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Development, Application and Challenges of Set Pair Analysis in Environmental Science from 1989 to 2020: A Bibliometric Review

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Abstract: Set pair analysis is a new intelligent algorithm for dealing with complex uncertain problems, and it is widely used in environmental science because of its concise structure and scalability of results. However, it is still unclear about the development stage distribution of set pair analysis in environmental science and the specific development and application in key areas. Therefore, based on the method of bibliometrics, this paper studies the development, application and challenges of set pair analysis in environmental science over the past 32 years (1989–2020). The analysis found that in terms of time dimension, the development process of set pair analysis is divided into three stages: the initial stage (1989–2011); the rapid development stage (2012–2015); the steady development stage (2016 to present). In terms of specific fields, this article focuses on the development and application of set pair analysis in the three fields of ecology, water resources, and atmospheric environmental science. It is found that set pair analysis is mainly used for environmental assessment, diagnosis and prediction. In particular, the development of partial connection numbers is a new research trend of set pair analysis, which plays an important role in environmental assessment, diagnosis and prediction. However, the current set pair analysis also has the shortcomings of strong subjectivity, an imperfect theoretical system, and unbalanced development at home and abroad. Only when these deficiencies are solved, can the development of set pair analysis in environmental science be further promoted.

Keywords: environmental assessment; environmental science; set pair analysis; bibliometrics; partial connection number; uncertain problem

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1. Introduction

As the global environment gradually deteriorates, environmental issues have gradually become hot topics. People are paying greater attention to environmental protection and their voices are getting louder. Environmental science plays a vital role in human survival and social development [1]. Environmental protection decision-making, risk assessment and pollution prediction in environmental science are particularly critical. In this context, various mathematical models for decision optimization, risk assessment, and prediction have been proposed and applied to environmental science. Scholars often used mathematical methods, such as the entropy weight method [2], the fuzzy method [3], the Hierarchical Cluster Analysis (HCA) method [4], the Principal Component Analysis (PCA) method [5], the System Dynamics (SD) approach [6], the Multi-objective assessment model [7], the projection pursuit assessment [8], the technique for order of preference by similarity to ideal solution (TOPSIS) method [9], and artificial neural networks [10] to analyze environmental science related issues. These mathematical analysis methods have their own advantages and have been used to solve many environmental problems. However, human beings have an incomplete understanding of nature and nature is uncertain. Set pair analysis is used to solve more uncertain problems [1].

Set pair analysis is a suitable mathematical method for assessing, diagnosing and predicting dynamic problems with uncertainties. Since set pair analysis was proposed by Zhao

Keqin in 1989 [11], scholars have begun to apply SPA's unique theories and methods for dealing with uncertainty problems in mathematics, physics, systems science, information science, management science, intelligence science, economics, Disaster science, agricultural science, water conservancy science, ecology, resource and environmental science, education and many other fields. At this stage, uncertainty analysis theory is enriched. Among them, set pair analysis in environmental science has many applications and involves a wide range of disciplines. Many scholars have used the set pair analysis model to deal with many environmental problems. For example, Jin Juliang used the set pair analysis model to study water resources carrying capacity evaluation [12], optimization of land consolidation plans [13], flood control operation [14], water resources system assessment [15], flood loss [16], flood classification [17], analysis of hydrological variables [18] and so on. Wang Wensheng used the set pair analysis model to study risk degree assessment of natural disasters in China [19], hazard degree assessment of landslide [20] and so on.

By the end of 2020, there were a total of 164 papers on the application of set pair analysis in environmental science on the web of science and there were a total of 191 papers on the application of set pair analysis in environmental science on CNKI (Chinese largest academic journal papers database). However, almost no one has specifically studied and summarized the development process, challenges and future prospects of set pair analysis in the direction of environmental science. This article summarizes the development and application of set pair analysis in environmental science since its inception. The detailed analysis from three main subject areas was carried out (ecology, water resource, atmospheric environmental sciences). The paper shows the annual article counts and article cumulative total counts of papers of SPA applied in ecology, water resource and atmospheric environmental sciences. The development stage, development process and practical application of SPA model in various fields are studied. Finally, the advantages and disadvantages of set pair analysis are analyzed. Problems of set pair analysis to be solved for future development are put forward.

2. Basic Concept of SPA

In 1989, Zhao first put forward the theory of Set Pair Analysis and used it to study the uncertainty problems. Set Pair Analysis is primarily used to judge and predict the change trend of the uncertainty problems [21]. Set pair refers to a pair of two collections that are related under the background of the specific problems, analyzing quantitatively on characteristics of two sets from three perspectives of "identity", "different", "contrary" [22], so as to predict the development trend of the research problem.

2.1. Connection Number

The connection number is an important concept in set pair analysis. It is expressed as follows:

$$\mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j \tag{1}$$

where N is the total number of features contained in all object sets, S is the same feature number in two object sets, P is the different feature number in two object sets, and F is the feature number that is neither the same nor different between two object sets. The relation is drawn as $N = S + P + F$. Set $a = S/N$, $b = F/N$, $c = P/N$, thus Equation (1) can be simplified into the form of the following connection number:

$$\mu = a + bi + cj \tag{2}$$

According to Equation (1), it can be known that $a + b + c = 1$, and a, b, $c \in [0,1]$, $i \in [-1, 1]$, $j = -1$. Where a is the same degree component, with coefficient 1, which belongs to the positive level; b is the difference degree component, and the coefficient range is $[-1,1]$, which is at the uncertainty level where a part is positive and part is negative; c is the component of the degree of opposition, and the coefficient is -1, completely at the negative level.

According to Equation (2), the multi-element connection number can be expressed as follows:

$$\mu = a + b_1 i_1 + b_2 i_2 + \ldots + b_n i_n + cj \tag{3}$$

where, $a + b_1 + b_2 + \ldots + b_n + c$=1, and $a, b_1, b_2 \ldots b_n, c \in [0,1]$, $i_p \in [-1 + \frac{2(p-1)}{n}, -1 + \frac{2p}{n}]$, ($p$ = 1, 2, … , n), $j = -1$, 'b_1+b_2+ … +b_n' represents the extension of 'b_i' in Equation (2). Since Set Pair Analysis is mainly used to deal with uncertain problems, there are dynamic variables b_i ($b_1 i_1, b_2 i_2, \ldots, b_n i_n$) in connection number expressions. The advantage of set pair analysis is that it can adapt to the uncertainty of the problem by adjusting the value of dynamic variables. The connection number can be used for environmental evaluation. For example, the water resources level of a city can be divided into three levels: excellent, medium, and poor. Then the ternary connection number Equation (2) can be used for evaluation. *a* corresponds to level 'excellent'. *bi* corresponds to level 'medium'. *cj* corresponds to level 'poor'. The same algorithm is used for multivariate connection number evaluation.

2.2. Partial Connection Number

Partial connection number also plays an important role in Set Pair Analysis. By calculating the partial connection number, the development trend of the uncertain problem can be obtained, and a prediction can be made. According to Equation (2), the first order partial positive connection number can be obtained as follows:

$$\partial^+ \mu = \partial^+ a + i\partial^+ b = \frac{a}{a+b} + \frac{b}{b+c} i \tag{4}$$

The first order partial negative connection number can be presented as follows:

$$\partial^- \mu = i\partial^- b + j\partial^- c = \frac{b}{a+b} i + \frac{c}{b+c} j \tag{5}$$

The first order total partial connection number:

$$\partial^\pm \mu = \partial^+ \mu + \partial^- \mu = \frac{a}{a+b} + \frac{b}{b+c} i + \frac{b}{a+b} i + \frac{c}{b+c} j \tag{6}$$

Then the second order partial positive connection number is defined as:

$$\partial^{2+} \mu = \partial^+ (\partial^+ \mu) = \frac{\partial^+ a}{\partial^+ a + \partial^+ b}, \left(\partial^+ a = \frac{a}{a+b}, \ \partial^+ b = \frac{b}{b+c} \right) \tag{7}$$

The second order partial negative connection number is expressed as:

$$\partial^{2-} \mu = \partial^- (\partial^- \mu) = \frac{\partial^- c}{\partial^- b + \partial^- c}, \left(\partial^- b = \frac{b}{a+b}, \ \partial^- c = \frac{c}{b+c} \right) \tag{8}$$

The total partial connection number of the second order is equal to the algebraic sum of the partial positive connection number of the second order and the partial negative connection number of the second order. Then the total partial connection number of the second order is:

$$\partial^{2\pm} \mu = \partial^{2+} \mu + \partial^{2-} \mu = \frac{\frac{a}{a+b}}{\frac{a}{a+b} + \frac{b}{b+c}} + \frac{\frac{b}{a+b}}{\frac{b}{a+b} + \frac{c}{b+c}} j \tag{9}$$

where $\partial^+ \mu$ reflects the positive development trend of the research objects, $\partial^- \mu$ reflects the negative development trend of the research objects, $\partial^\pm \mu$ represents the comprehensive development trend of the research objects, and i is the uncertainty coefficient. When $\partial^\pm \mu > 0$, the research objects will develop in a positive direction in the near future. When $\partial^\pm \mu < 0$, the research objects will develop in a negative direction in the near future. When $\partial^\pm \mu = 0$, the development trend of the research object is neither rising nor falling but

tends to stabilize in the near future. The concept of partial relation number can be used in environmental protection decision-making, risk assessment and pollution prediction. Similarly, The multivariate total partial connection number can also be obtained.

3. Development and Application of SPA in Environmental Sciences

During the 31 years from 1989 to the present, set pair analysis has been rapidly developed and widely applied. Several papers have been published on the research and innovation of set pair analysis. CNKI was searched for papers on the development and application of set pair analysis from 1989 to October 2020. One thousand seven hundred and ninety-nine (1799) papers were found. Figure 1 shows the proportion of the top 30 research directions from a paper on SPA in CNKI from 1989 to 2020.

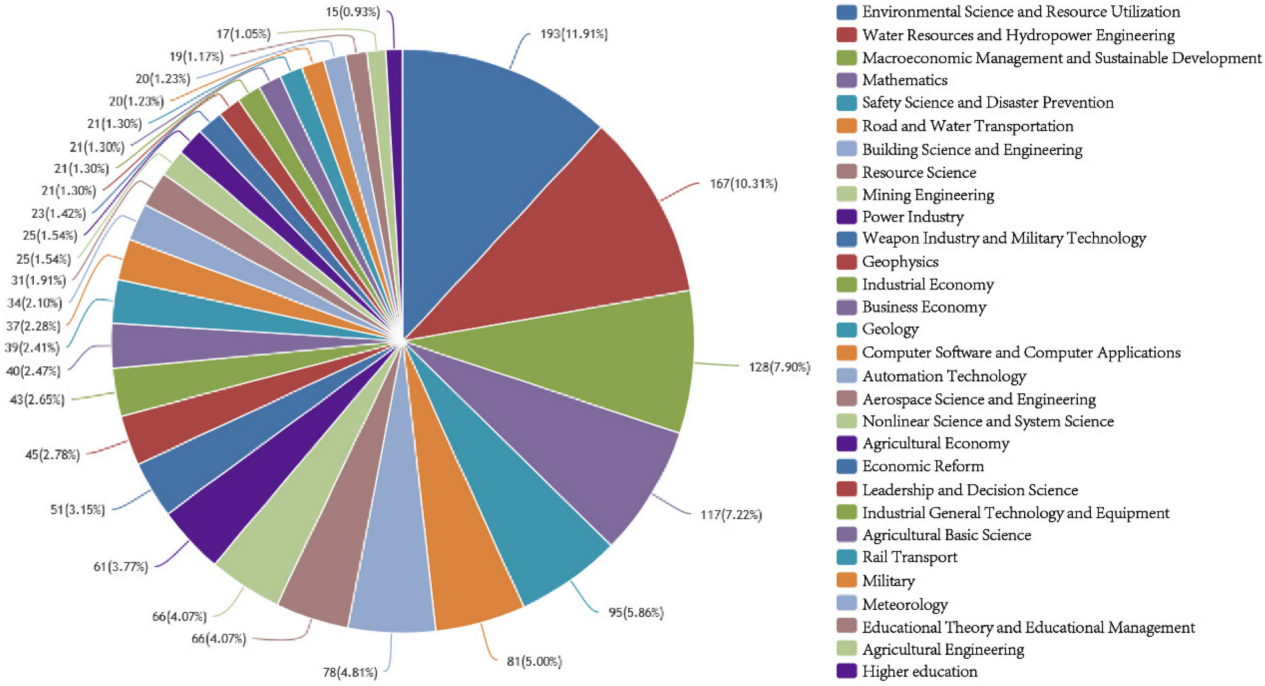


Figure 1. Proportion of top 30 research directions from a paper on SPA in CNKI (1989–2020).

Figure 1 shows papers in the field of environmental science are the largest, with 193 articles. Among all the top 30 directions in the number of papers, environmental science has the highest proportion, accounting for 11.91%.

As the Web of Science was searched for papers on the development and application of set pair analysis in environmental science from 1989 to 2020, 162 highly relevant English papers were found. All the papers on the development and application of SPA in environmental sciences mainly include three directions: ecology, water resource and atmospheric environmental sciences. VOS viewer was used to conduct a bibliometric analysis of these 162 papers. Network visualization analysis (Figure 2), overlay visualization analysis (Figure 3) and density visualization analysis (Figure 4) were generated from VOS viewer.

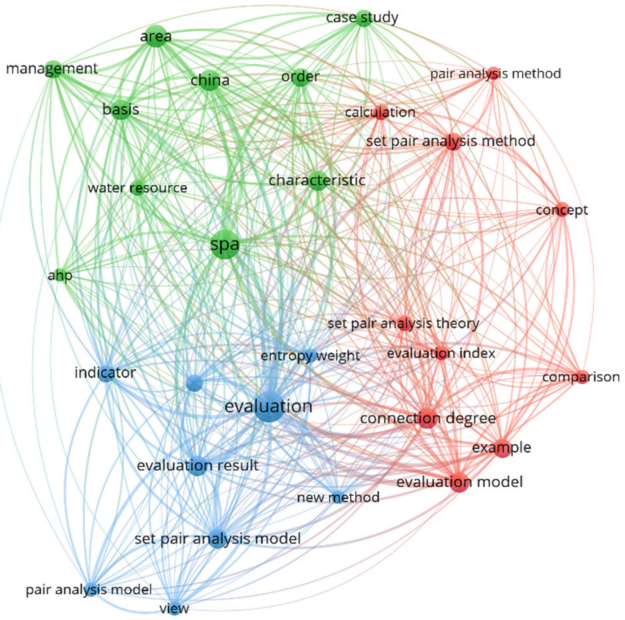


Figure 2. Network visualization analysis of English paper of SPA applied in environmental science (1989–2020).

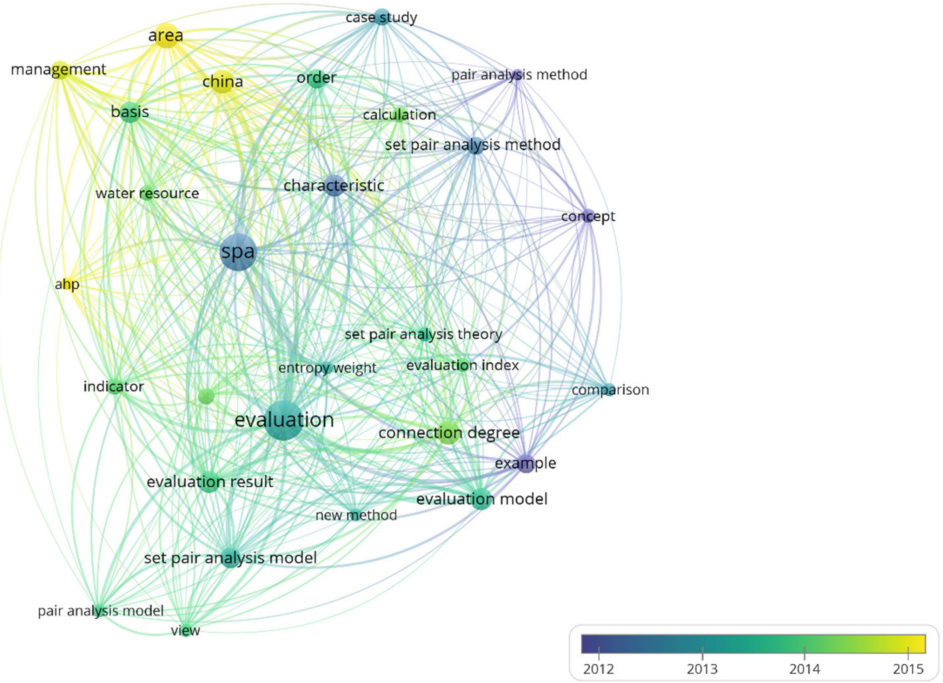


Figure 3. Overlay visualization analysis of English paper of SPA applied in environmental science (1989–2020).

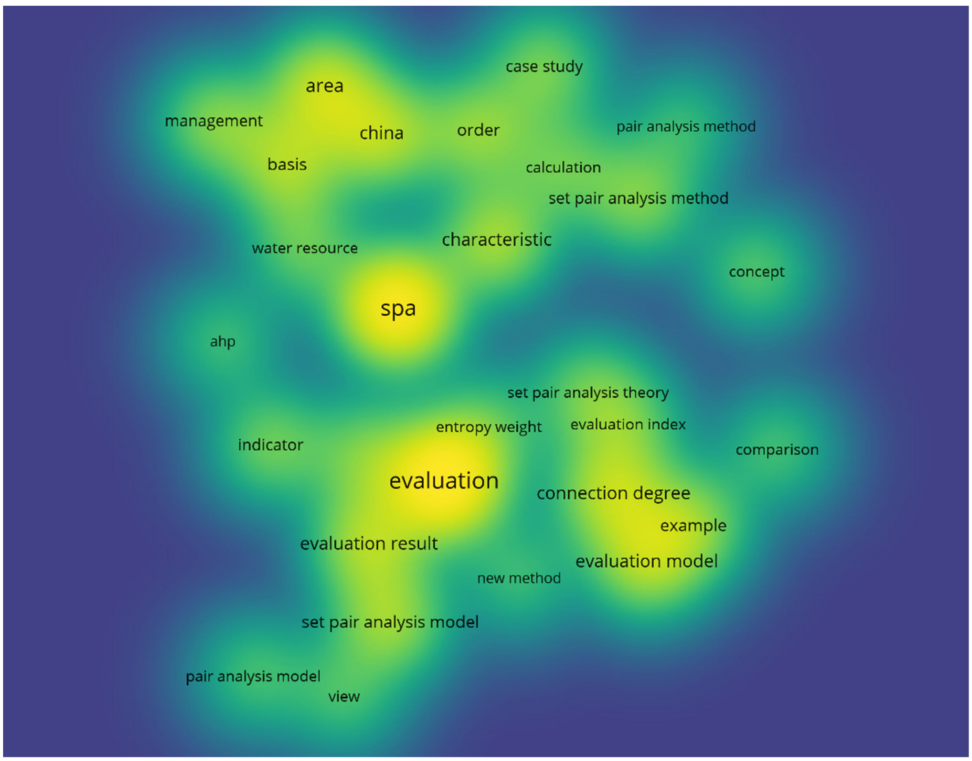


Figure 4. Density visualization analysis of English paper of SPA applied in environmental science (1989–2020).

In the network visualization analysis (Figure 2), the English papers on set pair analysis are mainly divided into three categories: method theory introduction (red part), method innovation and development (blue part) and specific research area application (green part). Each dot in Figure 2 represents the core word of the paper. The larger the dot, the more the number of papers related to the core word. Keywords of the first category (method theory introduction) are pair analysis method, calculation, set pair analysis method, concept, set pair analysis theory, evaluation index, comparison, connection degree, evaluation model and so on. Keywords of the second category (method innovation and development) are entropy weight, evaluation, indicator, evaluation result, a new method, set pair analysis model, view and so on. Keywords of the third category (specific research area application) are management, area, case study, basis, China, order, water resource, characteristic, SPA, AHP and so on. The core words that appeared most in set pair analysis papers are SPA (green), assessment (blue) and connection degree (red). This shows that the number of papers introducing the concept of connection degree and evaluating with set pair analysis is the largest. Each line in Figure 2 represents the citation relationship between papers. The thicker the line, the more citations. It can be seen that the papers on assessment with set pair analysis have the highest number of citations. Therefore, assessment is currently the most common application of set pair analysis in the direction of environmental science.

In the overlay visualization analysis (Figure 3), the larger the dot, the more the number of papers related to the core word. Each line in Figure 2 represents the citation relationship between papers. The thicker the line, the more citations. The points and lines have the same meaning as in Figure 2. However, the meaning of colors has changed. The colors show the publication date of the paper. The bluer the color, the earlier the publication time; the more yellow the color, the later the publication time. The time range of the searched paper is 1989–2020. The overlay visualization analysis can analyze the most concentrated time period for the English paper of SPA applied in environmental science from 1989 to 2020. It can be seen that the publication time of the paper is concentrated in 2012–2015. It shows that 2012–2015 is the fastest stage in the development and application of set pair analysis. Set pair analysis theory has been fully improved and spread during this period.

In the density visualization analysis, Figure 4 is composed of multiple regional color blocks of different sizes. The more journals and the closer the relationship (references and content) between journals, the redder the color. The less journals and the further the relationship (references and content) between journals, the bluer the color. From Figure 4, it is easy to see that there are more papers near area evaluation, SPA, China, basis, evaluation result, connection degree, set pair analysis model, water resource, evaluation model, characteristic, entropy weight and so on. Among them, the areas with the most papers are evaluation and SPA, and they are most closely related. Similarly, evaluation is currently the most common application of set pair analysis in the direction of environmental science.

Overall, evaluation is number one on development and application of SPA in environmental sciences. The development and application of SPA in environmental sciences developed faster during 2012–2015.

3.1. SPA Application and Development in Ecology

Set pair analysis was first applied in ecology in 1997 by Shen [23]. The author combined the actual environmental assessment and gives a method for determining the difference degree coefficient i. It provided a new solution for environmental assessment. After Shen's research, the SPA theory was gradually recognized by many Environmentalists and widely applied in environmental assessment. This is one of the important reasons why assessment is number one on the development and application of SPA in environmental sciences. Figure 5 shows annual article counts and article cumulative total counts of papers of SPA applied in ecology (1999–2020).

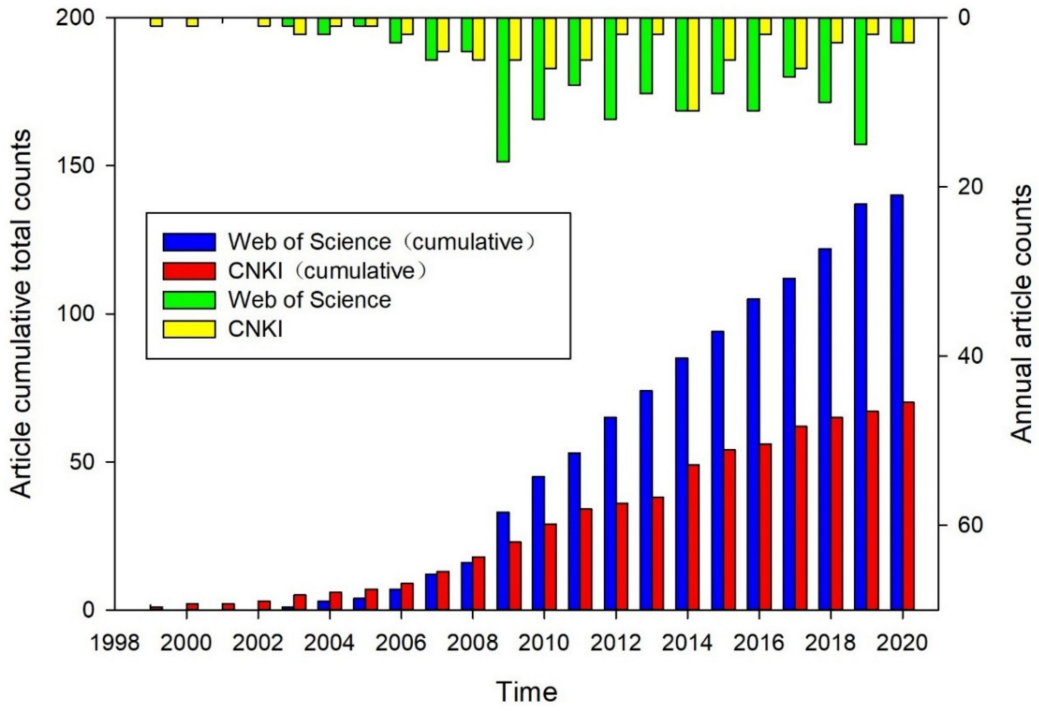


Figure 5. Papers of SPA applied in ecology (1999–2020).

It can be seen from Figure 5 that the number of papers of SPA applied in ecology in 1999–2008 is relatively small. Starting in 2009, the papers of SPA applied in ecology began to increase. The number of papers published on the Web of Science is larger than that on CNKI. About 20 papers are published every year. So far, the number of papers published on the web of science is 140, and the number of papers published on CNKI is 70.

Zhang et al. [24] constructed an SPA model of assessing air environmental quality by using sample value of monitoring compared with the value of standard grade in 2003. Using this model, describing the relationship between the two groups from all aspects

of the identity-different-contrary characteristics, the air pollution status can be accurately identified. Since then, many scholars have applied set pair analysis to air quality assessment. Deng et al. [25] built a new model for evaluating the region's eco-carrying capacity by SPA in 2006. The connection number is used to describe identity, differences and contrary between evaluated objects and criteria. The evaluated result showed relations between two sets. Compared with other analysis methods, it embodies the advantages of a more comprehensive and intuitive description of the information in set pair analysis, a clear concept, and simple calculation. Hu et al. [26] took into account the uncertainty and complexity in the process of river health system assessment and established a set pair analysis model for river health system assessment in 2008. This was the first time that set pair analysis was applied to a comprehensive assessment of complex river health systems; 1989–2008 is the embryonic period of set pair analysis in the direction of ecological environment science. During this period, the theory of set pair analysis has just been recognized by people, and its development and application in ecological environment science are extremely insufficient.

Since 2009, set pair analysis has been widely disseminated and rapidly developed in the direction of ecological environment science. The number of excellent papers on the development, improvement and application of set pair analysis increased significantly. The main way for the development and improvement of set pair analysis was to establish a coupling model by combining it with other models. Meng et al. [27] applied the theory of set pair analysis to comprehensively assess water quality and introduced the information entropy into the model in 2009.

A decade later, the Monte Carlo method was also incorporated into the whole model. At this time the set pair analysis and other mathematical methods that were used to deal with environmental science problems hence attracted the attention of many scholars. Afterward, many scholars also began to combine other mathematical methods (especially the entropy weight method) with set pair analysis to make the established model more complete and make the assessment results more reasonable and accurate. Su et al. [28] used the set pair analysis method to evaluate the urban ecosystem in 2009. The best set of the health of the urban ecosystem was calculated. A variety of health indicators were combined to describe the health of the urban ecosystem. The set pair analysis model was used to calculate the ecological health level of many cities from 1995 to 2003, such as Beijing, Shanghai, Wuhan, Xiamen and Guangzhou. In the same year, Su et al. [29] used the set pair analysis method to evaluate the urban ecosystem. This paper combines energy analysis with set pair analysis. Su et al. compared the ecological health level of typical cities in China from five aspects: structure, vigor, resilience, environmental impact and ecosystem service function maintenance. The analysis is more complete, and the number of research areas is also greater. The application of set pair analysis in the level of urban ecological health lays a solid foundation for future application of set pair analysis in the suitability of urban human settlements environment.

In the comprehensive assessment of regions, set pair analysis is also used more often. In 2010, Su et al. [30] used the set pair analysis method and vitality index to evaluate the urban ecosystem health. By introducing the set pair analysis method into the urban ecosystem health assessment, the uncertainty of the urban system is systematically evaluated. Because the set pair analysis possesses uncertainty, the optimal value of each indicator of the corresponding city can be calculated according to the current state of the urban ecosystem. The results obtained can be used to predict a relatively healthy urban ecosystem, and ultimately help promote the improvement of the health of the entire urban ecosystem. The three papers published by Su et al. in 2009–2010 had greatly promoted the application and development of set pair analysis and also provided many new ideas and opportunities.

Li et al. [31] proposed an improved set pair analysis model based on projection pursuit (RAGAPP-SPA) in 2010. The improved set pair analysis by Li et al. was necessary because most traditional assessment methods could not solve the complex nonlinear relationship

between assessment factors and water quality grades, and there were problems, such as subjective determination of weights. RAGAPP-SPA can perfectly solve these problems, thus making the assessment more objective and accurate. This is a very important breakthrough for set pair analysis applications. More and more scholars began to combine set pair analysis with other mathematical methods to solve ecological problems, such as Wu et al. [14] which established a coupled model of set pair analysis and BP neural network (BP-SPA) to calculate an optimal flood control dispatching plan in 2010. The difficulty of the research was to find the optimal solution among the feasible schemes. By introducing the set pair analysis model, the ideal solution could be found effectively. The results obtained were reasonable and reliable. The results proved that the coupled model of set pair analysis and bp neural network can also be used in the optimization process of other complex systems. This was the first time set pair analysis model was combined with the BP neural network to deal with environmental science problems.

In 2010, Yao et al. [32] used a set pair analysis model based on entropy and the analytic hierarchy process to study the carrying capacity of the geological environment in Daqing. Based on the assessment results, through the analysis of the degree of contrary and the degree of identity, specific strategies to improve the carrying capacity of the geological environment were proposed. This is the first time that the set pair analysis model has been applied to the field of geological environment in ecology. In this regard, the application scope of the set pair analysis method was expanded.

Wang et al. [13] established a set pair analysis model for land consolidation plans based on entropy in 2010. The optimal method of traditional land consolidation plans had a serious flaw: experts often establish land consolidation plans based on their past experience or personal preferences. The results showed that the use of a set pair analysis model could largely avoid the defect of much subjectivity in assessment. The improved model greatly improved the reliability and objectivity of the assessment results. For complex and uncertain environmental problems, set pair analysis is a very effective and simple mathematics method. Li et al. [33] established a new assessment model of river ecological health assessment based on set pair analysis and variable fuzzy sets in 2011. Considering many factors, such as water volume, water quality, biological conditions, water connectivity, and flood control standards, a river ecological health assessment index system and assessment grade standard was constructed. Compared with other methods, the result of the set pair analysis model was more reasonable, the calculation was more intuitive and simpler, and the advantages were obvious.

From 2012–2015 marked a rapid development period for the development of set pair analysis theory. Scholars used improved or coupled set pair analysis models with other models for regional ecological assessment [34–37], disaster risk assessment [38–41], water quality assessment [42–48], comprehensive safety assessment [49], and land assessment [50]. Wang et al. [51] conducted a comprehensive evaluation of water quality by improving the set pair analysis in 2012. Scholars used the scalability of connection degree to improve it and solved the problem of subtle differences of the 'identity, different, and contrary' in the set pair analysis. The entropy coefficient method, weighting method of over-standard multiples and fuzzy evaluation were all introduced into the evaluation system based on set pair analysis. This article also compared the evaluation results of several methods that were widely used at that time, including the gray clustering method, comprehensive index method, fuzzy neural network method and projection pursuit method, with the evaluation results of the set pair analysis method. The results showed that the improved set pair analysis assessment results were more accurate than other methods. This shows that set pair analysis is a scientific, credible, and forward-looking mathematical model with good development prospects. With the continuous improvement of the set pair analysis model, the results obtained will get closer to the real situation. Zou et al. [52] combined set pair analysis-variable fuzzy set model and fuzzy analytic hierarchy process to comprehensively evaluate flood risk in 2013. This paper proposed a new model for comprehensive flood risk assessment. This new model was based on set pair analysis

(SPA) and variable fuzzy set (VFS) theory, called set pair analysis-variable fuzzy set model (SPA-VFS). The fuzzy analytic hierarchy process was used to determine the weight of flood risk and vulnerability respectively. Then the flood disaster level and flood vulnerability level could be calculated. The results obtained could be used for flood risk management and decision-making. This model is very reliable and reasonable. SPA-VFS has a very high use value. Its biggest advantage is that it can be applied to other disaster risk assessments without much modification. This meant a breakthrough in the application of set pair analysis theory in disaster risk assessment. This article had also attracted the attention of many scholars.

From 2016 to 2020, the development and application of set pair analysis ended the first rapid development period and began a stable development period. Wei et al. [53] established an integrated carrying capacity prediction analysis model based on set pair analysis in 2016. The carrying capacity of a city includes the carrying capacity of urban resources, the carrying capacity of the urban environment, the carrying capacity of the urban ecosystem, and the carrying capacity of urban infrastructure. They constitute the main part of the comprehensive carrying capacity of the city and play a decisive role. It is only when the carrying capacity is greater than the load that the social economy can develop sustainably. Therefore, the reasonable prediction of the comprehensive carrying capacity is particularly important. A dynamic forecasting model is established using the set pair analysis model to predict the growth trend of integrated carrying capacity. The correctness of the model is verified through examples. The average error rate of the prediction model is only 0.38%, and the minimum error rate is 0.01%. This was the first time that scholars conducted a prediction analysis model based on set pair analysis theory since the establishment of set pair analysis. At this time, the evaluation and prediction model based on set pair analysis was initially formed. Li et al. [54] established a k-means clustering and set pair analysis coupling model to evaluate the water pollution risk in Shiyan, China. This was another new coupling model. Yan et al. [55] established a cloud model-set pair analysis (CM-SPA) coupling model and applied it to the risk assessment of biomass gasification stations. In this paper, the cloud weight was proposed as the index weight. Compared with the index weights of other methods, the randomness and ambiguity of cloud weights could effectively reflect the linguistic variables of experts. Then, Cloud Connectivity (CCD) is proposed instead of Connection Degree (CD), and the calculation method of Cloud Connectivity is given. CCD was used to analyze cloud descriptors and finally, the disaster level was determined. Scholars also carried out CM-SPA and AHP-SPA risk assessments on biomass gasification stations. The comparison of the evaluation results shows that the CM-SPA method is suitable and effective for the risk evaluation of biomass gasification stations, which can make the evaluation results more reasonable and scientific. This was the first time that set pair analysis was combined with cloud models, and the combined effect was good. Cui et al. [12] applied set pair analysis theory to evaluate and diagnose water resources carrying capacity in 2018. The innovation of this paper was mainly to apply the set pair analysis theory to the diagnosis of ecology problems. Until then, the evaluation, diagnosis, and prediction system of the set pair analysis model had been initially formed. The development of set pair analysis in the direction of ecological environment science had gradually entered a mature stage. Luan et al. [56] combined the extended Fourier amplitude sensitivity test and set pair analysis to evaluate sustainable development from the perspective of uncertainty analysis in 2018. Because the indicators in the sustainable development indicator system were uncertain. This was just the unique advantage of the set pair analysis model. Liu et al. [57] established an improved variable fuzzy set pair analysis (IVFSPA) as a new method of surface water quality evaluation in 2019. Because traditional evaluation methods were less accurate and reasonable. In order to avoid the shortcomings of traditional methods, Liu et al. established the IVFSPA model in two steps. In the first step, a new game theory comprehensive weighting method was proposed, which used the objective entropy method and subjective analytic hierarchy process to obtain reasonable weighting. The second step was to improve

the arithmetic form of "P-i" on the basis of the Nemerow index method to replace the fuzzy comprehensive evaluation method. After comparison, it was found that the IVFSPA model has better performance. By 2020, the application of set pair analysis in the direction of environmental science ecology is the most extensive and the number of documents is the largest. The evaluation-diagnosis-prediction system of the set pair analysis model has been initially formed. It can be said that the theory of SPA has initially developed to a mature stage. However, there are still many problems worthy of improvement, and it needs a long time to develop.

In summary, the number of papers on the application of set pair analysis in ecology was about 20 per year. The set pair analysis method formed a preliminary evaluation and prediction system in ecology. Moreover, set pair analysis was coupled with bp neural network, RAGAPP and other methods. It showed that by 2020, the application of set pair analysis in ecology had been relatively mature. Set pair analysis also had more applications in water resources. It was also a suitable method in dealing with water resources.

3.2. SPA Application and Development in Water Resource

The development of set pair analysis in the research direction of water resources was less extensive than in the direction of environmental science and ecology, and it started relatively late. Figure 6 shows annual article counts and article cumulative total counts of papers of SPA applied in water resources (1999–2020).

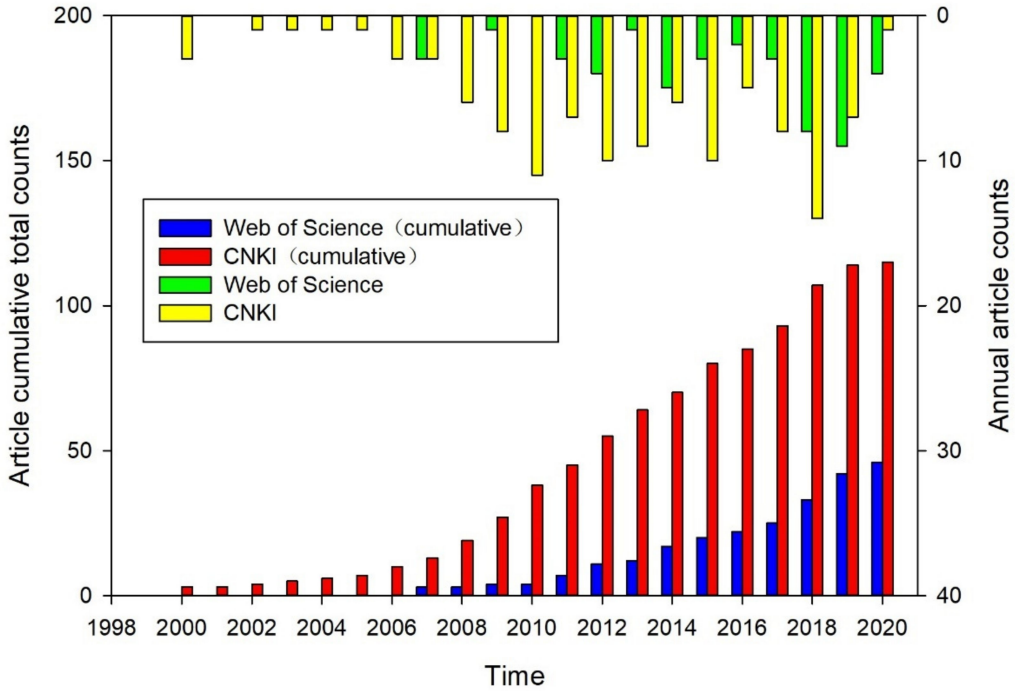


Figure 6. Papers of SPA applied in water resource (1999–2020).

It can be seen from Figure 6 that the number of papers of SPA applied in water resources in 1999–2007 is relatively small. Starting in 2008, papers of SPA applied in water resources began to increase. Unlike papers of SPA applied in ecology, the number of papers published on CNKI is much larger than that on the Web of Science. About 10–15 papers are published every year. So far, the number of papers published on the web of science is 46, and the number of papers published on CNKI is 115.

Tao et al. [58] used set pair analysis to evaluate the sustainable development of irrigation areas in 2007. Tao et al. established an index model of coordinated development between the project status, economic benefits and ecological environment of the irrigation area by using the "identity', "different", "contrary" situation sorting method based on the connection degree of set pair analysis. The most obvious advantage is a simple calculation,

reasonable results, and strong comparability. This is the first set pair analysis paper in the direction of water resources on the Web of Science. It can be clearly seen that the theory of set pair analysis has developed late in the direction of water resources. Wang et al. [59] established a water resources safety evaluation model based on entropy weight method and fuzzy set pair analysis method to evaluate and manage water resources safety in 2011. The method of constructing the model is basically the same as that of the fuzzy set pair analysis method mentioned above. The advantage of the model is that it is objective and reasonable, the method is simple, and the computer programming is easy to implement. Li et al. [60] combined entropy weight and set pair analysis to evaluate groundwater quality in Dongsheng City, China in 2011. The disadvantage of the traditional comprehensive water quality evaluation method is that the formula is complicated, so it is difficult to apply to water quality evaluation. The application of set pair analysis can make the entire calculation process simple. Moreover, the result is accurate and reasonable. Wang et al. [20] used set pair analysis to evaluate the risk of landslides in 2012. There are some problems with the traditional evaluation method of landslide risk: the method is complicated and the requirements for users are high; the method is difficult to use in practice. The set pair analysis method can effectively solve the problems of these traditional methods, and the results are reasonable. Jin et al. [61] established a coupling model of BP neural network and set pair analysis as an early warning model (BPSPA-FM) for sustainable use of water resources in 2012. In this model, accelerated genetic algorithm fuzzy analytic hierarchy process, bp neural network and set pair analysis were respectively used to determine the weight of the evaluation index, predict and update the value of the evaluation index of the model, and determine the sample of the fuzzy set of the relative member variable function value. The results show that the accuracy of BPSPA-FM is high. Moreover, BPSPA-FM is universal and can be used for early warning of different natural disaster systems. As mentioned above, in 2013, Zou et al. [52] used the set pair analysis model to make a comprehensive flood risk assessment. This paper has also received high attention in the field of water resources: it has been cited 163 times so far. Chou et al. [62] established a prediction model (SPA-SF) based on the set-pair analysis of the "identity", "different", "contrary" concepts and combined with wavelet denoising to predict annual runoff in 2014. Yue et al. [63] integrated life cycle analysis, set pair analysis and fuzzy set theory to comprehensively evaluate the impact of industrial wastewater under uncertain conditions in 2014. Like Wang and Yue et al., in the direction of water resources, many scholars combine set pair analysis theory and fuzzy set theory to evaluate or predict [64,65]. Guo et al. [66] combined game theory and set pair analysis for post-evaluation of the construction effect of rural drinking water safety projects. The concepts of "identity potential", "different potential", "contrary potential" in set pair analysis are introduced to explain the internal reasons for the transformation potential. Compared with the catastrophe evaluation method, the research results of the game theory-set pair analysis model were more reliable, and the information reflected was more comprehensive and reasonable. Like Wei et al. [53] and Li et al. [54] above, they also studied water resources issues through improved set pair analysis in 2016.

In 2018, the number of research papers on set pair analysis in the direction of water resources suddenly increased. The applications of set pair analysis to water resources were understood by more scholars. The development of SPA in water resources gradually began to become widespread. Li et al. [67] used set pair analysis to evaluate the risk of water inrush from coal seam floor in 2018. Men et al. [68] combined the s-type function and set pair analysis theory to evaluate the sustainable use of water resources in the Beijing-Tianjin-Hebei region and predict its development trend in 2018. The Spearman correlation coefficient method is used to compare with other traditional evaluation methods. The result proves that the set pair analysis method of the s-type function obtains a higher Spearman correlation coefficient than the traditional method. Tian et al. [69] established an improved set pair analysis model with game theory weightage in 2019. It was applied together with pollutant health risk assessment for groundwater quality assessment. Su et al. [70] established a set pair analysis-markov chain model to assess and predict groundwater

quality in 2019. The weighted average connection number in SPA was applied to calculating assessment and prediction. The model can effectively deal with the uncertainty in groundwater quality evaluation. It is a unique advantage of SPA. Wu et al. [71] applied improved set pair analysis to environmental impact evaluation of dam break in 2019. Although set pair analysis is good at dealing with uncertain problems, its results are relatively rough. Improved set pair analysis included a generalized set of potential and a connection degree of five grades. The results proved that the improved SPA model is scientific and practical. Yin et al. [72] used set pair analysis to build an ensemble surrogate model in 2020. In order to prevent prediction uncertainty caused by a single model, Bayesian and machine learning theories were introduced. The result was stable and reliable, and the amount of calculation was greatly reduced. This improvement greatly improves the applicability of set pair analysis in aquifer management of groundwater simulation models.

In summary, although the number of papers about set pair analysis in water resources was not as large as in ecology. There were about 10–15 papers published each year. Since set pair analysis was proposed in 1989, its most mature application in the direction of water resources is the set pair analysis system based on the analytic hierarchy process and entropy method. This system has been used by many scholars for evaluation and prediction. The result is reasonable, the process is simple, and it is worth promoting. According to the development trend in the past 31 years, the recent development of set pair analysis in the direction of water resources may be a peak period. There may be a significant increase in the number of related papers in the next ten years. At present, however, the development of set pair analysis in the direction of water resources at home and abroad is extremely uneven. The spread and development of set pair analysis in China is relatively fast, but its development in other regions is quite insufficient. More than 90% of relevant papers (both Chinese and English) are written by Chinese scholars. Most foreign environmentalists may not know that there is a set pair analysis method in the direction of water resources. This is the biggest obstacle to the development of set pair analysis in the direction of water resources. In fact, it is also an obstacle to the development of set pair analysis in the direction of environmental science as a whole. In addition to ecology and water resources, the set pair analysis method was also used by many scholars to solve the problems of atmospheric environmental science.

3.3. SPA Application and Development in Atmospheric Environmental Sciences

There are relatively few studies on set pair analysis in the direction of the atmospheric environmental sciences. Figure 7 shows annual article counts and article cumulative total counts of papers of SPA applied in atmospheric environmental sciences (1999–2020).

It can be seen from Figure 7 that relevant papers have been published almost every year since 2001. However, the annual article number is small and relatively average. There was no peak period. Before 2013, the number of papers published on CNKI is larger than that on the Web of Science. After 2013, the number of papers published on the Web of Science is larger than that on CNKI. About 0–5 papers are published every year. So far, the number of papers published on the web of science is 24, and the number of papers published on CNKI is 18.

Li et al. [73] published the first paper on set pair analysis in the direction of atmosphere in 2001. Li et al. used the fuzzy set pair analysis method to establish a mathematical model for the optimization of atmospheric environment monitoring points. Xue et al. [74] published the first paper on set pair analysis in the direction of meteorology in 2003. Because the meteorology forecast is a typical problem with uncertain factors. The biggest feature of set pair analysis is that it can handle uncertain problems. So the set pair analysis model is very suitable for meteorology forecasting. A large number of experiments proved that the model has good results [75,76]. The application of early stage set pair analysis in the atmospheric environmental sciences direction was relatively simple. Scholars just used the concept of connection number to make a simple atmospheric evaluation or temperature prediction. Therefore, the previous research on set pair analysis was not very in-depth. The

set pair analysis developed slowly in the direction of atmospheric environmental sciences in 1989–2010.

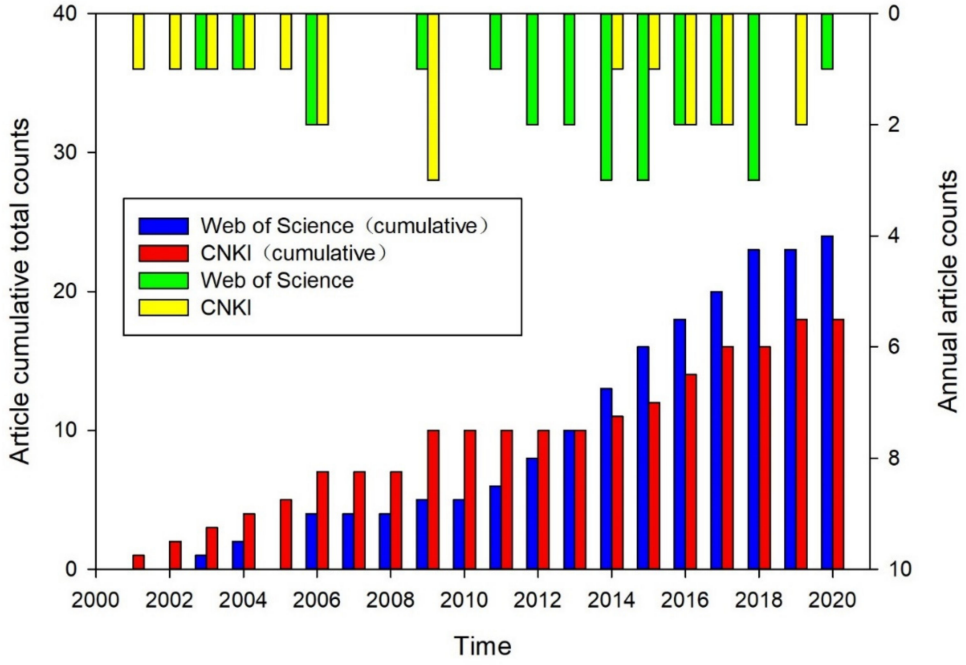


Figure 7. Papers of SPA applied in atmospheric environmental sciences (2000–2020).

Zhang et al. [77] in 2013 introduced a phase space reconstruction model to set pair analysis (SPA-PSR) to predict extreme temperature. In SPA-PSR, the phase space with delay time and embedding dimension were reconstructed by using chaos analysis. The results of the Mount Wutai sample showed that the average relative error of SPA-PSR was reduced by 65.97%, 59.32%, and 7.79%, compared with the autoregression (AR) model, rank set pair analysis (R-SPA) model and 3backpropagation (BP) neural network model. The application of set pair analysis significantly improved the prediction accuracy. Wang et al. [78] established a novel set pair analysis method based on variable weights for liquefaction evaluation in 2014. In the new model, the evaluation sample and the classification criteria constituted connection degree. The state variable vector was used to assign the composite weight of the evaluation index. Finally, the comprehensive correlation degree of each level was calculated for evaluation. With this model assessment, both qualitative and quantitative analysis can be carried out.

The new model of set pair analysis, rank-set pair analysis, has been applied several times in recent years. Rank-set pair analysis (RSPA) is a more reliable and efficient version of set pair analysis. It enriched and improved the theory of set pair analysis once again. Zhang et al. [79] combined rank set pair analysis and wavelet analysis to predict temperature series in 2015. This was the first time in recent years that set pair analysis theory itself had improved. The advantage of refined rank set air analysis is the non-parametric data-driven prediction. The results proved that the model could predict extreme temperatures. However, this method has not fully developed yet, there were still many aspects to continue testing and improvement. In order to accurately and quickly forecast the hydrometeorological time series, Wang et al. [80] applied a hybrid wavelet de-noising and rank-set pair analysis (WD-RSPA) approach to forecasting hydro-meteorological time series in 2018. The paper compared WD-RSPA with three other generic methods: the conventional Auto Regressive Integrated Moving Average (ARIMA) method, Artificial Neural Networks (ANNs) (BP-error Back Propagation, MLP-Multilayer Perceptron and RBF-Radial Basis Function) and RSPA alone. The result proved that the error metric of the prediction result of the WD-RSPA model was always small. WD-RSPA was accurate, feasible and effective. In particular, even if extreme events were included in the time series, WD-RSPA was the

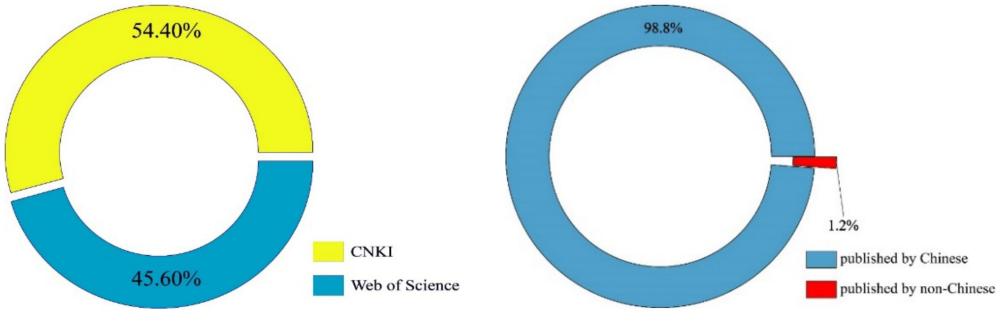
best. This research fully demonstrated the unique advantages of the set pair analysis model. The future of set pair analysis could be expected.

Compared with ecology and water resources, the application of set pair analysis in atmospheric environmental science started relatively late (2001). The number of papers published each year was also relatively small (about 5 papers per year). The evaluation and prediction system of set pair analysis was not mature either. It showed that the application of set pair analysis method in atmospheric environmental science still needed a long time to develop.

4. Challenges of SPA in Environmental Sciences

Set pair analysis has been developed for 32 years from 1989 to 2020. SPA has simple operations, easy-to-understand concepts and reasonable and accurate results. Therefore, set pair analysis has been widely developed and applied in the direction of environmental science. Because set pair analysis deals especially with the problem of uncertainty. Environmental issues are typical uncertain issues. Environmental science has become the field with the highest proportion (11.91%) of all set pair analysis papers on CNKI. Since its development, set pair analysis has been applied in all directions of environmental science. Moreover, SPA also formed a relatively complete environment evaluation, diagnosis and prediction system based on set pair analysis. Through the application of set pair analysis, many environmental problems have also been solved.

However, the current set pair analysis theory and system development are not complete. This will seriously hinder the future development of set pair analysis in the direction of environmental science. At present, set pair analysis has several obvious problems in the direction of environmental science. First, the theoretical system of set pair analysis is highly subjective and random. There is no standard evaluation, diagnosis, and prediction system for set pair analysis. Current evaluation, diagnosis, and prediction models all require the subjective construction of users. The accuracy and applicability of the model will depend on personal factors, such as the user's mastery of set pair analysis and accumulated experience. For example, the value of the uncertainty coefficient i, the key parameter used to deal with uncertain problems in set pair analysis, is highly subjective and random. Users often choose values subjectively in the range of [–1,1] based on their own experience and purpose. Different values of the coefficient i may have a certain influence on the result. Therefore, unifying the calculation standard of set pair analysis and reducing subjectivity is one of the urgent problems to be solved. Secondly, the theoretical basis of set pair analysis is still relatively weak at this stage. Many concepts, such as partial connection number and the situation, do not have a reasonable reasoning process. After these concepts were put forward, they were also questioned by some scholars. Although the rationality of the set pair analysis theory has been confirmed in many papers. The lack of a powerful derivation process still restricts more scholars from learning about it, and it also severely hinders its promotion, development and application. In short, the most urgent task is to come up with a complete and powerful reasoning process. Thereby enriching the theoretical basis of set pair analysis. Only when the credibility of the theoretical foundation is high, can set pair analysis gain more dissemination and development. Thirdly, the spread of set pair analysis theory in environmental science is seriously insufficient abroad. Figure 8a shows that the proportion of papers of SPA applied in environmental sciences on CNKI and Web of Science (1989–2020). Figure 8b shows that the proportion of papers of SPA applied in environmental sciences published by Chinese and non-Chinese on Web of Science.



(**a**) (**b**)

Figure 8. Proportion of papers of SPA applied in environmental sciences on CNKI and Web of Science in 1989–2020 (**a**), published by Chinese and non-Chinese on Web of Science in 1989–2020 (**b**).

From 1989 to September 2020, there were 193 Chinese papers and 162 English papers highly related to set pair analysis in environmental science (Figure 8a). However, among the 162 English papers, 98.77% of the papers were published by Chinese authors. Among all 355 papers, 99.44% of the papers were published by Chinese authors (Figure 8b). It can be seen that the set pair analysis theory is currently only widely spread in China. At present, few non-Chinese people understand set pair analysis, which seriously hinders the global development of set pair analysis. The small scope of development leads to fewer scholars in contact, which in turn leads to the slow development and supplement of set pair analysis theory. Eventually, the vicious circle will happen. The Chinese professor Zhao published a Chinese paper and proposed set pair analysis theory and related concepts in 1989 are the main reason for the slow development of SPA abroad. Scholars at home and abroad need to communicate more frequently about the theoretical knowledge of set pair analysis. Let more foreign scholars understand set pair analysis. Fourth, the development of set pair analysis in environmental science and its imbalance. From the perspective of an application function, the development of set pair analysis in environmental assessment is relatively fast, and the development in environmental diagnosis and prediction is relatively lagging. From the perspective of disciplines, the development of set pair analysis in the direction of water resources is relatively rapid, the development in the direction of the atmosphere is intermediate, and the development in the direction of solid waste is seriously lagging behind. The unbalanced development has seriously affected the further development of set pair analysis. Therefore, it is very important to strengthen the application of set pair analysis in various directions, especially in the direction of solid waste or environmental diagnosis and prediction.

To sum up, the main challenges of SPA in environmental science are the highly subjectivity and randomness, weak theoretical foundation, serious shortage of theoretical dissemination abroad and uneven development in environmental science.

5. Conclusions

After nearly 32 years of development, the research field of set pair analysis in the direction of environmental science has become more and more extensive, especially in the fields of ecology, water resources and atmospheric environmental sciences. Because of its simple calculation, the ability to deal with uncertain problems, and the reasonable results, set pair analysis is also used by more scholars to deal with environmental science problems. This paper uses the method of bibliometrics to analyze the development and application of set pair analysis in environmental science. The papers in the field of environmental science are the largest, with 193 articles. Among all the top 30 directions in the number of papers, environmental science has the highest proportion, accounting for 11.91%. The study found environmental assessment is currently the most common application of set pair analysis in environmental science. In the past 32 years, 2012–2015 is the fastest stage of development

and application of set pair analysis. In recent years, more and more scholars use ensemble analysis models for environmental prediction and diagnosis.

In the fields of ecology, the number of papers of SPA in 1999–2008 is relatively small. Starting in 2009, the papers of SPA applied in ecology began to increase. About 20 papers are published every year. By 2020, the application of set pair analysis in the direction of environmental science ecology is more extensive and the number of documents is larger than water resources and atmospheric environmental sciences. The evaluation-diagnosis-prediction system of the set pair analysis model has been initially formed.

In the fields of water resources, the number of papers of SPA in 1999–2007 is relatively small. Starting in 2008, papers of SPA applied in water resources began to increase. About 10–15 papers are published every year. According to the development trend in the past 31 years, the recent development of set pair analysis in the direction of water resources may be a peak period. There may be a significant increase in the number of related papers in the next ten years. At present, however, the development of set pair analysis in the direction of water resources at home and abroad is extremely uneven. The spread and development of set pair analysis in China is relatively fast, but its development in other regions is quite insufficient. It is an obstacle to the development of set pair analysis in the direction of environmental science as a whole.

In the fields of atmospheric environmental sciences, papers of SPA have been published almost every year since 2001. However, the annual article number is small and relatively average. There was no peak period. About five papers are published every year.

Set pair analysis theory is still being enriched and innovated continuously. The application of set pair analysis is becoming more and more extensive. However, the current SPA also has the disadvantages of high subjectivity and randomness, incomplete theoretical system and uneven development at home and abroad. Therefore, making the theory of set pair analysis complete and disseminating it widely abroad is the first task for the further development of set pair analysis.

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