Potential Impact of Flood on Schistosomiasis in Poyang Lake Regions Based on Multi-Source Remote Sensing Images

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Research

Keywords: Schistosomiasis, Flood disaster, Remote sensing, Water extraction

Posted Date: October 20th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-92265/v1

Version of Record: A version of this preprint was published on February 22nd, 2021. See the published version at https://doi.org/10.1186/s13071-021-04576-x.

Abstract

Background

Flooding may be the most important factors contributing to the rebound of *Oncomelania hupensis* in endemic foci. This study aimed to assess the risk of *schistosomiasis japonica* transmission impacted by flooding around the Poyang Lake region using multi-source remote sensing images.

Methods

Normalized Difference Vegetation Index (NDVI) data collected by the Landsat 8 satellite was used as an ecological and geographical suitability indicator of *O. hupensis* snail habitats in the Poyang Lake region. The flood-affected water body expansion was estimated using dual polarized threshold calculations based on the dual polarized synthetic aperture radar (SAR). The image data were captured from Sentinel-1B satellite in May 2020 before the flood and in July 2020 during the flood. The spatial database of snail habitats distribution was created by using the 2016 snail survey in Jiangxi Province. The potential spread of *O. hupensis* snails after the flood was predicted by an overlay analysis of the NDVI maps of flood-affected water body areas. In addition, the risk of schistosomiasis transmission was classified based on *O. hupensis* snail density data and the related NDVI.

Results

The surface area of Poyang Lake was approximately 2,207 km^2 in May 2020 before the flood and 4,403 km^2 in July 2020 during the period of the flood peak, and the flood-caused expansion of water body was estimated as 99.5%. After the flood, the potential snail habitats were predicted to be concentrated in areas neighboring the existing habitats in marshlands of the Poyang Lake. The areas with high risk of schistosomiasis transmission were predicted to be mainly distributed in Yongxiu, Xinjian, Yugan and Poyang (District) along Poyang Lake. By comparing the predictive results and actual snail distribution, the predictive accuracy of the model was estimated as 87%, which meant the 87% of actual snail distribution were correctly identified as the snail habitats in the model predictions.

Conclusions

Flood-affected water body expansion and environmental factors pertaining to snail breeding may be rapidly extracted from Landsat 8 and Sentinel-1B remote sensing images. The applications of multi-source remote sensing data are feasible for the timely and effective assessment of the potential schistosomiasis transmission risk caused by snail spread during the flood disaster, which is of great significance for precision control of schistosomiasis.

Background

Schistosomiasis japonica, caused by infection with *Schistosoma japonicum*, is a zoonotic parasitic disease [1]. In China, schistosomiasis is mainly concentrated along the south of the Yangtze River basin, and has a substantial impact on human health and socioeconomic development [2, 3]. *Oncomelania hupensis* is a freshwater snail species and the only intermediate host of *S. japonicum.* [4]. *O. hupensis* is mainly distributed along the river system and plays a critical role in the transmission of schistosomiasis. Studies have shown that the geographical distribution of schistosomiasis is strongly associated with the distribution of *O. hupensis*[3]. *O. hupensis* is predominantly distributed in marshland and lake areas along the middle and lower reaches of the Yangtze River in the provinces of Hunan, Hubei, Jiangxi, Anhui and Jiangsu. This area covers a landmass of 3.484 to 3.611 billion m^2 and accounts for a geographic distribution of 97.32% to 98.9% of snail habitats in China [5].

Since China moved towards elimination of schistosomiasis in 2016, disease endemicity has been maintained at a historically low level in the country, with the exception of regions with extensive snail habitats [6]. Regular seasonal fluctuation of the water body level create favorable conditions for snail breeding in marshlands around Poyang Lake. Flooding in the area in 2017 has contributed to the expansion of snail habitats along Poyang Lake [7-9] by 490 billion m^2, accounting for 98% of newly-detected and re-emerging snail habitats in Jiangxi Province [10]. Additionally, infected bovines maintain a reservoir of schistosomiasis infection in the Poyang Lake region, acting as a source of onward transmission [11]. Recently, regions at schistosomiasis transmission have been identified by wild feces surveillance [12, 13], detection of infected snails by loop-mediated isothermal amplification (LAMP) [14, 15] and sentinel mice-base surveillance [16, 17].

Since June 2020, continuous heavy rainfall along the middle and lower reaches of the Yangtze River has resulted in severe flood disasters along the Yangtze River basin and around the Poyang Lake area in China. The highest recorded water level exceeded that of previous record highs following flooding in 1998, and has led to dyke collapse and water logging in many urban areas in China. Control of schistosomiasis in flood-affected areas has been impacted by increased contact with infested water during the fight against floods, and increased spreading of snails attributed to flooding. The aim of this study was to predict the expansion of *O. hupensis* snail habitats impacted by flooding and to assess the associated potential risk of schistosomiasis transmission in the Poyang Lake area using multi-source remote sensing image data and Sentinel-1B satellite radar images.

Methods

Study area

Poyang Lake, the largest freshwater lake in China, is located in the middle and lower reaches of the Yangtze River in the north of Jiangxi Province (N 28˚22' to 29˚45', E 115˚47' to 116˚45'). The ecological and geographical features of the Poyang Lake are suitable for snail breeding. The lake is fed by water from inland rivers between April and June, and by the Yangtze River between July and September, maintaining a high water level during the spring and summer seasons..

A total of 13 counties (cities, districts) are endemic for schistosomiasis endemic around the Poyang Lake area, including Nanchang, Xinjian, Jinxian, the high-tech zone of Nanchang City, Yongxiu, Gongqingcheng, Lushan, Lianxi, Hukou, Duchang, Poyang, Yugan and Wannian (Figure 1).

Snail distribution

Data on snail distribution was obtained from a snail survey carried out in Jiangxi Province in 2016 [10]. The geographical and environmental characteristics of snail distribution were extracted for the 13 counties (cites, districts) in which schistosomiasis is endemic, and the spatial database of snail distribution in Poyang Lake areas was created accordingly. A 75% subset of the snail distribution data was randomly selected as a model training dataset, and the remaining 25% were assigned as the model validation dataset.

Multi-source remote sensing images

Remote sensing image data collected by the Landsat 8 satellite, with a spatial resolution of 30 m following geometric correction, convolution interpolation and resampling, were extracted from the NASA EarthData database (https://earthdata.nasa.gov/). Operational Land Imager (OLI) multi-wave remote sensing images were obtained for May 2016, the time period during which the snail survey was conducted. Sentinel-1B synthetic aperture radar (SAR) images were obtained from the European Space Agency (ESA) Earth Online database (https://earth.esa.int/), and remote sensing image data were obtained from the Sentinel-1B dual-polarized (HV + HH) SAR data for May 15, 2020 corresponding to the time period before the flood and for July 14, 2020, corresponding to the peak flood time period. An interferometric wide swath mode was assigned as the image mode.

Remote sensing image data inversion

NDVI data were used as a measure of vegetation coverage in snail habitats, calculated using the following formula:

$$NDVI = \frac{NIR-R}{NIR+R}$$

where *NIR* indicates the reflectance in near-infrared wavelengths, and *R* indicates the reflectance in visible red wavelengths. Maximum and minimum NDVI values for snail habitats around the Poyang Lake area were calculated based on a dataset of 75% of snail distribution sites.

Flood-cased expansion of water body areas were identified using dual polarized threshold calculations for the flooding time period [18]. SAR images were segmented by estimation of small backscattering coefficient thresholds of water on SAR images. Segmentation results were saved as classification result files and classification results were post-processed. Incorrect extraction images were removed through a human-computer interaction system to yield the final water body data. Sentinel-1B satellite data were processed using the SAR Scape module in ENVI software version 5.3, which mainly included radiometric calibration, filtering processing, terrain correction and geocoding. Radiometric calibration allows the transformation of image intensity into a backscattering coefficient (σ^0), which was calculated using the following formula:

$$\sigma^0 = \frac{A^2}{K} sin\theta$$

where σ^0 is the backscattering coefficient of each pixel, *A* is the digital number of original images, *K* is an absolute calibration factor, and is an incident angle.

Because the extraction of the water body data may be interfered with by the intrinsic speckle noise in SAR images, a Frost filtering algorithm (5 × 5) was employed to control the output of a wave filter based on the local statistical characteristics of images. The specific side-view mode of SAR images may lead to the occurrence of foreshortening, layover and shadow in mountains with terrain undulations, which affects the correct analysis of imaging data. Due to the occurrence of terrain undulations in the study area, terrain corrections of SAR images were performed to reduce the error of the water body data caused by geometric characteristics. Geocoding and radiometric calibration of filtered intensity data were also carried out using a digital elevation model (DEM) to generate backscattering coefficient images with dual-polarized (HV + HH) geographic coordinate systems. The index used for the water body data extraction was calculated based on the backscattering coefficients for HV and HH polarizations using the following formula:

$$\mathrm{R} = \ln (10 \times \mathrm{HV} \times \mathrm{HH})$$

Risk prediction of schistosomiasis transmission

Areas neighboring snail habitats which overlapped with flooded areas were extracted from SAR data to determine possible snail distribution zones following flooding. Snail density was estimated from snail habitat-neighboring areas, and the NDVI values corresponding to snail distribution were calculated to predict potential snail spread and associated schistosomiasis transmission risk. A 25% subset of observed snail breeding sites were selected as a validation dataset, and the distribution of snail breeding sites predicted using model results in ArcGIS software version 10.1. Model predictions corresponding to the validation dataset were extracted and the predictive accuracy of the model assessed by identifying snail breeding sites correctly identified by the model.

Results

Distribution of *O. hupensis* snails around Poyang Lake areas

Results of a snail survey carried out in in Jiangxi Province in 2016 found snail habitats mainly distributed in 13 marshland and lake counties (cities, districts), including Nanchang, Xinjian, Jinxian, High-tech Zone of Nanchang City, Yongxiu, Gongqingcheng, Lushan, Lianxi, Hukou, Duchang, Poyang, Yugan and Wannian. A total of 1,257 habitat settings were identified, with marshlands consisting of 74.94% of all identified habitat settings. Among 763 snail habitats identified, 99.48% were marshland areas. In a marshland area covering 126,756.75 hm^2, snail habitats accounted for78,900.89 hm^2. Snails were detected in 519 settings with a density of living snails ranging from 0.000,1 to 6.497,2 snails/0.1 m^2 and 0.01% to 84.44% occurrence within surveyed frames. Among these, 12 settings were identified with a density of living snails at 1 snail/0.1 m^2 and greater located in northern coast of the Poyang Lake (seven settings in Lushan, four in Hukou and one in Yongxiu), and eight settings with 50% and higher occurrence of frames with living snailslocated in northern coast of the Poyang Lake (five settings in Lushan, two in Yongxiu and one in Hukou) (Table 1).

Environmental identification for suitable snail habitats

NDVI values were estimated with a range of -1 to 0.61 in the Poyang Lake area based on Landsat 8 remote sensing image data. A total of 75% of snail distribution sites were randomly sampled from snail habitats identified by field surveys as a training dataset to extract the optimum thresholds of the maximum and minimum value of NDVI, with 95% confidential intervals from 0.08 to 0.59. Figure 2 shows the distribution of suitable snail habitats.

Extraction of flood-cased water body expansion

Radar echo intensity was determined by brightness in SAR data. Because of low echo intensity in water bodies and high echo intensity in corresponding to land areas, water body areas in SAR images appeared as dark or black and the land areas as grayish white or dark grey. Pre-processed SAR images from Sentinel-1B satellite images for the time period before and after flooding are shown in Figure 3. The speckle noise was effectively inhibited, and a more obvious water-land boundary was seen on original radar images in which the water and land were well differentiated and the water profile was more distinct.

Figure 4 shows a histogram of pre-processed SAR image scattering values before and after flooding. There are two apparent peaks in the histograms in images presented in Figure 4, with segmented SAR image thresholds of between -25.5 and -24 dB before observed by the visual interpretation before and after flooding.

Segmentation results were saved as classification results and transformed to a vector file. Following post-classification data processing, incorrect extraction images were removed through a human-computer interaction to generate a final water body dataset for the Poyang Lake area for the May 15 and July 14, 2020 time period.

Changes in water body areas before and after the flood disaster

The distribution of water bodies in the Poyang Lake area was overlapped before and after flooding. The blue areas in Figure 5 indicate the distribution of water bodies before the flood, and red areas describe the expansion of water bodies during flooding. Examination of the main body of the Poyang Lake and neighboring water areas from Sentinel-1B SAR images showed that the water area was approximately 2,207 km^2 on May 15 and 4,403 km^2 on July 14, an increase of 2,196 km^2 compared to May and an increase of 25.4% on the historical mean level during the same period (3,510 km^2). The water body expanded by approximately 99.5% after flooding relative to the water body areas before flooding, mainly identified in Xinjian, Duchang, Poyang, Yongxiu and Yugan (Figure 5).

Risk Predictions of potential snail diffusion and associated schistosomiasis transmission after the flood

Data indicating flood-affected water areas were transformed into a binary image of potential snail habitat distribution. Areas of predicted snail diffusion exhibited a patchy clustered distribution. After submersion of snail habitats following flooding, snail habitats were likely to be in neighboring settings. Snail distribution was predicted to cover an area of approximately 759 km^2, mainly occurring in the east of Yongxiu, south of Lushan, southwestern Poyang, southwestern Duchang, northwestern Xinjian and northwestern Yugan. This suggested that areas of the possible snail diffusion were predominately concentrated in marshlands around Poyang Lake (Figure 6).

NDVI values of suitable snail habitats were calculated based on snail density data, with values ranging from 0.15 to 0.35 in high density snail habitats, 0.35 to 0.42 in medium density snail habitats, and from 0.08 to 0.15 greater than 0.42 in low density snail habitats. NDVI values of flood-affected areas were estimated and the risk of potential snail spread classified accordingly. We found areas at high risk of snail distribution predominantly located in northwestern Yongxiu, southwestern Duchang, south of Lushan and southwestern Poyang (Figure 7). These high risk areas are also indicative of neighboring areas suitable for snail breeding where snail habitats are likely to emerge following flooding, and with potential for schistosomiasis transmission. Validation of predicted snail habitats was carried out using observational data on snail breeding habitats in order to assess the predictive performance of models NDVI value of snail habitats ranged from 0.1 to 0.52 using the 25% validation dataset, with 87% prediction accuracy indicating that the NDVI values are a good predictor of snail habitats.

Multiple dykes were observed to collapse following flooding in Jiangxi Province. Three sites in Yongxiu and Poyang counties where dykes had collapsed were found to overlap with areas classified as snail distribution risk areas. The sites in Yongxiu and Poyang County where dykes were observed to have collapsed was predicted to be medium risk areas of snail distribution, (Figure 7), suggesting that snail habitats were likely to emerge in both sites.

Discussion

Schistosomiasis is a neglected tropical parasitic disease strongly associated with ecological and geographic factors. Changes in the natural environments which affect the breeding, reproduction and distribution of intermediate host snails, are likely to impact transmission of schistosomiasis [19, 20]. Previous research has found snail distribution to be closely correlated with vegetation, humidity and temperature, as well as with human and livestock activities with *O. hupensis* snails favoring marshlands, ponds and ditches. As the geographical location of schistosomiasis is determined by snail distribution, surveillance of snail habitats is an important component in the national schistosomiasis control program in China.

Flooding frequently occurs along the south and middle and lower reaches of the Yangtze River, areas which are endemic for schistosomiasis. Flooding is considered to be one of the most important natural factors impacting the rebound of schistosomiasis in endemic foci. Periods of flooding impact the geographical expanse, reproduction and growth of *O. hupensis* snails, particularly juvenile snails and snail eggs, which spread via water flow [21-23]. Additionally, flood discharge or dyke collapse may facilitate expansion of snail populations into embankments resulting in the re-emergence of snails in areas where snails had not previously been present [24].

Currently, the endemicity of schistosomiasis in China is declining and the country is progressing towards elimination [11]. Many challenges to schistosomiasis elimination remain, however, due to natural, biological and social factors [6]. Prevalence of schistosomiasis is high in 11 counties of the 13 counties (districts) in the Poyang Lake area in Jiangxi Province, with the exception of the high-tech zone of Nanchang City and Wannian County. In 2018, three egg positive individuals were identified in Yugan County (eight egg positive cases in China) and two egg positive bovines identified in Duchang County (two egg positive bovines in China) in 2019, suggesting that risk of schistosomiasis transmission of remains in the Poyang Lake area. Interestingly, these areas were identified as high risk transmission areas by this study. In areas characterized by vast marshlands, multiple grasslands, dense vegetation, difficulty in management of water levels, and extensive snail distribution where schistosomiasis was once hyper-endemic and transmission had been controlled or interrupted [9], *S. japonicum* transmission potential remains due to the distribution of *O. hupensis* snails following flooding. Relaxing of control interventions would therefore likely result in reemergence of schistosomiasis infection.

Remote sensing image data has been widely employed for the surveillance schistosomiasis and intermediate host snails habitats [26-29]. Satellite-based remote sensing collects ecological and geographical data, such as land coverage, vegetation, soil type, surface moisture and rainfall, which may be used to monitor environmental changes, thereby assessing the suitability of snail breeding habitats of association potential of schistosomiasis transmission [30-32]. Some limitations are inherent in data of this type however such as a short wavelength and potential effects of cloud amount and severe weather. Most notably, during flooding continuous cloudy and rainy conditions may lead to failure in the accurate acquisition of image data in flood-affected areas. Radar images, characterized by full-time and full-weather, high-coverage, high-resolution observations and high revisit rate are not affected by meteorological conditions or light levels, and have been widely employed in the fields of disaster monitoring, agriculture and oceanography [33, 34].

In the current study, the distribution snail habitats was estimated using Landsat 8 satellite remote sensing image data, and areas where water body overlapped before and after flooding identified using Sentinel-1B dual-polarized image data. The water body area was estimated to have expanded by approximately 99.5% in the Poyang Lake region after flooding relative to the water body area before flooding. Snail habitats are likely to emerge in flood-affected areas after flooding has receded. All of these regions were found to be adjacent to, or connected with, original snail habitats, predominantly distributed in southwest and northwest of Poyang Lake. Snail distribution was predicted to mainly occur mainly in Yongxiu County, Lushan County, Poyang County, Duchang County, Xinjian District and Yugan County. It is predicted that multiple regions at high risk of schistosomiasis transmission are located in Yongxiu County, Duchang County, Lushan County and Poyang County. The classification of potential snail habitats is consistent with the spatial distribution of schistosomiasis transmission risk in the Poyang Lake regions based on schistosomiasis case reports [29, 35].

Conclusion

Remote sensing techniques were an effective quantitative tool for the rapid assessment of snail distribution, providing insights into e schistosomiasis risk for informing control programs. It is recommended that monitoring of *O. hupensis* and epidemiological surveys of *S. japonicum* infections should be conducted by schistosomiasis control institutions in the coming 2 to 3 years, so as to prevent the spreading of snail populations and to reduce the risk of transmission of schistosomiasis.

Abbreviations

NDVI: Normalized Difference Vegetation Index, SAR: Synthetic Aperture Radar, OLI: Operational Land Imager, LAMP: Loop-mediated Isothermal Amplification, *O. hupensis: Oncomelania hupensis,* DEM: Digital Elevation Model，ENVI: Environment for Visualizing Images,

Declarations

Acknowledgements

We are very grateful to all workers in Jiangxi Institute of Parasitic Diseases for their guidance and support during the field work. We also thank staff of schistosomiasis department in National Institute of Parasitic Diseases, Chinese Center for Diseases Control and Prevention for their arrangements to accomplish the data analysis and interpretation.

Authors’ contributions

SX and SZL designed the study. ZC and DDL coordinated and carried out the field work. JBX, XYW,LJZ, YWH, JX and SX analyzed and interpreted the data and wrote the initial manuscript. SX and SZL participated in the coordination and revised the manuscript. All authors read and approved the final manuscript.

Funding

Science and Technology research project of Shanghai Municipal Health Commission (No. 20194Y0359, 20174Y0188), the Special Foundation of Basic Science and Technology

Resources Survey of Ministry of Science and Technology of China (No.2017FY101203), The High Resolution Remote Sensing Monitoring Project (No. 10-Y30B11-9001-14/16).

Availability of data and materials

The datasets analyzed during the present study are available from the corresponding authors upon reasonable request.

Ethics approval and consent to participate

This study does not involve ethic issues.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1 Distribution of snail habitats in Poyang Lake areas

County	Total				Marshland				Ditch			
	No. settings	No. settings with snails	Area of settings (hm^2)	Area of snail habitats (hm^2)	No. settings	No. settings with snails	Area of settings (hm^2)	Area of snail habitats (hm^2)	No. settings	No. settings with snails	Area of settings (hm^2)	Are sna hal (hr
Nanchang	107	103	12389.1	11953.88	107	103	12389.11	11953.88	0	0	0	0
Xinjian	181	62	16248	9760.98	79	62	11999.03	9760.98	28	0	726.00	0
Jinxian	86	65	9160.01	4523.00	81	65	7040.62	4523.00	0	0	0	0
Nanchang High-tech Zone	16	1	2220.38	12.00	16	1	2220.38	12.00	0	0	0	0
Lianxi	58	35	3786.23	1531.08	41	32	3502.51	1488.78	12	3	223.73	42.
Hukou	102	18	4919.67	226.86	29	18	1424.00	226.86	6	0	155.94	0
Yongxiu	39	39	5011.71	5011.71	39	39	5011.71	5011.71	0	0	0	0
Duchang	253	183	42186.6	14505.77	217	183	42186.56	14505.77	0	0	0	0
Lushan	79	53	10552.8	5420.96	60	52	9274.88	5409.08	4	1	106.42	11.
Gongqingcheng	58	22	1613.12	606.02	57	22	1612.79	606.02	1	0	0.33	0
Poyang	145	111	18498.4	13749.08	144	111	18418.41	13749.08	1	0	80.00	0
Yugan	122	71	11653.7	11653.74	71	71	11653.74	11653.74	0	0	0	0
Wannian	11	0	225.5	0	1	0	23	0	0	0	0	0
Total	1257	763	138465.19	78955.07	942	759	126756.75	78900.89	52	4	1292.42	54.

Figures

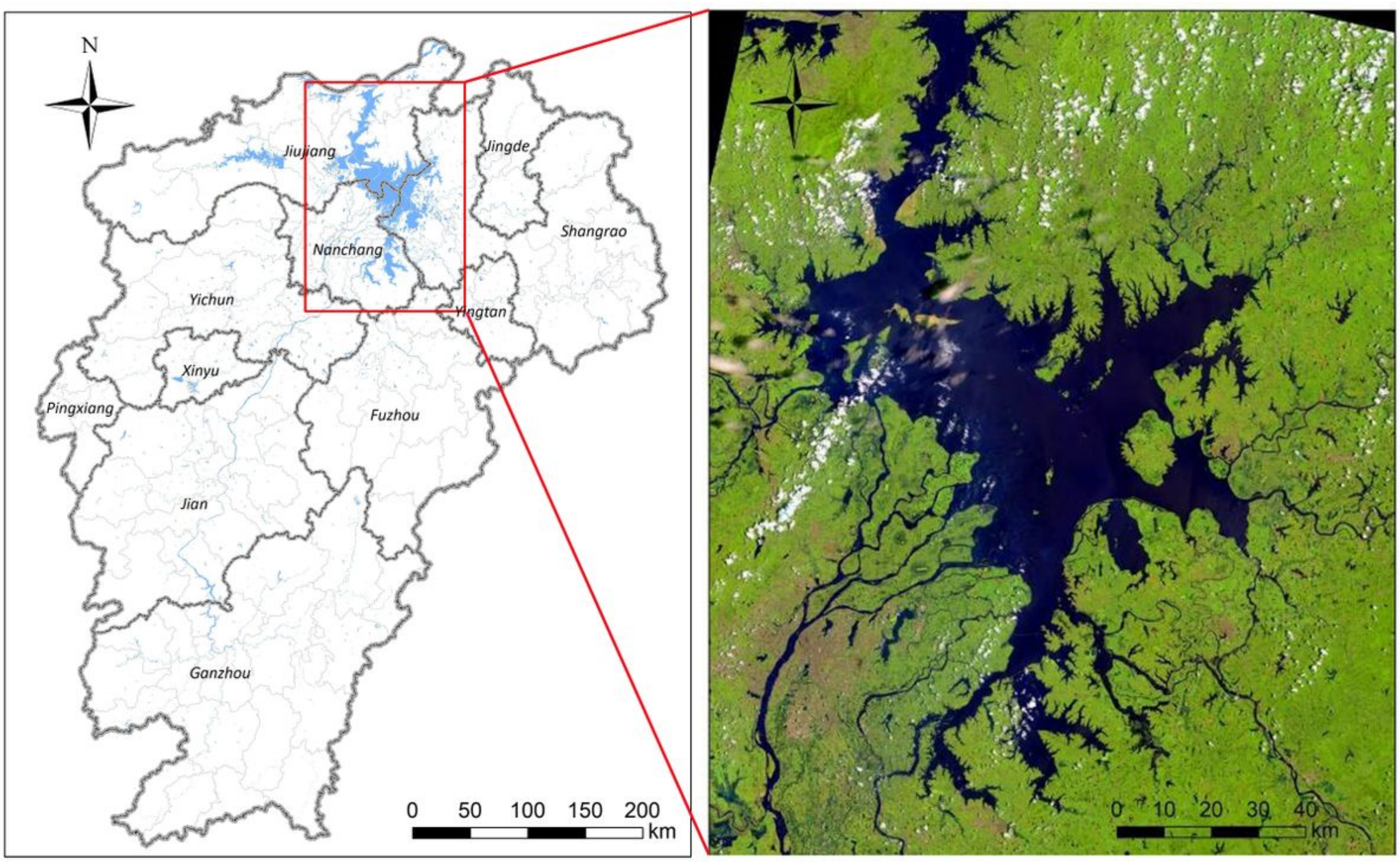

Figure 1

Geographical location of the study area. Poyang Lake is located in north of Jiangxi Province and northern coast of the middle and lower reaches of the Yangtze River and the natural geographical features of the Poyang Lake are very suitable for snail breeding. A total of 13 counties (districts) around the Poyang Lake areas, where schistosomiasis is prevalent, were included in this study. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

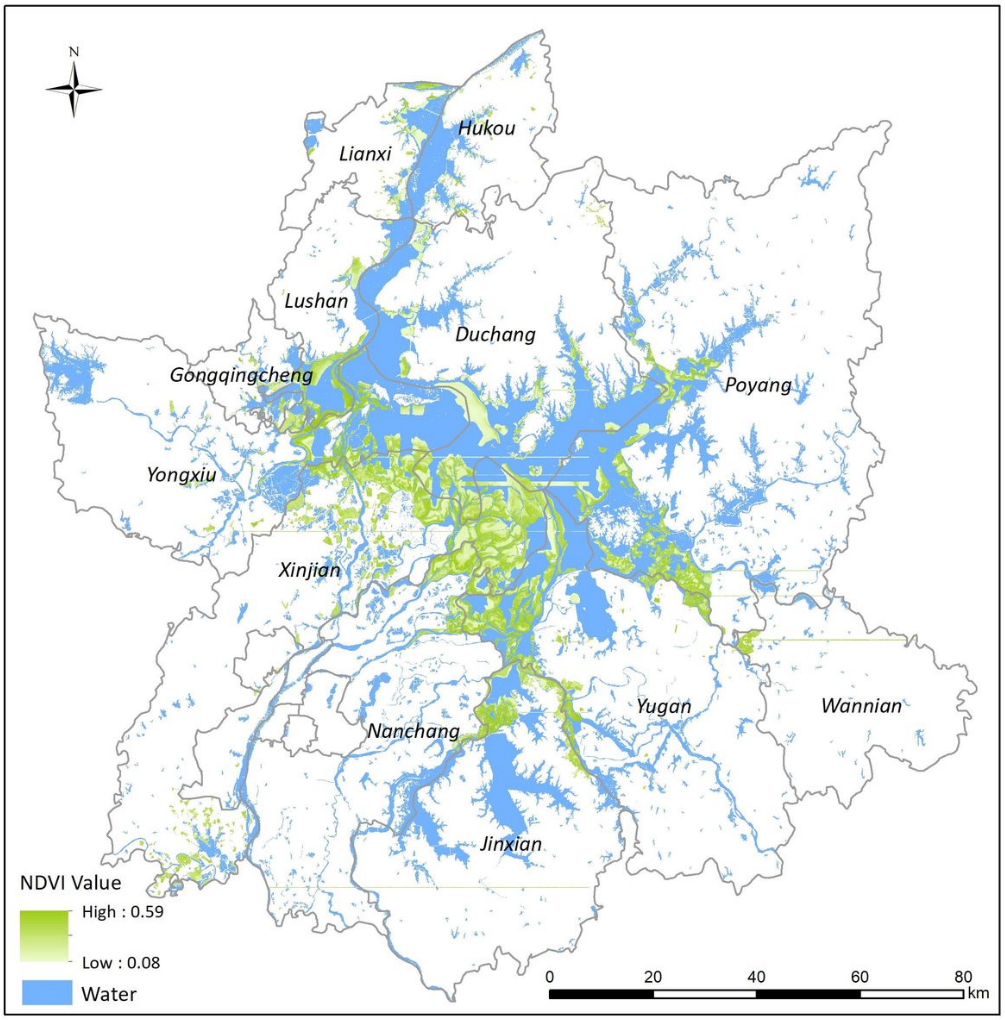

Figure 2

Distribution of snail habitats in Poyang Lake areas. Snail data were captured from the 2016 snail survey in Jiangxi Province. Normalized Difference Vegetation Index (NDVI) was employed to measure the vegetation coverage in snail habitats, which was collected from Landsat 8 satellite remote sensing images from the NASA EarthData database Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

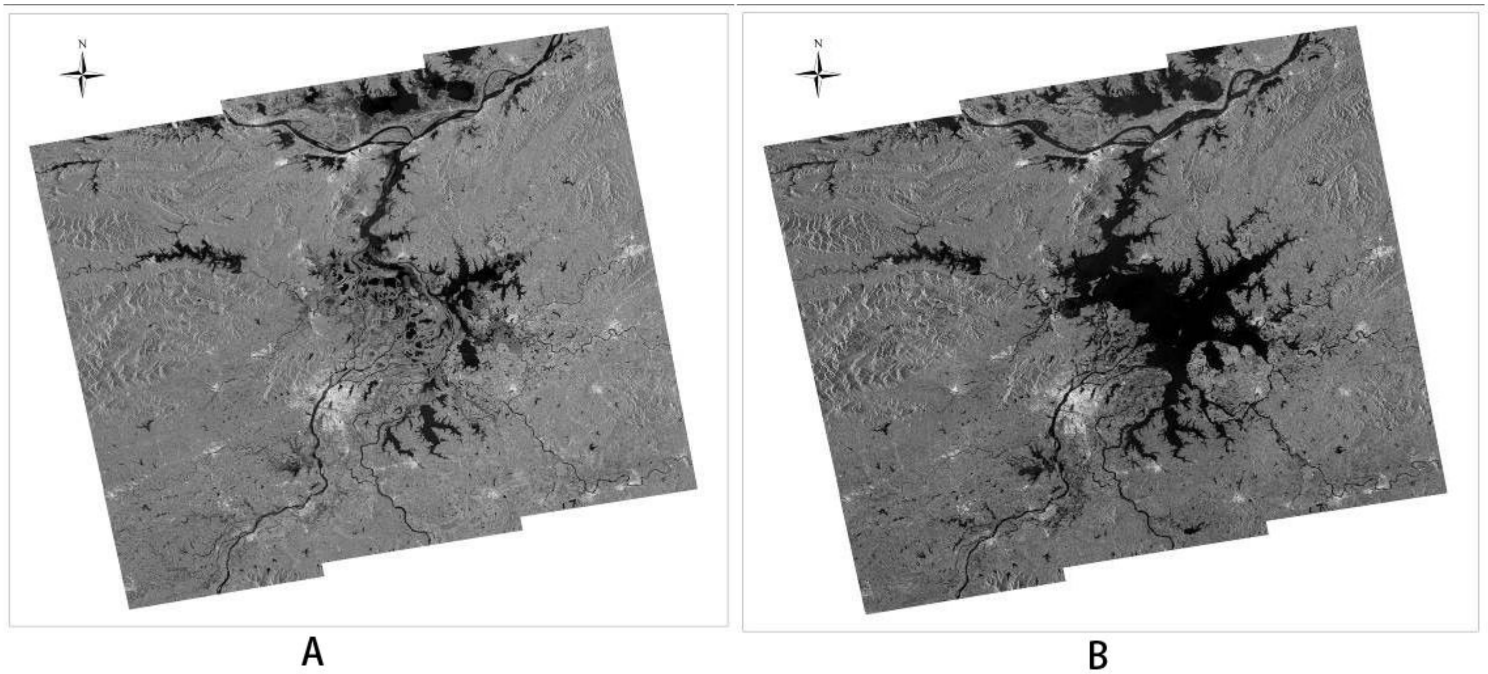

Figure 3

Water body extraction from remote sensing image data in Poyang Lake areas. Image data were collected from ESA Earth Online database of Sentinel-1B dual-polarized (HV + HH) SAR data on (A) May 15, 2020 before the flood and (B) July 14, 2020 during the period of the flood peak.

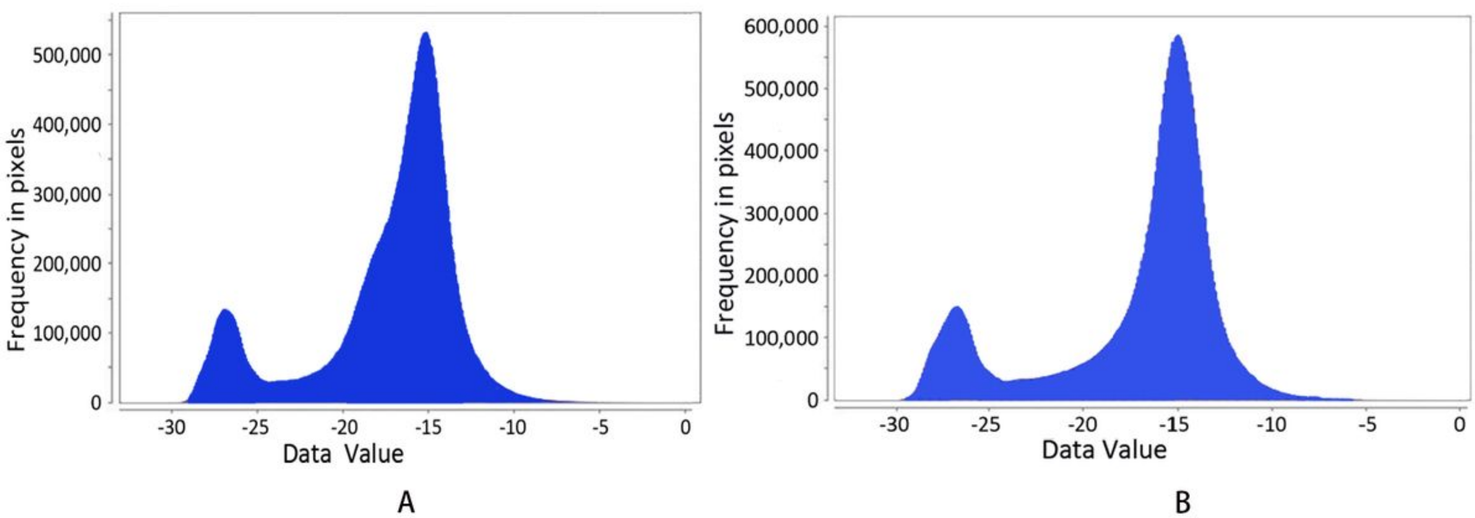

Figure 4

The histogram of scattering values of SAR radar images for waterbody extractions. A, an image captured on May 15, 2020; B, an image captured on July 14, 2020. There are two apparent peaks in the histograms of image and the thresholds for segmented SAR images were -25.5 and -24 dB before and after the flood disaster.

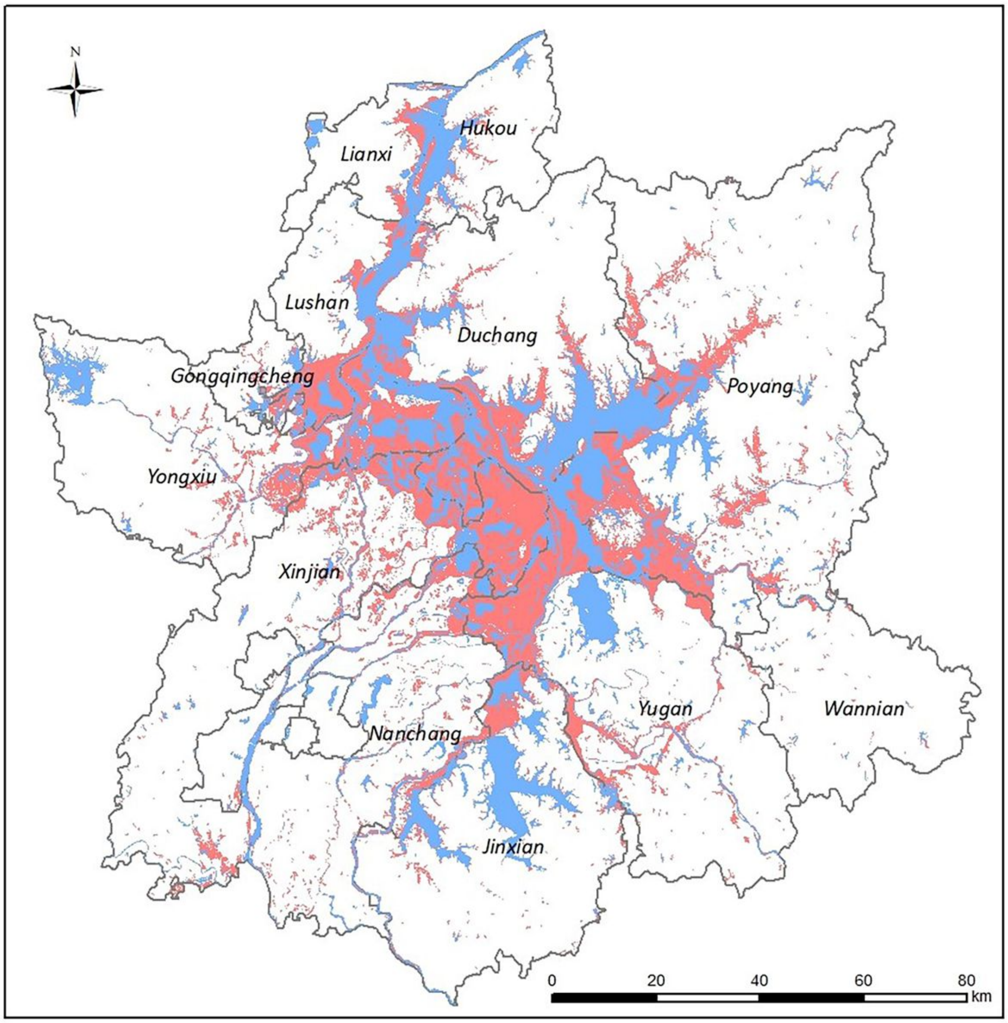

Figure 5

Changes of water bodies before and after the flood disaster in Poyang Lake areas. The blue regions indicate the water bodies on May 15, 2020 before the flood, and the red regions indicate the expansion of water bodies on July 15 during the flood period. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

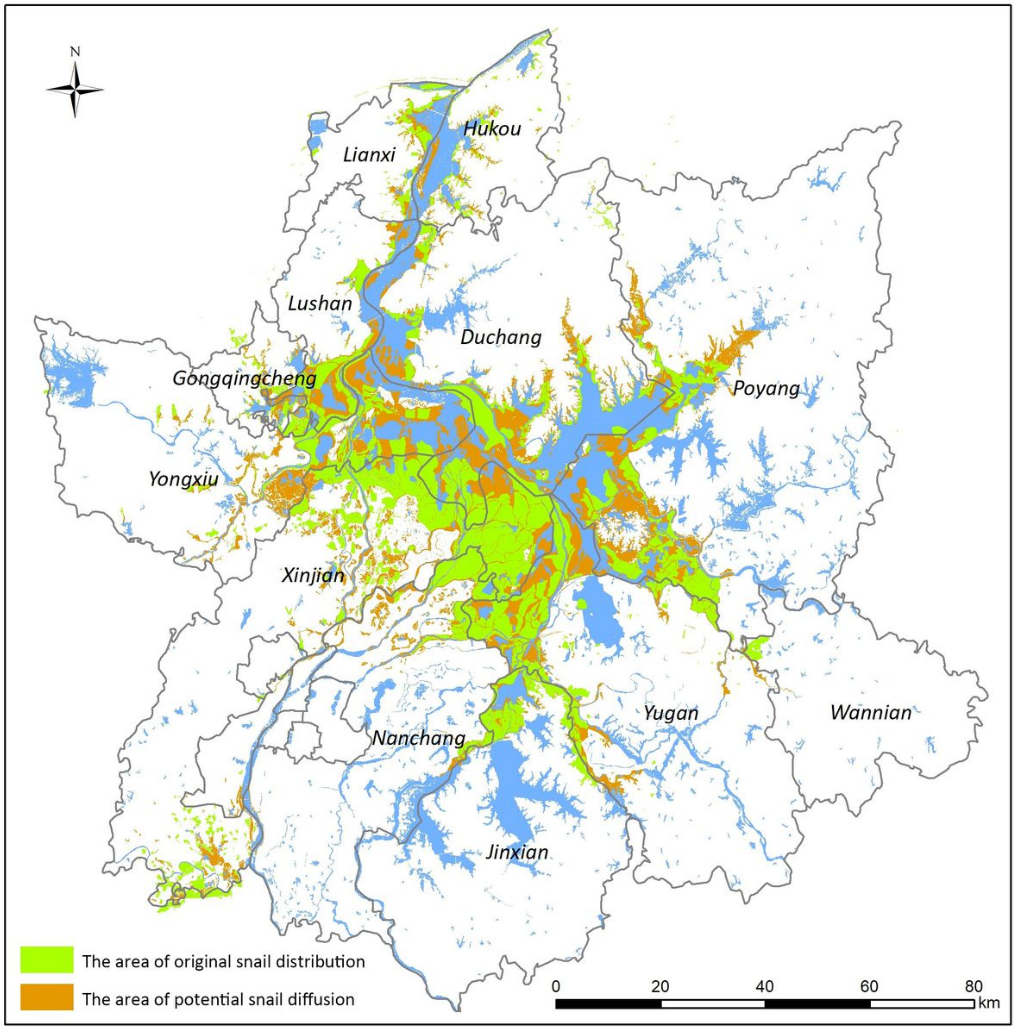

Figure 6

Prediction of snail habitats based on flood-affected settings. Snail spread might cover an area of approximately 759 km2, which mainly occurred in east of Yongxiu, south of Lushan, southwestern Poyang, southwestern Duchang, northwestern Xinjian and northwestern Yugan. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

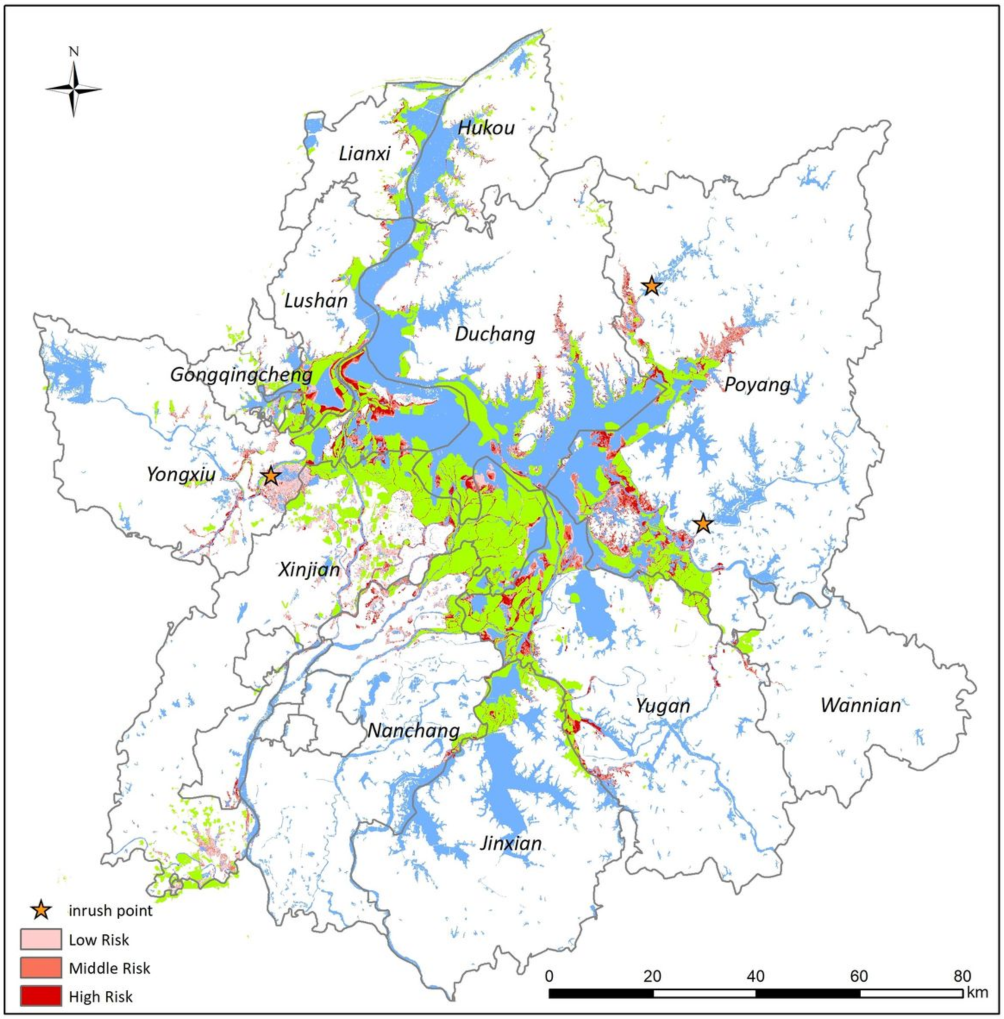

Figure 7

Risk classification of spread of Oncomelania hupensis. The NDVI values of suitable snail habitats were calculated based on snail density data, and the risk was classified as high density, medium density and low density snail habitats with reference to the NDIV values. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.