Analysis of the impact of water level fluctuations on macrophytes in Miyun Reservoir after receiving water transferred by the South-to-North Water Diversion Project

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Abstract. As the main primary producers in aquatic ecosystems, macrophytes affect the structure and function of aquatic ecosystems, and their distribution is controlled by water depth. Miyun Reservoir in Beijing will have to experience substantial changes in water level and surface area as it begins to receive water transferred by the South-to-North Water Diversion Project, which will have an adverse impact on the macrophytes growing there. In this study, a hydrodynamic model was constructed with MIKE21 and then used in a simulation in three scenarios: dry year, normal year and wet year. The results suggest that during water diversion, the annual and interannual water level fluctuations will be too significant for them to adapt and as a result, the original macrophytes in the reservoir tend to die and disappear completely. The area of the zone suitable for macrophyte growth, or suitable growth zone (SGZ), fluctuated. Restricted by the main dam and auxiliary dam to its south, the overall suitable growth zone moved toward the northeast and northwest of the reservoir, with a northeastward movement of its centroid. The distance and path of movement varied between scenarios. After the water diversion was completed, the suitable growth zone shrank in the three scenarios. It is predicted that the macrophyte species diversity and richness of the reservoir can recover to the levels recorded before water diversion only in dry year. These results suggest that manual interventions should be implemented after water diversion to speed up the natural recovery of aquatic plant communities in Miyun Reservoir and thereby maintain the stability of the aquatic ecosystem.

1. Introduction
Miyun Reservoir is located in the mountainous region in northern Miyun District, Beijing (figure 1). It was first constructed in 1958 as a large reservoir for multiple purposes such as water supply, flood...
control, irrigation, and power generation. The reservoir has a capacity of 4.375 billion m$^3$, dead storage of 0.419 billion m$^3$, and its normal water level, dead storage level, and flood control level are 157.5 m, 126.0 m, and 152.0 m, respectively. The inflows of Miyun Reservoir include Bai River, Chao River, Baimaguan River, Duijia River, Andamu River, Qingshui River and so on.

Since 1999, the reservoir had seen declining water level and shrinking water surface as a result of a continued lack of precipitation in the reservoir region and increased domestic water supply to urban Beijing. After considering the capacity of the reservoir, Beijing imposed limitations on the water extraction from Miyun Reservoir in 2004. Since then, the reservoir level has been maintained at around 135 m and the reservoir has been operating at low levels. As the only surface source of drinking water in Beijing, Miyun Reservoir supplies water to Beijing via two primary supply lines: the No. 9 water plant pipeline and Jingmi canal.

According to the Miyun Reservoir Ecosystem Survey Report (2012), there was a total of 15 macrophyte species living in the reservoir, including 8 emergent, 6 submerged and 1 floating-leaved species. Aquatic plants were distributed throughout the reservoir bank, especially concentrated in the northern shallow near-shore regions, such as Yanggezhuang Town, Yanluo Village, Bulaotun Town, and Gaoling Town. Besides, aquatic plants were also found in inner lake, while they scarcely existed in the southern areas due to the restrictive water depth.

Miyun Reservoir Regulation and Storage Project is an important part of South-to-North Water Diversion Project (SNWDP). The project plans to transfer water at a rate of about 0.2 billion m$^3$ per year into Miyun Reservoir by 9-stage pumping stations and through an 81 km long section of the existing Jingmi Canal and the 22 km long newly built underground pipeline (figure 2). The water inflow will replenish the reservoir so that the reservoir will experience no reduction in storage after supplying water to urban Beijing. Five years of continuous water storage, will raise the reservoir water level and expand the water surface, thus altering the distribution area of local aquatic plants and further affecting their growth and reproduction. In particular, macrophytes are likely to die due to increased water depth and violent water level fluctuations, resulting in changes in their distribution. Therefore, it is necessary to carry out relevant research, and quantitatively analyze the impact of water level fluctuations on macrophytes in different scenarios.
2. Method

2.1. Restrictive factors on macrophytes growth
As the main primary producers in aquatic ecosystems, macrophytes provide both food and diversified habitats to fish, zooplankton and other animals [1, 2]. Their distribution is primarily determined by water depth. Moreover, water depth can also regulate the composition and richness of aquatic plant...
species. Slow-flowing water is suitable for growth of macrophytes [3, 4]. From the reservoir bank to deep water, the dominant macrophytes are emergent, floating-leaved, and submerged macrophytes, respectively [5]. Emergent macrophytes live in about 1 m deep water and can tolerate water deeper than 3 m for a short period of time. Floating-leaved macrophytes are distributed in sublittoral zone at depths shallower than 5 m. Submerged macrophytes, the most adaptable macrophytes to water depth, normally live in water no deeper than 6 m [6]. Water depth is a dynamic factor that varies over time and space. Water level fluctuations can exert great influence on aquatic plants [7, 8]. Relevant research has suggested that, in order to maintain the plant species diversity and richness of a lakeside area, it is necessary to keep at least the following two variables within proper limits [9]. (1) Annual water level fluctuation: the most suitable annual water level fluctuation and fluctuation duration are 1 m and 1 month, respectively; the fluctuation duration must not exceed 2 months. (2) Interannual water level fluctuation: the interannual water level fluctuation over 10 years should be limited to between 1.0 and 4.0 m, or a wider range for larger lakes.

Therefore, the key to carry out this research is to find out how the water depth and the water level change, and the hydrodynamic numerical model is the best tool to solve the problem.

2.2. Model Construction
In this study, the MIKE21 software is used to build the two-dimensional hydrodynamic model of the study area.

2.2.1. Creation of terrain file. In order to guarantee the requirements of computational precision and operation speed, terrain grid shape was rectangular and its size was 300 m × 300 m. So the resolution of DEM data (provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences. http://www.gscloud.cn), was reduced from 30 m to 300 m by Resample, a built-in tool in ArcGIS. After that, the terrain file for Miyun Reservoir was generated using Bathymetries, a built-in tool in MIKE21 tool for creating terrains.

The accuracy of the terrain file was evaluated based on existing water level – storage curve. The results revealed that the storage error was less than 4% and surface area error was below 8%, as shown in figure 3, indicating that the accuracy of the terrain file met the research criteria.

2.2.2. Model setting. Because Bai and Chao Rivers contribute more than 90% of the total inflow to the reservoir, the simulation focused on Bai and Chao Rivers while the other tributaries were considered collectively based on the actual situation, and two inflow boundaries were applied to the model. The water diverted by the SNWDP entered Miyun Reservoir through an inlet at the Bai River dam, which was set as a source point. The outflows of the reservoir include the Bai River dam, the Bai River power plant, the No. 9 water plant at the source, and the Chao River dam. According to the project implementation plan, there would be no outflow except water extraction from the No. 9 water plant at the source. Therefore, only one sink point was set in the model (see figure 4). Figure 5 shows the process of water flow through the source and sink points. Precipitation and evaporation were included in the model. The simulated time period was set between January 1, 2015 and January 1, 2020, i.e. 1/1/2015-1/1/2020.
2.3. Scenario setting

A simulation was performed to quantitatively analyze the impact of project implementation and upstream and downstream inflows on the water level of Miyun Reservoir. Three scenarios (wet year, normal year and dry year, see table 1) were set in the simulation. The upstream inflows in different hydrological years (figure 6) were determined based on the *Environmental Impact Assessment of Miyun Reservoir Regulation and Storage Project – A Special Report on the Project’s Impact on Miyun Reservoir Aquatic Environment*. The initial water level of the reservoir was set at 134.2 m in light of the latest monitoring data.

![Figure 3. Terrain error.](image)

![Figure 4. Boundary, source and sink points.](image)
Table 1. Simulation scenarios.

| Number | Scenario name | Upstream inflow (billion m$^3$/year) | Precipitation (mm/year) | Evaporation (mm/year) |
|--------|---------------|--------------------------------------|-------------------------|-----------------------|
| 1      | Dry year      | 0.174                                | 310                     | 1355                  |
| 2      | Normal year   | 0.354                                | 469                     | 1144                  |
| 3      | Wet year      | 0.665                                | 546                     | 1230                  |

Figure 5. Process of water flow through the source and sink points.

Figure 6. Upstream inflow process.

3. Results and analysis

3.1. Changes in water level and surface area

After water diversion, water level in dry, wet, and normal years had increased by 14.8, 17.8 and 24.5 m, respectively; the corresponding increases in water surface area were 64.27, 79.59 and 105.87 km$^2$, respectively. Compared to the no diversion mode, the water level changes were between 11% and 18%, and surface area changes were in the range of 81% to 133% (table 2).
Table 2. Simulation results.

| Scenario  | Water level | Surface area |
|-----------|-------------|--------------|
|           | Initial (m) | Final (m)    | Difference (m) | Change extent % | Initial (km²) | Final (km²) | Difference (km²) | Change extent (%) |
| Dry year  | 134.2       | 149.0        | 14.8           | 11              | 79.54         | 143.81      | 64.27           | 81               |
| Normal    | 134.2       | 152.0        | 17.8           | 13              | 79.54         | 159.13      | 79.59           | 100              |
| Wet year  | 134.2       | 158.7        | 24.5           | 18              | 79.54         | 185.41      | 105.87          | 133              |

3.2. Annual and interannual water level fluctuations

In this study, annual water level fluctuation (AWLF) is the difference between the water levels at the beginning and the end of a year; interannual water level fluctuation (IAWLF) is the water level fluctuation over years. The results of simulation (figure 7) show that during water diversion, both AWLFs and IAWLFs decreased over time. The AWLFs ranged from 1.4 to 8.0 m, and IAWLFs were between 1.8 and 7.0 m. The wet year saw the strongest fluctuations, followed by the normal year, while the dry year saw smaller fluctuations than the other two scenarios.

3.3. Change in area of suitable growth zone

Previous analysis suggests that the region at depths shallower than 6 m is suitable for growth of aquatic plants. As shown in figure 8, the area of SGZ fluctuated; in dry, normal, and wet years, it peaked at 33.21, 30.60, and 33.03 km² on 2019/1/1, 2018/1/1, and 2017/1/1, respectively. After water diversion was completed, the area of SGZ increased 3.69 km² in dry year and decreased 2.43 km² and 4.32 km² in normal and wet years, respectively, compared to 27.54 km² before diversion.

3.4. Spatial variation in suitable growth zone

Restricted by the main dam and auxiliary dam to its south, the SGZ moved towards the northeast and northwest. The spatial variation in suitable growth zone was quantitatively studied through centroid analysis, a method commonly used to analyze spatial variation in land use [10]. A centroid, usually defined as the geometric center of a polygon or a plane, is an important index used to describe spatial distribution of geographic phenomena and it can be simplified as the equilibrium point at which the...
geographic target retains uniform distribution [11]. Centroid analysis is often employed to trace the
distribution of geographic targets. The centroid of a SGZ can be calculated using the following
formula:

\[
X_t = \frac{\sum_{i=1}^{n} (C_i \times X_i)}{\sum_{i=1}^{n} C_i}, \quad Y_t = \frac{\sum_{i=1}^{n} (C_i \times Y_i)}{\sum_{i=1}^{n} C_i}
\]

where \(X_t\) and \(Y_t\) represent the longitude and latitude coordinates of the centroid of SGZ in \(t\) year;
\(C_i\) is the area of \(i\) SGZ patch in \(t\) year; \(X_i\) and \(Y_i\) are the longitude and latitude coordinates of
the centroid of \(i\) SGZ patch in \(t\) year.

Figure 8. SGZ area change during water diversion.

Figure 9 shows the position and coordinates of the centroid (shown with black dot) in the first year
\((t=1)\), third year \((t=3)\), and fifth year \((t=5)\) since the beginning of water transfer \((2015/1/1)\). In order to
display its movement more clearly, the centroid was plotted in a two dimensional coordinate system,
where the X-axis points towards the east of the reservoir and Y-axis points to the north. It is clear from
figure 10 that the centroid followed different trajectories in different scenarios. In dry year, the
centroid moved eastward, then northward, and eastward again. In normal year, it moved eastward,
then northeastward, and finally northward. In wet year, it moved northeastward in the first two periods,
followed by a northwestward shift. After water diversion was completed, the centroid of SGZ had
moved 4613 m in dry year, 4838 m in normal year, and 5689 m in wet year, toward the northeast.

3.5. Analysis of impact on macrophytes

During water diversion, both AWLFs and IAWLFs will be so significant that macrophytes in the
reservoir will fail to adapt and tend to the die. As a result, the reservoir will see declines in both
biomass and richness of species.

After water diversion finished, the SGZ area has increased in dry year and decreased in normal and
wet years when compared to that before diversion. It can be predicted from the species– area
relationship [12, 13] and island biogeography [14] that after water diversion, the macrophytes species diversity and richness could recover to the levels recorded before water diversion only in dry year.

During water diversion, the SGZ moved toward the shallow and bay zones in the northeastern and northwestern parts of the reservoir as water depth increased, with a northeastward movement of its centroid. In dry, normal, and wet years, the centroid of SGZ had moved 4613 m, 4838 m, and 5689 m, respectively, toward the northeast after water diversion.

| Initial situation | Scenarios | The first year $(X_1, Y_1)$ | The third year $(X_2, Y_2)$ | The fifth year $(X_5, Y_5)$ |
|-------------------|-----------|----------------------------|-----------------------------|----------------------------|
| Dry year          |           | (2154,204)                 | (2499,1717)                 | (4261,1766)                |
| Normal year       |           | (2271,247)                 | (3959,1439)                 | (4161,2469)                |
| Wet year          |           | (1926,1314)                | (4918,2898)                 | (4589,3363)                |

**Figure 9.** SGZ (blue area) and their centroids (black point).

**Figure 10.** SGZ centroids moving trajectory in different scenarios.
4. Conclusions and Discussion

4.1. Conclusions

The impacts of water level fluctuations and water depth variation on the growth and distribution of macrophytes during and after water diversion are summarized below:

In dry, wet, and normal years, the water level climbed 14.8, 17.8, and 24.5 m, respectively, and the water surface area increased 64.27, 79.59, and 105.87 km², respectively. The water level changes were between 11% and 18% and water surface area changes varied between 81% and 133%.

During water diversion, the annual and interannual water level fluctuations gradually decreased, but were still too significant for macrophytes to adapt. The original aquatic plants in the reservoir tend to die and disappear completely and the distribution of macrophytes tends to change. The distribution area of macrophytes moved toward the northeast and northwest overall, with a northeastward movement of its centroid. The movement trajectory and distance of the centroid varied between scenarios.

After water diversion, macrophytes living in the reservoir will experience significant changes in distribution area, species biomass, and species richness. In dry, normal, and wet years, centroid of SGZ had moved 4613 m, 4838 m, and 5689 m, respectively, toward the northeast. In dry year, the area of SGZ increased compared to that before water diversion, indicating that the macrophytes species diversity and richness can recover to the levels recorded before water diversion.

4.2. Discussion

If no manual interventions are implemented, it will take a long time for aquatic plant communities to recover naturally after being damaged. Given the importance of aquatic plants in an aquatic ecosystem and the slowness of their natural recovery, manual interventions should be implemented after water diversion to accelerate the recovery of the community structure of Miyun Reservoir and thereby maintain the stability of the aquatic ecosystem. Moreover, special attention should be paid to the problems arising from mass death of macrophytes, such as the drop in water quality caused by decomposition of dead plants and reduction in food supply for herbivorous fish.

In addition to water depth, growth of aquatic plants is also affected by other environmental factors (e.g. wind speed, air temperature, and light), water quality, feeding of herbivorous fish and so on. This study was based on the assumption that the zones at depths shallower than 6 m are suitable growth zones for aquatic plants. Further actual measurements are needed to verify the data about area of suitable growth zone, distribution area of macrophytes, and distribution of macrophyte growth area presented in the conclusions.

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