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ORIGINAL PAPER

Selecting China's strategic petroleum reserve sites by multi-objective programming model

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Abstract An important decision for policy makers is selecting strategic petroleum reserve sites. However, policy makers may not choose the most suitable and efficient locations for strategic petroleum reserve (SPR) due to the complexity in the choice of sites. This paper proposes a multi-objective programming model to determine the optimal locations for China's SPR storage sites. This model considers not only the minimum response time but also the minimum transportation cost based on a series of reasonable assumptions and constraint conditions. The factors influencing SPR sites are identified to determine potential demand points and candidate storage sites. Estimation and suggestions are made for the selection of China's future SPR storage sites based on the results of this model. When the number of petroleum storage sites is less than or equals 25 and the maximum capacity of storage sites is restricted to 10 million tonnes, the model's result best fit for the current layout scheme selected thirteen storage sites in four scenarios. Considering the current status of SPR in China, Tianjin, Qingdao, Dalian, Daqing and Zhanjiang, Chengdu, Xi'an, and Yueyang are suggested to be the candidate locations for the third phase of the construction plan. The locations of petroleum storage sites suggested in this work could be used as a reference for decision makers.

Keywords Strategic petroleum reserve · Storage site selection · Multi-objective modeling · China

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1 Introduction

Oil, known as the lifeblood of industry, is a strategic raw material as well as a major source of energy supporting economic and social development (Karl 2007). The first of three oil crises began in 1970s, causing higher prices and a stagnant global economy (Helm 2002). Accordingly, western countries began to store emergency petroleum reserves (Fan and Zhang 2010). With the expansion in scale, a strategic petroleum reserve is considered as an effective tool to improve energy security and alleviate price fluctuations (Hubbard and Weiner 1985). According to the reserve agreement, 28 countries of the International Energy Agency were required to hold 90 days of net oil imports for their respective countries. As a second-largest oil consumer in the world, energy security in China is among the most serious challenges due to its increasing oil dependency (Dong et al. 2017). Additionally, the geopolitical impacts of OPEC on oil supply and prices are a significant factor for China to have its own SPR (Chen et al. 2016). Following other nations' establishment, China has built its own SPR to ensure that its oil supply will not be disrupted. The preliminary work on China's SPR was prepared in 1993, approved by the government in 2003, and commenced in 2004 (Jiao et al. 2014). The timeline of China's

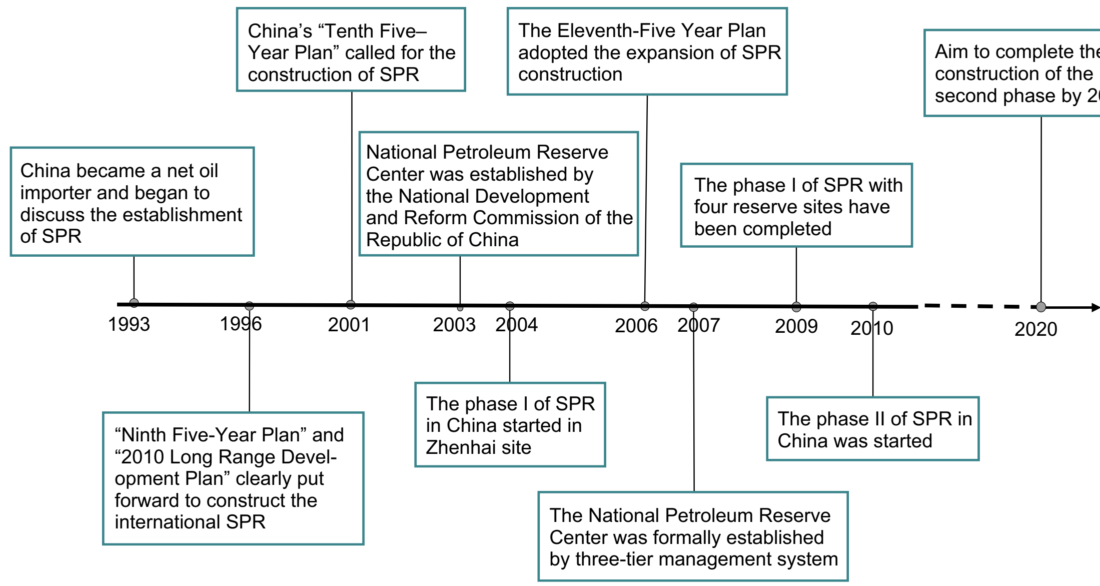

Fig. 1 Timeline of the China's SPR development

SPR program is shown in Fig. 1. According to China's stated policy on SPR, the country is expected to build storage capacity equivalent to 90 days of its net imports in three phases over 15 years. In reality, China has delayed completion of the second phase until 2020 (Park 2015). Generally, the establishment of an SPR in China has helped in dealing with oil crises and ensuring energy and economic security.

An SPR project is a complex system, and many practical questions need to be answered (Davis 1981). The selection of the petroleum reserve sites has a profound effect on SPR program operation. Not all locations are appropriate, so it is important for policy makers to identify the most suitable and efficient locations. Based on China's SPR construction status (Fig. 2), four reserve sites were selected in Phase I, locating in the coastal cities of Zhenhai, Zhoushan, Huangdao, and Dalian. Eight reserve sites in Phase II are planned for inland areas, including Tianjin, Jinzhou, Dushanzi, Xishan, Lanzhou, Jintan, Huizhou, and Zhanjiang. The third selection will likely be located in Wanzhou, Henan, Caofeidian, and Tianjian (Wu and Wang 2012). Three criteria affect the location selection at which China stores its purchased oil. The first is transportation convenience. Most sites are not only key petroleum import harbors but also near substantial demand centers, so the oil can be transported with low transportation costs and a short response time; the second factor is achieving maximum safety. The apparent move from coastal cities to inland is in consideration of increased safety for the SPR in underground tanks scattered around the country (Wu 2014). Third, the location distribution is closely associated with the layout of oil consumption and the routes of imports (Zhu 2007). Today, the preparatory work for the third phase has been launched and the sites selections are still being determined. How to decide on the storage sites rationally and scientifically is a practical issue we need to consider to achieve the full strategic, economic, and social benefits of the SPR program.

SPR site location is categorized as an emergency facility location problem (Farahani et al. 2012). The *p*-median method, *p*-center method, and covering method are widely used in the literature to decide emergency facility locations (Toregas et al. 1971; Roth 1969; Li et al. 2011). However, these discrete methods are proposed based on single objective such as minimum time and distance. With regard to the SPR site selection, there is limited related research. Zhang et al. (2008) presented an uncertain planning model to determine the location of SPR sites with minimal cost of transport based on hybrid intelligent algorithms. Based on fuzzy comprehensive evaluation and maximal covering models, Chen suggested 14 candidate cities for China's second and third SPR construction (Chen 2010). Compared with these methods, the prominent advantage of the multi-objective model is that it takes full consideration of cost and time (Wilson et al. 2013). The comparisons between this study and other facilities location study are given in Table 1 (De Vos and Rientjes 2008). Accordingly, this paper presents a time and cost multi-objective programming model to identify the optimal SPR storage site locations and guide the construction of SPR in China.

2 Factors influencing SPR storage site location

Generally, the location decision for an SPR storage site should consider the economic considerations and other non-economic considerations, such as safety, efficiency, and

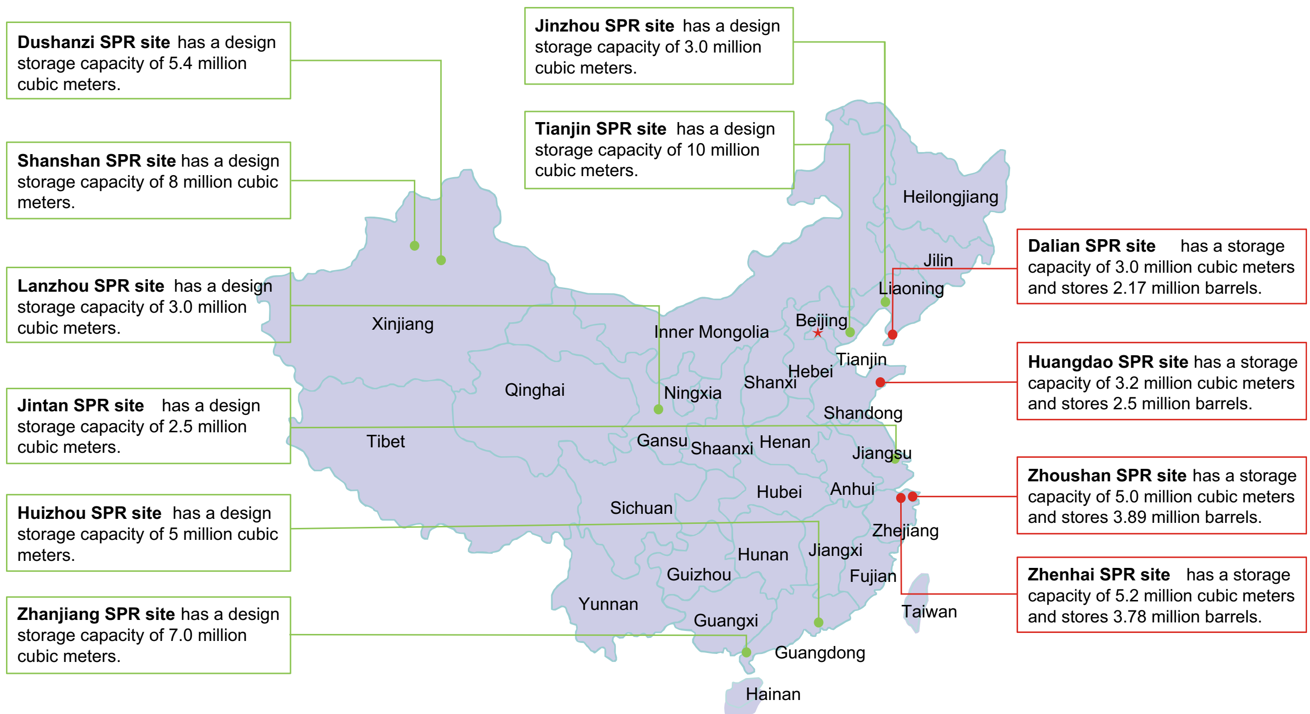

Fig. 2 Location of existing strategic oil reserve bases in China. *Red boxes* indicate SPR sites in Phase I; *green boxes* indicate SPR sites in Phase II

Table 1 Comparison between this study and other facilities location study

Items	Other facilities location studies	This study
Logistics network layer	Monolayer	Monolayer
Number of demand points	Certainty	Uncertainty
Number of facilities	Certainty	Uncertainty
Distance	Linear distance	Shortest distance
Objective function	Single objective	Multi-objective
Optional point capacity	Unlimited	Limited
Emergency response time	Unlimited	Limited
Purpose	Select location	Select location
		Determine reserve scale
		Distribute schedule

fairness. Among them, cost and time minimization is the two most important factors in the choice of a particular place to locate the SPR. In other words, the SPR site should be optimally located to achieve the minimum response time and construction cost (Dong et al. 2013). Because the SPR is characterized by providing emergency oil, the time to access the emergency oil supply must be as short as possible (Oregon 2003). Furthermore, as a construction project, reducing the construction cost is regarded as a basic goal in SPR site selection. With regard to the factors affecting SPR storage sites, it is necessary to take into consideration all the relevant factors. Niu indicated that five factors affected the location decision, including military benefit, economic benefit, transportation convenience, sustainability, and compatibility (Niu et al. 2010). According to Li and Tan, SPR storage site location should satisfy two principles: absorbing the imported oil and quickly transporting it to a refining center (Li and Tan 2002). In addition, the accessibility of the oil resource, the convenience of transportation, the superiority of storage, and the effectiveness of releasing the emergency oil should be taken into account in location decisions. Based on the previous work, the major factors influencing location are discussed below:

- *Availability of petroleum resources* in determining the reserve location for the SPR, the availability of petroleum resources is of vital importance, because the availability can ensure emergency supply and reduce the cost of production. The basic requirement for a reserve site is that it can hold enough petroleum to address supply disruptions (Bai et al. 2016a, b).

- *Proximity to refining centers* policy makers must consider nearness to refining centers. Petroleum is difficult to transport over long distances so an SPR should be located in close proximity to refining centers. Locating reserve sites near refining centers can reduce transportation cost and reduce response time (Majid et al. 2016).
- *Convenience of transportation* convenience of transportation also influences the SPR storage sites. The four modes of petroleum transportation (pipeline, water, rail, and road) play a significant role. Thus, the junction points of these transport types become priority areas for SPR location (Niu et al. 2013).
- *Petroleum storage consideration* petroleum storage consideration refers to storing the petroleum safely in natural and climatic conditions. These factors can influence the location of an SPR storage site. Stable geological conditions with underground petroleum storage caverns can provide an added advantage over conventional storage tanks in ensuring the storage security of the SPR (Tillerson 1979).
- *Distance between reserve site and demand center* the distance between the reserve site and demand center is associated with the effectiveness of SPR release. A long distance not only causes response time delay but also increases transportation cost. Accordingly, the reserve site should be located as close as possible to the demand center (Williams 2008).
- *Strategic considerations* as petroleum is a strategic commodity, strategic consideration is important in determining the SPR storage site location. The location decision should be consistent with the strategic planning for development with coverage as complete as possible (Bai et al. 2016a, b).

As mentioned above, the influencing factors address three aspects: demand point information, reserve site information, and information related to both (Liu et al. 2014). The information about demand points refers to the geographic location and the amount of emergency petroleum demand. The reserve site information contains the location and storage capacity. The distance between demand point and reserve site and the transportation conditions also have an effect on SPR site selection.

3 Methodology

3.1 Data

3.1.1 Demand points information

Based on the analysis of factors affecting site location determination and following the principle of proximity, we collected the information about SPR emergency demand points in terms of geological location and demand amount. According to the Chinese Statistical Bureau report in 2014, there were over 260 refineries (CNPC 2015). As the largest refinery companies, CNPC and Sinopec accounted for 28% and 38%, respectively, of the refining capacity. Furthermore, CNOOC, Yanchang Shaanxi Petroleum, and local enterprises played a significant role in Chinese refining (The Oxford Institute for Energy Studies 2016). Therefore, we selected 64 refineries located in 52 cities as the SPR demand points, as shown in Table 2. The demand amount is calculated by indicators based on the petroleum self-sufficiency ratio, risk probability, and transportation distance (Martínez-Palou et al. 2011). To ensure the 90 days of SPR supply, the reserve amount is assumed to equal the demand amount. Due to the limitation of data availability, this demand amount for each point is calculated based on data from 2012 when 270 million tonnes of imported crude oil were imported. Furthermore, the distribution of emergency demand of each city should follow the industry production ratio. The results are given in Table 3.

3.1.2 Candidate reserve site location

According to the regulation of National Petroleum Reserve in China, the reserve location should ensure the supply of emergency SPR efficiently and safely. Based on Liu, the candidate reserve site location is determined by three indicators: the flow function, the spatial structure, and the flow track. Table 4 shows the function types of crude oil flow in China based on calculation of the oil self-sufficiency ratio and liquidity ratio. The spatial structure of oil flow is consistent with the petroleum distribution in China, including source system, transit system, and sink system, as shown in Fig. 3. Taking the above factors into consideration, 55 prefecture-level cities are listed as candidate SPR sites in China. The detailed information is shown in Table 5. Specifically, the candidate sites include 17 coastal harbors, 18 input origins, 5 terminal hinges, 6 inland ports, and 9 intersecting regions. The selected site locations cover nearly all the key areas of petroleum resource mobility.

Table 2 Information of strategic oil reserve demand (unit: 10^4 tonnes). *Source* CNPC, Sinopec, CNOOC, Yanchang Shaanxi Yanchang Petroleum, and local enterprise official websites

No.	City	Refinery name	Company	Capacity	No.	City	Refinery name	Company	Capacity
1	AQ	Anqing Petrochemical	Sinopec	500	28	JZ	Jinzhou Petrochemical	CNPC	700
2	BJ	Yanshan Petrochemical	Sinopec	1000	29	LN	Liaoyang Petrochemical	CNPC	1000
3	QZ	Fujian Petrochemical	Sinopec	1200	30	PJ	Liaohe Petrochemical	CNPC	500
4	LZ	Lanzhou Petrochemical	CNPC	1050			Huajin Petrochemical	CSGC	500
5	QY	Qingyang Petrochemical	CNPC	300	31	HHHT	Hohhot Petrochemical	CNPC	500
6	YM	Yumen Petrochemical	CNPC	300	32	YC	Pagoda Petrochemical	Local	350
7	GZ	Guangzhou Petrochemical	Sinopec	1320	33	GL	Golmud Petrochemical	CNPC	150
8	HZ	Huizhou Petrochemical	CNOOC	1200	34	BZ	Zhonghai Asphalt	Local	500
9	MM	Maoming Petrochemical	Sinopec	2550	35	DZ	Hengyuan Petrochemical	Sinopec	300
10	ZJ	Zhanjiang Dongxing Petrochemical	Sinopec	500	36	DM	Dongming Petrochemical	Local	1200
11	BH	Beihai Petrochemical	Sinopec	500	37	DY	Local Refinery	Local	1000
12	QZ	Guangxi Petrochemical	CNPC	1000	38	JN	Jinan Petrochemical	Sinopec	500
13	CZ	North China Petrochemical	CNPC	1000	39	QD	Qingdao Petrochemical	Sinopec	500
		Cangzhou Petrochemical	Sinopec	350			Qingdao Petrochemical	Sinopec	1000
14	SJZ	Shijiazhuang Petrochemical	Sinopec	500	40	WF	Changyi Petrochemical	ChemChina	500
15	LY	Luoyang Petrochemical	Sinopec	800	41	ZB	Qilu Petrochemical	Sinopec	1050
16	DQ	Daqing Petrochemical	CNPC	1000	42	XA	Xi'an Petrochemical	Sinopec	250
17	HRB	Harbin Petrochemical	CNPC	500	43	YA	Yan'an refinery	Yanchang	800
18	JM	Jinmen Petrochemical	Sinopec	600			Yong-Ping refinery	Yanchang	450
19	WH	Wuhan Petrochemical	Sinopec	850	44	YL	Yulin refinery	Yanchang	1000
20	YY	Changling Petrochemical	Sinopec	800	45	XY	Changqing Petrochemical	CNPC	500
21	SY	Jilin Petrochemical	CNPC	1000	46	SH	Gaoqiao Petrochemical	Sinopec	1250
22	NJ	Jinling Petrochemical	Sinopec	1350			Shanghai Petrochemical	Sinopec	1600
		Yangzi Petrochemical	Sinopec	900	47	CD	Sichuan Petrochemical	CNPC	1000
23	JJ	Jiujiang Petrochemical	Sinopec	500	48	TJ	Dagang Petrochemical	CNPC	500
24	DL	Dalian Petrochemical	CNPC	2050			Tianjin Petrochemical	Sinopec	1500
		West Pacific Petrochemical	CNPC	1000	49	DSZ	Dushanzi Petrochemical	CNPC	1600
25	FS	Fushun Petrochemical	CNPC	1000	50	KRMY	Karamay Petrochemical	CNPC	500
26	HLD	Jinxi Petrochemical	CNPC	1000	51	Kuqa	Talimu Petrochemical	Sinopec	500
27	JZ	Jinzhou Petrochemical	CNPC	700	52	Urumqi	Urumqi Petrochemical	CNPC	600

City abbreviations are given in "Appendix 1"

3.1.3 Distance calculation

Petroleum transport is a major component of an SPR system with a range of transportation options available, including railway, pipeline, highway, and water networks. Considering the wide range of cities involved and the incomplete information on pipeline networks, we calculated the shortest distance between the demand point and candidate site based on the shortest path theory of railway mileage. The result is shown in Table 6.

3.1.4 Selection criterion

In the SPR site selection model, four important parameters should be discussed. The first parameter refers to the time the reserve site needs to respond to an emergency demand. In terms of economic and safety considerations, the candidate location can cover the demand point once. The storage capacity parameter of candidate reserve sites depends on the maximum and minimum capacity. Considering the limitation of SPR storage capacity, two maximum storage scenarios of 10 and 8 million tonnes are discussed based on Liu, which should outweigh the minimum capability (≥1 million tonnes). Then, the emergency response time should be evaluated on the basis of the average railway speed (90–100 km/h), so the response range is assumed to 900 km. The last parameter is the reserve numbers. Too few or too many reserve sites will affect the scheme. This paper will discuss 20 or 25 reserve sites considering the current status of and prospects for SPR construction.

Table 3 Strategic oil reserve demand for each demand point (unit: 10^4 tonnes)

No.	Demand point	Amount	No.	Demand point	Amount	No.	Demand point	Amount
1	AQ	66	19	WH	113	37	JN	133
2	BJ	133	20	YY	106	38	QD	199
3	QZ	159	21	SY	133	39	WF	66
4	LZ	139	22	NJ	299	40	ZB	139
5	QY	40	23	JJ	66	41	XA	33
6	YM	40	24	DL	405	42	YN	166
7	GZ	175	25	FS	133	43	YL	133
8	HZ	159	26	HLD	133	44	XY	66
9	MM	338	27	JZ	93	45	SH	378
10	ZJ	66	28	PJ	133	46	NC	133
11	BH	66	29	LY	66	47	TJ	265
12	QZ	133	30	HHHT	66	48	DSZ	212
13	CZ	179	31	YC	66	49	KLMY	66
14	SJZ	66	32	GM	20	50	KC	66
15	LY	106	33	BZ	20	51	WLMQ	80
16	DQ	86	34	DZ	66	52	ZH	305
17	HRB	66	35	DM	40			
18	JM	80	36	DY	159			

Table 4 Function types of crude oil flow in China. *Sources* China Energy Statistical Yearbook 2012

Flow function	Provinces
Source region	Tianjin, Heilongjiang, Shanxi, Qinghai, Xinjiang, Inner Mongolia
Sink region	Beijing, Zhejiang, Anhui, Fujian, Jiangxi, Jilin, Guangdong, Liaoning, Hubei, Jiangsu, Gansu, Sichuan, Hainan, Shanghai, Guangxi, Hunan, Ningxia, Henan, Shandong
Transit region	Hebei
Self-sufficient region	Yunnan

3.2 SPR site location model

3.2.1 Problem description

First, we define two sets, G and F, which are the function of potential demand points and reserve sites, respectively. G and F assume that the geographic location of the demand points and reserve sites, the distance between them, and the transportation costs are known. To provide emergency petroleum with minimal time and cost, the problem is to determine numbers of reserve sites from among the optional locations.

3.2.2 Assumptions

We have based our model on several assumptions as follows:

- The model is categorized to the discrete allocation problem, comprising various optional demand points and reserve sites.
- The demand points are evaluated by geographic location and amount of petroleum demand.
- Petroleum demand volume for each point is fixed.
- The storage capacity for each optional reserve site is limited by the maximum and minimum volume. The construction scale of reserve sites is restricted to the storage capacity.
- A demand point is supported by the reserve site under the assumption that the coverage frequency equals 1.
- The amount of petroleum supply from the reserve site should meet the demands under the coverage.
- The supply volume of the selected reserve site should be less than or equal to its maximum storage capacity.
- The transfer velocity is constant; that is, the transfer distance has an equivalence relation with transfer time.
- In reality, the location and construction of reserve sites satisfy the standard of technology that all the reserve sites are consistent with the technical standards.

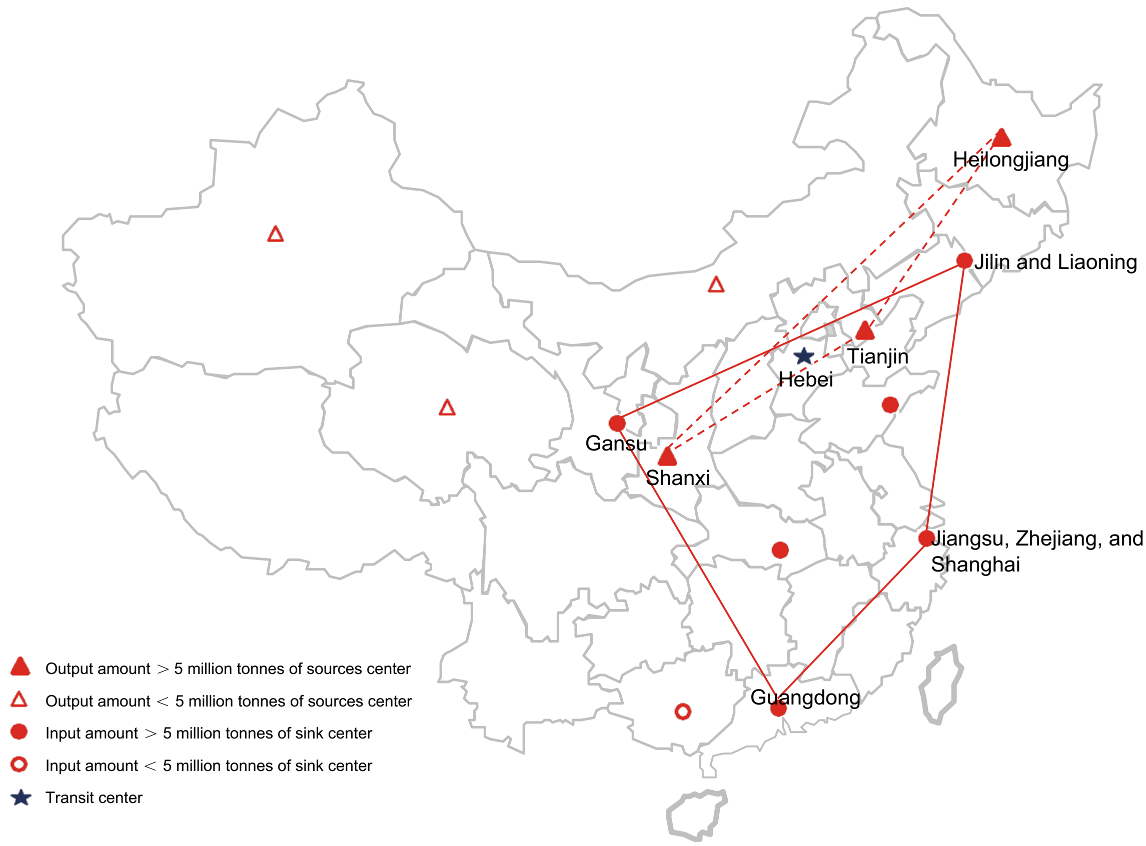

Fig. 3 Spatial structure of China's oil resources flow

Table 5 List of the candidate SPR storage sites

City	Function type	City	Function type	City	Function type
BJ	Terminal	XN	Input node	FZ	Coastal port
LZ	Terminal	YM	Input origin	GZ	Coastal port
CD	Terminal	RQ	Input origin	HZ	Coastal port
AS	Terminal	NY	Input origin	MM	Coastal port
SY	Terminal	PY	Input origin	ZZ	Coastal port
CZ	Transit	DQ	Input origin	QHD	Coastal port
SJZ	Transit	SY	Input origin	LYG	Coastal port
LY	Transit	PJ	Input origin	DL	Coastal port
ZZ	Transit	GLM	Input origin	DD	Coastal port
AQ	Inland port	HTG	Input origin	JZ	Coastal port
JM	Inland port	DY	Input origin	YK	Coastal port
WH	Inland port	XA	Input origin	QD	Coastal port
YY	Inland port	BKQ	Input origin	YT	Coastal port
NJ	Inland port	DSZ	Input origin	SS	Coastal port
JJ	Inland port	KMY	Input origin	TJ	Coastal port
TL	Input node	KC	Input origin	NB	Coastal port
BT	Input node	KL	Input origin	TS	Coastal port
HT	Input node	SS	Input origins		
YC	Input node	KM	Input origins		

3.2.3 Symbol

The SPR storage site selection model can be expressed as follows:

(1) Indices symbols

$G = \{G_i | i = 1, 2, \ldots, m\}$ is a set of SPR demand points;
$F = \{F_j | j = 1, 2, \ldots, n\}$ is a set of optional SPR storage sites;

(2) Parameters symbols

w_i is crude demand of SPR $i \in G$;
C_j^- and C_j^+ are the minimum and maximum storage capacity of reserve sites $j \in F$;
P is the constant parameters of the optional reserve sites;
d_{ij} is the distance between demand point i and candidate reserve site j;
λ is the emergency response time;
C is the total volume of SPR storage capacity in the country;

Table 6 Railway distance between demand cities (unit: miles)

	AQ	BJ	FZ	LZ	YM	GZ	HZ	MM	ZJ	CZ	SJZ	RQ	QHD	TS	LY	ZZ	NY	PY	TL	DQ	JM	WH	YY	SY	NJ	LYG	JJ
AQ	0	1199	784	1726	2534	1141	1053	1471	1547	996	1071	1083	1357	1216	815	746	655	798	1818	2336	605	357	513	2160	285	599	210
BJ	1199	0	1986	1485	2104	2149	2066	2485	2588	218	292	147	291	179	822	714	934	521	752	1323	1179	1156	1339	1148	1038	738	1338
QZ	859	1500	180	2409	3203	752	608	1047	1123	1883	1861	1920	2214	2101	1551	1507	1439	1559	2655	3193	1276	992	985	3018	1077	1361	772
LZ	1711	2087	2300	0	844	2330	2354	2653	2240	1473	1216	1400	1763	1622	1018	1124	1064	1307	2224	2836	1233	1382	1506	2567	1723	1672	1618
QY	1322	1160	1915	503	1326	2007	1965	2253	2371	1092	880	1060	1441	1300	631	737	677	881	1902	2420	843	993	117	2244	1335	1285	1229
YM	2534	2105	3128	848	0	3178	3178	3466	3119	2095	1838	2022	2385	2244	1852	1950	1890	2010	2846	3364	2057	2206	2330	3189	2549	2498	2442
GZ	1140	2150	927	2330	3132	0	150	340	416	2025	1952	2007	2404	2270	1489	1475	1323	1650	2862	3436	1108	1014	827	3208	1381	1676	933
HZ	1053	2065	786	2393	3177	151	0	458	534	1942	1865	1925	2318	2177	1555	1511	1389	1567	2779	3297	1224	977	930	3121	1295	1589	846
MM	1472	2484	1225	2658	3464	342	456	0	95	2361	2284	2343	2736	2596	1821	1807	1656	1982	3197	3716	1440	1346	1162	3540	1713	2008	1265
ZJ	1550	2593	1301	2576	3119	418	532	93	0	2471	2338	2453	2846	1661	1940	1926	1744	2092	3307	3832	1559	1465	1278	3650	1814	2084	1341
BH	272	2498	1926	1487	2106	577	690	253	178	2375	2242	2357	2750	2610	1891	716	936	522	755	3730	1463	1370	1182	3554	1998	747	1303
QZ	1561	2400	1499	2046	2924	616	730	291	213	2283	2150	2265	2658	2517	1752	1738	1586	1904	3119	3637	1371	1277	1090	3462	1811	2106	1385
CZ	997	215	1796	1477	2095	2030	1943	2362	2471	0	230	105	375	231	699	591	811	398	833	1351	1056	1033	1217	1176	841	580	1132
SJZ	1071	292	1789	1217	1835	1956	1868	2288	2323	230	0	200	568	427	519	411	663	324	1029	1598	908	959	1068	1372	917	663	1102
LY	815	822	1477	1014	1841	1492	1534	1823	1941	700	534	687	1075	934	0	138	225	321	1536	2054	473	563	687	1879	748	686	790
DQ	2337	1257	3021	2745	3364	3370	3282	3702	3810	1352	1546	1379	989	1129	2039	1931	2151	1738	556	0	2395	2372	2556	175	2117	1853	2470
HEB	2315	1237	2992	2740	3344	3350	3263	3683	3752	1332	1527	1359	970	1110	2019	1911	2131	1718	490	153	2376	2353	2537	225	2098	1816	2451
JM	605	1178	1166	1229	2055	1110	1212	1442	1560	1056	923	1038	1420	1292	472	511	259	677	1892	2410	0	246	306	2235	743	973	480
WH	357	1155	925	1380	2206	1019	977	1352	1470	1039	955	1015	1408	1267	563	515	398	654	1869	2431	255	0	235	2213	537	846	231
YY	513	1340	980	1495	2330	827	930	1160	1278	1218	1073	1200	1593	1452	687	673	521	839	2054	2572	306	229	0	2397	762	1057	333
SY	2146	1083	2847	2571	3190	3294	3108	3528	3636	1178	1372	1204	815	955	1865	1757	1977	1563	389	175	2221	2198	2382	0	1943	1661	2296
NJ	286	1026	910	1747	2554	1387	1299	1719	1795	840	915	927	1150	1009	747	678	675	713	1611	2180	749	542	766	1594	0	324	463
JJ	210	1298	697	1611	2441	927	847	1267	1343	1132	1098	1158	1493	1352	789	745	623	797	1954	2472	478	230	334	2296	459	753	0
DL	1912	539	1786	2335	2933	2270	2192	2602	2678	921	1115	948	558	698	1189	1089	1272	903	458	1013	1516	1974	1672	844	917	600	1346
FS	1800	745	2495	2219	2838	2834	2756	3176	3285	827	1021	853	463	603	1513	1405	1625	1212	99	653	1870	1847	2030	485	1582	1309	1954
HLD	1500	431	2152	1906	2525	2531	2444	2856	2972	514	708	540	150	290	1200	1092	1312	899	337	855	1557	1563	1717	680	1279	996	1632
JZ	1540	476	2227	1969	2570	2576	2488	2908	3016	559	753	585	195	336	1245	1137	1357	944	290	848	1601	1584	1762	624	1323	1041	1677
LY	1748	666	2417	2160	2760	2766	2678	3098	3206	749	946	780	385	525	1435	1327	1547	1134	151	7706	1792	1769	1952	538	1513	1231	1867

(3) Variables symbols

$$x_{ij} = \begin{cases} 1 & \text{if the demand point } i \text{ is assigned to reserve site;} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if the reserve site } j \text{ is selected;} \\ 0 & \text{otherwise;} \end{cases}$$

L is the maximum distance between demand point i and its covered reserve site j.

3.2.4 Objectives

An SPR storage site location model is a decision-making tool for identifying reserve locations in a landscape to achieve two objectives: minimum response time and minimum construction cost. Based on the current construction situation and the experience of other countries, the location should be near convenient traffic connections and refineries, which can decrease the response time and save costs. The first objective is the shortest response time, which means the distance between the emergency demand point and its nearest emergency reserve point is minimized. The formula can be described by the p-center model as follows (Current et al. 1990):

$$\min\ V_1 = L \tag{1}$$

The second objective is minimum response cost, which aims to ensure that the total weighted distance between each demand node and its closest reserve site is minimized. The p-median model is applied to minimize the response cost, which can be expressed as follows (Mladenović et al. 2007):

$$\min V_2 = \sum_{i=1}^{m} \sum_{j=1}^{n} w_i d_{ij} x_{ij}. \tag{2}$$

3.2.5 Constraints

A modeling constraint is a requirement for a candidate solution based on the objective function. In the SPR site selection model, the candidate base should be subject to the following constraints. Constraint (3) indicates that the distance between the SPR site and SPR demand should be less than the maximum L; Constraint (4) ensures the existing relation until the candidate site is selected. Constraint (5) means the frequency of the SPR site will be covered. Constraint (6) limits the total number of selected SPR sites. Constraints (7) and (8) present the volume limitation for SPR demand and supply, respectively.

$$\sum_{j=1}^{n} d_{ij} x_{ij} \le L \tag{3}$$

$$x_{ij} \le y_{ij} \tag{4}$$

$$\sum_{j=1}^{n} x_{ij} = g_i \tag{5}$$

$$\sum_{j=1}^{n} y_i = P \tag{6}$$

$$y_j C_j^- \le \sum_{i=1}^{m} w_i x_{ij} \le y_j C_j^+ \tag{7}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} w_i x_{ij} \le C \tag{8}$$

$$\max_i \left(\sum_{i=1}^{m} \sum_{j=1}^{n} d_i x_{ij} \right) \le \lambda \tag{9}$$

$x_{ij} \in \{0, 1\}, y_{ij} \in \{0, 1\}.$

3.2.6 Multi-objective model for SPR site selection

Combining the objectives and constraints, a time–cost multi-objective model for SPR site selection is elaborated. Furthermore, some constraints should be clarified in considering the current construction situation. Specifically, Constraint 4 should be modified so the value is less than P, and Constraint 6 indicates the volume of SPR demand, which is equal to C.

3.2.7 Algorithms

As a discrete objective decision-making model, the algorithm of goal programming is presented to solve the multi-objective problem (Aouni and Kettani 2001). Then, the analytic hierarchy process is applied to determine the weights of each objective. Finally, Lingo software is used to obtain the results.

4 Results and discussion

4.1 Results

Based on the SPR site location model, the optimal solution for the first and second objective function is calculated by Lingo, $V_1^* = 812$ and $V_2^* = 999{,}194.1$. Under the conditions of the emergency delivery distance of 900 km, the total number of reserve sites (20 or 30), and the storage capacity (800 or 1000), Figs. 4 and 5 present the results of optimal SPR site locations selected from candidate cities under two scenarios. Considering the equal significance of fairness and efficiency, the weight value of the two objectives equals to 0.5 applied in the multi-objective programming model, which consults Zhang et al. for a reference (Zhang et al. 2008).

4.2 Discussion

4.2.1 Four-scenario discussion

Table 7 shows the selected results under four scenarios. For scenario 1, the assumption is that the upper limits of the reserve numbers and storage capacity are 20 and 1000 ($P \leq 20,\ C \leq 1000$), respectively. Nineteen cities are selected as the final reserve sites. Among them, eight coastal ports and seven cities belong to the flow nodes; inland ports and intersection make up only two. To some extent, these locations are consistent with China's SPR reality by excluding Shanshan and Lanzhou. For scenario 2 ($P \leq 20,\ C \leq 800$), the results contain eight coastal ports and eight flow node cities; the number of both inland port and transit is two. However, compared with the current locations, the model does not select Shanshan, Lanzhou, Qingdao, Jinzhou, or Huizhou. For scenario 3 ($P \leq 25,\ C \leq 1000$), 21 cities are selected. Among them, five types of cities (coastal harbors, source, nodes, inland port, and transit) are nine, seven, seven, two, and three, respectively. The selection performs without Shanshan and Lanzhou and the scale. In scenario 4 ($P \leq 25,\ C \leq 800$), 23 cities are selected, including eight coastal harbors, nine source regions, nine source nodes, two inland ports, and four transits. However, Shanshan, Lanzhou, Qingdao, Jinzhou, and Huizhou do not feature in these results.

The results of scenarios 1 and 3 are superior to those of scenarios 2 and 4. Regarding the objective value, the maximum 10 million tonnes of storage capacity performs better than the maximum 8 million tonnes capacity. Therefore, for layout scheme matching, the scenario of the number of reserve sites being less than or equal to 25 and, meanwhile, the maximum capacity of reserve sites being 10 million tonnes provides the best the result.

Furthermore, 13 cities are selected in four scenarios, including Fuzhou, Dalian, Shanghai, Tianjin, Ningbo, Daqing, Xining, Xi'an, Dushanzi, Yueyang, Nanjing, Cangzhou, and Chengdu. Accordingly, the future construction work should mainly focus on these cities. In addition, concerning storage scales, Shanghai, Dalian, Tianjin, Ningbo, Xi'an, and Nanjing play an important role in reserving responsibility.

4.2.2 Model reliability and limitations

Model reliability can be verified because six cities in scenario 3 are in accordance with reality. Therefore, the results of scenario 3 should be adopted, taking full consideration of Tianjin, Qingdao, Dalian, Daqing, and Zhanjiang as future reserve sites. Meanwhile, Chengdu, Xi'an and Yueyang are expected to take reserve responsibility in China's SPR Phase III.

In fact, the SPR storage site location model is limited by several assumptions and constraints. For example, each parameter may change (storage capacity, distance) due to

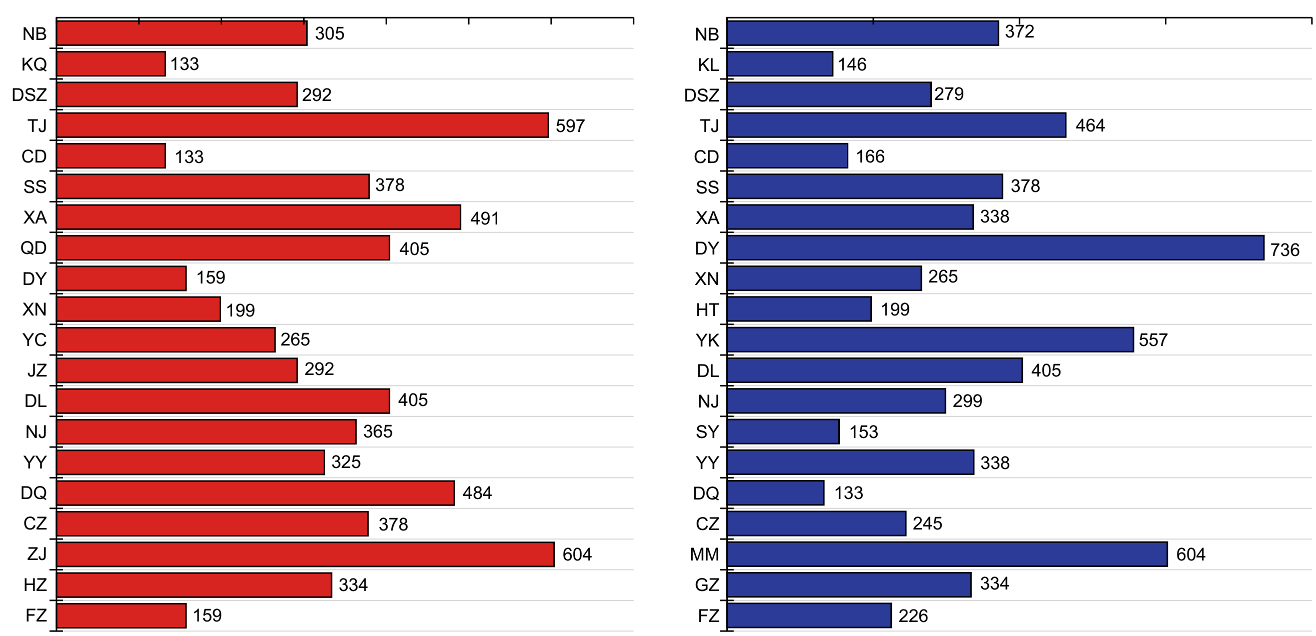

Fig. 4 Selection results in scenarios 1 and 2. *Red bar chart* represents the scenario 1 (reserve sites ≤20, storage capacity ≤1000 ten thousand tonnes). *Blue bar chart* represents the scenario 2 (reserve sites ≤20, storage capacity ≤800 ten thousand tonnes)

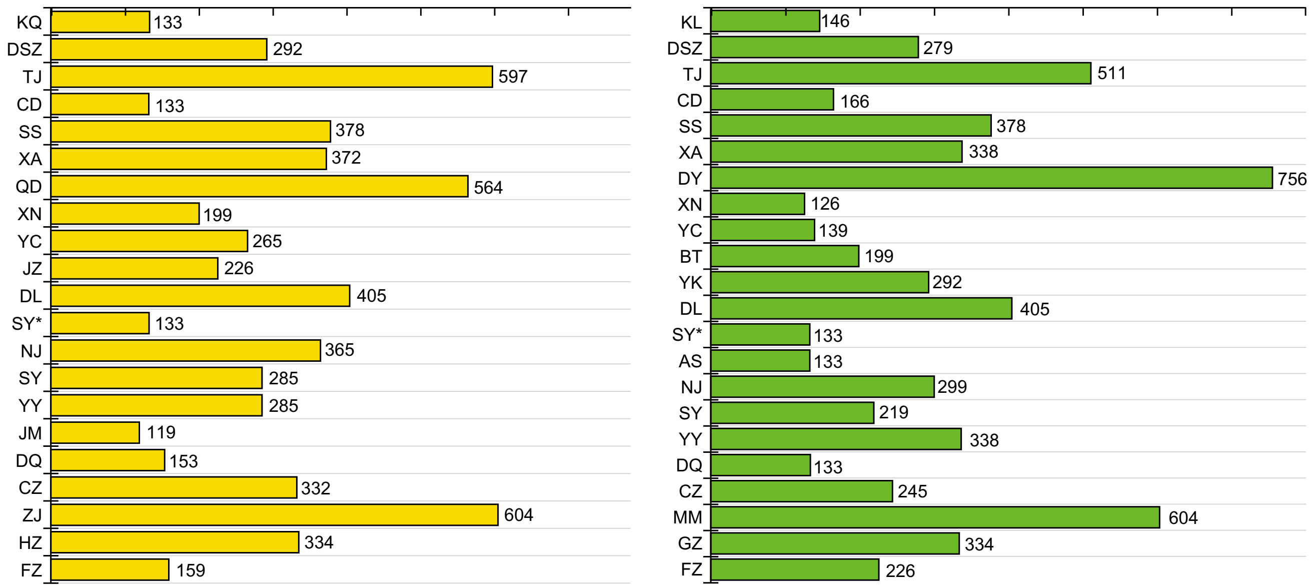

Fig. 5 Selection results in scenarios 3 and 4. *Yellow bar chart* represents the scenario 3 (reserve sites ≤25, storage capacity ≤1000 ten thousand tonnes). *Green bar chart* represents the scenario 4 (reserve sites ≤25, storage capacity ≤800 ten thousand tonnes)

Table 7 Four scenarios selected results

	Total amount ≤ 20		Total amount ≤ 25		Common
	Upper limit = 1000	Upper limit = 800	Upper limit = 1000	Upper limit = 800	
Coastal ports	FZ, HZ, DL, JZ, QD, SH, TJ, NB	FZ, GZ, MM, DL, YK, SH, TJ, NB	FZ, HZ, ZJ, DL, JZ, QD, SH, TJ, NB	FZ, GZ, MM, DL, YK, SH, TJ, NB	FZ, DL, SH, TJ, NB
Source	DQ, YC, XN, DY, XA, DSZ, KQ	DQ, SY, HH, XN, DY, XA, DSZ, KL	DQ, SY, YC, XN, XA, DSZ, KQ	DQ, SY, BT, YC, XN, DY, XA, DSZ, KL	DQ, XN, XA, DSZ
Inland ports	YY, NJ	YY, NJ	JM, YY, NJ	JM, YY, NJ	YY, NJ
Transit	CZ, CD	CZ, CD	CZ, CD, SY	CZ, AS, SY, CD	CZ, CD

economic, policy, and environmental influences, which can affect the accuracy location selection. However, considering the accessibility of domestic data, the model is only suited to a certainty situation. Generally, the emergency facility location model with uncertainty may estimate the locations more accurately. Although the SPR storage site location model takes into account the main influencing factors, the details of each reserve site, such as reserve type, reserve capacity, and future planning, are not discussed. Thus, policy makers should apply this model when more data are available to guide the SPR construction.

5 Conclusions

Determining optimal SPR storage site locations is an important and complicated problem. This study focuses on the problem of locating SPR storage sites in China. The location goals and influencing factors must be considered for resource accessibility, emergency efficiency, and a plausible spatial pattern. We have made assumptions which might overlook many features of China's SPR construction. However, our application of the reserve site selection model generates many reasonable sites for future consideration. We believe that it can provide decision makers with a useful reference for Chinese SPR Phase III construction. The main results obtained for the SPR storage site location model are as follows:

(1) The choice of SPR location is based on the minimum response time and minimum construction cost. The selection is based on the principles of justice, transparency, and efficiency. To achieve the goals, information about demand points and reserve sites and other related resources is explored for reserve site location determination.

(2) Combined with the basic facilities location models, a multiple-objective programming model for SPR storage site location that satisfies the limitations of a set of constraints, such as reserve scale, storage

capacity, and emergency periods, is introduced. Then, we design an algorithm based on Lingo to further improve the model.

(3) According to the principle of proximity and the distribution of petroleum resources, the information on 52 demand points and 55 candidate reserve sites was collected. The optimal reserve site locations for China's SPR vary under different scenarios. Specifically, the performance of 10 million tonnes of storage capacity is better than that of 8 million tonnes with the same reserve numbers; 13 cities are selected including Fuzhou, Dalian, Shanghai, Tianjin, Ningbo, Daqing, Xining, Xi'an, Dushanzi, Yueyang, Nanjing, Cangzhou, and Chengdu under each scenario. The scenario of number of reserve sites being less than or equal to 25 and, meanwhile, the maximum capacity of the reserve site being 10 million tonnes offers the best solution. Thus, policy makers should consider adopting the results of scenario 3 selecting Tianjin, Qingdao, Dalian, Daqing and Zhanjiang, Chengdu, Xi'an, and Yueyang to take the reserve responsibility in China's SPR Phase III.

(4) Although the built model has demonstrated its effectiveness for China's SPR storage site determination, the influence from other uncertain factors should not be ignored. Researchers can further demonstrate the model's feasibility by testing various uncertain factors.

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Appendix 1

See Table 8.

Table 8 Cities abbreviations

No.	Abbr.	City	No.	Abbr.	City	No.	Abbr.	City
1	AQ	Anqing	20	DQ	Daqing	39	GM	Gelmud
2	BJ	Beijing	21	JM	Jinmen	40	HTG	Huatugou
3	FZ	Fuzhou	22	WH	Wuhan	41	DY	Dongying
4	LZ	Lanzhou	23	YY	Yueyang	42	QD	Qingdao
5	YM	Yumen	24	SY	Songyuan	43	YT	Yantai
6	GZ	Guangzhou	25	NJ	Nanjing	44	XA	Xi'an
7	HZ	Huizhou	26	LYG	Lianyungang	45	SH	Shanghai
8	MM	Maoming	27	JJ	Jiujiang	46	CD	Chengdu
9	ZJ	Zhanjiang	28	AS	Anshan	47	TJ	Tianjin
10	CZ	Cangzhou	29	SY*	Shenyang	48	BKQ	Baikouquan
11	SJZ	Shijiazhuang	30	PJ	Panjin	49	DSZ	Dushanzi
12	RQ	Renqiu	31	DL	Dalian	50	KMY	Karamay
13	QHD	Qinhuangdao	32	DD	Dongdan	51	KC	Kuqa
14	TS	Tangshan	33	JZ	Jinzhou	52	KL	Korla
15	LY	Luoyang	34	YK	Yingkou	53	SS	Shanshan
16	ZZ	Zhengzhou	35	BT	Baotou	54	KM	Kunming
17	NY	Nanyang	36	HT	Hohht	55	NB	Ningbo
18	PY	Puyang	37	YC	Yinchuan			
19	TL	Tieling	38	XN	Xining			

Asterisk is used to separate the two cities. SY is short for Songyuan, SY* is short for Shenyang

Appendix 2: Lingo programming

```
sets:
a/1..52/:w;!i;
b/1..55/:y;!j;
link1(a,b):d,x;!;
endsets
data:
d=@ole('d.xls');! Shortest path matrix;
w=@ole('w.xls');! Amount of each demand
  point;
enddata
min=L
@for(a(i):@sum(link1(i,j):d(i,j)*x(i,j))<=L);
@for(a(i):@for(b(j):x(i,j)<=y(j)));
@for(a(i):@sum(b(j):x(i,j))=1);
@sum(b(j):y(j))<=25;
@for(b(j):@sum(a(i):w(i)*x(i,j))<=y(j)*1000);
@for(b(j):@sum(a(i):w(i)*x(i,j))>=y(j)*100);
@for(a(i):@sum(link1(i,j):d(i,j)*x(i,j))<=900);
@for(link1(i,j):@bin(x(i,j)));
@for(b(j):@bin(y(j)));
End
```

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