distance. Households or compounds that were clustered were also checked for proper distances and relative geometric relationships. Features of interest that had not been mapped were noted for later inclusion.

Demonstration data. Entomologic and parasitologic data were used to demonstrate simple GIS analyses. Entomology and parasitemia data for months June and September 1995 are presented to represent rainy and dry seasons, respectively. Since households were enrolled when a pregnancy occurred and eliminated if there were no eligible children, parasitemia and entomologic data are only available for a fraction of the mapped households at any one point in time. We had parasitologic and sufficient entomologic data (three or more visits during the month) for 394 households in June and 416 households in September. For this analysis, potential larval habitat was defined as the lakeshore, streams and rivers, and pits dug to collect water for cattle. Multiple linear regression, correlation coefficients, and r-square statistics for each month were used to examine the relationship between

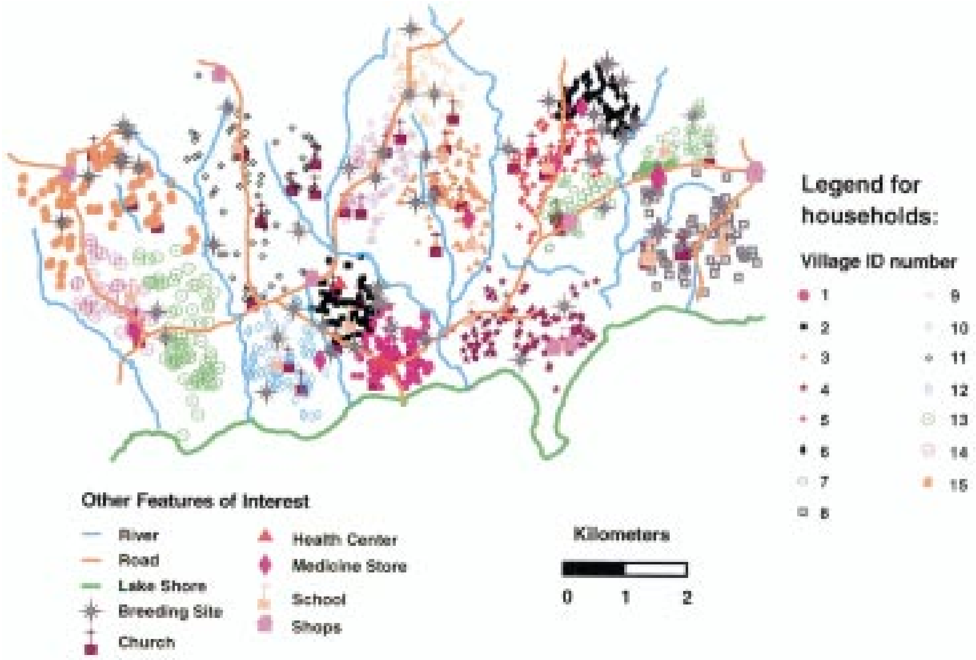

FIGURE 1. Map of households and other features of interest by village, Asembo Bay Malaria Cohort Project.

distance from major mosquito breeding sites and average numbers of trapped mosquitoes by species for each month.

RESULTS

A simplified version of the final map is shown in Figure 1. It covers an area of 69.8 km^2 over a rectangular area roughly 12 km long and 7 km wide, encompassing 15 villages. Geographic features include 1,169 houses (each with a plot character to designate its village), 15 schools, one nursery, one polytechnic school, 40 churches, six medicine shops, two clinics, one hospital, one health center, one rural acquired immunodeficiency syndrome counseling center, 48 major mosquito breeding sites, 10 borehole wells, seven shopping areas, major roads, streams, and the shore of Lake Victoria. In terms of distances, 42.0 km of roads, 54.3 km of streams, and 15.0 km of lake shore were mapped.

Of the twenty sessions taken with the two GPS units stationed next to each other, one (5%) had insufficient overlapping data to estimate a calibrated position. This is normally caused by the loss of a satellite signal during a session. Of the 19 remaining sessions, the longitudes had a standard deviation of 4.01 m, the latitudes had a standard deviation of 5.34 m, and the altitudes had a standard deviation of 4.78 m. The two dimensional standard deviation of these sessions was 3.11 m and the standard error of the mean was 0.714 m.

The results of the 165 uncalibrated control sessions showed that the initial control position was about 25 m from the center of the 165 measurements. The mean altitude was 14.2 m lower than the original estimate. The standard deviations for the latitude and longitudes of the sessions was 20 m, but was 40 m for the altitude. The latitudes and longitudes were normally distributed, but the altitude had a non-normal but roughly bell-shaped distribution. Ninety percent of the sessions were within 40 m of the center. All locations were transformed by adding 0.22 sec of latitude, 0.81 sec of longitude, and 14.2 m of altitude to adjust for the discrepancy.

Table 1 relates parasitemia prevalence and entomologic measures to the distance from the household to the nearest major larval habitat. For the month of June 1995, a rainy month, the average household prevalence of parasitemia in children less than five years old steadily decreased with increasing household distance from larval habitat, but this difference was not statistically significant ($P = 0.3437$, by linear regression). There was no relationship between distance to larval habitat and average parasitemia prevalence for the month of September, a dry month. Average numbers of trapped mosquitoes were related to the distance of the household to the nearest breeding site for *An. gambiae* for the dry month, but not the wet month (September: $P = 0.0039$; June: $P = 0.1530$, by linear regression). In contrast, average numbers of *An. funestus* appeared increase with increasing distance from larval habitat during the rainy month, but had no relationship to distance to major larval habitat during the dry month (June: $P = 0.0191$, September: $P = 0.6608$, linear regression).

Figure 2 shows the average number of trapped *An. gambiae* by household for the months of June and September 1995. Villages vary significantly in the numbers of mosquitoes trapped by household (both months; $P < 0.01$, by one-way analysis of variance [ANOVA]). However, there is considerable variation both among and within villages. *Anopheles funestus* also displayed significant variation by village (both months; $P < 0.001$, one- way ANOVA). The spatial pattern exhibited by *An. gambiae* was quite different than that of *An. funestus.* Variation in one species explains only 29.6% of the variation in the other during June and 7.8% in September (r-square, simple linear regressions).

TABLE 1

Parasitemia prevalence and entomologic measures by household and distance to the nearest mosquito larval habitat, June and September 1995

Distance to nearest larval habitat (m)	Parasitemia rate (%) in children <5 years old Month		*Anopheles gambiae* Average number trapped per collection Month		*Anopheles funestus* Average number trapped per collection Month	
	June	September	June	September	June	September
0–200	75.8 ± 39.1 n = 75	58.5 ± 47.8 n = 71	1.76 ± 2.53 n = 69	0.09 ± 0.19 n = 57	3.07 ± 2.94 n = 69	0.19 ± 0.34 n = 57
201–400	71.1 ± 42.7 n = 214	69.4 ± 43.4 n = 206	1.49 ± 1.71 n = 176	0.05 ± 0.18 n = 164	3.40 ± 3.76 n = 176	0.31 ± 1.42 n = 164
401–600	70.2 ± 43.1 n = 117	64.7 ± 45.3 n = 109	1.90 ± 2.31 n = 113	0.03 ± 0.10 n = 108	4.17 ± 5.58 n = 113	0.20 ± 0.37 n = 108
>600	67.1 ± 46.3 n = 39	57.8 ± 47.7 n = 30	2.09 ± 2.05 n = 37	0.02 ± 0.06 n = 33	4.70 ± 7.80 n = 37	0.34 ± 0.53 n = 33
*P**	0.3437	0.5594	0.1530	0.0039	0.0191	0.6608

* Linear regression, two-tailed test. Percent of children in household with parasitemia or average number of mosquitoes captured per weekly trapping session versus minimum distance (in meters) from household to nearest larval habitat.

DISCUSSION

We have shown that it is feasible to use differential GPS to produce a highly accurate map of study households and other points of interest in a large scale study of malaria in an area encompassing 15 villages over 70 km^2. Without differential GPS, positional errors are such that any mapping of objects within 200 m or so of each other will yield inconsistent spatial relationships between map features, since the errors associated with use of nondifferential GPS can be on the scale of 100 m. Use of simple GPS readings is appropriate when the objects to be mapped, such as villages, are relatively far apart.[7] Additionally, we have shown that it is easy to map linear features such as roads, rivers, and lake shores. The comprehensive maps have considerable use in the operational activities of the project and GIS allows the maps to be produced to customized needs in a rapid manner.

The magnitude of expense and effort to create this GIS were small relative to the other costs of this project, with expenses being less than $25,000. Of this amount, approximately $15,000 was for hardware and software that continues to be used on new projects conducted in this area. However, researchers doing one-time, short-term or small-scale studies may decide that the financial and time investment to be not worthwhile for their particular projects. The time needed to master differential GPS equipment would seem to make rental of equipment not worthwhile to the novice.

Our efforts at quality assessment raise several points. First, the results from the twenty sessions with the GPS units adjacent to each other demonstrate the greatly increased precision associated with differential GPS. A previous study[6] reported a standard error of 47 m associated with repeat measurements at 43 randomly selected households with an average discrepancy of 36 m from the original measurement. A 95% confidence interval on the average discrepancy is more than 90 m wide, which is in agreement with the stated error associated with crude GPS readings. Using differential GPS, the standard error (variablility of the mean of a group of 19 measurements) was 0.714 m, or a standard deviation of 3.11 m (reflecting the variability in the calibrated readings). Thus, DGPS greatly reduces the errors and variability in positional measurements associated with mapping. This allows mapping of features that are close together in a manner that will maintain spatial relationships with a high degree of integrity.

The 165 control point sessions allowed us to estimate the error associated with using an estimated position location (based upon one intitial measurement) for this point. The error of 25 m horizontal and 14.2 m vertical was corrected by adding the appropriate adjustment factor to each longitude, latitude, and altitude. This is analogous to sliding all points mapped east northeast 25 meters and lifting the map 14.2 m, which does not affect relative distances or directions between any of these points. As long as analysis is performed on only this data set, this correction is for aesthetic reasons; should the Asembo data be combined with independently produced maps from adjacent areas, the correction becomes essential. Comparison of estimates of variation between the twenty paired differential GPS sessions (standard deviations of 5 m of less) and the standard deviations of the 165 uncalibrated control sessions (20 m meters for horizontal measurements) again demonstrates the superiority of the use of differential GPS over a rather extreme example of using averaging to reduce error in GPS readings.

Training field staff to perform the necessary duties for DGPS mapping presented no difficulties. Because existing staff were employed for the mapping operations on a part-time basis, the new duties were a novelty, and the opportunity to use recent aerospace technology to produce a map of the study area was exciting to all involved. Moreover, recent improvements in GPS technology have greatly simplified mapping operations. Newer GPS units use all-in-view satellite technology, which records data from all GPS satellites in the sky versus only four satellites used previously. By connecting a GPS unit in a clear base location to a computer, field workers are guaranteed that any satellites that they use will also be received by the base location GPS. This eliminates the need for walkie-talkie communications and the planning software, which greatly speeds up data collection. Other improvements include faster GPS-to-PC communications, and the ability to obtain submeter accuracy by using carrier phase differential processing in sessions of less than 10 min. This type of GPS unit is the basis for the upgraded mapping operations for another, much larger scale, project recently begun in the same area. Data collection is approximately four times faster than before. Use of the base station

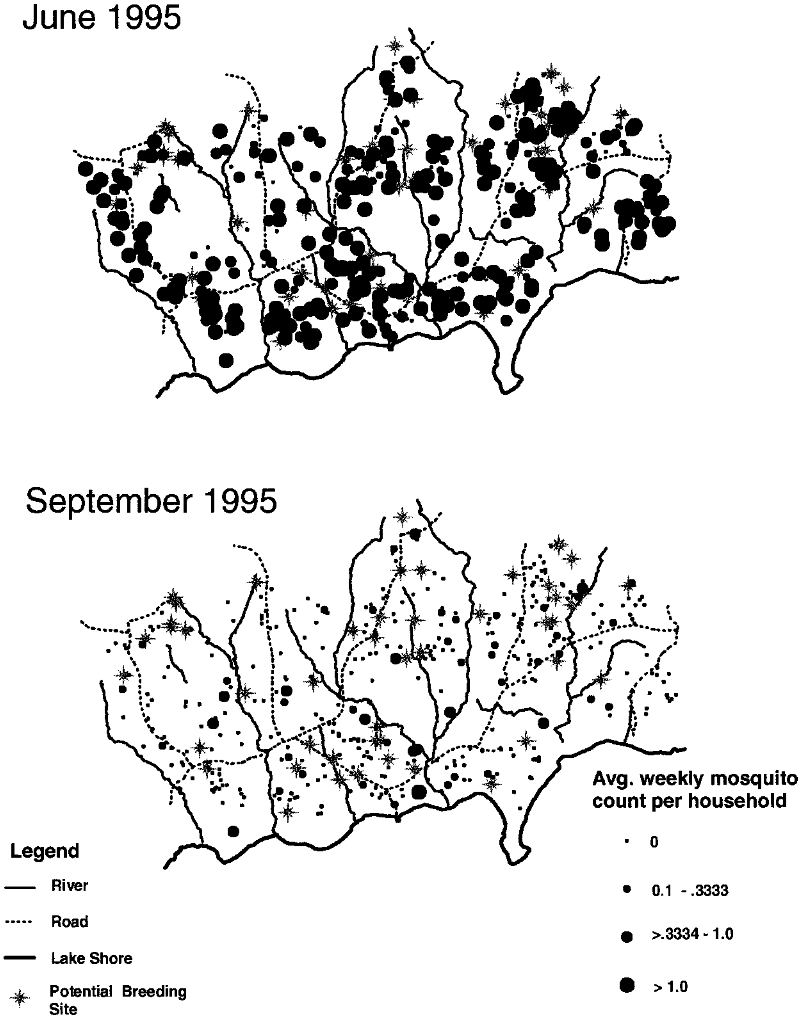

FIGURE 2. Mean weekly trap counts of *Anopheles gambiae* by household, June and September 1995. Avg. = average.

means that only one control point will be used, eliminating a previous source of error. Use of carrier phase differential processing, with its superior accuracy, is worth the few extra minutes spent at each location since so much time is saved in other parts of the GPS data collection process.

The analyses presented here were intentionally simple and were intended to present only some of the potential uses of the GIS/GPS data. Analyses did not account for a tremendous amount of available data such as daily rainfall, altitude of the household, age of the child, immunologic measures, longitudinal effects, previous infection history, or many other factors. However, the entomologic analyses raised several points. First, there is considerable variation both within and between villages for both mosquito species. Therefore, it is unlikely that a study that samples only a few households will adequately represent the entomologic experience of a given village. Second, we observed distinct patterns of abundance by household and village for each mosquito species that change between rainy and dry seasons.

We have shown that GIS software need not be mastered to conduct many useful spatial analyses once locational information has been obtained. Indeed, the spatial capabilities of the most popular entry level GIS programs are quite limited, and the automated computations of distances require supplementary programming efforts.[17] Fortunately, this can be easily done in a statistical program such as SAS or SPSS (SPSS Institute, Inc., Chicago, IL). Our example used distance from the household to the nearest major potential larval habitat. However, many other distance variables, such as distance to the nearest health clinic or medicine store, could just as easily be computed and additionally incorporated into a statistical analysis. The basic maps and spatial analyses produced by entry-level GIS programs are quite useful and might well satisfy a researchers' needs.

The analytic phase of this project has now begun in earnest by linking the base map produced by the methods described here to various longitudinal data sets. Researchers will now have the option of investigating the spatial aspects of any topic they are pursuing. Only time will tell as to the relevance of spatial issues in the many varied areas of malaria research. However, we do know for certain that we now have the practical ability to investigate these spatial issues as we never could before.

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