Remote Sensing and GIS for Schistosomiasis Control in Mountainous Areas in Sichuan, China

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Abstract
In this paper, we report some of our initial results obtained from a joint research project between a team at the University of California at Berkeley and the Sichuan Institute for Parasitic Diseases. The project began with an intent to apply mathematical modeling to schistosomiasis control and later evolved into the use of GIS and remote sensing to map and model the spatial heterogeneity for the study of schistosomiasis transmission dynamics and the identification of snail habitats. Following a description of our study site in China, we present our results on the use of Landsat Thematic Mapper imagery in mapping snail habitats and the use of a GIS database developed at the village level for schistosomiasis transmission control based on spatial network analysis.

I. INTRODUCTION

Schistosomiasis is a water-borne parasitic disease that affects 200 million people and poses a threat to 600 million in more than 76 countries (W.H.O. 1993). It is caused by infection by parasitic worms of the genus *Schistosoma*. These worms are transmitted via contact with contaminated water. The life cycle of the schistosome begins with the sexual pairing of adult worms in the blood vessels of the host and the excretion of eggs in feces (or urine in the case of *S. haematobium*). The eggs hatch in the water and release a free-swimming miracidium whose objective in life is to find and penetrate an appropriate snail in which to develop. After a period of asexual reproduction, tailed, free-swimming larvae called cercariae leave the snail and are transported in water where they actively seek an appropriate vertebrate host. Cercaria can penetrate the intact skin of the host, thus infecting them. They subsequently mature into adult worms and mate to complete the cycle (Figure 1).

Schistosomiasis is a disease whose distribution is particularly sensitive to environmental change, most clearly environmental change of human origin. There are two events in China looming which promise major environmental changes: the construction of the Three Gorges Dam and the increasing probability of global warming. The changes caused by these events promise to have a substantial impact on the distribution and extent of Schistosomiasis Japonica in China and on opportunities for extending our understanding of these processes. It is not generally understood, even in China, that there are at least three genetically distinct subspecies of *Oncomelania* in China living in considerably different ecological settings. The genetic and biogeographic differentiation of these taxa has only recently been clarified through research carried out by the Shanghai-based Tropical Medicine Research Center (Davis et al. 1995; Spolsky et al. 1996; Davis et al. 1997). The two major subspecies are *O. h. robertsoni*, which are found above the Three Gorges of the Yangtze River in Yunnan and Sichuan Provinces, and *O. h. hupensis*, occurring below the Three Gorges in the Yangtze River basin (Figure 2).

In Sichuan, life tables indicate that snails can live two or more years in the mountainous areas unaffected by the annual floods of the Yangtze river. These snails are adapted to a colder climate than those of the Yangtze basin, and live in terraces, nooks and crannies where there is an appropriate climate and mixture of soils, vegetation and organic matter on which to feed. They are often distributed along irrigation ditches that feed rice fields and terraces. Until now, the Three Gorges of the Yangtze have been an effective barrier separating the two subspecies and their schistosomes. Snails cannot survive the grinding of the 125 mile long string of canyons and rapids. The impact of global warming on the geographical distribution of schistosomiasis is more speculative.

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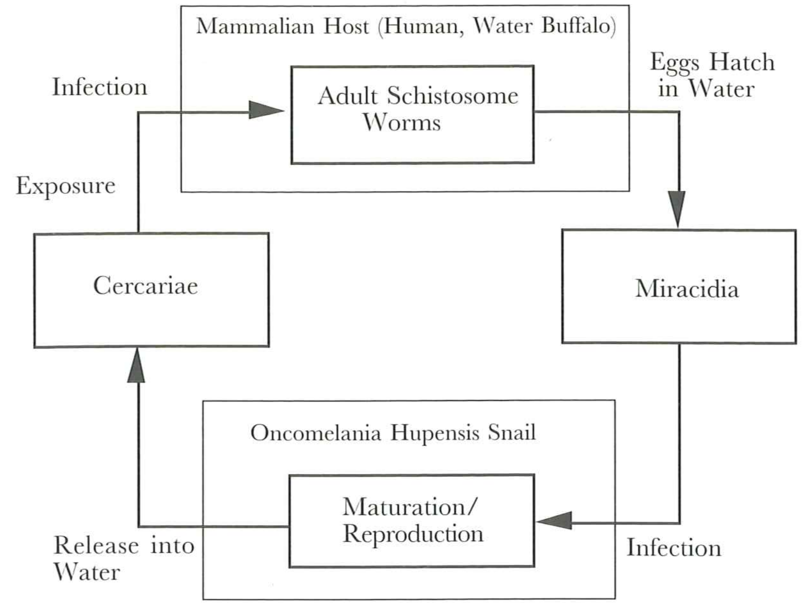

Figure 1. The life cycle of a schistosome

The work of Martens (1997) supports the possibility of the spread of the disease at higher altitudes in currently endemic areas like the eastern highlands of Africa and the mountainous regions of western China based on studies of the global warming potential using Intergovernmental Panel on Climate Change (IPCC) scenarios regarding greenhouse gas emissions and both the global climate change and general circulation models. Indeed there is some preliminary evidence in Hunan that colder mountainous areas at the edge of *Oncomelania* habitat in that province, e.g. Tao Yuan and Juzi Zhoutou, where disease transmission did not previously occur, became sites of transmission in July 1997. Experience in the mountainous regions of Sichuan suggests that disease transmission does not occur when mean annual water temperatures fall below 15°C. Hence, it can be forecast that global warming would increase the altitude range where the disease is endemic. On the other hand, the completion of the Three Gorges Dam may alter the distribution of the two snail species.

Figure 2. The study site in China

Over the last several years we have had access to a rich data set developed at the Sichuan Institute of Parasitic Disease (SIPD) beginning in 1987. The data set demonstrates SIPD's considerable success in reducing schistosomiasis prevalence in villages near Xichang using a combination of control interventions selectively directed at high risk groups, and timed with an understanding of the transmission cycle. Although the time-series data available from that study are sparse, a large amount of spatial information is available at each point in time. This database is thus allowing us to address questions of heterogeneity in prevalence and environmental risk. A goal of this analysis is to discern whether heterogeneity in parasite abundance is mediated more by heterogeneity in environmental risk or human activity patterns, and thus whether ecological studies or human activity surveys are more informative in directing selective control. The goal is to apply the lessons learned in the Xichang villages to endemic environments which present different landuse patterns or ecological circumstances. There is little question that the potential effects on schistosomiasis transmission of these large-scale environmental changes makes it essential to understand the ecological circumstances conducive to snail habitat and disease transmission. Remote sensing and GIS technology promise to aid the identification of new areas of potential snail habitat and sites with high potential for disease transmission, based on image analysis and specification of land-cover features associated with agriculture and human habitation. Remote sensing and GIS have been used effectively in the study of several infectious diseases including malaria, Lyme disease, and rift valley fever (Wood et al. 1991; Dister et al. 1993; Beck et al. 1994; Washino and Wood 1994; Glass et al. 1995; Linthicum et al. 1997).

In this paper, we report some of our preliminary work on the use of remote sensing and GIS for schistosomiasis control. We first report our effort in exploring the use of Landsat TM imagery in the Anning River valley for identifying the habitat of the *Oncomelania* snail. Then we will introduce a GIS-based spatial network analysis model at an even smaller scale for the control of schistosomiasis transmission. The implication of the GIS analysis to the remote sensing work will be discussed.

II. STUDY SITE: THE XICHANG VILLAGES AND THE ANNING RIVER VALLEY

The Xichang Villages for the GIS Study

In 1986, the Ministry of Health of the People's Republic of China funded the Sichuan Institute of Parasitic Disease to carry out an intensive and geographically-focused five-year investigation of the factors responsible for the high levels of schistosomiasis that have persisted in the mountainous regions of Sichuan Province for many years (Gu 1990a; Gu 1990b; Li 1990; Li et al. 1990). This investigation focused on two villages in Chuanxing County near the city of Xichang in southwestern Sichuan Province. The project was subsequently extended to 1995 with a focus on the development of intervention and control strategies. The first phase of the project was carried out over three annual cycles, beginning in 1987, in which baseline data were established on human and animal populations, snail populations and habitat, and relevant environmental variables. In the second cycle, control measures were instituted, and in the third the effectiveness of these interventions was assessed. Overall, the program has been highly effective in reducing the prevalence of schistosomiasis from 55% in 1987 to under 5% in 1995.

The Xichang study area consists of twelve residential groups organized into two villages, Minhe and Hexing. In the 1960s, the prevalence of schistosomiasis in Chuanxing County was about 30% and there were just over 200 hectares of snail habitat. The villages lie on the edge of the Anning river valley plain, and they were selected as being typical of the environment of about 90% of the population in the Daliang Mountainous Region. The living and working style of people in a residential group are usually very similar, and the fields that they farm are usually adjacent to their housing areas. In general, the agriculture typical of the river valley plains does not rely heavily on animal husbandry, hence the animal populations are relatively small in comparison with the high mountain valleys, also found in the Daliang region.

The population of the experimental area was 2642 in 1987. These populations lived in 33 hectares of residential land and worked in 314 hectares of agricultural land totaling 3.5 km^2. Within this area the maximum elevation is 2010 meters in the north dropping to 1530 meters in the south. The climate is subtropical with an annual average temperature of 17 °C and annual rainfall of about 1000 mm, over 90% of which falls between the beginning of June and the end of October. The main agricultural products are rice, wheat, rape, garlic, eggplant and tomatoes. There is a complex irrigation system which was substantially expanded in the late 1970s. Rainfall and mountain runoff feed the irrigation system in the wet season, and, during the dry season, water can be pumped from Qionghai Lake, several kilometers distant. Since the expansion of the irrigation system the prevalence of schistosomiasis has increased in the area. In Minhe village for example, the infection rate was 31.7% in 1977, 38.2% in 1978, 39.1% in 1980, 49.3% in 1984 and 56.7% in 1987. An important factor to sustaining the disease cycle in this area is that fertilization practices make extensive use of human and animal excrement which is moved from residential pit latrines to field storage pits without treatment and with minimal holding times.

Surveys of human infection were undertaken in April and May of 1987, 1989, 1992, 1993 and 1994. An extensive survey of human water contact activities was taken in 1987. In each year the entire population was tested with the exception of 1991-92 when only 24% were tested. In 1987, 1989, 1992 and 1994 surveys of snail density and infection rates were conducted in April and May, and assays of cercarial concentration in the water system were taken in July and August. Treatments utilizing praziquantel were given to infected people in a single oral dose (60 mg/kg) in August-September in each of the years 1987-1990 and in 1994. In 1987-89, treatment was targeted at the entire population and about 90% coverage was achieved. Subsequently, high risk populations were identified and treated. Two regimens were given to high risk populations in the years 1993-95, one in August and the second in November. In 1988 large-scale molluscaciding was done. The study site was divided into quarters and molluscacide applied to snail habitats in the north-east and south-west quadrants. Focal molluscaciding was used in subsequent years in risky environments defined by snail densities and contact sites.

Much of the data from the Xichang villages was geocoded in some way, motivating our interest in geographic information systems. An effort was made to integrate the Xichang data into a GIS managed by ArcView®. Our GIS and schistosomiasis modeling work was carried out with this database.

III. REMOTE SENSING OF SNAIL HABITAT IN THE ANNING RIVER VALLEY

As mentioned above, schistosomiasis is a disease sensitive to environmental conditions. In particular, suitable environmental conditions must exist for the snail vector to establish itself and complete the lifecycle of the parasite. Our most recent work has been in the use of remote sensing technology to locate these habitats suitable for schistosomiasis snail vectors. The goal in this study was to determine whether environmental conditions observable via Landsat TM imagery correlate with the presence of *O. h. robertsoni*. Due to the 30m limitation in the spatial resolution of TM imagery, neither snails nor their micro-environments can be seen directly. However, we hypothesized that at a macroscopic level visible from TM imagery there may exist environmental factors useful in the determination of habitats suitable for snails. These environmental factors may include vegetation, crop type, soil type, moisture, and temperature. All of these factors vary from region to region and may affect the suitability of an area to support snails.

For the remote sensing study, we extended the spatial scope to a larger portion of the Anning River valley in the vicinity of Xichang. The Anning River Valley is a high mountain valley at an elevation of about 1500 meters and is dense with irrigated farming of rice, corn, wheat, and a variety of vegetables and some export crops. The valley is also a highly endemic area for schistosomiasis. Two Landsat TM scenes (one Spring April 7, 1994, and one Fall October 16, 1994) were obtained for the region. Images from 1994 were obtained because the Xichang County Anti-endemic Station (XCAS) conducted a large-scale snail monitoring effort that year. This provided ample data on the status of snail habitat at different locations throughout the valley. Both images were free of cloud cover over the area of interest, and each represents a distinct agricultural season.

Ground data on the locations of snail colonies were obtained from the XCAS 1994 snail surveys. Data was located in 14 townships throughout the valley. Each data location was categorized as snail habitat or as non-habitat depending on whether snails were detected at that location during the 1994 surveys. These habitat and non-habitat sites were precisely located to 5 meter accuracy using Global Positioning System (GPS) differentially corrected measurements to allow for correlation with the two Landsat images. There are substantially different landscape types in this area. For simplicity, we chose only those sites that were irrigated farming areas in the river plain. This resulted in a total of 103 sites (55 classified as habitat and 48 as non-habitat).

Before conducting any analyses on the images, the two images were georeferenced to 11 ground control points located throughout the valley using differential GPS. Next, all 103 sites were located on the image. Each snail habitat and non-habitat site was specified as a 3 x 3 pixel area surrounding the site location as determined in the field by GPS measurements, where each pixel in the area corresponds to an individual data point. Each Landsat TM image contains 7 variables of information. These variables record the level of brightness for the blue, green, red, near infrared, thermal infrared, and two mid-infrared wavelength bands. For our initial classification work we included in the analyses all bands from both images, as well as a standard vegetation index calculated from the red and near infrared bands.

Despite the fact that we limited our site selection to only those that were irrigated farming areas located in the river plain, we soon discovered that the distribution of spectral data for the snail habitat sites varied greatly. The distribution for the non-habitat sites also exhibited this characteristic. Ignoring this variability and classifying the image into snail habitat and non-habitat areas with typical supervised classification methods resulted in poor accuracy. The problem seems to be that neither snail habitat nor non-habitat is a single well-defined land-cover type. Rather, the terms "snail habitat" and "non-habitat" encompass distinctly different environments which support, or do not support snails, respectively. That is why when either snail habitat or non-habitat is considered as a whole, it appears to be quite variable.

To deal with the existence of different snail habitats and non-habitats a two-tiered analysis approach was used (Figure 3). The first step relied on an unsupervised classification method called Isodata clustering to break up snail habitat and non-habitat classes into subclasses. The Isodata algorithm is an iterative process whereby the pixels of the image are grouped into clusters based on an examination of their multispectral brightness values. Pixels grouped into the same cluster are similar with respect to their spectral properties. The Isodata algorithm was first applied to those pixels corresponding to snail habitat sites. The algorithm split the pixels into 5 separate clusters. These 5 snail habitat clusters may correspond to different environments which are all suitable habitats for snails. The Isodata algorithm was then performed for the non-habitat sites to produce 5 non-habitat clusters. The spectral distributions for each of these 10 clusters were determined and used to perform the second part of this two-tiered analysis: supervised classification. A maximum likelihood classification was performed using the signatures of the 10 clusters. The resulting classified image is shown in Figure 3. In this figure, pixels belonging to any of the 5 snail habitat subclasses are shown in red. Pixels belonging to any of the 5 non-habitat subclasses are shown in green.

The accuracy of the classification was calculated by determining the number of correctly classified pixels for the GPS located snail habitat and non-habitat sites. For the pixels corresponding to 55 snail habitat sites, 3.6% were unclassified. Of the remaining 96.4%, 90.3% of the pixels were correctly classified as snail habitat. For the pixels corresponding to 48 non-habitat sites, 4.2% were unclassified. Of the remaining 95.8%, 86.6% of the pixels were correctly classified as non-habitat. A classification matrix showing the percentages of each cluster for both types of habitat is presented in Table 1.

The accuracy assessment we have discussed thus far is based only on the image pixels used to train the classification algorithm. A more rigorous validation of our classification requires field verification at randomly sampled locations of snail status predicted by a classified image. We are currently working on this using 1998 field data and Landsat TM imagery.

In addition, we have been exploring spatial variables that are readily available from the remote sensing imagery for improved identification of snail habitats. Using the PCI image processing program we digitized the main branch of the Anning River. A series of buffers of 10-pixel wide (300 m) has been generated centering along the digitized Anning River. Figure 4 shows the buffers of 20-pixel intervals. The snail and non-snail sites falling into each of those buffer zones are summarized in Table 2. It can be seen from Table 2 that approximately 84% of the snail habitat sites are located 1500 m away from the river stream while 82% of the non-snail sites are within 1500 m from the river stream. However, these results may seem to be contradictory with the general experience that the likelihood of snail habitat and transmission decreases with the increase of distance to river streams. Part of the reason that there is no habitat along the river could be because close to the stream is sandy and rocky without farming or even much wild vegetation. Since our snail and non-snail habitat sites were not randomly sampled and the sample size is relatively small, their spatial distribution may not be representative. While we must be cautious in interpreting the buffer analysis results, proximity to water is clearly an important factor for snail habitat identification.

IV. GIS-BASED SCHISTOSOMIASIS TRANSMISSION CONTROL

We developed a GIS-based spatial network approach (Figure 5) that bridges the GIS database and spatial epidemiological analyses (Zhou et al., 1996). The effort was made to explore how to move from descriptive to analytical uses of GIS in epidemiology. Spa-

Table 1. Percentage of pixels classified by cluster for snail habitat and non-habitat sites

			Snail Habitat Clusters					Non-habitat Clusters				
	Total # pixels	% Unci. pixels	% C1	% C2	% C3	% C4	% C5	% C6	% C7	% C8	% C9	% C10
48 snail non-habitat sites	432	4.2	6.9	3.7	0.2	1.6	0.2	28.9	9.0	18.3	11.8	15.0
55 snail habitat sites	495	3.6	31.3	23.6	8.5	17.6	6.1	4.8	0.0	4.0	0.0	0.4

Table 2. Snail and non-snail habitat site distribution around Anning River.

Buffer zones (m)	300	600	900	1200	1500	1800	2100	2400	2700	3000	3300	3600	3900	4200
Snail Sites (%)	4			8	4	12	12	8			12	15	8	8
Non-snail (%)	16	33	13	13	7	7	2	2	2	5				

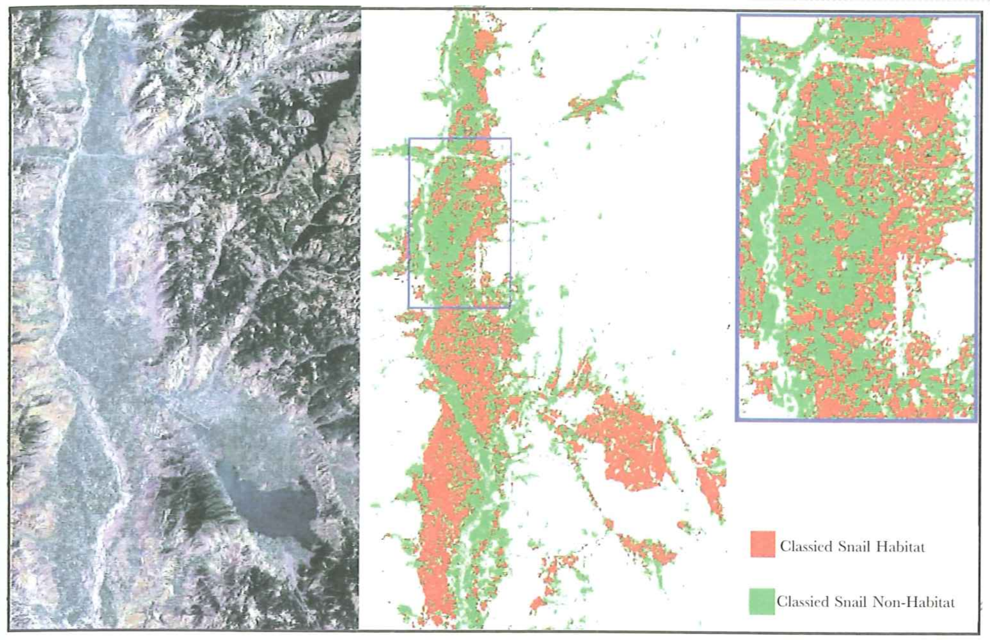

Figure 3. Three panels showing (from left to right) Landsat TM of Anning river valley, classification of habitat using Isodata and maximum likelihood algorithms, and enlargement of valley floor showing mixed habitat .

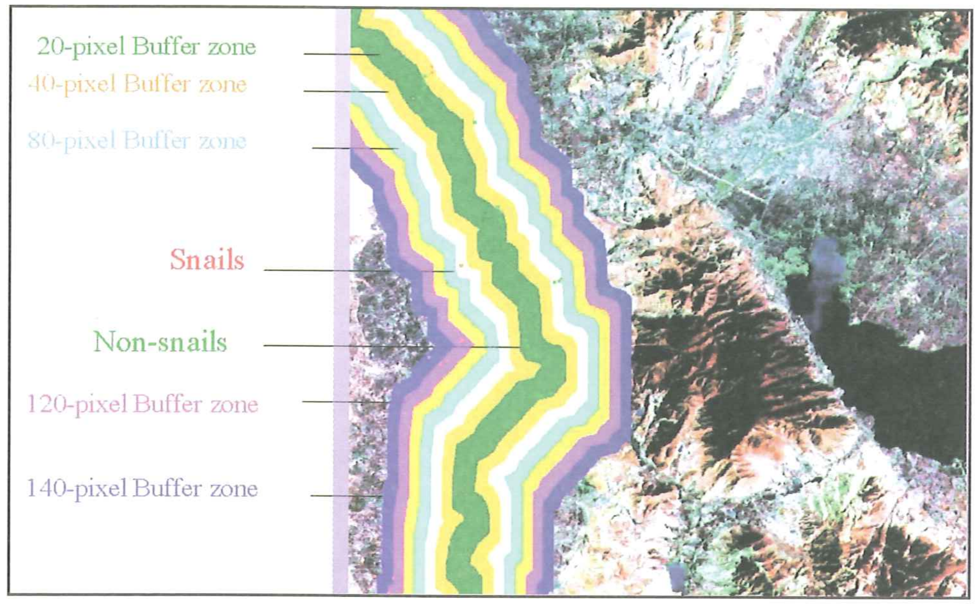

Figure 4. Buffer analysis of snail habitats around Anning River. Snail habitat and non-snail habitat locations are colored with red and green, respectively (right).

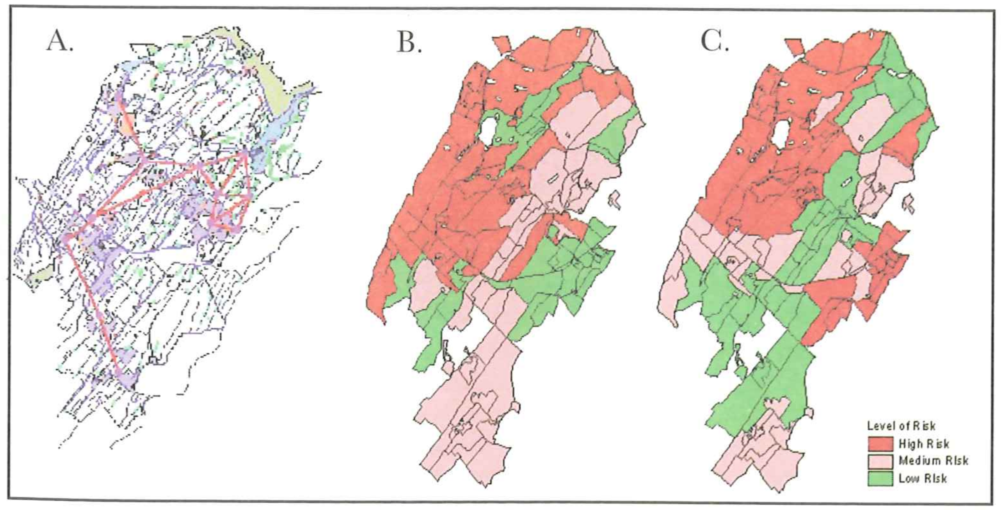

Figure 5. Network-based GIS analysis. A. a network linking geometric centers of 12 residence groups sharing a common boundary. B. traditional classification of endemic intensity. C. classification of residence groups according to their level of risks obtained from the analysis of spatial network sensitivity.

tial analysis can be done through the construction of a spatial network. Figure 5A shows such a network we used linking the 12 residence groups that share a common boundary. Having defined a network, it is possible to explore the spatial dependence within it. A spatial connectivity matrix can be constructed using the spatial network. The orders of neighborhood can be derived from the spatial connectivity matrix. For example, residence groups sharing common boundaries are considered as first order neighbors, and residence groups separated by only one residence group are considered as second order neighbors, and so on so forth. New analytical methods were developed based on the network approach and applied to assist both understanding and control of schistosomiasis transmission (Zhou, 1998). Spatial network autocorrelation and correlation can be calculated based on the spatial network to identify and quantify spatial dependence of risk factors within and between spatial units (e.g. residence groups). Spatial network regressive and autoregressive models can then be run to model and predict spatial transmission. Consequently, spatial network sensitivity analysis can be useful in understanding spatial dependence in transmission for developing cost-effective control strategies.

One interesting finding was that, in the 1987 baseline data, although infection variables such as disease prevalence, infection intensity (as measured by egg count data), and snail infection rates were correlated in space at the first order of neighborhood (Figure 6), no spatial autocorrelation was seen in underlying risk factors such as age, average water contact, or snail density (Figure 7). In both Figures 6 and 7, the ratios between autocorrelation and the autocorrelation value of significance at the 95% confidence level are plotted against the order of neighborhood from 1 to 5. Since the autocorrelation results are calculated based on only one type of spatial connectivity, other types of connectivity as measured by the length of common boundaries or distances will be examined in the future. The lack of spatial autocorrelation for snail density implies that spatial effects at the residence group level on snail distribution can be ignored. We suspect that an examination of the spatial autocorrelation of snail density at finer scales such as at distance intervals of 30 m (close to the Landsat TM pixel sizes) or shorter will change the scenario.

Traditionally, one would use a map made directly from the GIS database to indicate the endemic levels (prevalence or intensity), and to allocate limited control resources to higher endemic areas. Figure 5B shows the traditional approach that classifies the residence groups into high, medium, and low risk areas according to their endemic intensity. Such a risk map,

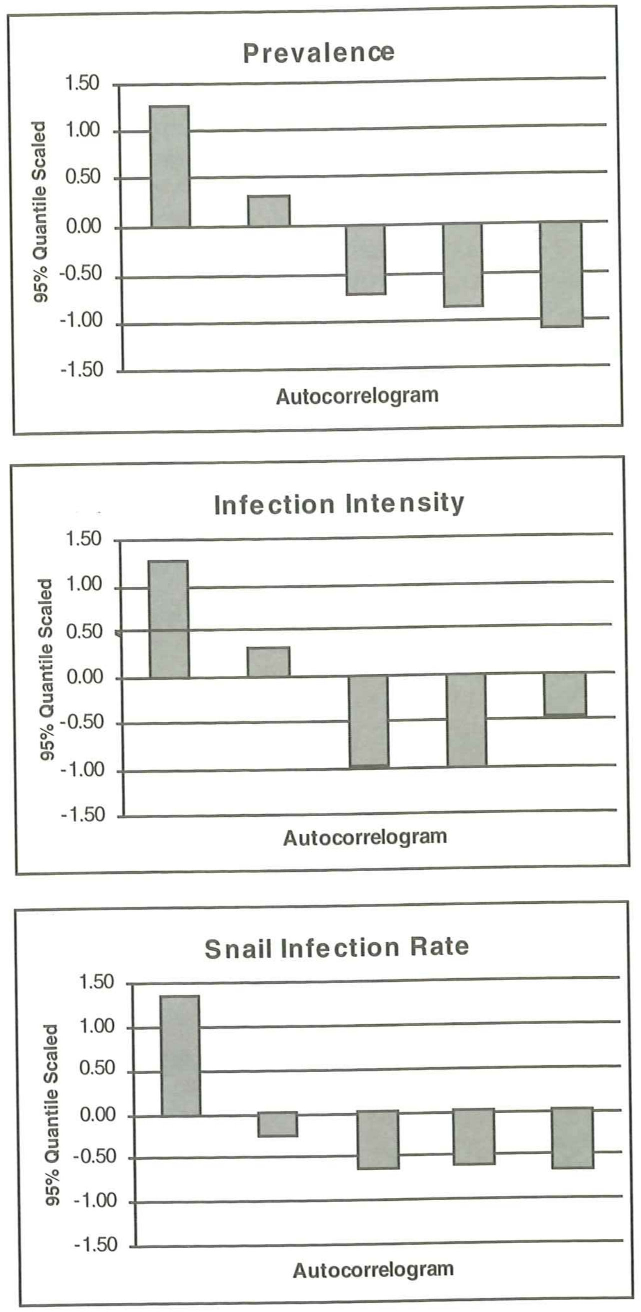

Figure 6. Autocorrelograms of Infection Variables. Horizontal axes are the order of neighborhood from 1-5. Vertical axes are the ratio between autocorrelation and the autocorrelation value of significance at the 95% confidence level.

however, does not contain information on the spatial interaction between the residence groups. Figure 5C shows that, using the spatial network sensitivity analysis, the residence groups can be classified into high, medium, and low risk areas according to their importance in terms of spatial transmission. A new control strategy was then developed to consider both endemic levels (Figure 5B) and spatial dependence in transmission (Figure 5C) among the residence groups (Zhou, 1998).

The GIS-based spatial modeling described here at a smaller spatial scale relates to the remote sensing research at the large scale. However, the remote sensing imagery provides finer spatial details than the spatial network approach but not sufficient for characterizing various physical conditions of snail habitat. The snail habitat and endemic foci are discontinuous in the mountainous and hilly region of China. On one hand, the identification of the patchy snail habitat using remote sensing relies on knowledge and understanding of the transmission factors from the small scale. On the other hand, if the identification of snail habitat is successful, we can target areas with snail habitat and apply the modeling approach developed at the small scale to determine whether or not local areas will become endemic and at what intensity. One current issue is that the habitat for *O. hupensis* is usually a micro-environment which is itself not detectable using most remote imaging because of the limitation in spatial resolution of those data sources. However, micro-environmental conditions may be affected by larger scale factors including local vegetation type and surrounding crops, fertilizer usage, and water and temperature patterns. These factors will cause local fluctuations in the basic environment and additionally in the remote sensing image. The question addressed at present is whether or not local areas can be accurately classified, based on large-scale environmental factors, as being suitable for these snail vectors or not, and thus at high risk for transmission.

As discussed from above, we hope to use remote sensing to identify snail habitat for GIS modeling and schistosomiasis control. The GIS network approach and our buffer analysis results provide insights for us to use spatial features in the remotely sensed imagery for improved snail habitat identification. Such spatial features may include texture, spatial proximity to water, ditches, and field boundaries.

V. FUTURE WORK

Although some general knowledge on the types of land cover suitable for snails is known, more quantitative measures of land cover types that correlate to snail habitat are not presently available. Such measures would improve our ability to identify snail habitat from remotely sensed data. While some of these measures can be obtained when remote sensing data at a spatial resolution finer than 1 m become available, the others may be available from field survey and the use of existing GIS data bases. Other measures such as the proximity to river streams, irrigation canals and field edges can be derived from higher resolution images. Before such data are available from satellite platforms, aerial photography at 1:10,000-1:20,000 scale will be evaluated. We will concentrate on the evaluation of currently available remote sensing methods and image analysis algorithms, as well as manual interpretation techniques where appropriate. Needs for new algorithms will be identified and subsequently developed.

Our plan is to collect more Landsat TM scenes of the

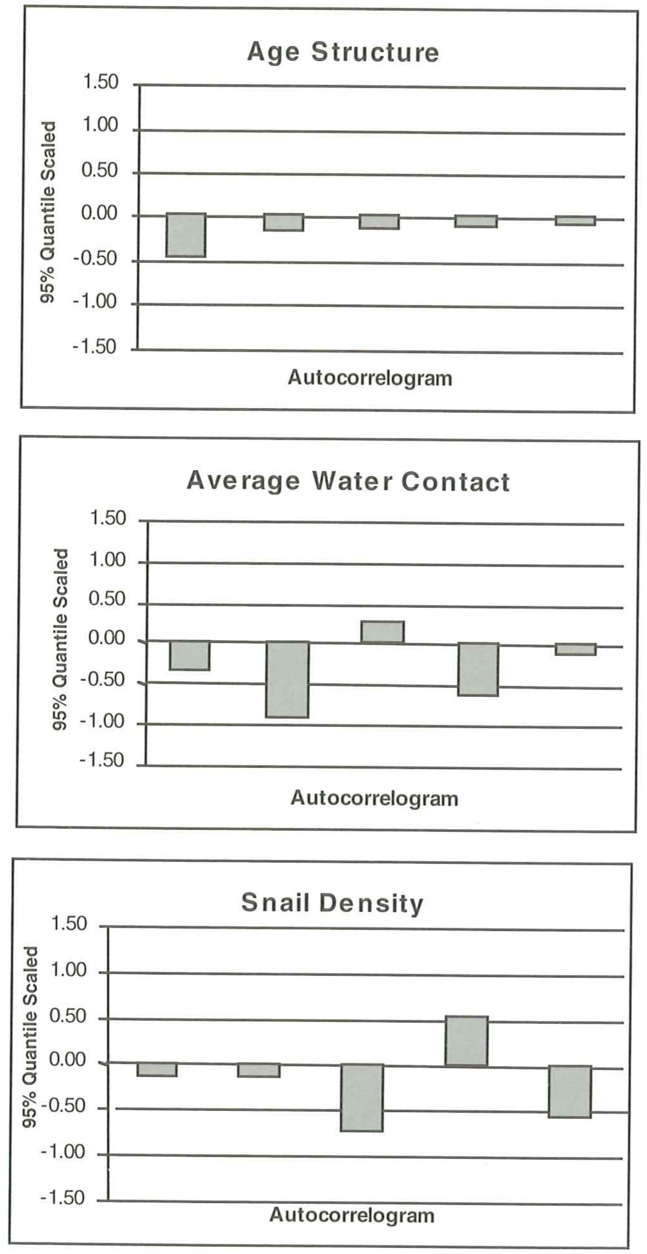

Figure 7. Autocorrelograms of Non-Infection Variables. Horizontal axes are the order of neighborhood from 1-5. Vertical axes are the ratio between autocorrelation and the autocorrelation value of significance at the 95% confidence level.

Anning River Valley and to conduct a series of spectral and spectral-spatial classification for the mapping of snail habitat. Classification results will be validated through field work. To further improve the classification, we will assess the use of ancillary ground data and ecological knowledge in the classification. This will be followed by an exploration of higher resolution remotely sensed data for snail habitat identification. If the results obtained are satisfactory, we will investigate the possibilities to extend the techniques we developed for Anning River Valley to other parts of the endemic areas in China including the Three Gorges Area.

The next step in applying the GIS-based spatial network analysis and modeling is to replicate the approach in a prospective mode to other endemic areas. Possible sites are the endemic areas in Meishan county roughly 100 km west of Chengdu. The SIPD in conjunction with the local anti-endemic stations has been active in these areas in 1996 and 1997. Activities have involved infection surveillance in human and animals, snail surveys, mouse bioassays, human water contact surveys, and both praziquantel treatment of selected groups and some environmental control activities. With the models developed in the Xichang study area, the research can move directly into the site-specific calibration of the models using the data generated by the SIPD from 1996 forward, and also the intervention history at the sites in the calibration activities. One issue that needs further research is how to model complex interaction of temporal and spatial aspects of transmission in a unified way.

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A Model of GIS Virtual Machine

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Abstract
This paper presents a model of Geographic Information System Virtual Machine. The GIS VM is a software architectural model that facilitates the development of Web-based GIS applications. It is a three-tiered system. Java applets or ActiveX objects, with Web browsers as the container, form the presentation tier that interacts with the user. The core of the GIS VM is the servers in the middle and third tiers. The middle tier includes server components for basic GIS functions and data discovery. The third tire mainly contains the spatial data access server. In addition to these basic servers, the GIS VM includes a model object manager (MOM) that establishes linkages with external models and other application programs. The MOM can also extract metadata about models and carry out the execution process on a user's behalf.

I. INTRODUCTION

The Internet can serve not only data but also sophisticated computation. Using the Web to perform spatial analysis, modeling, and advanced visualization is no longer just a novel idea. The technological foundation is in place. This paper discusses how we can adapt the technological advances to developing Web-based geo-computational services.

The model we are going to present is a GIS Virtual Machine (GVM). It is a software framework allowing different functional components to interoperate through the Internet to provide geo-computational services. It is "virtual" because all the parts are software components that reside on different locations. And the connections among these parts are established through "virtual" object buses. The GVM is a machine in the sense that it is able to produce information product by processing spatial data.

Although this is the first time the term GIS Virtual Machine is used, researchers have begun exploring distributed geo-computational services recently. Internet-based user interfaces has been a popular study for improving spatial data access and usability (Li, *et al.*, 1996). Lin and Zhang (1996) demonstrated a web-based GIS catalog browser for distributed spatial data retrieving. Li and Zhang (1997) presented a model of component oriented GIS, which explores the re-organization of GIS in light of the maturity of distributed object technology. Li (1999) further suggested that the Internet and distributed object technology would elevate existing GIS onto what he calls Geographic Information Services. Li (1998) also demonstrated the idea through a prototype of Geographic Computational Services, which allows a user to perform advanced spatial autoregressive modeling through the World Wide Web. These researches have shown the unprecedented opportunity and challenges for GIS research and development.

The aim of GIS VM is to make GIS a ubiquitous technology through the Web. Realizing this goal requires both conceptual and technical solutions. The fundamental questions have to do with what constitute the core of the GVM, how the components relate to each other, how the GVM integrates with the Web and existing legacy software systems. We hope this paper would contribute to the understanding of these technical and conceptual challenges.

We will first describe the conceptual framework of the GIS Virtual Machine. The discussion focuses on the three-tier structure, the essential server components, and the mechanisms for interoperations. The key server components, i.e., the catalog server, data access server, and the model manager are described in further detailed. We conclude with a brief discussion on the benefits of the GIS VM and anticipated problems in research and development.

II. CONCEPTUAL FRAMEWORK OF THE GIS VIRTUAL MACHINE

The idea of GIS Virtual Machine (GIS VM) was inspired by SUN Microsystem's "Java Virtual Machine"

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