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Water environmental safety assessment and dynamic evolution in China

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ABSTRACT

Water resources are one of the important factors affecting the sustainable development of China. If we could fundamentally solve the water environmental problems, it will contribute to national security and social stability quite a lot. Based on the "driving force—pressure—state—impact—response—management" model, a water environment safety evaluation index system in China was constructed, and the water environment safety of 30 provinces and cities in China except for Hong Kong, Macao, Taiwan, and Tibet was comprehensively evaluated by the entropy right Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method, then the nuclear density function is adopted to analyze the dynamic trend of water environment safety evolution in China. The results show that: the response subsystem in the evaluation index system accounted for the largest proportion of urban water supply and drainage channel density index of the water environment safety contribution to the largest; China's water environment safety level overall is low, Shanghai is the highest, Hainan is the lowest; Chinese provinces and cities water environment safety level steadily rising trend, the middle area of the right-tailing phenomenon is serious. To improve the safety of the water environment, a series of safeguards are put forward.

Keywords: DPSIRM model; Water environment; Nuclear density function; Entropy right TOPSIS

1. Introduction

Water is the source of life, is the basis for human survival and development. With the development of economy and society and human progress, water resources have been excessive development and utilization, a large number of industrial wastewater and domestic sewage discharge wanton, on the other hand also can be seen everywhere unreasonable waste, China's cities, especially the northern cities of water scarcity phenomenon is serious, water supply and demand contradiction, the form of Water Resources security is becoming more and more severe.

In response to this phenomenon, governments have introduced policies to promote the rational use of water resources, strengthen pollution protection measures of water resources, to meet the needs of sustainable human development. China is a country with a severe drought and water shortage, with a total of 27,462 billion cubic meters of water, but with only 1968.6 cubic meters per capita, it is a country with a moderate water shortage. Haihe River, Liaohe River and other seven rivers are subject to different levels of water pollution, water resources and ecological environment is deteriorating. Therefore, China's water environment safety objective real assessment, not only conducive to the rational use of water resources development in China, and to provide data support for the development of water resources development and other related policies.

2. Literature review

At present, domestic and foreign experts and scholars on the water environment safety evaluation issues were discussed. Water environmental safety factors. Ahmadi [1], Xiong [2] study on water safety in terms of water quality.

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Rijsberman et al. [3] discuss the safety of Water Resources; Bai et al. [4] make the analysis of water ecological security in Beijing by water-water ecological factors; Li et al. [5] take Xi'an city as the example, to study the quantitative relationship between urban water consumption, water efficiency, per capita water level and urbanization; Lu et al. [6] have constructed a water environment safety index system, and evaluated the water environment safety status of 31 provinces and cities in China from 2011 to 2013; Ho et al. [7] carry out the grade evaluation and calculation of water environment safety in Tianjin 2009–2011. From the perspective of Water Pollution Prevention and Control.

From the perspective of water resource safety assessment methods. Lin and Lu [8], Feng et al. [9] and Zhang et al. [10] take the fuzzy comprehensive method to evaluate the quality of the water environment, through the construction of fuzzy comprehensive evaluation system, the weight vector, the evaluation matrix, and synthesis, and ultimately the comprehensive evaluation of the water environment; Tang et al. [11], Zou et al. [12] use entropy to study water environmental safety.

In summary, the predecessors have done a lot of work in the evaluation of water environment safety, effective guidance on water environment safety. However, the above study there are still some shortcomings: the research methods, failed to overcome the effects of subjective factors, leading to the lack of fairness of each index weights; the study, mainly in the longitudinal comparison of a region, the lack of provinces lateral comparison between cities. In fact, in different development periods, the water environment security situation is not the same, so the best state of water environment security is to be close to the best state of water environment security, away from the worst state of water environment security. Compared with the previous literature methods used, entropy Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) entropy and advantages of the method can be combined TOPSIS, TOPSIS method has good adaptability in small samples and multi-target, and the smaller the amount of information loss, it is possible for the same year evaluation between objects horizontal comparison, but also on the same evaluation target different years of longitudinal comparison. Entropy law reflects more comprehensive information, more accurate, can better reflect the role of the indicators in the water environment safety evaluation index system. Therefore, this paper draws on the basic idea of entropy TOPSIS law, from the drive, pressure, status, impact, response and management aspects of leaving a comprehensive consideration of the water environment safety level, and to build water environment safety evaluation index system, based on China 2008 ~ 2017 data, take the entropy TOPSIS law to study on 30 provinces and cities in China water environment safety.

3. Construction of evaluation index system

Evaluation index system to determine the target is the key to the establishment of evaluation index system, the index should be selected with objectivity, effectiveness, comprehensiveness, representation and other attributes. In this paper, based on the reference "driving force-pressure-state-response" model, both to consider the impact of the water environment, but also take into account the external efforts in the water environment safety, build "driving force—pressure—state—impact—response—management" (DPSIRM model) to measure the water environment safety and sustainable conditions. Specific indicators are shown in Table 1.

4. Research methods

Entropy TOPSIS method is entropy weighting method combined with TOPSIS method, entropy method can be more objective evaluation of the weight of each measure, TOPSIS [13] is "approximation to the ideal value of the sorting method", Huang and Yoon proposed in 1981, mainly for multi-objective decision analysis, the basic principle is to find the most objective and the worst goal of multiple targets, according to the evaluation unit and the understanding of the close degree like, according to the size of the sort, ranging from 0 to 1, the closer to 1, indicating that the higher the level of the target. Combined with the objective evaluation method, we can overcome the influence of subjective factors, making the results more convincing, help to understand the relative merits of technological innovation policy.

The basic steps are as follows:

- Set m evaluation indexes and n evaluation objects (plans), obtained the evaluation matrix of multiple objects on multiple indexes according to the principle of combining qualitation and quantitation: $R = (x_{ij})_{m \times n}$

$$R = \left(r_{ij}\right)_{m\times n} = \begin{bmatrix} r_{11} \; r_{12} \cdots r_{1m} \\ r_{21} \; r_{22} \cdots r_{2m} \\ \vdots \quad \vdots \quad \vdots \\ r_{m1} \; r_{m2} \cdots r_{mn} \end{bmatrix} \tag{1}$$

Standardized the evaluation matrix R, and then obtained: $R' = (r'_{ij})_{m \times n}$

- Calculation of the proportion of characteristics

With the following Eq. (2):

$$f_{ij} = a_{ij} / \sum_{i=1}^{m} a_{ij} (i = 1, 2 \cdots m; j = 1, 2 \cdots n) \tag{2}$$

f_{ij} denoted that the proportion of characteristics of the jth index of the ith evaluation unit.

- Calculation of entropy.

$$H_j = -\frac{1}{\ln m}\left(\sum_{j=1}^{m} f_{ij} \ln f_{ij}\right) \tag{3}$$

- Calculation of the entropy weight

$$\delta_j = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j} \tag{4}$$

- Determination of the positive ideal solution S^+ and the negative ideal solution S^-

Table 1
Evaluation index system of water environmental safety

Subsystem	Index	Index properties
	Per capita GDP	Positive
Driving force subsystem	Population density	Negative
	Urbanization rate	Positive
	Urban per capita domestic water consumption	Negative
	Annual comprehensive water consumption per capita	Negative
	Utilization rate of water resources	Positive
	Per-10,000-yuan-GDP water consumption	Negative
Pressure subsystem	Per capita wastewater discharge	Negative
	Per capita daily COD	Negative
	Per capita fertilizer application rate	Negative
	Pesticide use per capita	Negative
	Proportion of tertiary industry output value	Positive
	Fertilizer application per mu of cultivated land	Negative
State subsystem	Per capita water resources	Positive
	Comprehensive production capacity of water supply at the end of the year	Positive
	Water Consumption of 10,000 Yuan industrial value added	Negative
Influencing subsystem	Ammonia nitrogen emission from the industrial output value of RMB 10,000	Negative
	Gross industrial output	Negative
	Gross output value of agriculture, forestry, animal husbandry and fisheries	Negative
	Number of students in general institutions of higher learning	Positive
	Disposable income of rural residents	Positive
	Per capita financial income	Positive
Response subsystem	Ratio of effective irrigation area	Positive
	Density of urban drainage pipeline	Positive
	Urban sewage treatment rate	Positive
	Density of urban water supply pipeline	Positive
Management subsystem	Green coverage rate of built-up area	Positive
	Investment in environmental pollution control as a proportion of GDP	Positive

$$S_j^+ = \sum_{1\le i\le m} \max(\gamma_{ij}) \quad j=1,2,\cdots n \tag{5}$$

$$S^- = \sum_{i\le 1\le m} \min(\gamma_{ij}) \quad j=1,2,\cdots n \tag{6}$$

- Calculate the distance by using the Euclidean distance Eq. (6), which is:

In Eqs. (7) and (8), dis_i^+ express the most ideal solution value for the *i*th index in the *j*th year, and dis_i^- express the most non-ideal solution value for the *i*th index in the *j*th year.

$$\text{dis}_i^+ = \sqrt{\sum_{j=1}^{n}\left[\delta_j \times (S_j^+ - \gamma_{ij})^2\right]} \quad i=1,2\cdots,m \tag{7}$$

$$\text{dis}_i^- = \sqrt{\sum_{j=1}^{n}\left[\delta_j \times \left(S_j^+ - \gamma_{ij}\right)^2\right]} \quad i=1,2,\cdots,m \tag{8}$$

- Calculate the closeness between each evaluation unit and the ideal solution, and the closeness represents the level of water environment safety, based on which to judge the change of water environment safety annually. The Eq. (9):

$$c_i = \frac{\text{dis}^-}{\text{dis}^- + \text{dis}^+} \quad i=1,2,\cdots\cdots,m \tag{9}$$

Sort each evaluation according to the closeness, and use c_i to measure the proximity of each evaluation object to the optimal solution over the years. The value range is [0,1]. The larger the value, the closer the regional water environment is to the optimal. Value = 1, it is most ideal. Value = 0, it is the least ideal.

5. Empirical analysis

5.1. Determination of evaluation index weight

In the paper, relevant data from 2008 to 2017 was taken to obtain the weight of each index, as shown in Table 2.

Table 2 indicates that the average weight is 3.45% in the evaluation index system for water environment safety, and 11 indexes are exceeding the average value, which is, in descending order, density of urban water supply pipes, density of

Table 2
Weights of water environmental safety evaluation indicators

Subsystem	Index	Weight
Driving force subsystem (9.94%)	Per capita GDP	5.25%
	Population density	1.10%
	Urbanization rate	3.59%
Pressure subsystem (20.63%)	Urban per capita domestic water consumption	1.72%
	Annual comprehensive water consumption per capita	2.98%
	Utilization rate of water resources	4.17%
	Per-10,000-yuan-GDP water consumption	1.67%
	Per capita wastewater discharge	1.00%
	Per capita daily COD	1.65%
	Per capita fertilizer application rate	2.19%
	Pesticide use per capita	1.04%
	The proportion of tertiary industry output value	1.62%
	Fertilizer application per mu of cultivated land	2.59%
State subsystem (14.98%)	Per capita water resources	7.43%
	Comprehensive production capacity of water supply at the end of the year	7.54%
Influencing subsystem (5.20%)	Water consumption of 10,000 Yuan industrial value-added	0.16%
	Ammonia nitrogen emission from the industrial output value of RMB 10,000	1.41%
	Gross industrial output	1.56%
	Gross output value of agriculture, forestry, animal husbandry, and fisheries	2.08%
Response subsystem (43.51%)	Number of students in general institutions of higher learning	5.73%
	Disposable income of rural residents	5.31%
	Per capita financial income	6.90%
	Ratio of effective irrigation area	1.60%
	Density of urban drainage pipeline	11.01%
	Urban sewage treatment rate	1.18%
	Density of urban water supply pipeline	11.77%
Management subsystem (5.75%)	Green coverage rate of built-up area	1.26%
	Investment in environmental pollution control as a proportion of GDP	4.48%

urban drainage pipe, aggregate water resources, comprehensive capacity of water supply, per capita water resources, per capita fiscal revenue, number of students in ordinary higher education institutions, disposable income of rural residents, per capita gross domestic product (GDP), investment in environmental pollution control, utilization rates of water resource, and urbanization rate. They had a greater impact on water environment safety. First, the density of urban water supply pipe and drainage pipe accounted for the largest proportion, respectively 11.77% and 11.01%, which indicated that the water supply and drainage pipelines had a positive effect on water environment safety. Secondly, 7.54%, the proportion of the comprehensive capacity of water supply, reflected the sustainability of the water environment. Finally, the per capita water resources amounting to 7.43% reflected the satisfactory state of water resources at the time, which indicated that the index was able to measure the safety level of the water environment perfectly. The remaining indexes played various roles in the water environment safety, which demonstrated that the evaluation index system in this paper was sensible.

5.2. Evaluation results of water environment safety

Based on weight measurement, calculated the positive and negative ideal solutions and relative closeness of each sample, and took the average value of the evaluation scores of each province and city. The results were shown in Table 3.

Table 3 indicates that in an average of water environment safety in China from 2008 to 2017, Shanghai's is the highest, at 0.562, which is much higher than other provinces and cities, with the trend of rising, followed by Guangdong, Beijing, Tianjin, Jiangsu, and other provinces and cities. The water environment safety level of Hainan is the lowest, at 0.196, followed by Gansu, Ningxia, Jilin and Shaanxi.

5.3. Dynamic evolution of water environment safety level

Used the nuclear density function to map the nuclear density functions of 2008, 2011, 2014 and 2017, and divided China eastern, central and western regions to observe the dynamic evolution characteristics of water environment

Table 3
Results of water environmental safety assessment in 30 provinces and municipalities of China from 2008 to 2017

Provinces	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean value	Ranking
Beijing	0.328	0.336	0.350	0.365	0.379	0.425	0.429	0.441	0.461	0.465	0.398	2
Tianjin	0.275	0.300	0.315	0.341	0.359	0.375	0.392	0.404	0.419	0.419	0.360	3
Hebei	0.217	0.223	0.230	0.240	0.235	0.237	0.241	0.240	0.250	0.264	0.238	15
Shanxi	0.217	0.221	0.227	0.230	0.241	0.244	0.245	0.245	0.274	0.251	0.239	14
Neimenggu	0.224	0.222	0.229	0.243	0.251	0.263	0.263	0.264	0.265	0.260	0.248	10
Liaoning	0.226	0.231	0.241	0.249	0.270	0.263	0.264	0.264	0.261	0.267	0.254	9
Jilin	0.198	0.203	0.214	0.213	0.220	0.222	0.226	0.225	0.236	0.240	0.220	24
Heilongjiang	0.202	0.210	0.212	0.211	0.221	0.236	0.227	0.228	0.239	0.239	0.223	22
Shanghai	0.458	0.485	0.512	0.562	0.575	0.591	0.603	0.596	0.617	0.627	0.562	1
Jiangsu	0.288	0.301	0.315	0.324	0.334	0.351	0.363	0.376	0.390	0.403	0.344	4
Zhejiang	0.255	0.247	0.265	0.266	0.281	0.291	0.309	0.322	0.338	0.345	0.292	6
Anhui	0.216	0.232	0.235	0.210	0.224	0.242	0.241	0.247	0.256	0.254	0.236	16
Fujian	0.195	0.200	0.221	0.214	0.230	0.234	0.241	0.249	0.267	0.267	0.232	19
Jiangxi	0.197	0.204	0.227	0.222	0.244	0.230	0.236	0.247	0.257	0.259	0.232	18
Shandong	0.254	0.262	0.265	0.271	0.277	0.286	0.297	0.306	0.319	0.329	0.287	7
Henan	0.216	0.225	0.231	0.233	0.245	0.247	0.255	0.264	0.274	0.288	0.248	11
Hubei	0.210	0.216	0.223	0.228	0.235	0.244	0.252	0.258	0.271	0.277	0.241	12
Hunan	0.195	0.202	0.208	0.210	0.220	0.223	0.232	0.246	0.247	0.259	0.224	20
Guangdong	0.308	0.321	0.334	0.325	0.331	0.340	0.348	0.367	0.377	0.387	0.344	5
Guangxi	0.183	0.181	0.188	0.180	0.196	0.200	0.205	0.217	0.218	0.226	0.199	29
Hainan	0.182	0.183	0.185	0.185	0.185	0.200	0.198	0.194	0.221	0.223	0.196	30
Chongqing	0.213	0.218	0.230	0.239	0.236	0.238	0.245	0.249	0.259	0.266	0.239	13
Sichuan	0.211	0.210	0.215	0.217	0.229	0.234	0.246	0.253	0.261	0.272	0.235	17
Guizhou	0.205	0.198	0.203	0.205	0.218	0.221	0.231	0.228	0.227	0.236	0.217	26
Yunnan	0.212	0.210	0.213	0.212	0.221	0.220	0.218	0.222	0.228	0.234	0.219	25
Shaanxi	0.205	0.208	0.216	0.213	0.218	0.227	0.235	0.236	0.241	0.240	0.224	21
Gansu	0.186	0.190	0.193	0.194	0.208	0.220	0.213	0.214	0.223	0.227	0.207	28
Qinghai	0.259	0.293	0.270	0.271	0.295	0.264	0.284	0.258	0.271	0.290	0.276	8
Ningxia	0.196	0.230	0.190	0.202	0.207	0.218	0.223	0.228	0.236	0.233	0.216	27
Xinjiang	0.187	0.195	0.201	0.198	0.225	0.238	0.246	0.230	0.243	0.251	0.221	23

safety level and regional differences. The result is shown in Fig. 1.

Fig. 1 indicates that the peak of water environment safety level in the east of China is shifted to the right, with a right tailing, and the curve changes from steep to smooth, which indicates that the water environment safety level in eastern China rises gradually and the overall level is higher. There is a big difference in the water environment safety curve in the central region. The peak shifts to the right and the overall position of the peak turns from flat to steep, with a right tailing, which indicates that there are small discrepancies between the water environment safety levels of the provinces and cities in the central region in 2008, while the discrepancies turn to big gradually over time and the crest moves from 0.2 in 2008 to 0.25 in 2017. From 2008 to 2011, the curve crest of the water environment safety in the western region shifts downwards and then shifts to the right, which indicates that the water environment safety level in the west was flat in the early stage and improved in the middle and late stages. The curve crest of China's water environment safety gradually shifts to the right, and the shape of the curve keeps consistent basically, which indicates that the water environment safety level of provinces and cities in China are increasing steadily, and the gaps between them have few changes.

6. Conclusions and inspiration

Based on the DPSIRM model, China's water environment safety evaluation index system was developed, and then according to the actual situation of China's water resources, we selected 28 relevant indexes by taking driving force, pressure, state, influence, response and management as the subsystem, with considering economic, population, environment, life, and management comprehensively. The entropy weight TOPSIS was used to measure the water environment safety level of China, and we used the nuclear density function to present the dynamic evolution trend. The result turned out:

In the evaluation index system, the response subsystem accounted for the largest proportion, which was 43.51%, followed by the pressure subsystem, 20.63%, the state

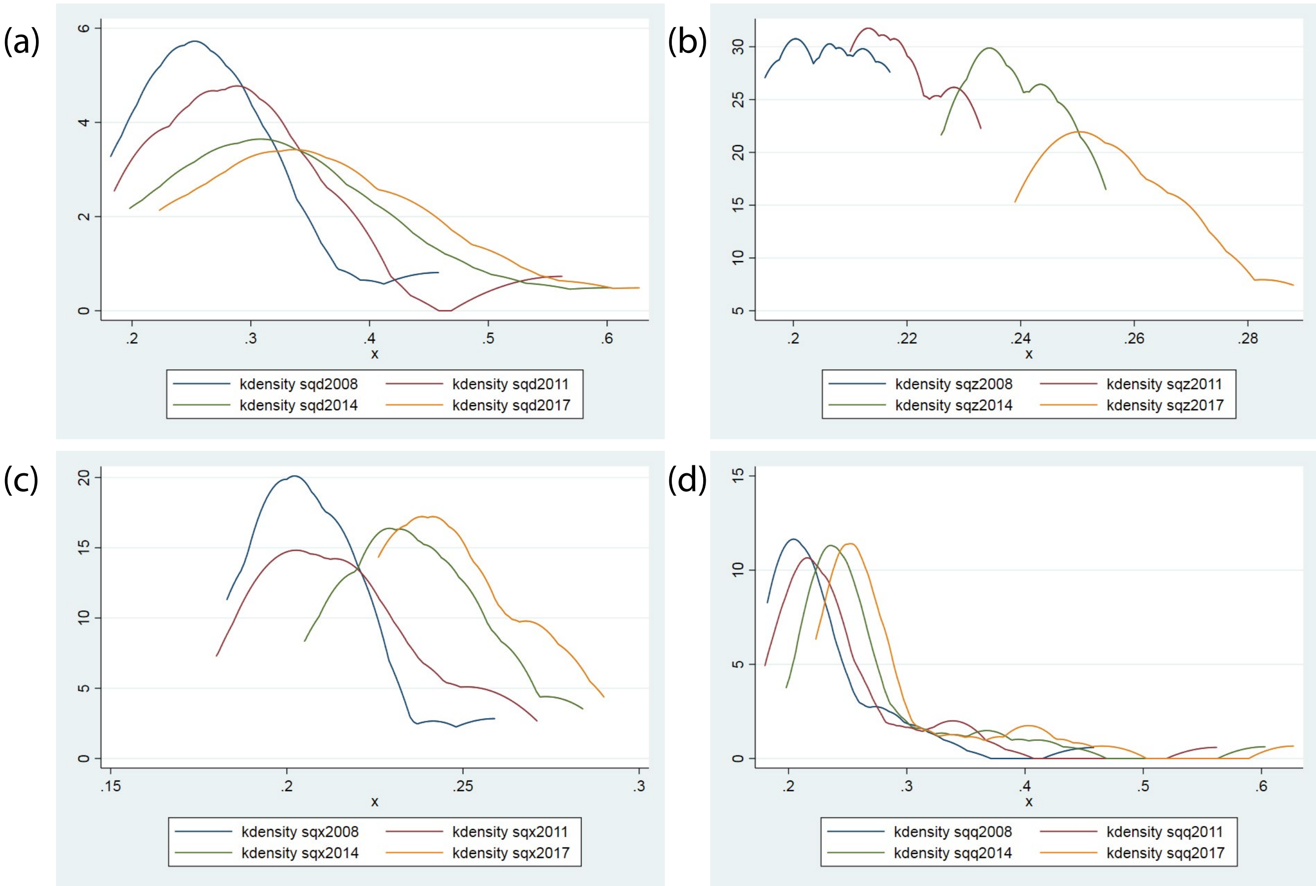

Fig. 1. Dynamic evolution chart of water environmental safety level in China, (a) Eastern region, (b) Central region, (c) Western region, and (d) China.

subsystem, 14.98%, the driving force subsystem, 9.94%, the management subsystem, 5.75%, and the impact subsystem, 5.20%;

Various evaluation indexes made different contributions to China's water environment safety system. The top five indexes were the density of urban water supply and drainage pipeline, the comprehensive production capacity of water supply, per capita water resources and per capita fiscal revenue, which could be good measurements for water environment safety.

In general, the level of China's water environment safety was low, with Shanghai, Guangdong, Beijing, Tianjin and Jiangsu ranking in the top five. The level of water environment safety of Hainan was the lowest, at 0.196, followed by Gansu, Ningxia, Jilin and Shaanxi.

In summary, levels of the water environment safety of provinces and cities in China went up steadily, and the gap between provinces and cities remained constant mostly.

According to the above results, it can be found that water environment safety in China is severe. To improve the safety of China's water environment, government departments should develop corresponding measures to prevent further deterioration of water pollution, such as strengthening the construction of urban water supply and drainage pipelines, combining water supply and drainage systems with sewage monitoring and treatment and improving the water environment with intelligent methods; controlling wastewater discharge at the source, reducing the use of effective substances including chemical fertilizers and pesticides, banning the discharge of toxic sewage and solid waste to waters and enhancing the centralized sewage disposal; alleviating the pressure on water supply in China, especially in the north, advocating water conservation in industry, agriculture and domestic water; increasing investment in environmental protection, building water conservancy projects and carrying out special treatment of sewage. It has a long way to complete water environment safety, thus we must endeavor to improve the water ecological environment and the residents living quality jointly.

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