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GEOGRAPHIC INFORMATION SYSTEMS AND THE ENVIRONMENTAL RISK OF SCHISTOSOMIASIS IN BAHIA, BRAZIL

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Abstract. A geographic information system was constructed using maps of regional environmental features, *Schistosoma mansoni* prevalence in 30 representative municipalities, and snail distribution in Bahia, Brazil to study the spatial and temporal dynamics of infection and to identify environmental factors that influence the distribution of schistosomiasis. Results indicate that population density and the duration of annual dry period are the most important determinants of prevalence of schistosomiasis in the areas selected for study. Maximum rainfall, total precipitation during three consecutive months, annual maximum or minimum temperatures, and diurnal temperature difference were not shown to be significant factors influencing *S. mansoni* prevalence in local populations or distribution of snail hosts. Prevalence of the disease was highest in the coastal areas of the state. Higher prevalence tended to occur in areas with latossolo soil type and transitional vegetation.

Schistosomiasis, which is caused by *Schistosoma mansoni,* was introduced into Brazil in the mid 1550s[1] and became established as a significant health problem in the endemic states of the northeast region of the country. Ecologic factors favorable to the intermediate snail hosts and the concentration of susceptible humans hosts living under substandard conditions have contributed to maintenance of the disease and expansion of the endemic area.[2] While spatial distribution and prevalence have remained constant in some regions since surveys done in the 1950s, outbreaks have been reported in regions previously considered free of schistosomiasis. Spread of the disease to newly settled areas is a major concern of the National Schistosomiasis Control Program.

Studies done on rural communities in Bahia[3–5] have shown that the number, distribution, and rate of infection of the intermediate host *Biomphalaria glabrata* and contact with domestic water were key determinants of human infection prevalence and that snail populations responded to seasonal rainfall patterns, with an increase in reproduction during the period October through January and proportional decreases during months of drought. A study contrasting communities with high and low prevalence rates of *S. mansoni* in Sao Paulo State revealed that high altitude, low population density, high standards of sanitation, and limited numbers of breeding sites for *B. tenagophila*, the principal intermediate host in the Sao Paulo area, contributed to low rates of infection.[5] A knowledge of the factors contributing to the size and location of snail populations is pivotal to planning and implementing effective programs of suppression using molluscicides. Since the number of intermediate hosts, their concentration, and rate of infection may be functions of rainfall, vegetation, topography, soil type, and characteristics of water bodies, geographic information system (GIS) methods may be suitable for analysis of the spatial relationships of the environment, mollusk intermediate hosts, and schistosomiasis in specific regions and communities.[6]

The application of a GIS to define the epidemiology of vector-borne diseases and parasitism has been documented for a number of diseases such as malaria,[7] Lyme disease,[8] fascioliasis,[9] trypanosomiasis,[10] and dracunculiasis.[11] In early studies on schistosomiasis, climate and vegetation indices calculated from satellite data were used to define risk of *S. japonicum* in the Philippines.[12] Recent reports on the distribution of schistosomiasis in Egypt suggested that diurnal temperature difference (dT) maps derived from Advanced Very High Resolution Radiometer satellite sensor data reflect regional hydrologic features that can be used to predict environmental risk of the disease.[13] Related studies comparing dT rank and numbers of *B. alexandrina* and *Bulinus truncatus* present in irrigation and drainage canals in Egypt showed an inverse correlation between dT and abundance of *B. alexandrina.* These reports suggest that a GIS can be used to implement computerized analysis of standard maps and existing epidemiological databases to assess environmental risk for schistosomiasis in Brazil. This paper documents the application of the Intergraph Modular GIS Environmental Systems Nucleus (Intergraph Corp., Huntsville, AL) to establish descriptive and quantitative parameters relating to the spatial and temporal dynamics of schistosomiasis in 30 municipalities in Bahia, Brazil.

MATERIALS AND METHODS

The study was conducted in the state of Bahia in northern Brazil, which has an area of 583,248 km^2 and 932 km of Atlantic Ocean coastline. Bahia is located between 8° and 18°30′S and between 36° and 46°W. The estimated population of Bahia exceeds 12 million people distributed through 415 municipalities at a median altitude of 400 m above sea level (0–700 m). A sample of 270 municipalities in the state of Bahia were selected for study. These municipalities were included in records of the Ministry of Health Schistosomiasis Control Program conducted in 1991–1993 and were subject to standard Ministry of Health chemotherapy and snail control intervention programs implemented under the direction of the National Foundation of Health (Ministry of Health, unpublished data). The population sample for prevalence data consisted of school children 7–14 years of age that were born and living in one of the 30 municipalities selected for the experiment. All school-age children were screened for infection using the Kato-Katz technique.[14]

A random sample scheme was used to select 30 of 270 municipalities after ranking by prevalence of schistosomiasis (Ministry of Health, unpublished data). Ten municipalities were selected from each of three prevalence groups: 1) mu-

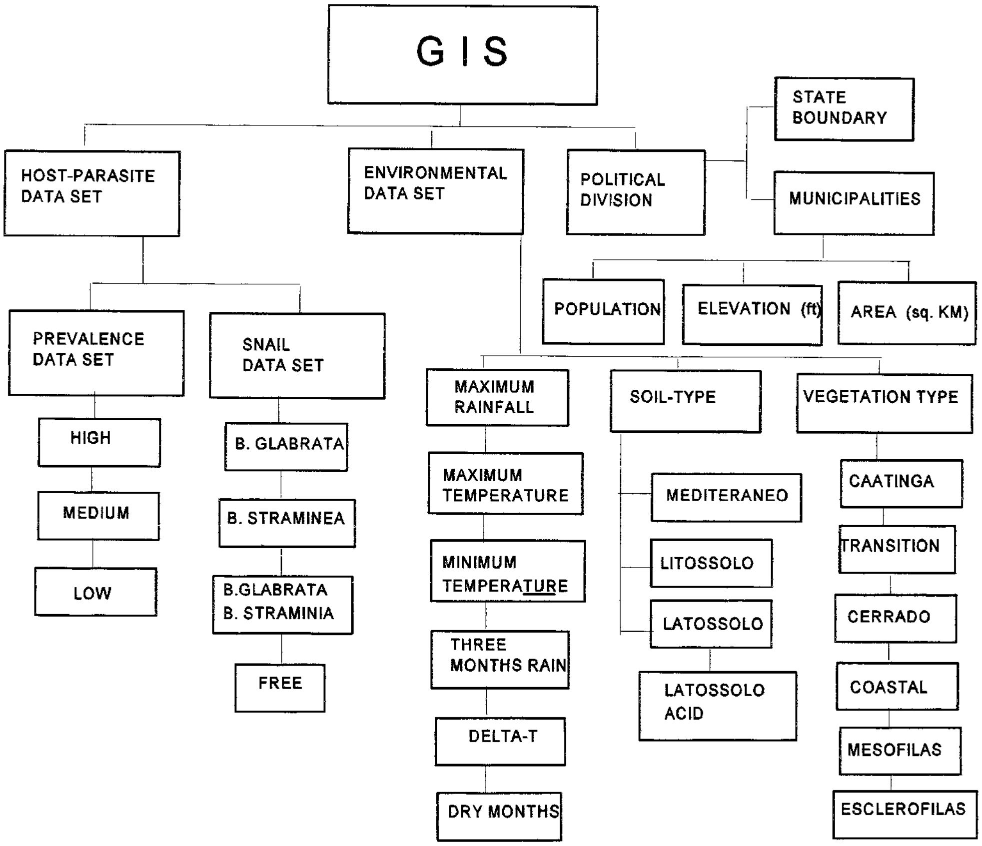

FIGURE 1. Computer graphic representation of the geographical information system (GIS) constructed for schistosomiasis in Bahia, Brazil. B. = *Biomphalaria;* DELTA-T = diurnal temperature difference.

nicipalities with schistosomiasis prevalence rates of 0.1–4.9% were assigned to the low prevalence group, 2) municipalities with prevalence rates of 6.3–18.0% were assigned to the medium prevalence group, and 3) municipalities with prevalence rates of 21–61% were assigned to the high prevalence group. Population density (people/km^2), based on a census data for each municipality, was obtained from the Brazilian Foundation Institute of Geography and Statistics.[15] Boundaries of municipalities were obtained from the Digital Chart of the World (DCW; 1993. Defense Mapping Agency, MIL-D-89009, Philadelphia, PA) at a 1:1,000,000 scale.

For snail distribution,[16] four categories were created: A + B = presence of *B. glabrata and B. straminia*; A = presence of only *B. glabrata*; B = presence of only *B. straminia*; C = presence of only *B. tenagophila* in the municipality, and F = municipality free of *Biomphalaria.* Snail distribution data was digitized from a 1:12,000,000 scale map.

Environmental databases included 1) elevation, obtained from the DCW database at a scale of 1:1,000,000 for each site, 2) climatic variables created from cartographic maps (1:5,000,000 scale), representing 30-year average climate data for each municipality in the study[17] including maximum rainfall, mean of number of dry months during the year, mean of maximum temperature, minimum temperature, mean rainfall in three consecutive months, temperature difference, mean monthly maximum and minimum temperature during the year for each municipality, 3) soil type, and 4) vegetation type. Maps of vegetation and soils at a scale of 1:10,000,000 were used.[18]

Spatial data were created, processed, and analyzed using Intergraph Modular Geographic Environment-MGE (Modular GIS Environment, 1990; Intergraph Corp.) software. Development of the GIS required integration of several techniques, including translating and importing digital spatial data, digitizing maps, transforming map projections, data management and analysis, edge matching adjacent maps, assigning attribute data to spatial features, and construction of spatial queries. The software allows creation of databases in a vector format and definition of specified categories and features of interest including coordinate systems. Individual digital GIS layers were created, including variables for climate, soil type vegetation, elevation, municipalities boundaries, area (km^2), disease prevalence, snail distribution, and population (Figure 1). Digitized maps were geo-referenced to the 1:1,000,000 scale DCW base maps. Using the MGE-MAP module and Systems Environment of the Intergraph software, the DCW files were converted from a three-dimensional geographic projection into a two-dimensional display and translated to Universal Transverse Mercator (UTM), Zone 23, Southern Hemisphere and the World Geodetic System 1984 (WGS84) spheroid.

For statistical analysis, the Student's *t* value was calculated for each group[19] at the 5% confidence level. Composite analyses were used to analyze the non-numerical variables

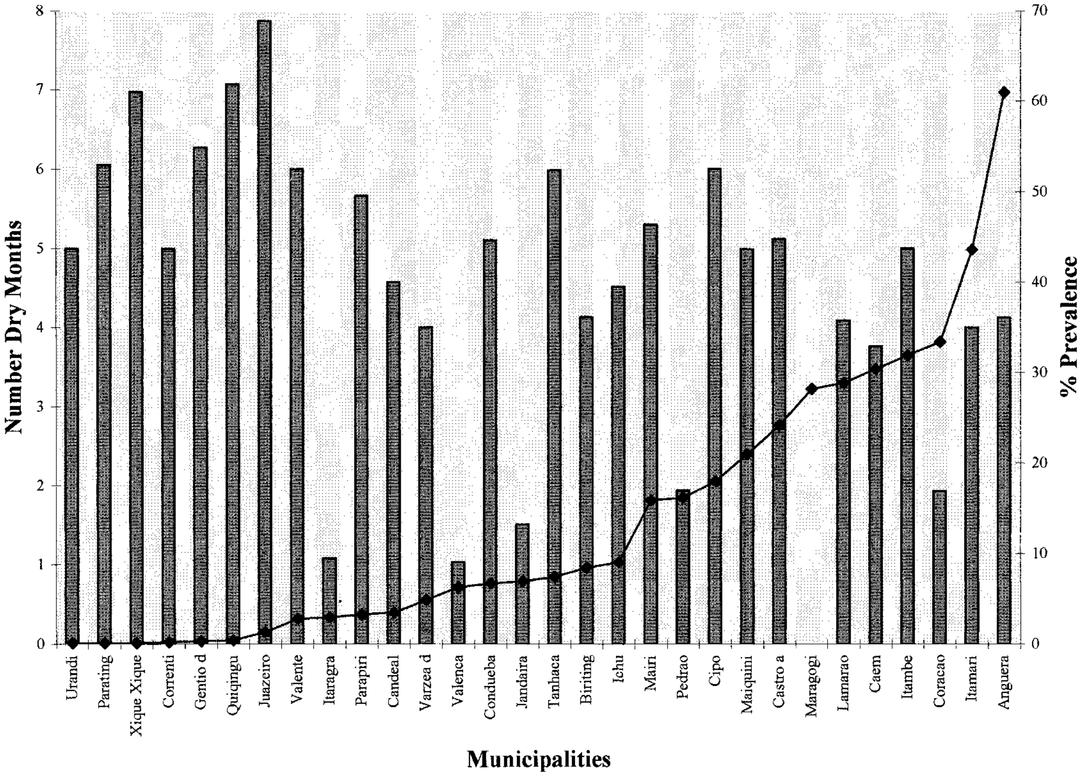

FIGURE 2. Average annual number of dry months based on 30-year average climate data compared with the 1990–1993 prevalences at 30 municipalities randomly selected from low, medium, and high prevalence categories of the 270 municipalities surveyed in the Bahia study area. Diamonds connected by the line are ranked prevalences.

e.g., soil types, vegetation types, and snail distribution. The mean and the mean difference values for each feature was calculated and correlated with each municipality prevalence group (low, medium, high). The SAS software was used to extract data results.[20]

RESULTS

Analysis of individual thematic layers of environmental and population variables with *S. mansoni* prevalence and snail host distribution databases revealed a significant relationship of length of dry period (Figure 2) and population density (Figure 3) with prevalence group and that *B. glabrata* was the major species of snail in high prevalence areas. For length of dry period, a mean of 3.2 months without rain was recorded for municipalities with high schistosomiasis prevalence rates. In the areas where prevalence rate was low, the mean number of dry months was 5.5. The medium prevalence group had a mean of 4.0 dry months. A significant difference in the mean values for length of dry period existed between municipalities with low prevalence versus medium prevalence and low prevalence versus high prevalence, but not between municipalities with median and high prevalence rates. Mean population density ranged from 19 to 50 people/km^2. Municipalities in the low prevalence group had the lowest population density. No significant differences were observed between mean values of rainfall, three consecutive months of rain, mean monthly maximum temperature, mean monthly minimum temperature, or temperature.

Of the three *Biomphalaria spp.* responsible for transmission of schistosomiasis in Bahia, *B. glabrata* was associated with areas of medium and high prevalence rates along the coast, extending through the middle part of the state. *Biomphalaria straminea* was found in association with *B. glabrata* bordering the states of Minas Gerais, Alagoas, Sergipe, and Pernambuco, whereas *B. tenagophila* was restricted to southern Bahia. *Biomphalaria glabrata* (with or without concurrent *B. straminea*) was present in 100% of the municipalities with high schistosomiasis prevalence rates. In contrast, this species was present in only 18.8% of the municipalities with low prevalence rates. *Biomphalaria straminea* alone was not found in areas with high and medium schistosomiasis prevalence rates. It occurred as the only snail host in one municipality in the low schistosomiasis prevalence category that was located in an area with a long dry period (Figure 4).

Using GIS analysis, the relative composition (area/km^2) of four soil types[15] (mediterranean, latossolo, latossolo acid, and litossolo) and six vegetation types (mesofias, esclerofilas, caatinga, cerrado, coastal, and transitional) was calculated for each of the 30 municipalities. A high proportion of the latossolo soil type was found in municipalities with a high disease prevalence; the difference between the mean values of this soil type in municipalities in high and low prevalence groups was statistically significant. There was a significant inverse relationship of the mean area of litossolo soil between municipalities with high and medium prevalence rates. A high proportion of transitional vegetation class

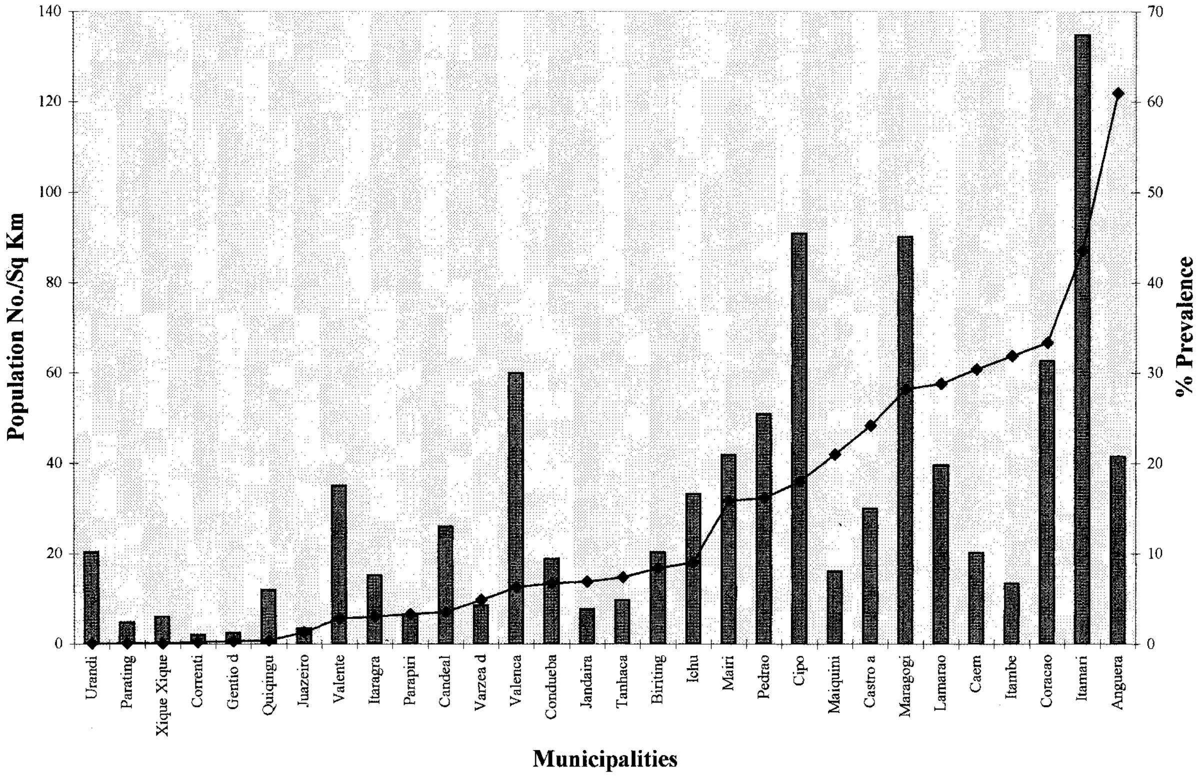

FIGURE 3. Population density per km^2 at 30 municipalities randomly selected from low, medium, and high prevalence categories of the 270 municipalities surveyed in the Bahia study area. Diamonds connected by the line are ranked prevalences.

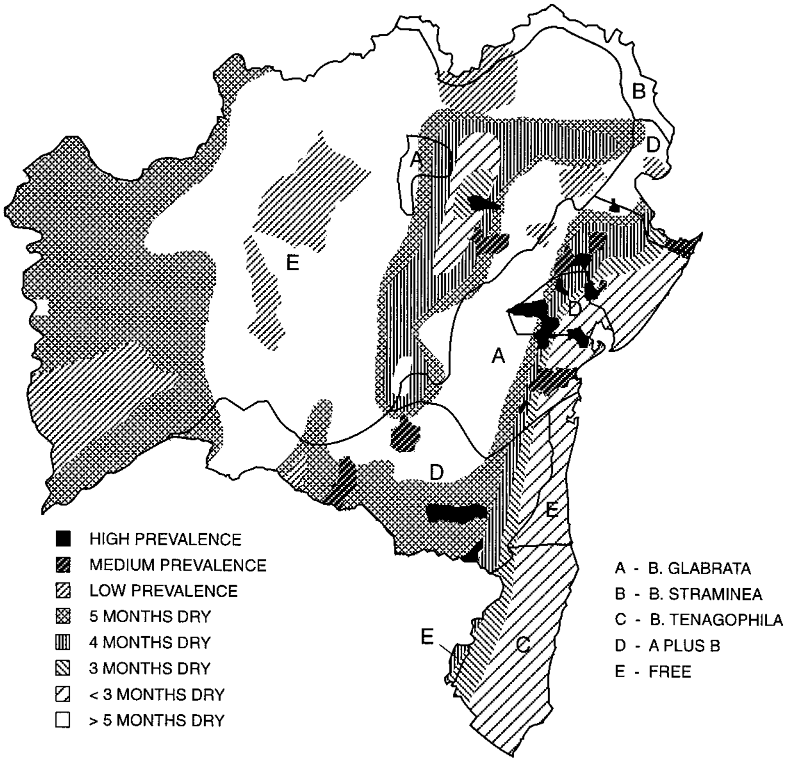

FIGURE 4. Map of geographic information system feature overlays showing the spatial distribution of 30 municipalities with low, medium, and high prevalence, boundaries of snail host distribution, and length of the dry period in Bahia, Brazil. B. = *Biomphalaria.*

was found in 44% of the group of municipalities with high prevalence rates; a significant mean difference between prevalence groups was found for high versus low disease prevalence.

DISCUSSION

Temperature and moisture are fundamental environmental factors that drive or limit the distribution and abundance of biologic systems.[21] A major aim of construction and analysis of the GIS in the present study was to develop ways to define spatial patterns of the population dynamics of snail intermediate hosts and extra-mammalian stages of *S. mansoni* in Bahia based on hydrologic factors and temperature.[22] Major soil and vegetation type zones were also examined. The pattern of rainfall in Bahia follows a tropical pattern; rainfall is concentrated during a few months in summer, with the exception of the coastal area where more extended rains occur. Study results indicate that the length of the dry season is more important than the quantity of rainfall or duration of the wet season in influencing both snail host distribution and the relative suitability of a site for life cycle development and transmission. Neither mean annual rainfall nor the amount of rain during three consecutive months were significantly different between the three categories of prevalence. Approximately 63% of all municipalities classified as medium and high prevalence areas were clustered around the east coast in areas characterized by a Mediterranean seasonal rainfall pattern. These areas had a mean dry period of 3.7 months each year. The mean length of dry period in municipalities with low prevalence rates was significantly different from that in areas with medium (4.0 months) and low prevalence of schistosomiasis (5.5 months).

The potential intermediate snail hosts of schistosomiasis found in Bahia are adapted to a wide range of environmental conditions, including streams, lakes, irrigation canals, ponds, flooded marshes, and wetlands. In general, snails inhabit shallow water with moderate light penetration, minimal turbidity, a mud substratum rich in organic matter, and submergent or emergent aquatic vegetation. Marshes and high elevation springs or ponds associated with the headwaters of rivers serve as permanent reservoirs from which *B. glabrata* can be disseminated to streams and marshes where transmission of the disease occurs.[4] Populations of *B. glabrata* in waterways are eliminated by heavy seasonal rains, and those in low-elevation marshes are decimated by seasonal drought.[23–25] Without constant immigration from the permanent reservoirs, snail populations in habitats at lower elevation disappear. In northeastern Brazil, snail hosts can estivate to survive adverse conditions during the dry season and quickly repopulate temporary habitats at the onset of the rainy season. Michelson and Mata[4] observed that in some areas of Bahia, snails that transmit *S. mansoni* were often found in habitats characterized by temporary wet periods and reported that unusual early rains in August resulted in a rapid onset of snail reproduction in a high prevalence area of Bahia. The observed relationship in the present study of length of drought period and prevalence may be manifest by the effects of drought stress on transmission from these temporary habitats, by greater reduction of post-drought snail populations available for dispersal from reservoir sites, and/or by the longer period in which surface hydrologic conditions are suited to life cycle propagation and transmission during the rainy season. In most of the areas where the annual dry season exceeds five months, snail hosts are often reported to be absent.[16]

At tropical latitudes, annual temperatures are less variable than in temperate areas and tend to exert a lesser effect on the development and limits of tolerance of a species than do local hydrologic conditions. Mean maximum and minimum temperatures and diurnal temperature difference in Bahia followed similar patterns in all selected municipalities. The variation that occurs in average annual mean temperature, which ranges from 18°C to above 26°C, is associated with latitude, topography, and the rainy season.

Plorin and Gilbertson[26] reported that a linear relationship exists between water temperature and the development rate of *S. mansoni* in *B. glabrata*; limits of development extended from 16°C to 32°C, with a 14.2°C null point at which no cercariae were produced. *Biomphalaria glabrata* and *B. straminea* are reported to survive at temperatures in the range of 12–40°C.[27] Assuming a situation where a noninfected snail estivates during a long dry period and emerges with availability of water, the development of *S. mansoni* can be depicted by the following relationship: $Y = 268/(X - 14.2)$, where $Y =$ the duration of *Schistosoma* development in the snail in days, $X =$ constant temperature in °C, and 268 is the required cumulative growing degree days (mean daily degrees above the minimum temperature for development of the parasite in snails). At temperatures prevailing in most parts of Bahia, cercariae would usually be shed between 27 and 31 days after infection of the snail host. This suggests that unless snails are infected before estivation, approximately one month of development in snails must be added to the time of snail emergence at the end of the dry period in a given area before major infection of humans can occur. These relationships should be taken unto account in planning disease control programs.

Significant differences were noted between the mean population densities (Figure 3) in municipalities with low (19 people/km^2), medium (36 people/km^2), and high (50 people/km^2) prevalence rates. Higher population density occurs along the east coast of Bahia. The concentration of the population in small areas can influence *Schistosoma* prevalence within specific municipalities.[25] The prevalence and intensity (parasite burden) of schistosomiasis in a population depends on quantum of parasites, frequency and length of exposure to infected water, and host susceptibility. In the present study, some municipalities with low and medium prevalence rates were found in areas with consistently high prevalence of schistosomiasis. The low population density in these municipalities is a possible reason for this anomaly.

The GIS analysis of soil types and vegetation revealed that latossolo and litossolo[15] soil types were significantly related to prevalence rate in the municipalities studied. Areas with latossolo soils were associated with high prevalence, especially in areas with a predominance of *B. glabrata* cohabiting with *B. straminea*. This may be attributed to the characteristics of this soil type, in which the composition of more than 35% clay and poor capacity for drainage favor accumulation of surface waters. The Litossolo soil type was present only in areas with a low prevalence of schistosomiasis where *B. glabrata* and *B. straminea* occur. This soil type is shallow with minimum development and a superficial horizon formed by accumulation of organic matter. Transitional vegetation (between caatinga and cerrado) and/or coastal vegetation types covered 67% of the municipalities with a high prevalence of schistosomiasis. No other soil or vegetation factors were related to the distribution of schistosomiasis in the municipalities examined in this study. However, the 1:5,000,000 scale soils and vegetation databases available made possible only very general evaluation of the importance and influence of different types of soils and vegetation, and evaluation of more detailed map data may reveal other associations with these factors.[16] Analysis of mean elevation of the three municipality classes also did not reveal an association of elevation with infection prevalence or snail distribution in the Bahia study area. Elevation in Bahia ranges from 0 to 700 m above sea level.

The GIS provides a systematic way to spatially link known epidemiologic data on disease systems with relevant features in the environmental to develop models that can then be used, by extrapolation, to predict risk of disease over broad geographic areas where data is not available. It is possible, using GIS, to systematically represent the spatial distribution and abundance of disease in terms of relative suitability and limits of tolerance, such as drought stress in the current studies, that allows discovery of the effect of factors that are not readily apparent by classical laboratory and field studies.[26,28] Results of the current study indicated that population density and the duration of the annual dry season are the most important factors in the determining the prevalence of schistosomiasis in the state of Bahia. In Bahia, regional differences in the prevalence of *S. mansoni* are determined more by the limiting effects of drought stress on life cycle development and transmission than by rainfall and temperature during periods suitable for life cycle progression. The duration of the dry season has received minimal attention from field investigators and there is a need for future studies on the effects of drought stress. Results further suggest that the design of programs for control of schistosomiasis in Bahia should be based on chemotherapy at the end of the dry season with the objective of diminishing the level of infection in the water, and that molluscicides should be used after onset of the period of rain when snails hosts are recovering from aestivation. Future GIS studies in Bahia are indicated to confirm and extend results by incorporation of environmental satellite data patterns and more detailed map databases on climate, hydrology, soils, and other features of the environment.

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