Potential impact of climate change and water resources development on the epidemiology of schistosomiasis in China

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Table of content

Abbreviations

AGDD	Annual Growing Degree Day
AICC	Akaike Information Corrected Criterion
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CAR	Conditional Autoregressive Regression
CI	Confidence Interval
COPT	Circumoval Precipitation Test
DALYs	Disability-Adjusted Life Years
DGI	Distributed Geographic Information
DIC	Deviance Information Criterion
DN	Digital Number
ELISA	Enzyme-Linked Immunosorbent Assay
ETM	Enhanced Thematic Mapper
FAO	Food and Agriculture Organization
GDD	Growing Degree Day
GIS	Geographic Information System
GPS	Geographic Positioning System
IC	Inverse Gamma
IPCC	Intergovernmental Panel of Climate Change
IPD	National Institute of Parasitic Diseases, Chinese Center for Disease Control and Prevention
JIPD	Jiangsu Institute of Parasitic Diseases
LST	Land Surface Temperature
MARA/ARMA	Mapping Malaria in Africa/Atlas du risque de la Malaria en Afrique
MCMC	Markov Chain Monte Carlo
MOH	Ministry of Health

MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
RS	Remote Sensing
SD	Standard Deviation
SNWT	South-to-North Water Transfer
SPOT	Système Pour l'Observation de la Terre
STI	Swiss Tropical Institute
TC	Tasseled Cap
TGD	Three Gorges Dam
USGS	United States Geological Survey
WBLP	World Bank Loan Project
WHO	World Health Organization

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Summary

Schistosomiasis japonica, caused by the blood fluke *Schistosoma japonicum*, has been endemic in China since ancient times. An estimated 11 million people were infected in the mid-1950s. Recognizing the huge public health significance and the economic impact of the disease, the central government of China implemented a large-scale control programme, which has been sustained and constantly adapted over the past half century. Today, the endemic areas are mainly confined to the lake and marshland regions along the Yangtze River in five provinces, namely Jiangsu, Anhui, Jiangxi, Hunan and Hubei. It is estimated that currently about 800,000 people are infected and that 40 million people are at risk of infection. Historically, the northern geographical limit where schistosomiasis transmission occurred was around the 33°15' N latitude (e.g. in Baoying county, Jiangsu province), governed by low temperature thresholds.

Based on various climate models, the Intergovernmental Panel of Climate Change (IPCC) recently concluded that the Earth has warmed by approximately 0.6°C over the past 100 years. This unusual warming has been particularly pronounced during the last three decades. There is growing consensus that the global trend of climate warming will continue in the 21st century. It has been suggested that climate change could impact on the distribution of the intermediate host snail of *S. japonicum*, i.e. *Oncomelania hupensis*.

The frequency and transmission dynamics of schistosomiasis can also be affected by water-resource development and management. Among others, the South-to-North Water Transfer (SNWT) project" is currently under construction in China, which intends to divert water from South (the snail-infested Yangtze River) to North (Beijing and Tianjing) via the lakes of Gaoyou, Hongze and others. The implementation and operation of this project could further amplify the negative effects of climate change and facilitate the northward spread of *O. hupensis*.

The main objective of this PhD thesis was to explore the potential impact of climate change and the SNWT project on the future distribution of schistosomiasis japonica, particularly in eastern China. The techniques used were geographic information system (GIS) and remote sensing (RS), coupled with Bayesian spatial statistics, which have become key tools for disease mapping and prediction.

First, we reviewed the application of GIS/RS techniques for the epidemiology and control of schistosomiasis in China. The applications included mapping prevalence and intensity data of *S. japonicum* at a large scale, and identifying and predicting suitable habitats for *O. hupensis* at a small scale. Other prominent applications were the prediction of infection risk due to ecological transformations, particularly those induced by floods and water-resource development projects, and the potential impact of climate change. We discussed the limitations of the previous work, and outlined potential new applications of GIS/RS techniques, namely quantitative GIS, WebGIS and the utilization of emerging satellite-derived data, as they hold promise to further enhance infection risk mapping and disease prediction. We also stressed current research needs to overcome some of the remaining challenges of GIS/RS applications for schistosomiasis, so that further and sustained progress can be made towards the ultimate goal to eliminate the disease from China.

Second, recognizing the advantages of combining GIS/RS techniques with advanced spatial statistical approaches, we developed Bayesian spatio-temporal models to analyze the relationship between key climatic factors and the risk of schistosomiasis infection. We used parasitological data collected annually from 1990 to 1998 by means of cross-sectional surveys carried out in 47 counties of Jiangsu province. Climatic factors, namely land surface temperature (LST) and normalized difference vegetation index (NDVI), were obtained from satellite sensors. Our analysis suggested a negative association between NDVI and the risk of *S. japonicum* infection, whereas an increase in LST contributed to a significant increase in *S. japonicum* infection prevalence.

Third, in order to better understand the changes in the frequency and transmission dynamics of schistosomiasis in a warmer future China, a series of laboratory experiments were conducted to assess the effect of temperature on the parasite-intermediate host snail interaction. We found a positive linear relationship between the development of. *S. japonicum* larvae harboured in *O. hupensis* and temperature. In snails kept at 15.3°C, *S. japonicum* larvae tend to halt their development, while peak development occurs at 30°C. The temperature at which half of the snails were in hibernation is 6.4°C. A statistically significant positive association was observed between temperature and oxygen intake of *O. hupensis* at temperatures below 13.0°C. We also detected a logistic relationship between snails' oxygen intake and their hibernation rate. Our results underscored the important role temperature plays both for the activity of

O. hupensis and the development of *S. japonicum* larvae harboured in the intermediate host snail.

Fourth, to substantiate the claim that global warming might alter the frequency and transmission dynamics of *S. japonicum* in China, we conducted a time-series analysis from 1972-2002, using temperature data from 39 counties of Jiangsu province. Using annual growing degree days (AGDDs) with a temperature threshold of 15.3°C, we forecasted changes in *S. japonicum* transmission. The final model included a temporal and a spatial component. The temporal trend consisted of second order polynomials in time plus a seasonality component, while the spatial trend was formed by second order polynomials of the coordinates plus the thin plate smoothing splines. The AGDDs of *S. japonicum* in 2003 and 2006 and their difference were calculated. The temperatures at the 39 locations showed an increasing temporal trend and seasonality with periodicities of 12, 6 and 3 months. The predicted AGDDs increased gradually from north to south in both 2003 and 2006. The increase in AGDD was particularly pronounced in the southern part of the study area. Our results suggest that alterations in the transmission intensity of *S. japonicum* in south Jiangsu will be more pronounced than in the northern part of the province.

Fifth, we further assessed the potential impact of climate change on the distribution of *O.hupensis* via a spatially-explicit analytical approach. We employed two 30-year composite datasets comprising average monthly temperatures collected at 623 meteorological stations throughout China, spanning the periods 1961-1990 and 1971-2000. Temperature changes were assessed spatially between the 1960s and the 1990s for January, as this is the critical month for survival of *O. hupensis*. Our results show that the mean January temperatures increased at 590 stations (94.7%), and that China's average January temperature in the 1990s was 0.96°C higher than 30 years earlier. The historical 0-1°C January isotherm, which has been considered the approximate northern limit of *S. japonicum* transmission, has shifted from 33°15' N to 33°41' N, expanding the potential transmission area by 41,335 km^2. This translates to an estimated additional 21 million people at risk of schistosomiasis. Two lakes that form part of the SNWT project are located in this new potential transmission area, namely Hongze and Baima.

Finally, we applied GIS/RS techniques to predict potentially new snail habitats around the lakes of Hongze and Baima, as well as Gaoyou lake, which is considered as a habitat where *O. hupensis* could re-emerge. A model based on flooding areas, NDVI and a wetness index extracted from Landsat images was developed to predict the snail habitats at a small scale. A total of 163.6 km^2 of potential *O. hupensis* habitats were predicted around the three study lakes.

In conclusion, our work suggests that global warming and a major water-resource development project could impact on the distribution of *S. japonicum* and its intermediate host snail in China and demonstrates that the combination of GIS, RS and Bayesian spatial statistical methods is a powerful approach in estimating their extent. The predictions can serve as a basis for health policy makers and disease control managers, and can be of use in the establishment and running of schistosomiasis surveillance systems. It is further suggested that an efficient early warning system should be set up in potential new endemic areas to monitor subtle changes in snail habitats due to climate change and major ecological transformations, and to assure the early detection of emerging and re-emerging schistosomiasis.

Zusammenfassung

Die asiatische Schistosomose wird durch die Infektion mit dem Trematoden *Schistosoma japonicum* verursacht. Die Krankheit ist in China seit dem Altertum bekannt und um 1950 wurde die Zahl der Infizierten auf ca. 11 Millionen geschätzt. In der gleichen Zeit erkannte die chinesische Zentralregierung die Bedeutung der Krankheit für die Volksgesundheit und den durch sie verursachten wirtschaftlichen Schaden, und lancierte ein grossangelegtes Kontrollprogramm. Dieses wurde über die letzten 50 Jahre fortgeführt und immer wieder den aktuellen Bedingungen angepasst. Heute sind die Endemiegebiete vor allem auf das Seen- und Überschwemmungsgebiet entlang des Yangtze-Flusses in den fünf Provinzen Jiangsu, Anhui, Jinagxi, Hunan und Hubei beschränkt. Gegenwärtig sind geschätzte 800'000 Chinesen mit diesem Parasiten infiziert und ca. 40 Millionen sind einem Infektionsrisiko ausgesetzt. Die traditionelle nördliche Grenze des Verbreitungsgebietes liegt bei ca. 33°15’ nördlicher Breite (z.B. im Bezirk Baoying in der Provinz Jiangsu). Es wird vermutet, dass das Endemiegebiet durch eine untere Schwellentemperatur begrenzt wird.

Das „Intergovernmental Panel of Climate Change“ (IPCC) berichtete, gestützt auf einer Vielzahl von Klimamodellen, dass sich die Temperatur der Erde in den letzten 100 Jahren um durchschnittlich etwa 0.6°C erhöht hat. Diese aussergewöhnliche Erwärmung war in den letzten drei Jahrzehnten besonders ausgeprägt und wird sich voraussichtlich auch im 21. Jahrhundert fortsetzen. Dieser Anstieg, so wird vermutet, könnte auch das Verbreitungsgebiet des Zwischenwirtes von *Schistosoma japonicum*, der Schnecke *Oncomelania hupensis*, beeinflussen.

Die Prävalenz und das Vorkommen der Schistosomose kann auch durch Wasserbauprojekte beeinflusst werden. In China wird gegenwärtig unter Anderem am grossangelegten „South-to-North water transfer project“ (SNWT Projekt) gearbeitet, welches Wasser aus dem südlichen und von Schnecken bewohnten Yangtze-Fluss über die Seen Gaoyou und Hongze sowie weitere Seen in den Norden nach Beijing und Tianjing liefern soll. Die Fertigstellung und der Betrieb dieses Projektes könnten die negativen Effekte der Klimaerwärmung weiter verstärken und die Verbreitung von *O. hupensis* nach Norden erleichtern.

Das Ziel dieser Dissertation war es, den möglichen Einfluss der Klimaveränderung und des SNWT Projekt auf das Vorkommen der asiatischen Schistosomose und ihres Zwischenwirtes im östlichen Teil Chinas zu untersuchen. Wir benutzten Laboruntersuchungen und moderne

Hilfsmittel zur Kartierung und Vorhersage, insbesondere geographische Informationssysteme (GIS), Fernerkundung und Bayes'sche räumliche Statistik.

Als erstes erstellten wir eine Übersicht über die Nutzung von GIS und Fernerkundung für epidemiologische Zwecke und zur Kontrolle der Schistosomose in China. Die Anwendungen umfassen die grossflächige Kartierung von Prävalenz- und Infektionsintensitätsdaten von Schistosomose sowie die Identifikation und Vorhersage von geeigneten Lebensräumen für *O. hupensis* in kleinem Massstab. Weitere wichtige Anwendungen sind die Vorhersage des Infektionsrisikos durch ökologische Veränderungen, vor allem Überflutungen und Wasserbauprojekte, und der mögliche Einfluss der Klimaveränderung. Danach diskutierten wir die Einschränkungen dieser Arbeiten und zeigten mögliche neue Anwendungsgebiete von GIS und Fernerkundung auf. Dies sind insbesondere quantitatives GIS, WebGIS und die Nutzung von neuen Satellitendaten, da diese die Kartierung von Infektionsrisiken und die Vorhersage massiv verbessern können. Wir betonten auch die Notwendigkeit weiterer Forschungsaktivitäten zu bestimmten Themen um einige der verbleibenden Probleme bei der Anwendung von GIS und Fernerkundung für die Forschung über Schistosomose zu lösen. Diese Fortschritte werden helfen, die Kontrolle dieser Krankheit in China weiter voranzutreiben und sie letztendlich ganz zum Verschwinden zu bringen.

In einem zweiten Schritt nutzten wir die Vorteile, welche die Kombination von GIS, Fernerkundung und Bayes'scher Statistik mit sich bringt, und untersuchten das Verhältnis zwischen klimatischen Faktoren und dem Infektionsrisiko mit Schistosomose mittels Bayes'schen Raum-Zeit Modellen. Hierfür nutzten wir parasitologische Daten, welche von 1990-1998 jährlich in Querschnittsstudien in 47 Bezirken der Provinz Jiangsu gesammelt wurden. Unser Modell umfasste auch die Erdoberflächentemperatur (land surface temperature, LST) und einen Vegetationsindex (normalized difference vegetation index, NDVI). Beide Klimafaktoren wurden mittels Satellitensensoren erfasst. Unsere Analyse deutete auf eine negative Assoziation zwischen NDVI und dem Infektionsrisiko mit *S. japonicum* hin. Andererseits ging eine erhöhte Erdoberflächentemperatur mit einem signifikanten Anstieg der Prävalenz von Schistosomose einher.

Als drittes führten wir eine Reihe von Laborexperimenten durch, um den Effekt der Temperatur auf die Interaktion des Parasiten mit der Zwischenwirtsschnecke besser zu verstehen. Dies mit dem Ziel, die Veränderungen in der Verteilung und der Übertragungsdynamik der

Schistosomose in China im Verlauf der vorhergesagten Klimaerwärmung abzuschätzen. Wir stellten eine positive, lineare Beziehung zwischen der Entwicklung der Larven in der Schnecke und der Temperatur fest. Werden die Schnecken bei 15.3°C gehalten, stellen die Larven ihre Entwicklung allmählich ein, wobei anderseits die Entwicklung bei 30°C am schnellsten verläuft. Die Temperatur, bei welcher 50% der Schnecken in Winterruhe verfallen, liegt bei 6.4°C. Unter 13°C wurde eine statistisch signifikante positive Assoziation zwischen der Temperatur und der Sauerstoffaufnahme der Schnecken beobachtet. Wir beobachteten auch eine einer logistischen Kurve folgende Beziehung zwischen der Sauerstoffaufnahme und dem Prozentsatz von *O. hupensis*, die in Winterruhe verfallen. Unsere Resultate unterstreichen die zentrale Bedeutung der Temperatur für die Aktivität von *O. hupensis* sowie für die Entwicklung der Larven von *S. japonicum* in ihrem Zwischenwirt.

Um die Behauptung zu prüfen, die Klimaerwärmung könne die Verteilung und Übertragungsdynamik von *S. japonicum* in China beeinflussen, führten wir zeitliche Analysen von Daten aus den Jahren 1972-2002 aus 39 Bezirken in der Provinz Jiangsu durch. Wir verwendeten jährliche Wachstums-Grad-Tage (annual growing degree days, AGDD) mit einem Temperaturschwellenwert von 15.3°C um die Übertragung von *S. japonicum* vorherzusagen. Das resultierende Modell umfasste eine zeitliche und eine räumliche Komponente. Sowohl der zeitliche wie auch der räumliche Trend bestanden aus Polynomen zweiten Grades. Für die Zeit verwendeten wir ausserdem eine Saisonalitätskomponente. Wir berechneten die AGDDs von *S. japonicum* in den Jahren 2003 und 2006 sowie den Unterschied in AGDDs zwischen 2003 und 2006 und stellten diese dar. Die Temperaturen der 39 Messorte zeigten einen zunehmenden zeitlichen Trend und eine Saisonalität mit Periodenlängen von 12, 6 und 3 Monaten. Die vorhergesagten AGDD nahmen sowohl 2003 als auch 2006 von Norden nach Süden allmählich zu. Die Zunahme der AGDDs war im südlichen Teil des Untersuchungsgebietes besonders ausgeprägt. Unsere Resultate prognostizieren eine stärkere Veränderung der Übertragungsintensität im Süden der Provinz Jiangsu als im Norden.

Weiter untersuchten wir den möglichen Einfluss der Klimaveränderung auf die Verbreitung von *O. hupensis* mittels räumlicher Analysen. Wir verwendeten zwei jeweils 30 Jahre umfassende Datensätze der mittleren Monatstemperatur von 623 meteorologischen Messstationen aus ganz China, welche die Perioden 1961-1990 und 1971-2000 abdeckten. Die Veränderung der Januartemperatur zwischen den 1960er und 1990er Jahren wurde räumlich analysiert da der Januar der kritische Monat für das Überleben von *O. hupensis* ist. Unsere Resultate zeigten, dass die mittlere Januartemperatur in 590 Stationen (94.7%) anstieg, und dass in China die mittlere Januartemperatur in den 1990er Jahren 0.96°C höher lag als 30 Jahre zuvor. Laut unseren Berechnungen verschob sich die historische 0-1°C Januar-Isotherme, welche als ungefähre nördliche Limite von *S. japonicum* gilt, von 33°15' N nach 33°41° N, was zu einer Ausweitung des potenziellen Transmissionsgebietes um 41'335 km^2 führte. In diesem Gebiet leben geschätzte 21 Millionen Menschen, die zusätzlich dem Risiko einer Infektion mit *S. japonicum* ausgesetzt sind. Die zwei Seen Hongze und Baima, welche auch Teil des „South-to-North water transfer projects“ sind, liegen in diesem neuen potenziellen Übertragungsgebiet.

Schlussendlich verwendeten wir GIS und Techniken der Fernerkundung, um potenzielle Schneckenhabitate um diese zwei Seen sowie dem Gaoyou-See, einem potenziell wieder kolonisierbaren Habitat, vorauszusagen. Um die Schneckenhabitate auf kleinerem Massstab vorhersagen zu können entwickelten wir ein Modell, welches die Überschwemmungsgebiete, den NDVI und die Bodenfeuchtigkeit, gewonnen aus Daten des Landsat-Satelliten, enthielt. Ein Total von 163.6 km^2 potenziellem Schneckenhabitat wurde für die Seen Hongze, Baima und Gaoyou vorhergesagt.

Zusammengefasst zeigten diese Studien den potenziellen Einfluss der Klimaerwärmung und von einem grossen Wasserbauprojekt auf die Verteilung von *S. japonicum* und seinem Zwischenwirt im östlichen Teil Chinas auf, sowie das Potenzial für ihre Abschätzung, welches aus der Kombination von GIS, Fernerkundungs und komplexer Bayes'scher räumlicher Statistik resultiert. Die Voraussagen können in Zukunft sowohl Planern im Gesundheitswesen als auch Leitern von Kontrollprogrammen als Grundlage dienen und bei der Ausgestaltung von Überwachungssystemen für Schistosomose helfen. Weiter schlagen wir vor, dass ein effizientes Frühwarnsystem in neuen potenziellen Endemiegebieten eingerichtet werden sollte, um die durch die Klimaveränderung und ökologische Transformationen hervorgerufenen Entwicklungen in den Schneckenhabitaten zu überwachen und das frühe Erkennen von neuauftretender oder wiederauftretender Schistosomose sicherzustellen.

1: Introduction

1.1 The current situation of human schistosomiasis

Schistosomiasis, also known as bilharziasis, is a parasitic disease caused by a blood fluke of the genus *Schistosoma*. There are five species of *Schistosoma* parasitizing humans, namely *Schistosoma mansoni, S. haematobium, S. japonicum, S. intercalatum* and *S. mekongi.* The former three species are the most important ones in terms of geographical distribution and number of people infected (Ross et al., 2002; Davis, 2003). *S. japonicum* is endemic in China, Indonesia and the Philippines, and is the primary species addressed in the thesis. It is interesting to note that schistosome eggs have been discovered in both Chinese and Egyptian mummies dating back over two millennia (Deelder et al., 1990; Zhou et al., 2005). These observations revealed that schistsosomiasis was part of early civilizations. The symptoms of the disease have been recognized for a long time. For instance, in the Far East, infection with *S. japonicum* was recognized and known as 'Katayama' disease, characterized by enlargement of the liver and spleen, bloody diarrhea and occasionally fever (the so called 'Katayama Fever') (Mao, 1990; Ross et al., 2001). However, the causative agent was not known until the middle of the 19th century, when it was discovery by Theodor Bilharz.

1.1.1 Global situation

At present, schistosomiasis remains one of the most prevalent infections in the world. It is endemic in 76 countries and territories, and continues to be of considerable public health significance, primarily in the developing world. A recent systematic literature review suggests that 779 million people are the risk of becoming infected with schistosomiasis (Steinmann et al., 2006). It is estimated that 207 million people are infected, of whom 120 million are symptomatic and 20 million have severe disease (Chitsulo et al., 2000; Engels et al., 2002). An expert committee reported to the World Health Organization (WHO) that the global burden of schistosomiasis might be as high as 4.5 million disability-adjusted life years (DALYs) (WHO, 2002). A recent meta-analysis suggests that the ‘true’ burden of schistosomiasis might be several-fold higher (King et al., 2005).

Figure 1 shows the global control status as of 2005. Large-scale chemotherapy-based morbidity control programmes are ongoing in Brail, China and Egypt (Engels et al., 2002), and that six countries in sub-Sahara Africa have recently launched national control programmes (Fenwick, 2006).

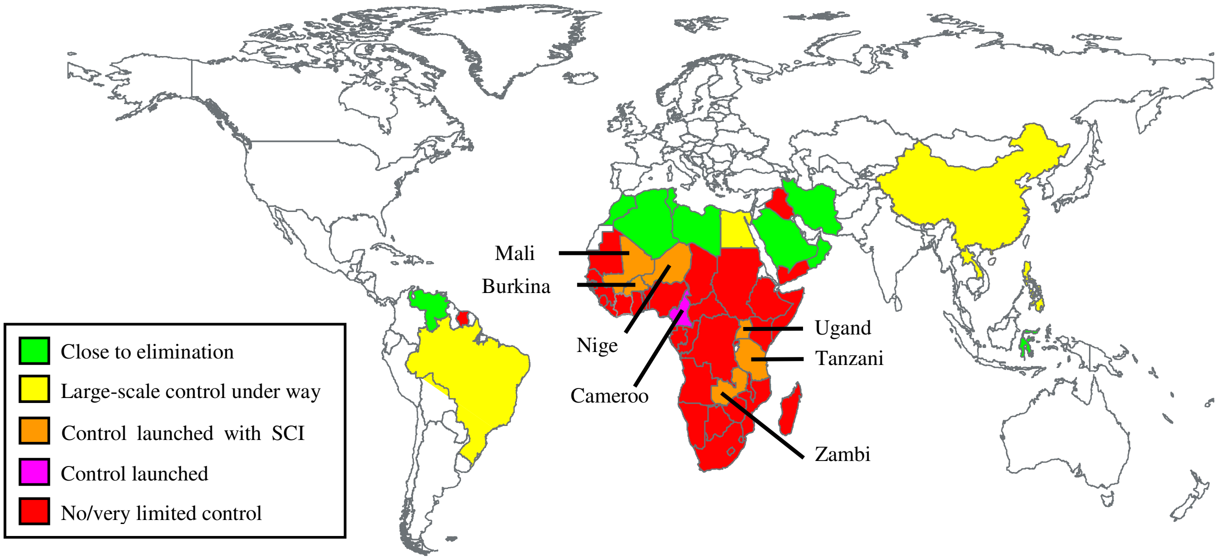

Figure 1. The global situation of schistosomiasis control in the world as of 2005 (Fenwick et al., 2006)

1.1.2 Chinese endemic situation

Schistosomiasis japonica has a very long history in China. *S. japonicum* eggs found in a female corpse of Western Han dynasty suggested that the transmission of schistosomiasis can be traced back over 2,000 years (Mao & Shao, 1982). After the founding of the People's Republic of China in 1949, large-scale epidemiological surveys were carried out by Chinese scientists to evaluate the prevalence, intensity, and incidence of *S. japonicum* infections. In China, the endemic areas of schistosomiasis were concentrated along the Yangtze River and extended southwards covering the Municipality of Shanghai, the Autonomous Region of Guangxi and 10 provinces, namely Jiangsu, Zhejiang, Anhui, Jiangxi, Hunan, Hubei, Yunnan, Sichuan, Fujian and Guangdong. The disease was reported from a total of 5102 townships in 373 counties (cities). The most heavily endemic areas were located in the lake and marshland regions, such as the Yangtze River basin and the two largest fresh-water lakes (Poyang and Dongting). More than 10 million people were estimated to be infected and over 100 million were at risk of infection. The habitats of the intermediate host snail, *Oncomelania hupensis*, covered a surface area of 14.8 billion m^2 (Mao & Shao, 1982; Chen, 1999; Chen & Feng, 1999).

Since the mid 1950s, great achievements have been made in the control of schistosomiasis in China. By the end of 2003, five provinces reached the criteria of transmission interruption, namely Guangdong, Shanghai, Fujian, Guangxi, and Zhejiang. The number of infected people and snail infested areas decreased by 92.7% and 73.6%, respectively, when compared to the data at the early stage of the national schistosomiasis control programme (Utzinger et al., 2005; Zhou et al., 2005).

1.1.3 Remaining and new challenges for schistosomiasis control in China

China has been recognized as one of the most successful countries in the world implementing integrated schistosomiasis control programmes. Prevalence and morbidity reached the lowest level in 2000, which is partially explained by mass chemotherapy facilitated through a 10-year World Bank loan project (WBLP) for schistosomiasis control initiated in 1992. However, there is still a great need to carry out control interventions in the areas where the disease continues to be a public health problem (Chen et al., 2003). For instance, favorable environmental factors and other parameters required for disease transmission in the endemic areas still exist, and it is difficult to maintain the current low level, especially after the WBLP came to an end in 2001. This challenge is more obvious in the lake and marshland areas that cover five provinces along the Yangtze River, namely, Jiangsu, Anhui, Hunan, Hubei and Jiangxi. In addition, ecological transformations bring about new challenges for control, most notably the Three Gorges dam project, and the South-to-North Water Transfer (SNWT) project as well as global warming (Xu et al., 2000; Zhou et al., 2002b). The Three Gorges area is currently free of schistosomiasis, but the disease is endemic both upstream and downstream from the water reservoir area. There is considerable concern about a schistosomiasis outbreak, 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 SNWT project could introduce *O. hupensis* from schistosome-endemic settings to non-endemic areas, as the water source is located in an area known to be endemic for the disease (Zhou et al., 2001). The effect of global warming on human health is an important topic that has gained in interest in recent years (WHO, 2003). For instance, it will trigger alterations in physical and biological systems, including shifts in the spatio-temporal distribution of disease vectors (Reiter, 2001; Hunter, 2003; Sutherst, 2004). It has been expected that climate change will impact the distribution of intermediate host snails and consequently the transmission of schistosomiasis, but the extent of these effects still needs further investigation (Zhou et al., 2002b; Yang et al., 2005).

1.2 Parasite and intermediate host snail

1.2.1 Life cycle of *S. japonicum*

The life cycle of *S. japonicum* includes a sexual phase in the vascular system of the definitive host and an asexual phase in the intermediate host snail, *O. hupensis* (Mao, 1990) (Figure 2). The life cycle includes the following stages of the parasite: egg, miracidum, sporocyst (mother sporocyst and daughter sporocyst), cercaria, schistosomula and adult worms.

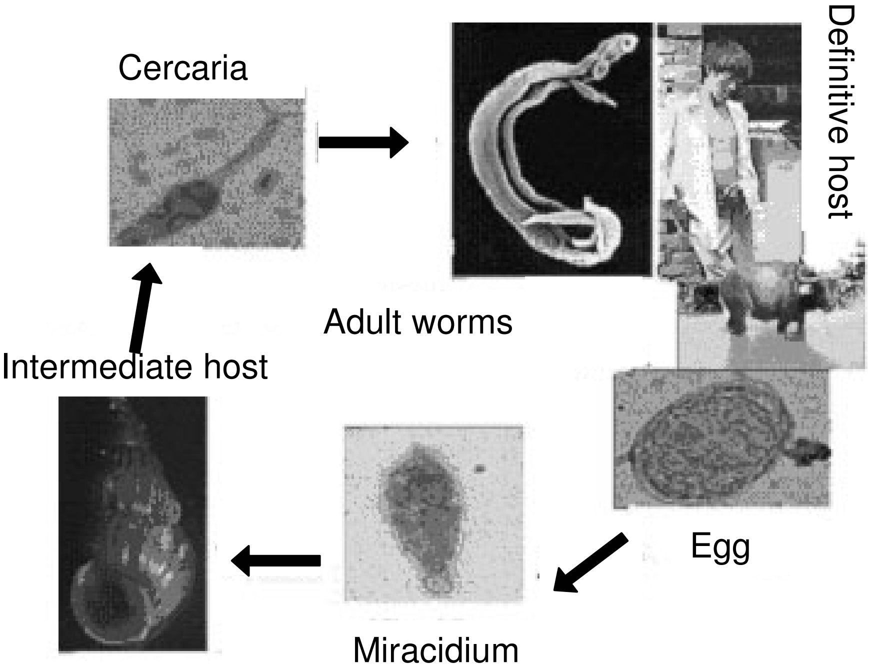

Figure 2 Life cycle of *S. japonicum*

1.2.1.1 *Egg*

An adult female *S. japonicum* discharges between 500 and 3,500 eggs per day, which are deposited within the wall of the small and large intestine. They derive nutrition for their development from the intestinal wall. A large proportion of the eggs pass in the faeces of the patient, whereas other eggs are trapped in tissues of different organs. Eggs that penetrate the intestinal wall destroy the tissue and blood vessels, which give rise to blood losses detectable stools. Some eggs are trapped in the liver. Disease manifestations arise from the host responses to the larval miracidia contained within the eggs. The colon, especially the rectosigmoid area, and the left lobe of the liver are usually the most affected organs (Mao, 1990; Ross et al., 2001; Davis, 2003).

1.2.1.2 *Miracidium*

The miracidium escapes from an egg promptly after the egg reaches a fresh-water body. The movement of the miracidium is determined by the temperature, illumination and post-hatching time. At a temperature of 20 to 25°C, the miracidium can survive for more than 10 hours. Once a miracidium meets with a susceptible intermediate host snail, it penetrates the snail and loses its cilia (Mao, 1990).

1.2.1.3 *Sporocyst*

The majority of the miracidia penetrate into susceptible snails via the head foot. A miracidium develops into a sporocyst once entering the snail. A sporocyst can asexually generate hundreds of cercariae, which are the larvae that can penetrate the definitive hosts (e.g. human). It takes approximately 56 days for the development of a miracidium into a cercaria at a temperature of 24 - 26°C (Mao, 1990). Temperature is the key feature which determines the development of the sporocysts. The higher the temperate, the more rapid the development of sporocyst within a certain temperature range (Ye et al., 1982; Mao, 1990).

1.2.1.4 *Cercaria*

S. japonicum cercariae are approximately 300 µm in length and they have a forked tail. After shedding from the snail, the cercariae stay on the water surface without movements. When humans come in contact with infested waters, the cercariae attach to the skin and immediately penetrate the skin and enter into the cutaneous capillary vessels. This penetration process consists of two sequential stages. First, it secretes proteolytic enzymes from its penetration gland. Second, once the cercaria is fully penetrated, its tail is cast off. Previous studies have revealed that water quality, pH level, temperature and illumination are the dominating factors influencing the cercaria shedding. The life span of a cercaria is short. At temperatures of 18-20°C, 73% cercariae die within 72 hours (Mao, 1990).

1.2.1.5 *Schistosomulum*

The tailless cercaria is termed schistosomulum, a parasitic stage which migrates through the systemic circulation via the lung, liver and finally settles in the mesenteric vein. The male and female schistosomulum can be distinguished 11 - 14 days post-penetration. A male schistosome begins holding a female in its gynecophoral canal at day 15 - 18 post-penetration.

The schistosomulum matures into the adult stage in 24 - 28 days. After this time, the female schistosome begins to deposit eggs. The pairing stage is important for the development of schistosome. It is important to note that both male and female schistosomes cannot mature without pairing (Mao, 1990; Davis, 2003).

1.2.1.6 *Adult worm*

Adult schistosomes live in pairs in the portal system and in the mesenteric venules. Males are 12-20 mm long and 0.5 mm wide, and have a ventral infolding from the ventral sucker to the posterior end forming the gynecophoric canal. Females are slender (0.3 mm in diameter) and longer (up to 26 mm in length), and are held in the gynecophoric canal.

1.2.2 Intermediate host snail: *O. hupensis*

1.2.2.1. *Distribution*

The limits of the geographical distribution of *O. hupensis* in the north is in Baoying County, Jiangsu Province (33°15' N); in the south it is in Yulin County, Guangxi Zhuang Autonomous Region (22°5' N); in the east it is in Nanhui County, Shanghai Municipality (121°51' E); and in the west is in Yunlong County, Yunnan Province (99°50' E). The altitude of the endemic areas ranges from sea level in Shanghai Municipality up to 2400m above sea level in Lijiang County, Yunnan Province (Mao, 1990; Zhou et al., 2005). Geographically, *O. hupensis* habitats can be generally divided into three ecological types: (i) lake and marshland region; (ii) hilly and mountainous region; and (iii) plain region with water networks. Schistosomiasis japonica is a strictly regional endemic disease. It corresponds to the distribution of *O. hupensis* (Mao & Shao, 1982). In the lake and marshlands regions, snails spread out in vast areas governed by the hydrology of the Yangtze River. The marshlands, which are flooded for about 2 to 5 months per year, become suitable habitats for snail breeding. The snails in the lake and marshland regions are readily spread by floods. In the hilly and mountainous regions, the snails are distributed along ditches, irrigation channels and river systems, but are isolated from one another. These areas are economically underdeveloped and access is often difficult. In the plain regions, the snails are distributed along river systems and schistosomiasis is thus widespread (Mao, 1990; Zhou, 2005).

Table 1. The classification and distribution of *O. hupensis* in mainland China

Classification	Distribution
Oncomelania hupensis Grendel 1881	China mainland
O.h. hupensis	Middle and lower reaches of Yangtze River basin

O.h. fauti strain	Mountainous or hilly environment
O.h. hupensis strain	Lake or marshland environment
O.h. tangi	Southern coast of China
O.h. tangi strain	Fujian Province
O.k. gangxi strain	Guangxi Province
O.h. subei strain	Northern Jiangsu province costal sand environment
O.h. robertsoni	Southwest China
O.h. yunan strain	Yunnan Province
O.h. sichuan strain	Sichuan Province

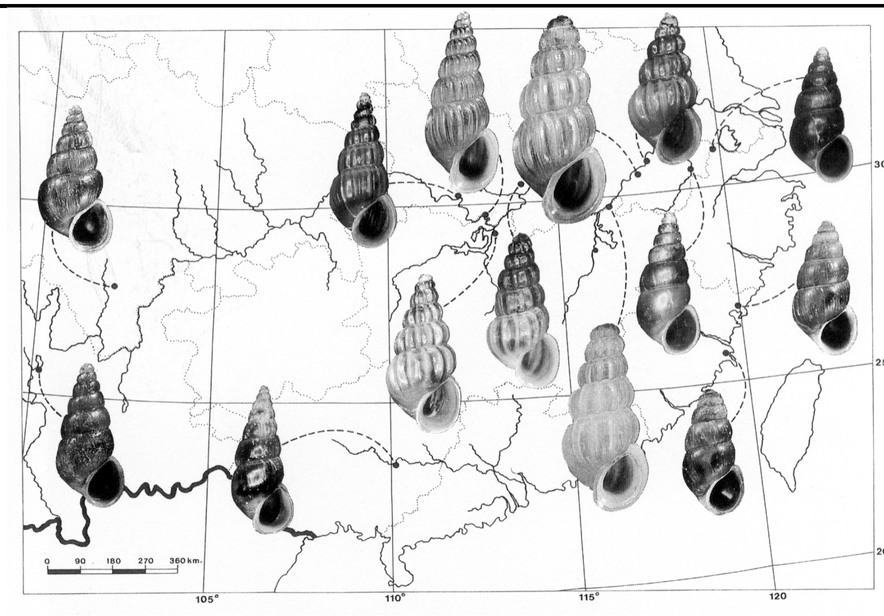

Figure 3. Classification and distribution of *O. hupensis* in mainland China (Davis et al., 1995)

1.2.2.2. *Ecological determinates of O. hupensis*

The distribution of the intermediate host snail is governed by many factors, such as temperature, rainfall, vegetation, sunshine, oxygen, and chemical elements in the earth. The former three are the most critical factors affecting *Oncomelania* survival.

Temperature influences the snail survival and activity. Laboratory investigation and field observations found that between 20 and 25°C are ideal for snail breeding and reproduction. The peak season for reproduction is during spring when the soil temperature rises above 10°C. Reproduction also occurs during autumn. The summer and winter months are less suitable for reproduction since either hot or cold temperatures prevent egg laying. When the temperature becomes too low or the environment experiences a drought, *Oncomelania* can bury deeply into the soil and hibernate. Historical data reveal that in the snail-infested areas the yearly mean temperature is over 14°C and the January mean temperature is higher than 0°C. As mentioned before, the northern geographic limit of snail habitats is located in Baoying county, Jiangsu province (33^{o} 15´ N). There is a large body of literature indicating that global warming could potentially alter the spatio-temporal distribution of disease vectors, and thus change the frequency and transmission dynamics of vector-borne diseases (Reiter, 2001; Hunter, 2003; Sutherst, 2004). The general agreement is that transmission dynamics is most sensitive to climate change around the boundaries of endemic areas (Sutherst, 2004). Some experts also emphasize on the impact of climate change on the distribution of snails that act as intermediate hosts for schistosomiasis (Morgan et al., 2001). The potential impact of global warming on schistosomiasis japonica in China has been pointed out recently, but it remains to be investigated how exactly, and to what extent, transmission will be affected (Zhou et al., 2002b).

Water is the second most important factor governing the distribution of snail. Adult *O. hupensis* are amphibious, living at the brink of water bodies. In northern China, one of the reasons explaining the absence of schistosomiasis transmission is the lack of water resources (lower precipitation, deeper water table than elsewhere in China). The snail-infested areas are restricted to regions where the annual precipitation is over 750 mm. For the lake and marshland schistosome-endemic settings, the areas with the highest snail density are found where the water is submerged for 2 - 5 months per year. If the submergence extends 7 months or is shorter than 1-2 months per year, the snail cannot survive. The annual floods facilitate the movement of the snails, particularly the young ones, to move around and disperse to new regions. Schistosomiasis control experts in Nanjing, Jiangsu Province, have noticed the yearly influx of infected snails in the flood plains along Nanjing. The huge flooding that occurred in 1998 resulted in a considerable expansion of the snail-infested areas (Zhou et al., 2002a). Implementation and operation of water resources development projects have a history of facilitating the spread and intensification of schistosomiasis (Jobin, 1999; Chitsulo et al., 2000; Hunter, 2003). Consequently, there is concern that the ongoing SNWT project might increase the transmission risk of schistosomiasis by enlarging the wetlands and transferring snails from south (the snail infested Yangtze River) to north (Beijing and Tianjing) via the lakes of Gaoyou and Hongze. Similarly, there is concern that the construction of TGD and its accompanied ecological transformation and human migration might negatively impact on schistosomiasis (Utzinger et al., 2005; Zhou et al., 2005) .

Vegetation is another important factor for snail survival. Vegetation provides food, and at the micro-habitat level can adjust humidity and temperature. For instance, vegetation protect snail from strong sunshine during the summer and keep warm in winter. The types and density of vegetation determine the distribution of snails. There is a strong positive correlation between snail distribution and vegetation coverage; high snail densities are observed in regions characterized by intense grass coverage. Regions without vegetation coverage are snail-free. Snails migrating with floods to new areas that are lack of sufficient vegetation coverage cannot survive. For example, newly formed islands in the middle and lower reaches of the Yangtze River are snail-free during the first 1-3 years, explained by the absence of vegetation. Subsequently, after grass starts to cover them, snails can survive.

1.2.3. Interaction between parasite and intermediate host snail

The sexual generations in the parasite life cycle, namely the stages of schistosomula and adult worm, are confined to the warm-blooded definitive host, i.e. humans and over 40 species of domestic and wild animals, such as bovines, cattle and goats (Wang et al., 2005). The asexual generations, namely egg, miracidium, sporocyst and cercaria, are developing in the external environment or in the cold-blooded intermediate host snail. It follows that the geographic distribution of *S. japonicum* is closely related to environmental factors (Mao, 1990; Ross et al., 2001; Yang et al., 2005).

Previous research has shown that the development of schistosome larva in the intermediate host snail is closely influenced by temperature (Shao & Xu, 1956; Pesigan et al., 1958; Nagasaki, 1960). How the temperature influences the interaction between the parasite and intermediate host snails has been studied in considerable detail for both *S. mansoni* and *S. haematobium* (Pfluger, 1980; Pfluger et al., 1983). With regard to *S. japonicum* the effect of temperature on the interaction of the parasite larva and *O. hupensis* is poorly understood, which in turn impedes the understanding of the potential impact of global warming on the frequency and transmission dynamics of schistosomiasis in China.

It is important to note that *S. japonicum* found in the Chinese mainland comprises different sub-strains in various geographic regions (He, 1993). Distinct genetic diversity was also detected between different sub-species of *O. hupensis* (Davis et al., 1995; Davis et al., 1999). The compatibility of different parasite strains and sub-species of *O. hupensis* is a subject that warrants detailed investigation.

It has been shown that the survival rates of a parasitic trematode and its intermediate host snail varied between the different stages of the parasite larvae and snails during hibernation. Early stage larva showed a significantly higher survival rate within snails than later stage larvae. However, snails carrying early stage larva had a better survival rate than snails with later stage larva. The authors concluded that if the development of the parasite starts before the hibernation, the risk of dying is high (Schjetlein & Skorping, 1995). Similar studies are needed for the interaction between schistosome larva and *Oncomelania*.

1.3 Ecological transformation related to transmission of schistosomiasis in China

The transmission of schistosomiasis japonica is governed by biological, ecological and socio-economic factors, which contribute to the current complex endemic situation (Mao, 1990). In the present thesis, pointed emphasis is on two ecological transformation issues and their potential impact on the transmission of schistosomiasis in China, namely, global warming and the SNWT project.

1.3.1 Global warming

The Earth is in a warming phase since the early 18th century (Reiter, 2001). This warming is thought to depend on both natural and man-made activities (Crowley, 2000; Huang et al., 2000). The main causes of climate change include (i) solar variability, (ii) volcanism, (iii) changes in greenhouse gases, and (iv) alterations in tropospheric aerosols. Systematic recording of the temperature commenced about 150 years ago and these records suggest that the Earth has warmed by approximately 0.6°C over the past 100 years (IPCC, 2001). Moreover, Diaz and Graham (1996) report that the elevation of the freezing level (0°C isotherm) in tropical latitudes (30°N–30°S) has shifted upwards by approximately 150 m (equivalent to about 1°C of local warming) since 1970. The warming of the 20th century has been particularly pronounced during the last three decades (Easterling et al., 1997; Crowley, 2000; IPCC, 2001; Haines & Patz, 2004). The increase in greenhouse gases due to human activity is the most likely driver of global warming (Crowley, 2000; IPCC, 2001). The predominant greenhouse gas is carbon dioxide (CO_2); its atmospheric concentration has increased by about 30% since 1890 (Reiter, 2001; Beggs, 2004). The Intergovernmental Panel of Climate Change (IPCC), based on various climate models, predicts that the mean global temperature will increase by between 1.4°C and 5.8°C from 1990 to 2100 (IPCC, 2001).

Climate change is characterized by considerable spatial and temporal heterogeneity. For example, warming is particularly pronounced at high latitudes of the northern hemisphere (Murphy et al., 2004; Stocker, 2004). Larger differences have been found for monthly average maximum and minimum temperatures during winter months when compared to the summer (Easterling et al., 1997).

Recently investigations attribute more than 150,000 deaths per year and a global burden of approximately 5 million DALYs annually to climate change. An area that has received particular attention is the potential impact of global warming on the transmission of vector-borne diseases (Reiter, 2001; Hunter, 2003; Sutherst, 2004).

Some models predict that global warming that will extend the area favourable for schistosomiasis transmission due to (Martens et al., 1995), while other models forecast a decrease in the epidemic potential of the disease (Martens et al., 1997). In China, we assume climate change will lead to an expansion northwards of the current distribution outline of *O. hupensis* breaking the northern geographical limit 33°15’ N latitude (Zhou et al., 2002b).

1.3.2 South-to-North water transfer project

The SNWT project is an ambitious water resources development project with the aim of alleviating water shortages in the northern part of China. The total water resources in China are 2810 billion m^3. Based on the calculated population and farmland in 1997, water resources per capita is 2200 m^3, only one-fourth of the world's average. It is predicted that by the year 2030, when the population in China might have reached 1.6 billion, water resources per capita will be only 1700 m^3.

In addition to the scarcity, the water and land resources are also unevenly distributed, i.e. sufficient water but insufficient land in the south, and sufficient land but insufficient water in the north. For example, 80.4% of water resources in China are concentrated in the Yangtze river basin and south of it. In this area approximately 53.5% of the total population lives, cultivating 35.2% of the farmland, generating 54.8% of GDP of the whole country.

The northern part of the Yangtze river is home to 44.4% of China’s population, has an estimated 59.2% of the farmland, and generates 43.4% of GDP. However, only 14.7% of the water resources of the whole country are found here. This area suffers the most serious inconsistency of water demand versus supply and most serious unmatched condition of water resources with economic and social development. In recent years, the Yellow river, once the second longest river in China, has at times been drained dry before reaching the East China Sea. It has been predicted for Beijing and Tianjin that the water tables might be drained down to bedrock within the next 15 years.

The Chinese large rivers flow from west to east. To date, a complete water network which would allow more equitable allocation and regulation of water resources has not been established. Flooding in the south and droughts in the north are common feature and often cause disasters such as the 1998 floods.

In parallel with further population growth and the economic development, the conflict between water supply and demand is likely to intensify, which might worsen ecological environment. Such environmental deterioration might jeopardize social and economic development of the north, and thereby slow down the development of the whole country. Thus the implementation of the SNWT project is a key factor for guaranteeing sustainable development.

The SNWT project includes three main lines -- Eastern, Central and Western -- linking the Yangtze river basin with north China. In this study, we are focusing on the eastern line since it is likely to influence the distribution of *O. hupensis* by pumping the water from schistosome-endemic region and to non-endemic areas further north.

1.3.2.1 Eastern Route

The construction of the 1162 km Eastern Route will be done in three phases. Phase I plays an important role for the potential enlargement of schistosome-endemic region. Phase I will upgrade and extend the Grand Canal and other existing water resources infrastructure in Jiangsu Province, in order to pump water from the Jiangdu City on the Yangtze river as far north as Dezhou City in the northern Shandong Province by 2008. The water will be pumped along a 483 km series of canals, rivers and lakes, most of which already exist. The Eastern Route reaches its highest point -- 40 m higher than Jiangdu -- at Dongping Lake in Dezhou City, just a few kilometers south of the Yellow River.

As water flows northwards along the Eastern Route, it will be temporarily impounded in any of five lakes by sequence from south to north, namely Gaoyou, Hongze, Luoma, Nansi and Dongping. Schistosomiasis may re-emerge in the current snail-eliminated Gaoyou lake and snails could be introduced to other currently non-endemic lakes.

Lessons of inadvertently creating suitable snail habitats by water resources development have been learnt in other epidemiological settings. For example, in the Nile delta below Cairo and in the Sudan, the prevalence of schistosomiasis parallels the degree of irrigation intensity, as the snails are pumped along with the water (Jobin, 1999). With the construction of the Roseires and Aswan dams in Egypt, year-round irrigation became possible and snail populations expanded. *S. mansoni* has prevailed throughout the Gezira irrigation system since 1970, when a storage dam was added to the original irrigation system of central Sudan (Amin et al., 1982). In China, subsequent to the construction of the Three Gorges dam on the Yangtze river, the snail distribution and annual prevalence of human schistosomiasis varied significantly in accordance with water levels in the Yangzte river, in a direct association with the snail density, the water table, annual rainfall, yearly evaporation and ground altitude (Xu et al., 1999).

Therefore, heighten surveillance and monitoring is warranted so as to detect changes resulting from ecological changes and to take rapid action if need be.

Figure 4. Sketch map of Eastern line of South-to-North Water Transfer project (dark line)

1.4 Surveillance and prediction of schistosomiasis transmission

It is widely acknowledged that the frequency and transmission dynamics of schistosomiasis is closely related to socio-economic and environmental factors, the latter including temperature, rainfall and vegetation coverage (Mao, 1990; Brooker, 2002). Geographic Information System (GIS) and Remote Sensing (RS) techniques, in concert with spatial statistical models, offer new opportunities for rapid assessment of endemic areas and can guide intervention strategies. These approaches can also predict disease distributions in areas that lack baseline data or are difficult to access (Hay et al., 2000; Kristensen et al., 2001; Malone et al., 2001).

GIS is a computerized system consisting of hardware, software, data and people for collecting, storing, managing, querying and displaying spatially reference data. It supports decision-making for planning and management of natural resources, environment, landuse, transportation, facilities and utilities, and many other areas where spatial information are used. RS can provide near-real time information about different features of the Earth surface and it is an important data for GIS analyses. In China, a large amount of work has been done by applying GIS and RS technologies for collection of data on schistosomiasis, specifically disease mapping, identification of *O. hupensis* habitats, and predicting transmission risk in relation to ecological transformation (Zhou et al., 2002a; Guo et al., 2005; Yang et al., 2005; Zhang et al., 2005).

Spatial statistical modelling allows the estimation of spatial correlation, identification of risk factors for disease transmission by taking into account spatial correlation, and the prediction the risk at unsampled locations. Standard statistical models assume independence of the observations. Spatial models take into account geographical correlation by introducing spatially structured random effects. These models are usually quite complex and have many parameters. Bayesian inference and Markov chain Monte Carlo (MCMC) (Gelfand & Smith, 1990) simulation methods provide the means for model-fit. There is now a considerable body of literature pertaining to Bayesian-based spatial analyses of infection risk and disease, but they have not been applied in *S. japonicum* research. Most of the previous work is rather descriptive, has not quantitatively assessed the relation between risk factors and disease prevalence, and has neither been used to predict the transmission risk nor the prediction error.

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2: Goal and Objectives

2.1 Goal

To investigate the potential impact of regional climatic change and water resources development on the transmission of schistosomiasis japonica, and the distribution of the snail intermediate host, *Oncomelania hupensis*. The hypothesis is that the schistosomiasis transmission region will expand northwards due to the climate warming and south-to-north water transfer project.

2.2 Objectives

1. To examine the spatio-temporal variations of *Schistosoma japonicum* infection risk in Jiangsu province, China, and the relationships between climatic factors and infection prevalence
2. To explore the temperature influence on the development of the *S. japonicum* larva harboured in the *Oncomelania* snail intermediate host, and the interaction between parasite and the host based on biological experiments in the laboratory.
3. To assess the potential impact of climate change on the spatial distribution at different scales (both Micro and Macro scales) of *O. hupensis*, the intermediate host of *S. japonicum*.
4. To establish schistosomiasis transmission forecast models based on biological thresholds from experiments and history continuous temperature dataset.

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

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3.1 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 guiding 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

3.2 Introduction

Schistosomiasis, a chronic and debilitating disease caused by intestinal trematodes (schistosomes), has been endemic in China since ancient times, particularly 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 centres. The sustained political commitment, including the training of personnel at these centres, 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 5 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 14.8 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.

3.3 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 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 (FAO)'s 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°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 system 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 progress 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).

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

Reference	Study aim	Area	Application		Data sources and parameters	
(Author, year)			Method	Scale	Environmental factors	Demographic and/or epidemiological factors
Maszle et al., 1998	To assess 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 1980-1998
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 1980-1998
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 1990-1998

3.4 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 Gorge 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 mm and 2000 mm, and total daylight of 1400-2100 h 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 collected 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 greenness feature. As a result, the specificity of the model was increased by approximately 30%. Preliminary model validation at 10 selected sites around Lake Poyang 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 Forth 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) analysed 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 analysed 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).

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
(Author, year)			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 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 the *O. hupensis* distribution in the marsh land 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 image 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	Jiangning, Jiangsu	RS, GIS	Micro	Terra-MODIS

	distribution of *O. hupensis*	province			
Guo et al., 2005	To predict *O. hupensis* habitats	Poyang Lake, Jiangxi province	RS, GIS	Meso	Landsat TM image for dry and wet seasons
Zhang et al., 2005	To predict *O. hupensis* habitats	Jiangning, Jiangsu province	RS, GIS	Meso	Landsat ETM+ image

3.5 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*. In fact, 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.

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., 1999c). Composite maps 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 (Zhou et al., 2002a).

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).

Table 3. GIS and RS application for schistosomiasis in China: appraisal of ecological transformation, water resource development and climate change

Reference (Author, year)	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., 2002a	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 1960-1999 at 623 meteorological stations across China

3.6 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 satellites 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.

3.6.1 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 socioeconomic 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.

3.6.2 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.

3.6.3 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™ 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 × 16.5 km, or a strip of 16.5 × 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.

3.7 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 socioeconomic 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 buffalo 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 1992-2001 (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 schistosomiasis control efforts. In addition, several large water resource development projects bring about new challenges for control, most notably the Three Gorges dam project and the south-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-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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4: A Bayesian-based approach for spatio-temporal modeling of county level prevalence of *Schistosoma japonicum* infection in Jiangsu province, China

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4.1 Abstract

Spatio-temporal variations of *Schistosoma japonicum* infection risk in Jiangsu province, China, were examined and the relationships between key climatic factors and infection prevalence were determined. The parasitological data were collected annually by means of cross-sectional surveys carried out in 47 counties from 1990 to 1998. Climatic factors, namely land surface temperature (LST) and normalized difference vegetation index (NDVI), were obtained from remote sensing satellite sensors. Bayesian spatio-temporal models were employed to analyze the data. The best fitting-model showed that spatial autocorrelation in Jiangsu province decreased dramatically from 1990 to 1992 and increased gradually thereafter. A likely explanation of this finding arises from the large-scale administration of praziquantel for morbidity control of schistosomiasis. Our analysis suggested a negative association between NDVI and risk of *S. japonicum* infection. On the other hand, an increase in LST contributed to a significant increase in *S. japonicum* infection prevalence. We conclude that combining geographic information system, remote sensing and Bayesian-based statistical approaches facilitate integrated risk modeling of *S. japonicum*, which in turn is of relevance for allocation of scarce resources for control of schistosomiasis japonicum in Jiangsu province and elsewhere in China, where the disease remains of public health and economic significance.

Keywords: Bayesian statistics; Conditional autoregressive model; Geographic information systems; Remote sensing; *Schistosoma japonicum*; China.

4.2 Introduction

It is widely acknowledged that schistosomiasis due to *Schistosoma japonicum* has been endemic in China for at least two millennia (Chen and Feng, 1999; Ross et al., 2001). Some 50 years ago, an estimated 12 million people were infected with *S. japonicum*, another 100 million people were at risk of acquiring the disease, and 14,000 km^2 of flood plains in the Yangtze River basin were identified as transmission zones (Chen and Feng, 1999; Ross et al., 2001). At that time, schistosome-attributable morbidity and mortality were high (Chen and Feng, 1999). In view of the great public health and economic impact the disease placed on the country, government officials embarked on vigorous research and disease control programmes.

A national sampling survey in 1995 revealed that the number of infected people was dramatically reduced to less than one million (Chen and Feng, 1999; Ross et al., 2001). The national schistosomiasis control programme of China therefore is considered to be one of the most successful ones in the world (Chitsulo et al., 2000; Engels et al., 2002; Utzinger et al., 2003). Despite substantial progress made over the past decades, transmission of *S. japonicum* still persists in seven provinces of China; namely, Anhui, Hubei, Hunan, Jiangsu and Jiangxi in the lake region, and Sichuan and Yunnan in the mountainous region. There is considerable concern that with the recent termination of a World Bank loan designated for schistosomiasis control, and with major water resource developments currently underway (i.e. Three Gorges dam and South-North water transfer project), the disease could re-emerge (Xu et al., 1999; 2000; Ross et al., 2001; Zheng et al., 2002).

Over the past decade, application of geographic information systems (GIS) and satellite remote sensing (RS) has become an integral part of China's national schistosomiasis control programme (Zhou et al., 2001; Yang et al., 2005). For example, areas at risk of high transmission intensities were identified, employing either the normalized difference vegetation index (NDVI), a climate risk index, or earth surface temperature and mean minimum temperature in January (Zhou et al., 1999). A comprehensive GIS database was established for the provinces of Anhui, Jiangsu and Jiangxi, and the annual *S. japonicum* infection prevalence data were analyzed longitudinally (Yang et al., 2002). Finally, the Chinese government now presents their annual reports on schistosome-endemic areas by means of digital maps, which aids the planning and operating of the national control programme (Chen et al., 2003).

It is important to note that most of the preceding work was based on collating, mapping and analyzing prevalence data, employing conventional statistical approaches. Only few attempts have been made to investigate spatio-temporal correlations and to assess how climatic factors affect these correlations. Furthermore, in areas with small population sizes, mapping of raw prevalence data can be confusing or even misleading, due to variability in the estimated prevalence. Consequently, it is difficult to tease apart chance variation from true differences (Sun et al., 2000). Bayesian spatio-temporal modeling has been recognized as a powerful means to provide more robust estimates, as it takes into account possible correlations and covariate effects, and allows to readily incorporating errors that may arise from mean or median estimates of the independent variables (Bernardinelli and Montomoli, 1992; Kleinschmidt et al., 2002; Basáñez et al., 2004; Dorny et al., 2004).

The purpose of this study is to investigate the relationship between climatic factors derived from satellite RS and prevalence of *S. japonicum* infection obtained from repeated cross-sectional epidemiological surveys. The focus is on the Jiangsu province, located at the lower reaches of the Yangtze River. By the end of 2000, 35 counties reached the criterion of transmission interruption for *S. japonicum*, in eight counties transmission control was achieved, but in the remaining 14 counties, transmission still occurred (Chen and Feng, 1999). We employed annual prevalence data for the period 1990-1998, and modeled the effects of two key climatic factors, utilizing a Bayesian approach to make predictions of infection risks over time.

4.3 Materials and methods

4.3.1 Approach and study area

In the study presented here, we combined GIS, satellite RS and Bayesian statistical methods for integrated spatio-temporal risk modelling of *S. japonicum*. The geographical focus is on Jiangsu province in eastern China.

4.3.2 Parasitological data

The prevalence data of *S. japonicum* infection were collected during cross-sectional, community-based surveys carried out annually between 1990 and 1998. At the beginning of the study, Jiangsu province contained 47 schistosome-endemic counties. The Jiangsu Institute of Parasitic Diseases (JIPD; Meiyuan, China) collected the data, adhering to standardized, quality-controlled field and laboratory procedures. In brief, all study participants initially underwent immunological examination. In a first step, a skin test was performed by injecting 0.03 ml of a schistosome egg or adult worm antigen. Those with a positive reaction were subsequently examined with the circum-oval precipitin test. Finally, when this second immunology test was positive, examination of a stool sample was carried out, employing the miracidium hatching test. Details of the immunodiagnostic techniques have been described elsewhere (Sleigh et al., 1998; Wu, 2002). According to Mao (1990), the miracidum hatching test is more sensitive than the Kato-Katz technique for diagnosis of *S. japonicum*, thus the former was utilized. Data management was also done by JIPD, and the database was kindly provided for the present study.

4.3.3 Climatic data

The climatic data utilized for the current study were (i) NDVI and (ii) land surface temperature (LST). They were derived from the Advanced Very High Resolution Radiometer (AVHRR), which is part of a polar-orbiting meteorological satellite. Ten-day composite images were downloaded from the AVHRR website for the period 1990-1998. These images were georeferenced and subsetted in ENVI version 3.5 software (Research System Inc.; Boulder, CO, USA). ArcGIS software (ESRI; Redlands, CA, USA) was used to extract average NDVI, band 4 (T4) and band 5 (T5) values, for each pixel of the image. The average was taken over the decadal values during the *S. japonicum* transmission season which occurs from April to October, separately for each year. The county-specific values were estimated as the median of all pixel values within the county.

The LST data were calculated for each year from the county-specific NDVI, T4 and T5 values, using the formula below, which was cited by Becker and Lee (1990):

$$
\begin{aligned}
LST = {} & 1.274 + (T_4 + T_5)/2\{1 + [0.15616(1-\varepsilon)/\varepsilon] - 0.482(\Delta\varepsilon/\varepsilon^2)\} \\
& + (T_4 - T_5)/2\{6.26 + [3.98(1-\varepsilon)/\varepsilon] + 38.33(\Delta\varepsilon/\varepsilon^2)\}
\end{aligned}
$$

where $\Delta\varepsilon = 0.01019 + 0.01344\ln(NDVI)$, and $\varepsilon = 0.984605 + 0.02228\ln(NDVI)$

4.3.4 Statistical analysis

The raw data were entered and validated, using internal consistency checks and analyzed in STATA version 8.0 (Stata Corporation; College Station, TX, USA) and WinBUGS version 1.4 (Imperial College and MRC, London, UK). In a first step, logistic regression analyses were performed to assess the bivariate relations between the infection prevalence of *S. japonicum* and the climatic covariates (Model 1). Next, a Bayesian spatio-temporal logistic model was fitted in WinBUGS (Model 2). Spatial correlation was modeled by county-specific random effects, which were assumed to arise from a conditional autoregressive model CAR (γ), where γ measures the amount of the spatial correlation. Temporal correlation was modeled by yearly random effects, under the assumption that they follow an auto-regressive process, AR (1), with lag 1. Model 2 assumed independence between the spatial and temporal effects. Finally, Model 3 was applied, assuming a separate set of spatial random effects for each year. Bayesian smoothing was carried out by employing conditional autoregressive models, CAR (γ_t), for the random effects corresponding to year t. The deviance information criterion (DIC) (Spiegelhalter et al., 2002) was used to compare the goodness of fit of Models 2 and 3, and hence to select the model which better quantifies the spatio-temporal correlation. The parameters of the models were estimated using Markov chain Monte Carlo (MCMC) simulation. Further details of the modeling approach are given in the Appendix.

4.4 Results

Table 1 shows parameter estimates from the non-spatial (Model 1), as well as the two spatio-temporal models (Models 2 and 3). The results obtained from the non-spatial analysis indicate that both climatic covariates investigated (i.e. LST and NDVI) are significantly related to the risk of *S. japonicum*. In particular, the infection prevalence of *S. japonicum* increases with decreasing values of NDVI (coef = -0.014; 95% confidence interval: -0.015, -0.013), and with increasing values of LST (coef = 0.047; 95% confidence interval: 0.041, 0.053).

Because this non-spatial model does not allow appraisal of possible spatio-temporal variation and accurate estimation of the standard errors of the parameters in the presence of these variations, spatio-temporal models were fitted to capture the space and time correlation in the data. Model 2 assumed that spatial correlation between counties remained unchanged during the entire study period. In addition, Model 2 included a temporal effect, which assumed that the risk of *S. japonicum* in a given year was only related to the one of the preceding year. In contrast, Model 3 assumed that the amount of spatial correlation was year-dependent. The DIC goodness of fit criterion suggested that Model 3 was superior to Model 2, as it resulted in a much smaller deviation between the observed and the fitted data ($\text{DIC}_{\text{Model2}} = 32306.2$ versus $\text{DIC}_{\text{Model 3}} = 2400.1$). Consequently, further interpretation of the results focused on Model 3.

Table 1 Estimates and their 95% confidence intervals (in brackets) of different parameters for modeling country level *S. japonicum* prevalence data in Jiangsu province, by means of a non-spatial model and 2 different spatio-temporal models

Parameter	Model specifications		
	Non-spatial	Spatio-temporal	
	Model 1	Model 2	Model 3
Constant (α0)	-17.28 (-19.16,-15.40)	-5.43 (-6.79, -4.74)	-1.69 (-3.21, -0.55)
NDVI (α1)	-0.014 (-0.015,-0.013)	0.11 (0.085, 0.12)	-0.093 (-0.097, -0.085)
LST (α2)	0.047 (0.041,0.053)	-0.069 (-0.077, -0.052)	0.037 (0.033, 0.040)
Temporal correlation (ρ)		-0.022 (-0.73,0.80)	
Temporal variation		0.76 (0.43,1.32)	
Spatial variation in 1990 (σ12)		3.75 (2.94,4.80)	3.52 (2.66, 4.68)
Spatial variation in 1991 (σ22)			3.09 (2.42, 3.97)
Spatial variation in 1992 (σ32)			3.57 (2.79, 4.62)
Spatial variation in 1993 (σ42)			4.29 (3.34, 5.56)
Spatial variation in 1994 (σ52)			4.42 (3.31, 5.93)
Spatial variation in 1995 (σ62)			4.04 (3.00, 5.46)
Spatial variation in 1996 (σ72)			4.12 (3.07, 5.57)
Spatial variation in 1997 (σ82)			4.41 (3.19, 6.11)
Spatial variation in 1998 (σ92)			4.39 (3.13, 6.22)
Spatial correlation in 1990 (γ1)		0.89 (0.61, 0.99)	0.89 (0.61, 0.99)
Spatial correlation in 1991 (γ2)			0.69 (0.10, 0.97)
Spatial correlation in 1992 (γ3)			5.87E-4 (-0.85, 0.77)
Spatial correlation in 1993 (γ4)			0.20 (-0.64, 0.84)
Spatial correlation in 1994 (γ5)			0.77 (0.35, 0.98)
Spatial correlation in 1995 (γ6)			0.79 (0.37, 0.98)
Spatial correlation in 1996 (γ7)			0.91 (0.69, 0.99)
Spatial correlation in 1997 (γ8)			0.92 (0.75, 0.99)
Spatial correlation in 1998 (γ9)			0.91 (0.72, 0.99)
Deviance information criterion		32306.2	2400.1

Model 3 supported the results of the non-spatial model (Model 1), as each of the two covariates investigated showed a statistically significant association to the risk of *S. japonicum*. As before, NDVI was negatively associated with infection prevalence of *S. japonicum* (coef = -0.093; 95% CI: -0.097, -0.085), whereas a positive association was found between LST and infection prevalence of *S. japonicum* (coef = 0.037; 95% CI: 0.033, 0.040).

The parameters. γ_1-γ_9 of Model 3 quantified the amount of spatial correlation of the infection risk between the counties over the 9-year observation period. The estimates of these parameters, including 95% credible intervals, are graphically depicted in Fig. 1. Results showed that the spatial correlation dramatically dropped from 0.88 in 1990 to 0.0006 in 1992. After 1992, a rapid increase was observed. During the last three years of the study, spatial correlation became stable, and quite narrow 95% credible intervals were observed.

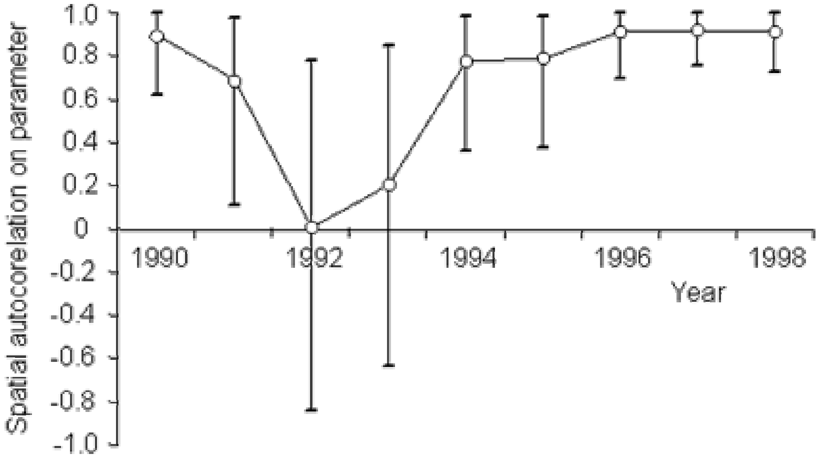

Fig. 1. Spatial autocorrelation parameter (γ_t) for county level prevalence of *Schistosoma japonicum* infection in Jiangsu province, China, from 1990 to 1998.

The smoothed annual *S. japonicum* infection prevalence data for the 47 counties from 1990-1998 are illustrated in Fig. 2. The infection risk decreased substantially from 1990-1998, most notably after 1992. In 1998, most of the counties had reached the criterion of schistosomiasis control, according to the definition of Chen and Feng (1999). The majority of these controlled areas are situated far away from the Yangtze River. In contrast, during the entire study period, the counties along the Yangtze River were at the highest risk of *S. japonicum*. Fig. 2 also shows that there was one county in the southern part of Jiangsu province, in which the infection risk increased from the year 1991 to 1992, and only decreased after 1993 to approach low levels towards the end of the investigated period.

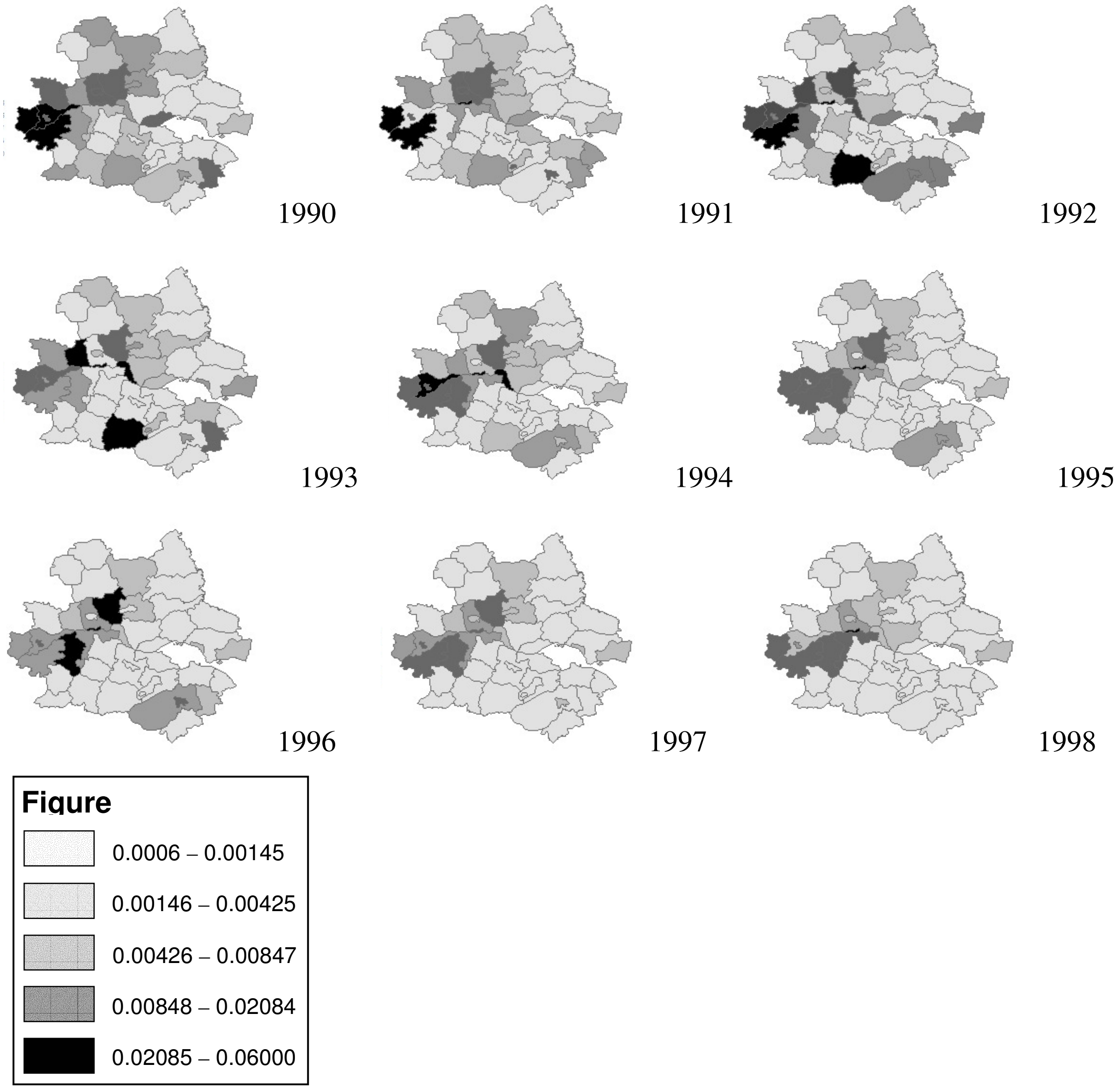

Fig 2. Smoothed maps of prevalence of *Schistosoma japonicum* infection in Jiangsu province, China, from 1990

Fig. 3 shows the maps of the residual spatial variation after adjusting for the effects of the climatic covariates for the study period of 1990-1998. It is apparent that in 1990, the counties with higher than average risk of *S. japonicum* are situated in the north-western part of the Jiangsu province. Since this pattern is less pronounced in Fig. 2, our modeling approach suggests that the climatic factors had a higher influence on that part of the province at the beginning of the study.

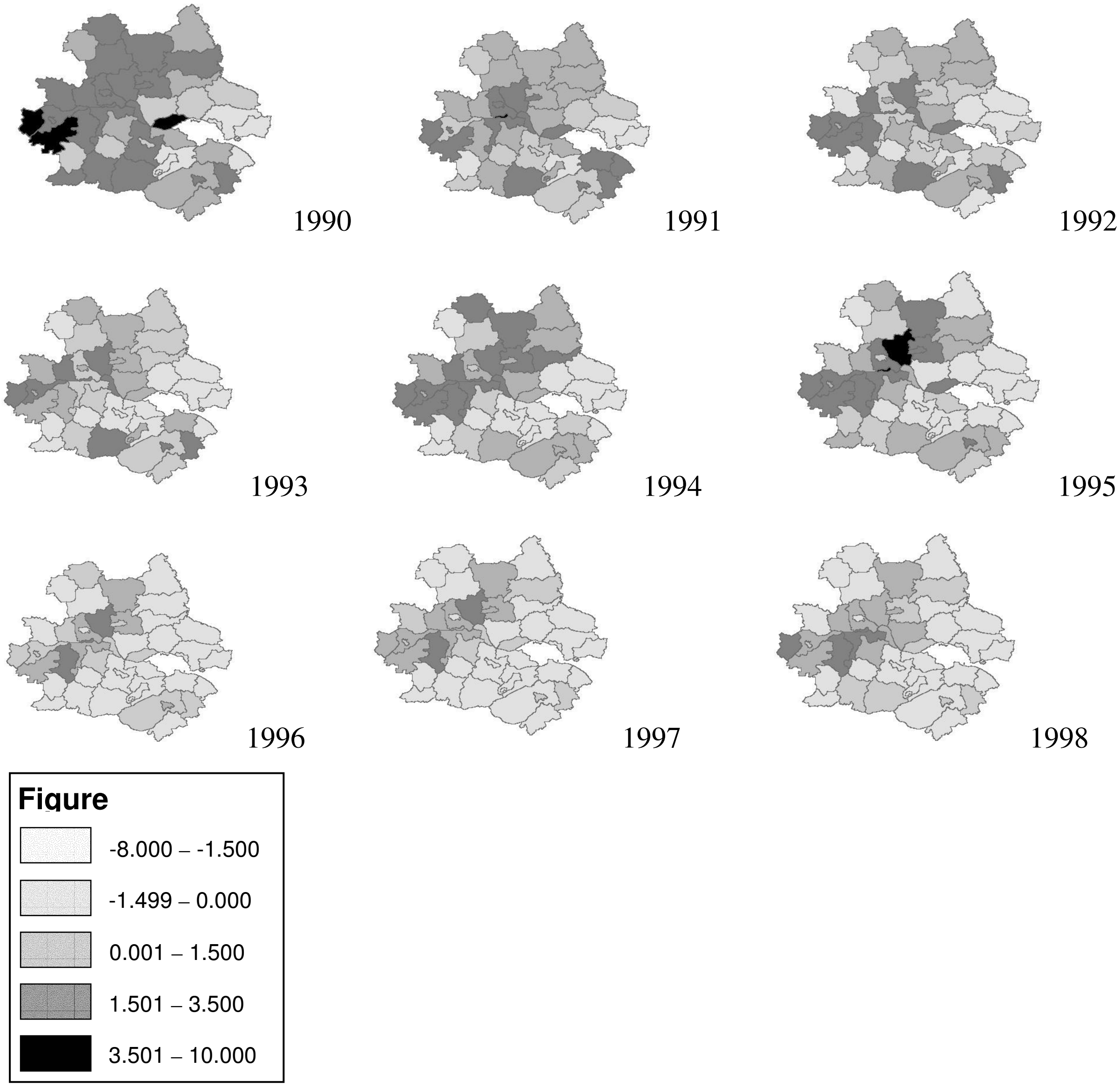

Fig 3. Maps of the residual spatial variation after adjusting for the effects of the climatic covariates in Jiangsu province, China, from 1990 to 1998

4.5 Discussion

Advances in GIS, RS and statistical methodology have opened new avenues to enhance our current understanding of spatio-temporal distribution of parasitic diseases (Hay, 2000; Malone et al., 2001; Zhou et al., 2001; Brooker et al., 2002). GIS and RS are convenient means for the creation of comprehensive geographical databases, and the display of the relevant data for policy discussion, guiding interventions and cost-effective monitoring at a range of spatial scales (Tatem & Hay 2004). Sound statistical methods are mandatory to examine the underlying determinants of the observed patterns in the light of sampling variation and spatio-temporal correlations. Developments in Bayesian-based approaches and MCMC inference have greatly advanced spatio-temporal modeling (Gelfand and Smith, 1990). These methods have been successfully applied for parasitological diagnosis where there is a lack of a gold standard (Hubbard et al., 2002; Utzinger et al., 2002; Basáñez et al., 2004) and disease mapping (Cancré et al., 2000; Vounatsou et al., 2000; Assunção et al., 2001; Basáñez et al., 2004).

Schistosomiasis is a water-borne disease and its transmission is strongly correlated with environmental factors. We considered two of the most important factors, namely temperature and wetness, which characterize the overall climatic suitability for schistosomiasis transmission (Mao, 1990; Hay, 2000; Malone et al., 2001; Brooker et al., 2002). RS and GIS techniques were applied to extract the climatic factors (i.e. NDVI, LST) from satellite images (NOAA-AVHRR). NDVI maps indicate how much vegetation is present at each location with higher values representing more intensive vegetation coverage. Values range between -1 and +1, where the negative values correspond to water bodies. LST is one of the key parameters in the physics of land surface processes, combining surface-to-atmosphere interactions and the energy fluxes between the atmosphere and the ground. With a view to the biology and transmission dynamics of *S. japonicum* at the macro-scale, survival of intermediate host snails is compromised by decreasing temperatures. On the other hand, the availability of suitable water bodies is conducive for enhanced snail dispersal, which in turn can increase transmission intensity, as well as enlarge potential transmission areas. Therefore, LST is an important aggregate measure to predict both transmission areas and the intensity of transmission there, while NDVI is a key factor to predict the level of transmission. The spatial resolution of the satellite images applied here was 8 km. In view of the inherent problem of scale in ecological studies (Levin, 1992), it is not practicable to predict the distribution of schistosomiasis at finer detail than at the county level. This is justified on three grounds. First, surface areas of the counties studied ranged between 900 km^2 and 3000 km^2. Based on our spatial resolution, we were able to estimate climatic variables exacted from the satellite images with a pixel size of 64 km^2. Second, we employed the median for NDVI and LST estimates instead of the mean, because many water bodies in our study area revealed extreme values, which would have biased the results. Third, the information extracted from the satellite images was more accurate than the data provided by meteorological stations in terms of spatial resolution. Consequently, application of GIS and RS, by using NDVI and LST, is a viable approach for the assessment and prediction of *S. japonicum* infection prevalence at the county level. However, it is important to note that derived median estimates for the RS variables have some errors built around them, which in turn can bias coefficients in the logistic regressions carried out.

For the Jiangsu province in China, we found a significant positive association between LST and the risk of *S. japonicum*. A plausible biological explanation of this result arises from the parasite's life cycle. It consists of the stages of the egg, miracidium, sporocyst, cercaria, schistosomulum and the adult worm pair. Previous work has shown that the development of the parasite residing in the intermediate host snail is closely related to the environmental temperature. The higher the temperature, the more rapidly miracidia develop into cercariae, if thermal limits are not exceeded (Pesigan et al., 1958; Nagasaki, 1960). It follows that in areas with higher temperature, the parasite can complete its life cycle more promptly, and hence more cercariae are released into freshwater environments. As a result, the disease transmission intensity is enhanced, since cercariae are the infective stage for both humans and mammalian reservoir hosts.

The NDVI showed a statistically significant negative association with the infection prevalence of *S. japonicum*. This result means that areas with lower NDVI have higher chances for dispersal of intermediate host snails, thus transmission intensity is increased and/or potential transmission areas are expanded. One possible explanation is that the intermediate host snail (i.e. *Oncomelania hupensis*) is amphibious. Areas where snail habitats are adjacent to water bodies are likely to be at an elevated risk of transmission, since low NDVI values indicate more water content. Hence, NDVI might be a good proxy for proximity to water bodies, which is a key factor in the transmission of *S. japonicum*. Another possible explanation is that areas with more dense vegetation tend to have lower LST and, as we argued above, lower temperatures were associated with a reduced risk of transmission.

The results of the spatio-temporal analysis showed a decrease in the spatial autocorrelation during 1990-1992, reaching the lowest value for the whole study period in

1992. The smoothed *S. japonicum* prevalence map indicates that the endemic situation in 1992 was worse than in the previous year, which probably can be explained by a major flooding event of the Yangtze River in 1991. Recent work has shown that enlarged snail-infested areas and increased risk of human-water contact are consequential to flooding events in the preceding year (Zhou et al., 2002). From 1993 onwards, *S. japonicum* endemicity in the whole province became more stable, as indicated by the higher spatial correlation. The most likely explanation arises from reviewing the recent history of schistosomiasis control in China. With the overarching goal of eliminating schistosomiasis as a public health problem, a multi-year control programme was launched in 1992, financed through the World Bank and the Chinese government (Yuan et al., 2000). The programme was highly effective in reducing the public health significance of *S. japonicum* in China. However, control efforts in the schistosome-endemic counties of the Jiangsu province along the Yangtze River proved particularly challenging. It is therefore not surprising that current estimates suggest that 95.7% of the snail-ridden areas and 85.6% of the *S. japonicum*-infected people are concentrated in the marshland and lake regions of the country (Yuan et al., 2002).

In view of ongoing ecological transformations as a result of major water resource developments (i.e. Three Gorge dam), it is conceivable that the marshland and lake regions will remain the “hot spots” of *S. japonicum* transmission in China in the years to come. These activities can be further exacerbated by economic developments that are often paralleled by domestic migration of both people and cattle/water buffaloes that also serve as reservoir hosts of *S. japonicum* (Xu et al., 1999; Zheng et al., 2002). Meanwhile, another large-scale water resource development, namely the South-North water transfer project (http://www1.people.com.cn/GB/shizheng/252/2283/), and also global warming, are likely to further extend the schistosome-endemic area further northwards. Hence, concerted efforts should be made to monitor and evaluate the effects of these ecological transformations on the frequency and transmission dynamics of schistosomiasis japonica. Bayesian-based spatial statistical approaches hold promise for monitoring and evaluation purposes. Further studies are warranted to assess and quantify climatic and ecological factors other than LST and NDVI, as well as socioeconomic risk factors. Outcomes of such studies will be of relevance for more efficient and cost-effective resource allocation for control of schistosomiasis japonica in Jiangsu province and elsewhere in China, so that the public health and economic significance can be conquered.

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4.8 Appendix

Let Y_{it} and N_{it} denote the observed counts of schistosomiasis cases and survey population, respectively in county i and year t, and let P_{it} denote the prevalence of *S. japonicum* for the i-th county in the t-th year. We assumed that the Y_{it}'s are conditionally independent given, the

N_{it} , P_{it} following a binominal distribution, i.e., Y_{it} ~Bin (N_{it} , P_{it}) and introduced the covariate effects as well as the spatial and temporal random effects on the logit transformation of P_{it} that is:

$$\log it(P_{it}) = \alpha_0 + \alpha_1 * NDVI + \alpha_2 * LST \qquad \text{(Model 1)}$$

$$\log it(P_{it}) = \alpha_0 + \alpha_1 * NDVI + \alpha_2 * LST + \varphi_i + \omega_t \qquad \text{(Model 2)}$$

where α_0 represents the mean prevalence over all counties and time periods, α_1 and α_2 are the coefficient of environmental factors NDVI and LST, respectively, φ_i is a random term that allows for spatially structured variation in the *S. japonicum* prevalence data and ω_t is a random term representing between-year variation. We introduce spatial dependence in the φ_i's by assuming a conditional autoregressive model CAR (γ), which implies that each φ_i is conditional on the neighbour φ_j follows a normal distribution with mean equal to the average of the neighbouring φ_j and variance equal to σ_1^2 scaled according to the number of the neighbours n_i of county *i*, that is $\varphi_i \mid \varphi_j, j$ neighbour of *i*~ $N\left(\frac{1}{n_i}\gamma\sum_{j=1}\varphi_j, \sigma_1^2 / n_i\right)$ where γ quantifies the amount of spatial dependence. We introduce the temporal dependence by assuming that ω_t's following an autoregressive process with variance σ_2^2 where temporal correlation ρ exists only with the preceding year.

A separate model was fitted assuming that spatial correlations evolve over time, that is:

$$\log it(P_{it}) = \alpha_0 + \alpha_1 * NDVI + \alpha_2 * LST + \varphi_{it} \qquad \text{(Model 3)}$$

This model 3 allows a different set of random spatial effects φ_{it} for each year *t* following a conditional autoregressive model $\varphi_{it} \sim \mathrm{CAR}(\gamma_t)$ with spatial correlation parameter γ_t .

We fitted the above models using Bayesian statistical methods. According to the Bayesian approach we need to specify prior distributions for all model parameters. We adopted non-informative Uniform prior distributions for the covariate coefficients, i.e., vague inverse gamma priors for the variances δ^2 and δi^2, *i*=1,…,9 and vague normal priors for all other parameters.

5: Effect of temperature on development of *Schistosoma japonicum* within *Oncomelania hupensis* and hibernation of *O. hupensis*

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5.1 Abstract

The objectives of this investigation were (1) to assess the effect of temperature on *Schistosoma japonicum* larvae harboured in *Oncomelania hupensis*, and (2) to determine the lowest temperature threshold of which hibernation of *O. hupensis* occurs. In the first experiment, adult infection-free *O. hupensis*, collected from Jiangsu province, China, were infected with *S. japonicum* and raised at different temperatures under laboratory condition. Development of *S. japonicum* larvae was monitored, employing the cercarial shedding method. In the second experiment, batches of *O. hupensis* were kept at temperatures below 13°C with temperature gradually reduced, and snail activity was assessed by a pin puncture method. We found a positive relationship between the development of *S. japonicum* larvae and temperature. In snails kept at 15.3°C, *S. japonicum* larvae arrested their development, while the fastest development occurred at 30°C. The temperature at which half of the snails were in hibernation (ET50) was 6.4°C. Our results underscore the pivotal role temperature plays on the biological activity of *O. hupensis*, as well as the development of *S. japonicum* larvae within the intermediate host. These findings are likely to have implications for schistosomiasis transmission in a warmer future China.

Key words: Developing speed, hibernation, *Schistosoma japonicum*, *Oncomelania hupensis*, temperature.

5.2 Introduction

Schistosomiasis is a snail-borne parasitic disease, which affects an estimated 207 million people in tropical and subtropical environments (Steinmann et al. 2006). In China, schistosomiasis has a documented history of over 2 millennia (Zhou et al. 2005). In the mid-1950s the disease was endemic in 12 provinces located along the Yangtze River and south of it, with more than 10 million people infected with the causative agent, i.e. *Schistosoma japonicum*. Historically, the geographic distribution of the disease was restricted south to the 33°15’ N latitude, governed by the distribution of its intermediate host snail, i.e. *Oncomelania hupensis* (Mao 1990; Utzinger et al. 2005; Zhou et al. 2005). Control measures implemented and sustained over the past 50 years have brought down the initial levels of human infection by more than 90%, and the disease has been eliminated in 5 provinces (Utzinger et al. 2005; Zhou et al. 2005).

The life cycle of *S. japonicum* consists of a sexual generation in the vascular system of the definitive host and an asexual generation in *O. hupensis*. The stages of schistosomulum and adult worm are confined to the warm-blooded definitive hosts, i.e. humans and over 40 species of domestic and wild animals, particularly bovines, cattle and goats (Wang et al. 2005). The other stages, i.e. egg, miracidium, sporocyst and cercaria, are developing in the external environment or in the cold-blooded intermediate host snail. Therefore, the geographic distribution of *S. japonicum* is closely related to environmental factors (Mao 1990; Ross et al. 2001; Yang et al. 2005a). Previous research has shown that the development of schistosome larvae within the intermediate host snail is tightly connected with environmental temperature (Shao and Xu 1956; Pesigan et al. 1958; Nagasaki 1960). The optimal temperature for *O. hupensis* ranges between 20 and 30°C. Temperatures below or above this range result in delayed or arrested development and reproduction of *O. hupensis* (Mao 1990; Liu 1993). Lower environmental temperatures can greatly reduce the physiological functions of *O. hupensis* (Mao 1990). Field studies found that *O. hupensis* can withdraw deeply into their shell without biological activities, such as feeding or moving. It has also been documented that hibernation occurs in *O. hupensis* when temperature drops below a critical threshold (Mao 1990). However, simple measures to determine whether or not snails are in a state of hibernation remain to be developed. We have recently documented that China's average temperature in January has increased by almost 1 ºC over the past 30 years (Yang et al. 2005b). The plausibility of this finding is supported by global warming, which is particularly pronounced in the northern hemisphere and during winter months (Murphy et al. 2004). The significance of this finding for the distribution of *O. hupensis*, and hence the level and extent of schistosomiasis transmission in China, has been stressed (Yang et al. 2005b).

In the present study, we carried out a series of laboratory investigations (1) to study the effect of temperature on the development of *S. japonicum* larvae in their intermediate host snail, and (2) to investigate the temperature at which *O. hupensis* shows hibernation, hence to determine the lowest thermal limit for both parasite and snail. This work is part of a larger investigation of the potential impact of climate change on the spatio-temporal distribution of *S. japonicum* in a future and warmer China.

5.3 Materials and methods

5.3.1 Effect of temperature on development of *S. japonicum* larvae within *O. hupensis*

Adult *O. hupensis* (age: approximately 6 months; presence of 7-8 whorls) were collected in November 2001 along the beaches of Xinba, Jiangsu province (geographical coordinates: 119º32' E longitude, 32º17' N latitude). The proportion of male to female *O. hupensis* was about 1:1. Snails were transferred to the laboratory and raised for 4 weeks at a temperature of 25°C. Each snail was tested twice for natural infection using the cercarial shedding method (MOH 1982). Since none of the snail had a natural infection, all were used for subsequent investigations.

One rabbit was infected with 2000 *S. japonicum* cercariae (Wuxi isolate) through the shaved abdominal skin. Forty-five days post-infection, the rabbit was sacrificed. The liver was removed, ground and screened through a wire (mesh size: 50 µm) to collect eggs of *S. japonicum*. Eggs were stored in de-chlorinated water at a temperature of 25°C and exposed to artificial light for miracidium hatching.

Approximately 15,000 freshly hatched miracidia were placed in a container with 200 ml of de-chlorinated water. Next, 750 snails were added, hence resulting in a snail to miracidium ratio of approximately 1:20. The container was covered with a fine-meshed gauze to prevent snails from escaping out of water. Snails were exposed for 4 h at 25°C under illuminated conditions. Snails were then removed and placed into 20 × 30 cm trays and kept on culture paper made of dried grass and bamboo materials, which served as food and for maintaining a certain moisture level (Jiang et al. 1997). De-chlorinated water was added daily to the culture trays to keep the moisture at a relative humidity of 85%. Snails were divided into 5 equally-sized groups (n = 150) and raised at different temperatures, i.e. 18, 21, 24, 27 and 30°C, in culture boxes at environmentally-controlled condition (accuracy of temperature: ± 1°C). The culture boxes were checked daily and dead snails were removed with forceps and counted. Culture paper was changed weekly to provide sufficient food and moisture for snails throughout the study (Jiang et al. 1997).

Since the development of schistosome larvae within intermediate host snails is closely related to environmental temperature, the first time point of checking snails for cercarial shedding in groups kept either at 30, 27, 24, 21 or 18°C was carried out at days 30, 40, 50, 60 and 70 post-infection, respectively. The number of snails that shed cercariae was counted and recorded. Those snails shedding cercariae were removed and the other snails were again tested for cercarial shedding 5 days later. This procedure was repeated at 5-day intervals until no cercariae were released for 3 successive sheddings. The remaining snails that survived until the end of the experiment, but failed to shed cercariae were dissected to check for the presence of sporocyst and cercariae, and hence whether they were indeed infection-free. The shortest, longest and average time from infection to cercarial shedding was noted for the different groups.

5.3.2 Effect of temperature on hibernation of *O. hupensis*

Active adult *O. hupensis* (age: approximately 6 months; presence of 7-8 whorls) were selected as candidate snails (Mao 1990). In total, 780 snails were divided into 26 groups of 30 snails each and placed in Petri dishes (diameter: 9 cm). Snails were kept at 13°C on culture paper made of dried grass and bamboo and de-chlorinated water was added daily as described before. Hibernation was investigated by gradually reducing the temperature. For snails belonging to groups 1-13, the temperature was reduced from 13 to 1°C at a rate of 1°C per day, while the temperature in the remaining groups was reduced at a rate of 1°C every other day.

Snail activity and hibernation status were observed as follows. Snails with a closed operculum and/or lack of movement were pinched by a pin either on the operculum or on the food-head. Snails which showed no reaction when pinched were placed in de-chlorinated water at a temperature of 13°C for several hours. Snails were tested again and in case normal activity was observed (i.e. response following pinching), they were considered in hibernation state before. The temperature at which hibernation occurred was recorded. Snails in the control group were raised at a constant temperature of 13°C. All experiments were repeated 2 or 3 times.

5.3.3 Statistical analyses

All data were entered in Excel (Microsoft Corporation; Redmond, WA, USA) and statistical analyses were performed by using version 8.0 of the STATA software package (Stata Corporation; College Station, TX, USA).

The shortest, longest and average incubation period of *S. japonicum* in different temperature groups were summarized by the arithmetic mean and standard deviation (SD). The development of schistosome larvae is the reverse of the incubation period, i.e. $V_P = 1/N$, where V_P is developing speed and N is the incubation period of larvae (Zou 1983). The Wilcoxon rank-sum test was used to compare the difference between hibernation of *O. hupensis* in groups 1-13 versus groups 14-26. The Kruskal-Wallis test was also applied to compare the incubation period between the different temperature groups.

Linear regression was used to investigate the effect of temperature on the development of schistosome larvae within *O. hupensis*. A logarithmic transformation was applied on V_P to transform to normality. In case V_P equals to 0, the logarithmic transformation $V_P + 1$ was used (i.e. $Ln(V_P + 1)$). A logistic regression was carried out to assess the relationship between the probability of snail hibernation and temperature (T).

5.4 Results

5.4.1 Effect of temperature on development of *S. japonicum* larvae within *O. hupensis*

Overall, 710 snails were screened by using the cercarial shedding method. Over the course of the experiment, 171 snails (24.1%) released cercariae. As shown in Table 1, the first test by shedding occurred at days 30 to 70 post-infection, according to the temperature at which snails were kept. The last test by shedding occurred between days 115 and 210, again depending on the temperature. Snails that were still alive at the end of the experiment, which failed to shed cercariae were dissected and they were found to be infection-free. All of the snails kept at 18°C had died by day 210 and none of them shed cercariae. Snails in the control group, kept at 24°C, were dead by day 195.

Table 1. *S. japonicum* cercarial shedding in *O. hupensis* and incubation period of *S. japonicum* larvae harboured in *O. hupensis* kept at different temperatures

Temperature (°C)	Initial no. of snails	First test by shedding		Final test by shedding		No. of snails shedding cercariae	Parasite incubation period (days)		
		Day	No. of snails	Day	No. of snails		Minimum	Maximum	Average (SD)
24*	150	50	147	195	0	-	-	-	-
18	150	70	138	210	0	0	-	-	-
21	150	60	135	180	20	18	110	165	128.9 (16.1)
24	150	50	145	160	45	34	65	145	95.0 (21.0)
27	150	40	149	115	50	57	50	100	71.9 (12.7)
30	150	30	143	115	45	62	40	100	62.7 (14.2)

* Control group

Table 1 also summarizes the minimum, maximum and average larvae incubation periods. The minimum and maximum incubation periods were 40 and 165 days, respectively. On average, the larvae incubation periods among snails kept at 21, 24, 27 and 30°C were 128.9 (SD = 16.1) days, 95.0 (SD = 21.0) days, 71.9 (SD = 12.7) days and 62.7 (SD = 14.2) days, respectively. The effect of temperature was highly statistically significant (Kruskal-Wallis test, chi-squared = 22.7, degrees of freedom = 3, $p < 0.001$)

5.4.2 Minimum thermal limit for *S. japonicum* larvae development in *O. hupensis*

The developing speed of schistosome larvae in snails kept at 21, 24, 27 and 30°C was 0.008, 0.011, 0.014 and 0.016 per day, respectively. The relationship between V_P and temperature is described by the following regression: $Ln(V_p + 1) = 0.025 Ln(T) - 0.067$ ($r^2 = 0.53$; F-test = 187.52; $p < 0.001$). The minimum thermal limit derived from the above regression is 15.3°C at which development of *S. japonicum* larvae is arrested (Figure 1).

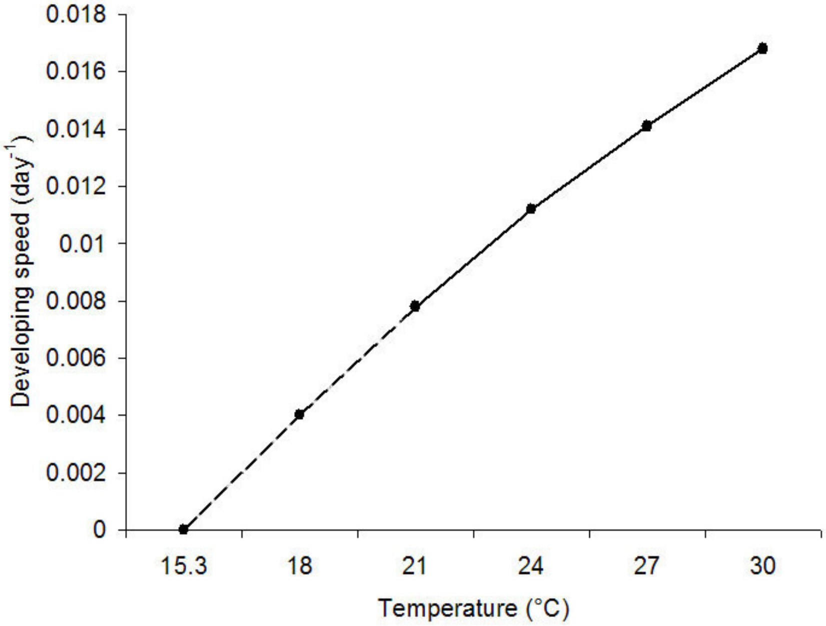

Figure 1 Relationship between temperature and *S. japonicum* larvae development within *O. hupensis*

5.4.3 Effect of temperature on hibernation of *O. hupensis*

Employing the Wilcoxon rank-sum test, no statistically significant difference was observed for the temperature at which *O. hupensis* hibernated, as assessed by 2 different temperature decline rates ($z = -0.128$, $p > |z| = 0.90$).

At temperatures below 13°C, the lower the temperature, the less active the snail were, and the higher the number of snails with closed operculum. The snails began to hibernate at a temperature of 11°C. The proportion of snails which hibernated at 6, 3 and 1°C were 56.7%, 91.7% and 100%, respectively. The logistic regression between the hibernation probability (H) and temperature is given by the following equation: $\log it(H) = 3.93 - 0.61 \times T$. The temperature at which half of the snails were hibernating (ET_{50}) was 6.4°C (Figure 2).

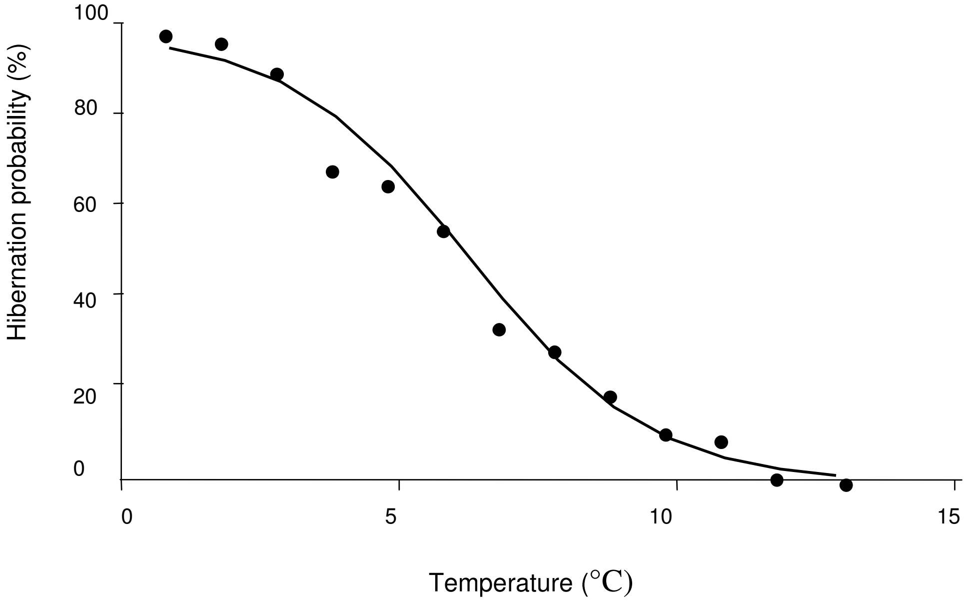

Figure 2 Relationship between temperature and the hibernation probability of *O. hupensis*

5.5 Discussion

Based on the report of the Intergovernmental Panel on Climate Change (IPCC 2001), the Earth's surface temperature is likely to increase, on average, by 1.4 to 5.8°C over the period 1990 to 2100. This increase is about 2 to 10-fold higher than the average temperature increase already observed during the 20th century. Climate change shows strong spatial and temporal heterogeneity. For instance, warming at high latitudes of the northern hemisphere is more significant than elsewhere (Murphy et al. 2004; Stocker 2004), and changes of average maximum and minimum temperatures in winter months are more pronounced than in the summer (Easterling et al. 2000).

The negative effect of climate change is likely to have on human health has been reviewed recently (Beggs 2004; Diza 2004; Haines and Patz 2004; Knowlton et al. 2004;

McMichael et al. 2006). The potential impact of global warming on the frequency and transmission dynamics of vector-borne diseases received particular attention, most notably malaria (Rogers and Randolph 2000; Reiter 2001; Hunter 2003; Sutherst 2004). With regard to schistosomiasis, some studies have addressed the potential impact due to climate change (Mao 1990; Martens et al. 1995; Yang et al. 2005b). It has been agreed that global warming influences transmission of schistosomiasis in 2 ways. First, it is thought that global warming will enhance transmission intensity and, second, it is likely to expand transmission areas (Zhou et al. 2002a). In our recent work, using geographic information system and remote sensing technologies, coupled with spatial statistics, we have shown that the 0-1°C January isotherm, the crucial temperature for *O. hupensis* survival, has shifted approximately 26' northward, which corresponds to 40 km. As a consequence, a new potential area of about 41,000 km^2 has been created where transmission of *S. japonicum* could theoretically occur (Zhou et al. 2002b; Yang et al. 2005b). In order to further our understanding of the regional effects of global warming on the transmission of *S. japonicum* in China, temperature thresholds for both the larval stages of the parasite and its intermediate host snail must be taken into account.

The development of cold-blooded animals is positively related with temperature. Development will arrest when temperature drops below a critical threshold, which is considered the lowest developing temperature or "biological zero" (Yiteng 1986). The development of schistosome larvae within the intermediate host snail follows this rule. The temperature at which snails hibernate is considered the lowest developing temperature, since the metabolic rate of the snail will drop dramatically to "biological zero" when it reaches the stage of hibernation (Storey and Storey 1990).

Our results confirm earlier findings; within a certain temperature range, the higher the temperature the shorter the incubation period of *S. japonicum* larvae in *O. hupensis*. We found a temperature of 15.3°C as the theoretical lowest developing temperature for *S. japonicum* larvae within *O. hupensis* under laboratory conditions. This temperature is considerably higher than that documented previously, i.e. 10°C (MOH 1980). The difference may be explained by the previous study examining each developing stage of larvae rather than observing the whole development process of larvae until cercariae are shed into the environment. The latter approach seems more meaningful when studying the transmission of schistosomiasis.

Previous studies have investigated parasite-intermediate host snail interaction with an experimental focus on *S. mansoni* and *S. haematobium*. It was found that the lowest developing temperature was higher than the theoretical minimum temperature threshold. For instance, the theoretical minimum temperature threshold of *S. mansoni* larvae harboured in *Biomphalaria pfeifferi* and *S. haematobium* in *Bulinus truncatus* are 14.2 and 15.3°C, respectively. However, no cercariae were shed when snails were kept at a temperature below 16°C in the case of *S. mansoni* and 17°C in the case of *S. haematobium*. In our study, *O. hupensis* failed to shed cercariae when snails were kept at 18°C, which is almost 3°C higher than the observed theoretical lowest developing temperature. Our findings thus confirm previous observations made with other human schistosomes species. Another possible explanation is that the theoretical incubation period of *S. japonicum* larvae within *O. hupensis,* which was calculated to be 256.9 days at a temperature of 18°C, is considerably longer than our observing period of 210 days.

Not only low, but also high temperature influence the development of schistosome larvae in the intermediate host snail. Previous investigations have shown that intermediate host snails failed to shed *S. mansoni* and *S. haematobium* when they were kept at temperatures above 35 and 33°C, respectively (Pflüger 1980; Pflüger et al. 1983). It remains to be investigated at what maximum temperature the development of *S. japonicum* larvae will cease.

Metabolic rate depression is a common adaptive strategy of hibernation (Storey and Storey 1990). We found that a simple pin pinch method applied to *O. hupensis* kept at cold temperatures, followed by transfer of snails into warmer water, is a simple method to test whether snails are in a state of hibernation.

The acquired information on the lowest developing temperature for *S. japonicum* larvae within *O. hupensis*, and the intermediate host snail itself, can be used to estimate the growing degree-days. In turn, this information will facilitate assessment of the impact of temperature on the development of both larvae and intermediate host snail and to better understand their interaction (Malone and Zukowski 1992; Zhou et al. 1999).

S. japonicum found on the Chinese mainland comprises a strain complex consisting of different sub-strains, which differ in their geographic distribution (He 1993). Distinct genetic diversity is also detected between different sub-species of *O. hupensis* (Davis et al. 1995; Davis et al. 1999). Whether the lowest developing temperature varies between different parasite strains and between different regions is among our current research emphases. Taken together, this line of investigation will enhance our understanding and prediction capabilities with regard to the level and extent of schistosomiasis transmission in a warmer future China.

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6: A growing degree-days based time-series analysis for prediction of *Schistosoma japonicum* transmission in Jiangsu province, China

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6.1 Abstract

It has been suggested that global warming may alter the frequency and transmission dynamics of vector-borne diseases. To test this claim for schistosomiasis, we conducted a time-series analysis from 1972--2002 for 39 of the 70 counties of Jiangsu province, eastern China, where Schistosoma japonicum is partially endemic. We used a modeling approach to estimate the annual growing degree-days (AGDD), employing a lower temperature threshold of 15.3°C. Our final model included both temporal and spatial components, the former consisting of second order polynomials in time plus a seasonality component, while the spatial trend was formed by second order polynomials of the coordinates plus the thin plate smoothing splines. We found that temperature increased over the past 30 years in all observing stations. There were distinct temporal trends with seasonality and periodicities of 12, 6 and 3 months, while only marginal spatial variation was observed. The predicted AGDDs for 2006 and 2003 showed increases for the entire Jiangsu province, with the AGDD difference between these two time points exhibiting an increase from north to south. Our data suggest that changes in temperature will alter the extent and level of schistosomiasis transmission, which is of relevance for the control of *S. japonicum* in a future warmer China.

Key words: Annual growing degree-days, time-series analysis, *Schistosoma japonicum*, global warming.

6.2 Introduction

Temperature is a key feature for the timing of biological processes, and hence the growth and development of living biota. The amount of heat energy an organism accumulates is often expressed as a unit termed "growing degree-day" (GDD).[1--4] GDD can be articulated as *Tavg* – *Tbase*, where *Tavg* is the average daily temperature, and *Tbase* is the base temperature or developing threshold of an organism.[5,6] This threshold is often considered as the lowest temperature below which growth and development does not occur. Two different interpretations have been reported with regard to how *Tbase* is incorporated into the above GDD equation.[5] The most widely used application, particularly in simulation models, is as follows: if *Tavg* is less than *Tbase*, then *Tavg* is set equal to *Tbase*, and hence GDD becomes 0.[5--8] Some applications also used an upper threshold, since temperatures exceeding a critical value result in slower development of an organism or its development is ceased altogether.[9]

GDD can be summed over an entire year. It is then termed annual GDD; AGDD in short, which is an important aggregate measure that has been found to correlate with the spatial distribution of living organisms.[10--12] The heat units an organism requires to complete its development is fairly constant, given by the temperature above a critical threshold summed over the time period this lower temperature threshold is exceeded. It follows that organisms with high heat unit requirements are more likely to develop into mature stages in areas where AGDD is high.[13]

There is mounting evidence of climate change due to anthropogenic activities, namely increased release of greenhouse gases into the atmosphere.[14--18] The predicted warming will result in increased AGDD, and hence alter biological processes and physical systems, including human health.[17] Although the relation between climate change and human health is a complex one, it has been estimated that > 150,000 deaths per year are attributable to global warming and changes in precipitation that occurred over the past 30 years.[19,20] Several studies have been carried out to predict phenological changes under the scenario of warmer ambient temperatures, including the use of GDD.[10] For example, Malone and colleagues[21] employed a modified forecast system based on GDD and the local Thornthwaite water budget to predict the risk of fascioliasis transmission in East Africa. The *Tbase* used in the forecast system was 10°C for *Fasciola hepatica* and 16°C for *F. gigantica*. In another application, a GDD-water budget analysis was combined with satellite climatology to assess the thermal-hydrological preferences and limits of tolerance of different parasite-vector systems, and hence to delineate the environmental foci of disease agents.[22,23]

With regard to schistosomiasis, only few attempts have been made thus far to predict changes in the frequency and transmission dynamics due to global warming.[24--27] The two studies by Martens and colleagues[25,26] came to different conclusions regarding the extent of schistosomiasis transmission under the scenario of a warmer climate. Among other reasons the lack of long-term, high quality datasets may explain the reported discrepancy.

Focusing on distinct eco-epidemiological settings in eastern China, with a sound knowledge-base on intermediate host snail biology, and an existing temperature dataset, we performed a time-series analysis spanning a 31-year period commencing in 1972, to develop a regional climate model. The established model was then used to predict the monthly temperatures between 2003 and 2006 at a spatial resolution of 0.01 degrees longitude and latitude. Employing a previously determined lower temperature threshold for *Schistosoma japonicum* larva development in the intermediate host snail, the predicted temperatures were then transformed to a measure of AGDD, in order to forecast the transmission of schistosomiasis japonica. This study forms part of a comprehensive investigation of the effects of climate change on the frequency and transmission dynamics of schistosomiasis in China.[28]

6.3 Materials and methods

Study area. We focus on Jiangsu province, located in eastern China. This is one of the seven provinces in China where *S. japonicum* remains endemic.[29,30] Transmission of the disease is restricted to the southern parts of the province, which has been explained by temperature suitability for the intermediate host snail, i.e., *Oncomelania hupensis*.[31,32]

Temperature data. Temperature data, covering the period from 1972 to 2002, were purchased from Wuxi Meteorological Center (Wuxi, China) for 39 of the 70 counties (56%) of Jiangsu province. Monthly mean temperatures were derived by averaging the continuous temperature data. Since the exact positions of the observing stations were not available, we assumed that the data were obtained at the centroids of the respective counties. The coordinates (latitude and longitude) of the counties' centroids were extracted in ArcGIS8.2 software (ESRI; Redlands, CA, USA). As shown in Figure 1, the selected counties are evenly distributed across Jiangsu province.

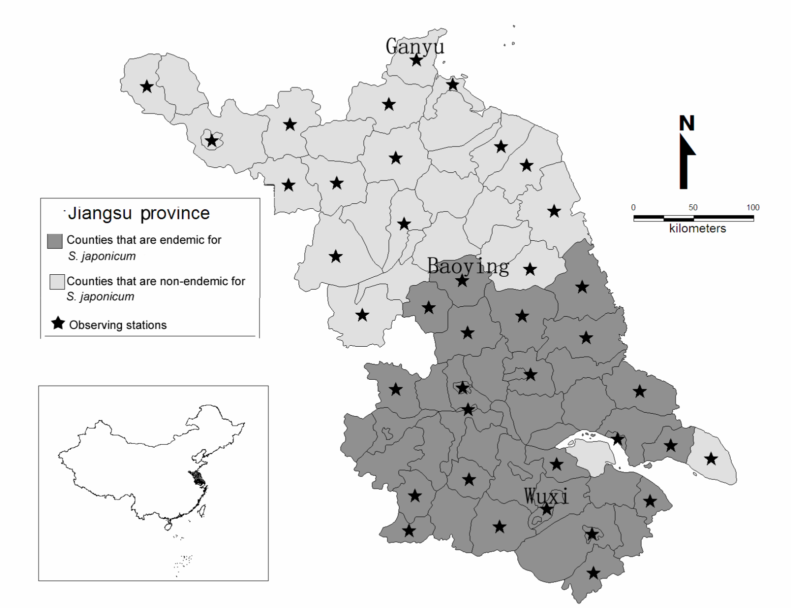


Figure 1. Map of Jiangsu province located in eastern China along the Pacific coast. Counties shaded in dark represent *Schistosoma japonicum*-endemic areas. The centroids of the 39 counties from which temperature data were available are indicated with asterisks.

Statistical analysis. Data management and statistical analysis were carried out in SAS software (SAS Institute Inc.; Cary, NC, USA). Spatio-temporal models were fitted to the monthly mean temperature data assuming a normal error distribution. Different models were fitted describing the spatial and temporal effects by temporal harmonic curves, month effects, temporal and spatial polynomial trends, north-south differentials, county effects, spatial thin-plate smoothing splines and interactions thereof. Models with spatial and temporal random effects were also fitted. The Akaike's information corrected criterion (AICC)[33] was used to identify the best fitting model, as determined by the smallest AICC.

The final model with the best fit captured the temporal trend via second order polynomials and seasonality through harmonic curves. This model also included a spatial trend term, consisting of second order polynomials of the coordinates plus thin-plate smoothing splines.[34] A detailed mathematical description of the model is presented in the Appendix.

For future predictions, the above-mentioned spatio-temporal model was projected on a regular grid of 0.01 degrees resolution between 116 and 122 degrees longitude and between 31 and 35 degrees latitude for the period 1972--2006. This spatial resolution corresponds to approximately 1 x 1 km.

The AGDDs of *S. japonicum* for the years 2003 and 2006 were estimated on the basis of a lower temperature threshold of 15.3°C. This value was established in our preceding laboratory investigations; it represents the lowest temperature at which *S. japonicum* larva develop in *O. hupensis*. Let $AGDD_{it}$ be the value at location i in the year t as follows:

$$AGDD_{it} = 30\sum_{j=1}^{12}(C_{ijt} - 15.3) \times 1(C_{ijt} > 15.3) \qquad (1)$$

where $1(\cdot)$ is the indicator function, giving the value 1 if the condition in the parenthesis is true and 0 otherwise. C_{ijt} is the temperature in °C at location i in month j and year t. The $AGDD_{diff}$ was derived by subtracting the predicted AGDD for the year 2006 with that of 2003.

6.4 Results

Temperature trend analysis for 1972--2002. Figure 2 shows the time-series of monthly mean temperatures between 1972 and 2002 for the 39 counties of Jiangsu province were temperature data were available. The plot depicts a strong temporal pattern, as expected by seasonality. We observed only very small spatial variation using the county as the unit of analysis.

The estimated periodogram for all 39 locations is shown in Figure 3. It confirms the seasonality with periodicities of 12 months (largest peak with frequency 1/12 = 0.08), 6 months (second largest peak with frequency 1/6 = 0.17) and 3 months (local mode in the right part with frequency 1/3 = 0.33).

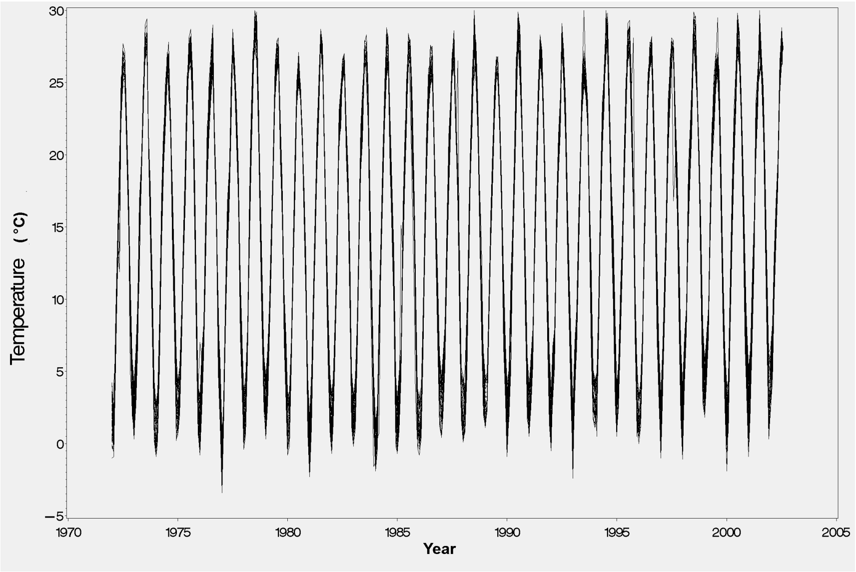


Figure 2. Monthly mean temperatures for the period 1972--2002 for the 39 selected counties in Jiangsu province, China.

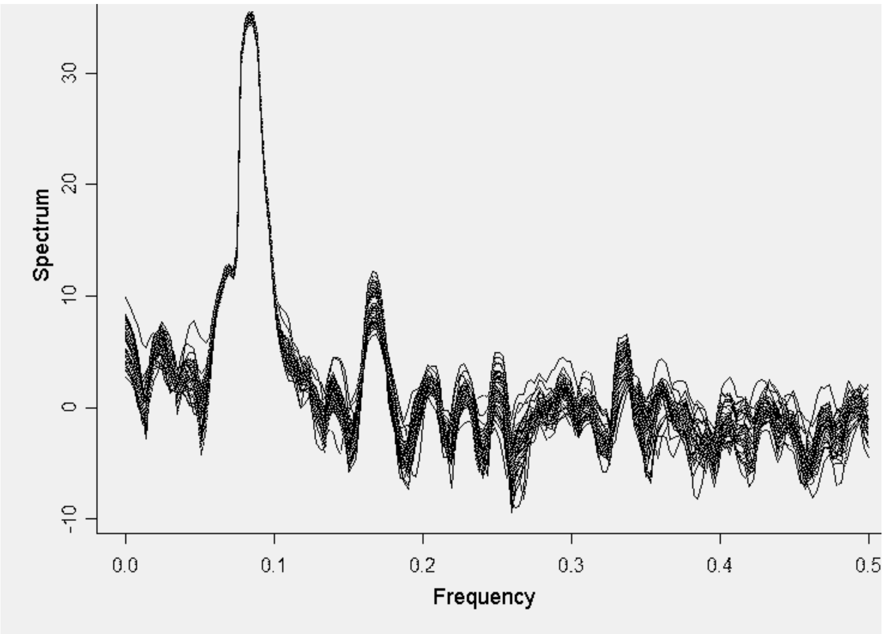


Figure 3. Estimated periodogram (Daniell smoother) of the de-trended time-series of monthly averaged temperatures for the 39 selected counties of Jiangsu province, China.

The best fitting spatio-temporal model according to the AICC consisted of a polynomial spatio-temporal trend, and temporal harmonics of periodicities 3, 4, 6 and 12 months. Parameter estimates of the regression model are shown in Table 1. The time-variable counts the number of months, commencing in January 1972. It shows a small downward trend in its linear component, but is dominated by the strong positive increase in the quadratic part. The sines and cosines fitted are numbered following the frequency orders; i.e. 1/12, 1/6, 1/4 and 1/3. The harmonic curves with higher frequencies were not found statistically significant.

Table 1.Parameter estimates for the monthly averaged temperature data from 1972--2002 for the 39 selected counties in Jiangsu province, China, using a regression model

Parameter	Estimate	95% confidence interval
Intercept	-691.46	-1137.98, -248.30
Longitude	10.62	4.21, 17.10
Latitude	5.46	1.49, 9.47
Longitude * Latitude	-0.051	-0.085, -0.018
$(\text{Longitude})^2$	-0.038	-0.061, -0.015
Time	-0.0026	-0.0033, -0.0019
$(\text{Time})^2$	0.000018	0.000016, 0.000019
Cosine 1	-12.42	-12.44, -12.39
Sine 1	-1.38	-1.40, -1.35
Cosine 2	-0.51	-0.53, -0.48
Sine 2	0.41	0.39, 0.44
Cosine 3	-0.24	-0.26, -0.21
Sine 3	-0.12	-0.14, -0.09
Cosine 4	0.17	0.15, 0.20
Sine 4	0.26	0.23, 0.28
σ^2	1.41	1.38, 1.45

A decrease in the absolute value of parameter estimates for the harmonic curves was found with decreasing periodicity. The least significant curve had a periodicity of 3 months. The parameter estimates for the coordinates indicated a spatial trend in temperatures ranging from south-east to north-west with highest predictions of temperature increases in the south-eastern part of Jiangsu province.

Temperature forecasts and risk prediction of schistosomiasis transmission. The time-series of predicted mean temperatures for 1972--2006 is depicted in Figure 4a. It revealed an increase in the temporal trend, particularly since the early 1990s. The AICC indicated that the variation in mean temperature is largely explained by seasonality, rather than spatial differentials. In the absence of a spatio-temporal interaction, we pooled the data and only present the overall temporal trend, which included the seasonality, as well as a second order polynomial trend.

The standard error of predicted temperatures for three selected cities – Ganyu in north, Baoying in central, and Wuxi in south of Jiangsu province – is depicted in Figure 4b.

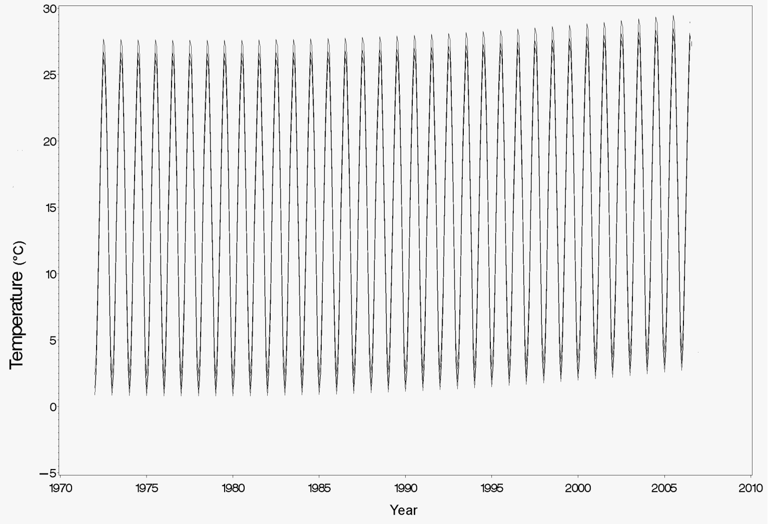


Figure 4(a) Predicted monthly temperature

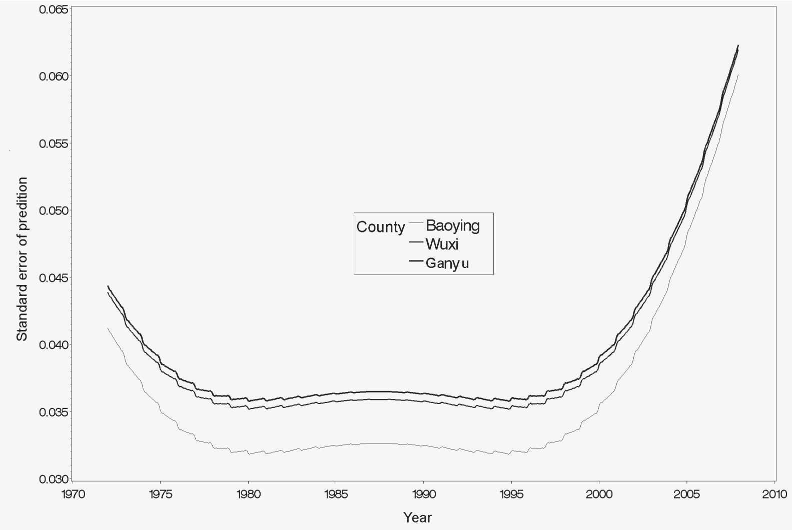
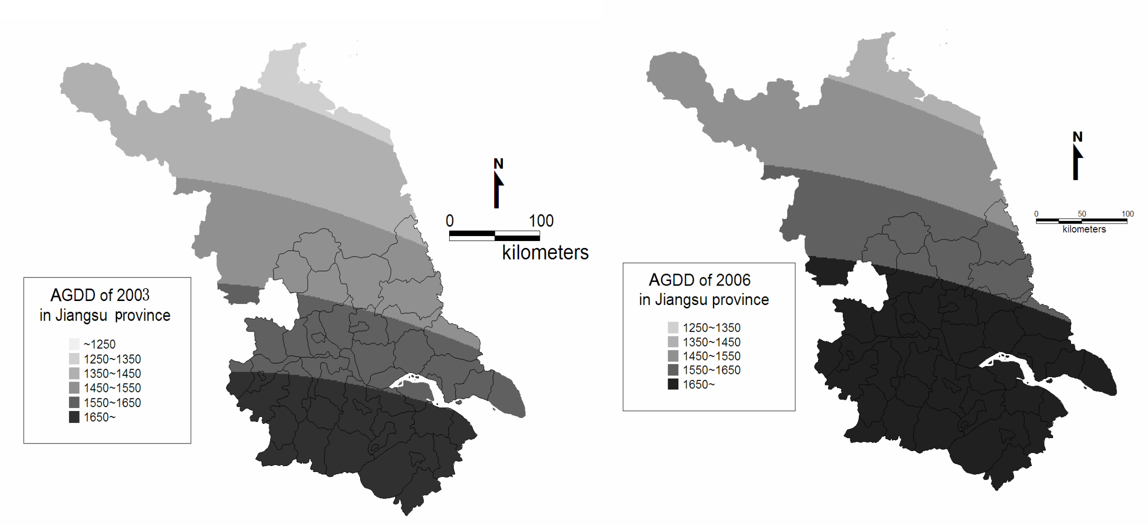


Figure4(b) Standard error of prediction

Figure 4. Predicted mean average temperature for the three cities Ganyu (north), Baoying (central) and Wuxi (south) for the years 1972--2006, based on data for the years 1972--2002.

The $AGDD_{2003}$, $AGDD_{2006}$ and $AGDD_{diff}$ were calculated based on the predicted temperature from the fitted linear regression model, and are presented in Figure 5. The predicted AGDD increased gradually from north to south in both 2003 and 2006. The regions with different AGDD levels in 2006 (Figure 5b) showed a northward shift, which occurred after 2003 (Figure 5a). Figure 5c predicts an increase in the estimated difference in AGDD between 2006 and 2003 for the entire Jiangsu province. The predicted increase in AGDD was particularly pronounced in the southern part of the study area.

5(a) 5(b)



5(c)

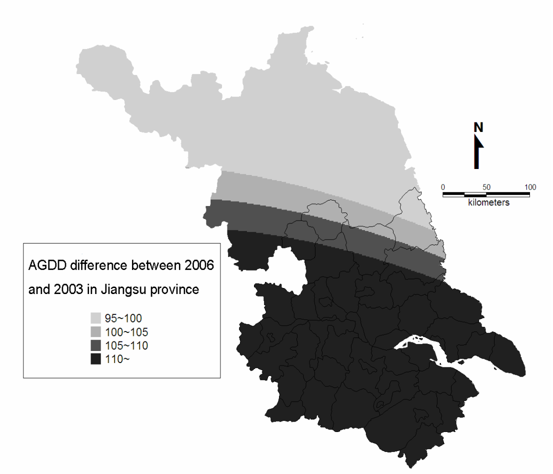


Figure 5 Annual growing degree-days (AGDD) for (a) 2003 and (b)2006, and (c) the AGDD difference ($AGDD_{diff}$) between 2006 and 2003 in Jiangsu province, China

6.5 Discussion

It has been estimated that the increase in temperature and changes in precipitation that occurred at an unprecedented pace over the past 30 years were responsible for the losses of as many as 150,000 lives and five million disability-adjusted life years per annum worldwide.[19] Currently available climate models consistently predict that the global mean temperature will continue to rise – according to different assumptions – by a range of 1.4°C to 5.8°C until 2100 when considering 1990 as the reference benchmark.[16] An important feature of global warming is the strong heterogeneity both in space and time. For example, the temperature increases in continental and high latitude regions are higher than those in coastal and tropical regions. Meanwhile, worldwide winter temperature is predicted to increase more pronouncedly than during the summer.[35,36]

In China, the current trend of warming will also continue in the 21st century, based on plausible extrapolations using different models.[37] We have recently documented that the mean January temperature in China has increased by almost 1°C over the past 30 years.[24] In some parts of northern China increases exceeding 3°C were noted over this period for the month of January. The present study not only confirmed that China's temperature is warming, but further predicted a growing trend in the years to come. Our predictions are based on a time-series analysis utilizing monthly mean temperatures over a 31-year period, collected in an ensemble of 39 observing stations across Jiangsu province. One needs to bear in mind that variability of the prediction becomes larger when extrapolated values are further away from the presence. Therefore, the current study only predicted temperatures until the year 2006, since higher standard error for future prediction renders the prediction less reliable (Figure 4b). In any event, the mean temperature in January 2006 in Baoying county (3.2 °C) was predicted to be 0.4 °C higher than that in January 2003 (2.8 °C).

Our current working hypothesis is that an increase in AGDD will alter the extent and level of schistosomiasis transmission in China. The underlying principle is that the number of parasite generations will increase by speeding up their development in longer growing seasons and extending the current area where parasite larva and intermediate host snail can proliferate.[38,39] As expected, our prediction maps revealed that AGDD in the southern part of Jiangsu province is higher than in the northern part. Thus transmission intensity of *S. japonicum* in south Jiangsu is expected to be higher than in the north of the province. Previous research established a minimum GDD of 842.9 for development of *S. japonicum* larva in the intermediate host snail.[40] It follows that *S. japonicum* can only thrive in areas where AGDD exceeds this threshold, which is at the root of Figures 5a and 5b. From the maps depicted on these two figures we can speculate that *S. japonicum* transmission could occur in the whole Jiangsu province. However, this will require availability of suitable snail habitats and means to spread the snails there (e.g., networks of natural or artificial water courses). Another crucial feature is the mean January temperature, as previous research has shown that can only survive in areas with mean January temperatures exceeding 0°C. This in turn delineates the potential transmission zones of the disease. Our recent work suggests that the distribution limits of *O. hupensis*, driven by the January 0--1°C isotherm, has shifted from 33°15’ N latitude to 33°41’ N latitude between the 1960s and the 1990s, which can be explained by global warming.[24] We have speculated that *S. japonicum* thus can be transmitted in these new areas, given that there are suitable breeding sites for *O. hupensis*. Indeed, previous experiments with *O. hupensis* kept in cages showed that the snails can survive and reproduce further north of the current endemic areas.[41]

Our time-series analysis found that the temperature increase in the southern part of Jiangsu province is considerable higher than in the northern part, which seems to contradict the global picture[35,36] and our previous results from China.[24] One possible reason for this discrepancy is that previous reports were based on studies conducted at large scales, i.e., global or continental regions, whereas the current study focused on a relatively small scale, i.e., a single province within China. Fundamental challenges arise for pattern recognition and the interfacing of phenomena that occur at different scales of space, time and organizational complexity.[42--44] Another reason might be the differences in topography; while the southern part of Jiangsu province is hilly, the northern part is flat. Previous studies suggested that the impact of climate change is more sensitive in mountainous areas than in lowland regions. Taken together, scaling, spatio-temporal pattern recognition, and topography are important issues to be considered for risk prediction of schistosomiasis under the scenario of a warmer future world.

The data used in the current study were average monthly temperatures. While *Tavg* has been widely used for estimating GDD, particularly for modeling,[5] other applications used minimum (*Tmin*) and maximum temperatures (*Tmax*). Depending on whether *Tavg* or half the sum of *Tmax* plus *Tmin* are employed, the *Tbase*, and hence estimation of GDD, can vary.[5] In the current study, daily night-time minimum or daily day-time maximum temperatures were not available. This in turn could add a bias to the study results, since the development of parasite larva in the intermediate host snail could cease when the night-time minimum temperature drops below a critical threshold or the day-time maximum temperature exceeds an upper threshold. It has been reported that natural temperature fluctuations aid the development of parasite larva in the intermediate host snail,[28] which had not been taken into account when estimating the parasite temperature threshold (i.e., 15.3°C), as it was done under stable laboratory conditions. Other sources of potential biases in predicting temperature changes are that night-time minimum temperatures are expected to increase more than day-time maximum temperatures and, as articulated before, winter temperatures are predicted to increase more pronouncedly than summer temperatures.[35,36] Furthermore, in the absence of exact geographical coordinates of the observing stations, we assumed that temperatures were obtained from the centroids of the respective counties. Since counties in Jiangsu are small, numerous and similarly shaped, it is unlikely that the placement of location at the county centroids introduced a severe bias, and our analysis is not sensitive to the approach chosen for selection of the location.

It is important to note that the key feature of using heat unit accumulation as expressed in GDD is that it focuses entirely on temperature, and that this measure has been widely and effectively used to describe timing of biological processes. Various modifications have been suggested to enhance the biological meaning of the GDD equation.[5] In future applications, it will be interesting to incorporate other factors, such as human activities, including changes in agro-ecosystems, water resources development and management and rapid urbanization, since they can alter climate change at regional levels.[45,46] The above-mentioned points illustrate that the prediction of global warming at different scales is a very complex manner. Further studies are warranted to improve upon the present time-series analysis model by considering other factors than temperature.

We conclude that climate change has occurred in China over the past 30 years.[24,28] It is predicted that temperature will continue to increase in the years to come, which is likely to bring along a myriad of implications, including altered frequency and transmission dynamics of schistosomiasis japonica. This in turn might jeopardize progress made for transmission control or even interruption since the launch of China's national schistosomiasis control program in the mid-1950s.[29,30] Rigorous surveillance[47] will be mandatory also in previously schistosome-free areas, so that further progress can be made with the ultimate goal of eliminating schistosomiasis from the mainland of China.

6.6 Appendix

Let C_{ijt} be the monthly average temperature in °C at location $i = 1,\ldots,39$ in month j and year t. We fit a linear regression model on C_{ijt} of the form:

$$C_{ijt} = \mu(jt)_{temporal} + \mu(i)_{spatial} + \varepsilon_{ijt}\,,\ \varepsilon_{ijt} \sim \mathrm{N}(0,\ \sigma^2)$$

The term $\mu(jt)_{temporal}$ captures the temporal trend and consists of a second order polynomial in time and an additive component ht to describe seasonality as follows:

$$h_t = \sum_{i=1}^{4} [\alpha_i \cos(t \times i \times \pi / 6) + \beta_i \sin(t \times i \times \pi / 6)]$$

The term $\mu(i)_{spatial}$ defines the spatial trend term consisting of second order polynomials of the coordinates plus thin-plate smoothing splines. For a location s these are defined as $\sum_{i=1}^{m} \beta_i \eta(\| s - \tilde{s}_i \|)$, where $\tilde{s}_i$ are fixed knots, $\| s - \tilde{s}_i \|$ is the Euclidean distance between s and $\tilde{s}_i$, and $\eta(z)$ is equal to $z^2 \log(z)$ [48]. We have chosen five knots at locations determined by the centers of clusters found by the CLARA software.[49]

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7: Potential impact of climate change and water resource development on the transmission of *Schistosoma japonicum* in China

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7.1 Abstract

There is growing consensus among climate modellers that the unusual global warming observed in the last decades of the 20th century is primarily forced by human activities, namely greenhouse gas increases in the atmosphere. Global warming will trigger alterations in physical and biological systems, including shifts in the spatio-temporal distribution of disease vectors, but the nature and extent of these changes are poorly understood. The purpose of the present study was to assess the potential impact of climate change and water resource development on the distribution of *Oncomelania hupensis*, the intermediate host snail of *Schistosoma japonicum*. We employed two 30-year composite datasets comprising average monthly temperatures collected at 623 observing stations throughout China, spanning the periods 1961-1990 and 1971-2000. Temperature changes were assessed spatially between the 1960s and 1990s for January, as this is the critical month for survival of *O. hupensis*. Our database shows that January temperatures increased at 590 stations (94.7%), and that China’s average January temperature in the 1990s was 0.96°C higher than 30 years earlier. The historical 0-1°C January isotherm, which was considered the approximate northern limit of *S. japonicum* transmission, has shifted from 33°15’ N to 33°41’ N, expanding the potential transmission area by 41,335 km^2. This translates to an additional 21 million people at risk of schistosomiasis. Two lakes are located in this new transmission area that form part of the proposed South-North water transfer project. Climate change, coupled with water resource developments in China, may pose additional challenges for the control of schistosomiasis.

Key words: China, Climate change, Geographical information system; *Oncomelania hupensis*, *Schistosoma japonicum*, Spatial analysis, Water resource development

7.2 Introduction

Temperatures in the northern hemisphere have been reconstructed over the past 1,000 years, with particular consideration of the effects of natural variability and anthropogenic influence (Crowley, 2000; Huang *et al.,* 2000). The main causes of climate change include (i) solar variability, (ii) volcanism, and (iii) changes in greenhouse gases and (iv) tropospheric aerosols. Since the early decades of the 18th century, the world climate has been in a warming phase (Reiter, 2001). Instrumental records, available for the past 150 years, suggest that the Earth has warmed by approximately 0.6°C over the past 100 years (IPCC, 2001). This unusual warming of the 20th century has been particularly pronounced during the last three decades (Easterling et al., 1997; Crowley, 2000; IPCC, 2001; Haines & Patz, 2004). Human activity, most notably the increase in greenhouse gases due to large-scale combustion of fossil fuels for energy production and transportation, is the most likely driver of forced global warming (Crowley, 2000; IPCC, 2001; Diaz, 2004). The predominant greenhouse gas is carbon dioxide (CO_2); its atmospheric concentration has increased from 290 parts per million (ppm) in 1890 to 373 ppm in 2002 (Reiter, 2001; Beggs, 2004). In their 2001 report, the 'Intergovernmental Panel of Climate Change' (IPCC) predicted that the mean global temperature will increase by between 1.4°C and 5.8°C from 1990 to 2100 . Recent model simulations over a wide range of parameterization under the scenario of a doubling CO_2 concentration predict a global warming of 2.4-5.4°C in the same time frame.

Climate change is characterized by considerable spatial and temporal heterogeneity. For example, warming is particularly pronounced at high latitudes of the northern hemisphere (Murphy *et al.,* 2004; Stocker, 2004). Larger differences have been found for monthly average maximum and minimum temperatures during winter months when compared to the summer (Easterling *et al.,* 1997). To capture localized climate changes, models are needed that can assign meteorological parameters at relatively small scales (Knowlton *et al.,* 2004).

There is a growing body of literature documenting the impacts of climate change on physical and biological systems, including human health (Patz *et al.,* 2000; Epstein, 2001; Beggs, 2004; Diaz, 2004; Haines & Patz, 2004; Knowlton *et al.,* 2004). An area that has received particular attention is the potential impact of global warming on shifts in the spatio-temporal distribution of disease vectors, and hence the frequency and transmission dynamics of vector-borne diseases (Reiter, 2001; Hunter, 2003; Sutherst, 2004). Most studies focused on malaria (Sutherst, 2004). An early estimate suggested that its epidemic potential may increase by 12-27% as a direct consequence of higher temperatures (Martens *et al.,* 1997). The use of mathematical models, coupled with geographical information system (GIS) and remote sensing techniques, revealed an increase of the population at risk of malaria transmission due to climate change, particularly at higher altitudes and to some degree also at higher latitudes (Lindsay & Martens, 1998; Tanser *et al.,* 2003).

Climate change will also impact the distribution of snails that act as intermediate hosts for schistosomiasis, but the nature and extent of these effects are poorly understood (Morgan *et al.,* 2001). While some models of global warming predicted an extension of the area conducive for schistosomiasis transmission (Martens *et al.,* 1995), other models forecasted a decrease in the epidemic potential of the disease (Martens *et al.,* 1997). It is generally agreed that the transmission dynamics is most sensitive to climate change around the boundaries of endemic areas (Sutherst, 2004). Implementation and operation of water resource development projects, which have a history of facilitating the spread and intensification of schistosomiasis (Hunter *et al.,* 1993; Jobin, 1999; Chitsulo *et al.,* 2000), could further amplify the negative effects of climate change.

The objective of this study was to assess the potential impact of climate change on the spatial distribution of *Oncomelania hupensis*, which is the intermediate host snail of *Schistosoma japonicum*. The geographical focus is on China, particularly around the 33°15’ N latitude, as historical records suggest that this was the approximate northern limit where *O. hupensis* occurred (Mao, 1990). Preliminary work put forth that the distribution of *O. hupensis* might expand northwards as a consequence of climate change (Zhou *et al.,* 2002b). We extracted average January temperatures from two 30-year composite datasets to assess and quantify localized temperature changes over the past 30 years, and used an integrated GIS approach to estimate areas and people at risk of schistosomiasis transmission.

7.3 Materials and methods

7.3.1 Digital map of China and meteorological data

A digital map of China, produced by the National Bureau of Surveying and Mapping, was purchased from the Chinese Center for Geographic Science (Beijing, China). It contains layers of administrative units from the provincial to the county level, and the hydrological network consisting of rivers and lakes.

Two datasets, each comprising 30-year composite average monthly temperatures collected at 623 meteorological stations throughout China, were obtained from the Climate Data Center, Chinese Meteorological Center (Beijing, China). The two datasets are spanning the periods of 1961-1990 and 1971-2000, respectively. All meteorological stations have been georeferenced (latitude, longitude and altitude). They are depicted on Figure 1.

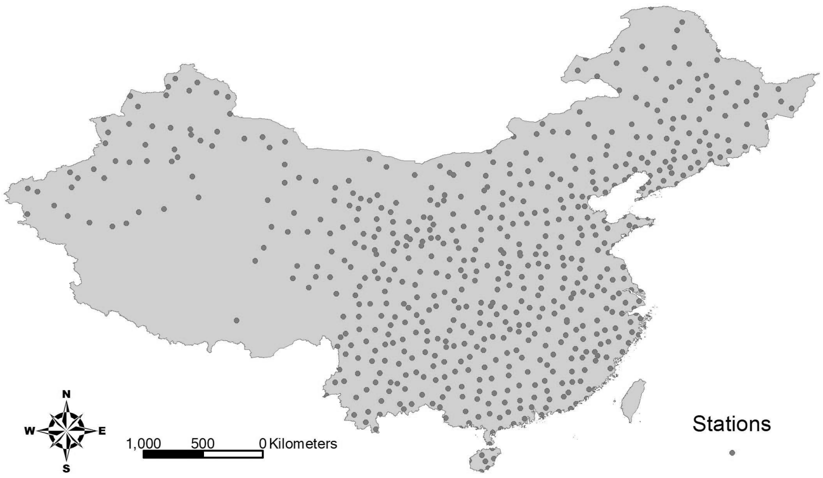

Figure 1. Spatial distribution of meteorological stations (n = 623) throughout China from which temperature data were derived for the current analysis.

7.3.2 Data management and analysis

A climate dataset, consisting of the average monthly temperatures of the two 30-year composites derived from the 623 meteorological stations, was created on an EXCEL spreadsheet (Microsoft Corporation; Redmond, WA, USA). Data analyses were done with version 8.0 of the STATA software package (Stata Corporation; College Station, TX, USA). The average January temperatures were extracted, as January is the coldest month of the year in China, and hence considered the critical climate factor that determines the distribution of *O. hupensis*, and thus the transmission of *S. japonicum* (Mao, 1990).

Box 1 shows the approach we adopted for calculation of changes in the average January temperature over the past 30 years. In a first step, two temperature datasets, i.e. T1 and T2, were created on the basis of the average January temperatures for the periods 1961-1990 and 1971-2000, respectively. We then generated a temperature difference dataset, i.e. Td, of the average January temperatures during the 10-year periods of 1961-1970 and 1991-2000, respectively, by subtracting T1 from T2 and multiplying this difference with a factor 3. This multiplication factor is necessary to convert the difference of the average temperatures over the two 30-year periods, namely 1961-1990 and 1971-2000, to the difference of the average temperatures over the non-overlapping 10-year-periods of 1961-1970 and 1991-2000, respectively.

Box 1. Calculation of temperature changes from 1960s to 1990s

$$Td = 3 * (T2-T1)$$

T1 represents average January temperature during the period of 1961-1990

T2 represents average January temperature during the period of 1971-2000

In view of historical records, considering the latitude of 33°15’ N as the edge of *O. hupensis* distribution (Mao, 1990), we divided the Td dataset into two parts, representing north and south of the 33°15’ N latitude (i.e. Td_{North} and Td_{South}). Overall, 345 (55.4%) stations were located in Td_{North}, whereas the remaining 278 (44.6%) stations were located in Td_{South}.

We employed a Wilcoxon signed-rank test for paired data to examine whether the differences in the respective Td, Td_{North} and Td_{South} datasets were statistically significant, thus comparing average January temperature between the 1960s and 1990s. Statistical analysis was also performed between the Td_{South} and Td_{North} datasets by using a two-sampled Wilcoxon rank-sum (Mann-Whitney) test.

7.3.3 Geographical information system and risk assessment

We created a GIS using version 8.2 of the ArcGIS software (ESRI; Redlands, CA, USA). The average January temperature differences between the 1960s and 1990s (Td) were attached to each of the 623 meteorological stations. A trend analysis was applied to the Td dataset, using the geostatistic analyst module of ArcGIS, to examine differences in the north-south and east-west dimensions. We employed ordinary kriging (Cressie, 1993) to generate a smoothed surface map of the Td dataset. Three separate models were fitted assuming polynomial forms for the location coordinates of order 1, 2 and 3, respectively. The model with the smallest root-mean-square standardized value, following cross-validation, was used for subsequent spatial analyses.

Finally, we generated surface maps of T1 and T2 that were also based on ordinary kriging models. We extracted the average January temperature belts of 0-1°C for T1 and T2, as areas within this belt are considered sensitive for survival of *O. hupensis*. We compared the spatial extent of these sensitive intermediate host snail habitats at the two time points and estimated the total surface area of the new potential transmission area of *S. japonicum*. Employing a mean population density of 500 people per km^2 (http://www.hzsin.gov.cn/ReadNews.asp?NewsID=550, 2003), we then estimated the number of people who have potentially become at risk of *S. japonicum* transmission due to climate change.

7.4 Results

7.4.1 Changes in average January temperature in China over the past 30 years

Examination of the Td dataset revealed that the average January temperature in China increased at 590 of the 623 meteorological stations (94.7%), whereas only 33 stations (5.3%) recorded lower average January temperatures in the 1990s when compared to those measured three decades previously. Overall, an increase of 0.96°C (95% confidence interval – CI: 0.90, 1.03°C) occurred in the average January temperature from the 1960s to the 1990s. This increase had a high statistical significance (Wilcoxon signed-rank test: $z = 19.91$; $P < 0.001$).

The mean values of the Td_{South} and Td_{North} datasets were 0.52°C (95% CI: 0.46, 0.59°C) and 1.32°C (95% CI: 1.22, 1.41°C), respectively. Thus, the increase in China's average January temperature over the past 30 years showed statistical significance both south ($z = 12.07$, $P < 0.001$) and north of the 33°15'N latitude ($z = 15.38$, $P < 0.001$).

According to the results of the Mann-Whitney test, the Td_{North} dataset was significantly higher than Td_{South} ($z = 12.95$, $P < 0.001$). In other words, over the past 30 years, more pronounced increases in the average January temperatures occurred in the northern rather than in the southern parts of China.

Figure 2 shows the results from the trend analysis applied to the Td dataset, using the geostatistic analyst module of the ArcGIS software. This trend analysis confirmed that average January temperatures increased with higher latitude, thus temperature increases in the north were larger than in the south (shown by the blue line on the Y-Z-axes surface). From west to east China, a parabolic trend in the change of the average January temperatures were observed between the 1960s and 1990s (shown by the green line on the X-Z-axes surface). It follows that the highest January temperature increases over the past three decades occurred in the north-eastern parts of China.

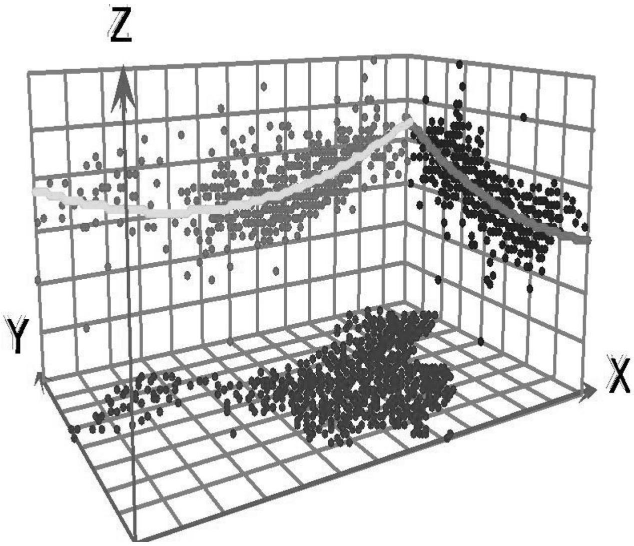

Figure 2. Trend analysis of climatic datasets (rotation angles: location = 0 degree). The trend of average temperature change in January from south to north China is shown as blue line on the Y-Z-axes surface and that from west to east China is shown as the green line on the X-Z-axes surface.

7.4.2 Smoothed map of average January temperature changes in China

The three kriging models we employed revealed root-mean-square standardized values of 1.101, 1.052 and 1.085, respectively. In view of the lowest root-mean-square standardized value of model 2, subsequent surface analyses were done with this model.

Figure 3 shows the smoothed changes of the average January temperature that occurred in China over the past 30 years. The map confirms that January temperatures have increased in most parts of China, and that changes were more pronounced in the north than in the south (orange and brown colours). Estimated temperature increases in the month of January in some areas in the northeastern part of China were as high as 3.0°C (dark brown colour). The smallest average January temperature changes were observed in central and south China. In two small areas the average January temperature actually decreased over the past 30 years. At some of the observing stations, the average January temperature rose by more than 3.0°C from the 1960s to the 1990s, with a maximum value of +4.5°C. Temperature declines by more than 0.6°C have also been observed with the lowest value of -3.3°C. However, on the smoothed map these climate change extremes were not apparent due to only few stations with such extreme values and the smoothing procedures.

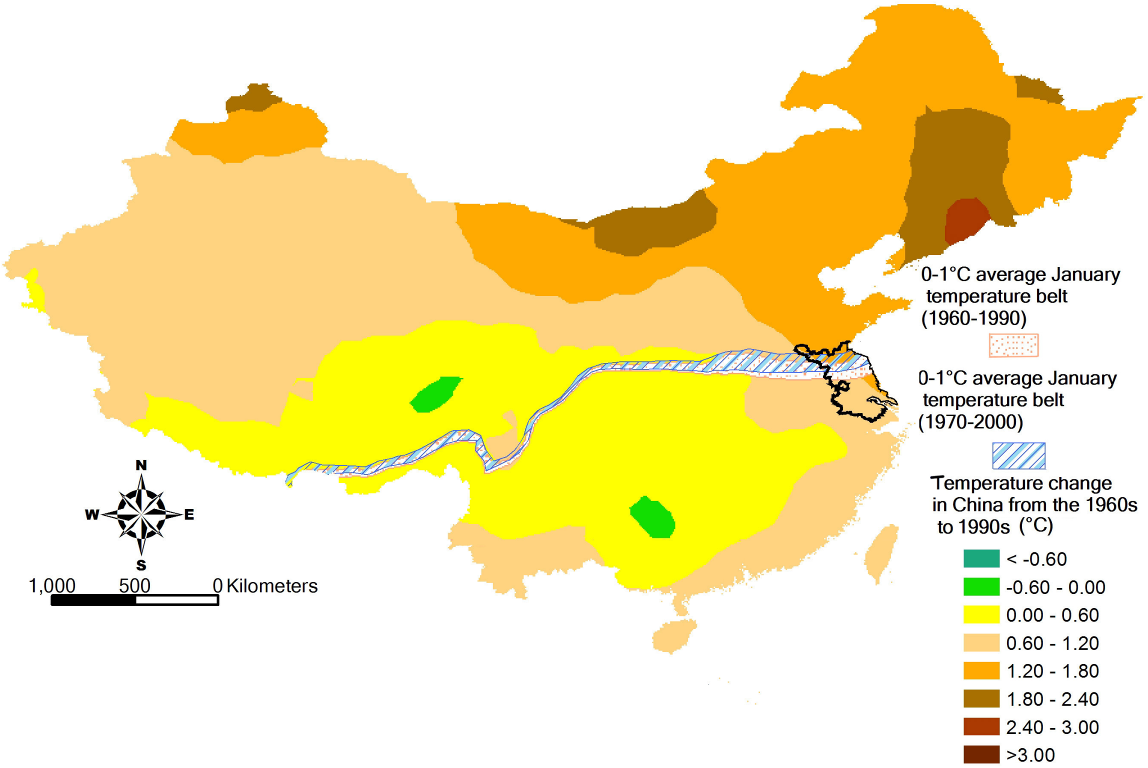

Figure 3. Smoothed map of China exhibiting the average January temperature difference between the 1960s and 1990s, including the new potential transmission area of *S. japonicum*. The black lines in the middle eastern part of China delineate the Jiangsu province

7.4.3 Potential new transmission area of *S. japonicum* and people at risk

Figure 3 also shows the two extracted 0-1°C belts of the T1 and T2 datasets that have been overlaid on the Td map described above. The two 0-1°C belts of T1 and T2 are displayed in white stipple and blue-white hatched colours, respectively. They extend in east-west direction across central China. The spatial analysis showed that the 0-1° belt of T2 extended further north when compared with the corresponding T1 belt, particularly in the eastern part of China. The areas within the 0-1°C belt of T1 that are not overlapping with the respective 0-1°C belt of T2 (delineated by white stipple colour only) indicate the new suitable habitats for permanent occurrence with *O. hupensis*, hence areas that have become potentially conducive to the transmission of *S. japonicum.* We found that the historic northern distribution edge of *O. hupensis* (33°15' N) extended some 0°26' further north to 33°41' N. Quantification of this new potential area of schistosomiasis transmission revealed a total surface area of 41,335 km^2. Multiplication of this estimated surface area with a mean population density of 500 people per km^2 in this part of China revealed that an estimated 21 million people have potentially become at risk of schistosomiasis. The areas delineated by blue-white hatched colour represent the new potential northern edges of *O. hupensis* distribution in China.

7.4.4 Effect of climate change coupled with water resource development

Figure 4 shows in greater detail the potential impact elevated January temperatures had on the spatial distribution of *O. hupensis*, and hence the transmission of *S. japonicum*. The focus is on the Jiangsu province, located in east China. As mentioned before, our GIS approach suggested that the areas of the 0-1°C belt of the T1 dataset (exclusively coloured in white stipple) have become suitable habitats for *O. hupensis* year-round. Consequently, the potential transmission area of *S. japonicum* extends further northwards. To better understand the potential impact of climate change in the face of water resource development and management, the hydrological layer (main rivers and lakes) has been added. Within the southern boundary of the 0-1°C band of the T1 dataset, there are two lakes, namely Hongze Lake and Baima Lake. Both lakes are located in the main route of the proposed South-North water transfer project (red lines), which in turn might further aggravate the risk of spreading *O. hupensis* further northwards.

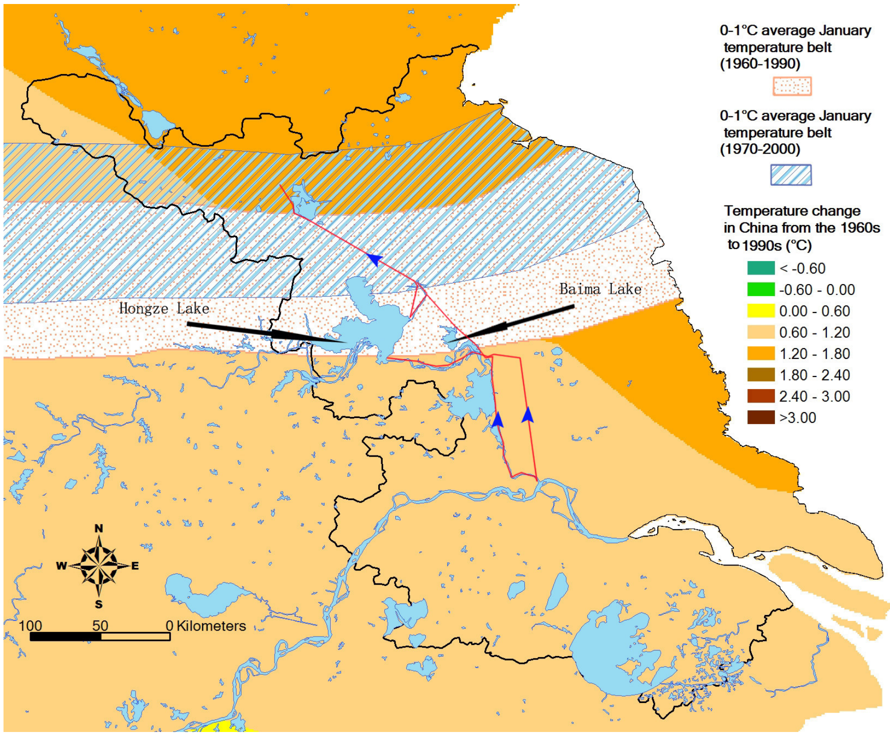

Figure 4. Potential transmission area of *S. japonicum* in Jiangsu province due to higher average January temperatures. Red lines indicate part of the eastern route of the planned South-North water transfer project. The blue arrows show the water flow direction.

7.5 Discussion

The majority of climate change risk assessments carried out thus far have focused on vector-borne diseases, particularly malaria (Sutherst, 2004). Using a modelling approach, often coupled with GIS and remote sensing techniques and appropriate spatial statistics, most of the analyses predicted an increase in the population at risk of malaria. The main underlying reason was the direct effect of increased temperature, thus expanding the geographical distribution of disease transmission into higher altitudes and higher latitudes, with the former more important than the latter (Lindsay & Birley, 1996; Martens *et al.,* 1997; Lindsay & Martens, 1998; Reiter, 2001; Tanser *et al.,* 2003; Sutherst, 2004). Interestingly, one study that employed an alternative statistical approach came to the conclusion that the current distribution of *Plasmodium falciparum* malaria will remain fairly constant in the future under various climate scenarios, including the most extreme ones (Rogers & Randolph, 2000). However, outcomes of this model have been challenged on various grounds, including (i) lack of specificity in the current distribution of malaria due to *P. falciparum*, (ii) inherent uncertainties in modelling moisture-related climate changes, (iii) vulnerability of adaptation mechanisms to cope with malaria in the face of social unrest and economic decline, and (iv) unsuitability of statistical models to take into account setting-specific idiosyncrasies in parasite-vector-host interactions (Sutherst, 2004). Despite these differences, there is consensus that malaria transmission is most sensitive to climate change in areas around the current distribution edges, and that small increases at low temperatures can change risk profiles disproportionately (Lindsay & Birley, 1996; Martens *et al.,* 1997; Sutherst, 2004).

Only few attempts have been made to assess the potential impact of climate change on the frequency and transmission dynamics of diseases other than malaria, including schistosomiasis. Analogous to malaria, it is acknowledged that the transmission potential of schistosomiasis is most sensitive on the periphery of current areas of endemicity (Martens *et al.,* 1997; Sutherst, 2004). However, two previous studies identified in the literature reported conflicting results on the potential impact climate change has on the extent of the area conducive for schistosomiasis transmission, and hence on the population at risk (Martens *et al.,* 1995; Martens *et al.,* 1997). We have now used a detailed time series of instrumental records in combination with an integrated GIS approach and spatial statistics. We estimate that 41,335 km^2 and 21 million people have become at risk of *S. japonicum* transmission in central China. These estimates are based on the direct effect of localized climate warming. In fact, we have found that China's average January temperature has increased by almost 1°C over the past 30 years with considerable spatial variation. In view of recent estimates that 652 million people live in areas at risk of schistosomiasis worldwide (Chitsulo *et al.,* 2000; Utzinger & Keiser, 2004), our finding of 21 million Chinese who have potentially become at risk of schistosomiasis due to climate change translates to 3% on a global scale. Such a result may have profound public health and economic significance, hence the strengths and weaknesses of our study warrant further scrutiny.

Regarding the strengths, five issues are offered for discussion. First, instrumental records were obtained from as many as 623 meteorological stations across China. This large ensemble of observing stations facilitates assessment of localized impacts of climate change with a high degree of accuracy at relatively small regional scales. It is important to note that few assessments of health impacts attributable to climate change have been made at a spatial resolution of tens of kilometres (Knowlton *et al.,* 2004). Instead, most of the previous modelling approaches were carried out at the global scale (Easterling *et al.,* 1997; Crowley, 2000; Huang *et al.,* 2000; Atkinson *et al.,* 2004; Murphy *et al.,* 2004; Thomas *et al.,* 2004). For example, maximum and minimum temperature trends over the past 100 years were analyzed on the basis of 5,400 observing stations around the globe (Easterling *et al.,* 1997).

Second, the overall increase in the average January temperature in China over the past 30 years (i.e. 0.96°C) fits well into the global and regional picture. Although this temperature increase is considerably higher than the 0.6°C average surface temperature increase observed worldwide over the past 100 years (IPCC, 2001), it has been noted that a large portion of the global warming occurred after the mid 1970s, and that temperature increases were more pronounced in the northern hemisphere, particularly at high latitudes, and were highest in winter months (Easterling et al., 1997; Huang et al., 2000; IPCC, 2001). Analysis of a 10-year time series from Tianjing city in China, for example, indicated that the average annual temperature in this urban setting increased by 0.7° from 1986 to 1995 (Yu *et al.,* 1998).

Third, our study confirmed the strong spatial heterogeneity of climate change within a single country. While we found two small foci where average January temperatures actually decreased slightly over the past 30 years, there were some areas where average January temperatures in the 1990s were more than 2 or even 3°C higher than in the 1960s. In support of item two articulated above, consistently larger temperature increases were observed in the northern part of China rather than in the south. In addition, temperature increases were somewhat more pronounced in east China when compared to the west.

Fourth, an important aspect of our study is that application of ordinary kriging within a GIS framework provides a sound basis for the creation of a smoothed surface map showing the difference of average January temperatures between the 1960s and 1990s. Such a map is a good means for policy discussions, as it highlights the areas that are most significantly affected by climate change; hence can guide subsequent mitigation measures. We have recently developed and applied Bayesian kriging for spatio-temporal modelling of county level data of *S. japonicum* infection prevalence in Jiangsu province, eastern China (Yang *et al.,* 2005) and for assessment and prediction of *S. mansoni* risk among schoolchildren in the region of Man, western Côte d'Ivoire (Raso *et al.,* 2005).

Fifth, we have shown that the GIS approach adapted here facilitated an integrated framework for schistosomiasis risk assessment, as it considered the potential impact of climate change coupled with water resource developments. In fact, we have identified two lakes that are located in contemporary risk areas of *S. japonicum* transmission, as the average January temperatures in the 1990s were above the critical thermal limits for *O. hupensis* survival (Mao, 1990; Liang *et al.,* 1996). The two lakes are in the main route of the proposed South-North water transfer project, which is a large-scale infrastructure development project that aims at social and economic development of the water-deprived northern part of China (Yang *et al.,* 2005). The negative effects of water resource development and management on the frequency and transmission dynamics of schistosomiasis have been documented in different ecological and epidemiological settings across Africa (Abdel-Wahab *et al.,* 1979; Hunter *et al.,* 1993; Mott *et al.,* 1995; N'Goran *et al.,* 1997; Southgate, 1997). There is considerable concern that the implementation and operation of large-scale water projects in schistosome-endemic areas of China may result in negative health effects (Xu *et al.,* 2000).

Regarding the weaknesses of our study, four issues are worth highlighting. First, in the absence of year-by-year average monthly temperatures for each of the 623 observing stations across China covering the period of 1961-2000, we used two 30-year composite measures with an overlap of 20 years. Consequently, the difference in the average January temperatures between the 1960s and 1990s reported in the present study is a gross estimate and, unfortunately, no detailed information was retrievable on a yearly basis.

Second, instrumental records measure ambient temperature; hence the increase in the average January temperature reported here is the observed change in ambient temperature that occurred over the past 30 years. However, empirical relations between schistosomiasis transmission dynamics and temperature have been established with respect to water temperature, because the disease is primarily transmitted in freshwater bodies where intermediate host snails release the infective stages of the parasite (i.e.

cercariae) that penetrate the human skin during occupational or recreational activities (Martens *et al.,* 1995). Since thermal conditions of shallow water reflect ambient temperatures quite well, it is conceivable that this measure can serve as a good proxy for shallow water temperature. An important peculiarity of *S. japonicum* transmission is that it can also occur in proximity to freshwater bodies (e.g. in marshland), as its intermediate host snail, namely *O. hupensis*, is amphibious. In contrast, intermediate host snails of the four remaining human schistosome species are all aquatic.

Third, our estimates of the potential area and population at risk of *S. japonicum* transmission due to climate change must be juxtaposed to coping mechanisms, which in turn can alter the shape of risk profiles. For example, China's sustained efforts to control schistosomiasis over the past 50 years are exemplary (Yuan *et al.,* 2000; Ross *et al.,* 2001; Chen *et al.,* 2005). In addition, China's rapid and sustained social and economic development that commenced in the late 1970s and, which goes hand-in-hand with environmental sanitation, is a major feature explaining the overall decline in mortality (Banister & Zhang, 2005), and the control of schistosomiasis in particular (Utzinger *et al.,* 2003; Chen *et al.,* 2005).

Finally, climate extremes were not considered in the current analysis. However, it should be noted that climate change not only results in higher temperatures, but it also increases the frequency of extreme climate events, including floods (Easterling *et al.,* 2000). A significant flooding event occurred along the lower reaches of the Yangtze River in 1998, which posed an excess risk of *S. japonicum* transmission. Whether or not this event was due to climate change remains to be investigated, although a GIS approach was earlier shown to be useful in predicting the distribution of *O. hupensis* in the face of such specific environmental conditions (Zhou *et al.,* 2002a).

We conclude that a significant increase has occurred in China's average January temperature over the past 30 years, and that spatial heterogeneity of this change was considerable. Development and application of an integrated GIS framework provides an excellent platform to assess the potential impact of climate change and an array of other factors – e.g. major water resource development projects – on the spatial distribution of *O. hupensis*, and hence on the frequency and transmission dynamics of *S. japonicum.* Such an integrated framework can serve as a powerful tool for policy makers and disease control personnel; hence it can further inspire and guide schistosomiasis control efforts in China and in other countries where the disease continues to be a major public health problem.

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8: Remote sensing for predicting potential habitats of *Oncomelania hupensis* in Hongze, Baima and Gaoyou lakes in Jiangsu province, China

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8.1 Abstract

Political and health sector reforms, along with demographic, environmental and socio-economic changes in the face of global warming, could cause the re-emergence of schistosomiasis japonica in areas where transmission had been interrupted and the emergence in previously non-endemic areas in China. In the present study, we used geographic information system and remote sensing techniques to predict potential habitats of *Oncomelania hupensis*, the intermediate host snail of *Schistosoma japonicum.* Our focus is on Hongze, Baima and Gaoyou lakes in Jiangsu province in eastern China. We developed a model by using the normalized difference vegetation index, a Tasseled-cap transformed wetness index, and flooding areas to predict snail habitats at a small scale. Data were extracted from two Landsat images, one taken during a typical dry year and the other taken three years later during a flooding event. Approximately 163.6 km^2 were predicted as potential *O. hupensis* habitats around the three lakes, which accounts for 4.3% of the estimated snail habitats in China. In turn, these predicted snail habitats are risk areas for transmission of schistosomiasis, and hence illustrate the scale of the possible impact of climate change and other ecological transformations. The generated risk map can be used by health policy makers to guide mitigation policies targeted against the possible spread of *O. hupensis,* and thus the transmission of *S. japonicum*.

Key words: Schistosomiasis, *Schistosoma japonicum*, *Oncomelania hupensis*, Snail habitats, Remote sensing, Geographic information system, Risk mapping and prediction, China.

8.2 Introduction

Schistosomiasis japonica is endemic in China and must have been perceived as a public health problem there in ancient times (Jordan, 2000). The historical evidence stems from the recovery of *Schistosoma japonicum* eggs from the liver and rectum of a well-preserved female corpse from the Western Han Dynasty (206 B.C.-24 A.D.) (Mao & Shao, 1982; Zhou *et al*., 2005). However, it was only in 1905 that *S. japonicum* was first described in the literature, with parasite eggs identified in an 18-year-old Chinese male with dysentery (Logan, 1905). Once it became clear that the disease caused substantial social and economic hardship (Mao, 1948; Maegraith, 1958; Chen & Feng, 1999), a national control programme was initiated, shortly after the establishment of the People's Republic of China in 1949. Dedicated control activities over the past 50 years have reduced the prevalence of human infections with *S. japonicum* by more than 90% (Utzinger *et al*., 2005; Zhou *et al*., 2005). In 2003, an estimated 850,000 people were still infected with *S. japonicum* with 65 million people at risk (Zhou *et al*., 2005). There is considerable concern that schistosomiasis might re-emerge, as active transmission has been reported from areas that had previously reached transmission interruption or transmission control (Liang *et al*., 2006). Underlying reasons include political and health sector reforms, demographic, environmental and socio-economic changes, and global warming (Bian *et al*., 2004; Zhou *et al*., 2004; Utzinger *et al*., 2005; Zhou *et al*., 2005).

Oncomelania hupensis is the only intermediate host snail of *S. japonicum.* In 2003, it was estimated that 3,787 km^2 of land were infested with *O. hupensis*, particularly in the marshlands surrounding the great lakes in southern China and the Yangtze River basin (Zhou *et al*., 2005). The two largest lakes in the middle reaches of the Yangtze River are the Dongting Lake and Poyang Lake (Ross *et al*., 2001; Guo *et al*., 2005; Zhou *et al*., 2005). It has been speculated that some non-endemic marshlands in the north of these lakes could become colonized by *O. hupensis* due to climate change and other ecological transformations (Yang *et al*., 2005a). For example, Hongze, Baima and Gaoyou lakes, situated north of the Yangtze River basin in the transition zone between warm temperate and sub-tropical climate zones, are potential risk areas for schistosomiasis. Snails might colonize the non-endemic Hongze and Baima lakes, and might re-emerge in Gaoyou Lake from where they were eliminated many years ago.

In one of our previous studies we documented that the average January temperature China increased considerably over the past 30 years (Yang *et al.*, 2005a). Since Hongze and Baima lakes are both in the predicted at-risk area of colonization with *O. hupensis*, there is concern that schistosomiasis might become a public health problem there. Implementation of the South-to-North water transfer (SNWT) project, the second largest water resources development project in China (http://www.nsbd.mwr.gov.cn/), could result in a wider distribution of snails by enlarging the wetlands and enabling direct snail transfers from the infested Yangtze River to Gaoyou, Baima and Hongze lakes.

In the study presented here, we used geographic information system (GIS), remote sensing techniques and a modelling approach to predict the potential habitats of *O. hupensis* around Hongze, Baima and Gaoyou lakes. Remotely-sensed environmental data included a surrogate vegetation index, the Tasseled-cap transformed wetness index, and information about flooding to predict snail habitats at a small scale.

8.3 Materials and methods

8.3.1 Study area and satellite imagery

The study area is located in central Jiangsu province, eastern China, and focuses on three lakes, namely Gaoyou, Baima and Hongze (Figure 1). Also depicted on this figure is the main route of the SNWT project, with arrows indicating the direction of water-flow.

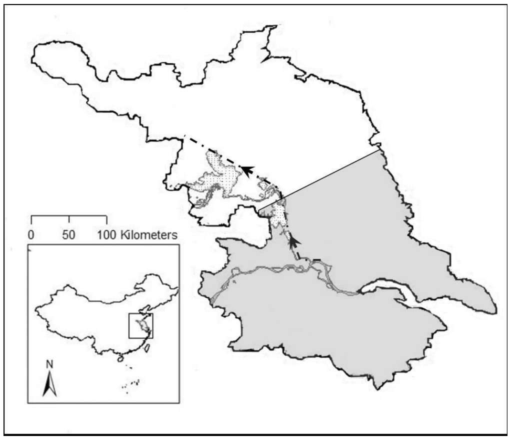

Figure 1. Study area in central Jiangsu province including South-to-North water transfer project. The region shaded is the current schistosome-endemic area.

Two Landsat TM images were purchased from China Remote Sensing Ground Station (Beijing, China). The first image was taken on 16 September 2000, representing a typical dry year. The second image was taken on 19 October 2003, which coincided with a flooding event. The images covered the regions stretching from 32° 5´ N to 34° 4´ N latitude and from 118° 4´ E to 119° 7´ E longitude. The spatial resolution of each image is about 30 x 30 m.

Satellite imagery analyses were performed in ENVI version 4.0 software (Boulder, CO, USA) and the following procedures were carried out: (i) georeferencing, (ii) classification for presence of water or land, (iii) extraction of the normalized difference vegetation index (NDVI) and the Tasseled-cap transformed wetness index. The results were then validated by ground truth historical snail data in a part of the study area.

8.3.2 Georeferencing

The two images were georeferenced by attributing 20-30 easily distinguishable and known coordinate locations in the reference layer to the images (e.g. road crossings and banks of water bodies). Following the georeferencing process, the coordinate system of the two images was adjusted to WGS_1984_UTM_Zone_50N.

8.3.3 Image classification

The images were classified by using an unsupervised classification approach (ENVI, 2003), and all sorted image pixels were grouped into seven categories according to their spectral values, by means of a cluster analysis algorithm without any user-defined training classes. Subsequently, the images were sorted into two categories, namely (i) water, and (ii) land.

The two classified images were then overlaid by subtraction, and we created a composite image with three classes as detailed in Box 1.

Box 1: Composite image classification

- Composite_1: water surface identified on both images (dry and wet year)
- Composite_2: regions with water identified during a flooding event and land during the dry year

In the year 2000 image, both NDVI and the Tasseled-cap transformed wetness index were grouped into three classes as summarized in Box 2. The regions classified as NDVI_3, Wetness_2 and Composite_2 were considered as potential snail habitats.

Box 2: Dry year image classification

- NDVI_1: regions with water
- NDVI_2: regions with lowest category (out of three categories) of NDVI value
- NDVI_3: regions with highest category (out of three categories) of NDVI value

- Wetness_1: regions with water

8.3.4 Validation

Validation of the model prediction was only possible for the Gaoyou Lake area, where we used ground truth data derived from historical snail records, since *O. hupensis* habitats had been eliminated in the early 1990s (MOH, 2000). Hongze and Baima lakes are not yet infested with *O. hupensis*, and hence validation was not possible there.

8.4 Results

The predicted *O. hupensis* habitats around the three lakes are depicted in Figure 2. The red colour corresponds to intermittently flooded areas covered by grass and where soil moisture is high. A total of 181,789 pixels were predicted as potential *O. hupensis* habitats, which correspond to approximately 163.6 km^2, given the spatial resolution of the Landsat images used. There were 94,684 pixels or about 85.2 km^2 of potential snail habitats around Hongze and Baima lakes, and a total of 87,105 pixels, corresponding to 78.4 km^2 of potential snail habitats, around Gaoyou Lake.

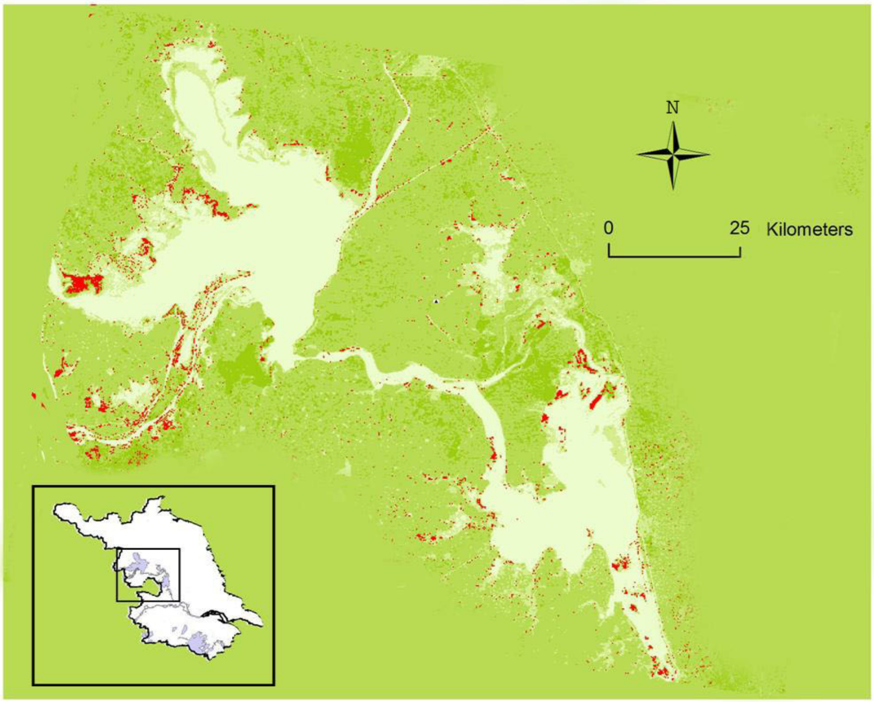

Figure 2. Potential snail habitats (in red) around Hongze, Baima and Gaoyou lakes in central Jiangsu province, eastern China

The values of NDVI and the Tasseled-cap transformed wetness index in these predicted snail habitats ranged from 0 to 4.9 and from -41 to -3, respectively. They are summarized in Table 1, along with ranges put forth by other research groups working in other areas of China.

Validation of our predicted snail habitats in the Gaoyou Lake area, using historical snail survey data, revealed that all former snail habitats around this lake were correctly predicted by our model.

Table 1. Remotely-sensed environmental features (normalized difference vegetation index, NDVI; second modified soil-adjusted vegetation index, MSAVI2; Tasseled-cap transformed wetness index) derived from satellite images by different research groups for prediction of *O. hupensis* habitats

Author (year)	Vegetation index value of snail habitats		Wetness index value of snail habitats	Image data transformation	Application area	Image archiving time
	NDVI	MSAVI2				
Lin *et al*. (2002)	6 highest classes out of 25 classes		-	Digital number	Poyang Lake, Jiangxi province	Flooding: 25 August, 1998 Dry season: 26 April 1999
Zhou *et al*. (2002a)	6 highest classes out of 25 classes		-	Digital number	Poyang Lake, Jiangxi province	Flooding: 25 August 1998 Dry season: 4 April 1999
	6 highest classes out of 15 classes				Lower Yantze River basin, Jiangsu province	Flooding: 8 August 1998 Dry season: 5 May 1999
Guo *et al*. (2005)	108 to 139		-88 to 48	Digital number	Poyang Lake, Jiangxi province	Wet season: 25 August 1998 Dry season: 16 April 2000
Zhang *et al*. (2005)		0.222 to 0.41	-0.23 to -0.152	Atmospheric correction	Jiangning county, Jiangsu province	11 November 2000
Yang *et al*. (2006)	0 to 4.9		-41 to -3	Digital number	Hongze, Baima and Gaoyou lakes, Jiangsu province	Dry season: 16 September 2000 Flooding: 19 October 2003

8.5 Discussion

There is little doubt that the unusual warming trend observed over the past 30 years is ─ at least partially ─ attributable to human activities, namely the increased greenhouse gas emissions (IPCC, 2001; Murphy *et al.*, 2004; McMichael *et al.*, 2006). The Earth has warmed by approximately 0.6°C over the last century according to systematic climate records available since 150 years. The increase in the globally averaged temperature has been particularly pronounced during the last three decades, amounting to 0.5°C (IPCC, 2001). New analyses suggest that climate change is responsible for over 150,000 deaths per year and a global burden of approximately five million disability adjusted life years lost annually (Hunter, 2003; WHO, 2003; Sutherst, 2004). In China, the averaged January temperature increased by 0.96°C between the 1960s and the 1990s. In some areas of north-eastern China, the mean January temperature increased by as much as 3.0°C (Yang *et al.*, 2005a).

The distribution of *O. hupensis* is restricted to the southern parts of China. Historical records suggest that this distribution is governed by the mean January temperature; snails only occur where the mean January temperature is higher than 0°C (Zhou *et al.*, 2002b). In the face of global warming, the January isotherm belt of 0-1°C is shifting northwards. We have estimated that over the past 30 years it might have shifted 26´ north, corresponding to 40 km (Yang *et al.*, 2005a). Thus, it is conceivable that new areas will become suitable habitats for *O. hupensis*, when considering temperature as a key ecological feature. Importantly, both Hongze and Baima lakes are located in this new potential area where snails could proliferate, whereas the mean January temperature in the Gaoyou Lake area provided suitable conditions for snails already before. In view of a large water resources development project underway, i.e. the SNWT project, *O. hupensis* could spread into this area and (re)colonize.

The distribution of *O. hupensis*, an amphibious snail, in areas where January temperatures allow survival are governed by a number of other factors that act at a micro-environmental scale. These factors include annual water fluctuations, dense vegetation cover and high soil moisture (Mao, 1990). The current study used three environmental features which have previously proved useful to identify potential snail habitats, i.e.

flooded region, NDVI and the Tasseled-cap transformed wetness index. Hongze, Baima and Gaoyou lakes are flood buffer lakes for the Huai River during the rainy season. The water level fluctuations between the dry and rainy seasons are among the predominant factors determining *O. hupensis* survival. The existence of grass is another indicator that has been used traditionally for snail surveillance by China's national schistosomiasis control programme.

The successful prediction of potential snail habitats in the lake and marshland regions of China by using GIS and remote sensing techniques has been widely documented (Lin *et al.*, 2002; Zhou *et al.*, 2002a; Guo *et al.*, 2005; Zhang *et al.*, 2005), and was reviewed recently (Yang *et al.*, 2005b). Most of the previous studies used two Landsat images corresponding to wet and dry seasons. The regions where flooding occurred were extracted, usually accompanied by extraction of a vegetation index and a wetness index, for prediction of snail habitats. The different ranges for these environmental features, as obtained by different research groups, are summarized in Table 1. Most studies used the NDVI, or the second modified soil-adjusted vegetation index (MSAVI2), coupled with a Tasseled-cap transformed wetness index (Crist & Cicone, 1984), as these features are relevant for snail survival (Guo *et al.*, 2005; Zhang *et al.*, 2005). Interestingly, the studies reported slightly different ranges for the vegetation and wetness indices within the predicted snail habitats, depending on the time of the year and the spatial location the images were taken from. In addition, there were slight differences in data processing techniques to obtain the vegetation index and the Tasseled-cap wetness index, which might explain some of the differences in the ranges of these indices. For example, there are two Tasseled-cap transformations applied on TM images, one is based on raw image data or digital number, while the other arises from a reflectance factor analysis. The latter takes into account atmospheric effects. Furthermore, the studies were carried out in different regions with distinct environmental characteristics, which may have influenced the ranges of the vegetation and the wetness indices. Other studies categorised the two indices and assumed that the regions with the highest category were at the highest risk for occurrence of *O. hupensis* (Lin *et al.*, 2002; Zhou *et al.*, 2002a). Considering the above mentioned points and the fact that limited field data is available for validation, we defined the highest index categories as the high risk areas for snail proliferation in the present study.

In previous work, validation with ground truth data was performed only in those areas where snails were predicted. All models represented high sensitivity, especially when applied at medium- and large-sized areas of marshlands (Lin *et al*., 2002; Zhou *et al*., 2002a; Guo *et al*., 2005; Zhang *et al*., 2005). However, none of these studies assessed the specificity since the models were not validated for those regions predicted as snail-free. Owing to the lack of ground truth data in two of the three lakes of the current study area, we were not able to assess neither the sensitivity nor the specificity of our model.

It has been suggested that an early warning system should be set up in China to monitor subtle changes in intermediate host snail habitats due to global warming and other natural or man-made ecological transformations (Zhou *et al*., 2002b). GIS and remote sensing provide a means to map, predict and monitor disease trends, including the dynamics of vectors and intermediate hosts. In addition, these techniques allow to develop models that can be used to predict changes in disease patterns. In this study, we have identified approximately 163.6 km^2 of potential new *O. hupensis* habitats in the vicinity of Hongze, Baima and Gaoyou lakes, which account for 4.3% of the total snail habitats in China. The generated risk map illustrates the scale of the possible impact of global warming and other ecological transformations on the distribution of *O. hupensis*, and is useful to inform mitigation policies to avoid the possible spread of intermediate host snails, and hence schistosomiasis japonica.

8.6 Acknowledgements

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9: Discussion

This thesis is part of a larger investigation with the overarching goal to assess the effect of climate change on the spatio-temporal distribution of *S. japonicum* in China, which is carryed out by a joint group from Jiangsu Institute of Parasitic Diseases, National Institute of Parasitic Diseases, Chinese CDC, and Swiss Tropical Institute. The specific aims of this thesis were to contribute to the above-mentioned inquiry, and hence to explore the potential impact of regional climatic change and water resources development and management on the transmission of *S. japonicum*, and on the distribution of *O. hupensis* in China, with particular consideration to Jiangsu Province in the eastern part of China. Our working hypothesis was that the transmission of schistosomiasis will expand northwards due to climate warming and the South-to-North Water Transfer project (SNWT). Laboratory investigations were also carried out to explore the effect of temperature on the development of *S. japonicum* larvae in the intermediate host snail *Oncomelania*, and to investigate the interactions between parasite and snail according to temperature. Several spatio-temporal models were established to assess the relationships between climatic factors and infection prevalence, and to forecast the transmission intensity by Bayesian spatio-temporal analysis and time-series analysis. The potential impact of climate change on the spatial distribution at different scales of *O. hupensis* was assessed by GIS and RS techniques.

The current discussion is structured following the three main topics on the basis of the objective of the thesis, namely:

1) To assess the potential impact of global warming on *S. japonicum* transmission;
2) To assess the potential impact of water resources management and anti-flood policy on *S. japonicum* transmission;
3) To develop an integrated approach using GIS/RS techniques and spatio-temporal models for prediction of *S. japonicum* transmission.

9.1 Assessment of the potential impact of global warming on S. japonicum transmission

Consensus has been reached among climate modellers that the global mean temperature will increase by a range of 1.4 to 5.8°C between 1990 and 2100 based on large ensemble models (IPCC, 2001). An important feature of global warming is the strong heterogeneity both in space and time. For example, the observed temperature increases to date in continental and high latitude regions are higher than those in coastal and tropical regions. Meanwhile, worldwide winter temperatures have increased more pronouncedly than during the summer months (Easterling et al., 1997; Murphy et al., 2004).

In China, the current trend of warming is consistent with the global picture. In chapter 7, we reported that the January mean temperature in China increased by 0.96°C over the past 30 years, which is considerably higher than the 0.6°C average surface temperature increase observed worldwide over the past 100 years. Our study also confirmed the strong spatial heterogeneity of climate change within a single country. Larger temperature increases were observed in the northern part of China when compared to the south. The parabolic trend went through from west to east. Generally, the temperature which increased most over the past three decades is in the northeast part of China. This result substantiates earlier findings of higher temperature increases in the north and northeastern part of China (Wang & Gong, 2000). In chapter 6, a time-series analysis utilizing monthly mean temperatures over a 31-year period across Jiangsu Province further confirmed the warming phenomenon in the eastern part of China. In addition, the analysis indicates a growing temperature trend in the years to come.

It has been estimated that 150,000 death and 5 million DALYs have been lost annually on a global scale due to climatic change over the past 30 years (Ezzati et al., 2005; Patz et al., 2005). One research field which has received particular attention is the impact of climate change on vector-borne diseases, most notably malaria. Vectors, pathogens (parasites), and hosts survive and reproduce within certain optimal climatic conditions. Changes in climate will alter the transmission of vector-borne diseases in different ways, such as changing the survival and reproduction rate of the vector and of the pathogen (parasite) as well as changing vector activities (Patz et al., 2000; Hunter, 2003). Morgan and others have postulated that climatic changes are likely to affect the geographical distribution of freshwater snails, such as *Biomphalaria* spp., the intermediate hosts of *S. mansoni* (Morgen et al., 2001).

The impact of global warming on the transmission of schistosomiasis japonica can be grouped into (i) direct impact and (ii) indirect impacts (Figure 1)

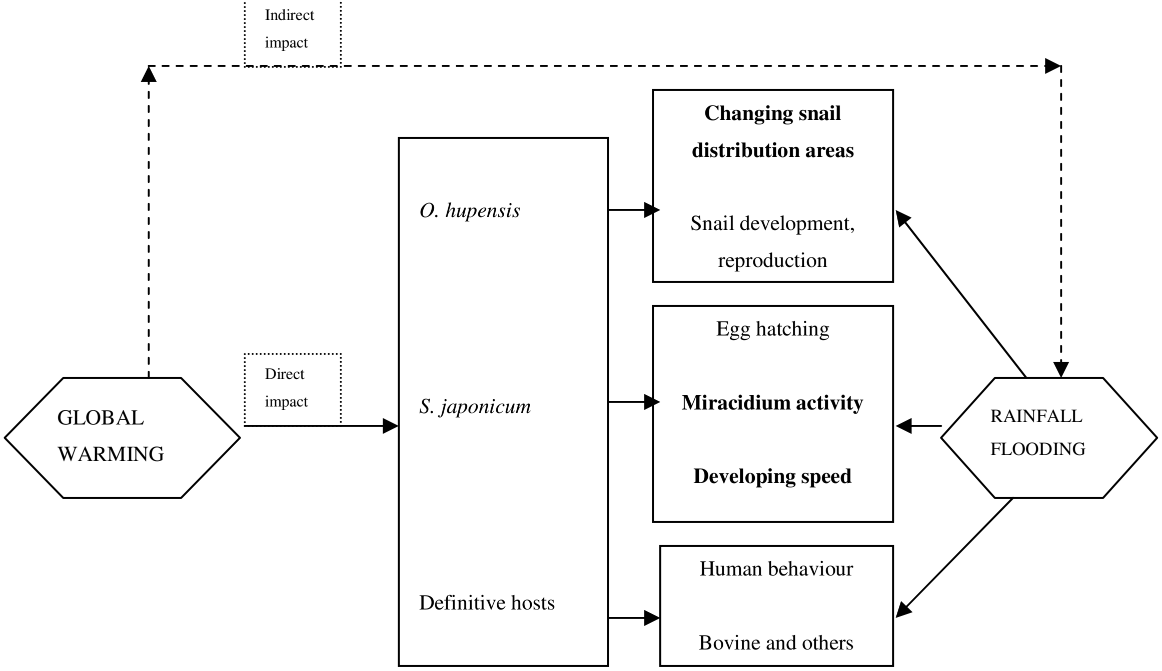


Figure 1 Direct and indirect impacts of global warming on the transmission of *S. japonicum*

9.1.1 Direct impact

(1) Impact on *O. hupensis*

Historical record shows that the distribution of *O. hupensis* in China is confined to areas where the January mean temperature does not drop below 0°C (Mao, 1990). This observation was confirmed by laboratory investigation by our group, i.e. *O. hupensis* die when the temperature drops below 0°C. In chapter 7, we reported that the 0-1°C isotherm in January, a crucial feature determining *O. hupensis* survival, has shifted from 33°15’ N latitude to 33°41’ N latitude between the 1960s and the 1990s. This shift translates to a surface area of 41,335 km^2, which potentially might become infested with snails. An estimated 20.7 million people are thus potentially at risk of *S. japonicum* infection in central China. In view of previous estimates that 652 million people are at risk of schistosomiasis worldwide (Chitsulo et al., 2000), our result of 20.7 million additional

Chinese who might come to live in an area at risk of schistosomiasis due to climate change translates to 3% on a global scale. Such a result may have profound public health and economic significance.

In addition to the geographic distribution, climatic change will also impact the development, reproduction and density of *O. hupensis.* Here, we only considered the low lethal temperature threshold of *O. hupensis*; future investigations should thus also focus on high lethal temperature limit and the Annual Growing Degree Days (AGDD) of the intermediate host snail. These issues need to be addressed both in the laboratory and in the field.

(2) Impact on *S. japonicum*

The development of *S. japonicum* larva in its intermediate host snail is determined by temperature (Mao, 1990). In chapter 5, we reported that the higher the temperature the shorter the incubation period of *S. japonicum* larva in *O. hupensis* within a certain temperature range. We also found that 15.3 °C was the theoretical lowest developing temperature for larva in its intermediate host. The 15.3 °C was used in our study to calculate the AGDD. The underlying rationale is that an increase in AGDD will enhance the transmission of schistosomiasis. Previous investigations showed that the snail infection rate increase with elevated temperature (Sun et al., 2000). The cercaria shedding is also determined by temperature. It has been reported that no cercaria shedding occurs in the temperature range of 1-3°C; only few cercaria were found at a temperature of 5°C. The optimal temperature range for cercaria infecting definitive hosts is 15-30°C (Mao, 1990). Temperatures outside this range will reduce the infection rate (Mao, 1990). The global warming, especial an increase in the the winter temperatures, is supposed to increase the snail infection rate, the amount of cercaria shedding and the infection rate in the definitive hosts.

In order to further our understanding at the regional effects of global warming on the transmission of *S. japonicum* in China, additional biological investigations are warranted, including determination of temperature thresholds for *S. japonicum* egg hatching. This biological information will help to build models to assess the impact of temperature on the transmission dynamics of schistosomiasis.

(3) Impact on definitive host behaviour

Definitive host contact with water is one of the key factors which facilitate the transmission of schistosomiasis. Human and more than 40 species of domestic and wild animals serve as reservoirs of *S. japonicum* in China (Wang et al., 2005). The behaviour of the definitive host contacting infested water varies according to season. Spring and summer are the high risk seasons to become infected. The warming phenomenon will increase infection risk by prolonging the time and frequency of water-contact.

9.1.2 Indirect impact

Global warming and the El Niño phenomenon has greatly changed the precipitation pattern in China (Zhou et al., 2002b). During periods of heavy rainfall, when the capacity of river is overwhelmed, excess water can create floods. The intensity of flooding is considered a key determinant for dispersal of snails. A prominent example is the huge flood which occurred in 1998 and led to enlarged snail habitats in the following 2-3 years. The impact of the 1998 flood on the dispersal of *O. hupensis* has been evaluated by others (Zhou et al., 2002a). After the 1998 flood, the Government of China placed more emphasis on flood management as a mitigation strategy. In fact, a “32-character-policy” was formulated immediately after the 1998 flood. This policy consists of eight items. Since items 3, 4 and 6 are closely related, they are always executed simultaneously in any enclosed land management project. Contents of these three items are as follows: 3) leveling dykes between main levees, 4) returning reclaimed lands into lakes, 6) relocating residents to form new township. In the next section, we will explain how these policies are related to the transmission of schistosomiasis (Zhou et al., 2005).

9.2 Assessment of the potential impact of water resources management and anti-flood policy on S. japonicum transmission

Water resources development is growing at a rapid pace in terms of total number and total area under irrigation. Large dams are an important international issue because nearly half of the world’s large rivers have at least one dam. Most of dams and irrigation systems are constructed to meet the demand of a prosperous economy and an expanding population. Large dams generate 20% of the world's electricity; 30-40% of the world's irrigated land relies on dams (WCD, 2000).

Large dams often have negative environmental effects, such as loss of aquatic biodiversity, creation of wetlands, and cumulative impacts on water quality. Controversy has surrounded some of the largest dams, including India's Sardar Sarovar project, Chile's Bio Bio river dam, Malaysia's Bakun dam, and Namibia's Cunene river dam. These disputed projects have been the focus of civil protest and international criticism (IRN, 2006).

The infrastructure of water resources projects in developing countries often affect water-related diseases including schistosomiasis (Steinmann et al., 2006), malaria (Keiser et al., 2005a), lymphatic filariasis (Erlanger et al., 2005) and Japanese encephalitis (Keiser et al., 2005b). For example, many dams contribute to the enlargement of the snail habitats and consequently deteriorate schistosome-endemic situation. The number of people who live in close proximity to large dam reservoirs (within 5 km buffer zone) and live in irrigated areas is about 100 million in the world, with the highest proportion of 53.2% in sub-Saharan Africa. In Southeast Asia and the Western Pacific regions, 10.1 million people live in at-risk areas, among which China account for 99% (Steinmann et al., 2006).

China has an impressive history of water resources development projects. The oldest dam is the Dujiang Dam, a 2,200 year-old project that still irrigates 800,000 hectares of farmland (Lei, 1998). China has almost as many large dams as the rest of the world combined, which illustrates the important role that China plays in the international dam-building community (Figure 2) (WCD, 2000).

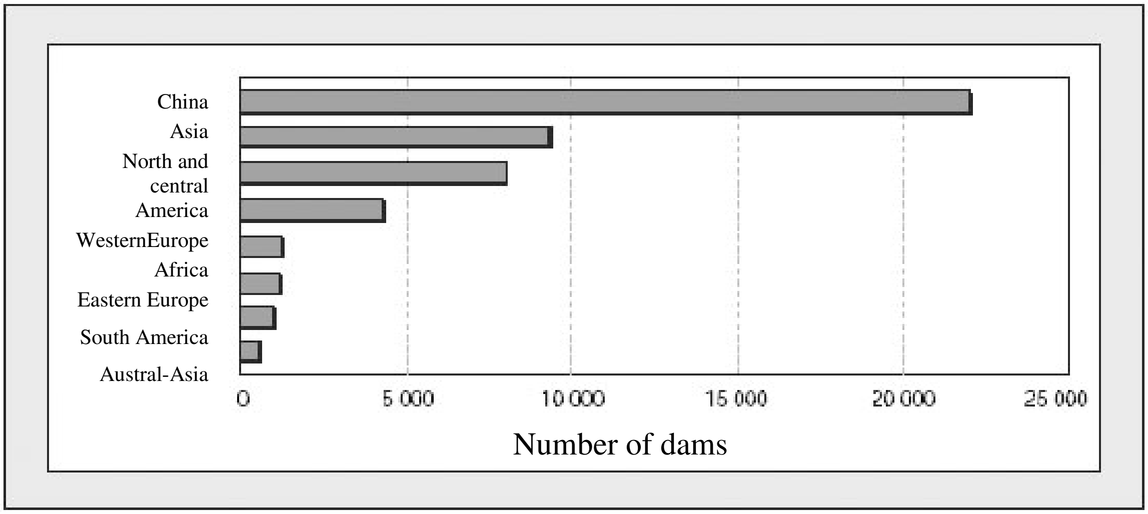
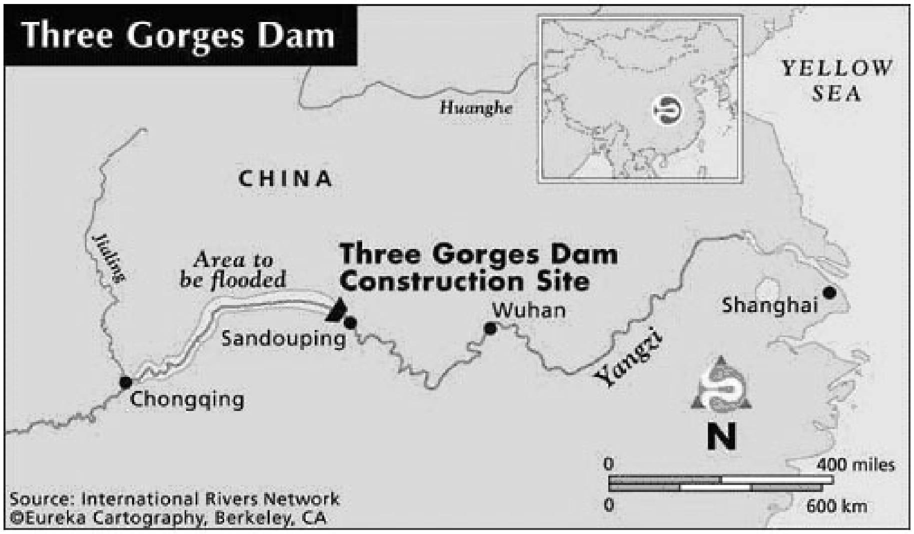


Figure 2: Regional distribution of large dams in 2000 (Report of the WCD, 2000)

In China, the average volume of water resources per capita was only 2220 m^3 in 1997, which ranks at position 121 among all other nations in the world. By the next 50 years, it is predicted that China will reach the threshold of water stress. The water resources distribution of China also shows great spatial and temporal variations (Zhou & Tol, 2004). The construction of the SNWT project is going to alleviate water shortage by transporting water from the Yangtze River in the south to rivers in the north. The project is by far one of the largest infrastructure constructions in China in terms of investment and complexity. In chapter 6, 7 and 8, we address the potential impact of the construction of SNWT project on the distribution of snail habitats at both the micro- and meso scale due to global warming. We conclude that the construction of the SNWT project (eastern line) will amplify the negative effect of global warming by introducing snails from schistosome-endemic region to the potential transmission region.

In China, another huge dam, namely the Three Gorges Dam (TGD) is under construction (see Figure 3). In addition to physical size, the TGD will be the world's largest power plant and will displace more people than any other water resource project (approximately 1.5 million people). The WHO Commission on Health and Environment notes that the environmental impact of the TGD in central China might have a significant effect on the transmission of schistosomiasis in that region. Although schistosomiasis is not endemic and its intermediate host snail does not occur in the reservoir area, the ecological conditions are suitable for snail survival and reproduction. Particularly, schistosomiasis is endemic only 40 km downstream and 500 km upstream of the dam. There is considerable concern that snails might migrate from either upstream or downstream to the reservoir. In addition, subsequent to the construction of the TGD on the Yangtze River, the snail distribution and annual prevalence of human schistosomiasis could intensify in the downstream region of the dam (Xu et al., 1999; Xu et al., 2000).



Source: International Rivers Network
©Eureka Cartography, Berkeley, CA

Figure 3. Sketch map of the Three Gorges Dam

As mentioned above, the items 3), 4), 6) of an anti-flood policy are closely related to the transmission of schistosomiasis. To date, 2,900 km^2 of land was returned to lakes and rivers around Dongting lake, Poyang lake and the Changjiang river, resulting in a storage capacity increase of up to 13 billion m^3. However, the implementation of this programme embeds a latent risk to amplify the current transmission areas of schistosomiasis.

The large social implication of both TGD and anti-flood policy involves the relocation of people. Estimates say that a total of 10.2 million Chinese have been relocated because of dams. Statistics showed that among these relocated people, about 46% live in ‘extreme poverty’. Also a large number of residents have been resettled to form new township due to the anti-flood policy. The large population movement either from non-endemic region to endemic region or another way round will deteriorate the endemic situation of schistosomiasis. Non-immune people from non-endemic region can become easily infected and they may develop severe chronic schistosomiasis once they are in schistosome-endemic regions. The population from endemic regions is likely to introduce disease into new potential region for schistosmiasis. Therefore, appropriate health education and surveillance of migrating population engaged in high risk professions, such as fishermen and boatmen, are warranted.

9.3 Development of an integrated approach using GIS/RS techniques and spatio-temporal models for prediction of S. japonicum transmission

GIS and RS technologies have opened new avenues for managing, summarizing and mapping digital data, and been successfully applied on vector-borne and water-borne diseases (Hay et al., 2000; Bergquist, 2001; Brooker, 2002; Yang et al., 2005a). They facilitate prediction of disease transmission, and in turn provide guidance to local authorities in decision-making and policy planning for cost-effective resource allocation. However, GIS/RS cannot assess the influence of the climatic, demographic and socio-economic factors on the spatial heterogeneity of infection risk. Spatial statistical methods model the relation between risk factors and the infection of diseases, and allow making predictions. These models however are highly parameterized and are difficult to fit by maximum likelyhood methods. Bayesian modelling approaches using Markov Chain Monte Carlo (MCMC) algorithms enable model fit. Further improvements in computing speed rendered Bayesian spatial modelling the state of the art in disease mapping. The main dilemma is the lack of software which can be used to fit the models (Dunson, 2001; Basanez et al., 2004). The only exception is the recently developed WinBUGS software which can be used for specific spatial models and for small to moderate size spatial data.

Numerous studies have applied GIS and RS technologies for infection risk mapping and predictive modelling of schistosomiasis japonica and its intermediate host snail distributions in China, which has been reviewed in chapter 3. Maps offer a convenient platform to display prevalence and/or infection intensity data of schistosomiasis. In the thesis, we detected that 0-1°C isotherm has shifted from 33°15’ N latitude to 33°41’ N latitude over the past 30 years through GIS analysis. In chapter 8, a model based on flooding areas, NDVI and wetness index extracted from Landsat images was applied to obtain the snail habitats at a small spatial scale. Both findings provide helpful information for policy discussion, as high risk areas warranting special control efforts.

There is now a considerable body of literature pertaining to Bayesian-based spatial analyses of infection risk and disease. Raso and colleagues (2005) applied Bayesian geostatistical models to investigate influence of the demographic, ecological and socio-economic factors on the *S. masoni* distribution in Côte d'Ivoire. 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). In chapter 4, we applied Bayesian-based spatial statistical approaches to investigate the relationship between environmental factors and epidemiological data of *S. japonicum* in the Jiangsu province. The best-fit model suggested a negative association between NDVI and risk of *S. japonicum* infection while a positive relation between LST and *S. japonicum* infection prevalence. By modelling the effects of environmental variables, we could make predictions of infection risks in response to ecological transformations. The model also showed that spatial autocorrelation in Jiangsu province decreased dramatically from 1990 to 1992 and increased gradually thereafter. A likely explanation of this finding arises from the same period large-scale administration of praziquantel for morbidity control of schistosomiasis.

In chapter 6, another spatio-temporal model, harmonic time-series analysis, was applied to predict changes in the transmission intensity of schistosomiasis due to global warming in eastern China. The best-fit model estimated spatial changes over time and predicted risk maps of *S. japonicum* in Jiangsu province. Following this approach, we were able to identify high risk areas and capture transmission dynamics. In a next step, we will validate the model by using the true ground data.

The investigation of the impact of ecological transformation on the transmission of schistosomiasis is a complex process. Any climatic or ecological factor can influence each link of the loop structure of parasite-intermediate host-parasite-definitive hosts. Temperature, water and vegetation are the three main ecological factors which determine the distribution of the intermediate host and transmission of schistosomiasis (Mao, 1990; Yang et al., 2005b). Further studies are required to assess and quantify the impact of climatic and ecological factors other than LST, NDVI, AGDD and wetness index.

Table 1. The main factors determining the transmission of schistosomiasis

Indicator	Source
Ecological index	Meteorological center RS images
Temperature	
Air temperature	
LST	
Water	
Rainfall	
Flooding	
Wetness Index	
Vegetation	
Vegetation Index	
Demographic index	Survey
Sex	
Age	
Occupation	
Behaviour	
Socio-economic index	Questionnaire
Intervention	
Chemotherapy	
Snail elimination	

There is growing consensus that transmission of schistosomiasis is determined by climatic, demographic as well as socio-economic factors. The main factors were summarized in Table 1. The intervention on schistosomiasis can influence the transmission of the disease to a certain extent based on the presence and intensity of control activities. Socio-economic and demographic factors, as well as intervention effects are the key factors dominating the disease transmission. One needs to bear in mind the important role of bovines in the transmission of schistosomiasis in China; in some places they contribute more to transmission than humans, e.g. observed in the lake regions of China (Zhou et al., 2000). Therefore, further research is warranted for GIS/RS and spatial statistic approaches which take into account the aforementioned risk factors within the frame of integrated schistosomiasis control programmes.

Application of GIS/RS and spatial statistical modeling has proved most useful for assessment and monitoring of ecological transformation, hence is holds promise to make further progress in the control of schistosomiasis in China. Furthermore, this integrated framework can be extrapolated to other vector-borne or infectious diseases in China and worldwide.

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10: Conclusions and Recommendations

10.1 Conclusions

1. 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. 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. 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. Advances in GIS, RS and statistical methodology have opened new avenues to enhance our current understanding of spatio-temporal distribution of parasitic diseases. We found that environmental factors extracted from remote sensing images, namely NDVI and LST, are significantly related to the schistosomiasis prevalence during 1990-1998 in Jiangsu province. In addition, the spatio-temporal results revealed that control efforts, i.e. WBLP, are related to the variation of prevalence coincidently.

3. The relationship between developing speed of *S. japonicum* larva harbored in *O. hupensis* and temperature was investigated during the study. The minimum thermal limit is 15.3 °C at which development of *S. japonicum* larva is halted. At temperatures below 13 °C, the lower the temperature, the less active the snail were, and the higher the number of snails with closed operculum. The snails began to hibernate at a temperature of 11 °C. The hibernation rate of snails kept at 6, 3 and 1 °C were 56.7%, 91.7% and 100%, respectively. The temperature at which half of the snails were hibernating (ET50) was 6.4 °C. At temperatures below 13 °C it was also found that the lower the temperature the lower O. hupensis' oxygen intake.

4. There was a temperature increase in January in most of China, practically in the north-east part, over the past 30 years (1960s~1990s). The historical 0-1°C January isotherm, which was considered the approximate northern limit of *S. japonicum* transmission, has shifted from 33°15' N to 33°41' N, expanding the potential transmission area by 41,335 km^2. This translates to an additional 21 million people at risk

of schistosomiasis. Two lakes, namely Hongze and Baima are located in this new transmission area that form part of the proposed South-North water transfer project.

5. The southern part of Jiangsu Province has the higher AGDD than the northern part. The transmission intensity of the schistosomiasis in south Jiangsu was expected to be higher than that in north Jiangsu. By using harmonic time-series analysis based on 31 year's monthly mean temperature in Jiangsu province, the current study result verified the global warming hypothesis. Extrapolated values are unreliable since the standard error of prediction increases when the prediction value is far from the true data.

10.2 Recommendations

On the basis of our finding and conclusions, we put forward the following recommendations to deal with the impact of ecological transformations on transmission of schistosomiasis.

Firstly, improved surveillance and monitoring system is required in the potential transmission areas to detect changes resulting from global climate and ecological transformation promptly and intervene immediately. For instance, the routine snail survey should be set up in that region. The surveillance of migrating population engaged in high risk professions, such as fishermen, boatmen, should be strengthened.

Secondly, an early warning system should be set up to aid in modifying control strategies so as to alleviate parasitic disease subsequent to estimated environmental changes. It is recommended that a regional modeling approach should be adopted to assess the extent and severity of the effects of environmental changes.

Thirdly, appropriate health education should be carried out in the potential transmission regions. For instance, knowledge about the life cycle of the parasite, its transmission and the importance and methods of its prevention and treatment should be delivered through school education, posters, reading material, films, television, etc.

Fourthly, the improvement in hygiene and sanitation should be encouraged in the endemic and potential transmission regions, such as provision of safe water and sanitation.

Fifthly, more researches are required in order to gain a better understanding of the ecosystem damage, which will consequently impact the morbidity and mortality of disease. Therefore, collaboration among scientists from different scientific fields, namely public health, ecology, and the social and physical sciences, are strongly recommended to develop broad risk estimation to aid local, national and international governments and decision makers. In addition, the implement of schistosomiasis control activities should be well integrated with other sectors, e.g. water resources development and agriculture programme.

Sixthly, it should be emphasized that health risks due to climatic change are varied in different areas and will change with time evolvement. Appropriate control strategies must be frequently re-defined based on the precedent experience and the epidemiological research.

Finally, well-established surveillance and forecasting systems could be adapted and applied in other vector-borne or parasitic diseases, such as malaria, other food-borne trematodes.

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