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A review of geographic information system and remote sensing with applications to the epidemiology and control of schistosomiasis in China

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Abstract

Geographic information system (GIS) and remote sensing (RS) technologies offer new opportunities for rapid assessment of endemic areas, provision of reliable estimates of populations at risk, prediction of disease distributions in areas that lack baseline data and are difficult to access, and guidance of intervention strategies, so that scarce resources can be allocated in a cost-effective manner. Here, we focus on the epidemiology and control of schistosomiasis in China and review GIS and RS applications to date. These include mapping prevalence and intensity data of *Schistosoma japonicum* at a large scale, and identifying and predicting suitable habitats for *Oncomelania hupensis*, the intermediate host snail of *S. japonicum*, at a small scale. Other prominent applications have been the prediction of infection risk due to ecological transformations, particularly those induced by floods and water resource developments, and the potential impact of climate change. We also discuss the limitations of the previous work, and outline potential new applications of GIS and RS techniques, namely quantitative GIS, WebGIS, and utilization of emerging satellite information, as they hold promise to further enhance infection risk mapping and disease prediction. Finally, we stress current research needs to overcome some of the remaining challenges of GIS and RS applications for schistosomiasis, so that further and sustained progress can be made to control this disease in China and elsewhere.

Keywords: Schistosomiasis; *Schistosoma japonicum*; *Oncomelania hupensis*; Geographic information system; Remote sensing; Epidemiology and control; Disease mapping and prediction; China

1. Introduction

Schistosomiasis, a chronic and debilitating disease caused by intestinal trematodes (schistosomes), has been endemic in China since ancient times, particu-

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larly along the Yangtze River and further south (Mao, 1990; Ross et al., 2001; Zhou et al., 2005). *Schistosoma japonicum* is the causative agent, which, in the chronic phase, frequently leads to liver enlargement and extensive fibrosis in the portal tracts (Utzinger and Keiser, 2004). Recognizing the public health and economic impact of the disease, the government of China initiated, in the mid 1950s, the creation of a large number of national, provincial and local anti-schistosomiasis control stations. The sustained political commitment, including the training of personnel at these stations, has facilitated the conduct of repeated large-scale epidemiological and malacological surveys that have guided the subsequent implementation of control approaches and strategies to date (Yuan et al., 2000, 2002; Chen et al., 2005).

Government-led efforts to control schistosomiasis in China have been exemplary (Chitsulo et al., 2000). As a result, the public health and economic impact of the disease has been reduced substantially, and transmission has been halted in many of the previously endemic areas (Yuan et al., 2002; Chen et al., 2005; Zhou et al., 2005). For example, control efforts against schistosomiasis japonica were so successful that the disease has been eliminated in five out of the 12 formerly endemic provinces. In parallel, the area infested by the intermediate host snail of the disease, *Oncomelania hupensis*, was reduced by over 75% (in the mid 1950s an estimated 14.5 billion m^2 were infested by *O. hupensis*). Importantly, the number of infected people, and the number of infected cattle/buffaloes that act as reservoir hosts, declined by 93.8 and 54.8%, respectively (Chen and Feng, 1999). However, in some settings, the control of *S. japonicum* proved particularly challenging, i.e. along the middle and low reaches of the Yangtze River in the provinces of Anhui, Hubei, Hunan, Jiangsu and Jiangxi, and in some mountainous areas in the provinces of Sichuan and Yunnan (Yuan et al., 2002). It is currently estimated that 95.7% of the snail-ridden areas and 85.6% of the *S. japonicum*-infected people are concentrated in the marshland or lake regions of China. The remaining snail-infested areas and infected individuals are concentrated in the mountainous regions (Yuan et al., 2002).

It is widely acknowledged that the frequency and transmission dynamics of schistosomiasis is closely related to socioeconomic, climatic and environmental factors, the latter including altitude, precipitation, temperature and vegetation coverage (Mao, 1990; Brooker et al., 2002a; Malone, 2005; Raso et al., 2005). The advent of geographic information systems (GIS) and remote sensing (RS) technologies has opened new avenues to evaluate digital map data generated by earth observing satellite sensors for spatial and temporal environment analyses (Hay, 2000; Yang and Zhou, 2001; Bergquist, 2002; Brooker et al., 2002b; Leonardo et al., 2005; Stensgaard et al., 2005). This facilitates prediction of schistosomiasis transmission, and in turn provides guidance to local authorities in decision-making and policy planning for cost-effective resource allocation (Brooker et al., 2002a; Raso et al., 2005). In China, the application of GIS and RS technologies to schistosomiasis dates back to the late 1980s and early 1990s. Particular emphases have been placed on mapping prevalence and infection intensity data, identification of *O. hupensis* habitats, and forecasting transmission risk in relation to ecological transformation, including water resource development and management, flooding events and climate change.

The purpose of this article is to review the various applications of GIS and RS, and to discuss their contributions to further our understanding of the epidemiology and control of schistosomiasis in China. In the next section, the paper summarizes GIS/RS applications for infection risk mapping and transmission modelling. In section 3, we review applications of GIS and RS for identification and prediction of risk areas due to the presence of *O. hupensis*. Section 4 summarizes GIS/RS applications with an emphasis on ecological transformation and climate change. It is followed by a section highlighting potential new applications of GIS and RS. Finally, we discuss current research needs and conclude that further progress in GIS and RS holds promise to overcome some of the remaining challenges in the control of schistosomiasis in China, which is likely to have broad applicability to other schistosome-endemic areas of the world.

2. GIS and RS for mapping and transmission modelling of schistosomiasis in China

Table 1 summarizes the different studies that applied GIS and RS technologies for infection risk mapping and transmission modelling of schistosomiasis in China. For each study, its aim, area, method and

Table 1
GIS and RS applications for schistosomiasis in China: disease mapping and transmission modelling

Reference	Study aim	Area	Application		Data sources and parameters	
			Method	Scale	Environmental factors	Demographic and/or epidemiological factors
Maszle et al. (1998)	To evaluate hydrological models in transmission areas severely affected by schistosomiasis	Villages of Minhe and Hexing in Sichuan province	GIS modelling	Micro	Air, water and soil temperature, rainfall, irrigation networks, and natural drainage systems	Disease incidence, residential location, water contact information and snail population densities, cercariae detection data
Zhou et al. (1998)	To predict the spatial transmission risk of schistosomiasis	Southern China	GIS modelling	Meso-macro	Temperature, rainfall, evaporation	–
Zhou et al. (1999a)	To identify 'hotspots' of high transmission intensity	Jiangsu province and adjacent areas	GIS modelling	Meso	NDVI, climate risk index, earth surface temperature and mean minimum temperature in January	Disease prevalence
Zhou et al. (2000)	To map the spatial distribution of schistosomiasis	China	GIS modelling	Macro	–	National Sampling Surveys in 1989 and 1995
MOH (2002)	To evaluate the impact of schistosomiasis control activities granted through the WBLP	Seven provinces in China	GIS mapping	Meso-macro	Wealth of environmental data accumulated during the implementation of the 10-year WBLP	Wealth of demographic and epidemiological data accumulated during the implementation of the 10-year WBLP
Liang et al. (2002)	To provide a framework for quantification of site-specific characterisation of schistosomiasis transmission.	Chuanxing, Sichuan province	GIS modelling	Micro	Local environmental data	Residents infection status and infection intensity, snail population densities
Yang et al. (2002a)	To display and analyse time-series data	Anhui, Jiangsu and Jiangxi provinces	GIS mapping	Meso	–	Prevalence data of *S. japonicum* from 1980 to 1998
Yang et al. (2002b)	To assess the spatial distribution of schistosomiasis	Jiangsu, Anhui and Jiangxi provinces	GIS modelling	Meso	–	Prevalence data of *S. japonicum* from 1980 to 1998
Chen et al. (2003)	To map schistosomiasis endemic areas	China	GIS mapping	Macro	–	Prevalence data of *S. japonicum* in 2002
Yang et al. (2005a)	To examine spatio-temporal distribution of *S. japonicum* infection risk	Jiangsu province	GIS modelling	Meso	NDVI, land surface temperature	Annual prevalence data of *S. japonicum* from 1990 to 1998

scale of application, and key environmental, demographic and/or epidemiological parameters are given. The majority of these studies focused on the meso (province) and/or macro (national) level.

Zhou and colleagues (1998) were the first to apply GIS for modelling the transmission of schistosomiasis in the southern part of China. They modified a model previously described by Malone and Zukowski (1992) and Malone and Yilma (1999) pertaining to a climate-based parasite forecast system. The conceptual basis of this model rests on the interaction of the parasite and its intermediate host snail, and parameters required for the development of both *S. japonicum* and *O. hupensis*. For southern China it was found that *S. japonicum*-endemic areas are restricted to settings with a transmission risk index exceeding 900, which is estimated by a model that employs monthly records from the Food and Agriculture Organization's (FAO) 30-year average climate database. The northern limit of the schistosome-endemic zone was defined by a 'freeze line', where the January mean minimum temperature is below $-4\,^{\circ}$C.

Using an improved GIS forecast model, a second study was carried out in Jiangsu province and adjacent areas (Zhou et al., 1999a). A GIS analysis utilizing the normalized difference vegetation index (NDVI) and mean minimum temperature in January, revealed 'hotspots' of high transmission intensities in defined spatial zones during different transmission seasons. Logistic regression analysis showed a strong relationship between the model's prediction and the actual prevalence of *S. japonicum*, with a high sensitivity of 88.9%.

More recently, Zhou and colleagues (2000) carried out a spatial analysis based on two datasets obtained from the 'National Sampling Survey on Schistosomiasis' in 1989 and 1995, respectively. The spatial distribution of *S. japonicum* prevalence data in the human population revealed that areas at risk of transmission were primarily located in the marshlands of the Yangtze River basin. Five main distribution zones could be delineated. Simultaneous mapping of prevalence data in bovines in the hyper-endemic areas of the lake regions showed that these were considerably higher than those in humans. In turn, these observations had important implications for control; praziquantel-based chemotherapy campaigns were not only indicated at the community level, but also for cattle and water buffaloes acting as reservoir hosts. These recommendations were underscored by the first comprehensive transmission model of *S. japonicum* (Williams et al., 2002).

A research group built around a Joint Research Interchange programme between academic institutions in China and the US made significant contributions to the application of GIS and RS for a better understanding of the epidemiology of schistosomiasis in mountainous areas in the Sichuan province, southwestern China. For example, at the micro-scale, hydrometric measurements were done to set up a model of water velocity and flow charges in an irrigation system (Maszle et al., 1998). This model enabled estimation of travel times of the infectious stages of the parasite from the sites where they were emitted by the intermediate host snails to human water contact exposure sites. Subsequently, the hydrological transport model, together with data on the drainage network, land use, and selected demographic and epidemiological information, were integrated into a GIS platform to model the transmission of *S. japonicum* in the catchments (Liang et al., 2002). An important epidemiological feature of the work was the integration of a schistosome worm burden model among risk groups, as defined by their location of residency and occupation. The model incorporated seasonality of infectious stages (both precipitation- and temperature-dependent), *O. hupensis* population dynamics, and site-specific seasonal patterns of human water contacts. Model parameters were grouped in two main classes, namely (i) those associated with the general biology of the parasite and its life cycle, and (ii) parameters associated with directly measurable features of the population's disease status and pertinent aspects of the local environment.

At the meso scale, another successful application of GIS was the temporal mapping of schistosome-endemic areas in the provinces of Anhui, Jiangsu, and Jiangxi from 1980 to 1998 (Yang et al., 2002a). This work confirmed that GIS databases provide a convenient way to store, display and analyse time-series data, which in turn can guide intervention strategies to optimize control programmes. The established GIS databases were further explored for spatial disease patterns with appropriate statistical approaches. The results showed that the spatial distribution of schistosomiasis was well fitted to the spatial autocorrelation and, generally, the autocorrelation coefficient (Moran's I) was higher in Anhui and Jiangxi provinces when compared to Jiangsu province (Yang et al., 2002b). Spatio-temporal modelling of *S. japonicum* prevalence data in the endemic counties of Jiangsu province between 1990 and 1998 proved useful to document progress of control interventions and to better understand the relationship of climatic and environmental features and the frequency distribution of the disease (Yang et al., 2005a).

Finally, it is important to note that the several hundreds of pages long final report from the World Bank Loan Project (WBLP) on schistosomiasis control in China presented maps abound to demonstrate progress towards controlling the disease in a spatially explicit way. Since 2002, the annual reports on schistosome-endemic areas in China are presented through georeferenced GIS maps, which provide important guidance to the design and implementation of the national schistosomiasis control programme (Chen et al., 2003).

3. GIS and RS for identification of intermediate host snail risk areas in China

The frequency and transmission dynamics of schistosomiasis japonica is intimately linked with the distribution of *O. hupensis*, which in turn is a result of the distribution and abundance of suitable snail habitats that consist of an appropriate mix of vegetation and aquatic environments. Table 2 summarizes the studies published to date with an emphasis on identifying snail-infested areas through appropriate combinations of GIS and RS technologies. The majority of studies focused on either the micro or the meso scale.

Li and colleagues (1990) first used RS techniques to identify *O. hupensis* habitats in two experimental areas (Xichang and Chengdu) and the prospected Three Gorges dam area. Employing satellite images, the study area was classified into several ecological zones, based on soil type and vegetation coverage. It was found that local residence areas situated in terraced fields on old mud sediment represented suitable ecological conditions for *O. hupensis*. In fact, this ecozone correctly identified the presence of *O. hupensis* in 83.4–100% of the sites studied at Xichang, 90% in Chengdu, and around 85% in the prospected Three Gorges dam area. Chen and Hu (1991) used Landsat MSS and National Oceanic and Atmospheric Administration (NOAA) satellite sensor data to identify flooded areas in different ecological zones. They associated the flooded zones with the known distribution of *O. hupensis* habitats in China, which facilitated mapping and quantification of snail-infested areas driven by the flooding. Tu and Wang (1995) created geomorphic, soil and land utilization maps as the key information sources through classification of RS images, namely Landsat MSS and Landsat TM. After geographic correlation analysis and principal component analysis, maps of *O. hupensis* distributions were created on the basis of land utilization maps combined with ground truth data, e.g. location and estimated size of *O. hupensis* infested areas. In Sichuan province, a study on potential *O. hupensis* habitats was performed by a spatial analysis of RS data. Investigations suggested an association with low magnesium content in the soil of areas predicted to be potential snail habitats by the model, but where no snails were found by the survey (Seto et al., 2002).

Scientists from Shanghai Medical University found that the presence of *O. hupensis* is restricted to areas with an annual mean temperature of 16–20 °C, annual rainfall ranging between 1300 and 2000 mm, and total daylight of 1400–2100 hours per year (Zheng et al., 1998a). In addition, based on the density of the intermediate host snail and the density of infectious snails, four types of marshlands could be classified. In another study, the incidence of acute schistosomiasis japonica in Xingzi, Jiangxi province, showed a strong positive association with the density of *O. hupensis* in the marshlands (Zheng et al., 1998b).

Recently, several studies were carried out in the Poyang Lake area to predict potential *O. hupensis* habitats, by means of multi-temporal Landsat TM image analyses. Guo et al. (2002) used two Landsat TM images, one taken from the dry season and the second during the rainy season, to identify potential *O. hupensis* habitats, and hence areas with high transmission potential for *S. japonicum*. The latter image was water- and land-shifted during the rainy season, and all snail habitats occurring in the dry season were extracted and classified by an unsupervised method. From the image taken during the dry season NDVI and tasseled cap transformation features were extracted. In the marshlands of the Poyang Lake, a high correlation coefficient of 95% was found between healthy vegetation and snail habitats. Wu et al. (2002) classified satellite images col-

Table 2
GIS and RS applications for schistosomiasis in China: identification of risk areas due to the presence of *O. hupensis*, the intermediate host snail of *S. japonicum*

Reference	Study aim	Area	Application		Data
			Method	Scale	
Li et al. (1990)	To identify *O. hupensis* habitats	Xichang, Chengdu and Three Gorges area	RS	Meso	MSS in 1976 and 1978, aerial images in 1982 and 1984
Chen and Hu (1991)	To identify risk areas due to the presence of *O. hupensis*	China	RS	Macro	Landsat MSS and NOAA
Tu and Wang (1995)	To identify *O. hupensis* habitats	Marshlands	RS	Meso	Landsat MSS in 1979 and TM in 1987
Zheng et al. (1998a)	To assess the effect of climatic factors on the ecology of *O. hupensis*	China	GIS	Macro	Snail data, climatic data
Zheng et al. (1998b)	To determine the relationship between floods and snail distribution	Xinzi, Jiangxi province	GIS	Micro	Snail data, annual flooding record
Zhou et al. (1999c)	To determine the relationships between the distribution of *O. hupensis* and snail population genetics	China	GIS	Macro	Snail distribution and snail population genetics
Lin and Lin (2001)	To create a land cover map of *O. hupensis* habitats in the marshland region	Chayegang, Jiangxi province	RS	Micro	Landsat TM
Guo et al. (2002)	To identify *O. hupensis* habitats	Poyang Lake, Jiangxi province	RS	Micro	Landsat TM images in 1998
Lin et al. (2002)	To assess the impact of the 1998 flood on *O. hupensis* distribution in the marshland around the Poyang Lake	Poyang Lake, Jiangxi province	RS	Micro	Landsat TM images in 1998
Seto et al. (2002)	To assess the effect of soil chemistry on the distribution of *O. hupensis*	Sichuan province	RS	Meso	Landsat TM
Wu et al. (2002)	To identify *O. hupensis* habitats	Poyang Lake, Jiangxi province	RS	Micro	Landsat TM images in 1999 and 2001
Zhang and Xu (2003)	To explore the vegetation landscapes in marshland snail habitats	Jiangning, Jiangsu province	RS	Micro	Landsat ETM+ image
Zhang (2003)	To analyse the relationship between NDVI and the distribution of *O. hupensis*	Jiangning, Jiangsu province	RS, GIS	Micro	Terra-MODIS
Guo et al. (2005)	To predict *O. hupensis* habitats	Poyang Lake, Jiangxi province	RS, GIS	Meso	Landsat TM images for dry and wet seasons
Zhang et al. (2005)	To predict *O. hupensis* habitats	Jiangning, Jiangsu province	RS, GIS	Meso	Landsat ETM+ image

lected in 1999 and 2001 by an unsupervised method. A snail identification model was established based on the ground truth data of the actual *O. hupensis* distribution and land cover types. The sensitivity of the classified snail habitats to correctly predict the actual snail habitats was high (90.0–95.6%) and a moderate specificity was found (61.1–68.6%). In the subsequent step, the model was further augmented by introducing the NDVI and tasselled cap transformation wetness feature. As a result, the specificity of the model was increased by approximately 30%. Preliminary model validation at 10 selected sites around Poyang Lake displayed excellent accuracy for predicting *O. hupensis* (Guo et al., 2005).

Lin and Lin (2001), also conducting research with a focus on schistosome-endemic marshlands, performed a Landsat TM satellite image analysis, using principal component analysis. They defined three broad land cover classes, namely class 1, the carex zone that is the dominant vegetation type and the main habitat utilized by *O. hupensis* in Chayegang, Jiangxi provinces; class 2, water bodies; and class 3, mixed vegetation. Malacological surveys carried out in spring 2000 revealed a density of *O. hupensis* in the carex zone of 2.51 snails per 0.11 m^2, whereas the density of *S. japonicum*-infected snails was 0.0069/0.11 m^2. Thus, the infection rate of snails was 0.28%. No intermediate host snails were found in land cover class 3; hence these areas could be set aside without the need for additional surveys.

In another study, Lin et al. (2002) overlaid two classified time difference images to display the potential snail habitats. In a next step, a random selection of habitats was drawn and compared with the ground truth data of the actual snail distribution. Statistical analysis revealed that 77% of all the snail habitats (30/39) were correctly predicted by the classified image when compared with the ground truth data. Predictive accuracy was particularly high in the large habitats with 92% (12/13) correctly identified, whereas medium-sized and small habitat types were correctly predicted in 86% (12/14) and 50% (6/12), respectively.

A group of scientists from the Fourth Military Medical University also carried out a series of studies applying GIS/RS techniques for identification of snail-infested areas in the marshlands. Zhang and Xu (2003) analyzed vegetation landscapes to predict snail habitats using Landsat ETM+ images. A GIS was constructed with the classified satellite image and the actual snail distribution overlaid. The analysis revealed that in Jiangning county, Jiangsu province, *O. hupensis* were most commonly associated with spares vegetation types typical for sandy beaches, as well as exuberant weed and bulrush. Highest snail densities were observed in the bulrush. Next, Zhang (2003) analyzed the relationship between NDVI and intermediate host snail distributions in the marshlands of Jiangning county, utilizing a Terra-MODIS image to map snail habitats at the micro scale for surveillance purposes. Recently, Zhang et al. (2005) showed that remotely sensed environmental data, i.e. modified soil-adjusted vegetation index, land surface temperature and wetness, combined with ordinary kriging resulted in a good predictive accuracy for the presence of *O. hupensis*.

An innovative application of GIS was described by Zhou et al. (1999b), who analyzed the distribution of *O. hupensis* across China to investigate potential spatial relationships between the observed distribution and snail population genetics. Employing relevant databases facilitated the creation of spatially explicit distribution maps on genetic heterozygosity, percentage of polymorphic loci and infection rates in *O. hupensis* populations. This study was the first of its kind documenting the use of GIS to define the spatial relationship of *O. hupensis* populations based on population genetic variation datasets. Importantly, it confirmed the discrete subpopulation model in the population structure of *O. hupensis*, thereby supporting the theory that sub-species of *Oncomelania* spp. indeed exist in China (Davis et al., 1999).

4. GIS and RS for appraisal of ecological transformation and climate change

GIS and RS provide a means for assessment and monitoring of ecological transformation over large areas and through time that may influence the distribution and abundance of *O. hupensis*. Applications performed to date are summarized in Table 3. The effect of major floods in China on dispersal of *O. hupensis* to areas previously known to be snail-free was predicted directly by RS data, using Landsat MSS scenes from 1983, a year when flooding occurred, and the subsequent relatively dry year. Employing appropriate image classification methods, four different 'wetland' classes were extracted. 'Wetness difference' maps were created that defined wetland changes between 1983 and 1984, focussing both on the period of highest water levels (to represent maximum snail dispersal areas), and the dry season (to represent stable snail habitat areas). Those areas that became flooded because of broken riverbanks and large shallow marshes showed up clearly in the wetness difference image, consequential to this flooding event (Zhou et al., 1999c).

More recently, this spatial 'wetness difference' model was applied to assess the impact of the 1998 flood in China, which was particularly severe in the areas of the Poyang Lake and in the Jiangsu portion of the Yangtze River (Zhou et al., 2002). Composite maps

Table 3
GIS and RS application for schistosomiasis in China: appraisal of ecological transformation and climate change

Reference	Study aim	Area	Application		Data
			Method	Scale	
Zhou et al. (1999c)	To assess the impact of floods on *O. hupensis* dispersal	Yangtze River	RS	Meso	Landsat MSS in 1983 and 1984
Zhou et al. (2002)	To assess the impact of flood events on *O. hupensis* dispersal	Poyang Lake, Jiangsu part of the Yangtze River	RS	Micro	Landsat TM 1998
Yang et al. (2005b)	To assess the potential impact of climate change on the spatial distribution of *O. hupensis*	China	GIS	Macro	Composite average monthly temperatures from 1960 to 1999 at 623 meteorological stations across China

were created from Landsat TM scenes in the summer flood and dry spring seasons. Interestingly, these analyses showed a more pronounced impact of the floods on snail dispersal in the Poyang Lake area than in the Jiangsu part of the Yangtze River. In fact, more extensive expansion of potential snail habitats occurred in the marshlands around islands of the river, when compared to marshlands along the riverbanks.

We have made a first attempt to assess the potential impact of climate change on the distribution of *O. hupensis*, and hence on the transmission dynamics of *S. japonicum*. Employing two 30-year composite datasets with average January temperatures from a large ensemble of observing station across China, we found that, on average, January temperature has increased by 0.96 °C over the past 30 years, and hence the distribution limits of *O. hupensis* have shifted from 33°15′N to 33°41′N. This shift translates to an expansion of the potential transmission area by more than 40,000 km^2 (Yang et al., 2005b).

5. Perspectives of GIS/RS

Our literature review showed that numerous studies have applied GIS and RS technologies, often in combination with spatial statistics, for infection risk mapping and predictive modelling of schistosomiasis japonica and its intermediate host snail distributions in China. However, there is scope for application of novel GIS/RS techniques, notably quantitative GIS, WebGIS, and innovative use of new satellite information that will become available shortly. These three areas are briefly summarized here, as they hold promise for more pointed application of GIS/RS with the aim to further improve current approaches and strategies for the control of schistosomiasis in China, and in turn might inspire control programmes elsewhere.

5.1. Quantitative GIS

Maps offer a convenient platform to display prevalence and/or infection intensity data of schistosomiasis. They are thus a useful tool for policy discussion, as high risk areas warranting special control efforts, can be highlighted with ease. Furthermore, the application of spatial analytical approaches assists in the identification of climatic, demographic, environmental and socio-economic factors that influence the spatial heterogeneity of infection risk. However, previous applications remain short on discussing issues of samples size and spatio-temporal patterns in disease. Mapping crude prevalence data derived from cross-sectional epidemiological surveys can be non-informative or even misleading when the sizes of the population for some of the units are small, resulting in large variability in the estimated prevalence. In such circumstances, it is difficult to distinguish chance variability from genuine differences. Pooling of neighbouring units often masks important real differences, which in turn is of relevance for the identification of the underlying causes (Sun et al., 2000).

Recent progress in empirical Bayes and Bayesian hierarchical modelling provide new opportunities to overcome some of these problems, since stable estimates can be obtained for small areas by using information from neighbouring areas (Lawson et al., 1999). The development of this field has been greatly advanced by rapidly developing computational tools such as the Gibbs sampler (Gelfand and Smith, 1990), as well as other Markov chain Monte Carlo (MCMC) methods for posterior analyses (Tanner, 1992). There is now a considerable body of literature pertaining to Bayesian-based spatial analyses of infection risk and disease. First applications with the aim to further enhance our understanding of the epidemiology and control of schistosomiasis in China have been reported at the micro scale, and produced promising results (Liang et al., 2002; Spear et al., 2002).

We have also applied Bayesian-based spatial statistical approaches to investigate the relationship between environmental factors and epidemiological data of *S. japonicum* in the Jiangsu province, employing and adapting our recently established malaria models (Gemperli et al., 2004). With the help of RS techniques, we derived the NDVI and land surface temperature from satellite images for the *S. japonicum*-endemic counties for the period of 1990–1998. By modelling the effects of environmental variables, we could make predictions of infection risks in response to ecological transformations. Bayesian models were used to estimate changes of spatial correlation over time and to produce annual smooth risk maps of *S. japonicum*. Following this approach, we were able to identify high risk areas and capture transmission dynamics (Yang et al., 2005a). In a next step, we will validate the model in a neighbouring area. Once a satisfactory model is available, it can be applied to other schistosome-endemic areas of China, which in turn may guide decision-making and improve allocation of scarce resources for control.

5.2. *WebGIS*

Considerable efforts are underway to develop GIS functionality, so that it can be deployed directly on the Internet and on readily established intranets of interested user groups. For that reason, such a system has been termed WebGIS. It holds promise to make distributed geographic information (DGI) available to far larger audiences than conventional GIS packages (Foote and Kirvan, 1997). Until recently, the usage of GIS was confined to a relatively small number of trained experts (Thoen, 1995). Employing the Internet as a vehicle to facilitate access to GIS applications is likely to result in an increase of potential users. However, this will require parallel improvements in user friendliness of GIS software, particularly for those unfamiliar with this tool. It is envisaged that Internet users will be able to access GIS applications from their own browsers at their working stations without purchasing proprietary GIS software. First trial versions of WebGIS were introduced several years ago, in combination with related map server applications for interactive cartography (Plewe, 1997). Once user-friendly WebGIS becomes widely available on the Internet, it could be readily applied to guide schistosomiasis control interventions and disease surveillance in China and other schistosome-endemic areas.

5.3. *Utilization of novel remote sensing data*

At present, study limitations are often due to low spatial resolution of remotely sensed environmental data. However, with the recent launch of new and powerful satellites, it has become possible to make use of higher resolution RS data at relatively low costs. A French satellite named ‘Système Pour l’Observation de la Terre’ (SPOT) provides images with a spatial resolution of 10 m. Currently, IKONOS satellite (derived from the Greek word for “image”) is the most sophisticated RS spacecraft, as it is capable of photographing objects on the ground with a spatial resolution of 1 m. Another multi-channel sensor is mounted on the ‘Advanced Spaceborne Thermal Emission and Reflection Radiometer’ (ASTER), with the 14 channels covering the entire spectral range from visible to thermal-infrared. It is an on-demand instrument. RADARSAT, Canada’s first series of remote sensing satellites, focus on the use of radar sensors to provide unique information about the Earth’s surface through most weather conditions and even darkness, thus overcoming important shortcomings of other sensors. Using overlay techniques in which pictures are combined with near-infrared images or other geographic information, customers can see interpretive geological images that show areas of vegetation combined with terrain features (Satellite Imaging Corporation, 2005).

The DigitalGlobe^{TM} QuickBird satellite, a commercial satellite with the highest publicly available resolution to date, was successfully lifted in the orbit in late 2001. This satellite has 0.61–0.72 m panchromatic and 2.44–2.88 m multi-spectral sensors, depending upon the off-nadir viewing angle (0–25°). QuickBird’s basic image products are delivered to cover a single area of 16.5 km × 16.5 km, or a strip of 16.5 km × 165 km. It enables the user to map large areas faster with fewer images, and less ground data to manage and process. QuickBird's high spatial resolution sensors have narrowed the gap between satellite images and aerial photos. Thus, it is conceivable that QuickBird's technology will replace aerial photos for various applications, depending on resolution and accuracy requirements (Toutin and Cheng, 2002). Consequently, the future prospects of GIS/RS for applications of disease mapping and prediction in general and schistosomiasis in particular are bright.

6. Remaining challenges and conclusion

Studies using GIS and RS technologies with applications targeted to schistosomiasis in China have shown the great utility for both risk mapping and prediction from the micro- to the macro-scale. Nonetheless, several important issues remain to be addressed, and require further study to refine the tools and broaden their applicability.

Our review underscores that optimal use of GIS/RS techniques for public health purposes requires a sound understanding of the epidemiology of the disease to be studied, and recognition of the inherent problem of pattern and scale in ecology (Levin, 1992). In fact, observed frequencies and transmission dynamics of infectious diseases depend on climatic, ecological, epidemiological and socio-economic determinants that are idiosyncratic to locality, and hence large heterogeneities occur at different scales. For example, an important environmental determinant that facilitates the transmission of *S. japonicum* is the thermal limits at which intermediate host snails can survive. Ecological transformations can alter this, e.g. through anthropologically induced climate change, and hence impact disease transmission dynamics (Yang et al., 2005b). A series of ecological studies pertaining to *O. hupensis* are currently undertaken by a research group at the Jiangsu Institute of Parasitic Diseases to investigate the thermal limits of intermediate host snail distribution over time. This will provide an important means to further improve the understanding of potential impact of global warming on schistosomiasis transmission.

An important aim of GIS/RS applications for schistosomiasis is to provide information on the distribution of infection risk to guide disease interventions. In this connection it is important to note that infection rates in bovines that act as reservoirs for schistosomiasis transmission can be significantly higher than that in humans, as observed in the lake regions of China (Zhou et al., 2000). The relevance of these findings for schistosomiasis control has been highlighted in this review, and the use of GIS and RS can play an important role for mapping and predicting bovine schistosomiasis. Consequently, further research is warranted for GIS/RS applications with an emphasis on the control of schistosome infections among cattle and water buffaloes within the frame of integrated schistosomiasis control programmes.

The substantial progress made in the control of schistosomiasis in China has been highlighted in several recent publications (Chitsulo et al., 2000; Engels et al., 2002). This is largely due to the government's political commitment, as well as external funding, such as the WBLP on schistosomiasis control in China from 1992 to 2001 (Yuan et al., 2000; Chen et al., 2005). However, there is a great need to rigorously implement control interventions in those areas where the disease continues to be endemic, as documented by the latest available data of schistosomiasis on a national scale (Chen et al., 2003; Zhou et al., 2005). In fact, swamp and lake areas that cover five provinces along the Yangtze River are characterized by high population densities, important domestic migration resulting from the booming economy, animal reservoirs, and large areas that are suitable for proliferation of intermediate host snails. These factors delay further progress of schistosomiasis control. In addition, several large water resource development projects bring about new challenges for control, most notably the Three Gorges dam project and the South-to-North water transfer project. The Three Gorges area is currently free of schistosomiasis, but the disease is endemic both upstream and downstream from the impoundment area. There is considerable concern about a schistosomiasis outbreak here, as a result of large-scale displacement of people, creation of new marshland areas around the perimeter of the dam's reservoir, and the expansion of irrigated farming in the area (Zheng et al., 2002). It has been discussed that the South-to-North water transfer project could introduce *O. hupensis* snails from schistosome-endemic settings to non-endemic areas through this new canal, as the water source is located in an area known to be endemic for the disease (Zhou et al., 2001; Yang et al., 2005b). Finally, global warming could result in the expansion of endemic areas further northwards (Yu et al., 1998; Yang et al., 2005b). Application of GIS/RS technologies has proven most useful for assessment and monitoring of ecological transformation, hence is holds promise to make further progress in the control of schistosomiasis in China.

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