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Review

Application of geographic information systems and remote sensing to schistosomiasis control in China

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Abstract

Progress in China on developing prediction models using remote sensing, geographic information systems and climate data with historical infection prevalence and malacology databases is reviewed. Special reference is made to the effects of the Yangtze river Three Gorges dam project on environmental changes that may impact changes in the spatial and temporal distribution and abundance of *Schistosoma japonicum* in China, and the future success of disease control programs. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

China represents the largest endemic area of *Schistosoma japonicum* infection in the world (Ross et al., 1997). The parasite life cycle is complex, with several factors affecting epidemiological and morbidity patterns of the disease. The endemic areas are distributed mainly along the Yangtze river basin, including the Dongting and Poyong lakes, all in all comprising 404 counties in ten provinces. At the beginning of the national control programme in 1949, there were about 14 billion square meters of snail infested area, about 11.6 million people infected with *S. japonicum*, and more than 100 million people at risk of infection. The highest risk areas occur along the Yangtze river, Dongting lake, and Poyang lake. Based on epidemiological characteristics and geographic patterns, schistosomiasis endemic regions in China have been stratified into three types (He et al., 1984): (1) plains with waterway networks, mainly in the Yangtze river delta including Shanghai, Jiangsu,

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and Zhejiang provinces; (2) swamp and lake regions, mainly in five provinces, i.e. Hubei, Hunan, Jiangxi, Anhui and Jiangsu; and (3) hilly and mountainous regions, mainly located in the Sichuan, Yunnan, Guangxi, Guangdong and Fujian provinces. The amphibious snail *Oncomelania hupensis* is the only species known to be an intermediate host of *S. japonicum*, and the distribution of *Oncomelania* snails is highly correlated with that of schistosomiasis in the Yangtze river basin (He et al., 1984).

The central government began a major campaign to eradicate the disease in 1949. The achievements are remarkable. Based on nationwide survey data, the number of people infected with *S. japonicum* decreased from 11.6 million in 1949 to 850 000 in 1995 (Mao, 1990). Presently, five provinces, municipalities or autonomous regions, including Shanghai, Fujian, Guangdong, Guangxi and Zhejiang, have met the criteria for schistosomiasis eradication. However, in spite of 50 years of intensive effort in the field control programme, immense tasks remain for control and ultimate eradication of schistosomiasis (Zhen, 1993). Favorable environmental factors and other transmission parameters needed for re-emergence of severe disease in the endemic area still exist, and it may be more difficult to maintain the prevalence or morbidity at current levels after mass chemotherapy made possible by a World Bank Loan for schistosomiasis control ends in 2001. Continuing work is needed to consolidate the achievements gained and to further minimize the transmission and intensity of infection. A particularly telling recent example of this was the 100-year record flood in the Yangtze river valley in 1998, in which both the snail-infested area, due to snail dispersal, and the possibility of infection with *S. japonicum* through water contact increased. The potentially major impact of the Three Gorges dam project on transmission of schistosomiasis in the middle and lower reaches of the Yangtze river remains unclear. There is a need to better define the impact of climate variation and flooding potential on the distribution and dispersal of *Oncomelania* snail hosts in the Yangtze river valley (Chen et al., 1999).

2. Reported applications of geographical information systems and remote sensing in the control of schistosomiasis japonica in China

The first complete national atlas of schistosomiasis was published in 1980 with all historical epidemiological data provided down to the county level (Qian et al., 1985). Later studies, aimed at better detection of areas inhabited by *Oncomelania*, were based on patterns seen in maps of snail distribution. Zhu (1992) used overlays of several historical maps to show that *Oncomelania* distribution in China coincided with the distribution of quaternary system geological strata in 12 provinces in southern China. Tang et al. (1998) showed that patterns of schistosomiasis transmission were related to changes of marshland along the Yangtze river by overlaying time-difference traditional maps.

With the development of geographical information systems (GIS) technology, it is possible for researchers to evaluate digital map data with earth observing satellite sensor data for environment analysis (Hugh-Jones, 1989; Sun et al., 1999). Transmission of schistosomiasis is closely related to environmental factors, and a number of studies have been undertaken to explore use of GIS to define transmission factors that relate to control. Cross and Sheffield (1984) predicted the area endemic for schistosomiasis japonica using weather variables and a Landsat digital map database to evaluate the potential for infection during military activities during different seasons in the Philippines.

In China, GIS has been used with good results in public health since the 1980s (Chen, 1991). Investigations using application of GIS and remote sensing for schistosomiasis surveillance in China were initiated in the 1990s to elucidate transmission factors that determine the geographic distribution of the disease and to improve policy-making in the national control programme. Chen and Hu (1991) used Landsat and National Oceanic and Atmospheric Administration (NOAA) satellite sensor data to identify ecological zones associated with *Oncomelania* habitats in China. Application of remote sensing was a component of recent efforts to develop a hydrological model of transmission of schistosomiasis by a team from the University of California and the Chinese Academy of Preventive Medicine in an agricultural village near Xichang, Sichuan province, one of the mountainous provinces endemic with *S. japonicum* (Liangsong et al., 1996; Spear et al., 1998). In Sichuan, long-term studies of infection and disease ecology in catchments were supplemented by detailed hydrometric measurements to produce a model of water velocity and flow in an irrigation system. The model provides a means of estimating travel times of infectious stages of the parasite from egg contamination sites to water contact exposure sites for intermediate vector snail populations and human hosts. The hydrological transport model is intended to be part of an overall model of schistosomiasis transmission in catchment basins. GIS and image analysis of Landsat TM data have been used in an effort to predict the extent of snail habitats in the Anlin river region (Maszle et al., 1998). Combining two images from spring and autumn 1994, training pixels were used to formulate a statistical model for predicting potential snail habitat sites. Results showed a correlation between snail sites and training pixels of 80%, as confirmed by snail survey and soil survey. In a later study to validate these results, a test of the model by similar analysis of Landsat TM imagery covering the same area in 1996 resulted in only 70% correlation. Further study suggested an association with low magnesium content in the soil in areas predicted to be potential snail habitats by the model, but where no snails were found by the survey.

In other models of GIS developed by the Hunan Institute of Economical Geography and the Hunan Institute of Parasitic Diseases, snail-infested marshlands (1:250 000 scale) were identified based on maps created from time difference Landsat MSS imagery for 1983 to 1984 in the Dongting lake region (Zhao and Li, 1987). With the creation of the snail-infested marshland maps, it was possible to measure snail-infested areas precisely and to monitor changes in snail-infested areas in different periods. It was not possible to measure the snail habitats directly since the pixel resolution of Landsat MSS (80 m^2) is not sufficient to identify them; there is thus a need to use satellite sensor data with the normal-field snail detection methods currently used by the Ministry of Health.

Scientists from Shanghai Medical University reported results of studies on GIS application in schistosomiasis using ARCINFO software (ESRI, Redlands, CA) to investigate: (1) the impact of climate factors on transmission; and (2) the relationship between snail distribution and water levels. They found that *Oncomelania* snails are normally present in areas with an annual mean temperature of 16–20°C, annual rainfall of 1300–2000 mm, and annual hours of daylight of 1400–2100 (Zheng et al., 1998a). Based on the density of living snails and infected snails, a Ward method in cluster analysis was used to classify the marshlands into four categories based on different snail distribution patterns and then to measure the influence of the number of days of flood per year on the distribution of the concentrated snail belt in marshlands in different water years. Results indicate the important role for the snail distribution played by the annual number of flood days. Interestingly, the distribution of acute schistosomiasis in Xinzi, Jiangxi Province, coincided with that of the snails in the marshlands (Zheng et al., 1998b).

After the 100-year record flood in 1998, greater effort was focused on the impact of flood events on transmission of schistosomiasis in relation to changes anticipated after completion of the Three Gorges dam (Zhou et al., 1999a). A group of scientists from Jiangsu Institute of Parasitic Diseases, in collaboration with the School of Veterinary Medicine at Louisiana State University and the Danish Bilharziasis Laboratory, has published a series of papers on this topic. First, they assessed the possibility of application of a climate-based parasite forecast model to predict the risk area and intensity of schistosomiasis transmission (Zhou et al., 1998). The FAOCLIM database (FAO, 1995) was used, combined with data derived from Advanced Very High Resolution Radiometer (AVHRR) satellite sensor data (http://edcdaac.usgs.gov/1KM/1kmhomepage.html) and the digital chart of the world (ESRI, Redlands, CA). Construction of GIS layers and spatial analysis was carried out using the software packages ARCVIEW 3.0A, with the Spatial Analyst extension, and ERDAS IMAGINE 8.3.1 (ERDAS, Atlanta, GA). Using monthly climate records and a modification of the Climate Based Parasite Forecast System described by Malone and Zukowski (1992) Malone and Yilma (1999), results indicate that the endemic areas of schistosomiasis in Southern China occur in areas carrying a risk index of over 900 (Fig. 1). The northernmost extent of the endemic zone was defined by a 'freeze line', where January mean minimum temperatures were less than −4°C. Encouraged that it is possible to predict the endemic areas and transmission intensity of schistosomiasis in China by GIS and remote sensing, a second study to improve the utility and accuracy of using the GIS forecast model was carried out in Jiangsu province and adjacent areas (Zhou et al., 1999b). Composite maps of Normalized Difference Vegetation Index (NDVI) were created for each of the four seasons and the transmission season (March–October). GIS analysis of NDVI values, climate risk index, earth surface temperature and mean minimum temperature in January, revealed 'hotspots' of higher transmission intensity in defined spatial zones and during different transmission seasons. Logistic regression analysis showed a strong relationship between model prediction and actual prevalence, with an 88.9% correct classification rate. The apparently limiting temperature of −4°C in January that distinguished endemic areas from non-endemic areas suggests the need for studies on the potential impact of global warming on schistosomiasis.

In a third study, the impact of flood events on snail dispersal to new areas was predicted directly by remote sensing data (Zhou et al., 1999c) using

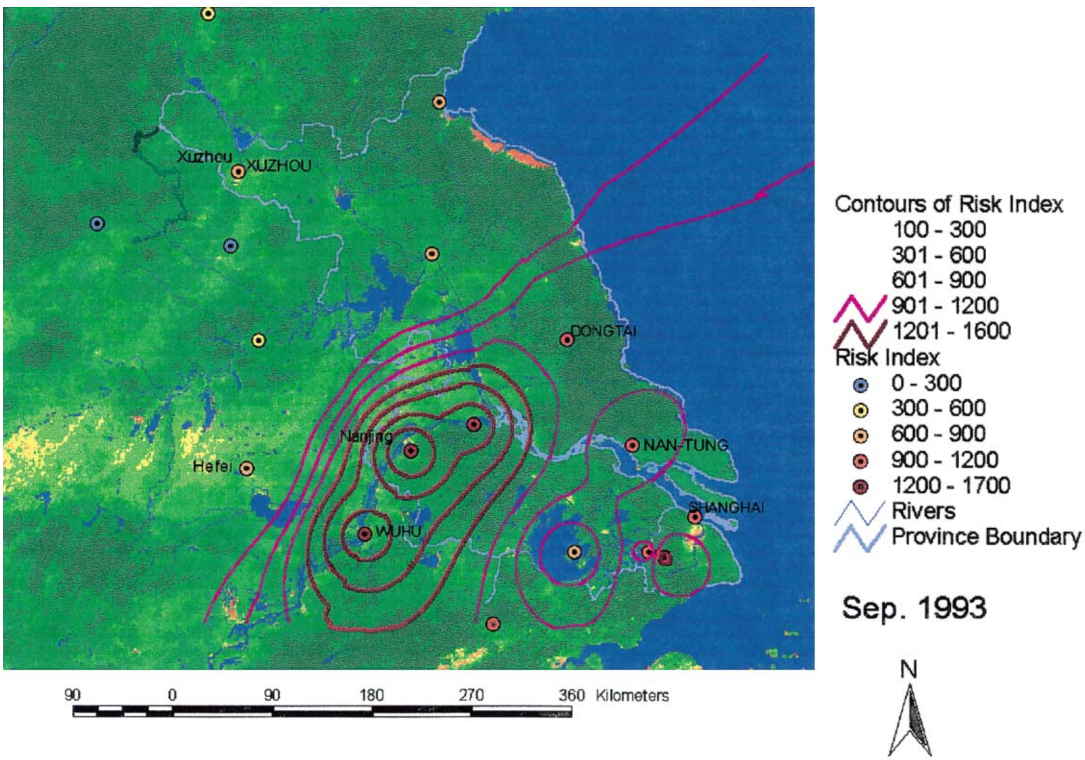

Fig. 1. Climate-based forecast of schistosomiasis risk for Jiangsu province using 30-year-average monthly data from 18 climate stations. The forecast was based on the growing degree day concept, water budget analysis and reported development requirements of *S. japonicum* in *O. hupensis*. Index value contours >900 indicate suitable areas for transmission.

Landsat MSS scenes from 1983, a major flood year, and 1984, a relatively dry year. Using image classification methods, four 'wetland' classes were extracted and compared among three different seasons: (1) the highest water level in the flood season of a 'wet' year (August, 1983); (2) the lowest water level in the following dry season (March, 1984); and (3) the highest water level in the flood season of a more 'normal' year (August, 1984). 'Wetness difference' maps were created that defined wetland changes between 1983 and 1984 during the high water flood period (to represent snail dispersal areas), and between the 1983–1984 flood season and dry season (to define stable snail habitat areas). Areas flooded because of broken levies and large areas of shallow marsh showed up clearly in the wetness difference images of the 1983 and 1984 flood seasons. While a general increase in snail infested areas in the marshlands was shown to occur during 1980–1989, with a logistic regression index curve ($Y = 10^{2.77+0.11x}$) and an average increase rate of 30.49%, an especially significant increase of snail habitats happened after the flood year in 1983. Further application of this spatial 'wetness difference' model to analyze the impact of 1998's flood in China was undertaken in the areas of Poyang lake and in the Jiangsu portion of the Yangtze river (Zhou et al., unpublished data). Composite maps from Landsat TM scenes in the summer flood and dry spring seasons were created. They showed a more serious impact of the flood on the snail dispersal in Poyang lake than in the Jiangsu part of the Yangtze river, with more serious expansion of habitats in the marshland around islands in the river than in marshlands along the riverbanks. The results suggest that more attention should be paid to the inland rivers directly connected to the Poyang lake and the Yangtze river, where more chances exist for snails to disperse into inland or downstream areas after major flooding. The 1983–1984 and 1998–1999 spatial models were snail ecological-based models that had a high correlation with data from surveys on the ground. 'Wetness difference' maps are thus proposed to provide a simple and fast way to predict the impact of individual flood years on snail dispersal areas in the Yangtze river valley.

Further studies were undertaken to understand the snail fluctuation mechanisms related to the changes of marshland, based on aerial photography maps. Sun et al. (1998) calculated the fluctuation of marshland area on one of the islands in the Yangtze river and along its two banks during 1973–1987, stretching for 16 km in length along the river bank. Results showed that due to river tide, a total of 1 936 000 m^2 of marshlands were scoured away, while 1 257 000 m^2 of marshlands were created or enlarged, resulting in a net loss of 679 ,000 m^2 of marshlands. The ratio between the enlarged and the lost marshlands was 1:0.36. In contrast, the marshlands in isolated islets were mainly enlarged by a ratio of 1:1.27. The average size of marshlands enlarged annually was 11 900 m^2, and 14.5% of these were infested with snails. Results suggest that enlargement of the snail-infested areas after flood years is not due to newly enlarged marshlands, but is mainly due to snail migration and changes of control strategy.

In a fourth study, Zhou et al. (1999d) analyzed the spatial habitat zones of *Oncomelania* snails in China to investigate potential spatial relationships between distribution of *Oncomelania* snails and snail population genetics. Spatial distribution maps on genetic heterozygocity, percentage of polymorphic loci and infection rates in snail populations were created based on relevant databases. A composite AVHRR NDVI map showed four distinguished spatial zones, including the Sichuan zone, the Yunnan zone, the lake and marshland zone, and East Coast zone. This study was the first documentation of use of GIS to define the spatial relationships of *Oncomelania* populations based on population genetic variation databases. Moreover, it confirmed the discrete subpopulation model in the population structure of *Oncomelania* snails, which supports the theory that sub-species of *Oncomelania* spp. exist in China (Davis et al., 1999).

A fifth study was undertaken to understand the current status and spatial distribution of schistosomiasis in China. Zhou et al. (2000) collected data for two dates from the National Sampling Survey on Schistosomiasis in 1989 and 1995 for analysis by the ARCVIEW GIS 3.2 software. The results showed that risk areas for schistosomiasis are mainly in the marshland along the Yangtze River, and that five distribution zones for schistosomiasis can be identified based on distribution of prevalence by spatial analysis. The five zones are: (1) Sichuan province in Western China; (2) Yunan province in Western China; (3) Hunan and Hubei provinces in Central China, (4) Jiangxi and the western part of Anhui province, and (5) the eastern part of Anhui, and Jiangsu and Zhejiang provinces in Eastern China. Both the distribution area and prevalence rate according to fecal/blood examination of cattle and water buffalo tend to be much higher than that in humans. A positive correlation was shown to exist between the human infection rate and cattle infection rate on both sampling survey dates. Therefore, while the strategy for schistosomiasis control differs in different spatial regions, results suggest current measures for control of cattle and water buffalo infection may be a weak link in the control program.

3. Projected impact of the Three Gorges dam project on schistosomiasis transmission in the Yangtze River Basin

The national project on construction of the Three Gorges dam will be completed by 2009 in the upper reaches of the Yangtze river. It is a major project aimed at speeding the economic development in China through, among other benefits, better use of water sources and reduction in flood damage during the wet season. On the other hand, the natural condition of 'land in winter and water in summer' in the marshland in the downstream reaches of the river may change in some areas after construction of the Three Gorges dam. For example, the water level increases during winter (January–April) and declines during summer (July–October). During January–April, the flow of water increases by approximately 1000–1500 m^3/s, which must be added to the downstream projection. River gauge water levels are projected to increase by 0.06–1.61 m downstream and, consequently, the natural conditions in the marshland modified hydrologically in ways that may change the transmission dynamics of schistosomiasis in the marshland along the river after the Three Gorges dam is built (Davis et al., 1999). Evaluation of the potential effect of the Three Gorges dam on schistosomiasis transmission along the Yangtze river has been investigated previously. After investigations in the field and comparative data analysis from 1995 to 1997, Cai et al. (1998) predicted no impact on the distribution of *Oncomelania* snails in the Dongting lake region in spite of some changes in the rate of flow from the river to the Dongting lake after construction of the dam. He felt that a shorter period of receding water levels in the lake in October and November would result in a shorter infection season in the autumn. The silt flowing into the lake is predicted to decrease, within 50 years after the dam construction, which would increase the infection rate of populations living there. After 80 years, silt flowing into the lake would have increased snail-infested areas by deposition of new marsh habitat areas. Ultimately, the reservoir is projected to be full of silt and the situation would be the same as that during pre-dam construction.

Wang et al. (1998) did comparative studies in the downstream reaches of the Yangtze river in Anhui province, and predicted a scenario in which the impact of variation of water level would have less impact on snail distribution after construction of the Three Gorges dam. For example, lower marshland would be submerged at pre-flood season while the higher marshland would emerge at pre-dry season. The snail habitat area would increase as sedimentation led to increases in the amount of marshland. Human infection due to anti-flood activities would decrease as floods come under effective control. The change of residents' activities and animal behavior was projected to also influence chance of infection.

The development of the Three Gorges dam will, in all probability, increase the extent of marshlands and irrigation in areas currently free of schistosomiasis. In studies carried out in the Three Gorges reservoir region, He et al. (1999) confirmed that no *Oncomelania* snail existed there. However, with the similarities to endemic regions of climate regime, soil type and identical plants to serve as food of *Oncomelania* as that in endemic regions, it is difficult to explain why no snails existed in the region previously. Yang et al. (1998) explained this as due to arid soil and lack of irrigation systems. Yang proposed that, along with economic development, improvement of water conservancy facilities, transformation of cultivated farmland and management of soil erosion during construction of the Three Gorges reservoir, snail habitats would be inevitably extended. The potential for the spread of schistosomiasis into these new areas is a major concern, and there is a continuing need to develop new ways to monitor the situation in the Three Gorges reservoir region and downstream of the Yangtze river during and after construction of the Three Gorges dam. Implementation of a GIS model system to manage spatial data on the drainage network, land use, infection sources and population centers may provide a practical way to accomplish this. Hydrological models can be of particular importance in assessing future environmental risk. Thus scientists are keen to apply GIS and remote sensing technologies to the monitoring process owing to the easier and faster approach GIS can provide .

4. Ongoing GIS and remote sensing projects focused on schistosomiasis control in China

GIS and remote sensing may be used to monitor the distribution and intensity of disease and to predict transmission tendency since the transmission of schistosomiasis is closely related to temperature and annual water levels of rivers and man-made canals, vegetation, altitude, soil types, human/animal behavior, and social activities. A number of projects on this topic are underway:

4.1. Assessment of schistosomiasis risk by evaluation of snail distribution by remote sensing and GIS in lower Yangtze river basin, China

The long-range goal of this project, carried out by the Jiangsu Institute of Parasitic Diseases in collaboration with the School of Veterinary Medicine, Louisiana State University and the Danish Bilharziasis Laboratory, Charlottenlund, Denmark, is to develop a GIS model for prediction of snail habitat distribution and schistosomiasis prevalence, using earth-observing satellite data and selected environmental parameters (soil, elevation, vegetation and hydrology), and to utilize the model for development of more cost-effective control programs for *S. japonicum* in China. The specific aims are: (1) to develop a geographic information system model, with emphasis on flooding patterns and other environmental changes that may affect snail habitats and disease prevalence, based on the available epidemiological data from 1982 to 1996 in the lower Yangtze river basin; (2) to utilize the established GIS system based on remote sensing data to identify the seasonal changes of snail habitats and active transmission sites, and to forecast schistosomiasis risk in the same areas (Zhou et al., 1999a,b).

4.2. Development of a forecasting system of schistosomiasis by application of GIS/remote sensing techniques in the middle and lower basin of the Yangtze river

This project is supported by the Ministry of Health and coordinated from the Jiangsu Institute of Parasitic Diseases, in collaboration with the Jiangxi Institute of Parasitic Diseases, the Anhui Institute of Parasitic Diseases, the Hubei Institute of Parasitic Diseases, the Hunan Institute of Parasitic Diseases, the School of Public of Health, Shanghai Medical University and the Schanghai Institute of Parasitic Diseases, Chinese Academy of Preventive Medicine. The objectives are to develop and implement a system capable of predicting well ahead in time, the status of schistosomiasis in China and the influences of natural or social factors, such as floods and the Three Gorges dam project, on transmission of the disease and distribution of snail habitats. The goal is to provide the scientific basis for strategies formulation in schistosomiasis control programme in the People's Republic of China. With the establishment of the GIS/remote sensing forecast system, four specific aims will be achieved: (1) establishment of the geographic distribution maps of schistosomiasis and relevant databases in the middle and lower basin region; (2) analysis of the influence of flood in 1998 on distribution of snail habitats in the region; (3) assessment of the effects of 'returning wetland to the lake' on snail distribution and transmission of schistosomiasis; and (4) evaluation and monitoring marshland changes and snail habitat changes due to the Three Gorges dam project (http://www.rnas.org). These activities would provide a scientific basis for strategy formulation in the schistosomiasis control programme in China.

4.3. Schistosomiasis control in China using remote sensing technologies

The long-term objective of this research program, supported by the National Institutes of Health and investigated by R. Spear and P. Gong from the University of California at Berkeley, is to determine the feasibility and effectiveness of using remote sensing technology for large scale surveillance of ecological conditions in China that may provide habitat for the *Oncomelania* spp. snail hosts, and changes of land-cover patterns in these regions, altered by human intervention or natural events, that are conducive to schistosomiasis transmission. The intermediate goal of these studies is to provide information for a surveillance plan targeting areas at high risk of transmission around the Three Gorges lake. The specific objectives are: (1) to validate preliminary analysis of ground and satellite data that suggests that the habitat of *O. h, robertsoni* in southwestern Sichuan Province can be statistically identified from Landsat TM imagery; (2) to determine whether this identification can be made more precise by supplementing the satellite data with ecological variables and landscape features obtained from existing ground data, and simultaneously to develop an ecological interpretation of the statistical classification of objective 1; (3) to explore the use of other image types, such as aerial photographs, SPOT or IRA-1D images, providing higher resolution of landscape features related to human activity proximate to snail habitat, with the objective of determining important predictors of disease prevalence that can be detected remotely; and (4) to replicate the Sichuan remote sensing studies at the Poyang lake in Jiangxi Province for a genetically differentiated subspecies of snail, *O. h. hupensis*, and to contrast the ecological parameters of these vastly different ecosystems with a view towards the development of a unified Three Gorges surveillance plan (http://ehs.sph.berkeley.edu/china/).

5. Future needs

The various projects that have been launched thus far for schistosomiasis control in China have yielded promising results that ultimately can be used for describing the distribution of disease and snail hosts, predicting the transmission tendency, and for informed policy-making. However, there are still problems that must be tackled without delay. (1) Current research efforts have focused on particular endemic areas in a given region. No project has addressed the problem at the national level, and a national GIS mapping system for schistosomiasis and factors that may influence effective control has yet to be constructed. (2) Multiple-layer analysis made possible by GIS should be applied in control programs so that the effect of multiple factors on transmission can be visualized. (3) Since snail distribution and development of the parasite in snails are both affected by environmental factors, priority should be directed at the establishment of a forecasting system on schistosomiasis transmission through a national GIS database for schistosomiasis control, investigation of the impact of environmental changes (such as floods, global warming and water management projects) on the emerging or re-emerging of schistosomiasis transmission, and the implementation of GIS model techniques in the national and provincial control programmes.

Considering that schistosomiasis is mainly distributed along the Yangtze River, and that prevalence is still high in some villages in swamp and lake regions (Zhang et al., 1999), the main emphasis on schistosomiasis control in China should be the swamp and lake region, including the Hubei, Hunan, Jiangxi, Anhui and Jiangsu provinces. In this region, the marshland changes annually with some land scoured away and concurrent creation of new land by accretion. The new marshland is developed from sandy land that becomes covered with grass or weeds over several years. Snail density is naturally correlated with a certain kind of vegetation and soil (Lu et al., 1988; Zhong et al., 1995) and once the marshland has been covered by grass or weeds, it is suitable for snails and reproduction. The waxing and waning of the marshland caused a natural fluctuation of snail habitats. Previous studies (He et al., 1984; Mao, 1990; Ross et al., 1997) have demonstrated that the snail distribution is correlated with schistosomiasis prevalence. In particular, acute infections are more likely to occur in places close to marshland infested with *Oncomelania* snails. It is thus important to continue monitoring changes of marshlands annually to allow prediction of the high-risk areas for transmission of schistosomiasis. The authors recommend that there is a need to accelerate the speed of research leading to application of GIS and remote sensing technologies in the national control programme to provide environmental analysis information needed to improve control measures and decision making by health agencies in China.

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