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Spatiotemporal characteristics and socioeconomic inequalities in water, sanitation, and hygiene access in China from 2000 to 2020: analysis of data from three national censuses

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Abstract

Background Access to water, sanitation, and hygiene (WASH) facilities presents a significant global public health challenge. This study aims to investigate the temporal and spatial characteristics of WASH access in mainland China, as well as the socioeconomic equity, using data from national censuses.

Methods We analyzed households' data from three national censuses spanning 2000 to 2020 to examine the characteristics of safe water, sanitary toilets, and hygiene bathing facilities over time. Spatial clustering of WASH facilities in 2020 was assessed using Moran's I analysis. Socioeconomic disparities in WASH access across provinces were quantified using the Slope Index of Inequality (SII) and Relative Index of Inequality (RII).

Results Between 2000 and 2020, access to safe water in China increased significantly from 45.7% to 91.3%, access to sanitary toilets rose from 18.7% to 78.5%, and access to hygiene bathing facilities climbed from 26.0% to 88.4%, reflecting continuous improvements in WASH access. Urban areas consistently outperformed rural areas, and the eastern region showed higher access rates compared to the central and western regions. Spatial analysis revealed statistically significant clustering of sanitary toilets and hygiene bathing facilities at the provincial level in 2020. Equity analysis indicated a notable improvement in the fairness of WASH access over the past two decades, with decreases observed in both SII and RII metrics.

Conclusion Mainland China has made substantial strides in enhancing WASH access over the last 20 years, accompanied by significant improvements in provincial equity. However, persistent regional disparities underscore the need for targeted financial support to rural, central, and western regions to further enhance WASH accessibility.

Keywords Water, Sanitation, Hygiene, Spatiotemporal characteristics, Socioeconomic inequalities, China

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Introduction

Access to water, sanitation, and hygiene (WASH) facilities is crucial for public health globally, playing a pivotal role in reducing disease transmission, improving nutrition, enhancing educational outcomes, and supporting economic development [1, 2]. The availability of clean water and adequate sanitation is not only a basic human

right but also essential for achieving various Sustainable Development Goals (SDGs), particularly Goal 6, which aims to ensure availability and sustainable management of water and sanitation for all by 2030 [3]. Despite significant global progress, disparities in WASH access persist, particularly in low- and middle-income countries where infrastructure development lags behind urbanization and population growth [4]. According to the World Health Organization (WHO) and UNICEF report, *Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender (2023)*, 73% of the global population had access to safely managed drinking water at home, while safely managed sanitation services were available to 57% of the population in 2022 [5].

China has undergone remarkable socioeconomic transformations over the past few decades, marked by rapid urbanization, industrialization, and rural development initiatives [6, 7]. Historically, access to WASH facilities in China faced substantial challenges, which include limited infrastructure in rural areas, financial constraints, and governance issues [8, 9]. China's journey towards enhancing WASH access dates back to the mid-twentieth century [10, 11]. The National Patriotic Health Campaign, initiated in the 1950s, laid the foundation for public health improvements, including water purification and sanitation infrastructure development [12]. The establishment of the Ministry of Housing and Urban–Rural Development in 2008 further bolstered efforts to address urban–rural disparities and promote the development of urban–rural integration with adequate WASH infrastructure [13]. According to statistics from that time, in 2006, only 61% of the rural population in China had access to clean water, while in urban areas, this proportion exceeded 80% [14]. Today, China's WASH policies are integral to achieving public health goals and fostering sustainable development nationwide. The government's commitment to improving public health through comprehensive WASH policies and initiatives has been underscored by initiatives such as the Healthy China 2030 Blueprint, the rural water supply project, and toilet revolution [15–18].

In China, previous studies have predominantly focused on urban–rural divides and regional disparities [19, 20]. Studies have shown that while urban areas and wealthier provinces have seen significant improvements in WASH infrastructure, rural areas and less developed regions continue to lag behind [9, 21, 22]. The World Bank's WASH Poverty Diagnostic Initiative has underscored the relationship between poverty and inadequate WASH services, highlighting the need for targeted interventions to address these disparities [23]. Despite existing literature, there remains a notable research gap in understanding the longitudinal dynamics and socioeconomic inequalities of WASH access in China. Few studies have systematically examined the WASH infrastructure development and equity across different regions over time in China. Moreover, comprehensive assessments integrating temporal trends and equity metrics are lacking, hindering targeted policy interventions and effective resource allocation strategies.

This study aims to comprehensively analyze the spatiotemporal characteristics and socioeconomic inequalities in WASH access in mainland China from 2000 to 2020. The specific objectives are: 1) to examine the evolution of access to safe water, sanitary toilets, and hygienic bathing facilities over the past two decades, highlighting both national and regional trends; 2) to investigate the geographical distribution and clustering of WASH facilities across provinces using spatial analysis techniques, such as Moran's I, to identify spatial patterns; 3) to assess the socioeconomic inequalities in WASH access across provinces using the Slope Index of Inequality (SII) and the Relative Index of Inequality (RII), providing insights into equity gaps and improvements over time. By addressing these objectives, the study aims to provide evidence-based insights that can inform policy interventions, further improving access to WASH infrastructure and reducing disparities across urban and rural areas, as well as among provinces of different socioeconomic levels in China.

Methods

Study design and participants

This study adopts an observational research design. The data is sourced from the household data collected during the national population censuses conducted in China in 2000, 2010, and 2020. The census targets natural persons within China and Chinese citizens abroad who have not settled elsewhere. The population census was selected as the primary data source due to its comprehensive coverage of all households across all 31 provinces in China. This dataset offers consistent nationwide information, allowing for a robust analysis of WASH trends over time. Additionally, the census provides reliable demographic and housing information at the national and regional levels, making it a suitable tool for examining long-term spatiotemporal patterns. Specifically, key demographic characteristics in census included age, sex, and employment status, while housing conditions focused on water sources, sanitation, and hygiene facilities. Regarding the classification of urban and rural areas, the 2000 population census was based on the "Provisional Regulations on the Statistical Division of Urban and Rural Areas" issued by the National Bureau of Statistics of China at that time, while the 2010 and 2020 censuses followed the "Regulations on the Statistical Division of Urban and

Rural Areas" issued in 2008. Although the 2008 regulations are largely consistent with those from 2000, some adjustments were made to the urban–rural classifications in certain areas. However, since our analysis of WASH trends is conducted at the national level, these changes have limited impact on the overall analysis.

The three censuses involved 33,188,549 households in 2000, 39,270,972 households in 2010, and 45,791,305 households in 2020. Information on household water usage, toilet facilities, and sanitary bathing facilities was collected from all households. The main point to note is that the survey on housing conditions is collected on a household basis. As the census does not disclose the education and income data of each household member, this study cannot directly link socioeconomic characteristics with WASH acquisition. Considering that WASH data was collected on a household basis, and household income has a direct impact on investment in WASH infrastructure, we used annual household disposable income as a variable to study socioeconomic inequality. The overall and urban–rural annual household disposable income data for the 31 provinces of China is sourced from the " China Household Survey Yearbook", and its definition of urban and rural areas is consistent with that used in the population census.

Measures

WASH

Based on previous studies [24–26], we employed three indicators (binary variable) to measure WASH. Firstly, safe water is defined as having piped water within the household. The census inquired whether households had piped water treated by public facilities, which we use as the indicator for safe water. Second, sanitation is defined as having a flush sanitary toilet in the home. Toilet types include flush sanitary toilets, non-flush toilet, pit latrines, and none in population censuses. A flush toilet is defined as one with a water supply system, or a toilet with a bucket (scoop flush), a seat or squat toilet with or without a water seal, where the excrement and wastewater are flushed into a sewer, septic tank, or pit, without causing flies or environmental pollution. This study uses flush toilets as the measure of sanitation. Personal hygiene is defined as the conditions that help maintain health and prevent the spread of diseases [26]. The census surveyed whether households had usable bathing facilities such as fixed bathtubs or showers, including centralized hot water supply systems (where hot water for bathing is supplied by the community, property management, or other public facilities), self-installed water heaters (including electric, gas, and other types of water heaters), other bathing facilities, or no bathing facilities. This study uses the presence of any bathing facility in the home as the measure of personal hygiene.

Regional characteristics

The census data provides information at the national level and for the 31 provinces, covering overall, urban, town, and rural areas. According to China's "Statistical Definitions for Urban and Rural Areas," [27] areas are categorized into urban and rural areas. Urban areas include city districts and town areas, while rural areas refer to regions outside urban areas. In this study, the urban data and town data from the census are combined to obtain the urban data for the entire country and each province. Following the previous division of China's three major economic regions and related research [28], this study divides the 31 provinces into three regions: Eastern, Central, and Western. The Eastern region includes 11 provinces: Shanghai, Beijing, Tianjin, Shandong, Guangdong, Jiangsu, Hebei, Zhejiang, Hainan, Fujian, and Liaoning. The Central region includes 8 provinces: Jilin, Anhui, Shanxi, Jiangxi, Henan, Hubei, Hunan, and Heilongjiang. The Western region includes 12 provinces: Yunnan, Sichuan, Ningxia, Guangxi, Xinjiang, Gansu, Xizang, Guizhou, Chongqing, Shaanxi, Qinghai, and Inner Mongolia.

Statistical analyses

Descriptive analysis was used to examine the changes in WASH access in China from 2000 to 2020, overall and by urban–rural and regional divisions. We used the frequency (proportion) of households to describe the access to WASH facilities, as this provides a more accurate reflection of infrastructure distribution at the household level rather than individual population data. We employed global Moran's I and local Moran's I [29] to analyze the spatial distribution characteristics and clustering degree of WASH access across 31 provinces in China in 2020. We chose to focus on the spatial patterns of 2020 primarily for the following reasons: First, the 2020 population census provides the most recent data, offering a clearer picture of the current spatial distribution of WASH facilities in China. Second, as the study aims to highlight the latest spatial patterns, the 2020 data is more relevant for informing current policy-making and resource allocation. While the 2000 and 2010 data can reveal long-term trends, we prioritized the detailed analysis of the most recent data to ensure that our findings are directly applicable to the present context. The global Moran's I ranges from −1 to 1, where $I > 0$ indicates positive spatial autocorrelation and clustering tendencies, while $I < 0$ indicates negative spatial autocorrelation and dispersion tendencies [29]. Local Moran's I is used

to analyze four local spatial agglomeration patterns of WASH access: High-High agglomeration (high values of WASH access clustered in neighboring provinces), Low-Low agglomeration (low values of WASH access clustered in neighboring provinces), High-Low agglomeration (negative correlation; provinces with high values of WASH access surrounded by provinces with low values), and Low–High agglomeration (provinces with low values of WASH access surrounded by provinces with high values).

Social-economic disparities in WASH access across Chinese provinces were quantified using the SII and the RII. Specifically, we ranked mainland China's 31 provincial-level administrative regions in 2000, 2010, and 2020 by their respective annual household disposable income, thereby reflecting provincial-level social-economic disparities. Following established criteria [30], SII measured the absolute difference in WASH access rates between the highest and lowest ranking provinces, indicating absolute inequality. RII measured the ratio of WASH access rates between the highest and lowest ranking provinces, indicating relative inequality. Regression analysis was conducted using WASH access rates as the dependent variable and annual household disposable income ranking as the independent variable to estimate SII and RII. Specifically, beta values from linear regression were used to determine SII, while the mean ratio from Poisson regression without log transformation was used to determine RII [31]. All analyses were used by STATA 17.0 (Stata Corp, College Station, TX, USA), and $P < 0.05$ indicated statistical significance.

Results

Temporal trends of water, sanitation, and hygiene access from 2000 to 2020

Table 1 presents the temporal trends in WASH access in China from 2000 to 2020. Substantial improvements in WASH access have been observed nationwide, in both urban and rural areas, as well as across eastern, central, and western regions. Specifically, from 2000 to 2020, access to safe water increased from 45.7% to 91.3%, a 45.6% rise over two decades. Access to sanitary toilets rose from 18.7% to 78.5%, marking a 59.8% increase, while access to hygienic bathing facilities saw the largest growth (62.4%), climbing from 26.0% to 88.4%. In terms of urban and rural areas, the rate of increase in rural WASH access has outpaced that of urban areas. Over the past twenty years, access to safe water in rural areas increased by 58.2%, access to sanitary toilets by 53.2%, and access to hygiene bathing facilities by 64.8%, compared to increases of 15.4%, 47.5%, and 48.1%, respectively, in urban areas. Regionally, the eastern region's rate of increase in WASH access over the past twenty years has been lower than that of the central and western regions. However, there are notable disparities in WASH access between urban and rural areas, with urban areas having significantly higher access rates. Additionally, access rates of WASH in the eastern region are higher than those in the central and western regions.

Table 1 The rates of safe water, sanitation, and hygiene access in China

Variables	2000	2010	2020
Safe water			
Total	15,169,758 (45.7)	25,361,269 (64.6)	41,822,672 (91.3)
Urban	10,185,589 (81.1)	17,304,291 (86.6)	27,937,860 (96.5)
Rural	4,984,169 (24.2)	8,056,978 (41.7)	13,884,812 (82.4)
Eastern region	7,968,603 (60.1)	13,375,768 (80.4)	18,762,973 (94.1)
Central region	3,922,988 (36.5)	6,225,538 (52.3)	12,168,602 (89.5)
Western region	3,278,167 (35.6)	5,759,963 (53.6)	10,891,097 (88.9)
Sanitary toilet			
Total	6,202,479 (18.7)	14,643,023 (37.3)	35,934,662 (78.5)
Urban	5,477,341 (43.6)	12,174,697 (61.0)	26,382,818 (91.1)
Rural	725,138 (3.5)	2,468,326 (12.8)	9,551,844 (56.7)
Eastern region	3,589,156 (27.1)	8,239,156 (49.6)	16,710,866 (83.8)
Central region	1,519,066 (14.1)	3,551,435 (29.9)	10,200,675 (75.0)
Western region	1,094,257 (11.9)	2,852,432 (26.5)	9,023,121 (73.6)
Hygiene bathing facility			
Total	8,623,254 (26.0)	21,360,933 (54.4)	40,485,900 (88.4)
Urban	5,763,287 (45.9)	14,339,065 (71.8)	27,225,591 (94.0)
Rural	2,859,967 (13.9)	7,021,868 (36.4)	13,260,309 (78.7)
Eastern region	4,794,288 (36.2)	11,333,863 (68.2)	18,182,097 (91.2)
Central region	2,026,777 (18.9)	5,352,845 (45.0)	11,807,839 (86.8)
Western region	1,802,189 (19.6)	4,674,225 (43.5)	10,495,964 (85.7)

Figure 1 shows the provincial level trend of water, sanitation, and hygiene access from 2000 to 2020. Although overall WASH access has been on the rise, there are disparities among provincial levels in China. From 2000 to 2020, Shanghai consistently ranked highest in safe water access, while Xizang ranked lowest. Provinces in the western regions showed obvious improvements, with Xinjiang rising from 9th place in 2000 to 4th place in 2020, and Ningxia from 16 to 5th place. Anhui province in the central region experienced the greatest increase (72.3%), rising from 21.5% to 93.8% in safe water access. In contrast, most provinces in the eastern region showed slower improvements compared to those in the central and western regions. Regarding access to sanitary toilets, Jiangxi province showed the greatest improvement (82.7%), increasing from 12.8% to 95.5%. However, the improvement rate for sanitary toilet access in eastern provinces was relatively lower, with Shanghai showing the smallest increase (25.5%). Nevertheless, eastern provinces generally ranked higher in sanitary toilet access

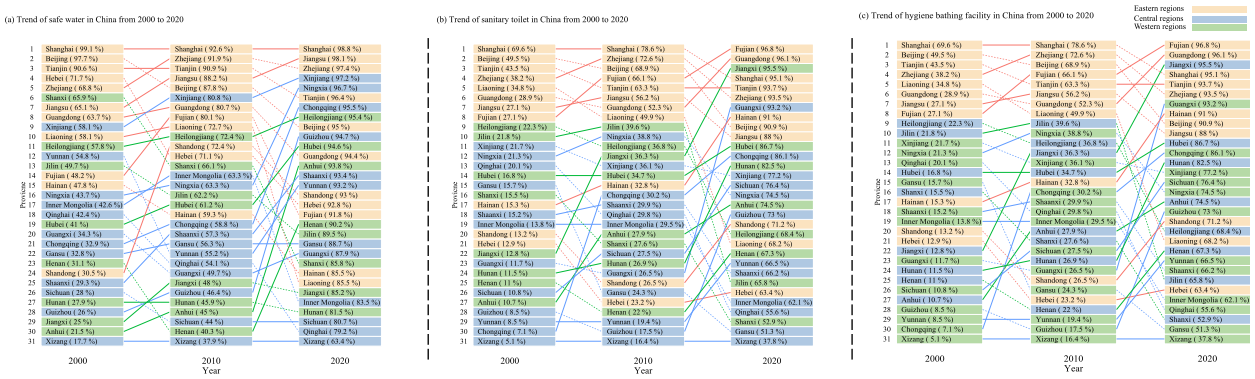

Fig. 1 Provincial level trend of water, sanitation, and hygiene access from 2000 to 2020. Note: Red lines show the change of provinces in the Eastern region; Blue lines show the change of provinces in the Central region; Green lines show the change of provinces in the Western region; Solid lines represent provinces with an increase or no change; Dashed lines represent provinces with a decrease

rates. For sanitary bathing facilities, eastern provinces consistently ranked higher, while central and western provinces showed significant increases. For example, Henan province increased by 79.4%, and Jiangxi province by 75.4%. It is noteworthy that Xizang remains at the lowest level, despite improvements in its WASH access, with the lowest access rates overall.

Moreover, from 2000 to 2010, China saw significant improvements in WASH access, with access to safe water increasing from 45.7% to 64.6%, and access to sanitary toilets rising from 18.7% to 37.3%. This decade was marked by accelerated infrastructure development, particularly in rural areas. The subsequent period from 2010 to 2020 witnessed even more substantial gains, with safe water access reaching 91.3% and sanitary toilet access increasing to 78.5%. The continued efforts in rural infrastructure, coupled with urban–rural integration policies, played a pivotal role in these improvements.

Spatial patterns of water, sanitation, and hygiene access in 2020

Figure 2 displayed the provincial distribution of water, sanitation, and hygiene access in 2020. The results of the global spatial autocorrelation analysis indicate that sanitary toilets (Moran's $I = 0.524$, $P < 0.001$) and hygiene bathing facilities (Moran's $I = 0.319$, $P = 0.002$) exhibit positive spatial autocorrelation, suggesting spatial clustering. However, safe water shows positive autocorrelation (Moran's $I = 0.099$, $P = 0.229$) without statistical significance. Table 2 presents the local spatial autocorrelation patterns for WASH. For safe water, both Low-Low and High-Low clustering patterns were identified. Qinghai and Xizang in western China exhibit significant Low-Low clustering, while Xinjiang shows High-Low clustering. For sanitary toilets, the local spatial autocorrelation analysis reveals both Low-Low and High-High clustering patterns. Provinces such as Zhejiang, Fujian, Jiangxi, and Guangdong exhibit High-High clustering, whereas Shanxi, Inner Mongolia, Xizang, Gansu, and Qinghai exhibit Low-Low clustering.

Fig. 2 Provincial distribution of water, sanitation, and hygiene access in 2020. Note: Provincial boundaries data were obtained from the National Catalogue Service for Geographic Information

Table 2 Agglomeration patterns of WASH in China in 2020

Patterns	Safe water	Sanitary toilet	Hygiene bathing facility
High–high		Zhejiang, Fujian Jiangxi, Guangdong	
Low–low	Xizang, Qinghai	Shanxi, Inner Mongolia Xizang, Gansu, Qinghai	Inner Mongolia, Jilin Heilongjiang, Qinghai
High–low	Xinjiang		Xinjiang

Hygiene bathing facilities display Low-Low and High-Low clustering patterns. Provinces like Inner Mongolia, Jilin, Heilongjiang, and Qinghai exhibit Low-Low clustering, while Xinjiang shows High-Low clustering.

Socioeconomic inequalities in water, sanitation, and hygiene access in China from 2000 to 2020

Table 3 shows the SII and RII of inequality for safe water, sanitation, and hygiene access in China from 2000 to 2020, divided into overall, urban, and rural categories. Over the past two decades, socioeconomic inequality in WASH access at the provincial level in China has consistently decreased, yet disparities persist. In terms of safe water access, overall socioeconomic inequality has significantly improved. In 2000, the SII was 50.4, indicating severe inequality, but by 2020, this index had decreased to 9.6, showing a marked reduction in inequality. Similarly, the overall RII decreased from 2.9 in 2000 to 1.1 in 2020. Urban areas experienced relatively stable inequality in safe water access throughout the period, with consistently low SII and RII values. However, rural areas saw more significant improvements, with the SII decreasing from 52.0 in 2000 to 9.4 in 2020, and the RII dropping from 6.7 to 1.1, indicating substantial progress in rural safe water access.

In addition, for sanitary toilets, inequality also improved but at a slower pace. The overall SII increased from 34.5 in 2000 to 47.7 in 2010, before decreasing to 35.6 in 2020, suggesting slower progress in this area. The overall RII decreased from 5.8 in 2000 to 1.6 in 2020. Urban areas experienced fluctuations in inequality levels, with SII and RII rising between 2000 and 2010 and then falling by 2020. In rural areas, while the SII increased from 15.7 in 2000 to 58.7 in 2020, the RII decreased dramatically from 78.4 to 3.1, indicating a significant reduction in relative inequality despite the increase in absolute inequality.

Regarding hygiene bathing facilities, overall inequality showed notable improvement. In 2000, the overall SII was 45.7 and the RII was 6.9, but by 2020, these indices had decreased to 26.6 and 1.4, respectively. Urban areas saw a decrease in SII from 40.0 in 2000 to 6.0 in 2020, with the RII also falling from 2.6 to 1.1, indicating reduced inequality in urban hygiene facilities. Rural areas also improved, with the SII decreasing from 35.9 in 2000 to 31.1 in 2020, and the RII dropping from 17.2 to 1.5,

Table 3 Slope index of inequality and relative index of inequality for safe water, sanitation, and hygiene access in China from 2000 to 2020

Variables	Overall		Urban		Rural	
	SII (95%CI)	RII (95%CI)	SII (95%CI)	RII (95%CI)	SII (95%CI)	RII (95%CI)
Safe water						
2000	50.4 (29.7–71.2)	2.9 (2.4–3.5)	7.6 (−5.5–20.6)	1.1 (1.0–1.3)	52.0 (26.4–77.6)	6.7 (5.2–8.6)
2010	43.2 (29.8–56.5)	2.0 (1.7–2.3)	10.8 (1.9–19.7)	1.1 (1.0–1.3)	45.2 (23.3–67.1)	2.8 (2.3–3.3)
2020	9.6 (0.8–18.5)	1.1 (1.0–1.3)	0.3 (−4.3–5.0)	1.0 (0.9–1.1)	9.4 (−7.2–25.9)	1.1 (1.0–1.3)
Sanitary toilet						
2000	34.5 (21.9–47.2)	5.8 (4.3–7.7)	9.2 (−7.0–25.3)	1.2 (1.0–1.5)	15.7 (6.6–24.9)	78.4 (34.4–178.8)
2010	47.7 (34.8–60.5)	3.7 (3.0–4.5)	16.6 (3.2–29.9)	1.3 (1.1–1.5)	42.1 (24.4–59.9)	30.6 (20.3–46.1)
2020	35.6 (20.8–50.5)	1.6 (1.4–1.8)	6.3 (−1.7–14.3)	1.1 (0.9–1.2)	58.7 (28.5–88.8)	3.1 (2.6–3.6)
Hygiene bathing facility						
2000	45.7 (31.2–60.3)	6.9 (5.3–9.0)	40.0 (21.5–58.6)	2.6 (2.2–3.2)	35.9 (23.0–48.8)	17.2 (11.7–25.4)
2010	51.6 (32.8–70.4)	2.9 (2.4–3.5)	36.1 (17.1–55.2)	1.7 (1.5–2)	55.7 (35.2–76.1)	5.9 (4.7–7.4)
2020	26.6 (8.9–44.2)	1.4 (1.2–1.6)	6.0 (−5.8–17.8)	1.1 (0.9–1.2)	31.1 (−1.1–63.2)	1.5 (1.3–1.8)

reflecting significant progress in reducing inequality in rural hygiene bathing facilities.

Discussion

This study, based on data from three Chinese censuses, reveals the temporal trends, spatial patterns, and provincial-level socioeconomic inequalities in access to WASH facilities in China from 2000 to 2020. Specifically, the access rate of safe water, sanitary toilets, and hygienic bathing facilities has significantly increased. In terms of spatial patterns, the year 2020 exhibited notable spatial autocorrelation and clustering of sanitary toilets and hygienic bathing facilities at the provincial level. Furthermore, socioeconomic inequalities in WASH access have markedly decreased over the two decades. These improvements have not only enhanced the quality of life for Chinese citizens but also contributed to broader public health goals.

From 2000 to 2020, China made significant progress in access to WASH facilities. The proportion of households with access to safe water increased from 45.7% to 91.3%, sanitary toilets from 18.7% to 78.5%, and hygienic bathing facilities from 26.0% to 88.4%. These improvements reflect the effective efforts by the Chinese government and various stakeholders to enhance public health infrastructure and services nationwide. Notably, the rate of WASH improvements was more pronounced in rural areas compared to urban areas, highlighting the government's efforts to bridge the urban–rural gap in WASH infrastructure development. A previous study based on the China Health Services Survey also found an upward trend in access to safe water and sanitation in urban and rural China from 2008–2018 [32]. These improvements can be attributed to key policies such as the "toilet revolution" and rural water supply projects aimed at addressing historical deficiencies in rural infrastructure [33, 34]. However, the persistent urban–rural disparity in WASH access still warrants serious attention. In particular, rural areas have lagged behind urban areas in water supply. In 2020, nearly all urban areas had access to improved water sources (over 95%), while rural areas still faced challenges with an access rate of about 82.4%. A similar gap exists in access to sanitary toilet. By 2020, improved sanitary toilet covered over 90% of urban areas, while rural areas, despite improvements, had coverage about 56.7%. Socioeconomic factors significantly influenced access to sanitary conditions [35], with urban populations generally having better access to WASH compared to rural populations, reflecting broader economic and infrastructure development disparities [36].

Additionally, regionally, the WASH access of central and western regions of China improved faster than the eastern region. However, the overall access rate in the eastern region remained higher, indicating persistent regional disparities. The eastern region had relatively high WASH access rates in 2000 and continued to improve over the past two decades. For instance, provinces such as Shanghai and Zhejiang have consistently led the country in safe water and sanitary toilet coverage. The higher economic development level in the eastern region, earlier and more comprehensive infrastructure development, and substantial government investment in public health have all contributed to these advancements [37, 38]. Moreover, the rapid urbanization in the eastern region has driven improvements in WASH facilities due to the higher hygiene awareness and demand among urban residents [39, 40]. The central region, which had lower WASH access rates in 2000, has made significant progress over the past two decades. With the implementation of the national strategy for the rise of the central region, economic and infrastructure development in central provinces like Henan and Hubei has significantly improved WASH facility coverage [41, 42]. However, there are still disparities within the central region, with some less economically developed provinces needing further improvements in WASH facilities. The western region had the lowest WASH access rates in 2000 but also achieved the most significant progress over the past two decades. For example, the coverage rate of safe water in Xinjiang and Xizang has significantly increased. This progress is mainly due to the national strategy for the large-scale development of the western region and a series of special policies and projects targeting the west, including rural drinking water safety projects and poverty alleviation initiatives [43]. However, the vast and sparsely populated areas, harsh natural conditions, and high costs of infrastructure development have made improvements in WASH facilities relatively slow and uneven in the western region.

Spatial analysis results showed a significant clustering in the spatial distribution of WASH facilities, especially sanitary toilets and hygienic bathing facilities. Specifically, sanitary toilets exhibited both high-high and low-low clustering patterns in certain provinces. These clustering patterns reflect significant differences in WASH access across provinces. For example, provinces like Zhejiang, Fujian, Jiangxi, and Guangdong exhibited high-high clustering of sanitary toilets, indicating high and concentrated access rates in these regions. Conversely, provinces like Shanxi, Inner Mongolia, Xizang, Gansu, and Qinghai exhibited low-low clustering, indicating low and concentrated access rates in these regions. A previous Chinese study on the spatial distribution of sanitary facilities from 2005–2015 similarly found that eastern regions such as Jiangsu, Zhejiang and western regions showed high—high and low—low clustering

characteristics, respectively [44], which further supports our finding. It should be mentioned that although the above study explored similar topics, there were differences in measurement methods due to the data used in the statistical yearbook was sourced from self-reported data from each province. The measurement of WASH in three national population censuses is unified and can be compared at the provincial level, providing a comprehensive and comparable perspective for the time dynamics of WASH acquisition. For hygienic bathing facilities, provinces like Inner Mongolia, Jilin, and Heilongjiang also showed low-low clustering, reflecting widespread inadequacies in WASH facility access. The importance of these spatial clustering patterns lies in their ability to reveal the unbalanced distribution of WASH access, highlighting the advantages and disadvantages of different regions in terms of sanitary facilities. High-high clustering areas may benefit from effective policy implementation and infrastructure investment, while low-low clustering areas may require more resources and policy support. Analyzing these patterns helps better understand and explain the development of WASH facilities in different regions, providing evidence-based decision-making to promote more balanced regional development [45]. For example, high-high clustering areas can serve as successful case studies for experience sharing [46], while low-low clustering areas need more policy and financial support to improve WASH facilities. Additionally, these patterns can reveal weaknesses in policy implementation, providing references for future policy adjustments and resource allocation to ensure equitable access to WASH facilities across all regions.

Another significant finding of this study is a significant progress in reducing socioeconomic inequalities in WASH access, particularly in rural areas, though the pace and extent of improvement vary across different facilities and urban–rural regions. A previous study found similar trends from 2008 to 2018 in socio-economic inequalities in safe water and sanitation [32]. In our study, the marked improvement in overall inequality in access to safe water is a positive development. The substantial decrease in the SII from 50.4 in 2000 to 9.6 in 2020 indicates that safe water access has become more equitable across different socioeconomic groups. The relatively stable inequality in urban areas suggests that initial disparities were less pronounced, and improvements have been maintained. However, the dramatic reduction in rural SII from 52.0 to 9.4 and the corresponding drop in the RII from 6.7 to 1.1 highlight the significant strides made in addressing rural water access disparities. These improvements can likely be attributed to targeted policy interventions and investments in rural infrastructure, emphasizing the success of such efforts in narrowing the urban–rural gap [16, 47]. While there has been progress in reducing socioeconomic inequalities in access to sanitary toilets, the pace of improvement has been slower compared to safe water access. The overall SII fluctuated, rising between 2000 and 2010 before declining by 2020, indicating periods of both progress and stagnation. The fluctuation in SII could be attributed to uneven policy implementation across provinces, varying levels of economic investment in WASH infrastructure, and changes in population distribution, particularly in rapidly urbanizing regions. Periods of economic slowdown or policy re-prioritization may have also contributed to these fluctuations. Due to the lack of data, the reasons behind this phenomenon need further exploration. The overall RII's decrease from 5.8 to 1.6 suggests some success in reducing relative inequality, though absolute disparities remain a concern. Urban areas experienced variable inequality levels, which might reflect uneven implementation of sanitation policies or varying local challenges. The significant reduction in rural RII from 78.4 to 3.1, despite an increase in SII, suggests that while more households now have access to sanitary toilets, the remaining disparities are more pronounced in absolute terms. This calls for sustained and enhanced efforts to improve rural sanitation, focusing not only on expanding access but also on enhancing the awareness and attitude of rural residents towards sanitation facilities [48]. In addition, the results for hygiene bathing facilities indicate notable improvements in inequality reduction. The overall decrease in SII and RII points to more equitable access across different population groups. Urban areas showed significant declines in both indices, reflecting successful urban sanitation and public health initiatives. Rural areas, despite starting from a higher baseline of inequality, also demonstrated considerable progress, as evidenced by the decreases in SII and RII. This suggests that interventions targeting hygiene facilities have been effective, though continuous efforts are needed to maintain and further these gains.

The findings underscore the importance of sustained and targeted policy interventions to reduce socioeconomic inequalities in WASH access. The success in improving rural access to safe water highlights the potential of focused infrastructure investments and policy measures. However, the slower progress in sanitary toilet access and the remaining absolute disparities in rural areas suggest that a multi-faceted approach, including community engagement, education, and continuous investment, is necessary to achieve comprehensive improvements. Future policies should continue to prioritize rural areas, ensuring that improvements in access to essential services are equitable and sustainable. Additionally, there is a need for ongoing monitoring and evaluation to adapt strategies to emerging challenges and

ensure that gains in inequality reduction are maintained. It is also important to advance the monitoring and evaluation of WASH access, continuously assessing the coverage of WASH facilities and socioeconomic inequalities, and timely adjusting policies to ensure that all populations benefit equitably from improvements in WASH facilities.

The innovation of this study lies in several key aspects. First, it offers a comprehensive long-term trend analysis of WASH access across China by using data from three national censuses spanning from 2000 to 2020. This 20-year longitudinal analysis provides a unique perspective on the historical evolution and improvements in WASH infrastructure, offering broader insights compared to previous studies that focused on shorter timeframes or single points in time. Second, the study employs spatial clustering analysis using Moran's I to investigate the geographic distribution of WASH facilities at the provincial level, especially for the year 2020. The identification of high-high and low-low clustering patterns reveals significant disparities in access to WASH across different provinces. This spatial approach adds a new dimension to understanding the regional imbalances in infrastructure development, providing valuable evidence for policymakers to address these disparities more effectively. Third, the study introduces a quantitative assessment of socioeconomic inequality in WASH access by utilizing the SII and RII. These indices allow for a clear measurement of the changes in inequality over time, both at national and urban–rural levels, offering precise insights for formulating policies aimed at reducing inequities in resource distribution. Fourth, the study highlights urban–rural and regional disparities by focusing on differences in WASH access across the eastern, central, and western regions of China. By examining the faster improvement rates in rural areas and central-western regions, it provides evidence of the effectiveness of regional development strategies and highlights areas that require further attention. Lastly, the use of consistent national census data over two decades ensures the comparability of findings across time and regions. This uniformity avoids potential biases that could arise from using multiple data sources, allowing for a more reliable and accurate analysis of the spatiotemporal dynamics of WASH access in China.

However, this study has certain limitations that must be acknowledged. First, it relies on national census data, which, while comprehensive, has certain limitations. One key limitation is the 10-year interval between census collections, which may miss finer annual trends in WASH access. Furthermore, census data aggregates information at higher administrative levels and the household data of smaller administrative units was not published, such as counties or cities, limiting the spatial resolution of our analysis. Additionally, the census data lacks detailed socio-economic factors such as healthcare access, which may provide further insights into the inequalities observed in WASH access. Future research could benefit from incorporating more granular and frequent datasets to address these gaps. Although other sources, such as the "China Health Statistics Yearbook" and the "China Statistical Yearbook", offer more frequent data and additional socio-economic indicators, these datasets do not cover all provinces consistently and do not include data on WASH access in the year 2000. Therefore, they were not suitable for this study, which aimed to analyze trends over two decades using uniform data sources. Future studies may consider integrating these alternative datasets as they evolve to provide a more complete view of socio-economic factors affecting WASH access. Second, due to the cross-sectional nature of the data, causal relationships cannot be established. While trends in WASH facility access can be observed, the specific causes of these changes cannot be determined. Future research could employ longitudinal data or experimental designs to better understand the impacts of policies and interventions. Second, while this study explores differences between the eastern, central, and western regions, it lacks analysis of smaller geographic units such as counties and cities. Intra-regional heterogeneity may obscure some local issues. Lastly, this study mainly uses annual household disposable income as a measure of socioeconomic status, which may not fully reflect the complex economic conditions of a region. Other socio-economic factors, such as education levels, health expenditures, and investment in infrastructure, may also significantly impact the use of WASH facilities. However, these were not adequately considered in this study, as the Chinese government did not publish provincial-level health expenditure data in 2000, nor did it include other factors like the educational level of family members. This data limitation constrains us from using more socio-economic indicators to explore socio-economic inequality in WASH. Future studies could integrate geospatial datasets, such as nighttime lights data (from VIIRS and DMSP), which can serve as proxies for economic activity and infrastructure development, providing additional layers of socioeconomic information that complement the census data.

Conclusions

China has made remarkable progress in enhancing WASH access from 2000 to 2020, driven by robust policy frameworks and substantial investments in infrastructure. While improvements in access to safe water, sanitary toilets, and hygiene bathing facilities have been substantial, disparities persist across regions and

socioeconomic groups. Future efforts should focus on sustaining momentum in infrastructure development, targeting underserved areas, and addressing remaining equity gaps to ensure universal access to WASH facilities and promote public health equity nationwide. Continued monitoring and evaluation of WASH access trends are essential to inform evidence-based policies and interventions that advance sustainable development goals in China.

Abbreviations

WASH	Water, Sanitation, and Hygiene
SDGs	Sustainable Development Goals
WHO	World Health Organization
SII	Slope Index of Inequality
RII	Relative Index of Inequality

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Authors' contributions
S.L. designed the study, accessed the data, conducted the analysis, and drafted the manuscript. A.G., Y.Y., and Q.S. verified the results and revised the manuscript. All authors read, contributed, and approved the final manuscript.

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Data availability
The data for this study comes from the Chinese population census, which has been publicly available on the website of the National Bureau of Statistics of China (https://www.stats.gov.cn/zt_18555/zdtjgz/zgrkpc/). The urban–rural annual household disposable income data and other household survey data are available through the China Household Survey Yearbook, which can be accessed via the China National Knowledge Infrastructure (CNKI) platform (https://data.cnki.net/).

Declarations

Ethics approval and consent to participate
This study used publicly available census data and did not require ethical approval and consent to participate.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Hutton G, Chase C. The knowledge base for achieving the sustainable development goal targets on water supply, sanitation and hygiene. Int J Environ Res Public Health. 2016;13(6):536.
2. World Health O. WHO water, sanitation and hygiene strategy 2018–2025. World Health Organization; 2018.
3. Weststrate J, Dijkstra G, Eshuis J, Gianoli A, Rusca M. The sustainable development goal on water and sanitation: learning from the millennium development goals. Soc Indic Res. 2019;143(2):795–810.
4. Rajapakse J, Otoo M, Danso G. Progress in delivering SDG6: Safe water and sanitation. Cambridge Prisms: Water. 2023;1: e6.
5. WHO/UNICEF Joint Monitoring Programme for Water Supply SaH: Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender. 2023.
6. Bian H, Gao J, Liu Y, Yang D, Wu J. China's safe and just space during 40 years of rapid urbanization and changing policies. Landscape Ecol. 2024;39(4):74.
7. Liu Y, Zang Y, Yang Y. China's rural revitalization and development: theory, technology and management. J Geog Sci. 2020;30(12):1923–42.
8. Jiang Y. China's water security: Current status, emerging challenges and future prospects. Environ Sci Policy. 2015;54:106–25.
9. Cheng S, Li Z, Uddin SMN, Mang H-P, Zhou X, Zhang J, Zheng L, Zhang L. Toilet revolution in China. J Environ Manage. 2018;216:347–56.
10. Shuchen M, Yong T, Jiayi L: Rural water supply and sanitation in China: Scaling up services for the poor. 2004;25–27.
11. Huang L, Qiu M, Zhou M. Correlation between general health knowledge and sanitation improvements: evidence from rural China. npj Clean Water. 2021;4(1):21.
12. Zhao X, Yuan B, Yu Y, Jian W. Governance function analysis of the patriotic health movement in China. Glob Health Res Policy. 2019;4(1):34.
13. Ye X, Christiansen F. China's Urban-Rural Integration Policies. J Curr Chin Aff. 2009;38(4):117–43.
14. Li Y, Dorsten L. Regional and urban/rural differences of public health in China. Global J Health Sci. 2010;2(1):20.
15. Sun B, Cheng Y, Li Y, Wang X, Zhao K, Yao X, Wang L, Tong S, Shi X. Healthy environment promotion campaign in healthy China initiative. China CDC Weekly. 2020;2(10):160.
16. Xu Q, Boelens R, Veldwisch GJ. Rural drinking water governance politics in China: Governmentality schemes and negotiations from below. Polit Geogr. 2022;97:102703.
17. Wang D, Shen Y. Sanitation and work time: Evidence from the toilet revolution in rural China. World Dev. 2022;158:105992.
18. Tan X, Wu Q, Shao H. Global commitments and China's endeavors to promote health and achieve sustainable development goals. J Health Popul Nutr. 2018;37:1–4.
19. Zhao L, Huo Y, Wang X, Huang J. Spatial difference analysis of water and sanitation in China's counties based on a spatial econometric model. Int Rev Econ Financ. 2024;93:1125–37.
20. Carlton EJ, Liang S, McDowell JZ, Li H, Luo W, Remais JV. Regional disparities in the burden of disease attributable to unsafe water and poor sanitation in China. Bull World Health Organ. 2012;90:578–87.
21. Zhang J, Mauzerall DL, Zhu T, Liang S, Ezzati M, Remais JV. Environmental health in China: progress towards clean air and safe water. The lancet. 2010;375(9720):1110–9.
22. Liu Q, Iossifova D. Socio-metabolic practices and heterogeneous sanitation infrastructures in urbanizing China. Transact Plann Urban Res. 2023;3(1–2):121–38.
23. World Bank. Water Supply, Sanitation, and Hygiene (WASH) poverty diagnostic initiative. 2019;2. https://www.worldbank.org/en/topic/water/publication/wash-poverty-diagnostic.
24. Calderón-Villarreal A, Abramovitz D, Avelar Portillo LJ, Goldenberg S, Flanigan S, Quintana PJE, Harvey-Vera A, Vera CF, Rangel G, Strathdee SA, et al. Water, sanitation and hygiene insecurity predict abscess incidence among people who inject drugs in a binational US–Mexico metropolitan area: A longitudinal cohort study. Int J Drug Policy. 2024;129:104485.
25. Lin J, Feng XL. Exploring the impact of water, sanitation and hygiene (WASH), early adequate feeding and access to health care on urban-rural disparities of child malnutrition in China. Matern Child Nutr. 2023;19(4):e13542.
26. Hamlet LC, Kaminsky J. Analytical utility of the JMP school water, sanitation and hygiene global monitoring data. Nature Sustainability. 2023;6(2):222–32.
27. China's State Council. Statistical definitions for urban and rural areas. 2006;10. https://www.stats.gov.cn/sj/tjbz/gjtjbz/202302/t20230213_1902742.html.
28. Nie Y, Li Q, Wang E, Zhang T. Study of the nonlinear relations between economic growth and carbon dioxide emissions in the Eastern, Central and Western regions of China. J Clean Prod. 2019;219:713–22.
29. Fischer MM, Getis A: Handbook of applied spatial analysis: software tools, methods and applications: Springer; 2010.

30. Mackenbach JP, Kunst AE. Measuring the magnitude of socio-economic inequalities in health: An overview of available measures illustrated with two examples from Europe. Soc Sci Med. 1997;44(6):757–71.
31. Lars E Kroll. RIIGEN: Stata module to generate variables to Compute the relative index of Inequality.2013;11. https://EconPapers.repec.org/RePEc:boc:bocode:s457736.
32. Feng XL, Zhang Y, Hu X, Ronsmans C. Tracking progress towards universal health coverage for essential health services in China, 2008–2018. BMJ Glob Health. 2022;7(11):e010552.
33. Zhou X, Simha P, Perez-Mercado LF, Barton MA, Lyu Y, Guo S, Nie X, Wu F, Li Z. China should focus beyond access to toilets to tap into the full potential of its Rural Toilet Revolution. Resour Conserv Recycl. 2022;178:106100.
34. Li H, Cohen A, Lin L, Zhang X, Zhang R. Water supply improvement and health promotion campaigns in rural areas - China, 1949–2020. China CDC Wkly. 2021;3(1):10–3.
35. Kryston A, Woods CG, Manga M. Social barriers to safe sanitation access among housed populations in the United States: A systematic review. Int J Hyg Environ Health. 2024;257:114326.
36. Quispe-Coica A, Pérez-Foguet A. A new measure of hygiene inequality applied to urban-rural comparison. Int J Hyg Environ Health. 2022;239:113876.
37. Zhou J, Raza A, Sui H. Infrastructure investment and economic growth quality: empirical analysis of China's regional development. Appl Econ. 2021;53(23):2615–30.
38. Chen T, Wang Y, Luo X, Rao Y, Hua L. Inter-provincial inequality of public health services in China: the perspective of local officials' behavior. Int J Equity Health. 2018;17(1):108.
39. Luo M, Lau N-C. Increasing heat stress in urban areas of Eastern China: acceleration by urbanization. Geophys Res Lett. 2018;45(23):130,60-013,069.
40. Sun KS, Lam TP, Tang WS, Chan HY, Lam KF, Chow ECY, Wu D, Zhou XD, Xu JY, Ho PL. Improving public toilet environment and hygiene practices in an Asian City: voices from Hong Kong residents. Asia Pacific J Publ Health. 2021;33(4):378–87.
41. Wang T, Sun D, Zhang Q, Zhang Z. China's drinking water sanitation from 2007 to 2018: a systematic review. Sci Total Environ. 2021;757:143923.
42. Liu Q, Wang S, Zhang W, Li J, Zhao Y, Li W. China's municipal public infrastructure: Estimating construction levels and investment efficiency using the entropy method and a DEA model. Habitat Int. 2017;64:59–70.
43. Liu M, Feng X, Wang S, Qiu H. China's poverty alleviation over the last 40 years: successes and challenges. Australian J Agric Res Econ. 2020;64(1):209–28.
44. Luo Q, Zhang M, Yao W, Fu Y, Wei H, Tao Y, Liu J, Yao H. A spatio-temporal pattern and socio-economic factors analysis of improved sanitation in China, 2006–2015. Int J Environ Res Public Health. 2018;15(11):2510.
45. Garriga RG, de Palencia AJF, Foguet AP. Improved monitoring framework for local planning in the water, sanitation and hygiene sector: From data to decision-making. Sci Total Environ. 2015;526:204–14.
46. Gallardo R, Stich B. The extent of cluster-based policies and the political/institutional context: a collective case study. Econ Dev Q. 2013;27(4):325–37.
47. Li H, Cohen A, Li Z, Zhang M. The impacts of socioeconomic development on rural drinking water safety in China: a provincial-level comparative analysis. Sustainability. 2019;11(1):85.
48. Guo S, Zhou X, Simha P, Mercado LFP, Lv Y, Li Z. Poor awareness and attitudes to sanitation servicing can impede China's rural toilet revolution: evidence from western China. Sci Total Environ. 2021;794:148660.

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