Application of Entropy Method in River Health Evaluation Based on Aquatic Ecological Function Regionalization

Yan-ting SHI 1, Jie LIU 1, Peng WANG 1,2, Xu-nuo ZHANG 1, Jun-qiang WANG 1 and Liang GUO 1,2,*

1 School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, China;
2 State key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China;
* Corresponding author at: School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, China; State key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China.

E-mail address: guoliang0617@hit.edu.cn

Abstract. With the implementation of water environment management in key basins in China, the monitoring and evaluation system of basins are in urgent need of innovation and upgrading. In view of the heavy workload of existing evaluation methods and the cumbersome calculation of multi-factor weighting method, the idea of using entropy method to assess river health based on aquatic ecological function regionalization was put forward. According to the monitoring data of songhua river in the year of 2011-2015, the entropy weight method was used to calculate the weight of 9 evaluation factors of 29 monitoring sections, and the river health assessment was carried out. In the study area, the river health status of the biodiversity conservation function area (4.111 point) was good, the water conservation function area (3.371 point), the habitat maintenance functional area (3.262 point), the agricultural production maintenance functional area (3.695 point) and the urban supporting functional area (3.399 point) was light pollution.

1. Introduction
Since 2008, the Ministry of Environmental Protection in the water pollution control and control of major science and technology projects carried out the research of aquatic ecological function regionalization, and in the "eleventh five-year" and the "twelfth five-year" topics, the special research construct the new ideas of aquatic ecological function regionalization system[1-2]. Through the management of different regionalization units using "zoning, grading, classification, staging" management mode, to ensure the ecological health of the whole basin and the normal function of aquatic ecology[1,3-4]. The establishment of river health rating system based on aquatic ecological function regionalization is helpful to the accurate management of river management. In the river health assessment, the establishment of index system is one of the most important part[5-6]. The evaluation of index weights is reasonable or not will directly influence the evaluation results. In the numerous method of index weighting, due to the actual objectivity of the monitoring data, it is
considered that the objective weighting method—entropy method—is more suitable for the river health evaluation study [7-9].

The concept of entropy originated from thermodynamics, it was more early proposed by the German physicist Boltzmann and Clausius in 1864 to describe the physical state of the system. Later, American mathematician, cybernetics and information theory founder Shannon put forward a broader information entropy based on it, as a measure of uncertainty[10]. Li Peiyue[11] etc. applied the entropy method to groundwater quality evaluation, and the method is simple, reasonable, reliable and intuitionistic. It can be used for groundwater quality evaluation and worthy of popularization. Guo Xiuying[12] gave an objective entropy method to determine the weight of each interval number index, which is the objective weighting of the index in the multiple interval decision making with unknown weight information. Zou Zhihong[13] etc. applied the fuzzy evaluation factor entropy weight method to the Three Gorges reservoir water quality evaluation, that the evaluation results are reasonable, the calculation process is simple. This paper attempts to apply the entropy method to the river health assessment based on aquatic ecological function regionalization. The Songhua River Basin is taken as an example to evaluate the river health.

2. The basic theoretical process of determining the weight of Index by entropy method

Entropy is a measure of the degree of system disorder in information theory, it also can measure the amount of the effective data provided information [14]. Therefore, entropy can be used to determine the weight. In river health evaluation, through the calculation of "entropy" to determine the weight, is based on the difference between the various monitoring indicators to determine the weight of each indicator.

Specific calculation steps are as follows:

There are m evaluation indicators, n evaluation objects, the formation of the original data matrix is 
\[ X = (x_{ij})_{m \times n} \]. For a certain index, the greater the difference of the index value, the greater the role of the indicator in the comprehensive evaluation. If the index values of all indicators are equal, then the indicator in the comprehensive evaluation of almost no effect[15].

Step 1: For calculating entropy weight when m water samples (i=1, 2, ..., m) are taken to evaluate the water quality and each sample is analyzed for "n" quality parameters (j=1, 2, ..., n), according to observed data, eigenvalue matrix X can be constructed.

In order to eliminate the influence caused by the difference of different quantity grades and different units, data pretreatment must be put into force[11]. The matrix is normalized as follows:

\[ R = (r_{ij})_{m \times n} \]  

Where \( r \) is the standard value of the j-th evaluation object on the i-th evaluation index, \( r_{ij} \in [0, 1] \).

The standardization process is as follows:

For the efficiency type, the construction function of normalization is:

\[ r_{ij} = \frac{x_{ij} - \min \{x_{ij}\}}{\max \{x_{ij}\} - \min \{x_{ij}\}} \]  

And for the cost type, the construction function of normalization is:

\[ r_{ij} = \frac{\max \{x_{ij}\} - x_{ij}}{\max \{x_{ij}\} - \min \{x_{ij}\}} \]

Step 2: Define the entropy

In the evaluation index of m indicators, n evaluation objects, the entropy of the i-th index is defined as

\[ H_i = -k \sum_{j=1}^{n} f_{ij} \ln f_{ij}, i = 1, 2, ..., m \]  

\[ f_{ij} = \begin{cases} 1, & \text{if} \quad x_{ij} \leq \bar{x}_i \\ 0, & \text{otherwise} \end{cases} \]  

where \( \bar{x}_i \) is the mean value of the i-th index.
Step 3: Define the entropy weight

\[ w_i = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i} \]  \hspace{1cm} (5)

Where \( 0 \leq w_i \leq 1 \), \( \sum_{i=1}^{m} w_i = 1 \).

3. A case study of river health evaluation based on entropy method

3.1. Compute objects and their data sources

In this paper, the monitoring sections of the Songhua River Basin, which belong to the five aquatic ecological function regionalization, are selected to study the river health comprehensive evaluation and the entropy method for the five years monitoring data of the Songhua River Basin. The water quality monitoring data used were from environmental monitoring bulletin.

3.2. The screening of calculated indicator factor

In the original monitoring data, there are 32 monitoring indicators, a primary screening are operated on them. Remove the auxiliary indicators and indicators of high undetection rate in monitor, including: water temperature, flow, pH, sulfate, volatile phenol, copper etc.

3.3. Evaluation factors and evaluation

After screening, 9 indexes of dissolved oxygen, permanganate index, five day BOD, ammonia nitrogen, chemical oxygen demand, total nitrogen, total phosphorus, fluoride and fecal coliform were selected as evaluation factor. Namely, \( U = \{ DO, COD_{m}, BOD_{s}, NH_{3}-N, COD, TN, TP, F^{-}, M \} \). According to the national surface water environmental quality standard (GB3838-2002), the water quality level is set to 5, so the evaluation set is \( V = \{ I, II, III, IV, V \} \).

3.4. Raw data processing

For the individual data that the original data are not monitored, the data are supplemented by the cubic polynomial interpolation method, taking into account the whole data. For the data below the detection limit in the monitoring, use the detection limit value of the monitoring indicators to assignment.

3.5. Weight calculation of partition index based on entropy method

According to the relationship between the monitoring points and the five levels of aquatic ecological function regionalization, the monitoring points were classified into five levels of aquatic ecological function regionalization, the results shown in Figure 1. In this paper, the name of the section is replaced by number.

The entropy weight formula is used to normalize the data to obtain entropy and weight. Take the monitoring data in August 2012 as an example. For the agricultural production maintenance functional area, the data are normalized to obtain the matrix as shown in Table 1.

The index entropy and the weight of the function partition are obtained as shown in Table 2.
Figure 1. Corresponding monitoring points of aquatic ecological function regionalization

Table 1. Standardization of data

| Monitoring section | DO  | COD | BOD | NH$_3$-N | COD | TN  | TP  | Fecal coliform |
|--------------------|-----|-----|------|----------|-----|-----|-----|----------------|
| D1                 | 0.000 | 0.861 | 1.000 | 0.560 | 1.000 | 0.796 | 0.813 | 0.630 | 0.922 |
| D2                 | 1.000 | 0.466 | 0.707 | 0.691 | 0.591 | 0.757 | 0.761 | 0.752 | 0.000 |
| D3                 | 0.387 | 0.284 | 0.523 | 0.871 | 0.240 | 1.000 | 0.926 | 0.817 | 1.000 |
| D4                 | 0.610 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.523 | 0.000 |
| D5                 | 0.518 | 0.257 | 0.640 | 0.748 | 0.909 | 0.514 | 0.074 | 0.569 | 0.977 |
| D6                 | 0.518 | 0.257 | 0.627 | 0.789 | 0.909 | 0.107 | 0.074 | 0.589 | 0.967 |
| D7                 | 0.860 | 0.375 | 0.747 | 0.597 | 0.877 | 0.803 | 0.875 | 1.000 | 0.993 |
| D8                 | 0.845 | 0.672 | 1.000 | 0.661 | 0.877 | 0.843 | 1.000 | 0.728 | 0.993 |
| D9                 | 0.415 | 1.000 | 0.333 | 1.000 | 0.130 | 0.253 | 0.415 | 0.467 | 0.984 |
| D10                | 0.549 | 0.358 | 0.653 | 0.773 | 0.455 | 0.026 | 0.000 | 0.386 | 0.892 |
| D11                | 0.671 | 0.324 | 0.813 | 0.696 | 0.195 | 0.408 | 0.188 | 0.549 | 0.917 |

Table 2. Index entropy and weight value

| Monitoring indicators | DO  | COD$_{\text{Mn}}$ | BOD$_3$ | NH$_3$-N | COD | TN  | TP  | F  | Fecal coliform |
|-----------------------|-----|-------------------|---------|----------|-----|-----|-----|----|----------------|
|                       |     |                   |         |          |     |     |     |    |                |

Note: The table values represent standardization factors for various monitoring indicators and their corresponding weight values.
| Functional area | Monitoring indicators | Recommended weight | Monitoring section | Recommended weight |
|-----------------|-----------------------|--------------------|--------------------|--------------------|
| The biodiversity conservation function area | DO | 0.153 | A1 | 0.204 |
| | COD$_{Mn}$ | 0.107 | A2 | 0.098 |
| | BOD$_5$ | 0.110 | A3 | 0.172 |
| | NH$_3$-N | 0.099 | A4 | 0.527 |
| | COD | 0.116 | | |
| | TN | 0.120 | | |
| | TP | 0.110 | | |
| | F | 0.086 | | |
| | fecal coliform | 0.100 | | |
| The water conservation function area | DO | 0.104 | B1 | 0.195 |
| | COD$_{Mn}$ | 0.124 | B2 | 0.037 |
| | BOD$_5$ | 0.107 | B3 | 0.565 |
| | NH$_3$-N | 0.099 | B4 | 0.204 |
| | COD | 0.129 | | |
| | TN | 0.141 | | |
| | TP | 0.102 | | |
| | F | 0.092 | | |
| | fecal coliform | 0.103 | | |
| The habitat maintenance functional area | DO | 0.119 | C1 | 0.017 |
| | COD$_{Mn}$ | 0.109 | C2 | 0.025 |
| | BOD$_5$ | 0.102 | C3 | 0.003 |
| | NH$_3$-N | 0.100 | C4 | 0.895 |
| | COD | 0.111 | C5 | 0.033 |
| | TN | 0.105 | C6 | 0.026 |
| | TP | 0.102 | | |
| | F | 0.131 | | |
| | fecal coliform | 0.121 | | |
| The agricultural production maintenance functional area | DO | 0.134 | D1 | 0.028 |
| | COD$_{Mn}$ | 0.171 | D2 | 0.039 |
| | BOD$_5$ | 0.113 | D3 | 0.029 |
| | NH$_3$-N | 0.082 | D4 | 0.567 |
| | COD | 0.109 | D5 | 0.048 |
| | TN | 0.093 | D6 | 0.059 |
| | TP | 0.102 | D7 | 0.030 |
| | F | 0.113 | D8 | 0.045 |
| | fecal coliform | 0.083 | D9 | 0.060 |
3.7. Comprehensive river health assessment

According to the standard limit value of the surface water environmental quality standard[16] (GB3838-2002) to score the evaluation index, the scoring standard was: { class I, class II, class III, class IV, class V } corresponds to {5, 4, 3, 2, 1}. According to the results of the above calculation, the monitoring data of Heilongjiang Province in January-May 2016 were comprehensively evaluated. The sections used in the evaluation in Heilongjiang Province and evaluation results are shown in Table 4:

| The biodiversity conservation function area | The water conservation function area | The habitat maintenance functional area | The agricultural production maintenance functional area | The urban supporting functional area |
|---------------------------------------------|--------------------------------------|----------------------------------------|------------------------------------------------------|-------------------------------------|
| Section | Score | Section | Score | Section | Score | Section | Score | Section | Score |
| A1 | 4.169 | B3 | 3.371 | C5 | 3.150 | D3 | 3.737 | E1 | 3.788 |
| A2 | 4.003 | | C6 | 3.346 | D7 | 3.786 | E2 | 3.355 |
| A3 | 4.174 | | | | D8 | 3.786 | E3 | 3.171 |
| | Score | 4.111 | | Score | 3.371 | | Score | 3.262 | | Score | 3.399 |

The grading standards of water eco-environmental quality is shown as follows: {5, 4, 3, 2, 1} corresponds to {excellent, good, slight pollution, moderate pollution, heavy pollution}. The river health status of the biodiversity conservation function area was good, the water conservation function area, the habitat maintenance functional area, the agricultural production maintenance functional area and the urban supporting functional area was light pollution. This is consistent with the water quality status of the Songhua River basin reported in the monthly water quality report. Moreover, due to the assignment of the partition weights, the indicators with higher pollution in the monitoring have received more attention.

4. Conclusion

(1) The result of weighting by the entropy method shows that the weights of the total nitrogen, dissolved oxygen and chemical oxygen demand in the five aquatic ecological function regionalization are relatively large, indicating that the information given by the monitoring data is large, also from the side indicates a serious degree of pollution. Through the comprehensive evaluation results can be seen, the overall river health status of the Songhua River is slight pollution. In terms of their ecological functions, the functional areas with high water quality requirements for maintaining biodiversity are in good health, while those for urban support functional areas are slightly polluted. This also fit in the basic requirements and laws of aquatic ecological function regionalization.

(2) Compared with the current "Surface Water Environmental Quality Assessment Method", river health assessment based on aquatic ecological function regionalization is more targeted to the river
evaluation than that of the entire river basin or the whole tributary. The evaluation combined with water demand of regionalization ecological functions providing a scientific basis for reasonable pollution control strategy.

(3) Compared with other methods, the entropy method based on data can objectively weigh the situation of monitoring data, and eliminate the influence of human subjective factors on the weight. And the entropy method can be calculated by MATLAB is very simple to achieve, simplifying the calculation steps to reduce the workload of the evaluation.

(4) The results show that entropy method is a more effective method, and it is reasonable in river health comprehensive evaluation.

5. Acknowledgement
This research was supported by Natural Science Foundation of China (71471050).

6. References
[1] Meng Wei, Zhang Yuan, Zhang Nan, etc. Study on aquatic ecological function regionalization and water quality target management in the river basin[J]. Acta Scientiae Circumstantiae, 2011, 31 (7) : 1345-1351.
[2] Huang Yi, Cai Jialiang, Zheng Weishuang, etc. Advances in the research on aquatic ecological function regionalization and partitioning methods[J]. Chinese Journal of Ecology, 2009, 28 (3) : 542-548.
[3] Meng Wei. Technology and demonstration of total amount control of water pollutants in river basins[M]. Beijing: China Environmental Science Press, 2008..
[4] Lei Kun, Meng Wei, Qiao Fei, etc. Study and application of the technology on water quality target management for control unit[J]. Chinese Journal of Engineering Science, 2013, 15 (3) : 62-69.
[5] Wang Tao, Wei Yani, Qian Hui. Influence of different weights on fuzzy comprehensive evaluation method for water quality[J]. South-to-North Water Transfers and Water Science & Technology, 2010, 8 (2) : 87-90.
[6] Wang Shenglong, Zou Zhihong. Application of information entropy-based grey clustering method on water quality assessment[J]. Mathematics in Practice and Theory, 2012, 42 (21) : 83-89.
[7] Wang Tiefeng, Pan Xiaohui. An application on entropy weight of fuzzy mathematics in water quality assessment[J]. Shanxi Architecture, 2010, 36 (14) : 359-360.
[8] Vahab Amiri, Mohsen Rezaei, Nasim Sohrabi. Groundwater quality assessment using entropy weighted water quality index (EWQI) in Lenjanat, Iran[J]. Environ Earth Sci (2014) 72: 3479-3490.
[9] Wu Jianhua, Li Peiyue, Qian Hui, etc. On the sensitivity of entropy weight to sample statistics in assessing water quality: statistical analysis based on large stochastic samples[J]. Environ Earth Sci (2015) 74: 2185-2195.
[10] Chen Qiyun, Qiu Wanhua, Relation entropy and transferable think of aggregation on group decision making[J]. Systems Science and Engineering, 2002, 11 (1) : 11-18.
[11] Li Peiyue, Qianhua, Wu Jianhua. Application of set pair analysis method based on entropy weight in groundwater quality assessment- a case study in dongsheng city, Northwest China[J]. E-Journal of Chemistry, 2011, 8(2), 851-858.
[12] Guo Xiuying. Improvement of entropy method for determining weights of interval[J]. Statistics and Decision Making, 2012 (17) : 32-34.
[13] Zou Zhihong, Sun Jingnan, Ren Guangping. Study and application on the entropy method for determination of weight of evaluating indicators in fuzzySynthetic evaluation for water quality assessment[J]. Acta Scientiae Circumstantiae, 2005, 25 (4) : 552-556.
[14] Meng Qingsheng. Information theory[M]. Xi'an: Xi'an Jiaotong University Press, 1989: 19-36
[15] Qiu Wanhua. Management decision and applied entropy[M]. Beijing: Machinery Industry Press, 2002: 193-196
[16] State Environmental Protection Administration, State Administration of Quality Supervision, Inspection and Quarantine. GB3838-2002Surface water environmental quality standard[S]. Beijing: China Environmental Science Press, 2002.