Water Quality Assessment of Danjiangkou Reservoir and its Tributaries in China

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Abstract. Danjiangkou Reservoir is an important water source for the middle route of the South to North Water Diversion Project in China, and water quality of Danjiangkou Reservoir and its tributaries is crucial for the project. The purpose of this study is to evaluate the water quality of Danjiangkou Reservoir and its tributaries based on Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI). 22 water quality parameters from 25 sampling sites were analyzed to calculate WQI. The results indicate that water quality in Danjiangkou Reservoir area, Hanjiang River and Danjiang River is excellent. And the seriously polluted tributary rivers were Shending River, Jianghe River, Sihe River, Tianhe River, Jianhe River and Jiangjun River. Water quality parameters that cannot meet the standard limit for drinking water source were fecal coliform bacteria, CODcr, CODMn, BOD5, NH3-N, TP, DO, anionic surfactant and petroleum. Fecal coliform bacteria, TP, ammonia nitrogen, CODMn were the most common parameters to fail.

1. Introduction
China has been suffering from severe water scarcity problems, especially in northern China. Water availability per capita in China is about 2068 m3, and 904 m3 in north China. In order to alleviate the water shortage problems faced in North China, three south to north water transfer projects were proposed. One of the most important projects is the middle route of south to north water transfer project delivering water from the Danjiangkou reservoir to Beijing and Tianjin [1]. The total length of the main channel is 1277km, and annually about 44.8 billion m3 water was transferred [2]. the middle water diversion project commenced transferring water in December 2014. From then on, the water quality of Danjiangkou Reservoir has attracted considerable public attention.

To evaluate water quality of source water, different water quality assessment methods has been widely studied and used all over the world. Single factor assessment methods were widely used in rivers, reservoirs, and lakes in China. Single factor assessment method is simple and convenient and can be used directly to compare the water quality parameter values with standards. Therefore it is easy to understand the water quality status with single factor assessment method. However, the single factor assessment method is very strict in some cases. For example, if water quality of all parameters in a drinking water source can meet the standard of drinking water source except faecal coliform, the water body will be evaluated as unfit for drinking purposes using single factor assessment method. However, the water can meet the drinking water quality standard after disinfection treatment in water treatment plant [3].

Water quality index is one of the best water quality evaluation methods [4-5]. Horton [6] first proposed water quality index in 1965, since then, various water quality indices for water quality evaluation have been proposed worldwide [7-13].
However, there is still no universally accepted water quality assessment indices. Most water quality indices in literature or in use in some countries rely on normalizing water quality concentration of parameters with water quality standards and interpreting water ‘good’ versus ‘bad’ concentrations [14].

Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) compares water quality monitoring results with a benchmark instead of normalizing the measured values with standards, where the benchmark may be a water quality standard or site specific background concentration [15–18]. Many researchers have successfully evaluated water quality with CCMEWQI [19–21].

The objective of this research is to (i) apply the widely used CCMEWQI to evaluate water quality of Danjiangkou Reservoir and 16 major tributaries, using 22 water quality parameters measured on a monthly basis for 16 months; (ii) to identify the main parameters influencing the water quality of Danjiangkou Reservoir and 16 major tributaries.

2. Methodology

2.1. Study area description
Geographical location of Danjiangkou Reservoir is 32°36′ to 33°48′N and 110°59′ to 110°49′E situated in the center of China. It started to impound water in 1967, became functional in 1968 and finished in 1973 with total storage capacity of 17.45 billion m³ and surface area of 400 km² at water level of 157m. The reservoir catchment area is 92,500 km².

From 2005 to 2010, to meet the needs of the South to North Water Diversion Project, the height of Danjiangkou Dam was increased from 162m to 176.6m, and the water level was increased from 157m to 170m Therefore, the Danjiangkou Reservoir is very large with a storage capacity of 29.05 billion m³, and a water area of 1022.75 km².

The Danjiangkou Reservoir dam is located at 0.8km downstream the junction of Danjiang River and Hanjiang River. So the Danjiangkou Reservoir can be subdivided into Han Reservoir and Dan Reservoir. The gate for the water diversion canal is located at Taocha. There are approximately 200 tributaries in the Danjiangkou Reservoir catchment, of which 16 main tributaries make up 90% of the whole drainage area. These 16 tributaries include Hanjiang River, Danjiang River, Qihe River, Laoguan River, Taohe River, Duhe River, Langhe River, Shending River, Sihe River, Guanshan River, Jianhe River, Jianghe River, Quyuan River, Jiangjun River, Tianhe River, Taogou River. Qihe River, Taohe River and Laoguan River are tributaries of Danjiang River. Duhe River, Langhe River, Shending River, Sihe River, Guanshan River, Jianhe River, Jianghe River, Quyuan River, Jiangjun River, Tianhe River and Taogou River are tributaries of Hanjiang River.

The Danjiangkou Reservoir lies within the northern subtropical zone, and the region exhibits a subtropical monsoon climate. The annual mean air temperature is 15-16 °C, frost free period is 230-250d and the annual precipitation is 800-1000 mm, 70%-80% of the annual precipitation falls in May to October.

2.2. Water quality monitoring
25 different sampling sites in Danjiangkou Reservoir and 16 main tributaries were selected. Six of these water quality monitoring sites, Hejiawan, Bashang (near the dam), Bashangzhong, Taizishan, Jiangbei Bridge, Taocha (the gate for the water diversion canal), were used to measure the water quality in the reservoir. Four of these water quality monitoring sites, Baihe, Liejinba, Yangwei, and Chengjiapo, were used to measure the water quality in Hanjiang River. 11 water quality monitoring sites located near the mouths of 11 main tributaries of Hanjiang River including Quyuan River, Tianhe River, Duhe River, Jiangjun River, Taogou River, Jianghe River, Sihe River, Guanshan River, Jianhe River, Langhe River, Shending River, were used to measure the water quality in 11 main tributaries of Hanjiang River. The water quality monitoring site Zijingguan was used to measure the water quality of Danjiang River. 3 water quality monitoring sites located near the mouths of 3 main...
tributaries of Danjiang River, Qihe River, Taogou River, Laoguan River, were used to measure the water quality in tributaries of Danjiang River.

The map of water quality monitoring sites distribution is shown in Figure 1. Water samples were collected in the middle of each month throughout 16 months from July 2013 to October 2014.

Stainless steel water sampler was used to sample water from the sampling location. The sampler was washed with detergent, tap water, 10% hydrochloric acid and tap water, sampling water in turn before use. 22 water quality parameters were analysed on the basis of “Standard Methods for the Examination of Water and Wastewater”. Samples for analysing bacteriological parameters were collected in glass bottles cleaned with tap water, detergent, diluted HNO₃, distilled water two times and disinfected at 105°C. Samples for analysing physical and chemical parameters were stored in polyethylene bottles. Before sampling, sample bottles were rinsed with sampling water and stored at 4°C to transferred to the laboratory for analysis. Temperature, pH and dissolved oxygen were analysed on site by using thermometer, HACH pH and DO meter respectively. While the other parameters were analysed in the laboratory.

![Figure 1. Water Quality Sampling Sites of Danjiangkou Reservoir and its tributaries](image)

2.3. Water quality standard
To evaluate water quality of Danjiangkou Reservoir and its tributaries, the Water quality standard of the class III in the National Environmental Quality Standards for Surface Waters in China (GB3838-2002) was used. The water quality standard of class III in GB3838-2002 was used for water quality assessment of drinking water source.

2.4. Calculation of Water Quality Index
CCMEWQI is calculated with the following equation [14–15].

\[
WQI = 100 - \frac{F_1 + F_2 + F_3}{1.732}
\]

Where: \( F_1 \) - the percentage of parameters that do not meet water quality standards

\[
F_1 = \frac{\text{Number of failed parameters}}{\text{Total number of parameters}} \times 100
\]

\( F_2 \) - the percentage of individual tests that do not meet water quality standards

\[
F_2 = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100
\]

\( F_3 \) - the excursion to which the failed test exceed the standard. \( F_3 \) is calculated in the following three steps.

1) Excursion calculation of: Excursion is the times of parameter value exceeding the standard. When the parameter concentration must not exceed the standard:

\[
\text{Excursion}_1 = \frac{\text{Failed parameter value}_1}{\text{Standard}_1} - 1
\]

When the parameter concentration must not less than the standard:

\[
\text{excursion}_1 = \frac{\text{Standard}_1}{\text{Failed parameter value}_1} - 1
\]

2) Calculation of the normalized sum of excursions (nse):
3) $F_3$ is calculated with an equation that scales the normalized sum of the excursions from standards (nse) to yield a value between 0 and 100.

$$F_3 = \frac{nse}{0.01 \cdot nse + 0.01}$$  \hspace{1cm} (7)

The above equation produces a value of WQI between 0 and 100 and the water quality is ranked into five categories as shown in Table 1.

| Categories | WQI value |
|------------|-----------|
| Excellent  | 95–100    |
| Good       | 80–94     |
| Fair       | 60–79     |
| Marginal   | 45–59     |
| Poor       | 0–44      |

### 3. Results and Discussion

#### 3.1. Descriptive Statistics of 22 Water Quality Parameters

400 samples were taken and 22 parameters were analysed. Among the 22 parameters analysed, 13, 5 and 4 parameters were found having very low concentration lower than method detection limit in the sampling sites in Danjiang Reservoir, Hanjiang River and its tributaries, Danjiang River and its tributaries, respectively. Statistic results for the parameters which include minimum, maximum, average and standard deviation for monitoring site in the Reservoir area, Danjiang River and its tributaries, Hanjiang River and its tributaries, are shown in Table 1, Table 2, and Table 3 respectively. Data less than the method detection limit was counted as the 1/2 method detection limit for statistical calculation.

The pH value of all samples measured varied from 7.12 to 8.7 indicating that the water is slightly alkaline. The maximum and average values of pH did not exceed the limit of Class III in GB3838-2002.

The minimum DO concentration in Danjiangkou reservoir was 5.81mg/L higher than the standard of 5mg/L, which indicates that all DO values in water samples from Danjiangkou Reservoir could meet the Class III water quality standard for drinking purposes. The minimum DO concentration in water samples from tributaries of Danjiang River and Hanjiang River was 1.7 and 0.6mg/L respectively, indicating that Do values sometimes couldn’t meet the Class III water quality standard for drinking purposes. The maximum and mean values of DO for the reservoir and rivers were arranged in the following order: Reservoir > Hanjiang River and its tributaries > Danjiang River and its tributaries.

The maximum and average values of all parameters except pH, DO, fluoride, copper for the reservoir and rivers were arranged in the following order: Reservoir < Hanjiang River and its tributaries < Danjiang River and its tributaries. All these phenomena indicate that the pollution status of Hanjiang River and its tributaries is the most serious, and water quality in the reservoir area is the best.

Table 4 shows the statistical results of all tests. 400 samples were taken and 8800 tests were conducted. 96 samples and 2112 tests were used to represent water quality in reservoir area, 64 samples and 1408 tests were used to represent water quality in Hanjiang River, 176 samples and 3872 tests were used to represent water quality in tributaries of Hanjiang River, 16 samples and 352 tests were used to represent water quality in Danjiang River, 64 samples and 1408 tests were used to represent water quality in tributaries of Danjiang River. The failed tests mean the results of the tests cannot meet the standard of Class III in National Environmental Quality Standards for Surface Waters (GB3838-2002). Among 8800 tests conducted, 372 tests failed. Water quality in the reservoir area was the best, among 2112 tests with samples from 6 water quality monitoring sites in reservoir, no failed test existed. Among 1408 tests conducted with samples from 4 water quality monitoring sites in
Hanjiang River, namely, Baihe, Liejinba, Yangwei and Chengjiapo, 10 tests were failed. The failed parameter was fecal coliform. Among 3872 tests conducted with samples from water quality monitoring sites in 11 tributaries of Hanjiang River, 345 tests were failed. The water quality in Shending River, Sihe River, Jianghe River, Tianhe River and Jianhe River was poor. The water quality of Laoguan River was also poor based the amount of failed tests.

There were 9 parameters exceeding the water quality standard of Class III in *National Environmental Quality Standards for Surface Waters* (GB3838-2002), including fecal coliform, COD$_{cr}$, COD$_{Mn}$, BOD$_{5}$, NH$_{3}$-N, TP, DO, anionic surfactant and petroleum. Figure 2 illustrates the percentage of parameters that exceeded water quality standards. This figure shows which parameters exceeded the standard (F1) and the percentage (%) of each parameter to the total number parameters exceeding water quality standards.

The four most frequently failed parameters were fecal coliform bacteria, TP, ammonia nitrogen, COD$_{Mn}$ with failed frequency of 30%, 14%, 14%, and 14%, respectively (Figure 2). The four parameters accounted for 72% of the exceedances in Hanjiang River, Danjiang River and their tributaries implying that they were the most common parameters exceeding standards and having the most influence on the water quality index.

Figure 3 shows the frequency of failed tests in different locations. Shending River, Sihe River, Jianghe River, Tianhe River and Jianhe River were the five most seriously polluted rivers with failed frequency of 33.24%, 23.30%, 16.48%, 5.68% and 5.68%, respectively. These five rivers are tributaries of Hanjiang River.

Among the 372 failed tests, 91.4% were in samples from tributaries of Hanjiang River (Figure 4), 4.84% were in samples from the tributaries of Danjiang River, 2.69%, and 1.08% were in samples form Hanjiang River and Danjiang River, respectively. Which indicates that water quality status from good to bad is arranged in the following order: Reservoir > Danjiang River > Hanjiang River > tributaries of Danjiang River > tributaries of Hanjiang River.

**Table 1.** Statistic Data of Water Quality in the Danjiangkou Reservoir Area (unit: mg/L, except pH and fecal coliform).

| No. | Parameter   | Min. | Max.  | Average | Std. Deviation |
|-----|-------------|------|-------|---------|----------------|
| 1   | pH          | 7.56 | 8.52  | 8.12    | 0.22           |
| 2   | DO          | 5.81 | 12.71 | 9.40    | 1.90           |
| 3   | COD$_{Mn}$  | 1.6  | 2.9   | 2.0     | 0.30           |
| 4   | BOD$_{5}$   | 1.0  | 2.2   | 1.5     | 0.29           |
| 5   | NH$_{3}$-N  | 0.063| 0.349 | 0.136   | 0.07           |
| 6   | TP          | 0.01 | 0.02  | 0.016   | 0.005          |
| 7   | F-          | 0.2  | 0.28  | 0.25    | 0.019          |
| 8   | Petroleum   | <0.01| 0.04  | 0.009   | 0.008          |
| 9   | Fecal Coliform (CFU/L) | <20  | 240   | 33      | 46             |

**Table 2.** Statistic Data of Water Quality in Danjiang River and its Tributaries (unit: mg/L, except pH and fecal coliform).

| No. | Parameter   | Min. | Max.  | Average | Std. Deviation |
|-----|-------------|------|-------|---------|----------------|
| 1   | pH          | 7.6  | 8.3   | 8.0     | 0.18           |
| 2   | DO          | 1.7  | 12.5  | 8.81    | 2.87           |
| 3   | COD$_{Mn}$  | 0.9  | 6.5   | 2.10    | 1.1            |
| 4   | COD$_{Cr}$  | <10  | 35    | 16.37   | 6.58           |
| No. | Parameter               | Min. | Max.   | Average | Std. Deviation |
|-----|-------------------------|------|--------|---------|----------------|----------------|
| 1   | pH                      | 7.12 | 8.7    | 7.89    | 0.37           |
| 2   | DO                      | 0.6  | 12.4   | 8.36    | 2.4            |
| 3   | COD<sub>Mo</sub>        | 0.6  | 19.3   | 3.1     | 1.95           |
| 4   | COD<sub>C</sub>         | <10  | 96     | 22.6    | 12.05          |
| 5   | BOD<sub>5</sub>         | <0.5 | 44.9   | 2.8     | 3.6            |
| 6   | NH<sub>3</sub>-N        | 0.025| 16.1   | 1.12    | 1.85           |
| 7   | TP                      | <0.01| 1.2    | 0.08    | 0.14           |
| 8   | F<sup>-</sup>           | 0.047| 0.643  | 0.201   | 0.080          |
| 9   | Cu                      | <0.005| 0.025 | 0.012   | 0.009          |
| 10  | Zn                      | <0.005| 0.111 | 0.023   | 0.023          |
| 11  | As                      | 0.0007| 0.0051 | 0.0017  | 0.0007         |
| 12  | Hg                      | <0.00001| 0.00017 | 0.00001 | 0.000027 |
| 13  | Pb                      | <0.005| 0.014 | 0.0095  | 0.0064         |
| 14  | CN<sup>-</sup>          | <0.004| 0.02  | 0.0067  | 0.0037         |
| 15  | Volatile Phenol         | <0.0003| 0.0306 | 0.002   | 0.0033         |
| 16  | Anionic Surfactant      | <0.05 | 1.4    | 0.11    | 0.10           |
| 17  | Petroleum               | 0.01 | 1.22   | 0.115   | 0.232          |
| 18  | Fecal Coliform(CFU /L)  | <20  | 2400000| 99610   | 221255         |

**Table 3.** Statistic Data of Water Quality in Hanjiang River and its Tributaries (unit:mg/L, except pH and fecal coliform).
Table 4. Statistics Data of All Tests.

| Location         | Sample site   | Samples /tests | Failed tests(%) | Failed parameters |
|------------------|---------------|----------------|-----------------|-------------------|
| Reservoir area   |               |                |                 |                   |
| Bahshang         | 16/352        | 0              | none            |                   |
| Taocha           | 16/352        | 0              | none            |                   |
| Taizishan        | 16/352        | 0              | none            |                   |
| Hejiawan         | 16/352        | 0              | none            |                   |
| Bashangzhong     | 16/352        | 0              | none            |                   |
| Jiangbei Bridge  | 16/352        | 0              | none            |                   |
| Hanjiang River   |               |                |                 |                   |
| Liejinba         | 16/352        | 0              | none            |                   |
| Baihe            | 16/352        | 1.70%          | FC              |                   |
| Chenjiapo        | 16/352        | 0.57%          | FC              |                   |
| Yangwei          | 16/352        | 0.57%          | FC              |                   |
| Quyuwan River    | 16/352        | 2.84%          | FC              |                   |
| Jianjune River   | 16/352        | 1.42%          | FC              |                   |
| Taogou River     | 16/352        | 0.57%          | FC              |                   |
| Langhe River     | 16/352        | 1.14%          | FC, COD Cr      |                   |
| Guanshan River   | 16/352        | 1.99%          | FC, COD Cr, TP  |                   |
| Duhe River       | 16/352        | 2.56%          | FC, COD Cr, NH3-N|                 |
| Jianhe River     | 16/352        | 5.68%          | FC, COD Cr, BOD5, COD Mn, NH3-N, TP | |
| Tianhe River     | 16/352        | 6.82%          | FC, COD Cr, BOD5, COD Mn, NH3-N, TP | |
| Sihe River       | 16/352        | 23.30%         | FC, COD Cr, BOD5, COD Mn, NH3-N, TP, DO | |
| Jianghe River    | 16/352        | 16.48%         | FC, COD Cr, BOD5, COD Mn, NH3-N, TP, DO, AS | |
| Shending River   | 16/352        | 33.24%         | FC, COD Cr, COD Mn, BOD5, NH3-N, TP, DO, AS, Petroleum | |
| Danjiang River   |               |                |                 |                   |
| Zijingguan       | 16/352        | 1.14%          | FC, COD Mn, NH3-N, TP | |
| Qihe River       | 16/352        | 0              | none            |                   |
| Taohe River      | 16/352        | 0              | none            |                   |
| Laoguan River    | 16/352        | 5.11%          | FC, COD Cr, COD Mn, BOD5, NH3-N, DO | |
| Total            |               | 400/8800       | 4.23%           |                   |

*FC-Fecal Coliform, AS- Anionic Surfactant
Applying the CCMEWQI equation on water quality analysis, Water quality indexes of all monitoring sites in Danjiangkou Reservoir were ranked 100, indicating water quality of the Reservoir was excellent and was protected with absence of threat. Water quality can meet the standard of drinking water source.

Water quality indexes at 4 monitoring sites in Hanjiang River, Chenjiapo, Yangwei, Baihe and Liejingba, were ranked 97.83, 97.85, 97.71 and 100 respectively. Water quality could satisfy the goal for drinking water sources.

Water quality indexes for 11 tributaries of Hanjiang River are shown in Table 5. Water quality indexes of Taogou River and Langhe River were between 95 and 100, indicating the water quality was excellent. Water quality indexes of Guanshan River, Quyuan River and Duhe River were between 80 and 94, indicating the water quality was good. Water quality indexes of Sihe River, Tianhe River, Jianhe River and Jiangjun River were between 60 and 79, water quality is fair. Water quality index of Jianghe River is 58, water quality is marginal. Water quality index of Shending River is 43.66, Water quality is poor.

| No. | Sampling sites   | WQI   | Water Quality   |
|-----|------------------|-------|-----------------|
| 1   | Taogou River     | 97.83 | Excellent water |
| 2   | Langhe River     | 95.68 | Excellent water |
| 3   | Guanshan River   | 93.47 | Good water      |
| 4   | Quyuan River     | 91.49 | Good water      |
| 5   | Duhe River       | 90.6  | Good water      |
| 6   | Jiangjun River   | 77.88 | Fair water      |
| 7   | Jianhe River     | 75.06 | Fair water      |
| 8   | Tianhe River     | 64.00 | Fair water      |
| 9   | Sihe River       | 60.05 | Fair water      |
| 10  | Jianghe River    | 58.00 | Marginal water  |
| 11  | Shending River   | 43.66 | Poor water      |

Water quality indexes of Danjiang River and its tributaries are shown in Table 6. Water quality index of Laoguan River was ranked 89.73, water quality was good. Water quality indexes of other sampling sites were higher than 94, water quality was excellent.
Table 6. Water Quality Index on Different Sampling Sites of Danjiang River and its Tributaries.

| Site No. | Sampling sites    | WQI    | Water Quality  |
|----------|------------------|--------|----------------|
| 1        | Zijingguan        | 95.43  | Excellent water|
| 2        | Qihe River       | 100    | Excellent water|
| 3        | Taohe River      | 100    | Excellent water|
| 4        | Laoguan River    | 89.73  | Good water     |

The percentage of each WQI category of 25 sampling sites is shown in Figure 5. Water quality of 60% of the sampling sites was categorized as excellent water.

Figure 4. Percentage of total failed tests versus locations

Figure 5. WQI Classification of 25 Sampling Sites

4. Conclusion

Water quality indexes of Danjiangkou Reservoir and its tributaries were calculated by using 22 water quality parameters from 25 sampling sites to evaluate the suitability as drinking water source. The following conclusions can be drawn on the basis of descriptive analysis and water quality index calculation.

1) Water quality indexes of Danjiangkou Reservoir were 100 which indicates water quality in the reservoir area was excellent and the water source was protected with a virtual absence of threat; the water source conditions were very close to natural levels.

2) Water quality indexes of the two major tributaries of Danjiangkou Reservoir, Hanjiang River and Danjiang River, were in the range from 95.43 to 100, indicating water quality of Hanjiang River and Danjiang River is excellent. Only a few tests of water quality monitoring are failed. The failed variables were fecal coliform bacteria, COD$_{Mn}$, NH$_3$-N, TP.

3) Water quality indexes of 11 tributaries of Hanjiang River were in the range from 43.66-97.83. Water quality of 11 tributaries from good to bad is in the following order: Taogou River > Langhe River > Guanshan River > Qinghun River > Duhe River > Jiangu River > Tianhe River > Sihe River > Jianghe River > Sheding River. The seriously polluted tributary rivers were Sheding River, Jianghe River, Sihe River, Tianhe River, Jiangu River and Jiangu River. The failed variables were fecal coliform bacteria, COD$_{cr}$, COD$_{Mn}$, BOD$_5$, NH$_3$-N, TP, DO, anionic surfactant, petroleum.

4) Fecal coliform bacteria, TP, ammonia nitrogen, COD$_{Mn}$ were the most common parameters to fail and having the most influence on the Water Quality Index.

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