# Fuzzy comprehensive assessment of water environmental quality of Wei River, China

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ABSTRACT
The Wei River, the largest tributary of the Yellow River in China, is the major source of water for the urban residents, industries and agriculture in the central Shaanxi plain. Water quality of Wei River was determined by collecting samples from 25 locations along the Baoji Xi'an reach of the river and analyzing for pH, EC, BOD5, DO, COD, F, Se, As and Hg. The fuzzy comprehensive assessment method was used to assess the water quality of the river and to classify its quality according to the National surface water environmental quality standards of China. Results indicate that the water quality of 23 sampling sites fall into the class V (bad level), whereas 2 sampling sites are in class IV (poor level). The Wei River is heavily polluted at most of the sampling locations with mercury as the major pollutant. Strict enforcement of the regulations for domestic and industrial wastewater discharges is vital to avoid damaging the aqueous environment and to protect human and ecological health.

RÉSUMÉ
Le fleuve Wei, le plus grand effluent du fleuve Jaune en Chine, est la source principale en eau pour les industries, l'agriculture et les résidants de la plaine centrale de Shaanxi. La qualité de l'eau du fleuve Wei a été déterminée en collectant des échantillons à partir de 25 locations le long de la rive Baoji Xi'an du fleuve en effectuant plusieurs analyses telles le pH, CE, DBO5, DO, et DCO, ainsi que la mesure des concentrations en F, Se, As et Mg. Une méthode complète d'analyse a été employée pour évaluer la qualité de l'eau du fleuve et pour classifier sa qualité selon les standards nationaux Chinois de qualité environnementale des eaux de surface. Les résultats indiquent que la qualité de l'eau de 23 des emplacements de l'échantillonnage tombent dans la classe V (niveau mauvais), tandis que 2 emplacements de échantillonnage sont dans la classe IV (niveau pauvre). Le fleuve Wei est fortement pollué au mercure dans la majorité des endroits de prélèvement. L'application stricte des règlements concernant les décharges domestiques et industrielles d'eau usagée est donc essentielle afin d'éviter d'endommager l'environnement fluvial et de protéger la santé humaine et écologique.

## 1 INTRODUCTION

Freshwater resources play unique roles for society through provision (e.g., products and food), support (e.g., waste water processing and supply of clean water) and enrichment or cultural (e.g., aesthetic and recreational) services (Yang et al. 2007). If water resources are not appropriately managed, it will be impossible to meet the growing demands for freshwater resources to sustain human activities. However, water is being adversely affected by urbanization and industrial activities leading to discharge of industrial wastewater and domestic sewage, and a potential crisis in the very near future (Charkhabi and Sakizadeh 2006). The shortage of water resources and water pollution is very serious in the arid and semiarid area of Northwestern China. Strengthening water quality management and conservation of impoverished water resources is indispensable and important for economic and social sustainable development.

Wei River, the largest tributary of Yellow River in China, originates from Gansu Province, passes through the central Shaanxi plain, and traverses about 502 km in Shaanxi province. The Wei River valley is the major region for agriculture, industry and commerce in Northwestern China. The river is a major source of water, including drinking water, industrial production and agricultural activities in the central Shaanxi plain. Although there are stringent rules in China for treatment of industrial wastes and disposal of untreated wastewater into drains, such discharges into the Wei River are very common, posing a potential health and environmental risk to people living in the central Shaanxi and downstream. Other sources of stream river pollution include surface runoff directly discharged to streams without treatment. Scientific assessment of water quality is very important for the Wei River in order to protect human and ecological health.

Numerous methods are used to assess water environmental quality. These include expert assessment (Croke et al. 2007; Nasiri et al. 2007), index assessment (Cude 2001), neural networks (Sudheer et al. 2006), and grey clustering (Wang et al. 2007).The pollution degree of water is a vague concept. Owing to inherent errors in analysis and imprecision in classification criteria, the boundaries between different classes of water are always fuzzy, and difficulties of classification and assessment always exist in the conventional assessment indicators such as the water quality index (WQI) when describing integrated water quality. A small increase/decrease in pollutant data near its boundary value can change the classification. This fuzziness has led some environmental researchers to look for advanced assessment methods based on fuzzy logic (Fisher 2003), such as fuzzy comprehensive assessment. Fuzzy comprehensive assessment, widely used in various environmental areas such as air pollution assessment (Fisher 2003; Haiyan 2002; Onkal-Engin et al. 2004), water pollution assessment (Chang et al. 2001; Dahiya et al. 2007; Haiyan 2002; Icaga 2007; Liu and Qu 2002; Singh et al. 2008; Song et al. 2006; Zou et al. 2006) and soil pollution assessment (Haiyan 2002; Shen et al. 2005), has proven to be effective in solving problems of fuzzy boundaries and in controlling the effect of monitoring errors on assessment results (Wang, 2002). In this study, fuzzy comprehensive assessment was used to evaluate the water quality of the Wei River to provide a scientific basis for water resource management.

## 2 MATERIALS AND METHODS

### 2.1 Sampling and analyzing

25 water samples were collected along the Baoji Xi'an reach of the Wei River during October and November, 2006. The selection of sampling sites was based on the vicinity of the main pollutant sources such as agriculture, industry, and residential land use (Figure 1). The samples were taken from 10 to 15 cm below the water surface using acid-washed, wide-mouth polyethylene plastic bottles. Standard sampling procedures were followed (HJ/T91-2002). Two samples were collected at each site, one of which was acidified by addition of 1 ml of concentrated hydrochloric acid to each one-liter sample for metal analyses to minimize precipitation and adsorption on the walls of the container. The water samples were transported to the laboratory and analyzed for pH, electrical conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD) and fluoride based on the standard methods (HJ/T91-2002). To analyze for total metal, the samples were digested without preliminary filtration using the nitric acid digestion method. Mercury, arsenic and selenium were analyzed using an atomic fluorescence spectrometer.

### 2.2 Fuzzy comprehensive assessment

Fuzzy comprehensive assessment uses a numerical scale to represent water quality and provides an alternative methodology for aggregating the values of the parameters to various quality features. It is designed to group raw data into several different categories according to predetermined quality criteria, which can be normally described using a set of functions designed to reflect the absence of sharp boundaries between adjacent criteria. The following procedure describes fuzzy comprehensive assessment (Chang et al., 2001; Haiyan, 2002; Shen et al., 2005; Singh et al., 2008; Song et al., 2006):

(a) Select assessment parameters and establish assessment criteria

It is crucial to select assessment parameters that are representative, rational and accurate to form an assessment factor set $U$, based on the actual local situation, expressed as

$$U = \{u_1, u_2, \ldots, u_n\} \quad [1]$$

where $n$ is the number of selected assessment parameters. The assessment criteria set $V$ is established from the National Environmental Quality Standards of China for Surface Water

$$V = \{v_1, v_2, \ldots, v_m\} \quad [2]$$

where m is the number of assessment criteria categories. The water quality is classified on five levels according to National surface water environmental quality standards of China (GB3838-2002) (Table 1).

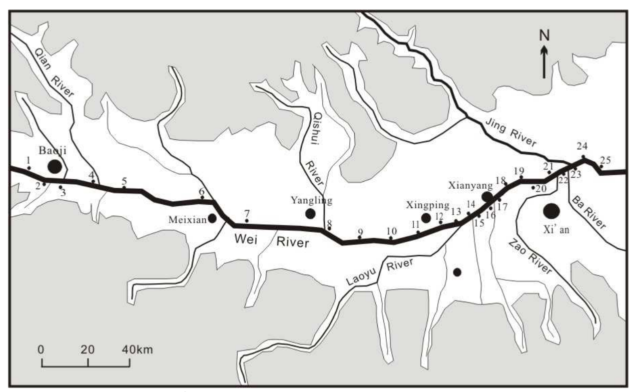


Figure 1. Map of sample sites along the Baoji Xi'an reach of the Wei River, China for water samples collected

Table 1. National surface water environmental quality standards of China (mg $l^{-1}$)

| Criterion Class levels | DO | $BOD_5$ | COD | Hg |
|---|---|---|---|---|
| I Excellent | 7.5 | 3 | 15 | 0.00005 |
| II Good | 6 | 3 | 15 | 0.00005 |
| III Ordinary | 5 | 4 | 20 | 0.0001 |
| IV Poor | 3 | 6 | 30 | 0.001 |
| V Bad | 2 | 10 | 40 | 0.001 |

(b) Establish membership functions of fuzzy environmental quality

The membership functions represent the degree to which the specified concentration belongs to the fuzzy set. The membership degrees of assessment parameters at each level can be described quantitatively by a set of formulae of membership functions as follows (Wang, 2002)

$$r_{i1}(c_i) = \begin{cases} 1 & c_i \le v_{i1} \\ (c_i - v_{i2})/(v_{i1} - v_{i2}) & v_{i1} < c_i < v_{i2} \\ 0 & c_i \ge v_{i2} \end{cases} \quad [3]$$

$$r_{ij}(c_i) = \begin{cases} 0 & c_i \le v_{ij-1}, c_i \ge v_{ij+1} \\ (c_i - v_{ij-1})/(v_{ij} - v_{ij-1}) & v_{ij-1} < c_i \le v_{ij} \\ (c_i - v_{ij+1})/(v_{ij} - v_{ij+1}) & v_{ij} < c_i < v_{ij+1} \end{cases} \quad j = 2, 3, 4 \quad [4]$$

$$r_{i5}(c_i) = \begin{cases} 0 & c_i \le v_{i4} \\ (c_i - v_{i4})/(v_{i5} - v_{i4}) & v_{i4} < c_i < v_{i5} \\ 1 & c_i \ge v_{i5} \end{cases} \quad [5]$$

where $c_i$ is the actual monitoring data for the $i$th assessment parameter, and $v_{ij}$ is the criteria value of the $i$th assessment parameter at the $j$th level ($i$ = 1, 2, …, $n$; $j$=1, 2, …, $m$).

(c) Calculate the membership function matrix

Substituting the data of each assessment parameter at each monitoring site and the national standards into the membership functions, we obtain the fuzzy matrix $R$

$$R = (r_{ij})_{n\times m} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix} \quad [6]$$

where $r_{ij}$ ($i$ =1, 2, …, $n$; $j$=1, 2, …, $m$) is the membership degree of the $i$th assessment parameter at the $j$th level.

(d) Calculate the weights matrix

The weights of each assessment parameter are allocated at each monitoring site to obtain matrix $B$ with $W_{i(k)} = a_{i(k)} \Big/ \sum_{i=1}^{n} a_{i(k)}$ and $a_{i(k)}=c_{i(k)}/s_i$. Here, the monitoring site is marked by $k$, $c_{i(k)}$ is the monitored concentration of the $i$th assessment parameter at the $k$th monitoring site, $s_i$ is the average assessment criteria of the $i$th assessment parameter, $W_{i(k)}$ is the weight of the $i$th assessment parameter at the $k$th monitoring site. $B_{(k)}$, the weight matrix $B$ at the monitoring site $k$, can be expressed as $B_{(k)}$= ($W_{1(k)}$, $W_{2(k)}$, …, $W_{n(k)}$) where $n$ is the number of selected assessment parameters.

(e) Determine fuzzy algorithm of $B{\cdot}R$

$B{\cdot}R$ can be computed by matrix multiplication. This method is described as follows

Fuzzy matrix $R = (a_{ij})_{n\times m}$, Weight matrix $B = (W_i)_{1\times n}$. Then, the assessment results can be obtained

$$B{\cdot}R = (b_1, b_2, \ldots, b_m) \quad [7]$$

where $b_j = \sum_{i=1}^{n} W_i a_{ij}$ , $j$ = 1, 2, …, $m$

## 3 RESULTS AND DISCUSSIONS

### 3.1 Status of water quality of Wei River

The measured water quality parameters in the Wei River water at the studied locations are shown in Figure 2. The pH values varied from 6.75 to 7.62. The EC values varied from 420 to 900 μS $cm^{-1}$. There is no distinct difference of pH and EC values among all sampling sites. The fluoride contents of the water samples ranged from 0.24 to 1.09 mg $l^{-1}$, all below the limitation of class I (1 mg $l^{-1}$) (GB3838-2002) except for two samples where the fluoride concentration was close to l mg $l^{-1}$. The DO, $BOD_5$ and COD concentrations in water samples ranged from 0.09 to 3.19, 0.4 to 78.0, and 24.8 to 239.1 mg $l^{-1}$, respectively. The higher $BOD_5$ and COD concentrations appeared in the water samples collected from the vicinal reach of Baoji (site 4), Xianyang (site 16) and Xi'an (site 21) cities. The trace elements As, Se and Hg in the water samples ranged from 1.10 to 42.0, 0.01 to 0.66, and 0.93 to 3.82 μg $l^{-1}$. Arsenic and Se concentrations in all water samples were below the limits for class I.

### 3.2 Fuzzy comprehensive assessment of water quality of Wei River

Fuzzy comprehensive assessment was applied to evaluate the water quality of the Wei River based on the monitoring data and the National surface water environmental quality standards of China. In the original monitoring data, pH and EC values of all samples are categorized in class I, whereas trace element As, Se and F concentrations in all measured water samples were below the limitations of class I. Therefore, only DO, $BOD_5$, COD and Hg were selected as assessment parameters to form an assessment factor set $U$ = {DO, $BOD_5$, COD, Hg}. The values of the above 4 assessment parameters in the 25 sampling sits are shown in Figure 2.

Membership functions of DO, $BOD_5$, COD and Hg to standards at 5 levels were established according to equations 3~5. For example, for DO

$$r_{11}(c_1) = \begin{cases} 1 & c_1 \ge 7.5 \\ (c_1 - 6)/1.5 & 6 < c_1 < 7.5 \\ 0 & c_1 \le 6 \end{cases} \quad [8]$$

$$r_{12}(c_1) = \begin{cases} 0 & c_1 \le 5, c_1 \ge 7.5 \\ (7.5 - c_1)/1.5 & 6 < c_1 < 7.5 \\ c_1 - 5 & 5 < c_1 \le 6 \end{cases} \quad [9]$$

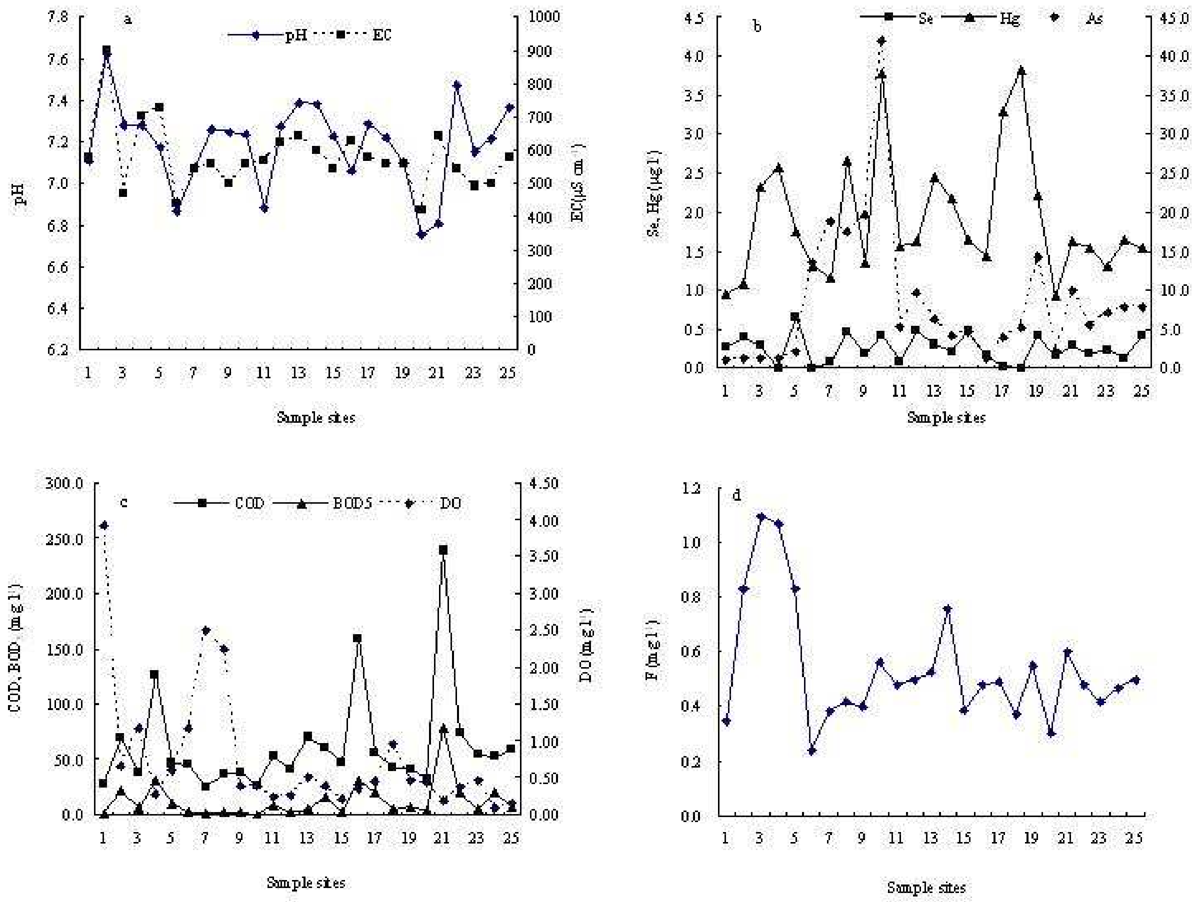


Figure 2. The data of the monitoring water quality parameters in Wei River water samples

$$r_{13}(c_1) = \begin{cases} 0 & c_1 \le 3, c_1 \ge 6 \\ 6 - c_1 & 5 < c_1 < 6 \\ (c_1 - 3)/2 & 3 < c_1 \le 5 \end{cases} \quad [10]$$

$$r_{14}(c_1) = \begin{cases} 0 & c_1 \le 2, c_1 \ge 5 \\ (5 - c_1)/2 & 3 < c_1 < 5 \\ c_1 - 2 & 2 < c_1 \le 3 \end{cases} \quad [11]$$

$$r_{15}(c_1) = \begin{cases} 0 & c_1 \ge 3 \\ 3 - c & 2 < c_1 < 3 \\ 1 & c_1 \le 2 \end{cases} \quad [12]$$

After substitution of actual monitoring data to equations 3~5, fuzzy matrices were determined for 25 water sampling sites. According to weight calculation method, after substitution of the monitoring data and standards values, weighted matrices, $B1$~$B25$, were obtained for the 25 water sampling sites. For example, for sampling site 1 the fuzzy matrix and weight matrix are

$$R1 = \begin{pmatrix} 0 & 0 & 0.45 & 0.55 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.29 & 0.71 & 0 \\ 0 & 0 & 0.07 & 0.93 & 0 \end{pmatrix} \quad [13]$$

$$B1 = (0.191 \;\; 0.062 \;\; 0.259 \;\; 0.489) \quad [14]$$

The fuzzy matrices and weight matrices for the other sampling sites are not given here. The major pollutant at each sampling site can be identified from the corresponding weight matrices, since the assessment parameter with the maximum weight is the major pollutant. For example, at water sampling site 1, Hg is the major pollutant. Fuzzy algorithm $B \cdot R$ gives

$$B1 \cdot R1 = (0.191 \;\; 0.062 \;\; 0.259 \;\; 0.489) \begin{pmatrix} 0 & 0 & 0.45 & 0.55 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.29 & 0.71 & 0 \\ 0 & 0 & 0.07 & 0.93 & 0 \end{pmatrix}$$

$$= (0.06 \;\; 0 \;\; 0.20 \;\; 0.74 \;\; 0) \quad [15]$$

The assessment result can be obtained from B1·R1 (equation 15). Since the membership degree of class IV (0.74) is higher than for classes I (0.06), II (0), III (0.20) and V(0), the water environmental quality at sampling site 1 belongs to class IV. In the same way, we can carry out the fuzzy comprehensive assessment of water quality at the other sampling sites. Results appear in Table 2. Among the 25 water sampling sites, the water quality at 23 sampling sites belong to class V, whereas 2 sampling sties belong to class IV. The water quality of the Baoji Xi'an reach of the Wei River is clearly seriously polluted, with the major pollutant being Hg.

Table 2. Fuzzy comprehensive assessment results of water quality of Wei River, China

| Class | Sampling sites |
|---|---|
| I | |
| II | |
| III | |
| IV | 1, 20 |
| V | 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24, 25 |

## 4 CONCLUSIONS

The water quality of the Wei River indicates that pH, EC and the concentrations of F, As and Se are below the limitations of class I, while $BOD_5$, COD and Hg concentrations are of serious contamination. The integrated water quality of the Wei River was assessed based on the actual monitoring data and the National surface water environmental quality standards of China using fuzzy comprehensive assessment. The water quality of all sampling sites belong to class V, except for two sampling sites which belong to class IV. The water of the Baoji Xi'an reach of the Wei River is polluted with mercury as the major pollutant. The spatial distributions of $BOD_5$, COD and Hg concentration show that higher values appeared in the water from the vicinal reach of the Baoji, Xianyang and Xi'an sites. Strict enforcement of domestic and industrial wastewater discharges management is vital to water resource protection and improvement of the Wei River.

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