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The effects of COVID-19 on the resilience of urban life in China

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Understanding the impacts of COVID-19 on citizens from different cities is crucial for urban resilience-building and reducing inequal resilience distribution. However, little research focuses on urban life at the individual level, particularly in second- and third-tier cities. An online survey was therefore conducted to collect data on how COVID-19 affected the cities and urban residents in mainland China. The results indicate that COVID-19 limited citizens' access to healthcare facilities and socioeconomic activities apart from the immediate health crisis. Most citizens suffered reduced income, unemployment, and social anxiety. However, COVID-19 also raised social awareness and actions for disaster adaptation. The Chinese pandemic management has strengthened governmental leadership and credibility among most citizens in the early stage. Importantly, the results suggested that citizens in first-tier cities appeared more resilient to pandemics than those in second-tier cities. A networked resilience framework was therefore discussed for resilience-building policy implications.

It is estimated that 68% of the world's population will be living in cities by 2050[1]. However, the increasing frequency and severity of disasters may damage and threaten urban populations worldwide. The growing risks of disasters, combined with rapid urbanization, are exposing the increasing vulnerability of cities and citizens. Developing urban disaster resilience to cope with future risks and hazards is increasingly important.

In 2020, COVID-19 struck cities worldwide and led to millions of confirmed cases. The COVID-19 pandemic is one of the biggest challenges and tragedies facing the world since the Second World War[2]. COVID-19 is a pandemic disaster and provides an opportunity to examine how pandemics affect cities, urban life, and urban responses. In this study, we assessed the impact on and reaction of cities and citizens to pandemics and other major disasters through the lens of the Building Resilient Infrastructure and Communities (BRIC) model. We conducted an online survey to examine the resilience of urban life in China under the stress of COVID-19 and to understand the impacts of pandemics on urban life from the perspective of citizens, based on their first-hand experience across different types of cities.

The concept of resilience has been adopted in various fields, including climate change, disaster mitigation, risk, and disaster preparedness[3]. From an ecological perspective, resilience refers to the capacity of the system to absorb disturbance and reorganize while changing to still retain essentially the same function, structure, identity, and feedbacks[4]. The concept of adaptive resilience was introduced and emphasized the adaptation ability of an ecosystem that transforms in response to disasters[5].

Over the last two decades, multiple dimensions have been integrated to enrich the concept of resilience in the urban context. Engineering resilience was first adopted in urban studies to describe the ability of physical urban infrastructure to survive natural hazards[6,7]. Social dimensions were later introduced as the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change[8]. It was then integrated into ecological resilience studies to form social–ecological resilience, which refers to a system's abilities to absorb, recover via self-organization, adapt, and transform[9]. Economic resilience was later integrated as the system's ability to respond toward outside impacts and to prevent potential losses at the level of family, market, and multiple layers of macro-economy[10]. In 2016, the integrated definition of urban resilience was proposed as the ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity[11].

Cities are complex social–ecological–technological systems where numerous actors and processes interact, often across geographic, institutional, and governance scales[12]. With rapid urbanization and the prospects of increasing uncertainties and disasters worldwide, cities and urban populations face greater challenges in tackling disasters and improving prosperity[13–16]. Urban resilience thus serves as the theoretical framework for understanding the impacts on and responses of cities to various major

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disasters and has been regarded as one of the major current concerns in urban planning and development, especially related to urban disaster mitigation and adaptation.

In practice, operationalizing resilience is not easy due to its multifaceted nature. Studies have argued that there is no consistently applicable definition[17]. In this study, we adopted the abovementioned definition of urban resilience[11]. Studies have also argued that the concept of resilience is puzzling and over-generalized, which has led to inapposite policy implementations[18–20]. However, we believe that urban resilience frameworks offer practical solutions by providing practitioners with tools to understand the impacts on and the response of cities to disasters by conceptualizing and measuring resilience quantitatively from multiple perspectives[21].

Several resilience frameworks and indexes have been developed. The commonly accepted frameworks include the BRIC[22] framework, the City Resilience Index (CDI)[23], and the Climate Disaster Resilience Index (CDRI)[24]. Given the scope of this study, we adopted the BRIC framework, because it is one of the most widely used frameworks at the community level[25,26]. The BRIC framework has been widely adopted in resilience research worldwide. Many studies have utilized this framework to set out and quantify the baseline resilience indicators at the community and regional levels. The indicators provide helpful information for assessing the resilience to natural disasters in various regions and communities with different climatic and geographic conditions[27–30]. The BRIC resilience framework was based on the previous place-based disaster resilience framework named Disaster Resilience of Place (DROP) framework[22,31]. Both the BRIC and DROP frameworks share the same mechanism and act as theoretical frameworks that interpret the mechanism of how a community reacts to a hazard situation via its inherent vulnerability and resilience (Fig. 1).

The BRIC framework can be described along the following process: the hazardous event occurs and interacts with the antecedent urban social–ecological system and then causes immediate effects. The immediate effects are affected by the inherent vulnerability and resilience of the city, which results from its surrounding nature (e.g., geographic features, ecological conditions) and inner urban conditions (e.g., physical infrastructure, administration, citizens). The frequency, duration, intensity, magnitude, and types of events also affect the immediate effects. The immediate effects can then be attenuated (minus sign) or amplified (plus sign) by the presence or absence of the city's coping responses, such as emergency planning. After the coping responses are implemented, the disaster impact is realized. This can then be reduced by the urban absorptive capacity, which can also be referred to as urban resilience capacity and indicates the community's ability to absorb the impacts and remain functional. Not exceeding the absorptive capacity will lead to short-term, controllable disaster impacts, which results in a high degree of recovery. However, overwhelming disasters or lack of absorptive capacity can cause the disaster to exceed the local absorptive capacity, resulting in protracted impacts. Exercising adaptive resilience via improvisation and social learning might be useful to reduce the protracted impact of disasters. Improvisation includes impromptu actions that may decrease the harmful impacts and accelerate the recovery process. Social learning refers to the diversity of adaptations and the promotion of strong local social cohesion and mechanisms for collective actions[32]. After the adaptive resilience has been implemented, if the absorptive capacity returns to a level where it is not exceeded, a higher degree of recovery can be expected. However, if the disaster continues to exceed the absorptive capacity and the adaptive resilience is insufficient or absent, a lower degree of recovery will be realized. Finally, the degree of recovery and information obtained from the adaptive resilience exercises will affect future urban socioeconomic, natural, and infrastructural conditions, which will form the antecedent conditions for the next event cycle[22].

Using the BRIC framework also helps to classify resilience into measurable categories. The attributes of urban resilience can be condensed into the following four perspectives: social, economic, institutional, and infrastructural resilience[22,26].

- Infrastructural resilience refers to a reduction in the vulnerability of built structures (e.g., buildings and transportation systems), sheltering capacity, healthcare facilities, the vulnerability of buildings to hazards, critical infrastructure, and the availability of roads for evacuation and post-disaster supply lines.
- Institutional resilience refers to governmental and nongovernmental systems that administer a community.
- Economic resilience refers to a community's economic diversity in such areas as employment, the number of businesses, and their ability to function after a disaster.
- Social resilience refers to the demographic profile of a community by sex, age, ethnicity, disability, socioeconomic status, and other groupings, and the profile of its social capital. Although difficult to quantify,

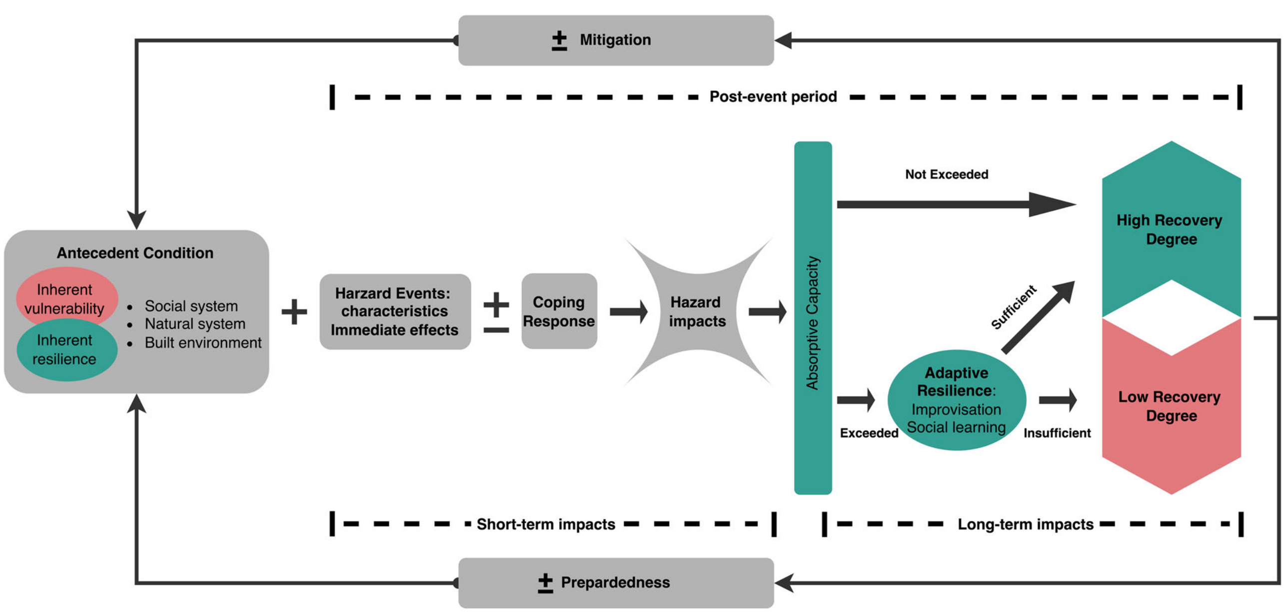

Fig. 1 | Schematic representation of the BRIC/DROP model. A community generally means a place-based population group; here, it means a city and accommodated citizens. High/low-level recovery refers to a community's ability to recover from dysfunctional states caused by disruptions (e.g., external hazards), to a functional condition. Under the resilience theory, the recovery process typically ends with returning to its original state or transferring to a new desired state.

social capital refers to a sense of community, the ability of groups of citizens to adapt, and a sense of attachment to a place.

Pandemics could result in extensive infections and affect regional and global socioeconomic safety and development[33–35]. COVID-19 provided an opportunity to understand the impacts and influencing factors of pandemics through the lens of resilience to reduce harmful effects and improve future preparedness. Many studies have investigated the effects of COVID-19 on the economic and public health domains. The reduction and unequal distribution of economy and resources, as well as the public health issues such as mental health, anxiety, and suicide risks due to COVID-19 have been the concern of many studies[36–40]. Understanding the effects of the pandemic in different cities is critical for enhancing urban pandemic resilience, reducing inequality, and improving the efficiency of resilience investments. Most studies on urban resilience to pandemic disasters have focused on the resilience of the healthcare system at the national level or the psychological resilience of families and individuals[41–44]. Also, despite the diversity in geographical conditions and hazard types, the existing literature on urban resilience mostly used the "popular" cities as cases[45–50]. Generally, they are often major cities or parts of these cities (e.g., a slum block in a metropolitan) with high-level population density, mostly in coastal or near-river regions[51–56]. Such bias commonly might result from the issues of data availability and support from local officials. However, the "ordinary" middle cities (e.g., many in-land cities) and small cities (less-populated cities and towns) often become less visible in the existing literature despite their vulnerability and lack of resilience capacity. Moreover, the investigation of urban resilience at the individual level remains a shortage. Detailed studies that looked at the effects of COVID-19 on cities and urban life at the individual level using first-hand data remain relatively limited, especially in less popular cities. As a contribution regarding this point, this study investigated third-tier cities as well. In addition, a value-added contribution of this study is the first-hand data reflecting the effects and resilience-building regarding citizens and urban life before COVID-19 turned into a morass of ideological and political debates.

The BRIC framework offers multi-dimensional indicators to measure the resilience of a community. It also provides a point of view to treat resilience as the outcome resulting from multi-dimensional attributions. Individuals are the essential components of the community. Therefore, the dimensions and measurements for a community's resilience can largely overlap with an individual's resilience. With the exclusion of environmental aspects (urban citizens are less likely to be negatively impacted by environmental issues during COVID-19) and some modifications of the indicators to suit individual measurements, the BRIC framework could be used at an individual level to measure citizens' resilience. Conceptually, this work is inspired by and building on Bai et al.'s paper which calls for building networked resilience across cities. We aim to extend this concept and provide a framework for future policy implications[57]. Using COVID-19 as an example, this study seeks to address the following research questions: (1) What are the impacts of pandemics on urban functions and life in different cities from the perspective of citizens?; (2) What management tools are perceived to be most effective and well-accepted by citizens?; and (3) What lessons can be drawn from the empirical evidences, and what are the conceptual and practical implications for building a more resilient response system? The findings would deepen our understanding of pandemic impacts, provide information on the perspectives of citizens to enhance urban pandemic resilience and assist decision-makers in improving pandemic resilience in different cities.

Results

Limitations of urban life in different cities

In general, COVID-19 negatively affected citizens socially and economically, as well as reducing the infrastructural accessibility of food, transportation, and healthcare facilities. Regression analysis indicates that citizens in first-tier cities tended to have relatively higher life satisfaction. Reduced access to entertainment, impacts on communication with others, financial impact, and reduced household income contributed to declines in life satisfaction after COVID-19. Also, compared to first-tier cities, second- and third-tier cities were more prone to show declines in life satisfaction (Table 1).

Table 1 | Logit regression on whether life satisfaction declined after COVID-19

Variable	Estimate	Std. error	Statistic	*p*-value
(Intercept)	−3.951	0.835	−4.729	0.000***
Age	−0.062	0.141	−0.437	0.662
Gender1	−0.321	0.229	−1.404	0.160
People_in_household	0.069	0.100	0.689	0.491
Entertainment	0.503	0.171	2.939	0.003***
Communication	0.416	0.191	2.175	0.030**
Transports	−0.000	0.202	−0.001	0.999
Healthcare	0.060	0.225	0.268	0.789
Hospitals	−0.301	0.248	−1.216	0.224
Food	0.036	0.159	0.227	0.821
Occupation	−0.016	0.138	−0.112	0.911
Finance	0.609	0.202	3.014	0.003***
Famliy_income_decline1	0.933	0.241	3.864	0.000***
City2	0.743	0.256	2.903	0.004***
City3	0.593	0.287	2.068	0.039**

**$p < 0.05$, ***$p < 0.01$.

The results suggest that urban life in second-tier cities was the least resilient during COVID-19. Socioeconomically, the percentage of citizens with no impacts in first-tier and third-tier cities was higher than in second-tier cities, except for the impacts on communication (Fig. 2). Only 16.6% of the sample in second-tier cities reported no financial impacts, whereas the numbers in big and third-tier cities were 32% and 28.8%. Similarly, only 21.5% of the responses in second-tier cities reported no occupational impact, whereas the numbers were 32.7% in first-tier cities and 40.4% in third-tier cities.

Infrastructurally, most citizens experienced reduced accessibility to critical infrastructures and living materials. However, the percentage of citizens with medium and heavy impacts in second-tier cities was higher than in first-tier and third-tier cities (Fig. 3). Nearly 70% of citizens in

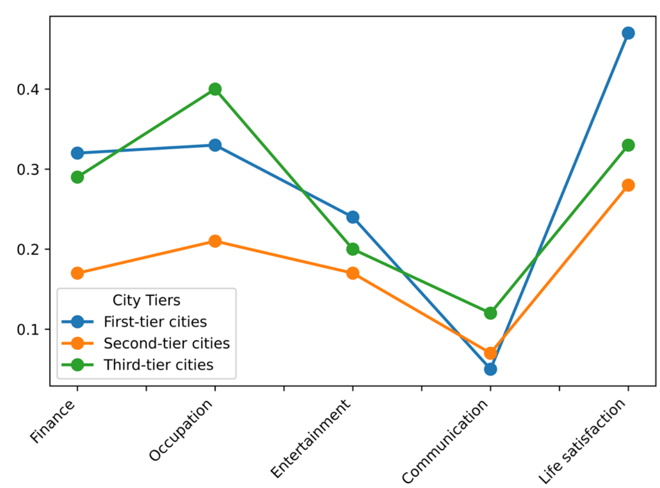

Fig. 2 | Percentage of citizens with no socioeconomic impacts. The values on the left indicate the percentage of impacted samples to one decimal place. The categories at the bottom represent the different socioeconomic impacts.

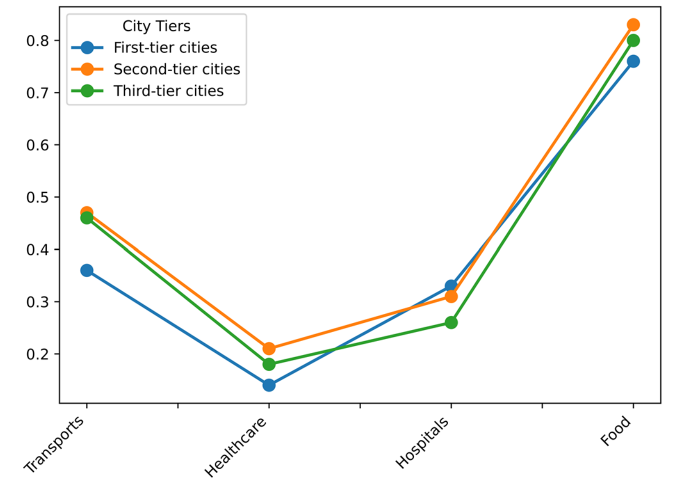

Fig. 3 | Percentage of citizens with medium and heavy infrastructural impacts. The values on the left indicate the percentage of impacted samples to one decimal place. The categories at the bottom represent the different infrastructural impacts.

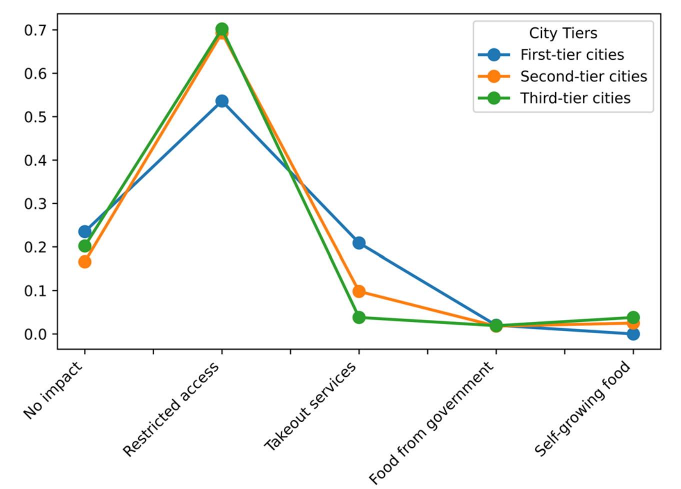

Fig. 4 | Impacts on food accessibility. The values on the left indicate the percentage of impacted samples to one decimal place. The categories at the bottom represent the different impacts on food accessibility.

second-tier and third-tier cities were restricted to food stores, which is 16% more than in first-tier cities. Meanwhile, takeout services contributed 20% of total food accessibility in first-tier cities, which is 10% more than in second-tier and third-tier cities (Fig. 4).

Social awareness and public opinions

Results from thematic analysis suggest that the COVID-19 pandemic created a wide range of institutional adjustments and social awareness. In terms of enhancing resilience to COVID-19, the text analysis of the answers to the open-ended questions indicated that the institutional aspect was citizens' biggest concern, with 32% of respondents sharing their opinions. The critical elements included effective emergency response, governmental actions and leadership, and community-based management. Infrastructural enhancement was another primary consideration from the citizens' perspective, including medical care facilities and basic infrastructure. Increasing voluntary activities and self-awareness were the top two items mentioned by citizens from a social perspective (Table 2). Regarding pandemic management, city-level isolation, social distancing, and rapid virus testing were the top pandemic regulation choices according to public opinion (Fig. 5).

Table 2 | Thematic analysis on resilience-building

Variable	Themes	% of overall comments
Economic perspective		
	Economic recovery and stability	6.32
	Employment and income	5.88
	Financial support by government	4.90
	Cooperation	1.82
	Promotion of consumption	1.25
Infrastructural perspective		
	Medical facilities enhancement	8.89
	Basic infrastructure	5.11
Institutional perspective		
	Effective emergency response and planning	8.19
	Governmental actions and leadership	6.16
	Community-based management	3.00
	Publicity and Transparency	1.74
	Network-based management	0.95
	Cooperation between citizens and government	0.89
Social perspective		
	Voluntary activities	2.50
	Self-awareness and actions	2.40
	Life well-being	1.63
	Social adaptation	1.19
	Basic living materials (e.g., food)	1.15
	Social equality	0.65
	Psychological and emotional health	0.46

Discussion

The results indicate that most aspects of urban life in second-tier cities were the least resilient during COVID-19. Compared to second-tier cities, first-tier cities typically have a more complex economic structure, making them more resilient to socioeconomic disruption such as COVID-19[58]. The more flexible pandemic restrictions in first-tier cities allowed the continuity of socioeconomic activities such as delivery services for food and other living materials. The results suggest that food delivery contributed 20% of total food resources in first-tier cities during COVID-19 (Fig. 4). The more complex socioeconomic structure also allowed citizens in first-tier cities to have higher income and savings, more occupation choices, and better employment protection regulations, which helped secure citizens' job or promote re-employment. In addition, first-tier cities hold critical political, social, and economic values nationwide in the Chinese context, which attracts the most economic support and political support from the central government, including financial subsidies that benefit local businesses and citizens.

Surprisingly, the results suggest that urban life in third-tier cities was more resilient to a pandemic than in second-tier cities, especially economically. On the one hand, third-tier cities tended to have fewer confirmed cases of COVID-19; for better medical treatment, the confirmed cases would then be transferred to provincial capitals (second-tier cities). These reduced the pandemic restrictions and allowed relatively active socioeconomic activities in third-tier cities. On the other hand, urban life in third-tier cities also costs less, and citizens tend to have a more stable occupation status, making them more resilient financially. The results suggested that 40% of the urban population in third-tier cities reported no impacts on occupation status, which was twice that of second-tier cities and 7% higher than in first-tier cities. The reason for this might be the proportion of state-owned employees in third-tier cities being significantly higher than in the other two.

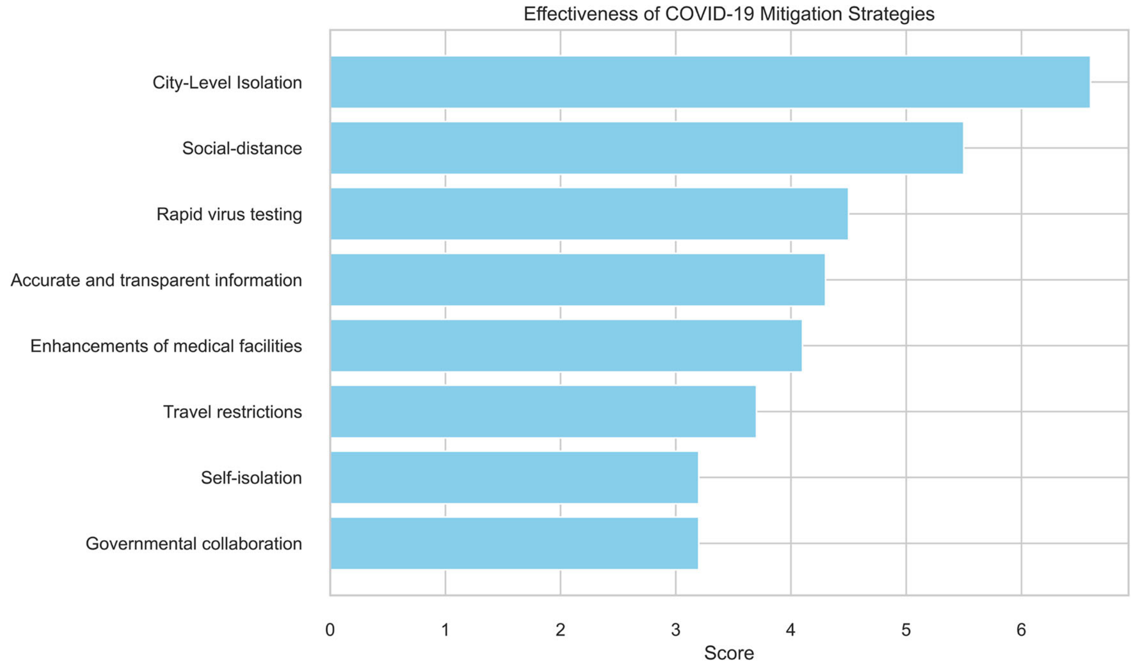

Fig. 5 | Public choices on COVID-19 regulation. The calculation method was an option average comprehensive score =(Σ frequency × weight)/number of people answering the question. The weight was determined by where the options were arranged. A higher score indicates a higher comprehensive ranking.

Using three cities, Shenzhen (first-tier city), Dongguan (second-tier city), Zhanjiang (third-tier city), from Guangdong province as an example, the proportion of state-owned employees is 3.00%, 6.54%, and 27.99% of the total urban population in Shenzhen, Dongguan, and Zhanjiang, respectively[59–61]. The distribution ratio of state-owned employees aligns with these results, which indicate that, even with a less resilient economic structure in third-tier cities, the citizens could still have fewer financial losses.

In facing pandemics like COVID-19, which do not physically destroy the urban physical environment, the resilience of cities is primarily influenced by the resilience of their citizens since the citizens could improve hazard mitigation, facilitate adaptation, and ensure proper urban functions. The resilience of urban citizens to pandemics is influenced by their social–economic safety, accessibility to critical infrastructure (e.g., healthcare facilities and transportation system), and the accessibility to adequate municipal services. The first-tier cities have higher population sizes and social–economic achievements and play important roles in the national transportation system. The high-level social–economic connections and political importance contribute to receiving national and other external support[62–64]. This means that even with large populations, the first-tier cities have more resources to mitigate the negative impacts caused by COVID-19 on their citizens and, therefore, presented with higher resilience to COVID-19.

The third-tier cities have less population and less risk of COVID-19 exposure since they do not attract population flow. In addition, the confirmed cases detected in third-tier cities would normally be transferred to provincial capitals (second-tier cities) for better treatment. Also, as mentioned above, the high ratio of state-owned employees contributes to greater job security and more savings among citizens in third-tier cities. Therefore, even with less political importance and relatively lower accessibility to public services, the citizens in third-tier cities still have relatively adequate social–economic capacity and access to critical infrastructures to ensure a decent resilience to pandemics.

However, the second-tier cities (primarily provincial capitals) have to absorb population flow, take greater responsibility for treating patients, and provide the necessary support to other cities with emergencies. Moreover, the average external support received in second-tier cities is often unparalleled to their expenditures for tackling COVID-19. Together, these resulted in less resilience to pandemics in second-tier cities and their citizens.

Existing literature on urban resilience-building typically uses cities as separate case studies. Also, such research operates biasedly toward first-tier and coastal cities worldwide, often leaving poorer cities out of solutions[65]. This study contributes by offering the comparison based on the tiers of cities and incorporating smaller and less-developed cities in the resilience-building practice through the networked resilience framework. Our finding extends the scope of the current resilience research, which has tended to focus on first-tier cities or other "popular cities" and view urban resilience at the city level. The results suggested that the resilience of a city could be different from the resilience of its citizens. Compared to third-tier cities, second-tier cities have overall advantages in social–economic achievements and urban infrastructure at the city level. However, COVID-19 exposed the vulnerability of citizens in second-tier cities to pandemics, especially in terms of economic and infrastructural aspects. The combination of limited resources and national support, high population, the higher number of confirmed cases, and less resilient economic structures decreased the resilience of urban life in second-tier cities. The decreased resilience of citizens of a city will then have negative impacts on the city itself, such as increasing the difficulties in hazard mitigation and hindering adaptation. These findings suggest that the urban resilience implementation needs to consider the different urban contexts and question of the resilience of what and to whom.

It is important to note that our study does not conclude that the Chinese second-tier cities will be less resilient than the first and third-tier cities. Rather, our results suggested that, under the hazardous context, cities with densified populations and limited resources, such as Chinese second-tier cities during COVID-19, can be less resilient than other first and third-tier cities. Also, small cities and their citizens might not be as vulnerable as many would think, even with their relatively less-diversified social–economic structure. Such phenomena are often neglected in the existing literature and policy documents in resilience-building.

The results suggest that COVID-19 raised self and social awareness and facilitated disaster adaptation on both community and personal levels. Central and local governments issued travel and working restrictions and social distancing guidelines to reduce population flows and mitigate viral transmission. The results suggest that such restrictions interrupted daily urban transportation, delayed the processes of urban infrastructure construction, affected local businesses, reduced individual incomes, interrupted access to basic living materials and healthcare services, cut off outdoor entertainment activities, and ultimately, contributed to the decline of life satisfaction through COVID-19 (Table 1). These results align with studies that argued that travel restrictions and lack of transportation accessibility might affect the communities' freedom of movement, which causes problems for mental health[66]. Social inequality and social tensions were also a matter of concern among citizens, especially economically. The respondents commonly reported anxiety resulting from rent and price increases. The transparency and anti-corruption of local governmental organizations such as Red Cross Societies and more restrictions on imported cases from other countries were also mentioned.

COVID-19 also raised social awareness and voluntary actions at the community level. Communities were critical in population flow regulation, monitoring confirmed cases, supplying basic living materials, and assisting vulnerable groups during COVID-19; 24% of respondents reported they were engaged in voluntary activities at the community level to benefit local pandemic management and provide essential assistance for vulnerable groups such as the old and physically disabled. Studies support the suggestion that community-based responses have a significant contribution to containing the epidemics and preventing them from spreading[67,68]. Other studies have also shown that integrated governance at the city level, strong leadership, and stakeholder participation are essential in facing pandemic disasters and are known to be effective[69]. The results also indicate that, in the short term, the success in preventing COVID-19 strengthened governmental credibility in China at the national level. In 2020, the Chinese government succeeded in preventing the pandemic via massive intervention at the national level, which strengthened the citizens' trust in the national government. The increased trust in the national government allowed some large-scale pandemic regulations to be possible in the future. For example, despite the criticism in early 2020, city-level isolation later became the most agreed public choice for pandemic management (Fig. 5).

However, trust in government may have mixed effects on the resilience of urban citizens when controversial interventions are introduced. For example, the trust in the local government declined due to the ineffective pandemic regulation and fast-growing cases during the latest COVID-19 outbreak in Shanghai. Shanghai's citizens have heavily criticized the massive interventions like city-level isolation because of its impacts on the local economy and daily life. Research also indicated that people with higher degrees of trust in government might perceive lower consequences of potential risks, which leads to less preparedness[70]. Moreover, the trust in the national government and local government could be different, especially in China, where trust in local government tends to be lower than trust in the national government[71]. We argue that social awareness and trust in government might positively affect urban resilience in the short term, especially when introducing massive and strict interventions. However, such trust should not be abused, and careful considerations regarding trust in different levels of government and the effectiveness of social awareness are needed in resilience-building practices. Massive interventions and over-control, which boldly rely on trust in government and confidence in urban citizens, might lead to unwanted outcomes.

This study explored the impacts of pandemics on citizens and urban life in different cities in mainland China, and how to improve urban resilience to pandemics and infectious diseases from citizens' perspectives by using COVID-19 as an example. The results indicate that urban life in cities with high population density and limited resources (second-tier cities in mainland China) could be less resilient to pandemics compared with top-leading cities and cities with less population (first and third-tier cities in mainland China). Unlike other major disasters, instead of damaging the urban physical environment, pandemics could have prolonged and negative socioeconomic effects on citizens at the inter-city level. Social awareness and institutional adaptation could be induced by pandemic mitigation and prevention practices.

This study raised inequality concerns about resilience-building in second and third-tier cities. It highlighted the inter-city heterogeneity of the impact of COVID-19 that differentiates from previous research. The findings provide first-hand information on the impacts of COVID-19 on citizens and urban life, and public opinions on enhancing urban resilience to pandemics. Based on the findings, the paper forwarded the networked resilience framework with the consideration of baseline resilience to cope with the "overreaching goals" problem of the current urban resilience agenda and to mitigate the inequality issue faced by less-developed cities in resilience-building. The networked framework offers an efficient approach to facilitate inter and intra-city collaborations and enhance urban resilience when there are competing and limited resources. Overall, this paper offers perspectives regarding resilience-building towards COVID-19 at the individual level and provides prevention mechanisms for establishing resilience to long-term pandemic outbreaks of infectious diseases and other prolonged hazards.

This study has the following limitations: (i) the region of this study is limited to mainland China. The impacts of COVID-19 and regulation strategies might differ due to the different administration structures in other countries; (ii) data from some disadvantaged and vulnerable groups, such as the aged citizens remain absent, which may need further investments. Future research should go beyond focusing on the metropolis and should pay more attention to how to enhance urban resilience in second- and third-tier cities. Interdisciplinary research that links public management and urban study to design the proper measurements and implementation for urban resilience could also be promising.

The above results and discussion suggest that governmental support plays an important role in economic recovery and assists urban life during COVID-19. The results also suggest that citizens in second-tier cities tend to be less resilient financially and infrastructurally. This indicates that other than first-tier cities, large-scale disasters like COVID-19 can overwhelm the resilience capacity of less-developed cities. To maximize resilience with a limited budget, universal approaches that are suitable for coping with multiple disasters should be considered[23]. The evidence of Chinese COVID-19 management has shown the possible benefits of inter-city collaboration when facing large-scale disasters[72]. It is important to realize that there are inter-city differences in terms of resilience performances, such as food accessibility, employment, social–economic status, political importance, and institutional capacity. These differences contribute to uneven resilience performance in different cities. However, such uneven distribution of resilience is often neglected in current resilience-related literature. Also, it is challenging to demand each city build a sufficient level of resilience to different hazards on its own, especially in developing regions or cities with limited resources. Under these contexts, we argue that to build urban resilience in multiple cities, it is reasonable for cities to collaborate to form urban networks to share resources and knowledge to build resilience and mitigate negative impacts through inter-city support and collaboration. This networked resilience framework could provide conceptual insights for cities to realize their resilient states via urban networks. The conceptual framework of networked resilience was forwarded[57] and represented below (Fig. 6).

Recently, some work has been conducted looking at financial system resilience, but mostly from a vulnerability perspective instead of active resilience-building[73,74]. Also, the "integrated approach" mentioned in several existing literature primarily focuses on integrating different sectors and stakeholders at an intro-city level (e.g., Public–Private Partnership) or collaboration among limited premier cities[75–78]. The proposed networked resilience framework suggested the importance of building resilience through inter-city networks that incorporate less-developed cities and offered some potential practices in implementation. This framework has three major contributions. One is that it improves resource use efficiency in building resilience capacity. Two is that it highlights the importance of cities and could help build resilience in undeveloped cities. Three is that it helps enhance resilience capacity in both the short-term and long-term.

Cities are inextricably linked to their surrounding regions and globally through commodity, social, economic, political, and infrastructure

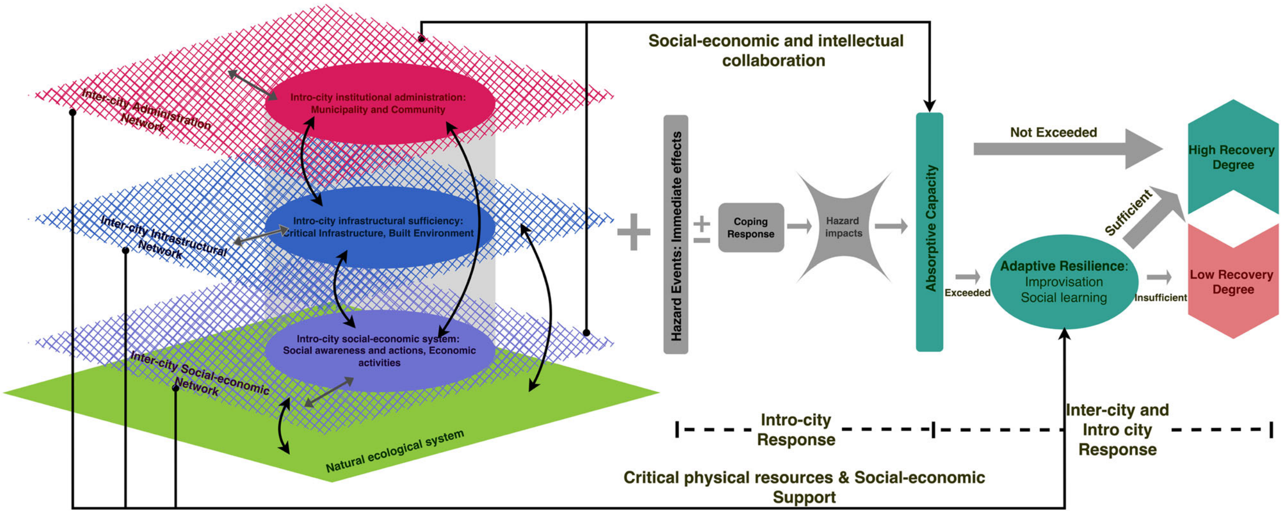

Fig. 6 | Schematic representation of the networked resilience framework. The component urban subsystems facilitate intra-city and inter-city activities. These activities provide both physical (e.g., infrastructure and material supplies) and non-physical (e.g., institutional services and intellectual outputs) resources, contributing to various absorptive and resilience capacities at both intra-city and inter-city levels. Collectively, the interwoven urban subsystems interactively produce adaptive resilience capacities essential for post-disaster recovery and adaptation.

networks[12,79,80]. The resilience of a city, therefore, necessitates consideration of its relationships to larger networks of flows; these scalar dimensions often receive insufficient attention in empirical contexts[18,81]. Such complexity and neglection in resource flow often result in inefficient resource usage and unequal resource distribution, especially when multiple cities compete for similar resources. The networked resilience approach addresses the above concerns by enabling material and workforce flow from one city to another via inter-city collaboration when needed. Compared to traditional community-based resilience approaches, which often operate in an isolated manner, the networked resilience approach could dramatically increase the sufficiency of critical resources in multiple cities and improve the efficiency of material flow across the urban network. This could improve long-term disaster preparedness and the effectiveness of disaster mitigation. Under the networked resilience framework, the burden of building redundancy for resilience is shared by multiple cities, which could particularly benefit less-developed cities that typically lack sufficient resilience capacity.

The networked resilience framework could facilitate the building of integrated regional resilience. However, the existing integrated approaches mainly concentrate on building regional resilience. The unit for planning and policymaking of such approaches is often at the regional level rather than in cities. Also, integrated regional approaches typically focus on long-term resilience-building rather than a rapid response to disasters[57,82]. The networked resilience framework differs from the existing integrated approaches by highlighting the importance of cities and the urban network. With the over-concentration of population and lagging investment, cities, especially undeveloped cities, are facing increasing challenges in ensuring sufficient hazard preparedness within the urban area. When it comes to emergent and severe hazards, the quickest approaches to mitigate the impacts on cities and citizens are pre-planned emergency responses and artificial efforts that could ensure sufficient resources and workforce to facilitate disaster mitigation and adaptation. Such resource demand might be challenging for a single city, yet the urban network could facilitate the resource flow to ensure the emergency demand. Also, the networked approach could help improve long-term disaster preparedness and the effectiveness of disaster mitigation via intellectual collaboration and investments. Under the networked resilience framework, the burden of building redundancy for resilience is shared by multiple cities, which could particularly benefit less-developed cities.

The city of Wuhan, for example, was isolated for 76 days due to COVID-19, which overwhelmed the local urban resilience capacity[72]. During the isolation, inter-city and national-local governmental support for living materials such as food and medical resources—including testing gear, medicine, and labor—were critical for Wuhan to tackle COVID-19. The central government, other provincial and city-level governments, and other organizations all sent resources and professionals to Wuhan to provide help. As a result, the city built multiple mobile hospitals in around 10 days to provide adequate healthcare services for increasing cases and was able to return to normal shortly after the pandemic[72]. The materialistic support and workforce assistance for Wuhan city strongly enhanced Wuhan's adaptive resilience capacity, which helped the city return to its functional state. Also, the remaining healthcare facilities and intellectual collaborations among the healthcare professionals and administrations increased the urban absorb capacity for future pandemic hazards. Also, social awareness via COVID-19 includes many aspects related to urban life and emergency plans. Social awareness contributes to the absorbing capacity by improving the preparedness of citizens and administrations, and to the adaptive resilience practice by speeding the implementation process.

Wuhan's example demonstrated the promising potential of the networked framework in the case of a healthcare crisis, which can also be seen in the Wenchuan earthquake in 2008 and the recent COVID-19 outbreak in Shanghai. China has a history of implementing the pairing aid system to enhance healthcare capacity. The pairing aid system is a long-term practice that aims to improve the professionalism of healthcare workers via intellectual collaboration and enhance medical infrastructure via financial support, especially for undeveloped regions. The system contributes to the networked resilience framework to improve the urban adsorb capacity (social-economic and intellectual collaboration). The concept of networked resilience concept considers building resilience through networks across multiple cities. Hence, it goes beyond pairing city practice[57]. Under emergency healthcare crises, the networked framework can also boost the pairing system by allowing more workforce flow and materialistic support. In facing prevalent and prolonged disasters like COVID-19, long-term visioning and coordination of activities in different sectors could be conducive to building urban resilience[69,83]. For example, large-scale pandemic regulations such as city-level isolation and massive virus testing require the involvement of inter-city collaboration to provide sufficient resources to sustain urban life in the isolated city. The networked framework provides a solution for both intra-city and inter-city collaboration on information, knowledge, resources, and social supports to cope with healthcare crises and other hazards that exceed a single city's resilience capacity.

Building baseline resilience should be prioritized. The current agenda for enhancing urban resilience covers a wide range of piecemeal factors and often results in a massive assortment of overreaching goals, which are highly costly and almost impossible to finish. Studies have argued that the concept of resilience might be overreaching, losing its meaning, and becoming an "empty signifier"[19,20,84]. Such overreaching goals often ignore inter-city inequality, including the differences among cities, as the results suggested; this inequality includes different classes, administration versus citizens, and isolated and vulnerable groups, as has already been argued[85–87]. Instead of accomplishing these larger goals, building "baseline resilience" could be possible in most cities and would cost-effectively address the above challenges. Baseline resilience includes investment in critical infrastructure, essential financial insurance, effective emergency plans, and social support, which are vital components that keep cities and urban life functional even under overwhelming strain.

Building baseline resilience prioritizes the factors that benefit the urban system and citizens most. For example, as the results suggested, top-listed terms—such as economic recovery and support, medical and basic infrastructure improvements, and emergency planning—are critical in enhancing resilience and post-disaster recovery according to the citizen perspective (Table 2). These suggestions represent the basic needs of citizens, as their baseline resilience and often align with the studies on resilience enhancement. Studies have shown that many elements of basic urban infrastructure, such as road systems, are a platform for disaster mitigation and sustainable development[88]. Adequate investment in primary healthcare systems and coordination of activities in different sectors are also conducive to tackling pandemics. Addressing inequalities in healthcare accessibility is crucial for preventing future pandemics[69,83]. This type of baseline resilience is also highly transferable, meaning that it can serve to tackle COVID-19 and provide essential functions in future local and global hazards such as climate change and climate-related disasters.

Combining baseline resilience and networked resilience, approaches could help reduce inequality in both intra- and inter-city contexts, balance the problem of long-term and short-term investments, and build adaptability to multiple disastrous scenarios rather than to specific cases. For example, to address the intense demand for medical services, the portable hospital approach used in Wuhan during COVID-19 was later adopted in many other cities[72]. In less-developed countries, many governments could be reluctant to invest sufficiently in their long-term healthcare systems. The example of Wuhan could be a reference point for providing essential medical services in the short term. The short-term investment could offer critical services to vulnerable groups, because they are unlikely to have healthcare services and more likely to become infected[89]. Last, such short-term approaches could be transferred as part of long-term resilience planning and implementation. Other than intra-city concerns, the baseline resilience approach could also be implemented at the inter-city level under the networked resilience framework. The combination of these two approaches would ease the burden of building resilience capacity at the city level, especially in third-tier cities.

Methods

Survey and variable explanation

We used the largest online survey platform in China, named Sojump to conduct the survey (Available at https://www.wjx.cn/index.aspx.). On average, over ten million live respondents are filling out surveys on this platform on a daily basis. This platform has over six million registered audiences distributed across the nation. We used samples from the year 2020 since, at that time, COVID-19 was at its early stage and commonly regarded as a global healthcare crisis without unnecessary political and ideological considerations. Firstly, given the objective of this study, we limited the audience to Chinese adult urban citizens living in Chinese cities during the COVID-19 outbreak in 2020 (i.e., counties and above) because these citizens were the primary units of urban socio-economic interactions and often the prominent financial support for families despite their social groups. Secondly, other than being restricted to urban citizens, the samples were randomly selected via Sojump's sampling service without other demographic features or any particular biases regarding their social groups (e.g., age, ethnicity, region, religion, etc.). Thirdly, we aim to collect more than 385 responses given the overall Chinese urban population in 2020 (around 848,430,000 total urban population, with a Confidence level of 95%, a Margin of Error of 5%, and a Population Proportion of 50%)[90]. We collected 501 responses in total with the sampling service. After excluding the respondents with invalid and missing data, we finalized 420 valid responses. The samples' distribution is proportional to the urban population where the samples live. The demographic characteristics of the samples are listed in Table 4. Overall, based on the sample characteristics (Table 4), the samples represent working-class Chinese urban citizens, aged mostly from 18 to 54, with no regional and occupational biases and no specific engagement with governmental and healthcare services.

We seek to explore the resilience of the "common" urban life at the individual level, which is unlikely to be affected by citizens' ethnicity, religion, and other social characteristics. In terms of inter-city representativeness, we acknowledge that the sample size is relatively small comparing the total urban population, given the sensitivity of COVID-19 in 2020 and funding limitations. There could be only one or a few samples in one city. However, the objective of this study focuses on the tiers of Chinese cities as a whole rather than the comparison of individual cities. In this regard, the shortages in sampling size at individual cities and other cultural-related differences among each city do not undermine the research's validity.

The questionnaire contained 21 questions, including eight demographic questions, ten scale questions related to the impacts of COVID-19 on urban life from social, economic, and infrastructural perspectives, one multi-choice question, and two open-ended questions related to citizen opinions on institutional perspective and enhancing urban pandemic resilience. The questionnaire was reviewed and permitted by the Human Ethics Committee and adjusted according to the experts' feedback (Supplementary Reference 1).

To compare citizens in different cities, we classified all cities into three categories based on the 2018 national urban population statistics and considering their political and socioeconomic status: first-, second-, and third-tier cities[90]. The cities in China have some distinctive features, including high population density and large-scale inner-country immigration flow. In this paper, the first-tier cities in China exclusively refer to Beijing, Shanghai, Guangzhou, Shenzhen, Tianjin, and Chongqing, all with populations over ten million. In this list, Beijing, Shanghai, Tianjin, and Chongqing are categorized as the direct-administrated municipalities with provincial-level political importance, which holds essential social–economic and political status. Shenzhen (Special Economic Zone) and Guangzhou (Provincial capital) are two leading cities in Guangdong Province (Highest provincial GDP in China). Both cities have distinctive political statuses, in which Guangzhou is the provincial capital and Shenzhen is listed as the special economic zone.

In addition, the first-tier cities typically attract populations from near-region and nationwide and act as centers of national social–economic activities. Given its unparalleled social-economic and political status, we categorized these six cities into the first tier. The second-tier cities include provincial capitals (except Beijing, Tianjin, Shanghai, Chongqing, and Guangzhou) and some coastal cities with relatively similar populations and social–economic statuses (e.g., Suzhou, Dongguan). The second-tier cities typically have an urban population of over one million (an average population of three million in this study) and absorb regional population flow and social–economic activities at the provincial level. It is noticeable that some cities may have a higher population, but their political and social–economic status is similar to other second-tier cities. Therefore, these cities were still categorized as second-tier cities rather than one-and-a-half cities, including Wuhan, Xi'an, Nanjing, and Chengdu. The third-tier cities include the rest prefectural cities and counties. The third-tier cities rank lower in terms of political importance and typically have an urban population under one million. The socio-economic development in third-tier cities is also less developed than in the first and second-tier cities. In addition, the third-tier cities do not attract population flow since many citizens born in third-tier cities will leave for first and second-tier cities for education and employment. It is important to know that the "fourth-tier cities" (towns) are excluded in this paper. The reason is the importance of Chinese cities is highly related to their political status and economic status, "the fourth-tier cities" (towns) are subjected to the counties, which are typically regarded as part of the rural area. The aim of the study is to show different cities have different response capacities and resilience to unexpected shocks, and therefore it is important to build networked resilience. Although this categorization may not be readily applicable to other countries, they may nonetheless draw parallels to different tiers of cities in the context, and the main findings may be applicable across contexts.

Table 3 contains the variables included in the questionnaire. It is worth mentioning that we included a variable of whether family income declined for statistical analysis by using the family income after COVID-19 minus the family income before COVID-19. Together, there were 13 independent variables included in the statistical analysis.

Principal component analysis was conducted to support the validity of the scale questions (Tables 4 and 5). The analysis suggested that transportation accessibility correlated with all three categories because it closely interacts with other aspects of urban life; however, it is categorized as an infrastructural perspective in this study due to its traditional meaning and slightly higher coefficient. The reliability of the scale questions was tested for validity with a Cronbach's α coefficient value of 0.72.

Statistical analysis and qualitative approach

Logit regression was conducted to determine the correlations between life satisfaction and other impacts of COVID-19 and provide information on which impacts were significant in causing alterations in life satisfaction through COVID-19. Whether life satisfaction declined was calculated and used as the dependent variable to explore the factors affecting urban function and urban life from the citizen's perspective. Questions on the degree of life satisfaction before and after COVID-19 were included in the questionnaire as five-point scale questions, with five being the least satisfied and one being the most satisfied. The data on whether life satisfaction declined during COVID-19 was obtained by using life satisfaction after COVID-19 minus life satisfaction before COVID-19. The other impacts of COVID-19 on social, economic, and infrastructural aspects were treated as dependent variables (Table 3).

The logit regression model was adopted because the dependent variable is dichotomous. The model has developed rapidly in both theoretical and empirical dimensions over the decades and has been widely used in policy evaluation and behavior studies[91,92]. It is a nonlinear model, and the parameters were estimated using the maximum likelihood method (MLE). The general form for the binary logit model is presented below[93].

For sample i (or an interviewee in this study), the dependent variable y_i is regarded as the value for the random variable Y_i, which is either 0 or 1. Assuming that the probability of Y_i being 1 is π_i, then the probability that Y_i is equal to 0 is $1-\pi_i$. Y_i follows (0–1) distribution with the parameter π_i, and its probability distribution is expressed as Eq. (1):

$$\Pr\left[Y_i = y_i\right] = \pi_i^{y_i}(1-\pi_i)^{1-y_i}, y_i = 0, 1 \tag{1}$$

The linear regression model cannot be used to analyze binary variables due to its assumption that variance is fixed. There is a linear transformation: $\pi_i = x'_i\beta$, where x'_i is the explanatory variable vector that affects the probability of π_i, and β is the coefficient vector. Notably, the value range of π is between 0 and 1, while the value on the right side of the formula can be any value. Viewed in this light, logit transformation is required to address this problem. This transformation is defined in Eqs. (2) and (3):

$$\Omega_i = \frac{\pi_i}{1-\pi_i} \tag{2}$$

where Ω_i is interpreted as odds. The odds must be 1 given that π_i is 0.5. Then, the log of odds is expressed as

$$\text{logit}\left(\Omega_i\right) = \text{In}\left(\Omega_i\right) = \text{In}\left(\frac{\pi_i}{1-\pi_i}\right) \tag{3}$$

After the transformation of Eqs. (2) and (3), the value of the new dependent variable (logit(Ω_i)) can cover the whole real number. Equivalently, the fact that the value of π_i is 0.5 entails the value of logit(Ω_i) being 0. That is, providing that π_i is <0.5, the log-odds is smaller than 0, not the other way around. Through the above transformation, the definition of the logit model can now be specified as Eq. (4):

$$\text{logit}\left(\Omega_i\right) = \text{In}\left(\frac{\pi_i}{1-\pi_i}\right) = x_i'\beta \tag{4}$$

where x'_i is the explanatory variable vector that affects the probability of π_i, and β is the coefficient vector. Anti-logit can easily be obtained by inverting the logarithm, specified as Eq. (5):

$$\text{P}\left(y_i = 1|x_i\right) = \pi\left(x_i\right) = \frac{\exp(x_i'\beta)}{1+\exp(x_i'\beta)} \tag{5}$$

Further, y_i can be interpreted as Eq. (6):

$$y_i = \pi\left(x_i\right) + \varepsilon_i = \begin{cases} 1, if\,\varepsilon_i = 1-\pi\left(x_i\right) \\ 0, if\,\varepsilon_i = -\pi\left(x_i\right) \end{cases} \tag{6}$$

where ε_i is a random interference term and has two values, $1-\pi(x_i)$ if $y_i = 1$, and the corresponding probability is $\pi(x_i)$; $-\pi(x_i)$ if $y_i = 0$, and the corresponding probability is $1-\pi(x_i)$. Therefore, ε_i follows a distribution with a mean of 0 and a variance of $\pi(x_i)[1-\pi(x_i)]$. In this study, the Y_i used in the logit model was whether life satisfaction declined before or after the COVID-19 outbreak (Table 3).

Qualitative approaches, including text and thematic analysis of the answers to open-ended questions, were utilized to explore the institutional impacts on urban systems and urban life, as well as to obtain information on citizens' perspectives on enhancing urban resilience to pandemics. Thematic analysis of the open-ended questions was conducted via Nvivo12. Unstructured text data from the answers to the open-ended questions were coded and organized into meaningful themes to understand public opinion on resilience enhancements. Word frequency analysis was first used to identify the keywords in the text data and to construct the original text nodes. The original nodes were then viewed and adjusted through the lens of the BRIC resilience framework and categorized into four themes: social, economic, institutional, and infrastructural. The nodes were manually classified into sub-themes under the four resilience categories to obtain information on enhancing urban resilience to pandemics from the perspective of citizens. For multiple choice questions, a comprehensive score was used to rank the public choices on COVID-19 regulation. The calculation method was an option average comprehensive score = (Σfrequency × weight)/number of people answering the question. The weight was determined by where the options were arranged. A higher score indicates a higher comprehensive ranking.

Table 3 | Variable definition and descriptions

Question/variable	Statistical usage	Description	Mean	s.d.	Min	Max	*n*
Demographic variables							
Age	Independent variable	Age range of the respondents (1 = 19–24, 2 = 25–34, 3 = 35–44, 4 = 45–54, 5 = 55–64, 6 = 65–74, 7 = Over 75)	2.06	0.82	1	5	420
Gender	Independent variable	Dummy Variable (1 = Male, 2 = Female)	1.44	0.5	1	2	420
People_in_household	Independent variable	Family member in each household (1 = Single, 2 = Couple, 3 = Parents with one child, 4 = Parents with more than one child, 5 = Grandparents, parents and children)	2.64	1.1	1	5	420
City	Independent variable	Types of cities the respondents were during COVID-19 (1 = First-tier cities, 2 = Second-tier cities, 3 = Third-tier cities)	1.88	0.77	1	3	420
Famliy_income_before	For calculating the independent variable	Family income before COVID-19, per year, per household (1 = $0–$3500, 2 = $3500–$85,00, 3 = $8500–$20,000, 4 = $20,000–$49,999, 5 = $50,000–$74,999, 6 = $75,000–$99,999, 7 = $100,000–149,999, 8 = $150,000–$199,999, 9 = $200,000 or more)	4.05	1.87	1	9	420
Famliy_income_after	For calculating the independent variable	Family income after COVID-19, per year, per household (1 = $0–$3500, 2 = $3500–$8500, 3 = $8500–$20,000, 4 = $20,000–$49,999, 5 = $50,000–$74,999, 6 = $75,000–$99,999, 7 = $100,000–$149,999, 8 = $150,000–$199,999, 9 = $200,000 or more)	3.8	1.8	1	9	420
Social variables							
Entertainment	Independent variable	Impacts on access to entertainments (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2.79	0.7	1	4	420
Communication	Independent variable	Impacts on communication with other people (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2.3	0.62	1	4	420
Infrastructural variables							
Transports	Independent variable	Impacts on the citizens' access to urban transportation (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2.41	0.6	1	4	420
Healthcare	Independent variable	Impacts on the citizens' access to urban healthcare facilities (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2.26	0.59	1	4	420
Hospitals	Independent variable	Impacts on the citizens' access to urban hospitals (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2.15	0.55	1	4	420
Food	Independent variable	Impacts on the citizens' access to food resource (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2	0.69	1	4	420
Economic variables							
Occupation	Independent variable	Impacts on the citizens' occupational status (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	2.03	0.84	1	4	420
Finance	Independent variable	Impacts on the citizens' financial status (1 = No impacts, 2 = Slight impacts, 3 = Heavy impacts, 4 = Cut-off)	1.87	0.6	1	4	420
Famliy_income_decline	Independent variable	Whether the family income declined after COVID-19 (0 = No, 1 = Yes)	1.27	0.45	1	2	420
Overall life satisfaction							
Life_BEFORE	For calculating the dependent variable	Life satisfaction before COVID-19 (1 = Satisfied, 2 = Partially satisfied, 3 = Partially dissatisfied, 4 = Totally dissatisfied)	1.36	0.63	1	4	420
Life_AFTER	For calculating the dependent variable	Life satisfaction after COVID-19 (1 = Satisfied, 2 = Partially satisfied, 3 = Partially dissatisfied, 4 = Totally dissatisfied)	1.84	0.76	1	4	420
Life_Satisfaction_decline	Dependent variable	Whether the life Satisfaction declined after COVID-19 (0 = No, 1 = Yes)	1.43	0.5	1	2	420

Table 4 | Kaiser–Meyer–Olkin (KMO) and Bartlett's test

Kaiser–Meyer–Olkin measure of sample adequacy		**0.739**
Bartlett's test of sphericity	Approx. Chi-Square	735.531
	Df	45
	Sig	0.000

Table 5 | Principal component analysis of the scale questions

Rotated component matrix	Component		
Life satisfaction after COVID-19	0.751		
Finance	0.744		
Occupation	0.568		
Food		0.309	
Transports	0.371	0.424	0.307
Healthcare		0.833	
Hospital		0.855	
Entertainment			0.831
Communication			0.698

Inclusion and ethics

All authors stated the "Inclusion and ethics" issue was well conducted in this research. Ethical review procedure for human-related research was obtained and approved by Fenner School of Environment and Society, Australian National University.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. We also attached the original questionnaires' responses information as complementary material.

Code availability

Logit regression was conducted (via R software) to determine the correlations between life satisfaction and other impacts of COVID-19 and provide information on which impacts were significant in causing alterations in life satisfaction through COVID-19 (R code will be submitted via request).

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H. Han and X.M. Bai designed and conducted the research; H. Han analyzed the data and wrote the manuscript; L. Dong supervised this research work and manuscript writing, provided guidance and revised the manuscript; R. Costanza provided guidance and revised the manuscript. All authors contributed significantly to this work by reading and editing.

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