GIS Analysis Application of Flood Risk Map in Beijing, China

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NORTHERN ILLINOIS UNIVERSITY
GIS Analysis Application of Flood Risk Map in Beijing, China
A Capstone Submitted to the
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In Partial Fulfillment of the
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With Honors
Department Of
Earth, Atmosphere and Environment
By
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Abstract

From the end of July to the beginning of August 2023, Beijing, China, affected by Typhoon "Dusuri", experienced the most precipitation in the Beijing area in 140 years of instrument measurement records. This event led to the evacuation of more than 1.8 million people across the Beijing-Tianjin-Hebei region and the tragic loss of 62 lives. After experiencing such fierce heavy rainfall and flood disasters, how to predict and prepare for such catastrophic events and avoid losses in the future has become a crucial problem. Geographic information systems (GIS) can integrate different layers of geospatial information and provide us with powerful tools and methods to understand, predict, and better prepare for flood disasters. This study leverages the digital elevation model (DEM) of Beijing and the Height Above Nearest Drainage (HAND) model to create flood risk maps under different flooding scenarios. The HAND model-based flood risk analysis can help governments and decision-makers to better understand the spatial distribution characteristics of floods. In addition, this research also utilized Python and other statistical tools to estimate the discharge of a 100-year flood and assess the relationship between different flood levels and the spatial distribution of population, land price, and land use. These results offer valuable information for the government and decision-makers to direct their flood control resources to the most needed areas and devise effective evacuation plans in advance for future flood disasters.

Keywords: Flood Risk, Hydrology, Beijing, GIS (Geographic Information System), Height Above Nearest Drainage (HAND) Model, Python, Spatial Analysis.
1. Introduction and Background

Nowadays, floods continue to be a serious natural disaster affecting society. Between 1900 and 2006, nearly one-third of all-natural disasters in the world were floods, and they accounted for nearly half of all people affected by natural disasters (Adikari and Yoshitani, 2009). In recent years, global warming has caused an increase in the frequency and intensity of extreme rainfall events, which then causes more floods in many parts of the world (Alfieri, 2015). With the intensification of global warming, summer storms are also having a greater impact on China in East Asia, which leads to more frequent flooding events. In China, it is one of the major natural hazards that cause death and millions of dollars in economic losses (Hu, 2017).

After decades of research by natural scientists, they have realized that environmental changes have an important impact on flood disasters, and human activities are the main cause of flood disasters (Liu, 2016). As the capital city of China, Beijing plays an important role as the political center, cultural center, and international exchange center. It is also highly urbanized. The correlation between flood events and human activities underscores the significant influence of environmental changes on the occurrence of flood disasters within the region. Therefore, this paper is committed to studying the simulated flood effects of different depths (0.2m, 0.4m, 0.6m, 0.8m) in Beijing on different layers of ground objects. The aim is to explore potential flood risk areas in Beijing and relevant prevention and control measures.

The Yongding River is Beijing’s largest river. It originates from Shanxi, flowing through Hebei, nourishing Beijing, and merging into Tianjin, and is commonly known as the “Mother River” of Beijing (Jiang, 2014). From 1980 to 2010, the mean annual rates of
streamflow decline were 0.44 cubic meters per second per year (Guanting), 0.42 cubic meters per second per year (Yanchi), and 0.03 cubic meters per second per year (Sanjiadian) (Jiang, 2014). After experiencing decades of mostly dried-up riverbeds, this river saw its waters surging past the border between Beijing and Hebei on May 12th, 2020 (Xinhua Net, 2020). It is expected to soon regain its full flow and still has a large potential to increase flood risks in the future. This paper collected the monthly average discharge data of the Guanting Reservoir observation station in Yongding River Basin from 1949 to 1988, and used Python and Excel for visual analysis; the objective was to explore the estimated 100-year flood peak discharge and take historical data into account for the current flood prediction.

2. Study Area and Data Sources

2.1 Study Area

Beijing (40°N, 116°E) is located in the northeastern part of China (Figure 1), more specifically on the northern edge of the North China Plain. To its northwest through the Hebei Province is the Inner Mongolia Plateau; to its northeast through the Hebei Province out of the sea Pass is the Northeast plain; to its east through Tianjin is the Bohai Sea, only 150 kilometers away. In terms of elevation, Beijing is higher in the northwest than in the southeast. The urban area of Beijing covers about 42% of the total area, which is marked by the red boundary in Figure 1. Notably, the urban terrain appears relatively flat, rendering it more susceptible to flood hazards.

When it comes to climate, Beijing boasts a humid continental climate influenced by monsoons (Köppen classification: Dwa), with elements of a cold semi-arid climate (Köppen: BSk) particularly evident in its southern and northwestern regions. Summers are typically hot
and humid due to the East Asian monsoon, while winters tend to be cold and dry owing to Siberian anticyclones. Precipitation peaks during the summer months (June-August), coincide with the research period of this paper.

### 2.2 Data Sources

The digital elevation model (DEM) data was downloaded from the 30-meter Shuttle Radar Topography Mission (SRTM) Tile Downloader ([https://dwtkns.com/srtm30m/](https://dwtkns.com/srtm30m/)), which has a resolution of 30-meter. The stream network and Yongding He River’s historical monthly mean discharge data was obtained from the Global Runoff Data Center ([GRDC, https://wbwaterdata.org/dataset/global-runoff-data-centre-grdc](https://wbwaterdata.org/dataset/global-runoff-data-centre-grdc)). The 2020 100m resolution gridded population data was from WorldPop ([https://hub.worldpop.org/geodata/summary?id=131](https://hub.worldpop.org/geodata/summary?id=131)). The urban park data, the 2010 Beijing urban population data, the 2013 Beijing land price data, and the land use of Beijing were from Beijing City Lab ([https://www.beijingcitylab.com/](https://www.beijingcitylab.com/)).

### 3. Hypothesis

Given Beijing's topographical variance—higher terrain in the northwest and lower in the southeast—a hypothesis emerges suggesting that the southeastern region faces greater vulnerability to floods compared to the northwest. Furthermore, the significant urbanization
concentrated in the city center amplifies the risk of urban waterlogging, rendering the central districts more susceptible to flooding than suburban areas. In addition, urban green spaces improve the retentiveness of hydrological systems in urban areas and dampen peak flows from storms that can lead to flooding (Kim, 2016). So, it is assumed that urban areas that lack green space are more prone to floods.

4. Methodology

After using the basic geoprocessing tools to process the initial data (e.g., clipping all the data to the study area), the following methods were used to get an in-depth analysis of the data.

4.1 Height Above Nearest Drainage (HAND) Model

The HAND raster is a drainage-normalized and flow path-coherent version of a DEM (Nobre, 2016). The HAND raster is calculated as the difference between the elevation of a land grid cell and the elevation of its nearest drainage (stream) cell following flow direction (Figure 2). The flood inundation is derived by comparing the flood depth and HAND raster; if a cell’s HAND value is less than the flood depth, that cell is inundated (Figure 2). The following main steps are involved. First, DEM data are imported in ArcGIS Pro and the flow direction grid is derived; second, the upstream endpoint of a river (stream) line is extracted and the raster version of the streamline consistent with DEM data is derived based on flow direction; third, the HAND tool in the Hydrologic toolbox is used calculate the HAND raster; finally, the appropriate inundation depth is selected to derive the inundation maps of Beijing under different flood depths. The flood depths explored in this study were 0.2m, 0.4m, 0.6m, 0.8m (Liu, 2016). After the inundation maps of different flood depths were obtained, they
were overlayed with other data layers to assess the impact of these different flood scenarios.

![Figure 2. Schematic diagram of HAND model by David Maidment](image)

### 4.2 Matplotlib and Pandas in Python

Matplotlib is a comprehensive library for creating static, animated, and interactive visualizations in Python. Matplotlib makes easy things easy and hard things possible (Matplotlib, 2012). Pandas is a fast, powerful, flexible, and easy-to-use open-source data analysis and manipulation tool, built on top of the Python programming language (Pandas, 2018). These Python tools were used in this study to analyze the data and generate visualization of results in plots and maps.

```python
import matplotlib.pyplot as plt
import pandas as pd

ydh2 = pd.read_csv("yongdinghe49-88.csv")

ydh2['Date'] = pd.to_datetime(ydh2['Date'])
ydh2.set_index('Date', inplace=True)

plt.figure(figsize=(10, 6))
plt.plot(ydh2.index, ydh2['Value(MQ)'], color='blue', marker='.', linestyle='-')

plt.xlabel('Year')
plt.ylabel('Discharge (m^3/s)')
plt.title('Monthly Discharge of Yong Ding He (1949-1988)')
```

![Figure 3. Code implementation of Matplotlib and Pandas](image)

### 4.3 Band Collection Statistics
Band Collection Statistics is a Geoprocessing tool in ArcGIS Pro for calculating the statistics of a set of raster bands. The layer of inundation area under different flood depth scenarios based on the Height Above Nearest Drainage (HAND) Model and the 2020 population gridded population raster layer of Beijing were used to figure out if there is any correlation between the distribution of the population and the impact of the flood.

4.4 Estimating discharge of a 100-year flood based on historical record

While flood paths can be used to determine the effective control structure for a given flood, the possibility that a flooding level exceeds the designed specifications of a flood control structure always exists (Hornberger, 2014). At this point, the question of how to calculate the probability of these floods occurring in any given year, or whether the possibility of exceeding expectations is acceptable, becomes crucial.

To calculate the discharge value of a 100-year flood (or the flood that will be exceeded with a 1% probability), it is necessary to have a long historical record of annual peak floods. The peak discharge of each year needs to be extracted from the monthly historical data, forming the annual maximum flood flow sequence. These annual maximum flood flows are then ranked in order of size (the largest is ranked first). Next, the logarithm of the maximum flood discharge (with a base e) and the exceedance probability of the flood are calculated:

\[ p = \frac{r}{(n+1)} \]  

(1)

where \( p \) is the exceedance probability and \( r \) is the ranking of the flood.

NORMSINV is the inverse of the standard normal cumulative distribution and is available in MS Excel spreadsheet (Yang, 2010). In this case, after getting the exceeded
probability, the normsinv equation is used to calculate the z score. A linear relationship can be established between the z score and the logarithm of the maximum flood discharge. The slope and intercept of the fitted linear relationship and the corresponding z-value will be used to estimate the 100-year flood peak discharge.

5. Results

The DEM-generated flood inundation maps under 0.2, 0.4, 0.6, and 0.8 meters flood depth scenarios are presented in Figure 4. It is worth noting that the map uses only the streams with a Strahler order of 2 or greater to ensure the readability of the map.

![Flood Inundation Maps in 0.2, 0.4, 0.6, 0.8 meters Flood Depth Scenarios, Beijing, China](image)

Figure 4 (left). The inundation area under different flood depth scenarios is based on the Height Above Nearest Drainage (HAND)Model.

![River connections of Beijing](image)

Figure 5 (right). The river connections of Beijing (Fan, 2014).

Most of the rivers in Beijing's urban area belong to the North Canal system (Figure 5) and Figure 4 shows that the southeastern part of Beijing is indeed more vulnerable to flooding, partly consistent with the hypothesis stated earlier. This is related to the distribution of terrain.
of Beijing, high in the northwest and low in the southeast. Contrary to earlier assumptions, however, the Miyun Reservoir in the northeast of Beijing is also shown to be prone to flooding. The Miyun Reservoir serves as both a water source and a reservoir. As a water source, it provides drinking water to parts of Beijing. Simultaneously, as a reservoir, the Miyun Reservoir also serves the role of water storage and distribution. Because of the highest flood risk level, the government should pay more attention to the flood control around Miyun Reservoir. Based on the overlay of the Beijing urban area with the flood map, most urban areas will not be affected by the strongest level of flooding. However, due to the flow of the North Canal (Figure 5) and the low terrain, the areas of northeast edges of the urban areas in Beijing are more vulnerable to flooding.

This study also conducted a multi-factor comprehensive analysis based on the population density distribution data of Beijing in 2010, land price distribution data of Beijing in 2013, urban green area distribution, major building distribution data, and the flood risk map (Figure 6). In general, the flood risk level in the high-priced land and high-density population areas in Beijing is low, which indicates that the Beijing Municipal Government has carried out flood risk prevention and control well. The Beijing Municipal Government is also aware that "since 1963, nearly sixty years have passed without Yongding River experiencing a flood exceeding the once-in-twenty-years threshold. Now, facing a significant flood, uncertainties arise once the embankments are underwater, posing considerable risks" (Beijing Municipal Government Press Office, 2023). However, due to the proximity of the urban and suburban parts in the northeast of Beijing, land prices are relatively lower compared to the downtown area. Consequently, this region exhibits higher building density and population distribution. This
deserves the attention of the government’s planning departments, and the area should become the focus of flood control during the rainy season in Beijing.

In addition, it is not obvious from the map that areas that lack green space distribution are more prone to floods (Figure 6). However, it is still necessary for the municipal government to increase the construction process of sponge cities so that the surface runoff can be converted into groundwater to the maximum extent when the flood comes, which can not only reduce the peak flow but also increase the storage of urban groundwater.
Tables 1 and 2 are the output of the “Band Collection Statistics.”

Furthermore, the correlation analysis using Band Collection Statistics reveals that despite expectations, there is no discernible correlation between the flood risk layer and the distribution of population, as indicated by the correlation matrix (Tables 1, 2).

A monthly discharge hydrograph of the Yongding River at the Sanjiadian observation Station is visualized by using Pandas and Matplotlib and the results show that the maximum flood peak during the study period was about 240 cubic meters per second around 1950 (Figure 7). As mentioned above, the Yongding River basin in Beijing has gradually dried up since the 1980s, so the analysis of the average monthly runoff of the river is only used as a reference for historical flood peak data.
The linear relationship between the $z$ value and the logarithm of the maximum runoff derived from the monthly mean runoff of Yongding River is presented (Figure 7). The fitted equation (2) is obtained. Finally, the estimated 100-year flood peak discharge is calculated using equation (2) and displayed in Table 3.

\[
\ln(Q) = -0.8593 \times z + 4.1596
\]  \hspace{1cm} (2)

<table>
<thead>
<tr>
<th>p</th>
<th>$z$</th>
<th>$\ln(Q)$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100yr</td>
<td>-2.32635</td>
<td>6.158631</td>
<td>472.7804</td>
</tr>
</tbody>
</table>

Table 3. Initial probability and calculated $z$ value, $\ln(Q)$, and $Q$

The estimated peak discharge for a 100-year flood event is 472.7804 cubic meters per second. By acquiring and analyzing forecast data, valuable insights can be gleaned to inform future strategies for mitigating the impact of such rare, yet potentially catastrophic, once-in-a-hundred-year floods.

6. Discussion
This study utilizes DEM data to create a flood risk map, providing a more practical approach to regular flood prevention and control compared to relying solely on time-bound precipitation forecasts. However, this study also has a major limitation, it does not use the latest data of Beijing's once-in-140-year extreme flood in 2023 as the flood depth data of the HAND-based flood inundation map. The Yongding River study also did not use the most recent runoff data. Future research will focus on how to combine actual flood depth data with theory.

7. Conclusion

In general, using a DEM-generated flood map to explore the flood risk map of Beijing is beneficial to the municipal government and the planning department for flood prevention and control. The Beijing Municipal government should conduct further flood risk screening for areas with higher flood risk levels in the northeastern urban areas identified in this study. Although there is no obvious data in this study indicating that the central urban area of Beijing is flood-vulnerable, relevant departments should still pay attention to flood prevention and control in the central area to minimize economic losses.

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9. References


