Spatial variation of water quality in upper catchment of Miyun Reservoir
Erqi Xu, Hongqi Zhang, Guanglong Dong, Lei Kang and Xuejiao Zhen

ABSTRACT
Miyun Reservoir is the main surface source of drinking water for Beijing, China. Water eutrophication has compelled authorities to improve the water quality in its upstream catchment. However, a water-quality survey of the entire catchment was lacking. A total of 52 monitoring sites covering the entire catchment were sampled approximately monthly from July–September 2013, in response to rainfall and runoff. Six water nutrient concentrations were used to characterize the eutrophication, which was relatively severe. The total nitrogen pollution was classified as the worst grade of the water-quality standard. The water quality of Bai River was superior to that of Chao River, while the quality of tributaries was better than that of main rivers. The upstream and downstream reaches of main rivers and small tributaries usually had cleaner water than the middle reaches. The worst pollution mainly appeared in the middle reaches in Hebei Province. Spatial variations in water quality were closely related to land use quantitative characteristics of sub-watersheds. We suggest that a balanced, transparent compensation mechanism focused on Hebei Province would assist to improve water quality.

Key words | Miyun Reservoir, spatial distribution, water conflict, water eutrophication

INTRODUCTION
Beijing, the capital of China, is confronted with a severe shortage of water and an intensified conflict between water supply and demand. Rapid urbanization has led to concerns about the quantity and quality of available water resources (Wolf et al. 2003). Miyun Reservoir, the largest in northern China, has become the main surface source of potable water for Beijing (Ma et al. 2010). However, nitrogen and phosphorus pollution has caused the eutrophication and degradation of water quality of this reservoir (Wang & He 2002). This pollution reduces the volume of clean water availability and threatens the sustainability of the water supply to Beijing.

The rapid development of agricultural facilities, with the attendant risk of nutrient losses to the water from excess fertilizers, is expected to increase. At the same time, the increasing population and development of rural tourism would also increase the sewage and pollutant discharges. Studies show that nutrient levels of the water in the upper catchment of Miyun Reservoir have increased since the 1990s (Du et al. 2004; Jiao et al. 2015). From 1990 to 2010, the nitrogen concentration in the catchment increased significantly (Li et al. 2013). Moreover, measured against the water quality standards in China, results from most water quality monitoring sites indicate that the total nitrogen (TN) concentration in the catchment was of the worst grade (Jiao et al. 2015).

The upper catchment of Miyun Reservoir covers Beijing and Hebei Province. Since two-thirds of the catchment area is located in Hebei, the land and water use systems in this province have a considerable effect on the water quality of Miyun Reservoir (Peisert & Sternfeld 2005). The water shortage in Beijing has intensified the conflict between Beijing and the...
Hebei Province over the use of water (Zhou et al. 2009). Consequently, Beijing authorities have entered into negotiations with upstream counties in Hebei and have been compensating farmers for reducing their water use. In addition to increasing the supply of water, Beijing has requested Hebei provincial authorities to improve the water quality. Consequently, the water management authorities focused their attention on improving the water quality, especially of upstream reaches in Hebei (Peisert & Sternfeld 2005).

Recent studies have concentrated mainly on the lakeshore catchment near the Miyun Reservoir, which belongs to Beijing (Wang et al. 2001, 2009a; Wang & He 2002; Ou & Wang 2011; Jiao et al. 2015). However, limited information is available on the upstream reaches in Hebei Province. Various models, such as the Soil and Water Assessment Tool (SWAT) (Xu et al. 2009) and Geomorphology-Based Hydrological Model (GBHM) (Tang et al. 2011) can simulate spatial variations of the water pollution. However, these models can only be validated by data from the limited number of hydrological stations, mainly near the Miyun Reservoir, leading to considerable uncertainties, especially pertaining to the upstream reaches. As the water quality in upstream reaches is important for effective decision making, a detailed survey and evaluation of the water quality within different sub-watersheds, relevant to the entire catchment area, is needed.

The objective of this study is to investigate and comprehensively evaluate spatial variations of water pollution in the upper catchment of Miyun Reservoir. We collected water samples at different monitoring sites. Based on spatial analyses and statistical methods, we analyzed spatial variations of the water quality between sub-watersheds. Additionally, we identified important land uses contributing to pollution in an effort to inform policy development and support sustainable water management.

MATERIALS AND METHODS

Study area

The Miyun Reservoir is located approximately 100 km north of Beijing. Its upper catchment, the Chaobai River catchment, covers an area of 15,788 km² and is located roughly between 40°19′–41°38′N latitudes and 115°25′–117°35′E longitudes (Figure 1). The catchment comprises Yanqing County, Huairou District and Miyun County in Beijing.
and the counties of Fengning, Luanping, Chicheng, Chengde, Guyuan, and Chongli in Hebei. Chaobai River is part of the Haihe River, with the east branch of Chao River and the west branch of Bai River. Chao River originates in Fengning County, flows through Luanping and Miyun, and flows into the Miyun Reservoir near the Xin Village. The Andamu, Qingshui, and Hongmenchuan rivers are the three tributaries of the Chao River. Bai River originates in Guyuan County, flows through Chicheng, Yanqing, and Huairou, and, subsequently, flows into the reservoir near the Zhangjiafen Village, together with its tributaries, including Hei, Tang, and Baimaguian rivers.

The upper catchment lies within the warm, semiarid monsoon climate zone, with a mean annual temperature of 9–10 °C and a mean annual precipitation of 489 mm. The precipitation between June and September accounts for 80–85% of the total annual precipitation. The elevations range from 65 to 2,300 m. Four principal soil types are found, namely, cinnamon soil, brown soil, meadow soil, and chestnut soil. The main economic activity of counties in Hebei is agriculture, with a relatively weak industrial development. The main cereal crops are corn, rice, sorghum, millet, and soybeans, and the cash crops include peanuts, sesame seeds, and tobacco.

**Water sample collection**

Using the hydrological analysis tool in ArcGIS 10.1 (ESRI Inc., USA) and digital elevation data, coupled with the field study, the whole catchment area was divided into various sub-watersheds. The digital elevation data were obtained from the global topography database (http://www.gscloud.cn/), with a spatial resolution of 30 m and a vertical resolution of 20 m. Several sub-watersheds with ephemeral rivers were excluded. We identified 52 sub-watersheds, with each monitoring site located at the outlet of the corresponding sub-watershed (Figure 2). The average area of sub-watersheds was 252 km², the maximum area was 1,269 km², and the minimum area was 15 km².

Rainfall is generally considered the main source of the annual runoff, and precipitation during the rainy season accounts for 80 to 85% of the total annual precipitation. Consequently, we collected monthly water samples from the 52 monitoring sites during the rainy season, from July to September 2013. Because several rivers were ephemeral, we collected 48, 52, and 51 water samples in July, August, and September, respectively. Water samples collected during the day were submitted to the laboratory for chemical
analysis the next day. The monthly water samples were collected within a 4-day sampling period after a heavy storm. During the sampling period, there was no rainfall and the runoff resulting from the previous rainfall had become smooth, which could mitigate the impact of flow conditions on water nutrients. Also, the runoff from the same rainfall occurrence would reduce the variability of the flow conditions between different watersheds to a large degree.

**Land use qualitative calculation**

Using four Landsat-8 Operational Land Imager images from 2013, we visually interpreted the land use map of the study area. Four land use types, including arable land, forest, grassland, and residential land, which are closely related to water nutrients, were interpreted. The other types of land use, including open water, industrial and mining land, and road and unused land, were grouped together as ‘other land’. A total of 910 ground reference data were used to assess the accuracy of the land use map. The overall accuracy and the kappa coefficient (Congalton 1991) were 0.902% and 91.70%, respectively, confirming that the land use map was highly accurate. To analyze the relationship between the land use and water quality variables at the sampling sites, boundaries of sub-watersheds (Figure 2) were used to delineate the limited contribution range of land uses to water nutrients and calculate land use proportions.

**Chemical analysis methods**

To fully characterize the water eutrophication level in the catchment, six water nutrient concentrations were analyzed in the samples from 52 monitoring sites. TN, nitrate nitrogen (NO$_3^-$-N), ammonium nitrogen (NH$_4^+$-N), total phosphorus (TP), chemical oxygen demand (COD) and biological oxygen demand over 5 days (BOD$_5$) were measured. All analyses were done in accordance with the national quality standards for surface water in China (HJ554-2010). The chemical analysis methods employed were TN, alkaline potassium persulfate digestion, coupled with ultraviolet spectroscopy; NO$_3^-$-N, ultraviolet spectrophotometry; NH$_4^+$-N, Nessler’s reagent spectrophotometry; TP, the ammonium molybdate spectrophotometric method; COD, the potassium dichromate titration method; and BOD$_5$, the dilution and seeding method over 5 days.

**Statistical analysis methods**

Cronbach’s Alpha Reliability Coefficient (Gliem & Gliem 2003) was calculated by using six water nutrient concentrations, collected by repeated sampling over three months to assess their internal consistency at the sampling sites. The coefficient normally ranges between 0 and 1, and can be interpreted with the following rule of thumb: >0.9 is ‘Excellent’; [0.8, 0.9] is ‘Good’; [0.7, 0.8] is ‘Acceptable’; [0.6, 0.7] is ‘Questionable’; [0.5, 0.6] is ‘Poor’; and <0.5 is ‘Unacceptable’ (George & Mallery 2003).

Factor analysis was applied to interpret the observed relationships among six water nutrient concentrations and to yield simpler relationships that provide insight into the underlying structure of variables (Liu et al. 2005). Each group of water nutrient concentrations from 52 monitoring sites was standardized using the mean and variance. Factor analysis reduces the contribution of less significant variables by means of a varimax rotation on the factor-loading matrix. Using the linear model, all the original water nutrient concentrations can be reduced into new and limited variables, which can be interpreted as factor 1, factor 2, etc. Factors, of which the eigenvalues exceeded a value of 1, were extracted (Pekey et al. 2004) to interpret more simply and intuitively the water quality. SPSS 18.0 software was used to perform the factor analysis.

**RESULTS**

**Statistical characteristics of nutrient concentrations**

The average nutrient concentrations of 52 sub-watersheds in the upper catchment of the Miyun Reservoir for the period July to September are shown in Table 1. During the three months, different water nutrient concentrations showed different trends, with the TN, NO$_3^-$-N, COD, and BOD$_5$ concentrations showing an increasing trend over this time. The average BOD$_5$ concentration increased most significantly, changing from 4.7 mg/l in July to 8.0 mg/l in September. In contrast, NH$_4^+$-N and TP concentrations showed a
decreasing trend, especially from August to September, when the concentrations decreased significantly.

Using Cronbach’s Alpha Reliability Coefficient, we checked the internal consistency of nutrient concentrations for the three-month period. The coefficients of TN and NO₃⁻N concentrations were 0.920 and 0.912, respectively, which show excellent temporal consistency, while TP, with a coefficient of 0.822, shows good temporal consistency. The temporal consistencies of COD and BOD₅, with coefficients between 0.7 and 0.8, can be considered acceptable. Only the NH₄⁺-N concentration, with a coefficient of 0.547, presented poor consistency over the study period. Nevertheless, we calculated the average water-nutrient concentrations within the three-month period for the subsequent analysis.

The basic statistical characteristics of nutrient concentrations are shown in Table 1. A comparison of nutrient concentrations with the water quality standards in China (GB3838-2002) (Table 2) shows that the water eutrophication status of the catchment was a cause for concern. The TN pollution was acute, with the average TN concentration of all sites at grade 5 (the worst grade of the water quality standards). The average NO₃⁻N, NH₄⁺-N, TP, COD, and BOD₅ concentrations were at grades 4, 3, 3, 1 or 2, and 5 of the water quality standard, respectively. Only the NH₄⁺-N, TP, and COD pollution scored well according to the water quality standards.

### Table 1 | Statistical characteristics of water nutrient concentrations

<table>
<thead>
<tr>
<th></th>
<th>TN</th>
<th>NO₃⁻N</th>
<th>NH₄⁺-N</th>
<th>TP</th>
<th>COD</th>
<th>BOD₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>N(Average) (mg/l)</td>
<td>16</td>
<td>14</td>
<td>0.75</td>
<td>0.16</td>
<td>10</td>
</tr>
<tr>
<td>August</td>
<td>N(Average) (mg/l)</td>
<td>19</td>
<td>17</td>
<td>0.64</td>
<td>0.15</td>
<td>12</td>
</tr>
<tr>
<td>September</td>
<td>N(Average) (mg/l)</td>
<td>21</td>
<td>18</td>
<td>0.19</td>
<td>0.05</td>
<td>14</td>
</tr>
<tr>
<td>From July to September</td>
<td>N(Minimum) (mg/l)</td>
<td>2.05</td>
<td>1.47</td>
<td>0.18</td>
<td>0.02</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>N(Maximum) (mg/l)</td>
<td>38.9</td>
<td>34.2</td>
<td>1.2</td>
<td>0.5</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>N(Average) (mg/l)</td>
<td>18.9</td>
<td>16.5</td>
<td>0.52</td>
<td>0.12</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>N(Standard deviation)</td>
<td>8.82</td>
<td>7.84</td>
<td>0.23</td>
<td>0.10</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>N(Coeficient of variation)</td>
<td>0.47</td>
<td>0.47</td>
<td>0.44</td>
<td>0.85</td>
<td>0.63</td>
</tr>
<tr>
<td>Main rivers</td>
<td>N(Average) (mg/l)</td>
<td>21.5</td>
<td>18.7</td>
<td>0.58</td>
<td>0.15</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>N(Coeficient of variation)</td>
<td>0.41</td>
<td>0.41</td>
<td>0.39</td>
<td>0.80</td>
<td>0.73</td>
</tr>
<tr>
<td>Tributaries</td>
<td>N(Average) (mg/l)</td>
<td>17.0</td>
<td>14.8</td>
<td>0.48</td>
<td>0.1</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>N(Coeficient of variation)</td>
<td>0.50</td>
<td>0.51</td>
<td>0.48</td>
<td>0.86</td>
<td>0.55</td>
</tr>
<tr>
<td>Chao River catchment</td>
<td>N(Average) (mg/l)</td>
<td>21.5</td>
<td>18.8</td>
<td>0.43</td>
<td>0.14</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>N(Coeficient of variation)</td>
<td>0.42</td>
<td>0.42</td>
<td>0.50</td>
<td>0.75</td>
<td>0.47</td>
</tr>
<tr>
<td>Bai River catchment</td>
<td>N(Average) (mg/l)</td>
<td>16.6</td>
<td>14.4</td>
<td>0.61</td>
<td>0.11</td>
<td>9.81</td>
</tr>
<tr>
<td></td>
<td>N(Coeficient of variation)</td>
<td>0.49</td>
<td>0.51</td>
<td>0.35</td>
<td>0.96</td>
<td>0.77</td>
</tr>
</tbody>
</table>

### Table 2 | Water quality standards in China (GB3838-2002)

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN</td>
<td>0.2</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>NO₃⁻N</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>NH₄⁺-N</td>
<td>0.15</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>TP</td>
<td>0.02</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>COD</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>BOD₅</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

The upper limit value of NO₃⁻-N in these standards is 10 mg/l, but there is no detailed grading standards. The grading standards of NO₃⁻-N concentration refers to the study of Liu et al. (2001).

### Spatial variation of nutrient concentrations

A comparison of the nutrient concentrations of Chao and Bai rivers is presented in Table 1. Except for NH₄⁺-N concentrations, other average nutrient concentrations for the Chao River catchment were noticeably larger than for the Bai River catchment. For example, the COD concentration (14.7 mg/l) for the Chao River catchment was found to be approximately 50% higher than for the Bai River catchment (9.81 mg/l). Conversely, the variation coefficients of nutrient concentrations for the two catchments showed contrasting characteristics. Except for NH₄⁺-N, other variation
coefficients of nutrient concentrations for the Chao River catchment were noticeably smaller than those for the Bai River catchment.

Nutrient concentrations of the main rivers and tributaries were also compared in Table 1. It shows that TN, NO$_3^{-}$-N, NH$_4^+$-N, and TP concentrations in the main rivers were 21.5 mg/l, 18.7 mg/l, 0.58 mg/l, and 0.15 mg/l, respectively, obviously larger than the 17.0 mg/l, 14.8 mg/l, 0.48 mg/l, and 0.10 mg/l, respectively, in the tributaries. Only COD and BOD$_5$ concentrations in the main rivers were smaller than those for the tributaries. Interestingly, the variations of TN, NO$_3^{-}$-N, NH$_4^+$-N, and TP concentrations for the main rivers were smaller than for the tributaries, but variations of COD and BOD$_5$ concentrations in the main stream were larger than those for the tributaries.

The spatial variations of every nutrient concentration at the 52 sites were mapped in Figure 3. Two groups (TN and NO$_3^{-}$-N, COD and BOD$_5$) presented similar spatial distributions (Pearson coefficients of two groups at the 52 sites were 0.990 and 0.997). The different spatial variations of nutrient concentrations were as follows:

1. High TN and NO$_3^{-}$-N concentrations appeared mainly in the middle reaches. The TN and NO$_3^{-}$-N concentrations in the downstream reaches and lakeshore near the reservoir were relatively low. The pollution was especially low in several tributaries, including the Baima, Liuli, Caishi, and Hei rivers.

2. The NH$_4^+$-N concentrations in the major reaches of Chao River catchment were relatively low. In Bai River catchment, high NH$_4^+$-N concentrations mainly appeared in the upstream and middle reaches, but the NH$_4^+$-N concentrations of downstream reaches and the lakeshore were relatively low.

3. High TP concentrations appeared mainly in the middle and downstream Chao River and the upstream Bai River. TP concentrations of the downstream Bai River catchment and the lakeshore were relatively low. In particular, TP concentrations of the Qingshui and Liuli rivers and the main Bai River flowing into the Miyun Reservoir were at or close to grade 1 (very clean) of the water quality standard.

4. High COD and BOD$_5$ concentrations appeared mainly in the upstream and middle Chao River, the upstream Bai River, and the lakeshore near the Miyun Reservoir. Low COD and BOD$_5$ concentrations were mainly found in the downstream Bai River catchment.

**Factor analysis of water quality data**

Factor analysis was used to describe the observed nutrient concentrations in a reduced number of factors. Our study finally extracted three factors, following the rule that eigenvalues exceed 1 (Pekey et al. 2004). Factors 1, 2, and 3 account for 39.23, 34.48, and 19.43% of the total variance in the original data. Factor loadings, indicating the correlation between factors and original variables, were calculated, and are presented in Table 3. Using the criteria of Liu et al. (2003) to judge the degree of correlation, factor loadings $>0.75$, $[0.5–0.75]$, and $[0.3–0.5]$ were considered to be strong, moderate, and weak correlations, respectively. Because of the high correlation between the TN and NO$_3^{-}$-N concentrations, and the COD and BOD$_5$ concentrations, these two groups were reduced to be described by factors 1, and 2, respectively. Factor 1 has a strong correlation with TN and NO$_3^{-}$-N, and a medium correlation with TP. Factor 2 has a strong correlation with COD and BOD$_5$, while factor 3 has a strong correlation with NH$_4^+$-N.

The scores for factors 1, 2, and 3 were plotted to generate a three-dimensional map (Figure 4(a)) to comprehensively evaluate the water quality. The sites were located in the quadrant with negative values in the $x$, $y$, and $z$ axes, which means that all nutrient concentrations were relatively low. The farther away from the origin point, the lower were the nutrient concentrations of the site. Sampling sites with serial numbers 24, 26, 27, 40, 41, 43, 44, 45, 46, 48, 49, 50, and 51 were identified and labelled as a cluster (Cluster 1), as shown by the box in Figure 4(a).

In contrast, there were limited sites in the quadrant with positive values in the $x$, $y$, and $z$ axes, including those with serial numbers 18, 20, 28, and 29. Except for site number 20, the scores for three factors in the other three sites were not high simultaneously, only parts of the factors were high. It indicates that the pollution is not significantly serious in these sites. Summing scores for three factors and ranking them, we identified sites with ten minimum values and excluded the site 18 to label them as two clusters with...
Figure 3 | Spatial distribution of: (a) TN; (b) NO$_3$-N; (c) NH$_4^+$-N; (d) TP; (e) COD; and (f) BOD$_5$. 
the most serious water eutrophication. According to Figures 4(b) and 4(c), two clusters were located far from the origin point in the first axis. The cluster, including sites 6, 20, 29, 30, 36, and 37 (Cluster 2) had high NH₄⁺-N, COD, and BOD₅ concentrations. Cluster 3, including sites 10, 33, and 35, had high TN, NO₃⁻-N, TP, COD, and BOD₅ concentrations.

As land use is closely related to water quality, we calculated land use structures of the above mentioned three clusters and compared them with the mean values of 52 sub-watersheds (Table 4). The comparison showed that area proportions of the arable land, grassland, and residential land of Cluster 1, with low nutrient concentrations, were obviously lower than the mean values, but the forest proportion was much higher. In contrast, Clusters 2 and 3, with severe incidence of water pollution, would have higher area proportions of the three nutrient sources, but a

Table 3  Varimax rotated factor loading of water nutrients

<table>
<thead>
<tr>
<th>Factor</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN</td>
<td>0.983</td>
<td>0.074</td>
<td>-0.013</td>
</tr>
<tr>
<td>NO₃⁻-N</td>
<td>0.984</td>
<td>0.085</td>
<td>-0.033</td>
</tr>
<tr>
<td>NH₄⁺-N</td>
<td>-0.031</td>
<td>-0.083</td>
<td>0.957</td>
</tr>
<tr>
<td>TP</td>
<td>0.627</td>
<td>0.312</td>
<td>0.498</td>
</tr>
<tr>
<td>COD</td>
<td>0.089</td>
<td>0.992</td>
<td>-0.005</td>
</tr>
<tr>
<td>BOD₅</td>
<td>0.137</td>
<td>0.984</td>
<td>-0.025</td>
</tr>
</tbody>
</table>


Figure 4  Factors of waters nutrient concentrations in the coordinate axis: (a) factors 1, 2, 3; (b) factors 1, 2; (c) factors 2, 3; and (d) factors 1, 3.
lower forest proportion. In particular, a much higher area of residential land for Cluster 2 implied that nutrients were mainly from the rural waste discharge. In addition, nutrients could be mainly from the arable land and grassland in Cluster 3, where there was a much higher proportion of these land uses.

**Land uses related to water quality**

The 52 sub-watersheds showed significant differences in proportional land use (Figure 5). Significant correlation between the land use proportions and water quality was observed (Table 5). Arable land, grassland, and residential land proportions were positively correlated with the factor scores. Conversely, the proportion of forest was negatively correlated with the identified factor scores. Arable land, forest, and grassland were significantly correlated with factor 1 at a confidence level of 99%. In addition, a significant correlation was found at a confidence level of 99% between factor 2 and the arable and residential land. No significant correlation was identified between factor 3 and the land use proportions analyzed.

**DISCUSSION**

**Spatial distribution of water quality**

Better quality water was found in the upstream and downstream reaches and several small tributaries, while the severe water pollution mainly appeared in the middle reaches of main rivers. Human activities are considered the main cause of polluted rivers (Ou & Wang 2008; Wang et al. 2009b), a conclusion supported by the positive correlation found between human land use (agriculture, residence) and water quality variables. Furthermore, different land use structure characteristics represented different nutrient sources for the two severely polluted clusters. This information can be a guide in planning land uses and implementing the amelioration measures to combat the pollution.

Consequently, the spatial distribution of human activities would affect the spatial distribution of the water quality (Tang et al. 2011). Limited disturbance by human activity of upstream sub-watersheds was evident from the limited effect on the quality of the water. Additionally, strict protection policies and engineering measures were implemented in area near the Miyun Reservoir (Jia et al. 2012), which effectively control and improve the water quality of downstream reaches and the lakeshore. However, sub-watersheds located in the middle reaches of main rivers are lower-lying areas, with the majority of towns being located...
near the main river including the county seats of Chicheng and Fengning counties in Hebei Province. The high population density generates considerable sewage and garbage flowing into the watercourse (Jiao et al. 2015). Furthermore, the livestock and poultry farms located mainly in these areas have become additional pollution sources to these rivers (Wang et al. 2009b).

**Water quality conflicts between Beijing and Hebei**

As nutrients in the water of the catchment derive mainly from non-point sources (Jiao et al. 2015), the widespread pollutant sources of the entire catchment area have to be managed and controlled. Moreover, almost all the severely polluted rivers are located in Hebei Province and they significantly affect the water quality of the Miyun Reservoir (Peisert & Sternfeld 2005). Although nutrients from the Hebei decay significantly over the long flowing distance to the downstream area, the continuous discharge of nutrients into the river pose a significant risk to the water of Miyun Reservoir and a considerable threat to the health of residents of Beijing. The spatial difference found in the water quality of Beijing and Hebei has to be taken into consideration in decision making.

The increasing demand for potable water in Beijing has aggravated the water disputes between Beijing and Hebei. Several projects and measures have been implemented to increase the supply of water to Beijing and to improve the water quality (Cui et al. 2014). Beijing and the national government of China compensate the residents of Hebei for restricting their water use in order to supply more water to Beijing (Zhou et al. 2009; Cui et al. 2014). However, there is a significant gap between the current compensation levels and the income levels and production losses of the farmers (Zhou et al. 2009; Cui et al. 2014). The inadequate compensation has a negative effect on the enthusiasm and willingness of the residents concerned to participate in relevant projects. Therefore, a balanced and transparent compensation policy could be developed and implemented to protect the water resources in the catchment. In addition, more direct and effective measures could be developed to control pollutant sources and reduce nutrients flowing into the watercourses of the severely polluted area of Hebei.

**CONCLUSION**

A comprehensive investigation into, and evaluation of, the water quality was conducted in the catchment of Miyun Reservoir. TN, NO₃⁻N, NH₄⁺-N, TP, COD, and BOD₅ concentrations from 52 monitoring sites, situated over the entire catchment were analyzed to characterize the water pollution. Results indicated relatively severe water eutrophication in the catchment. The TN pollution was the most significant, and the average TN concentration was at the worst grade of the water quality standards. NO₃⁻N, NH₄⁺-N, TP, COD, and BOD₅ concentrations were at grades 4, 3, 3, 1 or 2, and 5 of the water quality standards, respectively. The nutrient concentrations observed showed relative temporal consistency from July to September, according to Cronbach's Alpha Reliability Coefficients. Results showed that water quality from the Bai River was better than that from the Chao River, and the water quality of tributaries was superior to that from the main rivers. The watercourses with good quality are located mainly in the upstream or downstream reaches and in several small tributaries, while severe water pollution was found mainly in the middle reaches of main rivers. Furthermore, almost all severely polluted rivers were located in Hebei. Land use was closely related to spatial variations of water nutrient concentrations. The correlation between nutrient concentrations and different land use characteristics in sub-watersheds can help guide land use planning and the implementing of measures to combat the severe pollution. A balanced and transparent compensation mechanism is suggested for Hebei to control pollutant sources and reduce nutrients flowing into the Miyun Reservoir, particularly with regard to the severely polluted area identified by our study.

**ACKNOWLEDGEMENTS**

This work was jointly supported by the Director Innovation Fund sponsored by the Institute of Geographical Sciences and Natural Resources Research, and the National Basic Research Program of China (973 Program) (2015CB452702).
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First received 1 June 2015; accepted in revised form 14 December 2015. Available online 14 January 2016