Original Article

Dynamics of Rodent and Rodent-borne Disease during Construction of the Three Gorges Reservoir from 1997 to 2012*

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Abstract

Objective To investigate the impact of impoundment and active public health interventions on rodent populations and rodent-borne diseases in the Three Gorges reservoir region from 1997 to 2012.

Methods Surveillance data from 1997 to 2012 were extracted from the Public Health Surveillance System of The Three Gorges established in 1997. Temporal changes in the incidences of hemorrhagic fever with renal syndrome (HFRS) and leptospirosis, rodent density, pathogen-carrying rates, and their correlations were analyzed.

Results The average indoor and outdoor rodent densities decreased overall from 1997 to 2012. The average densities decreased by 47.72% (from 4.38% to 2.29%) and 39.68% (from 4.41% to 2.66%), respectively, after impoundment (2003-2012) compared with before impoundment (1997-2002). The average annual incidence rates of HFRS and leptospirosis were 0.29/100,000 and 0.52/100,000, respectively, and decreased by 85.74% (from 0.68/100,000 to 0.10/100,000) and 95.73% (from 1.47/100,000 to 0.065/100,000), respectively, after impoundment compared with before impoundment. Incidences of HFRS and leptospirosis appear to be positively correlated with rodent density in the reservoir area.

Conclusion This study demonstrated that rodent density and incidences of rodent-borne diseases decreased and were maintained at low levels during construction of the Three Gorges dam. Measures that reduce rodent population densities could be effective in controlling rodent-borne diseases during large-scale hydraulic engineering construction.

Key words: Three Gorges reservoir; Rodent density; Rodent-borne diseases

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INTRODUCTION

The Three Gorges Reservoir (TGR) in China, the world's largest hydropower project, was initiated in 1994 and was completed in 2009[1]. The Three Gorges Reservoir Region (TGRR) is located between latitude 28°56'-31°44' north and longitude 106°16'-111°28' east, with a total area of 58,000 km^2, involving 19 counties and municipalities between Chongqing and Yichang City. The construction period of the TGR was separated into three distinct phases, with phase III full implementation of the hydroelectric facilities from 2003-2009. The TGR first began storing water in 2003; since that time, water levels have increased more than 70 m to 135 m. After completion of the Three Gorges project in 2009, the water storage level went to 175 m and a huge reservoir 1084 km^2 in area and 39.3 billion m^3 capacity was formed. As a result, large areas of agricultural, forest, and grassland ecosystems will be inundated and 1.13 million people will eventually be resettled[1]. The natural environments, regional climates, and lifestyles of local residents in the TGRR have been affected. Although the Three Gorges hydropower project has great potential benefits for flood control, power generation, and navigation, its impact on population health has been a concern.

Before construction of TGR, health assessment surveys performed by experts in China indicated that hemorrhagic fever with renal syndrome (HFRS) and leptospirosis were diseases endemic to the TGRR. Rodents, as the host-animal of these diseases, are very sensitive to changes in their habitat environments due to food and habitat limitations, as well as climate change caused by rising water levels, which may lead to changes in density and species, thus leading to variation in disease transmission intensity[2-3].

In order to avoid outbreaks or epidemics of rodent-borne infectious diseases due to reservoir construction[4], many control measures, such as deratization and enhanced monitoring of rodent and rodent-borne infectious disease, were undertaken during reservoir construction. However, to our knowledge, the effects of the deratizations on the abundance and diversity of rodent species as well as incidences of rodent-borne diseases have not yet been assessed.

In this study, we investigated the dynamics of rodent-borne disease and rodent populations during implementation of deratization measures from 1997 to 2012. The information can be used to inform disease control measures for large-scale hydraulic engineering projects.

METHODS

The Public Health Surveillance System

The Public Health Surveillance System of the TGRR was established in 1997. Based on the historical epidemiology of rodent-borne infectious diseases, geographical landscape, flood situation, and rodent habits, rodent monitoring and assessment of the incidence of rodent-borne infectious diseases were conducted in 19 townships of five surveillance points in the TGRR near the Yangtze River. These five surveillance points were distributed throughout the Central Districts of Chongqing, Fengdu, Wanzhou, Fengjie, and Yichang (where the Three Gorges Dam is located). The distance between adjacent surveillance points is about 150 kilometers. The 19 townships are located at about the same altitudes and within 3 kilometers of the Yangtze River, as shown in Figure 1.

Surveillance of Rodent Density and Composition

Rodent surveillance surveys were conducted twice yearly in the TGRR from 1997 to 2012, on April 15th and September 15th. At least 130 medium-sized steel traps were set at each surveillance location in either indoor or outdoor areas (including crop fields, vegetable fields, and wastelands) likely to be habitats for rodent reservoirs, using the following approach. Traps baited with peanuts were set at night and recovered the next morning. One indoor trap was placed approximately every 15 m^2 and no more than three traps were placed in each household. Outdoor traps were placed in rows at intervals of approximately five meters, with 50-meter intervals between rows. Captured rodents were identified at a species level and their gender and maturity were recorded. The relative rodent densities were calculated using the following formula: rodent density = number of captured rodents/number of effective traps × 100%.

Hantavirus and Leptospira Detection in Lung and Kidney Samples

All captured rodents were transferred to the laboratory and their lung and kidney tissues collected. A minimum of 35 captured rodents were required from each surveillance location. No fewer than 35 rodents were evaluated for the presence of Hantavirus and *Leptospira* at every surveillance location during every survey. If this minimum was not met, rodents captured by other methods within the scope of the surveillance locations were collected to supplement the collection.

Lung tissues collected from the captured rodents under sterile conditions were immediately frozen in liquid nitrogen and sliced into 4-5 μm thick frozen sections and used for hantavirus antigen detection by direct immunofluorescence, as described previously[5].

Fresh kidneys collected from the captured rodents were cut into small pieces, immediately inoculated into Korthof's medium, and incubated at 28 °C. The cultures were evaluated weekly by dark field microscopy for up to two months. Standard strains were provided by China CDC.

Data Collection

HFRS and leptospirosis are notifiable diseases diagnosed by clinicians according to the unified diagnostic criteria issued by the Ministry of Health of the People's Republic of China. Detailed data of the two kinds of infectious diseases cases are reported to the Chinese Notifiable Disease Reporting System (NDRS).

Statistical Analysis

Rodent densities and incidences of HFRS and leptospirosis were compared across different years as well as before (1997-2002) and after (2003-2012) impoundment. Spearman's correlation was tested among incidences of HFRS and leptospirosis, rodent density, and the frequency of rodents that carried hantavirus and leptospira. Statistical analyses were performed using PASW Statistics for Windows, version 18.0 (SPSS, Inc., Chicago, IL, USA), and two-tailed P-values <0.05 were considered statistically significant.

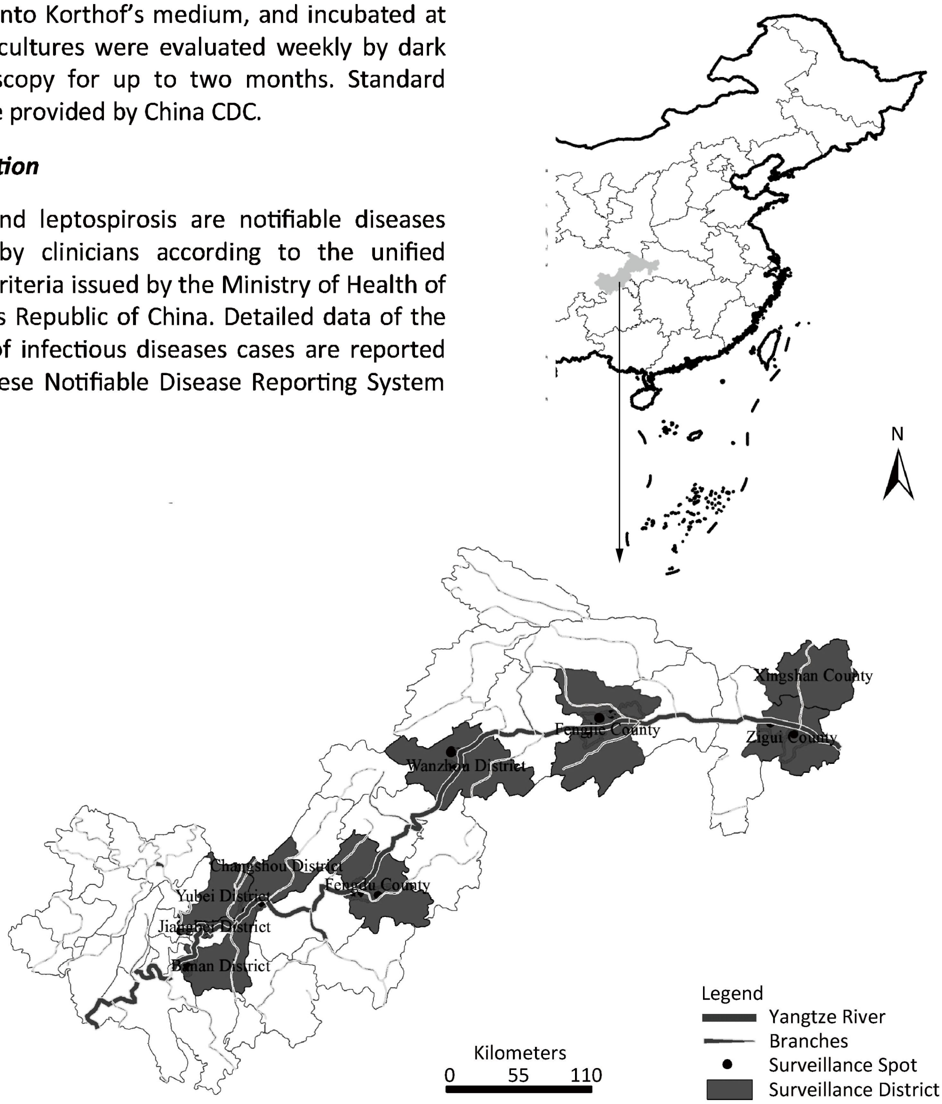

Figure 1. Distribution of surveillance points in the TGRR.

RESULTS

Temporal Changes and Impact of Impoundment on Incidences of HFRS and Leptospirosis

A total of 26 cases of HFRS were reported (average annual incidence rate 0.29/100,000) from 1997 to 2012, with 20 and 6 cases reported before and after impoundment, respectively. A total of 53 cases of leptospirosis were reported (average annual incidence rate 0.52/100,000) from 1997 to 2012, with 44 cases reported before impoundment and 9 cases after. Overall decreasing trends in the average annual incidence rates of both HFRS and leptospirosis were observed in the TGRR from 1997 to 2012, with annual incidence rate variations by year (Figure 2). After impoundment, the average annual incidence rate of HFRS and leptospirosis decreased by 85.74% (from 0.68/100,000 to 0.10/100,000) and 95.73% (from 1.47/100,000 to 0.065/100,000) respectively, compared with before impoundment.

Although there were a limited number of reported cases during the study period, the seasonal distribution of HFRS and leptospirosis cases by month in the TGRR showed that leptospirosis occurred most frequently from July to October, during which 80.85% of cases were reported; in comparison, more HFRS cases were reported in the spring (Figure 3).

Temporal Changes in Rodent Density

A total of 58,690 effective indoor traps were set from 1997 to 2012 and 1725 rodents were captured; a total of 90,363 effective outdoor traps were set, and 2891 rodents were captured. The average indoor rodent density was 2.94%, with the highest and lowest recorded densities in 1997 (6.75%) and 2003 (1.37%), respectively. The average outdoor rodent density was 3.02%, highest in 1997 (7.19%) and lowest in 2006 (1.90%). We observed an overall decrease in the indoor and outdoor rodent density in the TGRR over time (Figure 4).

The captured rodents consisted mostly of *Rattus norvegicus*, *Mus musculus*, and *R. flavipectus*, as well as *Apodemus agrarius* and *Insectivora,* which are the known hosts of hantavirus and *Leptospira*[6]. Analysis by habitat revealed that the dominant indoor species were *R. norvegicus* (52.70%), *M. musculus* (26.32%), and *R. flavipectus* (15.19%), while *Insectivora* (48.39%), *R. norvegicus* (16.05%), and *A. agrarius* (12.21%) were the major species captured outdoors.

The indoor and outdoor densities of different key rodent species changed differently over time (Figure 5). For instance, among indoor densities, *R. norvegicus* and *M. musculus* showed an overall decline, while the density of *R. norvegicus* declined substantially from its maximum in 1997 (4.66%) to its minimum in 2009 (0.46%). The density of *R. flavipectus* was low from 1997 to 2006, increased sharply in 2007, and peaked in 2008 (1.35%). Finally, the indoor density of *A. agrarius* showed no significant fluctuations over time. Among outdoor densities, *R. norvegicus* and *A. agrarius* peaked in 1997 (2.01% and 1.52%, respectively), followed by a significant decline to their minimum densities in 2008 (0.14%) and in 2004 (0.21%), respectively. The

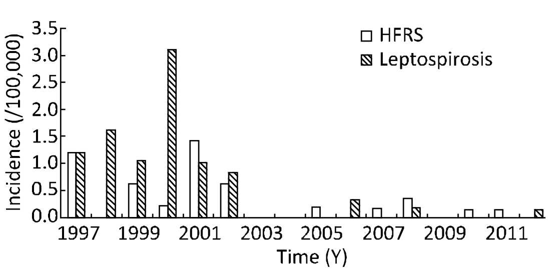

Figure 2. Annual incidences of HFRS and leptospirosis in the TGRR, 1997-2012.

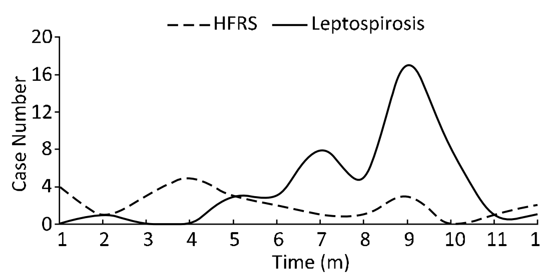

Figure 3. Seasonal distributions of HFRS and leptospirosis cases by month in the TGRR, 1997-2012.

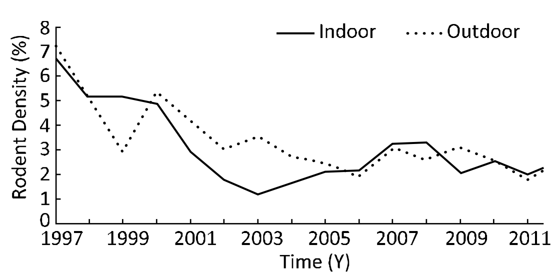

Figure 4. Temporal changes in indoor and outdoor rodent densities in the TGRR, 1997-2012.

densities of *M. musculus* exhibited three peaks in 1998 (0.56%), 2002 (0.88%), and 2010 (0.38%), and remained relatively low in the other years. Finally, the density of *R. flavipectus* rose slightly after 2007 (Figure 5).

Impact of Impoundment on Rodent Density

The average indoor rodent density decreased significantly from 4.38% before impoundment to 2.29% after impoundment (χ^2_{indoor}=193.40, P<0.05). The average outdoor average rodent density decreased significantly from 4.41% before impoundment to 2.66% after impoundment ($\chi^2_{outdoor}$=188.40, P<0.05). Among different rodent species, the densities of *R. norvegicus* and *M. musculus* decreased after impoundment, while that of *R. flavipectu* increased after impoundment (Figure 6).

Pathogens Carried by Rodents

From 1997 to 2012, 5758 rodent lung samples and 6310 rodent kidney samples were collected and tested for the presence of rodent-borne pathogens. Of the rodent lung samples tested for hantavirus, 117 (2.03%) were positive. The positivity rate increased from 2006 to its maximum in 2010 (6.61%) (Figure 7). Among all test-positive rodents, the proportion of *R. norvegicus* was the highest (56%). Of 6310 rodent kidney samples tested for *leptospira*, the average positivity rate was 0.97%, with a maximum of 2.39% in 2009 (Figure 7). Of all tested positive rodents, the proportions of *A. agrarius* and *R. norvegicus* were higher than those of other rodent species, at 32% and 26% respectively.

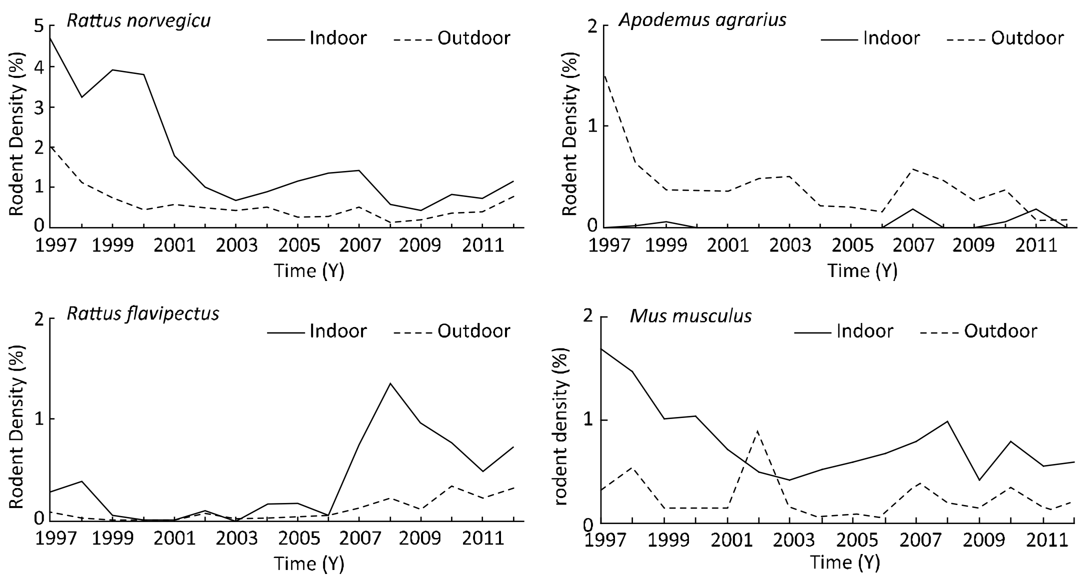

Figure 5. Indoor and outdoor rodent densities of key rodent species in the TGRR, 1997-2012.

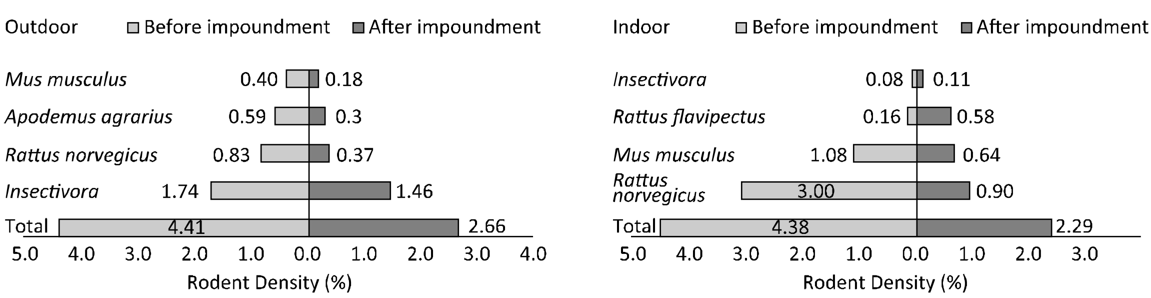

Figure 6. Changes in indoor and outdoor densities of different rodent species before and after impoundment.

Correlation among the Incidence of HFRS and Leptospirosis, Rodent Density, and Rodent Pathogen-carrying Rates

Analysis of the correlations among the incidence of HFRS and leptospirosis, rodent density, and the pathogen-carrying rates of the rodents indicated that rodent density was positively correlated with incidence of HFRS (r=0.54, P=0.03) and leptospirosis (r=0.74, P<0.01). There was no correlation between the pathogen-carrying rates of the rodents and the incidences of HFRS and leptospirosis (Tables 1 and 2).

DISCUSSION

The construction of large-scale water conservation projects not only affect natural environments and regional climates, but may also impact lifestyle[7]. These changes are often accompanied by outbreaks or epidemics of natural-focal infectious diseases, insect-borne infectious diseases, waterborne disease, and endemic disease in the reservoir regions[8-12].

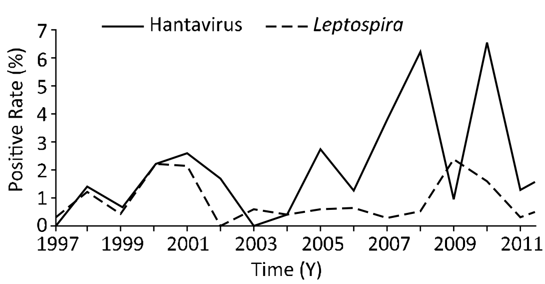

Figure 7. Proportion of rodents carrying Hantavirus and Leptospira, 1997-2012.

Previous studies showed that leptospirosis and HFRS were endemic in the TGRR[13]. Rodents are the most important vectors of these diseases. The TGRR is characterized by weed overgrowth, abundant rainfall, and humid climate. It is located in a subtropical monsoon climate zone suitable for rodent survival and proliferation[6,14-15]. *R. norvegicus, A. agrarius, Insectivora*, and *M. musculus* as the host animals of leptospirosis and HFRS pathogens are widely distributed in the TGRR[16]. The environmental impact assessment of the Three Gorges Project suggested that the rodent population would migrate from inundated areas to regions of higher altitude due to riding water levels following impoundment, potentially leading to a sudden localized increases in rodent densities and increased transmission of rodent-borne pathogens[16-17]. In order to prevent outbreaks of rodent-borne diseases, sanitary clearance of the bottom of the reservoir and deratization were performed before every impoundment during the construction of the TGRR. Large-scale deratizations were carried out three times: in 2003 (when the Three Gorges reservoir first began storing water), 2006, and 2008. Rodent densities below 1% are defined as acceptance criteria and predictive thresholds for HFRS, and HFRS is rare when the rodent density is below 1%[18]. After each deratization effort, the rodent density decreased sharply (3.72% before 2003 to 0.15% in 2003; 1.98% before 2006 to 0.46% in 2005; and 3.41% before 2008 to 0.54% in 2008) and was also much lower than 1%. Analysis of surveillance data over 16 years, revealed a general decrease in both indoor and outdoor rodent densities and sharp decreases after impoundment compared with before impoundment. The predicted phenomenon of rapid rodent density

Table 1. Pearson's Correlation Coefficients(r) among the Incidence of HFRS, Rodent Density and Pathogen-carrying Rates of Rodents in the TGRR, 1997-2012

Variable	Rodent Density	Incidence of HFRS	Hantavirus Carrier Rate
Rodent density	1.00	-	-
Incidence of HFRS	0.54 (P<0.05)	1.00	-
Hantaanvirus-carrying rate	-0.24 (P=0.37)	-0.064 (P=0.81)	1.00

Table 2. Pearson's Correlation Coefficients(r) among the Incidence of Leptospirosis, Rodent Density and Pathogen-carrying Rates of Rodents in the TGRR, 1997-2012

Variable	Rodent Density	Incidence of Leptospirosis	Leptospira Pathogen Carrier Rate
Rodent density	1.00	-	-
Incidence of Leptospirosis	0.74 (P<0.05)	1.00	-
Leptospira-carrying rate	0.20 (P=0.46)	0.38 (P=0.14)	1.00

increase due to impoundment did not occur.

During impoundment of the reservoir, the limitations on food source and the reduction and change in habitat with rising water levels may affect the composition and distribution of rodent populations[2]. Our study showed that *R. norvegicus, M. musculus*, and *R. flavipectus* were the dominant indoor rodent species in the reservoir region. The average indoor *R. norvegicus* density was 1.55%. *Insectivora*, *R. norvegicus,* and *A. agrarius* were the dominant outdoor rodent species, with average densities of 1.55%, 0.51% and 0.39%, respectively. The compositions of the dominant species did not alter after impoundment. Compared with the results from national vector surveillance sites between 2005 and 2012[19], the density of these dominant rodent species in the TGRR was higher, although the density of these dominant species decreased after impoundment. *A. agrarius* and *R. norvegicus* were very important reservoir hosts of the causative pathogens of HFRS and leptospirosis in the TGRR, which are consistent with previous survey results and shows the potential risk of disease transmission in the TGRR. However, exception indoor *R. flavipectus* density increased significantly after impoundment and became the predominant species in 2008-2009. This observation might due to the tolerance of *R. flavipectus* to drugs used for deratization and habitat change, such as the newly built houses for local immigration in the reservoir region after relocation, with harder floors are not suitable for ground-burrowing rodents such as *R. norvegicus*, granting the species a fitness advantage over other rodent competitors. In order to reduce the adverse impact on the environment, the drugs used for deratization included ingredients such as lime that are stable in water. In addition, the measures included disposal of the dead rodents and baits.

HFRS and leptospirosis are closely associated with rodent densities, rodent pathogen-carrying rates, frequency of human-rodent contacts, and human immune levels[20-25]. Variations in the incidences of these rodent-borne diseases are associated with fluctuations in rodent population density and can be accurately predicted from analysis of the population dynamics of the rodent hosts[3,22,26-27]. In this study, we consistently observed a positive correlation between rodent population densities and the incidences of HFRS and leptospirosis. This correlation suggests that measures that directly reduce rodent density, including deratization, can effectively control rodent-borne diseases. Compared with the incidences before impoundment, the average incidences of HFRS and leptospirosis after impoundment decreased more in the TGRR than the average national level in the corresponding period. This can be attributed to the lower rodent density, the large number of rural residents in this area migrating to urban areas for better salary, and agricultural production transforming to citrus orchard after impoundment in the TGRR, factors that reduced the risks of transmission from rodents to humans[28].

Tian Sheng Qiao Hydropower Station, located on the border between the Guangxi Zhuang autonomous region and Guizhou province, has warm weather and humidity similar to the Three Gorges Reservoir region. In July 2000, a human outbreak of plague was reported in this reservoir region. The survey indicated that the environmental changes due to the rising water level resulted in a rapid increase in rodent density and population, resulting in increased pathogen transmission. The direct cause of the outbreak was the lack of deratization before impoundment. Our study results indicate that effective deratization before impoundment during construction of the Three Gorges Dam likely helped to decrease the rodent density and prevent outbreaks of rodent-borne diseases.

This study had several limitations. First, there is the potential for combined effects of environmental variations (temperature, rainfall, food availability, habitat and competitor et al.) on rodent density and species; however, we only assessed the effect of sanitary clearance of the bottom of reservoir and large-scale deratization, which were used as direct measures reduced rodent density. Second, HFRS and leptospirosis cases were identified by passive surveillance, so the number of cases was likely underreported. Finally, the limited coverage of the surveillance site might result in information bias due to use of surveillance data.

Environmental changes caused by impoundment and the associated water-level fluctuations after starting operation are large and rapid. The long-term responses of the rodent populations to the environmental changes as well as the long-term effectiveness of the control measures are not yet fully understood. The surveillance system described in this study could be useful for monitoring future demographic changes in rodent populations as well as predicting its impact on public health.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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