supplementary material

A quantitative sustainability assessment framework for contaminated site remediation: integrating LCA, economic analysis, and social big data

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1. Satellite Imagery of Site Historical Transformation

Historical satellite imagery for the three target sites is presented herein. The images selected correspond to the most recent available data prior to the commencement of remediation activities (circa 2018) and a post-remediation period approximately five years following project completion (circa 2023). This multi-temporal dataset provides a visual and analytical basis for assessing the spatial and temporal landscape evolution resulting from the remediation efforts, highlighting changes in land use, vegetation cover, and overall site conditions.

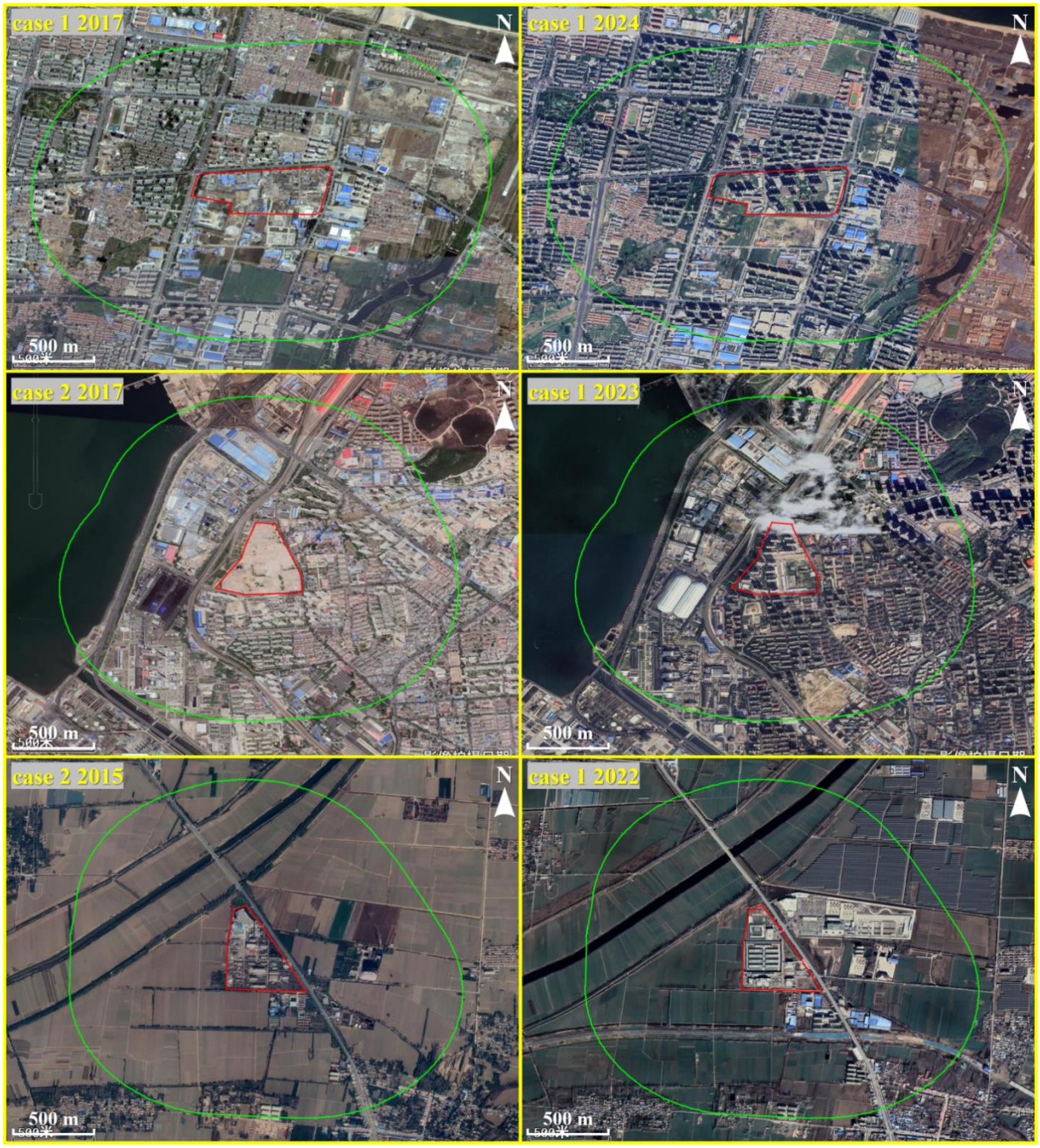


Figure S1: Satellite images of the site before and after remediation, comparing the state around 2017 before remediation with the state approximately 5 years after remediation. The green line delineates the 1-kilometer buffer zone surrounding the site.

2. Inputs for Remediation Process in Environmental Assessment

The tables below provide a detailed summary of the material and energy inputs required for each remediation project at the three target sites. These inputs—including consumables (such as chemical reagents), energy sources (e.g., diesel and electricity), and auxiliary materials (such as well-construction components)—are systematically categorized and quantified. This structured presentation offers core data support for subsequent environmental impact assessments.

Table S1: Inventory of material and energy consumption for the remediation of Site 1.

Process	Sub-process	Item	Unit	Amount
Solidification/stabilization of heavy metal-contaminated soil (35,000 m^3)	Excavation and transport	Diesel [1]	L	11,550
	Chemical dosing & curing	Quicklime	ton	584
		Fly ash [4]	ton	147
		Blast furnace slag [4]	ton	584
		Water	ton	1,170
		Diesel [2]	L	8,400
Ambient-temperature thermal desorption of VOCs-contaminated soil (1,600 m^3)	Excavation and transport	Diesel [1]	L	528
	Chemical dosing & curing	Quicklime	ton	130
		Diesel [2]	L	384
	Waste gas treatment	Activated carbon	ton	3.71
Groundwater pump and treatment (20,000 m^3)	Well construction	PVC pipe	kg	1,200
		Quartz sand	kg	6,400
		Bentonite	kg	450
		Diesel	L	900
	Extraction & treatment	Activated carbon	ton	4
		Sodium sulfide	ton	2
		PAC	ton	2
		PAM	ton	2
		Electricity [3]	kWh	18,000
Solid waste disposal	Water treatment sludge disposal	Sludge	ton	11.6
	Activated carbon disposal	Activated carbon	ton	7.71

Notes: [1] The diesel consumption for soil excavation and on-site transportation is calculated at 0.3 L/m^3. The additional excavation volume generated by natural slope cutting during the excavation process is accounted for at 10%. [2] For the ALLU screening bucket, it can uniformly mix 100 m^3 of contaminated soil with stabilizer per hour, with a fuel consumption of 24 L/h. [3] The energy consumption for groundwater pumping is calculated at 0.9 kWh/m^3. [4] It belongs to industrial solid waste, and its production process is not included in the environmental footprint calculation; the transportation distance is set at 15 km.

Table S2: Inventory of material and energy consumption for the remediation of Site 2.

Process	Sub-process	Item	Unit	Amount
Ex-situ solidification/stabilization of heavy metal-contaminated soil (0–4 m) (94500 m^3)	Excavation and transport	Diesel [1]	L	31185
	Chemical dosing and curing	Attapulgite clay	ton	14790
		Diesel [2]	L	22680
In-situ solidification/stabilization of heavy metal-contaminated soil (4–8 m) (5500 m^3)	Chemical injection	Attapulgite clay	ton	860
		Water [3]	ton	570
		Diesel [4]	L	1300
Ex-situ chemical oxidation of organic-contaminated soil (0–4 m) (31800 m^3)	Chemical dosing & curing	H_2O_2	ton	819
		Ferrous sulfate	ton	1638
		Sulfuric acid	kg	964

Process	Sub-process	Item	Unit	Amount
		Diesel [2]	L	7632
	Tail gas treatment	Activated carbon	ton	20
		Electricity [5]	kWh	3600
In-situ chemical oxidation of organic-contaminated soil (4–8 m) (1200 m^3)	Chemical injection	H_2O_2	ton	31
		Ferrous sulfate	ton	62
		Sulfuric acid	kg	36
		Water [3]	ton	62
		Electricity	kWh	6000
Groundwater pumping and treatment (9900 m^2)	Well construction	PVC	kg	1200
		Quartz sand	kg	6400
		Bentonite	kg	450
		Diesel	L	900
	Extraction & treatment	PAC	ton	2
		PAM	ton	2
		Electricity [6]	kWh	17820
		Activated carbon	ton	12
Solid waste disposal	Water treatment sludge disposal	Sludge	ton	11.5
	Activated carbon disposal	Activated carbon	ton	32

Notes: [1] The diesel consumption for soil excavation and on-site transportation is calculated at 0.3 L/m^3. The additional excavation volume generated by natural slope cutting during the excavation process is accounted for at 10%. [2] For the ALLU screening bucket, it can uniformly mix 100 m^3 of contaminated soil with stabilizer per hour, with a fuel consumption of 24 L/h. [3] The target moisture content of the slurry is calculated at 40%. [4] High-pressure jet grouting equipment with a power of 30–50 kW is adopted, and the calculation is based on a fuel consumption rate of 6.5 L/h and a total operation duration of 200 h. [5] A fan with a power of 5.5 kW operates continuously for 24 hours, with a remediation construction period of 30 days. [6].The energy consumption for groundwater pumping is calculated at 0.9 kWh/m^3

Table S3: Inventory of material and energy consumption for the remediation of Site 2.

Process	Sub-process	Item	Unit	Amount
Ex-situ solidification/stabilization of heavy metal-contaminated soil (148,000 m^3)	Excavation and transport	Diesel [1]	L	49,800
	Chemical dosing and curing	MetaCon-A	ton	3,000
		MetaCon-B	ton	1,800
		Diesel [2]	L	35,520
In-situ groundwater monitoring (20000 m^2)	Well construction	PVC	kg	260
		Quartz sand	kg	715
		Bentonite	kg	918
		Electricity	kWh	660
	Sampling and analysis	Sample	unit	100

Notes: [1] The diesel consumption for soil excavation and on-site transportation is calculated at 0.3 L/m^3. [2] MetaCon® is formulated by compounding basic materials (mineral materials, biomass materials, redox agents, adsorbents, pH regulators). It stabilizes heavy metals via a series of physical-chemical reactions with them, including adsorption, precipitation, complexation, isomorphous substitution, and redox. [2] For the ALLU screening bucket, it can uniformly mix 100 m^3 of contaminated soil with stabilizer per hour, with a fuel consumption of 24 L/h. [3] Five groundwater monitoring wells are sampled and tested once a quarter for a continuous monitoring period of five years.

3. Data Processing for Economic Indicator Evaluation

3.1 Land value appreciation

The Shandong Provincial Department of Natural Resources regularly releases quarterly urban land price monitoring reports that encompass all 17 prefecture - level cities within the province.

These reports furnish data regarding four categories of land prices: comprehensive, commercial, residential, and industrial.

For this study, the average land price levels of Yantai, Qingdao, and Liaocheng were extracted on a quarterly basis from the published data. In light of the land - use conversion scenarios of the studied sites, particularly the transformation from industrial land to residential land, as well as to educational and management service land, the corresponding land price values were ascertained. Sites intended for schools and management services were assessed in accordance with comprehensive land price standards.

This methodology facilitated the tracing of land price fluctuations over time for the three studied sites based on their respective land - use conversion routes.

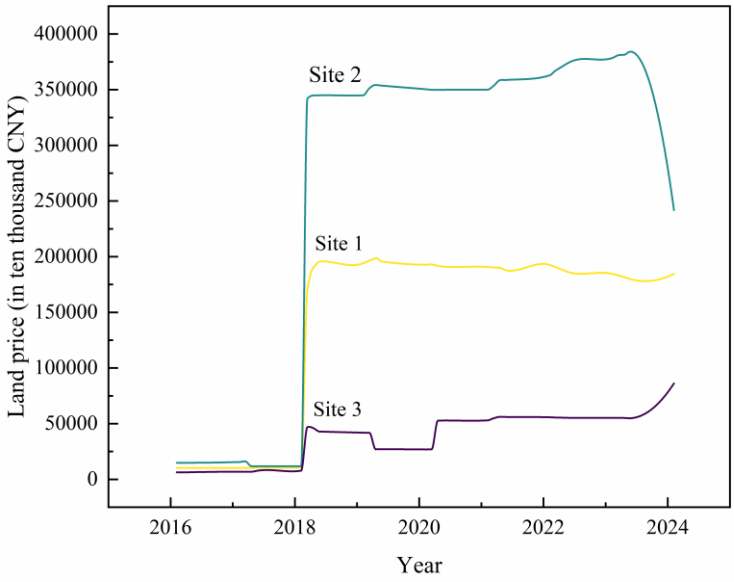


Figure S2: Changes in land prices at the site location. Unit land prices are retrieved from the Department of Natural Resources of Shandong Province, http://dnr.shandong.gov.cn/.

3.2 Surrounding housing price premium

In the economic dimension indicator system of this study, the indicator of "surrounding residential property prices" was initially planned to be included. The objective was to assess the potential impact of site remediation on nearby property values by examining historical housing prices and their appreciation in adjacent residential areas. However, during implementation, several issues arose that limited the effective application of this indicator:

(1) Non-urban Location of Site 3: Site 3 is situated in a non-urban area with no formal residential zones in its vicinity. Housing in this region consists primarily of self-built homes constructed by rural residents, for which there are no official channels for collecting property price data. This makes it difficult to obtain accurate and representative housing price information, thereby hindering effective quantitative analysis of price changes in the area.

(2) Limited Access to Housing Price Data: During data collection, it was found that government websites typically do not publish average housing prices; such data are mainly released by market agencies. However, accessible housing price data generally cover only the three years prior to the query, making it challenging to obtain longer-term historical data. This limitation restricts a comprehensive assessment of the long-term impact of site remediation on property values.

(3) Multiple Factors Influencing Housing Prices: Property prices are affected by a combination of factors, including transportation convenience, regional planning, economic development levels, and market supply and demand. In recent years, the COVID-19 pandemic has contributed to a

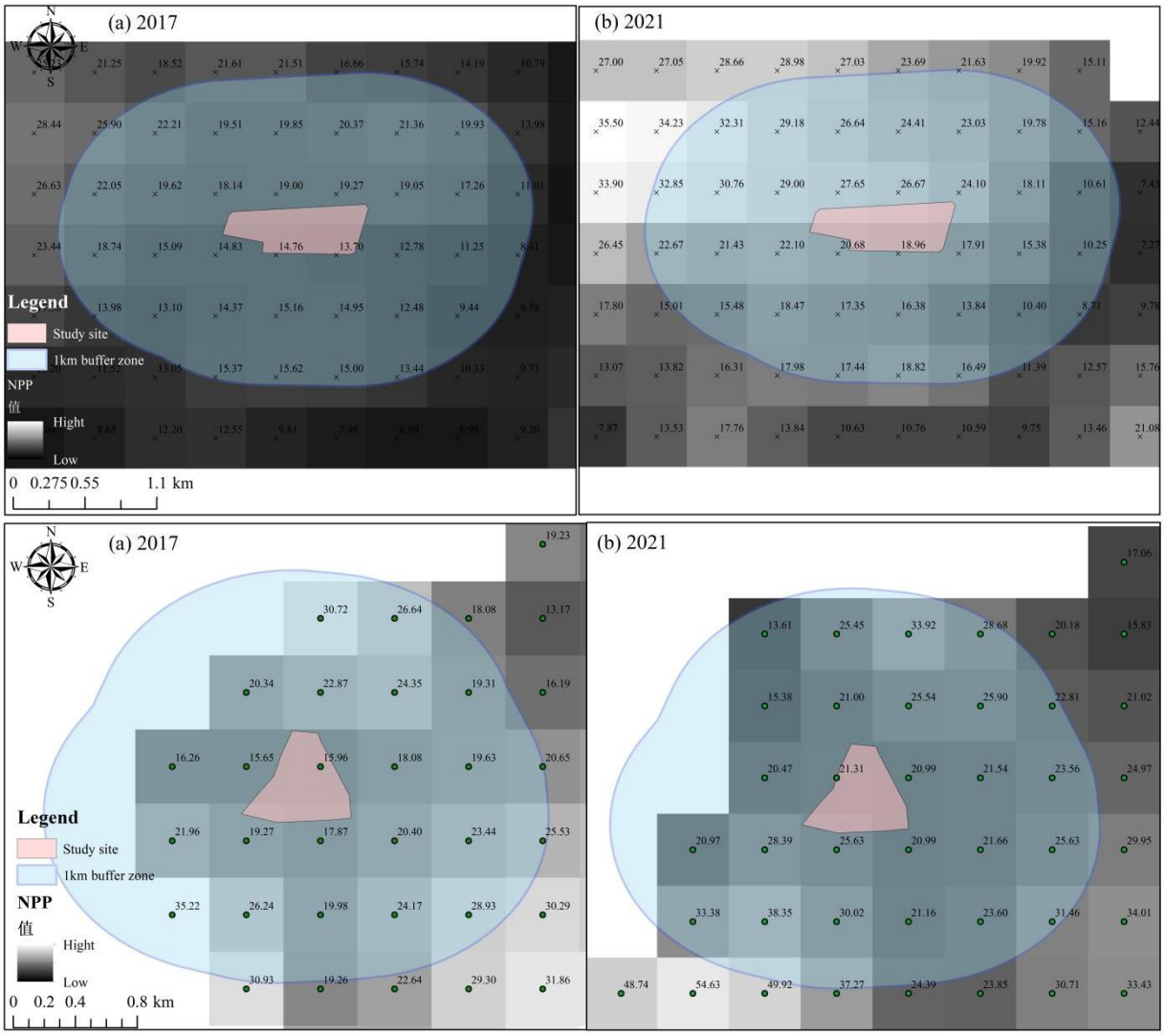
general decline in housing prices. Against this backdrop, it is difficult to isolate the dominant effect of site remediation on price increases among numerous influencing factors. In other words, it is not feasible to accurately quantify the specific contribution of site remediation to housing price appreciation, which further reduces the validity of this indicator.

(4) Land Price Appreciation Already Included in Economic Indicators: In light of the above issues, the indicator of "land price appreciation" has already been incorporated into the economic dimension indicators. Taking into account expert opinions, it was concluded that the "surrounding residential property prices" indicator, under current data and analytical constraints, cannot accurately reflect the economic effects of site remediation. Therefore, it was decided not to include this indicator in the final economic dimension indicator system.

In summary, although surrounding residential property prices are theoretically an important economic indicator, practical challenges related to data availability and the complexity of multiple influencing factors prevented its inclusion in this study's economic indicator system. Future improvements in data collection methods and analytical techniques may warrant reconsideration of this indicator.

4. Data Processing for Social Indicator Evaluation

4.1 NPP - VIIRS data



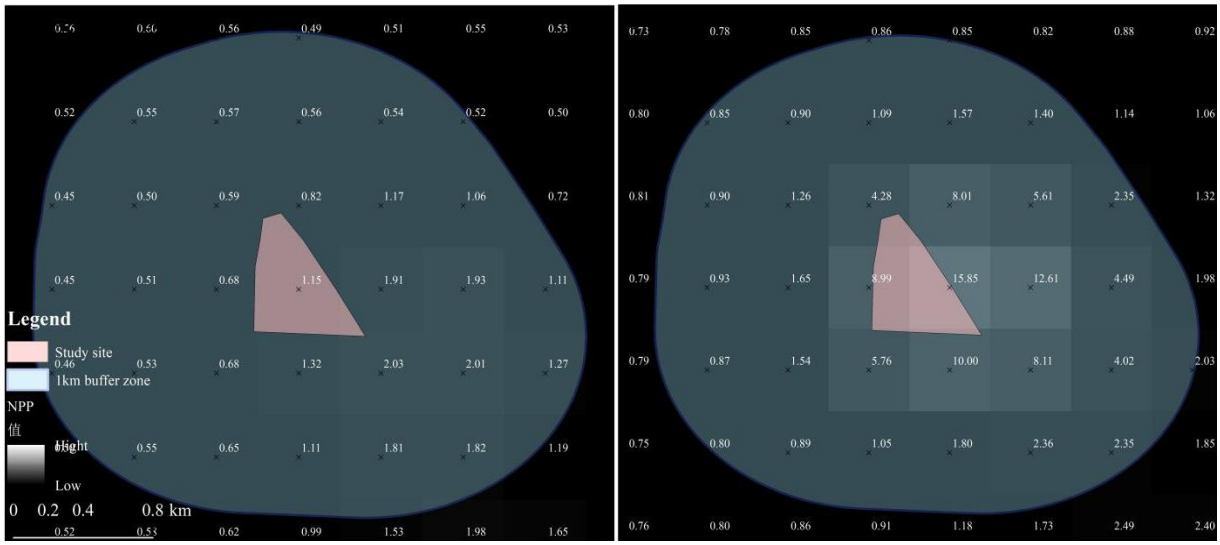


Figure S3. Processing flow of nighttime light data for the study sites.

4.2 Amap Point of Interest (POI) data

By conducting a Point of Interest (POI) search within a 1 km radius of the site using Gaode Map, the surrounding public service facilities are as follows. We conducted a search for common public management and service structures, including facilities such as hospitals, schools, kindergartens, shopping malls, libraries, police stations, parks, and other similar venues.

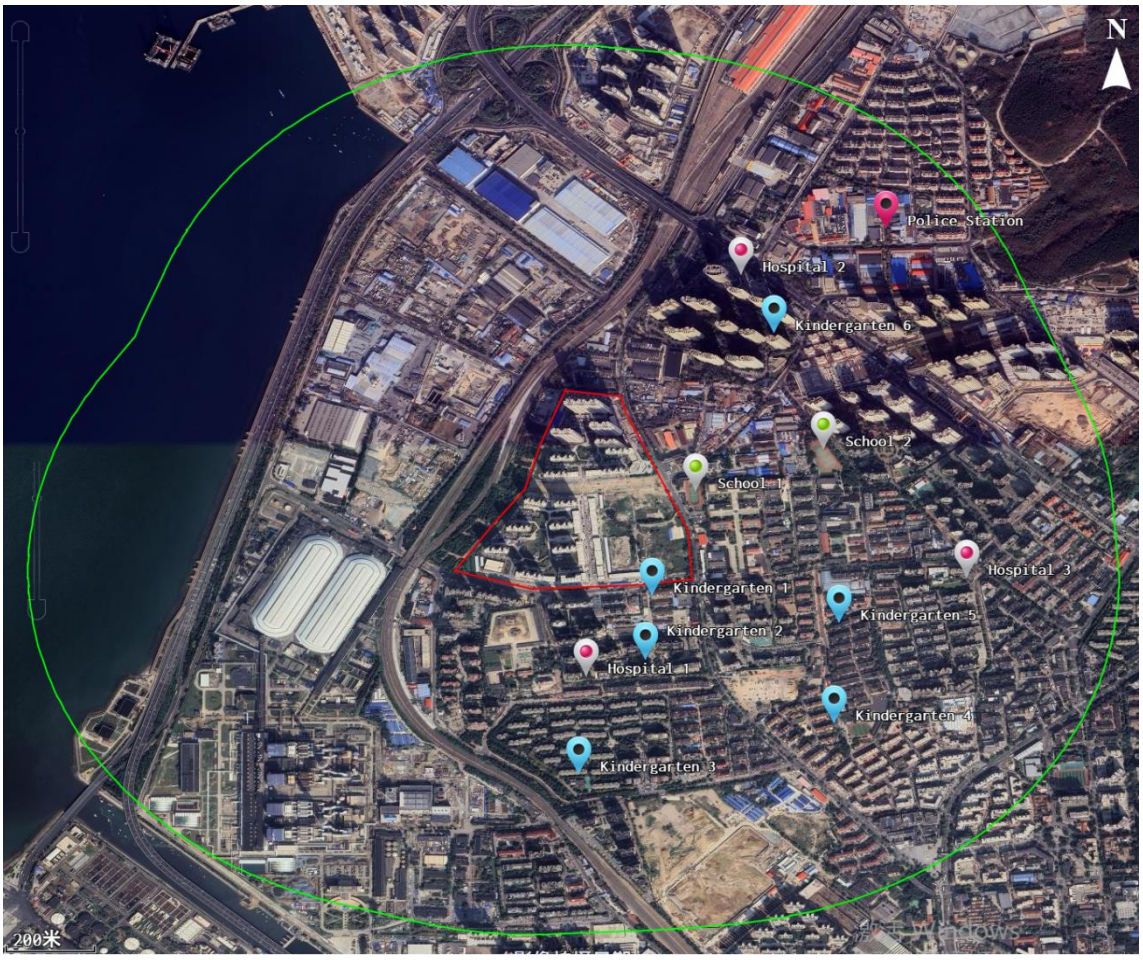


Figure S4. Location of public service facilities within a 1-km radius of Site 1.

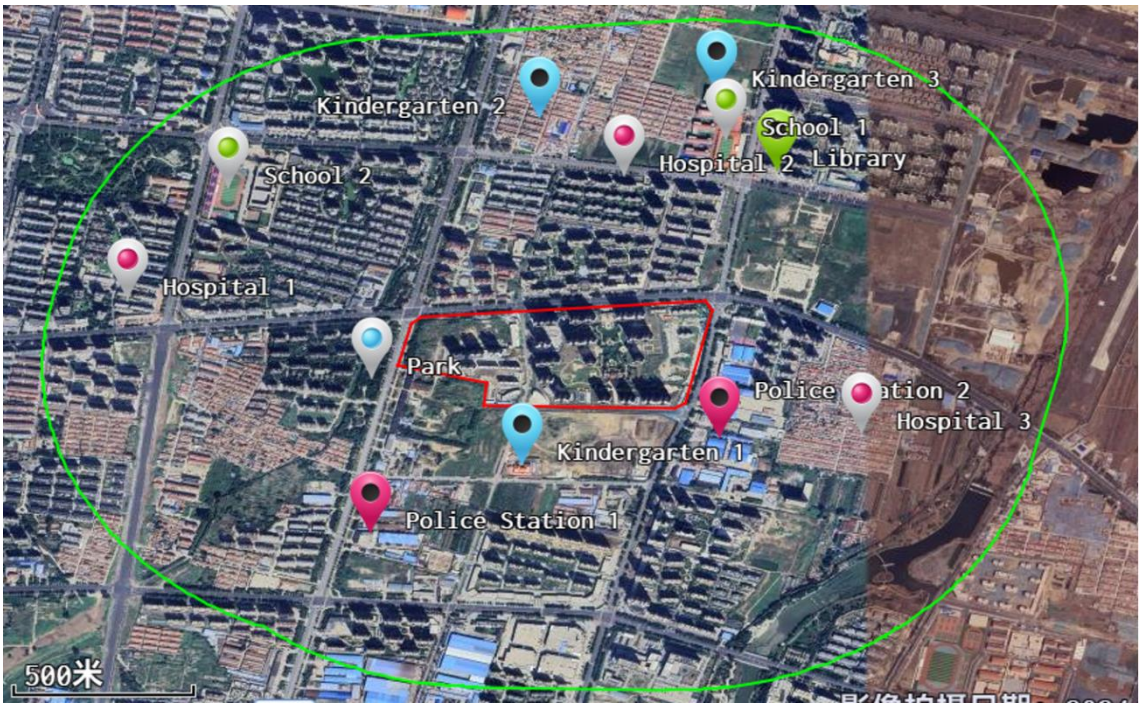


Figure S5. Location of public service facilities within a 1-km radius of Site 2.



Figure S6. Location of public service facilities within a 1-km radius of Site 3.

4.4 Sentiment analysis of social media public opinion.

Table S4. Sentiment analysis results of social opinion based on VADER.

ID	Text preview	Neg. s	Neu. s	Pos. s	Com. s	Classification
Social Opinions on Site 2						
1	Recently, there have been new developments regarding two shantytown renovation projects in Shibei Di...	0.054	0.869	0.078	0.6124	Positive
2	The much-anticipated plot at No. 31 Yichang Road in Shibei District is finally set for a land tender...	0.073	0.893	0.033	-0.3612	Negative
3	Starting from August 26, compensation agreements for expropriation will be signed for 9 centralized ...	0.06	0.912	0.029	-0.3182	Negative
4	With the 2023 Chinese New Year approaching, 'returning home' has become an increasingly urgent expec...	0.046	0.861	0.092	0.296	Positive
5	To ensure project implementation, the primary and 分管 leaders of the Shibei District Urban Constructio...	0.143	0.801	0.056	-0.4588	Negative
6	The land parcel at No. 31 Yichang Road recently completed its land tender, auction, and listing proc...	0.042	0.958	0	-0.296	Negative
7	Resettlement housing projects scheduled for delivery this year have yet to commence construction; de...	0.084	0.839	0.077	-0.128	Negative
8	The Provincial Department of Ecology and Environment organized experts to review the excavation effe...	0.114	0.836	0.05	-0.3818	Negative
9	After the relocation of the old enterprise 'Shuangtao Chemical,' why has there been a delay in start...	0.093	0.907	0	-0.6522	Negative
10	In Qingdao, there was once a saying, 'Breakfast at Oriental, Dinner at Haitian.' The Oriental Hotel,...	0.087	0.913	0	-0.7236	Negative
11	Why hasn't construction started on the resettlement housing plot at No. 31 Yichang Road? The officia...	0.056	0.916	0.027	-0.296	Negative
12	Hello, may I ask about the progress of the environmental impact assessment for the plot at No. 31 Yi...	0.036	0.803	0.161	0.9332	Positive
13	The No. 31 Yichang Road plot in Shibei District, Qingdao, a 2017 shantytown relocation and resettlem...	0.041	0.959	0	-0.296	Negative
14	Recently, the Municipal Planning Bureau announced an adjustment to the plan for the No. 31 Yichang R...	0.046	0.954	0	-0.296	Negative
15	According to information from the Municipal Planning Bureau, the regulatory plan adjustment for Plot...	0.038	0.962	0	-0.296	Negative
16	Recently, the Municipal Environmental Protection Bureau published the environmental impact assessmen...	0.045	0.955	0	-0.296	Negative
17	Environmental Impact Assessment Announcement for the Contaminated Soil Remediation Project at No. 31...	0.038	0.962	0	-0.296	Negative
18	This year, the Qingdao Land Reserve and Consolidation Center has completed land banking work for sev...	0.028	0.95	0.022	-0.1027	Negative

ID	Text preview	Neg. s	Neu. s	Pos. s	Com. s	Classification
19	Qingdao Shuangtao Chemical, located at No. 31 Yichang Road, ceased all production by the end of last...	0.04	0.96	0	-0.296	Negative
20	At 10:16 today, at the old plant site of Qingdao Shuangtao Fine Chemical (Group) Co., Ltd. at No. 31...	0.039	0.896	0.065	0.1027	Positive
21	There have been new developments regarding the relocation of old enterprises in the Binhai New Area....	0.034	0.966	0	-0.296	Negative
22	Recently, there have been new developments regarding the relocation of old enterprises in the Binhai...	0.058	0.919	0.024	-0.3818	Negative
Social Opinions on Site 3						
23	In accordance with the requirements for the construction of the supporting projects of the South-to-...	0	0.893	0.107	0.8555	Positive
24	The Traffic Police Detachment of Liaocheng Public Security Bureau has issued an announcement. In acc...	0	0.884	0.116	0.8957	Positive