



Rapid urban expansion and potential disaster risk on the Qinghai-Tibetan Plateau in the 21st century

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Abstract

Context Cities are still expanding in many parts of the world in the 21st century, especially in developing regions, where socioeconomic transition has triggered urbanization. The Qinghai-Tibetan Plateau, characterized by its high elevation, developing economy, and fragile environment, has undergone rapid urbanization in the past twenty years, potentially heightening

the region's risk of geological and hydrometeorological disasters.

Objectives This article examines the process of urbanization on the Qinghai-Tibetan Plateau in order to better understand the relationship between urban expansion and population change and to explore whether geological and hydrometeorological disasters threaten urban expansion.

Methods We created a high-resolution urban built-up boundary dataset from 2000 to 2020 based on remote sensing and GIS. By examining the spatio-temporal pattern of urban expansion and its population dynamics from 2000 to 2020 in 15 cities across the Qinghai-Tibetan Plateau, we quantified the urban expansion characteristics and explored the rising geological and hydrometeorological disaster risks urban areas face.

Results The Qinghai-Tibetan Plateau has experienced rapid and uneven urbanization in the past 20 years. The total expansion rate was over 252% – 1.48 and 2.81 times higher than that of China and the world, respectively. Urban expansion exceeded population growth in most cities throughout the whole period. The urban built-up areas and population of the Qinghai-Tibetan Plateau tended to concentrate in the Yellow River-Huangshui River Valley of Qinghai Province and the Yarlung Zangbo River and its two tributaries of Tibet. High-density urban built-up areas and population distribution were exposed to geological and hydrometeorological disasters. The urban boundary dataset produced in this study has better

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accuracy than the other five existing datasets, for the given area and time range.

Conclusions This study will not only provide a scientific reference for urban development research and future urban planning on the Qinghai-Tibetan Plateau at the regional scale, but will also contribute to research on the urbanization process of the plateau and mountainous regions on a global scale, raising awareness of geological and hydrometeorological disaster risk prevention in these areas worldwide

Keywords Urbanization · Urban expansion · Disaster risk · Population growth · Qinghai-Tibetan Plateau · China

Introduction

Cities are the world's future, as urban areas are already home to 55% of the world's population, with this figure expected to grow to 68% by 2050 (UN 2022). The dawn of the 21st century has illuminated the swift urban transition in developing nations, with China serving as a prominent archetype. Over recent decades, China's urbanization rate has surged from 36 to 64%, mirroring its robust economic ascent. This demographic shift is not solely confined to China's coastal metropolises; it extends to inland regions, notably the Qinghai-Tibetan Plateau. The turning point for the plateau's accelerated urban growth can be traced back to the introduction of the Western Development Strategy in 2000 (Li et al. 2021), coupled with a policy fostering targeted support partnerships with China's developed eastern provinces (Zhong 2013). As a result, post-2000, urbanization on the Qinghai-Tibetan Plateau has witnessed a marked uptick.

The Qinghai-Tibetan Plateau, nestled in southwestern China, stands as a focal point in global change research, given its remarkable elevation, harsh winter temperatures, reduced oxygen levels, intricate physical geography, and distinct socio-human evolutionary trajectories (Zhang et al. 2019). Widely heralded as the 'roof of the world' or the 'third pole', this plateau offers invaluable insights for disciplines ranging from geography and biology to archaeology, ethnology, and environmental science. To unravel the intricate tapestry of its physical, societal, and economic dynamics, China has embarked on two phases of the

Qinghai-Tibetan Plateau Comprehensive Scientific Expedition. The inaugural phase in the 1970s (Zhang and Zhang 2021) paved the way for a subsequent phase initiated in 2017, delving into the climatic, biodiversity, and environmental shifts over the preceding years (Yao et al. 2022). Although there exists a wealth of research probing the spatial-temporal urban growth dynamics of China's colossal cities (Chen et al. 2022; Fei and Zhao 2019; Meng et al. 2020; Wang and Gu 2022; Xu et al. 2020; Yin et al. 2021), the Qinghai-Tibetan Plateau remains largely underexplored. The spatial-temporal contours of urban expansion are key to understanding the plateau's socio-ecological shifts and sustainable development. Regrettably, compared to other Chinese territories, detailed accounts of urbanization patterns within this plateau are sparse. Most extant studies predominantly shine the spotlight on central and eastern provinces or western megacities like Chengdu, Chongqing, and Xi'an, leaving the Qinghai-Tibetan Plateau in relative obscurity. This is a consequence of the plateau's remoteness, socio-economic underdevelopment, limited media and policy attention, and data scarcity. Additionally, the availability of usable remote sensing imagery from the area is limited, with many Landsat and Sentinel captures marred by excessive cloud interference. Current urban built-up area (UBA) boundary datasets, such as Globeland 30 (Chen 2018), GLASS-GLC (Liu et al. 2020a), and GAUD (Liu et al. 2020b)—primarily derived from Landsat images or Nightlight data—boast commendable precision for eastern urban centers but falter when it comes to the Qinghai-Tibetan Plateau. This dearth of trustworthy urban boundary datasets hinders research endeavors specific to the plateau. Furthermore, some studies have attempted to couple urban expansion areas and population growth in other parts of China. However, due to the lack of appropriate models or indicators, urban expansion and population growth can only be discussed separately before correlation analysis is conducted (Li et al. 2020b; Yu et al. 2022). This has led to a lack of quantification, especially the inability to fully quantify and integrate area and population changes for the most intuitive analyses.

The Qinghai-Tibetan Plateau, characterized by its pronounced tectonic uplift, intricate topography, and capricious climate, stands as a region susceptible to both geological and hydrometeorological catastrophes (Cui et al. 2017). Over the past century,

this region has borne witness to devastating events, including the 2000 Yigong landslide, resulting in 130 fatalities; the 2010 Yushu earthquake, claiming 2,698 lives; the 2010 Zhouqu mudslide with 1,765 reported deaths and disappearances; the 2013 Lhasa landslide, causing 83 casualties and disappearances; and the more recent 2022 Datong flash flood-mudslide and 2023 Nyingchi snowslide, with 31 and 23 deaths, respectively. While these calamities have exacted a heavy toll in terms of both human life and property, academic research on the Qinghai-Tibetan Plateau's geological and hydrometeorological threats has predominantly centered around understanding the mechanics and evolutionary processes of these disasters. Studies have delved into identifying high-risk zones for these events (Cao et al. 2020; Gong et al. 2022; Qi et al. 2021; Sun et al. 2021; Wang et al. 2022a), but have largely neglected the intricate interplay between urban expansion and these disaster risks, especially against the backdrop of burgeoning urbanization. The latent threats posed by such disasters amidst the region's rapid urban transition remain under-addressed. Furthermore, the phenomenon of glacial lake outburst floods (GLOFs), exacerbated by climate change, looms large over the plateau. Past GLOFs events have unleashed considerable human and infrastructural damage (Allen et al. 2019; Zheng et al. 2021). However, most cities on the Qinghai-Tibetan Plateau are built along the rivers. The consequences of a significant flood or geological disaster in a densely populated area would be grave, especially at night when escape or rescue is more difficult.

Urban construction on the Qinghai-Tibetan Plateau shifted from slow development to a high-speed development stage after 2000 (Zhang et al. 2019), which is significant in the background of geological and hydro-meteorological disasters. Rentschler et al. (2023) showed that countries worldwide have been building villages, towns, and cities in flood plains faster than in areas less likely to be inundated (Rentschler et al. 2023). Specifically for the Qinghai-Tibetan Plateau region, urban expansion in a multi-hazard context is unknown.

To understand urbanization patterns and processes on the Qinghai-Tibetan Plateau, we examine the relationship between urban expansion and population change and explore whether urban expansion in the region is threatened by geological and hydro-meteorological disasters. Based on Google Earth's

historical image data, we produced a high-accuracy UBA boundary dataset for Qinghai Province and Tibet between 2000 and 2020 using the human-computer interpretation method. Based on GIS spatial analysis methods and urban analysis indicators, the spatio-temporal pattern of urban expansion was analyzed and focused on the rapid and uneven character of urban expansion in the Qinghai-Tibetan Plateau region. We used an index that combined UBA area expansion with population growth to quantitatively examine population change in the urbanization process. Through a comprehensive analysis of urban expansion, population, terrain, and the spatial distribution characteristics of historical disasters, we combined quantitative and qualitative analyses to reveal the potential geological and hydrometeorological disaster risk in the urbanization process of the Qinghai-Tibetan Plateau. This study will not only provide a scientific reference for urban development research and future urban planning on the Qinghai-Tibetan Plateau at the regional scale, but will also contribute to research on the urbanization process of plateaus and mountainous regions on the global scale.

Study area and data source

Study area

Situated in southwestern China, the Qinghai-Tibetan Plateau (Fig. 1) boasts an impressive average altitude of over 4,000 m, earning its moniker, the "Roof of the World." Due to its frigid conditions, rivaled only by the North and South Poles, it is also often dubbed the "Third Pole" (Qiu 2008; Zhang et al. 2016). The plateau's vast expanse stretches from the Pamir Plateau in the west to the Hengduan Mountains in the east, spanning roughly 2,945 km across 31 longitudes. From its southernmost point at the edge of the Himalayas to the northern boundaries defined by the Kunlun Mountains-Qilian Mountains, it measures approximately 1,532 km, covering 13 latitudes. With an expansive area of 2,542,300 km², the plateau constitutes 26.48% of China's total land area. Administratively, it encompasses parts of six provincial regions: Tibet, Qinghai, Gansu, Sichuan, Yunnan, and Xinjiang. Notably, the primary territories of Tibet and Qinghai collectively account for 74.62% of the plateau's overall area (Zhang et al. 2002, 2014).

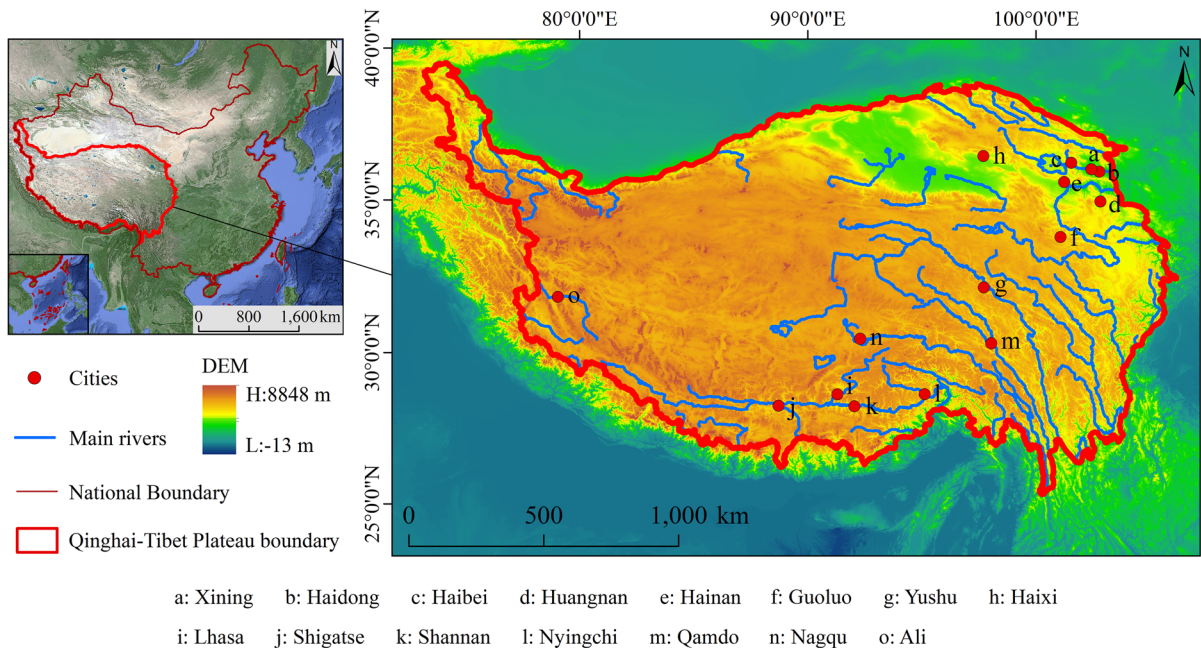


Fig. 1 Geographical location and extent of the Qinghai-Tibetan Plateau

This study took Qinghai Province and Tibet of China as the main study area, including 15 prefecture-level administrative units (eight cities, six states, and one region), amounting to a total of 1.95 million km² and accounting for 20.32% of China's total area. According to the seventh national census results, the total resident population was 9,572,100. The 15 cities in the study area, according to the basins in which they are located, can be divided into the Huangshui River Basin (Xining, Haidong, Hebei), the Yellow River Basin (Huangnan, Hainan, Guoluo), the Tongtian River Basin (Yushu), the Bayinguole River Basin (Haixi), the Yarlung Zangbo River Basin (Lhasa, Shigatse, Shannan, Nyingchi), the Lancang River Basin (Qamdo), the Nujiang River Basin (Nagqu), and the Shiquan River Basin (Ali).

Data sources

This study includes 10 data sources: (1) Historical image data sourced from Google Earth Pro (<https://www.google.com/earth/versions/#earth-pro>), including 30 m medium-resolution images dating to before 2005 and all 1 m high-resolution images dating to 2005; (2) LandScan population data from 2000 to 2020 (<https://landscan.ornl.gov/>), with a spatial

resolution of 1 km (a few districts and counties in 2000 were corrected in conjunction with the results of the Fifth Population Census of China); (3) Water system data from the 1:1 million basic geographic information data showing the distribution of rivers in cities (<https://www.webmap.cn>), published in 2015; (4) The National Qinghai-Tibetan Plateau Data Center DEM data with a spatial resolution of 0.008°×0.008° (<http://www.tpdac.cn>), published in 2013. (5) Boundary data of the Qinghai-Tibetan Plateau released by the National Earth System Science Data Center (<http://www.geodata.cn>) (Zhang et al. 2002, 2014), published in 2002 and 2014 with a scale of 1: 1 million; (6) China Urban Construction Statistical Yearbook from 2000 to 2020 (<https://www.mohurd.gov.cn/>); (7) Spatial distribution data of geological and hydrometeorological disaster points on the Qinghai-Tibetan Plateau, updated to 2019 (<https://www.resdc.cn/>); (8) Five types of UBA data or land use data (Chen et al. 2014; Gong et al. 2019; Kuang 2021; Li et al. 2020a; Liu et al. 2020b) used for accuracy comparison and evaluation with the dataset produced by this study (detailed in Table 1); (9) Multi-scale dataset of environment and element-at-risk for the Qinghai-Tibet Plateau, updated to 2019 with a spatial resolution of 1 km (<http://www.tpdac.ac>

Table 1 Information about the five available UBA datasets

Short name	Type	Time range	Spatial resolution	Data source
Li et al. 2020	UBA	1985–2018	30 m	http://data.ess.tsinghua.edu.cn/
Gong et al. 2019	UBA	1978–2017	30 m	http://data.ess.tsinghua.edu.cn/
Liu et al. 2020	UBA	1985–2015	30 m	https://doi.org/10.6084/m9.figshare.11513178.v2
Kuang 2021	UBA	2000–2015	30 m	http://data.tpdc.ac.cn/
Globeland 30	Land use classification	2000–2020	30 m	http://www.globallandcover.com/

cn); and (10) Comprehensive risk of multiple natural disasters dataset in Himalaya and Asian water tower area, updated to 2021 with a spatial resolution of 1 km (<http://www.tpdc.ac.cn>).

Research methods

In this study, we extracted a high-resolution urban built-up area boundary dataset for the Qinghai-Tibetan Plateau from 2000 to 2020 based on Google Earth high-resolution historical imagery through human-computer interactive interpretation. We then evaluated the accuracy of this dataset and compared it with the existing datasets listed above. Next, we carried out the following processes: (1) analyzed the spatio-temporal characteristics of urban expansion using GIS spatial analysis methods and urban analysis indicators; (2) introduced the USI index to quantitatively couple urban expansion and population growth (3) explored potential disaster risk in the urbanization process by combining urban built-up area boundaries, population distribution, terrain, historical disaster data and using GIS spatial analysis methods. Finally, we discussed the urbanization process of the Qinghai-Tibetan Plateau through national and global perspectives. Figure 2 shows the overall flowchart of this study.

UBA boundary extraction method for Qinghai-Tibetan Plateau

Urban built-up area refers to the area within a city administrative district that is developed and constructed continuously, and where municipal utilities and public facilities are available (Yin et al. 2020). Based on Google Earth historical image data, this

study extracts the UBA boundary range of 15 cities in Qinghai Province and Tibet from 2000 to 2020 through human-computer interaction interpretation with a time interval of 5 years.

In human-computer interaction interpretation, researchers input remote sensing images into a computer system. They then visually analyze these images, leveraging both their specialized knowledge and practical experience to deduce the geographic information contained within. This approach is extensively employed in fields such as land use assessment, environmental monitoring, and urban planning.

Analytical method of the spatio-temporal pattern of urban expansion

GIS spatial analysis methods and indicators such as urban spatial morphological expansion mode and the rate of urban expansion were used (Yin et al. 2022) to analyze the urban spatial evolution of the study area from 2000 to 2020.

The spatial expansion of UBA in the Qinghai-Tibetan Plateau region is susceptible to the influence of natural conditions, and the urban layout pattern was explored in conjunction with the topography. According to the relationship between urban expansion and rivers, the cities can be divided into river valley-type cities distributed along both sides of rivers or riverside-type cities distributed along one side of rivers.

Quantitative method for analyzing urban expansion combined with population growth

Population and urban land area are important indicators used to measure urbanization, and this study uses the urban sprawl index (USI) to monitor the degree of urban

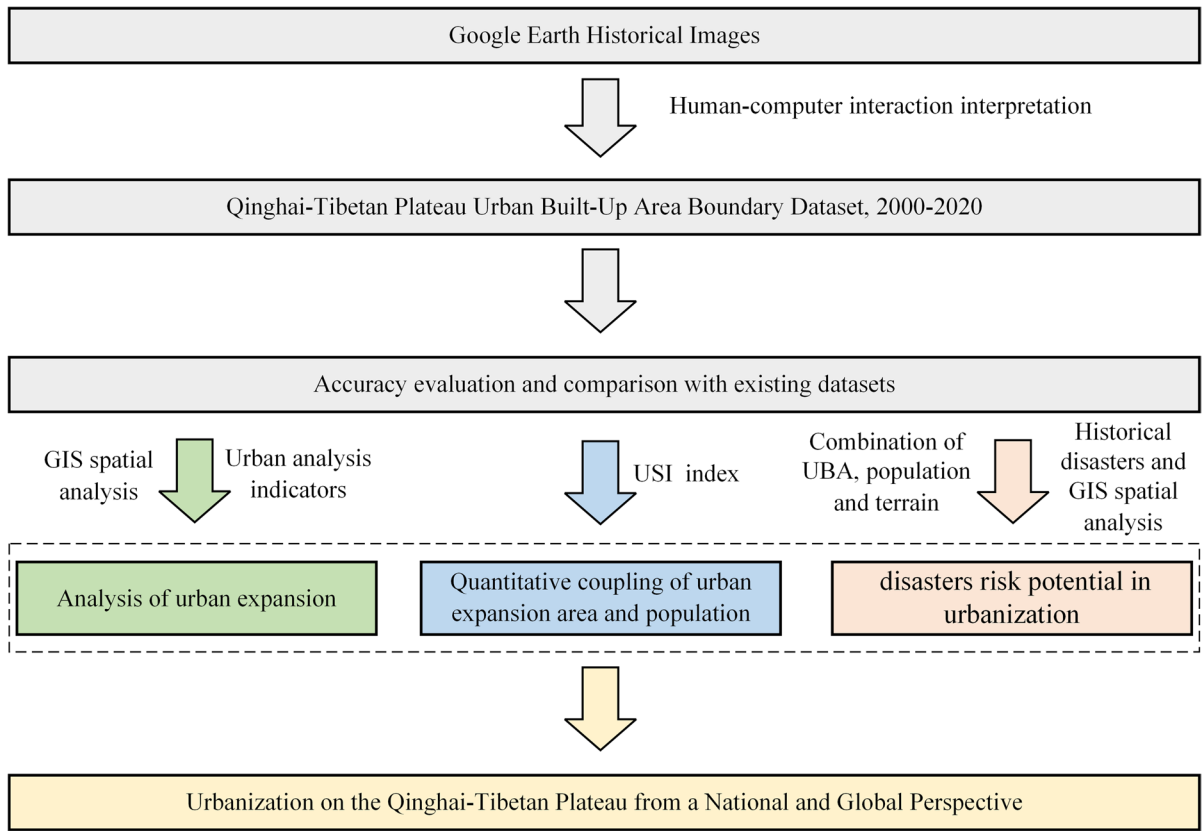


Fig. 2 Flowchart of steps for this study

expansion. USI is an index that compares the growth rates of urban populations and urban areas. Urban land area needs to be increased in the urbanization process to accommodate the growing urban population (Guan et al. 2020). In a given period, if the increase in urban area exceeds the increase in population, a significant expansion is considered to have occurred (Marshall 2007). In other words, a higher value of USI indicates a greater degree of urban expansion. Therefore, using UBA area and population to build USI is an effective method to quantitatively describe the relationship between area and population in urbanization. The formula for calculating USI is as follows (Gao et al. 2016):

$$USI_{(t_1,t_2)}^i = UA_{(t_1,t_2)}^i - UP_{(t_1,t_2)}^i \tag{1}$$

$$UA_{(t_1,t_2)}^i = \left(\left(\frac{A_{t_2}^i}{A_{t_1}^i} \right)^{\frac{1}{t_2-t_1}} - 1 \right) \times 100\% \tag{2}$$

$$UP_{(t_1,t_2)}^i = \left(\left(\frac{P_{t_2}^i}{P_{t_1}^i} \right)^{\frac{1}{t_2-t_1}} - 1 \right) \times 100\% \tag{3}$$

where $USI_{(t_1,t_2)}^i$ is the USI value of city i from t_1 to t_2 , $UA_{(t_1,t_2)}^i$ and $UP_{(t_1,t_2)}^i$ are the annual growth rates of the area and population of city i from t_1 to t_2 , A^i represents the area of city i , and P^i represents the population of city i .

Disaster risk assessment method

This study integrated urban expansion dynamics, population growth and distribution, urban terrain,

and historical disaster data. We also referenced the method of Rentschler et al. (2023) in analyzing flood hazards in the global urban expansion process. We used both quantitative and qualitative methods and GIS spatial analysis to assess disaster risk in the urbanization process of the Qinghai-Tibetan Plateau.

Results

UBA extraction results and accuracy evaluation

The UBA boundaries for the study region were delineated using the methodology presented in Section [UBA boundary extraction method for Qinghai-Tibetan Plateau](#). To offer a visual juxtaposition of the spatial-temporal dynamics of the UBA across the 15 cities under consideration, we overlaid the UBA boundaries of each city, as illustrated in Fig. 3. Cumulatively, the urban boundary dataset created for the period 2000–2020 for Qinghai Province and Tibet aptly captures the comprehensive profile and intricate details of the UBA within these 15 cities. Each city's expansion trajectory exhibits unique characteristics, leading to diverse UBA distributions. To quantitatively evaluate the accuracy of the UBA extraction results for this study, 300 random points were generated in each of the study cities. The points were then judged point by point in Google Earth historical imagery to be correct or not. The above process was repeated for each year. After validation, the overall accuracy of this dataset was 98.81%, which is sufficient to finely characterize the urban expansion process in the Qinghai-Tibetan Plateau region, and is higher than other existing urban boundary datasets. Based on the extracted urban boundary datasets of Qinghai Province and Tibet, Section [Analysis of the spatio-temporal evolution of urban expansion](#) of this paper is introduced to further analyze the spatial and temporal characteristics and evolutionary patterns of urban expansion.

Analysis of the spatio-temporal evolution of urban expansion

Investigating this growth facilitates a more nuanced understanding of urban development patterns, allowing for judicious land resource allocation and enhancing the overall efficacy of urban management. To

depict each city's expansion, river vector data was overlaid onto DEM raster base maps. Figure 4 and Supplementary data Figures S1–S4 show the expansion of the cities including each basin along the major rivers from 2000 to 2020. Overall, the cities were mainly expanding along both sides of the river, with more expansion parallel to the river's flow direction than in other directions.

The fifteen cities spanning various basins within Qinghai Province and Tibet predominantly align along rivers, classifying them as either valley-type or riverside-type. Of these, eleven are designated as river valley-type cities, while four are identified as riverside-type. Examining this from a basin-specific perspective, cities across all basins predominantly exhibit a singular expansion pattern, with the notable exceptions being those within the Huangshui and Yellow River Basins, where both urban expansion types coexist.

The river forces on the land on both sides of the river are divided into two types: accumulation and erosion. If the city expands along the erosion side of the river, it may increase the risk of flooding and threaten the safety of the city. Table 2 demonstrates the characteristics of urban expansion and the urban expansion area along both sides (accumulation and erosion) of the major river between the different basins. Among the fifteen cities, twelve (80%) mainly expanded on the accumulation side; only Hainan, Haixi, and Lhasa, located in the Yellow River, Bayingoule River, and Yarlung Zangbo River basin, respectively, expanded beyond the accumulation side, on the erosion side as well. In the four cities that expanded only one side of the river (Haidong, Haibei, Guolu, and Nagqu), this expansion occurred on the accumulation side.

Figure 5 illustrates the changes in the UBA area for each city within Qinghai Province and Tibet from 2000 to 2020. Given the pronounced polarization when including the two provincial capitals, the visual representation of the area increment for the remaining thirteen non-capital cities becomes less discernible. For clarity, the two provincial capitals—Xining and Lhasa—are presented separately from the other thirteen cities. Specifically, Fig. 5a highlights Xining and Lhasa, while Fig. 5b portrays the remaining thirteen non-capital cities. In these graphics, the horizontal axis denotes the area increment, while the vertical axis lists the city names.

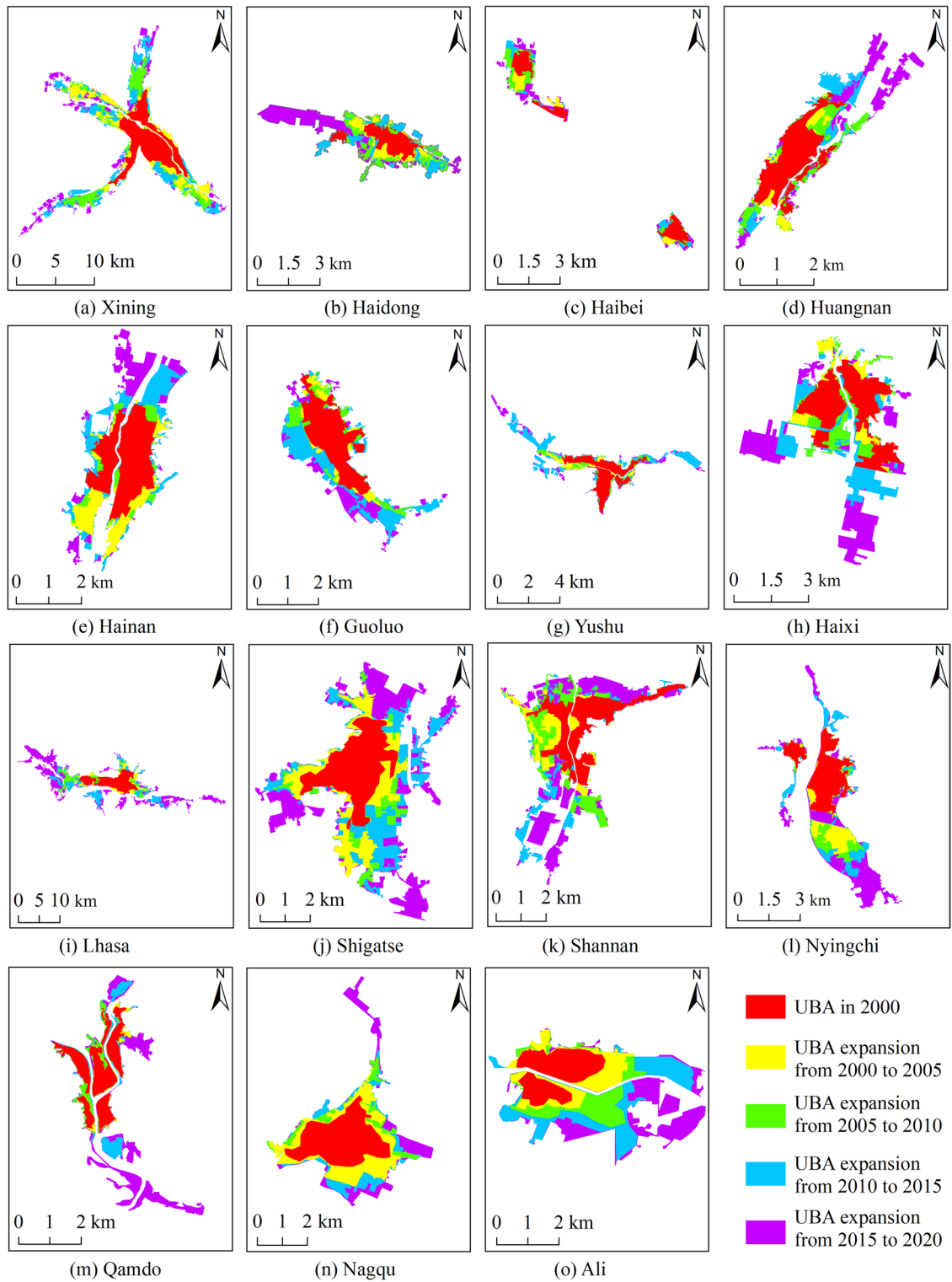


Fig. 3 UBA range superimposition results from 2000 to 2020 for 15 cities on the Qinghai-Tibetan Plateau

As of 2020, Lhasa, the capital of Tibet, has the largest UBA with an area of 181.94 km². However, Xining, the capital of Qinghai Province, follows with a UBA of 179.45 km², which is not significantly different from the UBA of Lhasa. Xining was the largest city in both Qinghai Province and Tibet from 2000 to 2015, but was overtaken by Lhasa in the period from 2015 to 2020. Among the remaining 13 cities in Qinghai Province and Tibet (not including Lhasa and Xining), the only one with a UBA larger than 30 km² is Shigatse, with 31.43 km². Shigatse and Haixi (with a UBA of 28.83 km²) are the only two of these cities with a UBA larger than 20 km². The smallest cities, in contrast, are Haibei, Haixi, and Qamdo, all with UBAs of less than 10 km².

There are significant differences in the area growth of UBAs in each city of Qinghai Province and Tibet, forming a polarization. The area growth of provincial capital cities is significantly larger than that of non-capital cities. There is also a large development imbalance among non-provincial capital cities, showing a concentration of urban expansion in the major basin areas. Among the seven cities in Tibet, Lhasa, Shigatse, and Shannan (the three cities included in the Yarlung Zangbo River and its two tributaries) rank in the top three in terms of UBA area in 2020, accounting for 79.01% of all of Tibet. The two non-capital cities of Shigatse and Shannan also ranked 1st and 3rd out of 13 non-capital cities in Qinghai Province and Tibet. Among the eight cities in Qinghai Province, the five cities included in the Yellow River-Huangshui River Valley (Xining, Haidong, Haibei, Huangnan, and Hainan) account for 80.12% of the Province's UBA in 2020. However, Huangnan and Haibei in this area are ranked 2nd and 3rd from the bottom among 13 non-capital cities in Qinghai Province and Tibet.

To present the 15 cities in a way that reduces the effect of bipolar differences, the relative values of urban expansion areas are highlighted instead of the absolute values. The change in relative growth rate (expansion rate) of the area from 2000 to 2020 was calculated for each city in Qinghai Province and Tibet, as shown in Fig. 6. The cities with the highest and lowest expansion rates differ over the four time periods from 2000 to 2020, and the poles of Lhasa and Xining are not always the highest. From 2000 to 2005, the cities of Shigatse and Nagqu had the highest expansion rates, both above 70%. Both cities had

a UBA of more than 10 km² by 2005, ranking 3rd-4th among the 15 cities, respectively. Other cities with expansion rates above 50% in the same period, from high to low, are Ali, Xining, and Haidong. From 2005 to 2010, the only city with an expansion rate of more than 50% was Haidong, with 52.17%. From 2010 to 2015, the expansion rate for Yushu and Guoluo exceeded 50%, with 62.79% and 52.47%, respectively. Both cities ranked 4th and 6th among the 15 cities in terms of UBA area in 2015. From 2015 to 2020, Lhasa had the highest expansion rate of 71.53% and ranked first among the 15 cities in terms of UBA area in 2020. The city with an expansion rate of more than 50% in the same period was Qamdo at 55.49%.

Quantitative evaluation of urban expansion combined with population growth

From the methods introduced in Section [Quantitative method for analyzing urban expansion combined with population growth](#), the USI index for 2000–2020 was calculated for each city in Qinghai Province and Tibet (Fig. 7) and used for the quantitative evaluation of urban expansion combined with population growth.

The average USI value for the 15 study cities over the twenty years was 0.04. Among the 15 cities, 13 (86.67%) experienced significant expansion from 2000 to 2005. Urban expansion exceeded population growth in most cities throughout the whole period. Eight cities exceed the USI average, four in Qinghai Province, all located in the Yellow River-Huangshui River Valley (located in the northeastern part of Qinghai Province). The regional scope includes the part of the Huangshui River basin in Qinghai Province and the section of the Yellow River basin from Longyangxia to Sigouxia, with an area of about 3.30 km², which is the valley area formed by the alluvial accumulation of Huangshui River, Yellow River, and its tributaries (Luo et al. 2014). The geographical location is shown in Fig. 8. There are four cities in Tibet, among which Shigatse and Shannan are located in the Yarlung Zangbo River and its two tributaries (the central basin area of the Yarlung Zangbo River, Lhasa River, and Nianchu River). They are located in the southern part of Tibet, with an area of about 66,700 km², accounting for 5.48% of the total area of Tibet (Wang et al. 2021). The geographical location is shown in Fig. 8. Cities with USI less than 0 are Lhasa and Qamdo in Tibet.

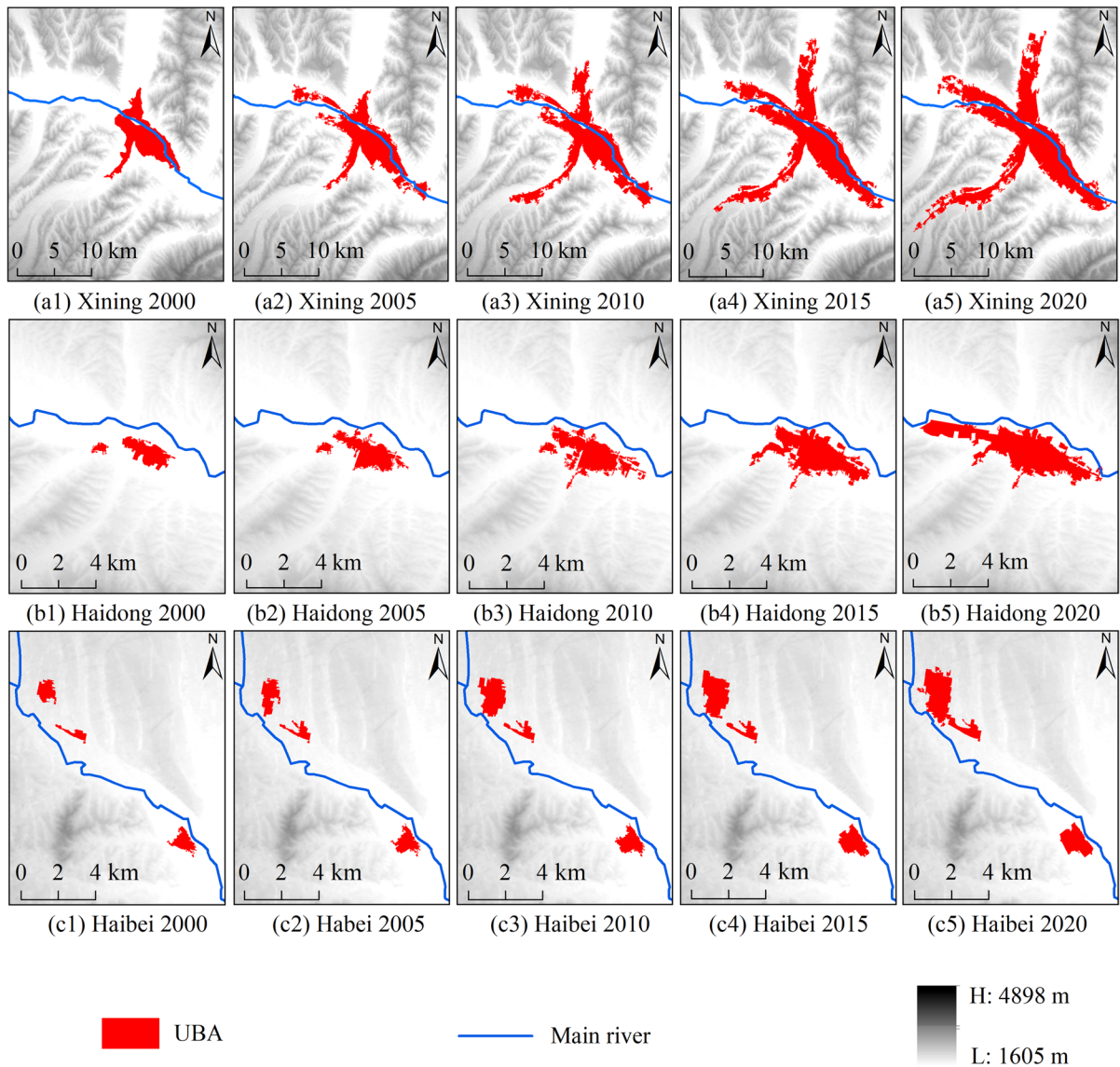


Fig. 4 The expansion of 3 cities in the Huangshui River Basin along major rivers from 2000 to 2020

From 2005 to 2010, all cities showed significant expansion. Seven cities exceeded the USI average, four in Qinghai Province, all in the Yellow River-Huangshui River Valley, and three in Tibet, with Lhasa and Shannan in the Yarlung Zangbo River and its two tributaries. From 2010 to 2015, 12 cities showed significant expansion, accounting for 80.00% of all cities. Six cities exceeded the USI average, three in Qinghai Province, including Haidong and Hainan in the Yellow River-Huangshui River Valley, and the second largest city in Qinghai, Haixi. There are three cities

in Tibet (Nagqu, Nyingchi, and Qamdo, consistent with the Yarlung Zangbo River and its two tributaries) with a USI less than 0. From 2015 to 2020, all cities show significant expansion. Nine cities exceed the USI average, three in Qinghai Province, including Haidong and Huangnan in the Yellow River-Huangshui River Valley, and another in Haixi. Tibet has six cities show significant expansion (including all three cities in the Yarlung Zangbo River and its two tributaries).

Table 2 Characteristics and area of urban expansion on both the accumulation and erosion sides of major rivers in 15 cities in different basins on the Qinghai-Tibetan Plateau from 2000 to 2020

Basins	Cities	Major rivers and flow directions	Expansion characteristics	Expansion area on the accumulation side/km ²	Expansion area on the erosion side/km ²
Huangshui River	Xining	Huangshui River NW - SE	Valley type	70.54	55.66
	Haidong	Huangshui River NW - SE	Riverside type	13.02	0
	Haibei	Huangshui River NW - SE	Riverside type	5.5	0
Yellow River	Huangnan	Longwu River SW-NE	Valley type	3.54	1.86
	Hainan	Chabcha River NW-SE	Valley type	4.31	5.09
	Guoluo	Gequ River SE - NW	Riverside type	7.38	0
Tongtian River	Yushu	Zhaqu River NW - SE	Valley type	6.59	3.41
Bayinguole River	Haixi	Bayin River NE - SW	Valley type	9.03	10.03
Yarlung Zangbo River	Lhasa	Lhasa River NE - SW	Valley type	66.6	74.75
	Shigatse	Nianchu River S-N	Valley type	21.23	2.32
	Shannan	Yalong River SW-NE	Valley type	8.46	5.14
	Nyingchi	Niyang River NW - SE	Valley type	11.65	1.26
Lancang River	Qamdo	Lancang River N - S	Valley type	3.66	1.29
Nujiang River	Nagqu	Chengqu River NE - SW	Riverside type	11.96	0
Shiquan River	Ali	Shiquan River E-W	Valley type	8.02	3.88

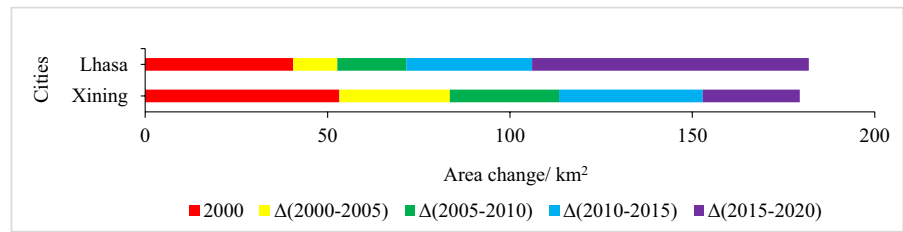
The overall expansion of the 15 cities is most significant from 2015 to 2020, while the period from 2010 to 2015 is the least important compared to other years. The expansion trend of Tibet’s Yarlung Zangbo River and its two tributaries has gradually increased over the 20 years and has become highly significant in the period from 2010 to 2020. Qinghai Province’s expansion center from 2000 to 2010 is located in the Yellow River-Huangshui River Valley. After 2010, the Yellow River-Huangshui River Valley also has a strong expansion trend, but the advantage is not as evident as in the previous decade. Outside of the Yellow River-Huangshui River Valley, Haixi, the second-largest city in western Qinghai, has seen its UBA grow faster than its population.

To further explore the population changes of 15 cities in Qinghai Province and Tibet during the urbanization process in 20 years, the population density changes in each city from 2000 to 2020 were calculated separately under the city scale, as shown in Fig. 9. Among them, Fig. 9a–e shows the population density distribution of different cities in each year,

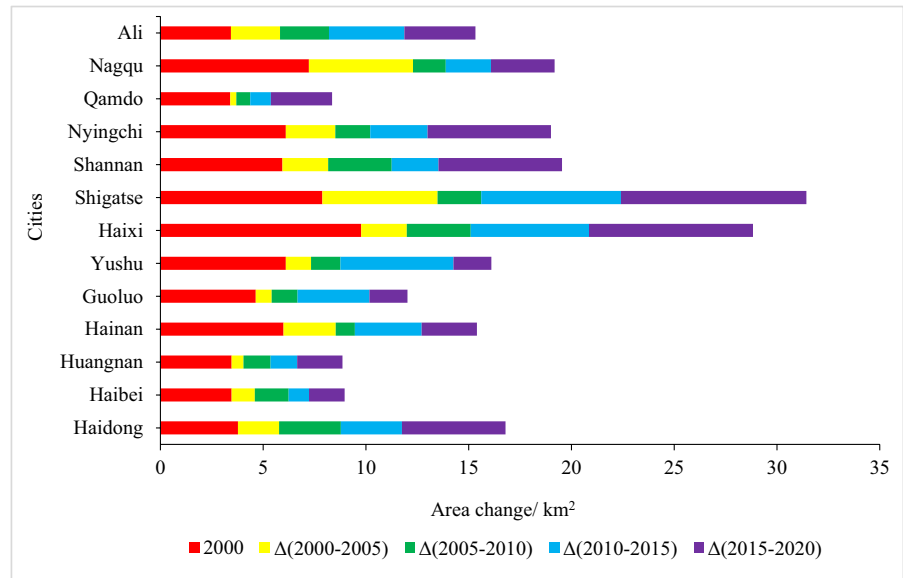
and Fig. 9f shows the population density growth of each city over 20 years. According to the population density values of the 15 cities, the population density levels are divided into six classes, which is convenient for the hierarchical display of each city.

In the past 20 years, the densely populated areas of Qinghai Province and Tibet have always been concentrated in the Yellow River-Huangshui River Valley and the Yarlung Zangbo River and its two tributaries. The city with the highest aggregation and growth value is Xining, which grew from 279.74 people/km² in 2000 to 379.23 people/km² in 2020. The cities with the second level of population density (50.01–200.00 people/km²) changed from Haidong in 2000 to Haidong and Lhasa in 2005, and continued until 2020. The cities with the third level of population density (20.01–50.00 people/km²) changed from Lhasa and Shannan in 2000 to Shigatse and Shannan in 2005 and until 2020. By 2020, the five cities with population densities greater than 20 people/km² are located in the Yellow River-Huangshui River Valley (Xining and Haidong) in

Fig. 5 Change in the UBA area of 15 cities on the Qinghai-Tibetan Plateau from 2000 to 2020

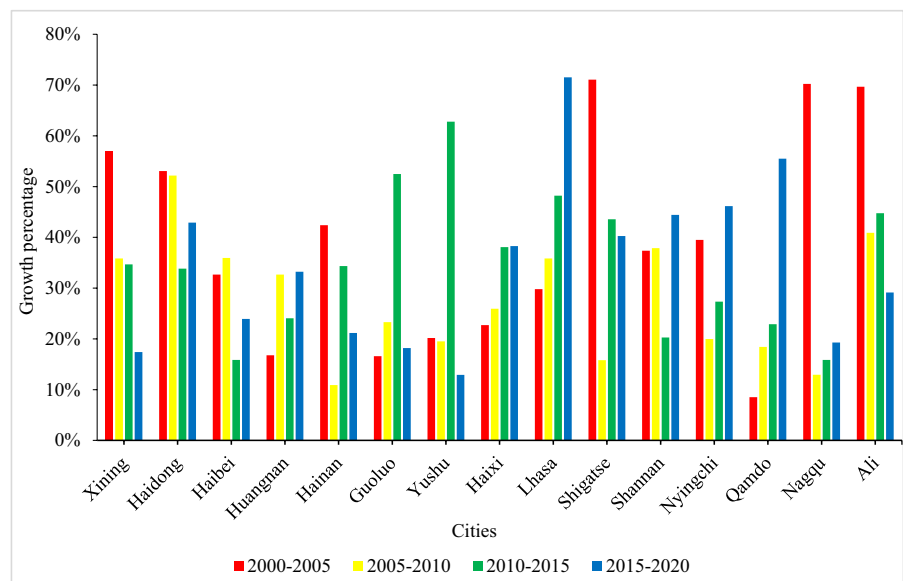


(a) Changes in UBA in Xining and Lhasa from 2000 to 2020



(b) Changes in UBA in the remaining 13 non-provincial capital cities from 2000 to 2020

Fig. 6 Change in the expansion rate of 15 cities on the Qinghai-Tibetan Plateau from 2000 to 2020



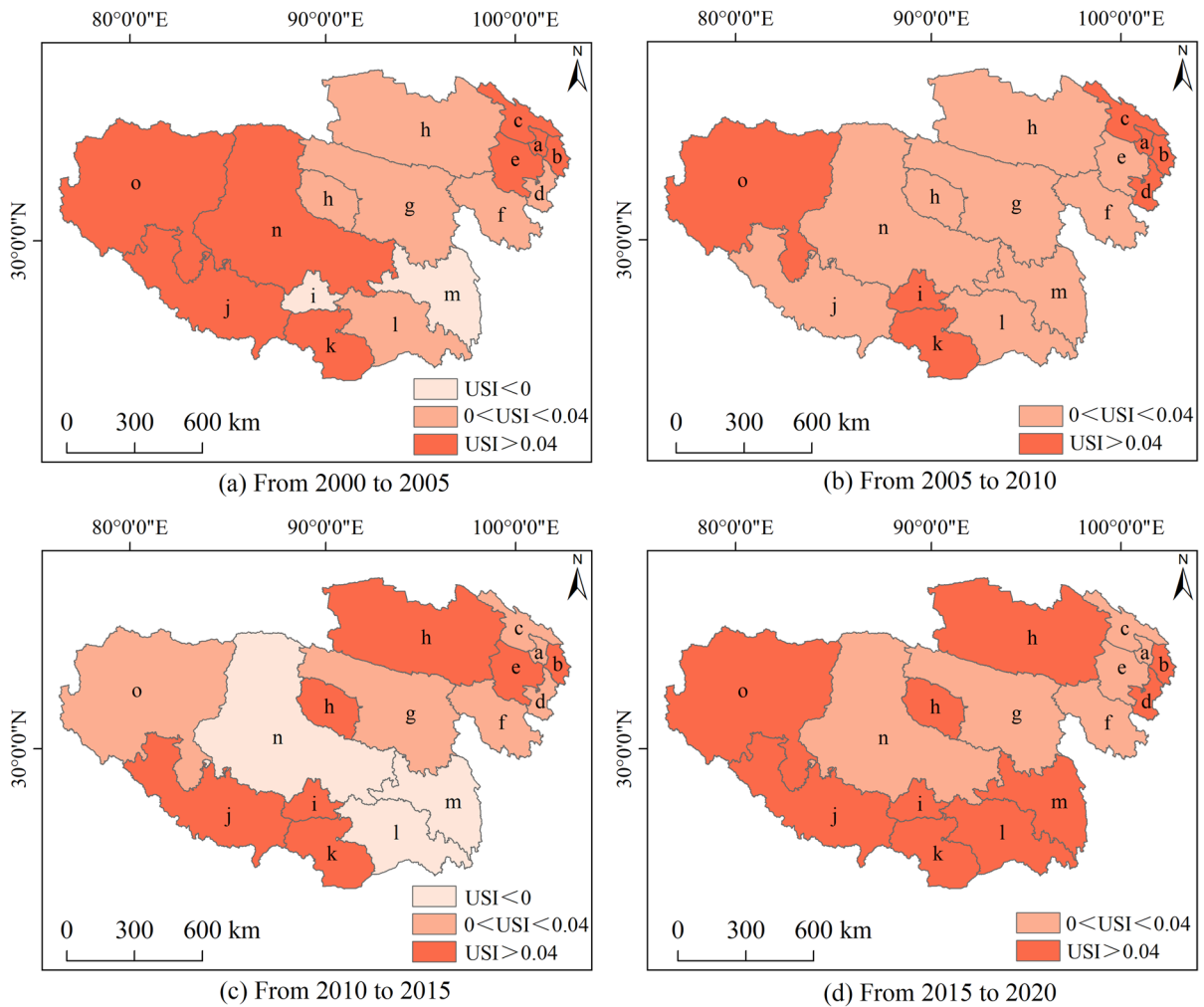


Fig. 7 USI index for 15 cities on the Qinghai-Tibetan Plateau from 2000 to 2020

Qinghai and the Yarlung Zangbo River and its two tributaries in Tibet (all three cities). The five cities mentioned above, with only 10.53% of the land area of the 15 cities, occupy 75.81% of the population and 73.84% of the UBA area. Among them, the population share has been generally stable over the 20 years, with a slight downward trend from 78.78% in 2000 to 75.81% in 2020. The main reason for the slight decrease in the population share is, on the one hand, due to some population growth in Huangnan, Qamdo, Nyingchi, Nagqu, and Yushu, which are outside the above five cities. On the other hand, it is due to the slowdown of population growth in Haidong City among the five cities. In this city, the

percentage of UBA area showed an obvious rising trend, growing from 67.53 to 73.84%.

Regarding population density growth, excluding the highest Xining, the fastest-growing city is Lhasa, with a growth value of 24.37 people/km² over 20 years. In addition, Shigatse, located in the Yarlung Zangbo River and its two tributaries, Huangnan in the Yellow River-Huangshui River Valley and Qamdo in eastern Tibet also have faster growth rates than other cities, with 7.35, 5.25, and 5.90 people/km² respectively.

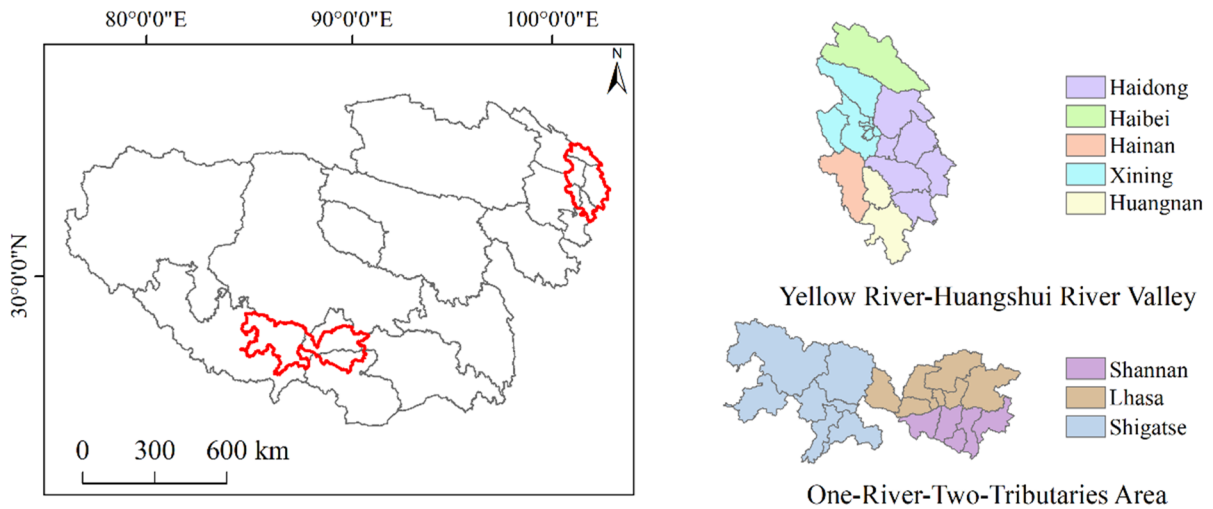


Fig. 8 Geographical location and administrative divisions of the Yellow River-Huangshui River Valley in Qinghai and the Yarlung Zangbo River and its two tributaries in Tibet

Geological and hydrometeorological disaster risk potential in the urbanization of the Qinghai-Tibetan Plateau

As can be seen from Fig. 4 and Supplementary data Figures S1–S4, almost all of the urban expansion occurred in the flatter river valley/ valley zones, constrained by the topography of the Qinghai-Tibetan Plateau itself. Given the encircling high mountain ranges and rivers meandering through or around these cities, there's an augmented potential for major geological catastrophes. In the event of a geological disaster, it can cause enormous damage.

The Qinghai-Tibetan Plateau is frequently subjected to geological and hydrometeorological disasters, with a notable pattern where multiple types of these disasters often co-occur. Several studies showed that the high-risk areas of geological and hydrometeorological disasters (landslides, mudslides, flash floods, snowstorms, etc.) on the Qinghai-Tibetan Plateau are mainly located in the east and south, especially in the Yellow River-Huangshui River Valley of Qinghai Province and the Yarlung Zangbo River and its two tributaries of Tibet, which are under greater threat (Cui et al. 2015, 2017, 2019). Figure 10 offers a visual representation of the spatial distribution of geological and hydrometeorological disaster occurrences on the Qinghai-Tibetan Plateau.

As highlighted in Section [Quantitative evaluation of urban expansion combined with population growth](#), the Qinghai-Tibetan Plateau's population predominantly resides in the Yellow River-Huangshui River Valley of Qinghai and the Yarlung Zangbo River, along with its two tributaries in Tibet. Intriguingly, while the Yellow River-Huangshui River Valley and the Yarlung Zangbo River basin (including its tributaries) constitute merely 1.86 and 3.52% of the Qinghai-Tibetan Plateau's total area, they account for a disproportionate 18.15 and 15.11% of the region's disaster occurrences, respectively, totaling 33.26%. Furthermore, these two regions cumulatively represent 79.56% of the plateau's total UBA area and 59.14% of its population. This underscores a concerning overlap: the regions of greatest urban and population concentration align significantly with areas at heightened risk of geological and hydrometeorological events. Consequently, urban development in these areas faces substantial threats from potential geological and hydrometeorological disasters.

Figure 11 shows the value classes of disaster-bearing bodies in the Qinghai-Tibetan Plateau region, with higher value classes representing greater losses in the event of a disaster. According to the results, the areas with high and relatively high disaster-bearing bodies value in the Qinghai-Tibetan Plateau region are mainly located in the Yellow River-Huangshui River Valley in Qinghai Province, and followed by

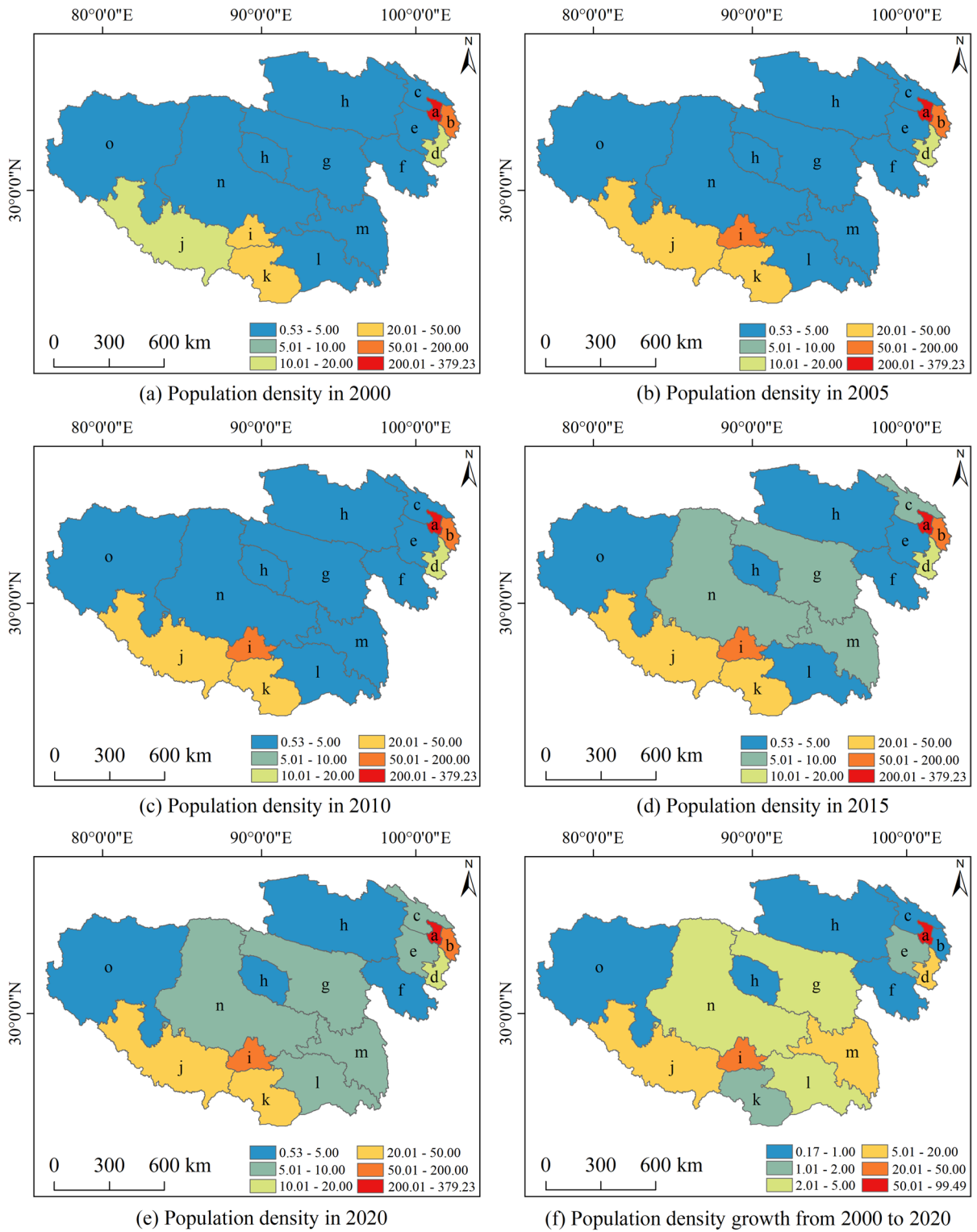


Fig. 9 Population density changes on the Qinghai-Tibetan Plateau from 2000 to 2020

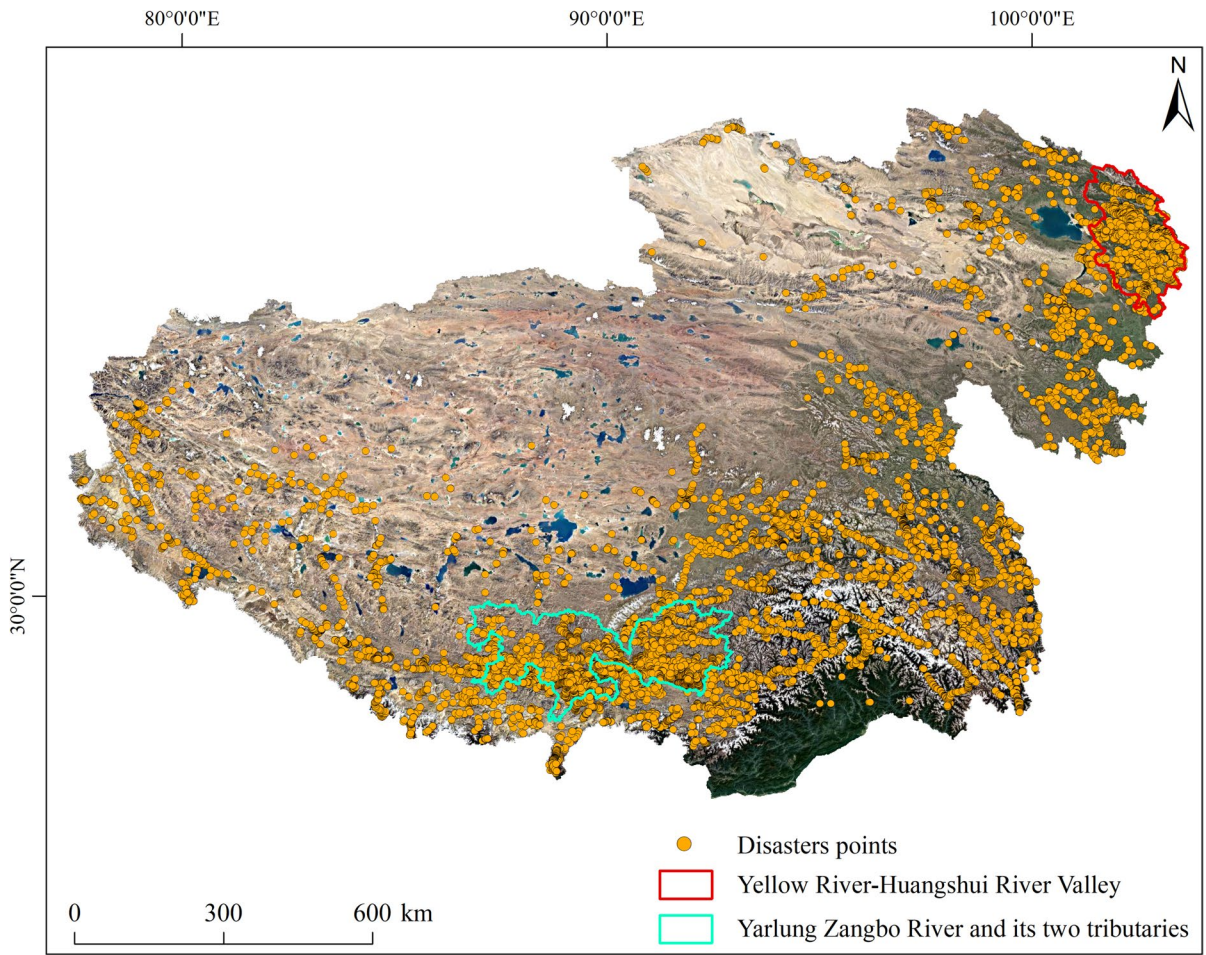


Fig. 10 Spatial distribution of geological and hydrometeorological disaster points on the Qinghai-Tibetan Plateau

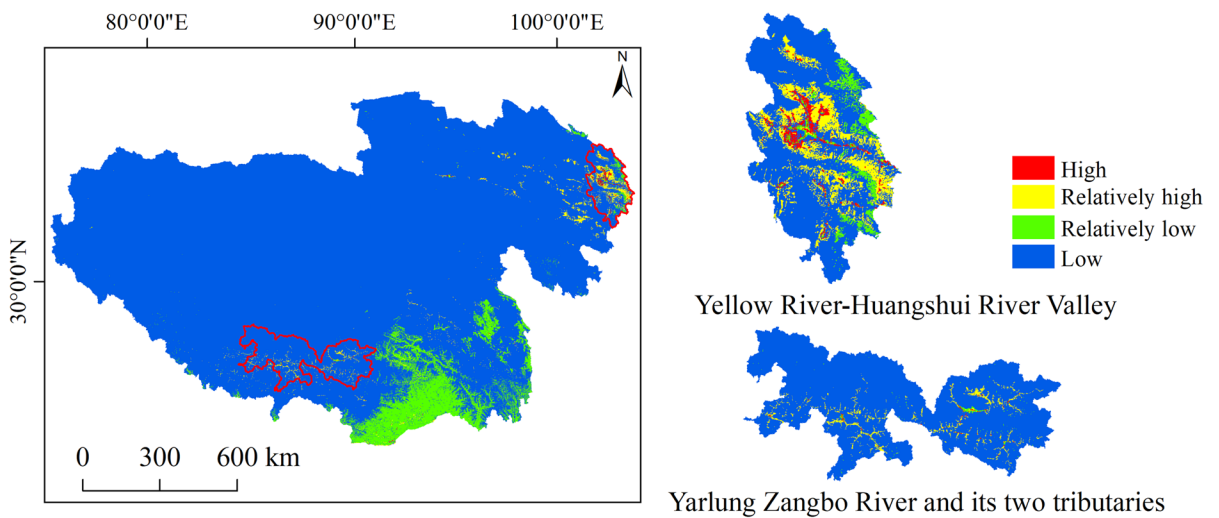


Fig. 11 Value classes of disaster-bearing bodies on the Qinghai-Tibetan Plateau region

the Yarlung Zangbo River and its two tributaries in Tibet. Among them, the area of the Yellow River-Huangshui River Valley with high and relatively high disaster-bearing bodies value is 79.79 million km², accounting for 22.63% of the area of the district, and 39.12% of the area of the entire Qinghai-Tibetan Plateau with high and relatively high disaster-bearing bodies. The area of the Yarlung Zangbo River and its two tributaries with high and relatively high disaster-bearing bodies value is 26.90 million km², accounting for 13.19% of the entire Qinghai-Tibetan Plateau with high and relatively high disaster-bearing bodies area. The two regions account for 52.31% of the area of the Qinghai-Tibetan Plateau with high and relatively high disaster-bearing bodies. This is corroborated by the results shown in the previous section that the UBA and population coincide highly with the high-risk areas for geological and hydrometeorological disasters.

Discussion

Comparison of extraction results with other existing datasets

High-quality UBA boundary data is the basis for accurate urban expansion analysis and thus for a thorough exploration of urbanization. To visualize the advantages of the data set extracted from this study over other existing data sets, the UBA results extracted from this study were compared with five other existing data sets, city by city and year by year. Due to the limitation of figure space, some cities are selected for display (Fig. 12). After comparison, this dataset outperforms the other five existing datasets regarding extraction accuracy and effectiveness for each extraction city and year. This is demonstrated as follows: (1) In terms of timescale, the dataset of this study has been updated to 2020. All of the five existing datasets, except for Globeland 30, have not been updated to 2020. The temporal resolution of this dataset is five years, which is better than Globeland 30 (10 years) and consistent with the other four existing datasets. (2) At the spatial scale, this dataset reaches the meter level except for some earlier years when the spatial resolution is 30 m due to the limitation of the data source. In contrast, the spatial resolution of other datasets

is 30 m. (3) Regarding UBA extraction accuracy, human-computer interaction interpretation is now widely considered the most accurate method for urban land use mapping (Kuang et al. 2021). Since the researchers involved in this study have more experience in UBA extraction and urban expansion analysis. Based on the rich a priori knowledge and geographic background, the dataset extracted by human-computer interaction interpretation can show the complete profile and details of UBA of 15 cities in Qinghai Province and Tibet. However, the existing dataset basically adopts the idea and method of large-scale automatic classification. The UBA of some cities in the Li et al. (2020) dataset is completely missing. The reason may be that this dataset's spatial scale is global, and the cities on the Qinghai-Tibetan Plateau are neglected. Among the cities in this dataset that can successfully identify UBA, there are again different degrees of misclassification (classifying land cover types that do not belong to UBA as UBA) and omission. In Gong et al.'s (2019) dataset, the UBA profile of some cities is too fragmented, which is not in line with the logic and facts of urban development, and there is a degree of misclassification. The main problems with the dataset of Liu et al. (2020) are consistent with those of Gong et al. (2019), but the fragmentation of the UBA profile is more severe. The completeness of the UBA boundary contours in the Kuang (2021) dataset is good, but there is a certain degree of misclassification and omission, and the UBA is completely missing in some cities. The main problem with the Globeland 30 dataset is misclassification, which may be because the land use classification method used in Globeland 30 does not effectively avoid the interference of feature information such as bare soil, which is widely present in the images.

The dataset of this study has the advantages of high temporal and spatial resolution. At the same time, the extraction effect and accuracy of this dataset are better than the five existing datasets. It provides high-quality data support for studying the urbanization process in the Qinghai-Tibetan Plateau region in the 21st century. However, the disadvantage of this dataset is that the production process is relatively time-consuming and may not be able to support high-resolution and high-accuracy mapping of urban boundaries at the global scale.

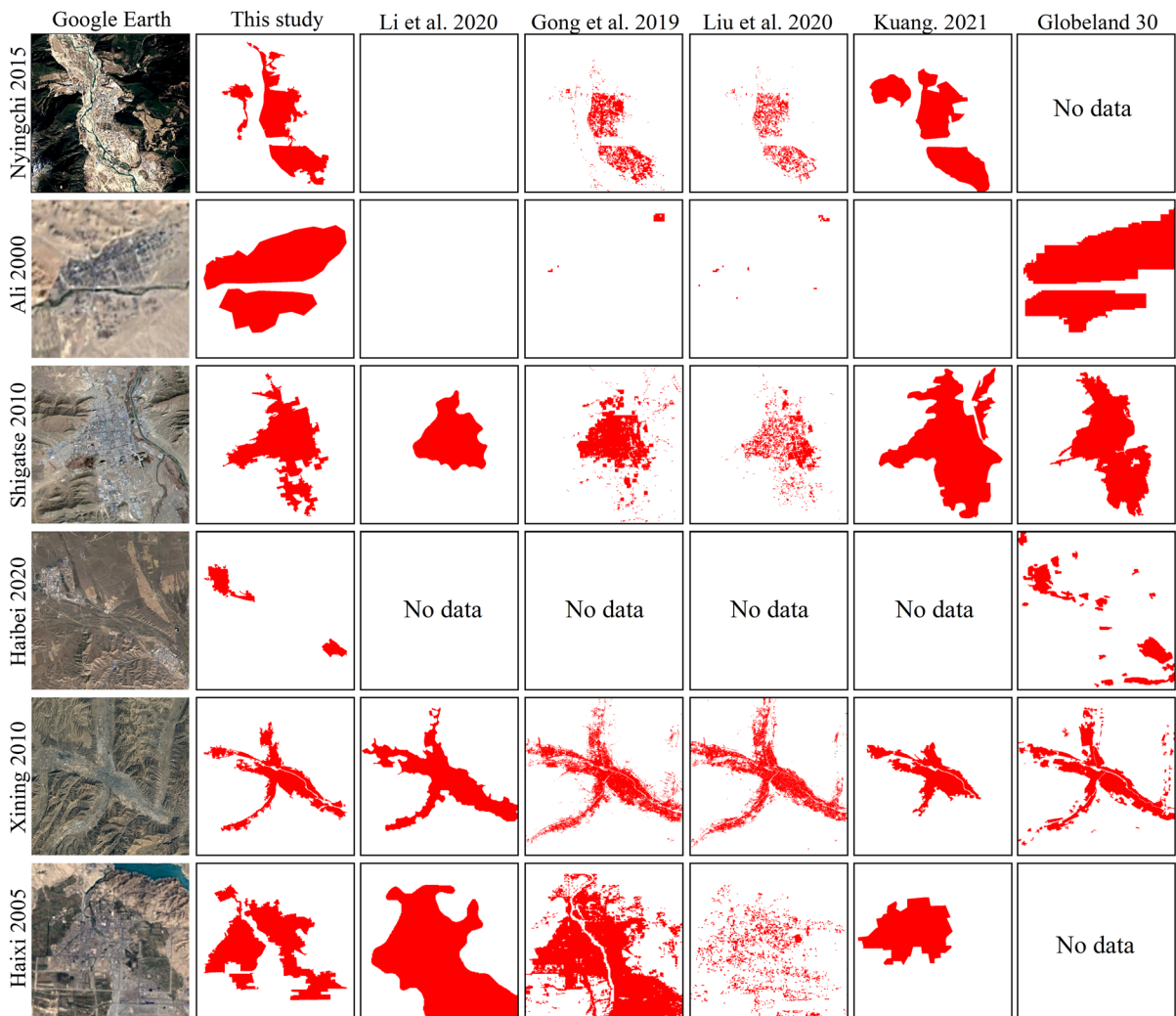


Fig. 12 Comparison of the dataset in this paper and other existing datasets

Does urban expansion occur more in disaster-prone areas?

Rentschler et al. (2023) showed that countries worldwide have been building cities in disaster-prone areas faster than areas where disasters are less likely to occur. To further explore whether urban expansion on the Qinghai-Tibetan Plateau also shares this trend, we produced a multi-hazard disaster risk class map for eight cities on the Qinghai-Tibetan Plateau based on existing data sources combined with GIS spatial analysis methods (Fig. 13). Due to the limitation of the data source, the result only fully included the built-up areas of

the eight cities in our study area. In these eight cities, 44.95% of the urban built-up areas were distributed in medium and high risk areas in 2000. While in 2020, the urban built-up areas distributed in these two types have grown to 52.13%. Among the new urban built-up areas added in the last two decades, 54.95% of the growth occurred in the medium and high risk areas of disaster—significantly more than in the relatively low and low risk areas of disaster. However, this is the result of including just the Yarlung Zangbo River and its two tributaries without the Yellow River-Huangshui River Valley. Otherwise, this trend would be more pronounced if the results based on Section [Geological and](#)

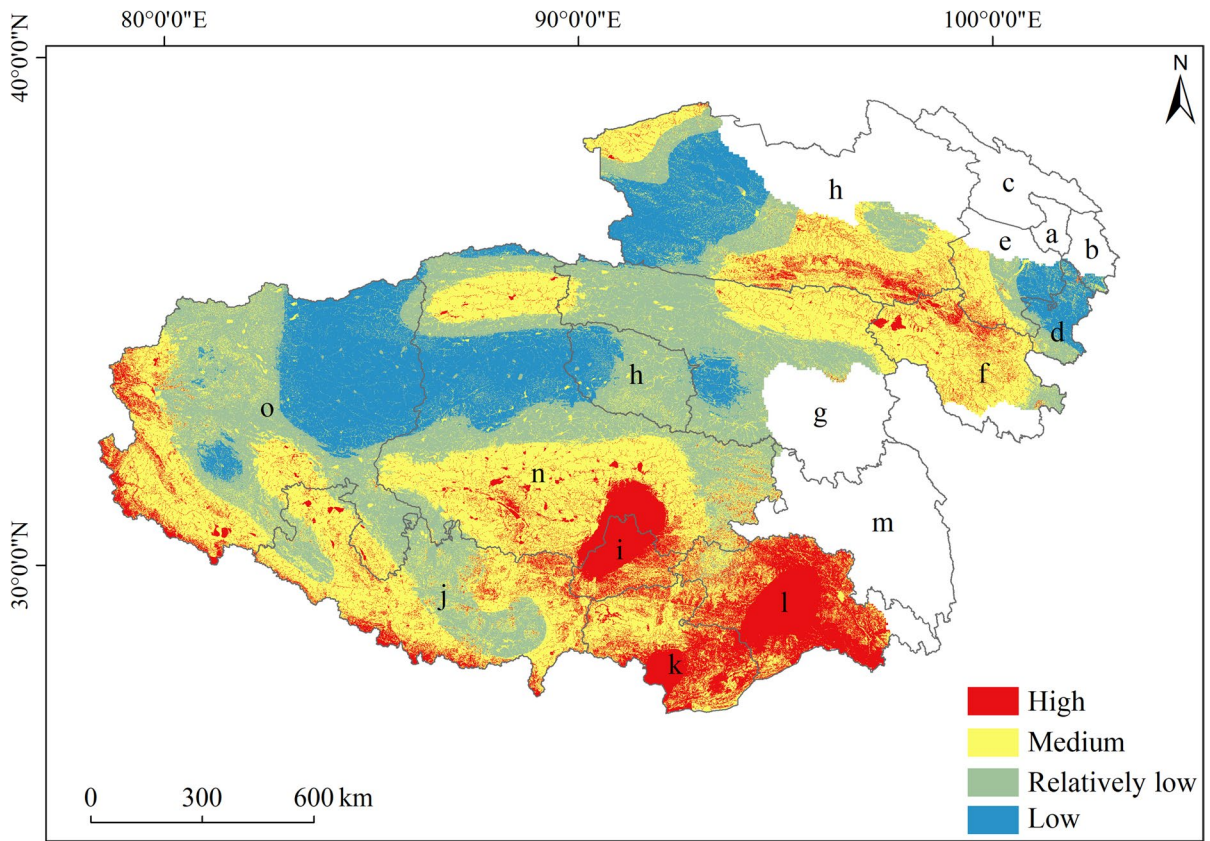


Fig. 13 Combined disaster risk classes for eight cities on the Qinghai-Tibetan Plateau

hydrometeorological disaster risk potential in the urbanization of the Qinghai-Tibetan Plateau were extrapolated.

In addition, The Qinghai-Tibetan Plateau region has a relatively low level of education and a shortage of technical personnel compared to the central and eastern parts of China. Transportation is inconvenient, and disaster risk prevention capabilities must be urgently improved. In the next stage of urban development planning, care should be taken to focus on disaster risks and minimize potential disasters.

Urbanization on the Qinghai-Tibetan Plateau from a National and global perspective

We compared the expansion rate of urbanization in the Qinghai-Tibetan Plateau with that of China and globally since 2000. The total and annual expansion rates of the Qinghai-Tibetan Plateau from 2000 to 2020 were 252.25% and 12.61%, respectively. The

total area of national UBA in China from 2000 to 2020 was obtained from the China Urban Construction Statistical Yearbook, and the total and annual expansion rates were 170.60% and 8.53%, respectively. The global UBA area uses the 2000–2018 GUB dataset published by Li et al. (2020a), with total and annual expansion rates of 80.71% and 4.48%, respectively. The urbanization process in the Qinghai-Tibetan Plateau region is faster than the Chinese and global averages, with expansion rates 1.48 and 2.81 times higher than those of China and the world, respectively.

Due to the unique geographical environment and topographic constraints of the Qinghai-Tibetan Plateau, urban built-up areas and populations are concentrated in specific valley areas, which is different from the typical urbanization pattern in other regions of China, especially in the plains of eastern China. In addition, numerous nature reserves on the Qinghai-Tibetan Plateau require more ecological

protection measures in urbanized areas than in other regions.

This study shows that urban built-up areas and population distribution on the Qinghai-Tibetan Plateau coincided with high-risk areas for geological and hydrometeorological disasters. This finding highlights the importance of considering geological and hydrometeorological disaster risks in the urban planning and construction process, especially in the special geographical environment. It will help to provide scientific reference for the formulation of future urban development policies and plans in the Qinghai-Tibetan Plateau and other plateau and mountainous regions in the world, and to raise awareness of geological and hydrometeorological disaster risk prevention in these regions. Also, in addition to areas of high geological and hydrometeorological disaster risk, urban construction in a wide range of low geological and hydrometeorological disaster risk areas should be alerted to the consequences that may result when a disaster occurs.

New contributions of this study to the existing literature on urbanization

This study adds new contributions to the literature by addressing the urbanization process on the Qinghai-Tibetan Plateau since the 21st century. In addition to the existing studies stated in the introduction, we have also focused on comparing the studies in this field in the last three years to ensure the currency and novelty of this study. In studies of urban expansion on the Qinghai-Tibetan Plateau, Wang et al. (2023a) used GF-1 images that extracted the distribution of urban impervious surfaces in Lhasa in 2014 and 2021 (Wang et al. 2023a). With a spatial resolution of 2 m, the urban expansion of Lhasa was finely delineated and analyzed. However, the study only analyzed one provincial capital city and lacked representativeness for the entire Qinghai-Tibetan Plateau. In contrast, the 15 cities selected for our study can comprehensively represent the characteristics of the entire study area. In addition, the timeframe of Wang's study was only 2014–2021, failing to provide data since 2000 as our study does. Nie et al. (2022) used multi-source remote sensing historical image data and employed the human-computer interaction interpretation method to obtain reliable urban expansion data for Lhasa (Nie et al. 2022). It further proved that the

human-computer interaction interpretation method used in our study is feasible. However, the study by Nie et al. (2022), like the study by Wang et al. (2023), only studied the city of Lhasa and is not representative of urban expansion in the entire Qinghai-Tibetan Plateau region. Wang et al. (2023) analyzed the dynamics of urban expansion in the Qinghai-Tibetan Plateau region with nighttime lighting data, which represents the entire study area (Wang et al. 2023b). However, the limitation of the data source resulted in a spatial resolution of only 1 km for the urban boundary dataset. In the study of risk in urbanization, Wang et al. (2023) considered ecological risk rather than disaster risk in the urbanization process in the Qinghai-Tibetan Plateau region (Wang et al. 2022b). The study by Dai et al. (2022) addressed hydrometeorological hazards, but only studied one city of Lhasa and lacked overall representation of the Qinghai-Tibetan Plateau region (Dai et al. 2022). At the same time, our study explored the disaster risks in the urbanization process in the Qinghai-Tibetan Plateau region.

In the analysis of the coupling between population growth and urban area expansion, most of the existing literature has used qualitative methods to combine the two, and the degree of quantification is insufficient. Our study used the USI index to quantitatively analyze the relationship between population and urban built-up areas, which can enrich the quantitative research in this field. In terms of geological and hydrometeorological disaster risk, the existing literature on disasters in the Qinghai-Tibetan Plateau mainly discusses the mechanism and evolution process of geological and hydrometeorological disasters and the determination of disaster risk areas in the Qinghai-Tibetan Plateau, without any work on the rapid urbanization process in the 21st century. Research on geological and hydrometeorological disaster risk on the Qinghai-Tibetan Plateau has been a hot spot in the international literature. This study provides a new contribution by combining geological and hydrometeorological disaster risk with rapid urbanization since 2000.

At the level of technology and data support, our study has produced the first high-accuracy and high-resolution urban boundary dataset for the Qinghai-Tibetan Plateau from 2000 to 2020 based on remote sensing and GIS technologies, which is a new reliable data set for documenting urban

expansion in this region. In the past, the quantification of urban studies in this region has been lacking due to the lack of detailed urban boundary data. With this dataset as a research base, not only urbanization studies in the Qinghai-Tibetan Plateau region can be conducted, but also a series of urban-related works.

As mentioned, less attention has been paid to the urbanization of the Qinghai-Tibetan Plateau region compared to other regions in China for various reasons. Although the Qinghai-Tibetan Plateau remains underdeveloped compared to other regions, our study shows the rapid urbanization experienced in recent years. The international literature is currently rich in research on the natural domain of the Qinghai-Tibetan Plateau, but insufficient in the urban domain. This study can attract more scholars to pay attention to the urbanization of the Qinghai-Tibetan Plateau while enriching the literature in the urban field in this region, and providing a basis and support for the research of urbanization in relatively underdeveloped areas.

Finally, understanding the complex relationship between urbanization and the environment is crucial for sustainable development. This study shows that urban expansion and population growth on the Qinghai-Tibetan Plateau are mainly concentrated in specific river valley areas. In other words, urban expansion occurred mainly in areas with abundant water resources and flat terrain. Since the Qinghai-Tibetan Plateau region is known as the water tower of Asia, this may lead to environmental impacts such as soil erosion of river banks and pollution of water sources. In urban expansion, water resources need to be used wisely to ensure water supply for urban and rural residents. It also prevents pollution and damage to water sources so that they are not affected downstream.

Future research should explore the climate response of the urbanization process and human activities on the Qinghai-Tibetan Plateau in the context of global climate change. Global climate change will inevitably affect the urbanization process on the Qinghai-Tibetan Plateau; in turn, human activities will affect the temperature, water cycle, and ecological systems on the Qinghai-Tibetan Plateau, thus in turn impacting global climate change.

Conclusion

This study produced a high-precision UBA boundary dataset from 2000 to 2020 in Qinghai Province and Tibet and evaluated it in comparison with other existing datasets. We conducted a spatial and temporal evolution analysis of the UBA expansion on the Qinghai-Tibetan Plateau and quantitatively assessed the population changes alongside urbanization. We also combined quantitative and qualitative data to reveal the risk of geological and hydrometeorological disasters in the Qinghai-Tibetan Plateau's urbanization process. The main conclusions obtained are as follows:

(1) The urban boundary dataset produced in this study from 2000 to 2020 in Qinghai Province and Tibet can show the complete outline and details of UBA of all cities. The accuracy and effect are better than the other five existing datasets. The Qinghai-Tibetan Plateau has experienced rapid and uneven urbanization in the past 20 years. The total expansion rate was 252.25%, which was 1.48 times and 2.81 times higher than the same period in China and the world, respectively. Urban expansion exceeded population growth in most cities throughout the whole period. However, internal urban expansion was highly uneven, with significant differences and polarization. The area growth in provincial capitals was significantly larger than that in non-capital cities, and there was also a considerable development imbalance among non-capital cities.

(2) The UBA and population increase on the Qinghai-Tibetan Plateau were both characterized by a concentration in the main basin areas (the Yellow River-Huangshui River Valley of Qinghai and the Yarlung Zangbo River and its two tributaries of Tibet). Among them, Xining, Haidong, Lhasa, Shigatse, and Shannan, with only 10.53% of the land area of 15 cities, occupied 75.81% of the population and 73.84% of the UBA.

(3) Nearly two decades, urban expansion occurred more in disaster-prone areas, rather than disaster low-risk areas. Constrained by the topography of the Qinghai-Tibetan Plateau itself, almost all urban expansion has occurred in the river valley/ valley zones where the terrain is relatively flat. The areas of UBA and population concentration are highly coincident with the high-risk areas of geological and hydrometeorological disasters, and urban development is

faced with the great potential danger of geological and hydrometeorological disasters.

Author contributions Conceptualization: Chenglong Yin, Ruishan Chen; Methodology: Chenglong Yin, Ruishan Chen, Qiang Zhou, Fenggui Liu, Qiong Chen; Formal analysis and investigation: Chenglong Yin, Ruishan Chen, Fei Meng, Xiaona Guo; Writing - original draft preparation: Chenglong Yin, Ruishan Chen; Writing - review and editing: Chenglong Yin, Annah Lake Zhu, Ruishan Chen, Qiang Zhou, Fei Meng; Funding acquisition: Qiang Zhou, Ruishan Chen, Xiaona Guo; Resources: Ruishan Chen; Supervision: Ruishan Chen.

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Declarations

Competing interests The authors declare no competing interests.

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