Beijing’s Water Crisis:
A Historical Analysis of Beijing’s Waterways using Geographic Information Systems

by

Rebecca Tisherman

A Thesis Submitted in Fulfillment of the Requirements for Honors in a Degree of Bachelor of Arts in Environmental Studies

Connecticut College
May 2013

Thesis Committee:

Thesis Advisor:	Beverly Chomiak, Ph.D. Environmental Studies Program Department of Physics, Astronomy, and Geophysics
Second Reader:	Doug Thompson, Ph.D. Environmental Studies Program Department of Physics, Astronomy, and Geophysics
Third Reader:	Yibing Huang Department of East Asian Languages & Cultures

Table of Contents

Acknowledgements..4

Abstract..5

Introduction..6

General Map of Beijing's Rivers..9

Background..10

Ancient History of Beijing..10

Modern History of Beijing..14

Geography and Geology of Beijing..19

Beijing's Water Resources..23

Hydrological Planning for Cities..28

Methodology..30

Results..36

Discussion and Analysis..46

Surface Water Then and Now..46

Urbanization and the Water Crisis..53

Conclusion..56

Literature Cited..57

Appendix..61

1912 Beijing Waterways..61

1926 Beijing Waterways..62

1983 Beijing Waterways..63

2012 Beijing Waterways..64

Hydrographic Model of the Beijing Area...65

Stream Change Statistics...66

Urbanization in Beijing..67

Beijing Fault Lines...68

# Acknowledgments

I would like to thank my thesis advisor, Dr. Beverly Chomiak, for all of her help and support throughout this project. It started out as a crazy idea and she helped me narrow it down into a feasible, yearlong project. I would not have been able to do this without her help in collecting maps, running them through GIS, and analyzing them through many sleepless nights. She deserves most of the credit for this endeavor. I would also like to thank Dr. Douglas Thompson, my academic advisor and second reader, for his insight and feedback along the way. On those days where it felt like this project would never reach its fruition, he helped me sift through my data and analyze some of the more detailed aspects of this project. I also wish to thank Professor Yibing Huang for helping me over the years and encouraging me to conduct an honor's thesis.

Abstract

Beijing has a complex system of waterways inside the city of 20 million people, while the rivers just outside of the city run dry most of the year. Geographic Information Systems was used to analyze the historical changes of the waterways, geo-cover, precipitation, and other factors that have affected the water supply to the city. The manmade canals in the city expanded with urbanization until 1983 when there were canals in every corner of the city. The water became too polluted for human use, so canals were slowly converted to culverts. Groundwater was depleted over time as well, so the natural flow of water has been completely disrupted in the city. The rivers and groundwater need to recover so the city can have a natural supply of water again. To do this, the water system needs to return to a more natural flow of the rivers, rather than concrete canals entering and leaving the city. This would help control groundwater levels, flood and drought problems, and the overall lack of accessible water for the city.

Introduction

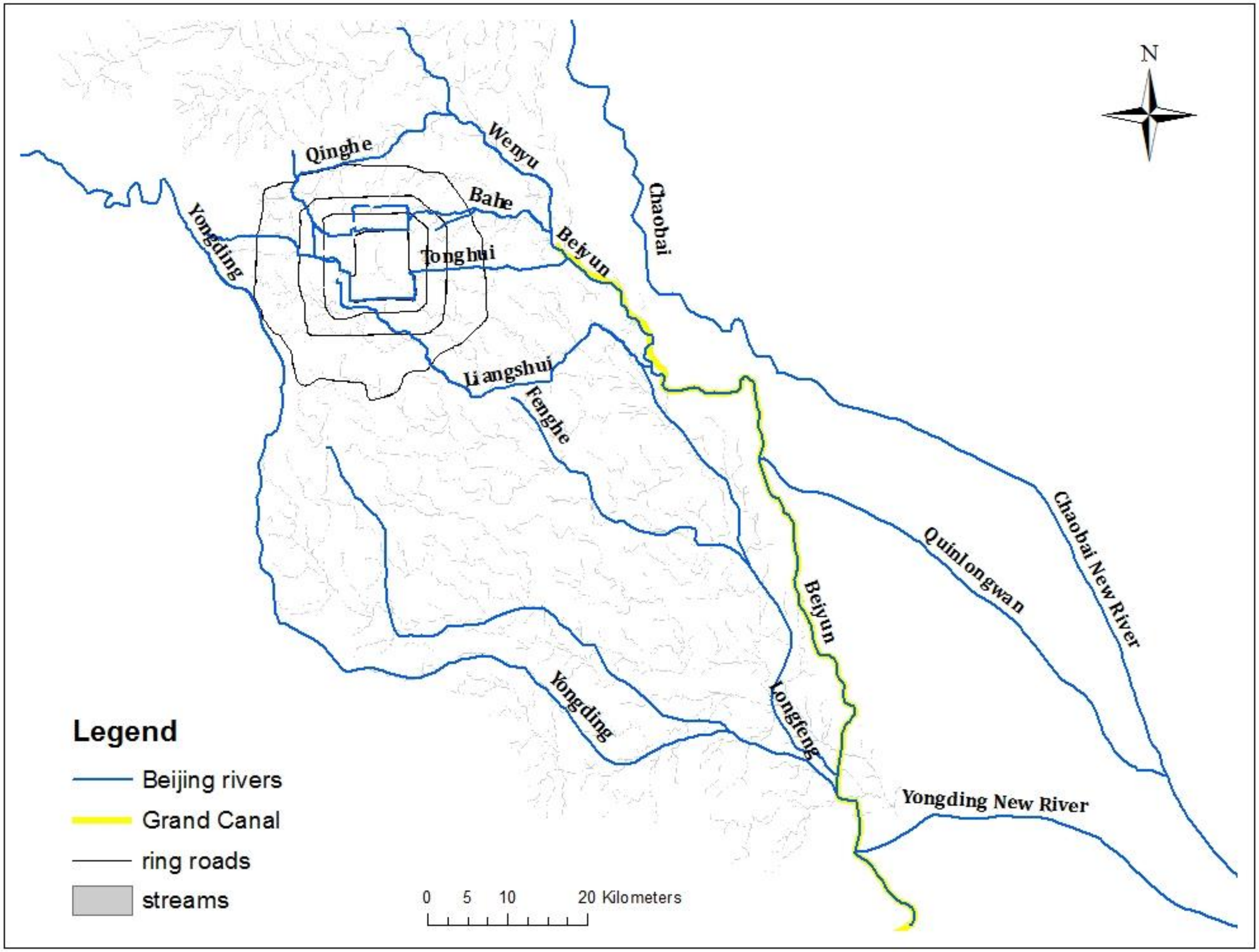
The waterways of Beijing, China are a maze of manmade canals that exist in every corner of the city. Some of them are flowing regularly, while others are merely dried up beds of algae, waiting to convey water again. While there is an intricate network of canals inside the city, outside of the city there are two dried up riverbeds that once fed water to this bustling metropolis. The riverbeds used to naturally dry up during the fall and winter and flood during summer. Within the past thirty years, however, the drying of riverbeds has become so severe that flowing rivers are now a faint memory [Beijing's Water Crisis, 2008]. Interestingly, some of the manmade canals and waterways throughout this semi-arid region still retain water, whereas, the natural flowing rivers run dry for the majority, if not all of the year. Illustrating the historical changes in waterways can help answer the question as to why Beijing is running out of water, why the natural riverbeds have run dry, and also help solve the huge water crisis that Beijing is currently facing. This Geographic Information System (GIS) research project aims to analyze these historical changes in the waterways of Beijing and to discover why and when the canals were made and assess how the canals are currently affecting the area.

To assess the overall changes over time and the impact that waterway diversions and dams have had on the rivers and water supply in the area, GIS software was used to view, compare, and analyze maps from four different time periods of the city. The maps were compared to a model of the natural streamlines in the city and also population, precipitation, geologic, and urbanization data. GIS provides a visual representation of how humans have impacted the water systems of the city, and illustrates some possible solutions for the water crisis facing Beijing.

The city gets its water supply primarily from groundwater and two reservoirs north of the city, the Guanting and the Miyun. However, currently only one out of two of the reservoirs for the city can still be used for drinking water [Sit, 1995]. This has had a widespread detrimental effect on the region. Due to poor quality of the Guanting and lack of water in the Miyun, the reservoirs now only supply water to Beijing and not to any of the numerous cities and towns downstream. Yet, many of the canals and tiny streams in the city are still flowing and still enable the rivers to flow downstream of the city. The canals contribute to the drying of the major rivers and to the water crisis that Beijing is facing today. Transferring water through this complex series of canals not only deters it from naturally flowing downstream into rivers, but also depletes the groundwater in the system, as water is not able to infiltrate into the soil due to the concrete lining of the majority of the canals. This increases risks of floods in the area and negatively impacts the overall ecosystem in the province. No matter the cause, Beijing is in a serious water crisis, and if they do not act fast, they will soon run out of potable water.

The city itself is framed by hills to the northwest, and lies on an alluvial plane that slopes to the southeast directly to the ocean. It was officially settled in the Western Zhou Dynasty (1046-771 BCE) and since then, Beijing has been altered by construction under twelve more dynasties, three fires that burned the city to the ground, foreign leadership, destruction of its most sacred areas, and ultimately one of the fastest city growths the world has ever seen. The urban population increased over 60% from 1982 to 2000 alone [Shen *et. al*, 2006].

The current layout of canals, streams, and rivers throughout the city clearly is not helping the crisis, and therefore something needs to be done to improve water movement throughout the city. The changes over time of the supply and drainage canals in the city to deal with the changing times, increasing population, and increasing urbanization are causing detrimental effects to the water cycle in the area and can be used to help change and improve the water system for the future. Changes need to be made to ensure that not all of the natural water flow is lost and to improve not only the water sources for people in the area, but also the entire water cycle for the area.



General Map of Beijing's Rivers

Background

Ancient History of Beijing

The earliest recorded settlement in Beijing was during the Western Zhou dynasty (1027-770 B.C.) [Aldrich, 2006]. During the Zhou Dynasty there was a set of criteria that builders followed when constructing cities that can still be seen today in Beijing. The required physical features included: the city had to be placed in precise alignment with the four directions, the city walls had to form a square or rectangle, the main gate had to face south, the city had to be located on level ground near water, and the city had to have a walled in central area with a second wall around the industrial and artisanal quarters.[1] The original city from the Zhou dynasty was located in the southwestern corner of the current-day city and only remnants of the city wall have been uncovered [Sit, 1995]. The city was required to be near a running source of water, which is thought to have been the Ximagou River; the ancient location of this river was to the southwest of the city center (Figure 1) [Angelaskis et. al, 2012].

During the Jin Dynasty (265-420), the city, named Zhongdu at the time, utilized water from the Lianhua Reservoir and from wells. The reservoir no longer exists, as it was insufficient even in those times, but the canal from it ran into the south gate from the west through a canal from the Ximagou River (Figure 1) [Hou, 1979].

The construction of the city of Beijing as it is known today did not start until the Yuan Dynasty (1271-1368). In 1260, the grandson of Genghis Khan decided to make Beijing his new capital named Dadu, located in current day Beihai Park in Beijing, just west of the center of the

[1] This list does not include all of the criteria as it excludes details about the functional zones of the walled in areas, and the placement of temples or political buildings.

city [Sit, 1995]. Thus, the city moved from the Ximagou River watershed to the Gaoliang River watershed.

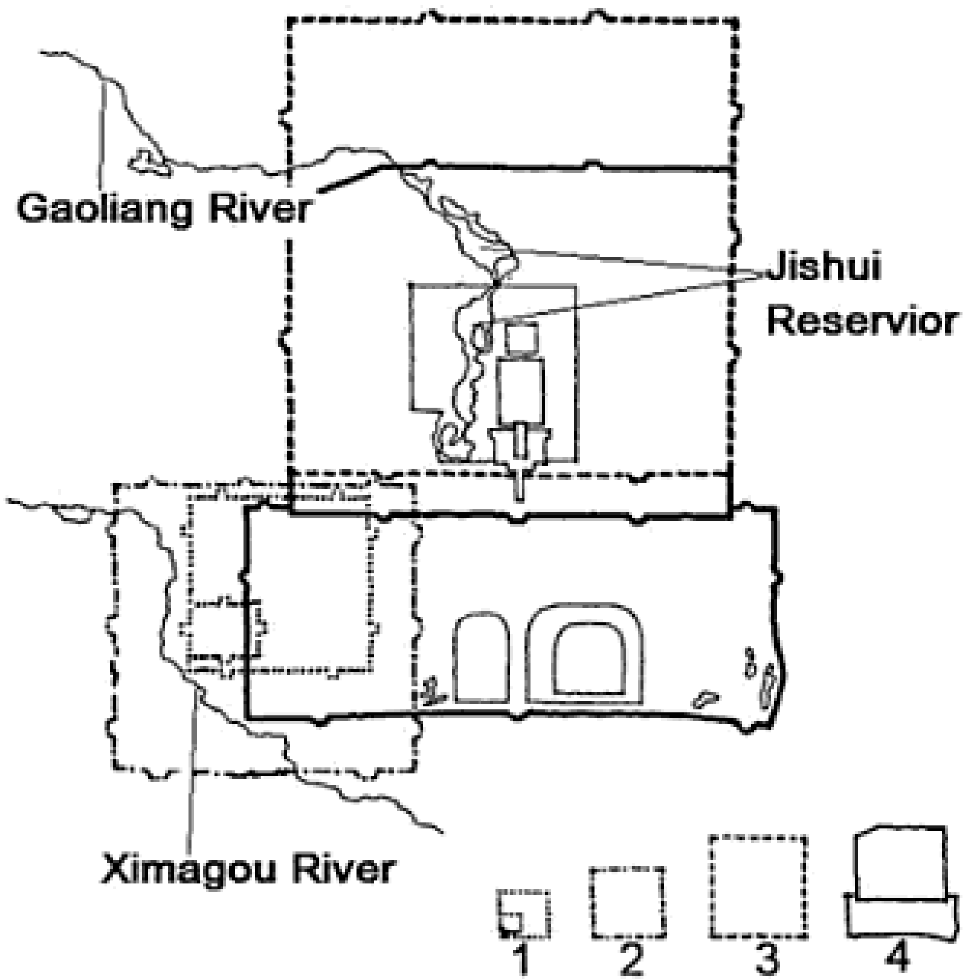


Figure 1- Rivers in the vicinity of Beijing during its growth under the dynasties: 1. Liao Dynasty, 2. Jin Dynasty, 3. Yuan Dynasty, 4. Ming-Qing Dynasty [Angelaskis et. al, 2012].

This time, the revised guidelines for building a city from the Zhou Dynasty were used with a more specific description of how the city should be planned [Angelaskis, *et. al*, 2012]. In order to meet the demands of the growing populations, canals were built from springs in the western mountains to the Gaoliang River. One of these canals was directed specifically to the Imperial Palace from a hill north of the Summer Palace and extended to modern day Xizhimen in the northwestern corner of the city. It lead into what was then the Taiye Pond, or current day Zhongnanhai, a series of lakes in the center of Beijing. This started the construction of the biggest lakes in Beijing, created from the Gaoliang River (Figure 1) [Angelaskis, *et. al*, 2012]. The six large lakes are still in existence today. A second canal was built for mainstream water supply, however, with the already depleted supply from the northwest, they had to come up with new hydraulic transport to obtain more water. Guo Shoujing, a famous hydrologist in the Yuan dynasty, created a system of channels and a weir to divert water to the Kunming Lake, the current day Summer Palace lake. This canal still exists today and flows from the Summer Palace through the Purple Bamboo Park in northwestern Beijing. This connected to Zhongnanhai and then to a new canal built for outflow from the city; the course used to be the Zhahe River in the Jin Dynasty but it was renamed the Tonghui River. This allowed for ships to enter the city through the Tonghui River, which was connected to the Grand Canal. The Grand Canal connected Beijing to Hangzhou for over 1,300km to transport between the two cities and is still the longest manmade canal in the world. [Angelakis et. al, 2012].

During the Yuan Dynasty, the groundwater from wells in the city began to increase in salinity due to the bedrock underneath the city, leading to greater need for the diversion of water from rivers. Water began to be supplied at three different levels: washing, cooking, and drinking tea. People also began to sell water, as there was a great lack of clean water available to the public. The quality only decreased over the years and as of 1885 there were still 1,245 wells but the water was salty and bitter [Angelakis et. al, 2012].

The Ming Dynasty saw the much-needed change in water supply, as the old system was not sufficient enough for the population. The Tonghui River was abandoned because of lack of water leaving the city through it. The Gaoliang River could not supply enough water to the lakes.

In the inner city, this meant that water was collected in Kunming Lake to the northwest and then transferred into Zhongnanhai. From there, the water was distributed to the Forbidden City and to the Tonghui River to attempt to revive it [Zheng, 1985]. Wells still could supply some water but not of high quality and selling water was still a profession. Ming Dynasty also saw the construction of Jingshan, or coal hill, the highest point in Beijing. The hill was made from the soil dug from the moat around the Forbidden City and piled to the north to protect the Imperial Palace from evil spirits, according to the principle of *feng shui* [Sit, 1995].

Starting in the 1400's, the city began to grow rapidly as temples and altars were constructed for the emperor to perform rituals to appeal to heaven. It was thought that emperors possessed The Mandate of Heaven, and if the emperors failed in their duties then the Mandate would be passed on to the next emperor [Aldrich, 2006]. A new dynasty conquered the Ming in 1644 after a peasant army from the south overthrew them, and then they were subsequently taken over by the Qing Dynasty. Beijing was in flames, but the leader of the dynasty along with many other emperors in Beijing's history wanted to preserve the majority of the city to give the appearance of continuity in leadership. The Qing Dynasty was the last of the Chinese dynasties and lasted until 1912 [Aldrich, 2006].

The increasing population meant that more water was needed, so the Qing Dynasty expanded Kunming Lake and constructed a dam to make it the first official reservoir inside the city of Beijing. To increase flow into the reservoir, canals from the mountains to the west were constructed to divert streams from that area [Hou, 1998]. The depth and size of the lake was similar to that of today's Kunming Lake.

China did not have any significant contact with any western countries until the late 1700's when Europeans started to trade opium for Chinese manufacture goods, sparking the first of the opium wars in the country. China eventually lost the opium wars to the British, opening up the rivers to Europeans and starting western influence in Beijing [Aldrich, 2006]. Europeans burned the Emperor's Summer Palace to the ground and foreign ministries began claiming land in Beijing. The first railroad was also installed in 1895, causing part of the city wall to be torn down, and the face of Beijing began to change forever [Belsky, 2000].

Modern History of Beijing

After the fall of the Qing Dynasty in 1912, there was a thirty-five year period of instability in China, in which the Nationalist Party ruled and slowly transformed Beijing into a modern city. Public parks were developed, trams were introduced onto streets, sanitation and water utilities were installed, and the charm of old Beijing struggled to be upheld in a newly renovated Beijing. The small, one-story ancient *hutong* houses of the city slowly began to be overshadowed by taller buildings and Beijing was introduced to the 20th century of the western world [Aldrich, 2006].

The Municipal Council was established to oversee the changes for the city, and in 1928, during one of its first meetings, goals were set out for the water supply of the city, but it is unclear the actual quantitative values of those goals. The eastern boundary of the city was to be expanded to towards the Chaobai River in the northeast and to a similar extent in the southeast. They also wanted to include a section of the Yongding River in the southwest for agricultural purposes. However, protests from the cities in the surrounding areas forced the council to decrease the area of its planned annexation [Dong, 2003].

The Nationalist and Communist parties' disagreements over the fate of the country finally turned into a civil war in 1947. The war ended in 1949 when the Communists defeated the

Nationalists and the People's Republic of China was founded with Beijing restored as its capital and Mao ZeDong as its leader. It was during Mao's early years that the government continued to redo the entire city, including repairing the water plant and extending the water supply system to 95% of the city [Aldrich, 2006].

The expansion of the city continued with the arrival of Russian experts in 1949 to help transform the city into an industrial center. Limits were initially set for the population at a maximum of 4 million, but were subsequently revised as the years passed. This was the first plan where ring roads were to be built around the city; industries were going to be built to the south and east of the city whereas the mountains to the north and west were to be left for recreational purposes [Sit, 1996]. The Municipal Planning Commission outlined at least five different plans for consideration, but the discrepancies between the plans on where the administrative center should be located caused much conflict between the Russians and Chinese working on the project [Sit, 1996]. The Russian's felt that the Imperial City could be destroyed to make room for newer structures while the Chinese architects insisted they be left intact. Based on these conflicts, no plan was formally adopted until 1953 [Sit, 1996].

In 1953 a plan was finally agreed upon and was named the First Five Year Plan (Figure 2). The population limit was revised to five million, the urban area was set at a maximum of 600 square kilometers, and diameters were set for the ring roads and other road systems [Sit, 1996]. Industrialization and expansion of agriculture were a priority in this plan [Spence, 1990]. The plan also stated that, "Beijing lacks sufficient water resources, and is plagued by wind and sand. Such environmental conditions should be altered to provide better conditions for the development of industry" [Sit, 1996]. To reach this goal, new canals were included in the plan to ensure there was enough water for people and the growing industry in the city.

After the completion of the First Five Year Plan in 1957, Mao started The Great Leap Forward (1958-1961), the goal of which was to “catch up to America” industrially and agriculturally in fifteen years [Aldrich, 2006]. Industrial output during the First Five Year Plan had increased 18.7 percent, but agricultural production had only increased 3.8 percent, so Mao designed a new plan for increasing agricultural output during the Great Leap Forward.

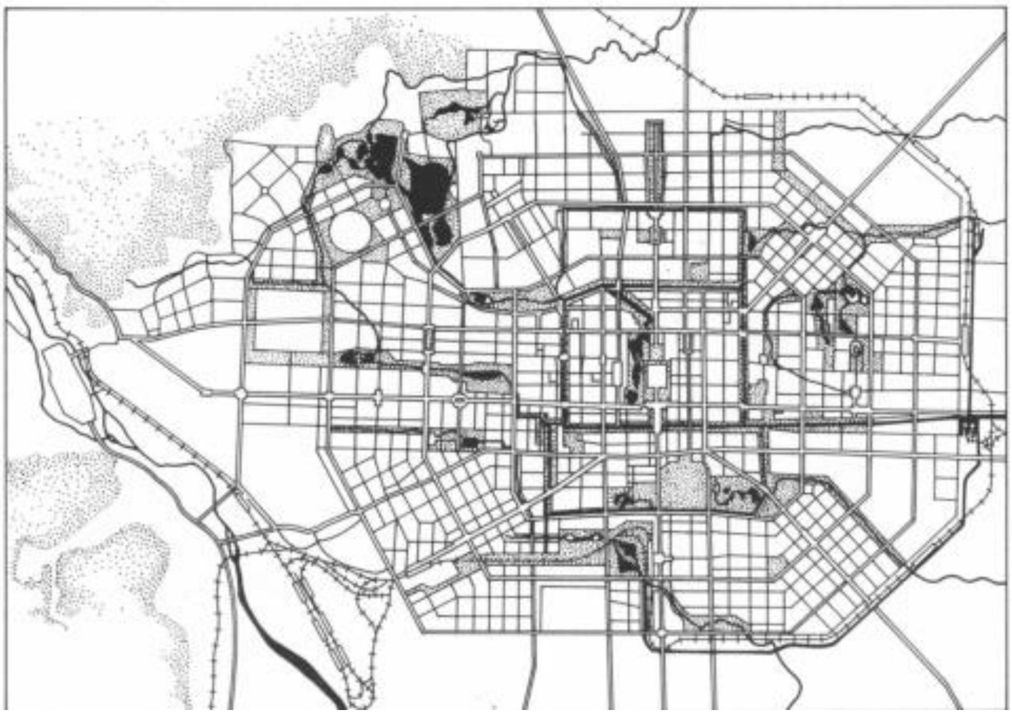


Figure 2- The proposed plan of the city in the First Five Year Plan [Sit, 1996].

Starting in late 1957, Mao mobilized 100 million peasants for new tasks in water control and irrigation, and allegedly opened up 7.8 million hectares of arable land nationwide [Spence, 1990]. By December 1958, 99% of the peasant population had been placed into agricultural communes [Spence, 1990]. It is still uncertain when people started to cultivate the land in the Beijing area, but domesticated rice has been identified as early as 8000 B.C. in the Beijing area [Shelach, 2000]. During this time period, temperatures and annual precipitation were slightly higher than today, and either climatic pressure, or the need of abundant fertile soil pushed people to start farming in northeast China. Rice has always been the most abundant crop grown in China, but over time in the Beijing area, irrigated crops, such as wheat, sorghum, corn, and vegetables replaced rice.

The project, however, was quickly failed and it changed the landscape of the Chinese countryside drastically, as thousands of untouched acres were transformed into irrigated fields for agricultural production, including untouched acres around Beijing [Spence, 1990]. The Great Leap Forward ended after only five years, because the overestimation of grain production and the decreasing availability of food in the communes led to the estimated death of 20 million people [Aldrich, 2006]. The median age from the beginning of the Great Leap Forward to the end of it in 1963 decreased from 17.6 years to only 9.7 years old [Spence, 1990].

Beijing had still held on to its ancient, imperial charm, until the Great Leap Forward when Mao changed it forever. He tore down the thousand-year old city walls and gates so highways could be constructed. New monuments and buildings were built in Tiananmen Square to change the whole center of the city. Mao felt that anything that represented the old regime in Beijing was a threat to the new one and must be discarded. This included the people, sparking the subsequent Cultural Revolution (1966-1976) after the Great Leap Forward [Spence, 1990]. The mass chaos caused by this revolution meant that changes in the expansion of Beijing were slow during this period, while social issues became a higher priority.

The city did not see the rapid urbanization still happening today until after Mao Zedong's death in 1976. The Four Modernizations: industry, agriculture, science and technology, and national defense, set out by Zhou Enlai in the early 1960's, were now the focus of the country. In 1981, another plan for the city was developed to have concentric ring roads expanding from the city and the historical relics in the center of the city would be restored [Dong, 2003]. The Beijing

Town Planning Commission was established in 1981 to continue setting goals for the city with a revised population limit of ten million and an urban area of 750 km^2, but these were frequently revised [Dong, 2003].

The plan set out in 1982 by the Commission put an emphasis on "greening" the city and protecting the natural environment [Sit, 1996]. In 1979, there was approximately 23 km^2 of pond and river space in the city that had not seen any change since 1949. The total urban area on the other hand was 750 km^2 in 1986, which composes approximately 4.5% of the province [Sit, 1996]. This had increased from approximately 557 km^2, 3.3%, in 1979. Before 1980, the growth of the city was primarily within the central mass of the urban area, but after 1980 the city grew outward, mainly to the west (Figure 3) [Sit, 1996]. After this urbanization process, the plan was to simply condense the areas urbanized in the west. The vast areas towards the outskirts of the city would not be as urbanized. The 1992 General Plan stated that there would only be 290 km^2 of urban land and a population of 2.3 million by 2010 [Sit, 1996]. It is clear that these estimates vastly underestimated the growth of the city, and subsequent five-year plans revised the area and the population limits for the city.

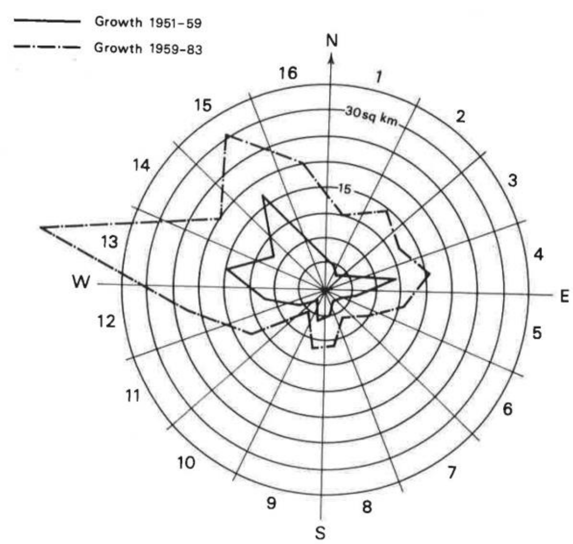


Figure 3- Increase in urbanization in Beijing for two different time periods [Sit, 1996].

Geography and Geology of Beijing

The city of Beijing is currently 3,497 km^2 and has a population of approximately 11.7 million people. The central urban area composes approximately 1,000 km^2 and the rest of the city is considered to be suburban. The entire municipality has an area of 16,801 km^2 and a population of 20 million people [Peisert et. al, 2003]. Beijing is one-third the size of the state of Connecticut with more than five times the population. Within the city limits, there are sixteen districts, two counties, and 289 towns and villages. The innermost city is split up into four different areas, which are surrounded by the inner suburbs. The outer suburbs are located to the north [Shi, 1924].

Beijing is structured along a north-south axis on which the majority of the famous monuments were constructed. At the northernmost point stands the Olympic Buildings. South of them is Jingshan Park, situated on a forty-six meters high hill. It was originally built as the center of the city. Just south of Jingshan is the Forbidden City, which was built in 1406 [Sit, 1995]. Tiananmen Square is south of the Forbidden City and then the Temple of Heaven stands at the southernmost point. Modern Beijing spreads out symmetrically around the axis with concentric ring roads acting as beltways around the city; the second ring road mimics the shape of the city wall. The sixth and final ring road was constructed in 2003 [Sit, 1995].

Beijing is located southeast of the Xishan and Yanshan mountain ranges between longitude 115^{o}25'E and 117 ^{o}30'E and latitude 39^{o}8'N and 49^{o}25'N [Sit, 1995] (Figure 4). It is on an alluvial plane ranging in elevation between twenty and sixty meters that slopes towards the southeast. The plane extends to the east towards the Bohai Sea and south towards the Yangtze River. Beyond the mountain ranges, to the northwest is the Gobi Desert, which periodically sends sand storms to Beijing in the spring. Beijing is located on the northeast edge of the North

China Plain on sediment deposits originating from the erosion of the mountains to the west. The plain extends farther south, encompassing the Yellow River basin. It covers approximately 158,000 square miles, has large coal and oil reserves, and is a large source of cotton, wheat, sorghum, and millet production [Shi, 1924]. The mountains compose approximately 62% of Beijing province and consist of two different systems. The northern hills are composed of igneous rock whereas the western hills are mainly sedimentary rock. The hilly areas are approximately 14% medium height (over 800 m) hills and 35% low hills (200-800 m). Terraces and broad valleys cover 51% [Sit, 1996].

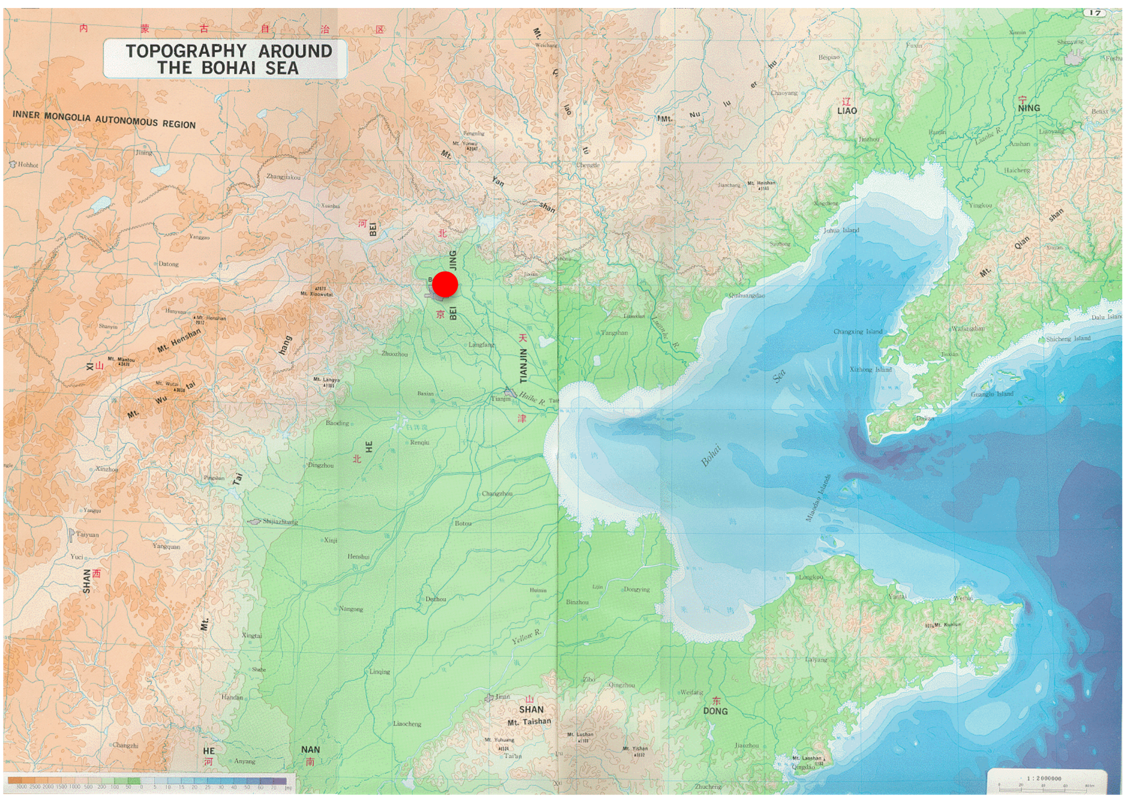


Figure 4- Beijing (red dot) is situated at the foot of the Xishan and Yanshan Mountains, in the northwest corner of the North China Plane, about 140km northwest of the Bohai Sea [Chinese Academy of Sciences Institute of Geography, 1990].

Beijing is located in a warm temperate continental monsoonal climate, which is characterized by humid summers and cold, dry winters. It has a yearly precipitation of approximately 0.61 meters a year. The yearly distribution of the precipitation, however, is uneven as 80% of the precipitation is in the summer [Yang, 2003]. This causes a natural tendency for the rivers to flood during the summer, and to be dry for 300 days of the year [Kaisar et. al, 2007].

Beijing is prone to large shifts in precipitation due to its warm, temperate, continental, monsoonal climate. The 205-year average precipitation is 602 mm; there was a record high in 1959 of approximately 1400 mm and a record low in 1869 of 242 mm [Xie, 2009]. Studies have shown that there is a 42-year cycle, in which 20.3 years are considered drought conditions and 21.3 years are considered wet conditions; however, this is just an average estimate as droughts and floods are not predictable [Sit, 1995].

In 1976, a rainfall of approximately 287 mm caused part of the Miyun Dam to collapse, and in 2012, a rainfall of approximately 460 mm in the southwest outskirt of Beijing and 170 mm in the city caused the death of over eighty people [Jia *et. al*, 2009]. Droughts are nearly as common as floods. The most significant drought lasted from October 1970 to February 1971 and had 114 consecutive days without rain. Statistically, in a ten-year period, Beijing will experience one year with a larger than average flood, one year with a greater than average drought, and three years of average conditions, with the other five years experiencing less significant droughts or floods [Sit, 1995].

Beijing lies on the North China Craton, which consists of two blocks of Archean aged crust that collided before 1800 million years ago [*Gondwana Research*, 2003] (Figure 5). The region between the two blocks is known as the Trans-North China Orogen and the city of Beijing is located about 80 kilometers south-east of this dividing line [Lu, *et. al*, 2008]. The eastern block is very active, thus earthquakes are commonly felt in the city. The collision of the two blocks is responsible for north to north-northeast oriented folds and foliation in the ancient basement rocks. The city of Beijing is located above a north-northeast oriented aulacogen, or failed rift, which opened up about 1800 million years ago. The aulacogen filled up with 1500 million years worth of strata, starting with layers of rift related clastic sediment, and then layers of near shore carbonate and clastic sediment [Zhao, *et. al*, 2003].

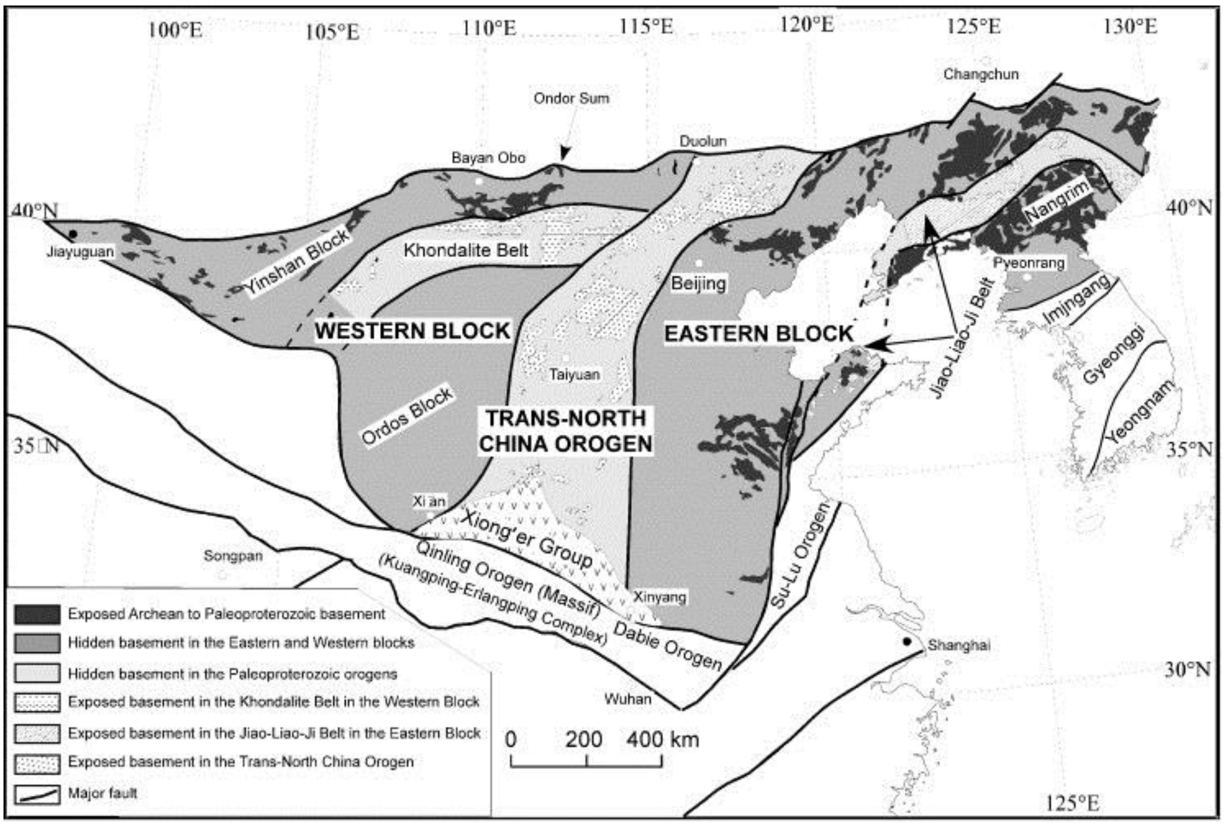


Figure 5- Tectonic divisions of the North China Craton [Lu, *et. al*, 2008].

The eastern block was reactivated about 300 million years ago, at the onset of the collision between the Eurasian and Indo-Australian plates. Deep first-order faults follow the north-northeast trend of the basement rocks [Zhao, *et. al*, 2003]. Shallow rift basins in the younger rocks trend northeast and record modern transtensional forces. There are secondary faults that are oriented southeast to east-southeast as well (Figure 6). The eastern block today resembles the basin-and-range province of the United States [Zhao, *et. al*, 2003].

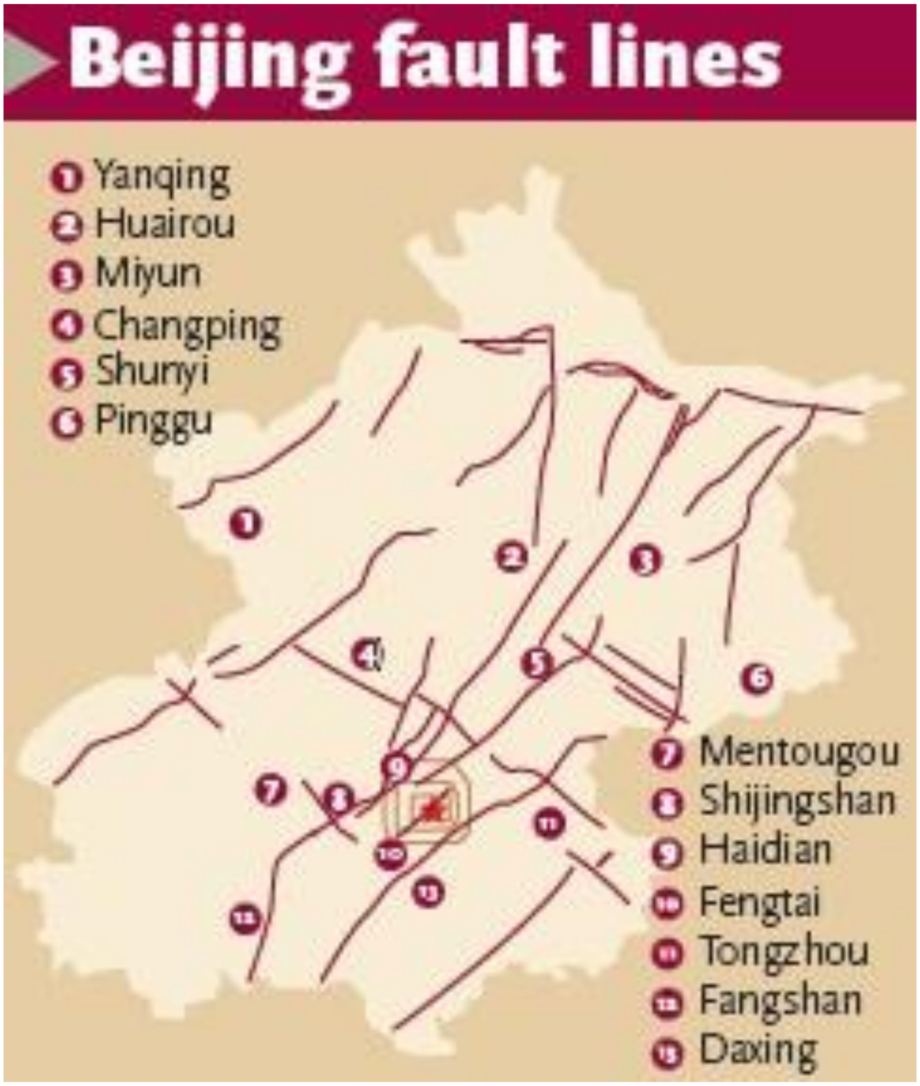


Figure 6- Fault lines in the Beijing area [Huang, 2010].

Beijing's Water Resources

China on average has a total of 2,812 billion m^3 of water annually available, which amounts to 2,195 m^3 per capita per year. The Hai River basin, where Beijing is located, has the lowest water per capita out of the nine basins in the country, with only 230 m^3 per capita per year in 2007 [Yang, 2003]. The evaporation rate of the city is approximately 1,842 mm per year, indicating that water storage in the area is very low.

The water supply for the city of Beijing depends on groundwater supply and reservoirs. The city has on average 2.178 billion m^3 of surface-water resources, of which 90% is in the outskirts of the city in reservoirs. The Guanting and Miyun reservoirs are the largest resources of surface freshwater for the city and are located north and west of the city. Groundwater is the main source of drinking water for the city and there is 2.521 trillion m^3 of groundwater resources in the area [Han, 2003]. However, the water table has decreased more than twenty meters around the city in the past forty years [Kaiser *et. al*, 2007]. In the 1970s there were over 40,000 wells in the municipality that extracted 2.6 to 2.7 billion cubic meters of groundwater a year. Overall, water consumption is approximately 3.7 billion m^3 per year.

As of 2007, the Beijing area used approximately 44.6% of its water for agricultural uses but that number decreased as the province industrialized and the city expanded. The rest of the water was split up with 21.8% of the water used by industry, 31.8% is for municipal use, and 2.3% for ecological use. As more people move into the city, the municipal use increases and the agricultural use decreases. The total amount of water used has also decreased slightly over the past twenty years [Zhang, *et. al*, 2007].

Increased irrigation agriculture and water consumption by farmers coincide with the construction of the Miyun and Guanting Reservoirs. Irrigated farmland was only 14,200 hectares (ha) before the construction of the dams and increased drastically to 95,300 ha in 1958 [Chang, 1998]. In 1991, 2.27 billion m^3 of water were consumed for agricultural purposes composing 62.4% of the total water consumption in the municipality. This number has decreased significantly to 44.6% in 2007, which coincides with the decrease in land used for agriculture.

From 1980 to 1990 alone, rice fields in the municipality were reduced from 53,000 ha to 32,700 ha [Chang, 1998]. As water demand increases in the future, it is expected that irrigated agriculture will continue to decrease in the province.

The Hai River basin starts in the mountains northwest of the city and flows into the Bohai Sea to the southeast. It covers an area of 318,000 km^2 and sustains a population of 120 million people [Wang *et. al*, 2009]. There are three main rivers in the system flowing through the Beijing province, with the Chaobai to the northeast of the city being the second largest and the Yongding to the southwest of the city being the largest (Figure 7). The Wenyu River is directly north of the city and leads into the Beiyun River and the Grand Canal system (Figure 7) [Beijing's Water Crisis, 2008]. Each of the rivers has tributaries that flow through the area of the province. The course of each of the rivers have changed over time by human and natural causes, and some of them were diverted around the city to prevent flooding in urban areas or into the city to provide water for the manmade lakes in the inner city [Beijing's Water Crisis, 2008].

The Yongding River is the largest river in the Beijing province. It flows from the Guanting Reservoir and runs southwest of the city towards the Bohai Sea. The Guanting Reservoir was built in 1954 under the rule of Mao to serve as a source of water for industrial use and for the canals in the city. Before the construction of the dam, the Yongding River would swell from 500 meters to 2,000 meters wide during the rainy season [Beijing's Water Crisis, 2006]. The reservoir is located sixty miles northwest of Beijing, has an area of 253 km^2, holds an average of 2.3 billion m^3 of freshwater, and provides 300 to 400 million cubic meters of freshwater per year to the river.

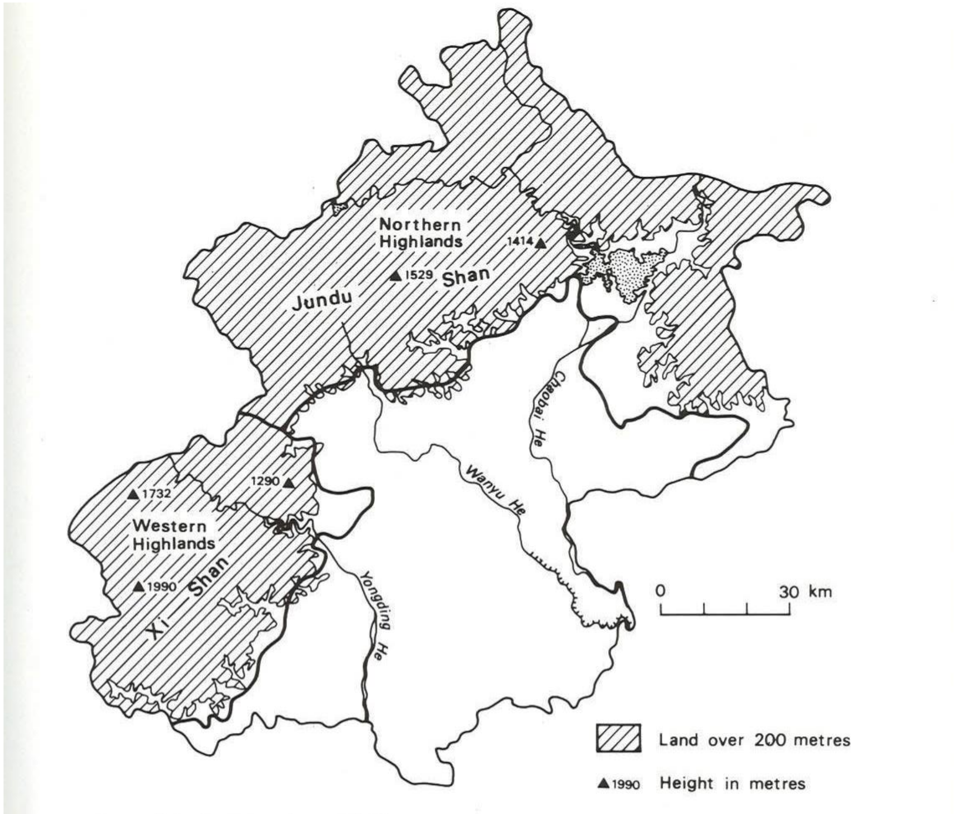


Figure 7 – The three rivers, the Yongding, Chaobai, and Wenyu, start in the highlands and wind their way through the province [Sit, 1995].

When it was first built, the annual flow of water in the river was 1.9 billion cubic meters so it has been reduced by about 85% [Beijing's Water Crisis, 2006]. Since its construction, two additional large reservoirs, 17 medium reservoirs, and 248 smaller reservoirs have been added to the 43, 304 km^2 watershed. Farmers are also diverting the water upstream on the Yongding River as there is a lack of coordinated national water policy. Since its construction, the intended capacity has been reduced to 9% of its original capacity from 2.3 billion m^3 to about 220 million m^3. [Beijing's Water Crisis, 2006].

The region around the Guanting Reservoir has also undergone a significant amount of agricultural and industrial development over the past forty years, which has caused water and soil pollution in the reservoir area. In 1997, the water was deemed too polluted from sources upriver to permit anything but industrial use and is no longer used as a source of drinking water. Prior to 1997, the water was utilized for urban, industrial, and agricultural uses [Luo *et. al*, 2007]. From 2001 to 2005, an increased shortage of drinking water due to drought caused the government to ban fishing in the area to improve the water quality of the reservoir. The reservoir subsequently was deemed Level III specified by the Environmental Quality Standards for Surface Water to be used as an auxiliary water source for Beijing in future [He *et. al*, 2008]. A study conducted in 2008 showed that the water does not qualify as a drinking water source, but that it is also not so polluted that it could not still be used as an auxiliary drinking water source if needed in Beijing.

The second largest river in the Beijing province is the Chaobai River, which flows through the Miyun Reservoir north of the metropolitan area. It is the convergence of the Chao and Bai Rivers in the Hebei province, north of Beijing. The Miyun dam was constructed in the 1960's, along with a 95 km canal to deliver water to Beijing [Beijing's Water Crisis, 2006]. It was designed with a capacity for 4.375 billion m^3 of water to control floods, provide water for the municipality, and for farmland irrigation. The manmade lakes of Beijing were also refilled using the water from the reservoir. With the depletion of the Guanting Reservoir, Beijing became solely dependent on the Miyun Reservoir and cut off the city of Tianjin from any water supplied from it. In 2003, only a few hundred cubic meters were left in the reservoir due to consistent usage of the water and droughts starting in 1999 [Beijing's Water Crisis, 2006]. Miyun also faces the same problems as the Guanting Reservoir, as more dams are being built upstream in Hebei Province. The inflow was reduced by more than 75% from 1955 to 1984 alone, and consistent droughts in recent years have kept the inflows consistently low [Jun *et. al*, 2005].

After seeing the pollution problems in the Guanting Reservoir previously, Beijing began to set up strict regulations for the Miyun watershed to prevent excess industrial and agricultural pollution. To decrease any pollution risk, cage-raised fish were abandoned from the reservoir, fruit tree farming was promoted as opposed to the production of grains, and dairy farms were forbidden by the government [Beijing's Water Crisis, 2006]. Another problem facing the Miyun Reservoir is related to soil erosion. Changes in land cover in the upper basin over the past fifty years have caused increased erosion in the tributaries and sedimentation of the reservoir [Tian *et. al*, 2007].

Hydrological Planning for Cities

Hydrological planning in cities is primarily dependent on climatological conditions, hydrological conditions, and the interactions with surrounding areas. The size of the river basin, location of the river basin, proximity to water divide, and the size of the surrounding water bodies all need to be taken into account as water management for cities is assessed [Niemczynowicz, 1999]. The magnitude and timing of floods and droughts was also necessary for proper planning.

The increase in impervious areas resulting from the increase in concrete, steel, etc. in the city changed the whole hydrological cycle. As infiltration rates decrease in the area, groundwater does not recharge as quickly. Now, when there is a large rainstorm, water flows across the surface causing shorter time to peaks for floods and floods tend to be larger (Figure 8). This means that floods will occur a lot faster after a rainfall, and will be a lot stronger than prior to urbanization [Dunne *et. al*., 1978]. This cause culverts and bridges to reach their maximum capacity and sometimes exceed it. Channels to erode faster to compensate for the large floods, with increased erosion in the entire urban area.

For cities such as Beijing, water is transported through canals to force water to run through the center of the city. A canal by definition is a human-engineered waterway used for irrigation, navigation, water-power, flood mitigation, land-drainage, defense, or water-supply [Hughes, 1995]. Canals are channelized waterways that can increase erosion in the area as water has a higher velocity when it flows through impervious areas and straightened channels [Dunne *et. al*, 1978].

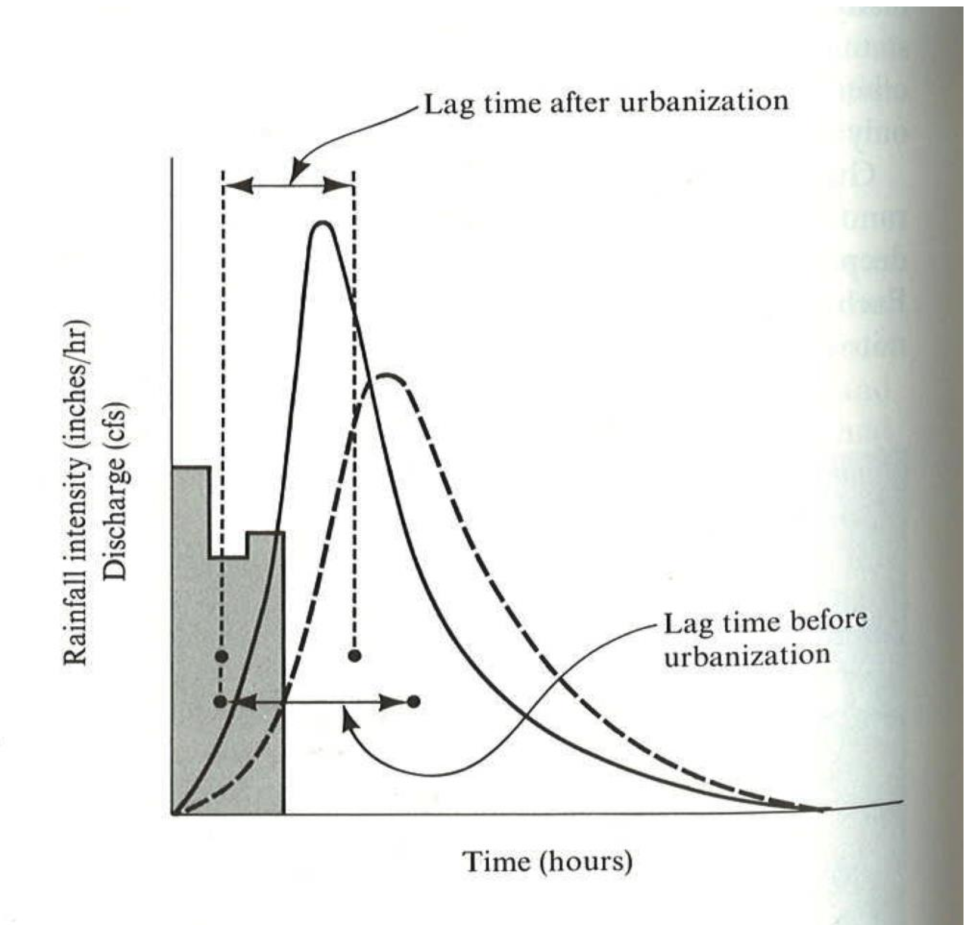


Figure 8- Flooding increase after urbanization [Dunne *et. al.* 1978].

Methodology

To study the development of the complex waterway system of Beijing, a series of historical maps from 1912, 1926, 1983, and a satellite image from 2012 were analyzed using ArcGIS 10.1 GIS software. The 2012 satellite image was provided via ArcGIS Online and is a Digital Globe 2012 image courtesy of Bing Maps [Bing Maps, 2012]. The 1912 map illustrates the distribution of drinking water in Beijing, has a scale of 1:100,000, and was surveyed from 1908 to 1912 [Bouillard, 2012]. The 1926 map was originally from the Great Britain War Office and has a scale of 1:50,000 [Great Britain War Office, 1927]. The 1983 map was published in Russia in the Soviet Military Plans and has a scale of 1:25,000 [Beijing, 1983].

The 1912 map was scanned into the computer and the 1926 and 1983 maps were downloaded in digital format. Each of the maps was georeferenced using the 2012 imagery for a common reference. The RMS error for each of these was 41, 10, and 11 meters respectively.

The first step in analyzing the changes in the water systems of Beijing was to digitize the canals, streams, and rivers in the Beijing vicinity to make individual vector layers for each stream pattern in the four different years. Features were digitized at a map scale of 1:20,000. Each of the maps had different limits of the area they covered with the smallest area being one million square kilometer (1926 map) and the largest being 5.7 million square kilometers (1912 map). The type of waterway was noted during the digitizing process, as well as the direction of flow with the larger canals, streams, and rivers. Each waterway was classified upon visual inspection. Different colors and thicknesses of lines were used to differentiate between thin and wide canals and natural streams and rivers. Natural streams were considered anything flowing towards or away from the city that was clearly not an artificially straight line. Rivers were classified by being larger than streams and also not manmade, straight lines. For 2012, the size of the canals could be deciphered by simply observing them, and it was clear what was a natural stream or river compared to a canal by the pretense or absence of a cement barrier. The satellite image was also analyzed for evidence of waterways being converted to culverts or waterways that have been repurposed. Water bodies were also digitized with flow-through lines so not to leave holes on the canals or streams.

To find the drainage divide of the watersheds, a hydrographic model of the Beijing area was produced. A digital elevation model (DEM) of the Beijing area was acquired from the HydroSHEDS database [Lehner, 2008] and clipped to the basins covering the Beijing region. The DEM was then “filled” to make sure there were no “sinks” to disrupt the direction of flow. Then, the Flow Direction tool was used to assess the course that water should flow based on the elevation. To define the regional streams and higher order basins, a flow accumulation grid was made using the flow direction grid. The final result is a network of the ultimate flow of water, from the smallest streams to the largest rivers. To locate the drainage divides within the city, pour points were marked on the watersheds where streams and rivers converged or diverged. This then allowed for the construction of the major tributaries to the Yongding and Chaobai rivers and showed the natural flow of rivers and streams in the area based off of modern elevation, as well as the outlines of lower order basins in the city of Beijing. The local flow direction and flow accumulation layers were then made to assess the flow of water only in the basins that affect Beijing. The model indicates surface flow directions out of Beijing. The most important error that could arise with this model is that the DEM could pick up the height of large buildings and perturb the streamlines or drainage divides.

The combination of these three layers produced by hydrographic analysis and digitizing old maps of the city, allowed for analysis of the changes in drainage density over time, sinuosity of the streams over time, and increases in the number of culverts in the city over time.

To determine changes in sinuosity over time for the Yongding River, small sections were measured two ways. First, the length of the stream sections was calculated using ArcGIS's "Geometry Calculator". Then the straight-line end-to-end length was measured using the Measure tool in ArcGIS. The actual length of the river was divided by the length of a straight line between the two points. This determines the extent to which a stream is meandering or straight.

Drainage Density is a measurement of the sum of the channel lengths per unit area and is expressed in terms of kilometers of channel per square kilometer. The drainage density of the system was measured by taking the total length of all of the waterways in the city and dividing it by the watershed area to assess how many canals have been added or taken away from the area. The area for each map was different as each map covered different extents for the city.

To assess the increase in culvert usage in the Beijing area, the 2012 map was analyzed for decreases in canals from 1983 and for gaps in canals over the entire area. It is impossible to tell the whole extent of culverts underneath the city, but a general assessment can be determined.

All of the vector layers were specially prepared for statistical analysis. Digitized line-work for a given year was dissolved into a single complex polyline and then broken down into topologically correct node-to-node segments using the Dissolve and Multipart To Singlepart tools. The Interpolate Shape tool was then used on the topologically correct line-work to convert it to a 3D shapefile with the HydroSHEDS DEM as an elevation source. The two endpoints of every line segment were generated using the Feature Vertices to Points tool. The elevation attribute was then added to the 3D points and calculated with the Calculate Geometry tool. The from-node is listed first in the ID attribute and the to-node is listed second, so it was easy to locate the line segments with a to-node higher than the from-node (i.e. flowing the wrong way). Then the direction of these line segments was flipped with the Flip tool. This consisted of about 20% of the shorter line segments. When the elevation of the to-node and from-node were identical, flipping was not done in order to keep a random sample of directions on level channels.

The Linear Directional Mean tool was used to calculate the mean direction of the streams and canals for each year by treating them as vectors. This tool describes the direction in which the general flow is occurring and the "circular variance" of the vectors provides a measure of how closely the streams follow the mean direction. The Directional Distribution tool was used to calculate the standard deviational ellipse of the streams for each year, treating them as points rather than lines. An eccentric ellipse indicates that the streams are concentrated in an elongate area whose trend is described by the "rotation" of the major axis. A more circular ellipse indicates that the streams are more spread out across the study area. The 3D points for all the years were merged to create a sample of the HydroSHEDS surface for a trendsurface analysis. The Trend tool was used to calculate a trend surface, or a best-fit plane, for the sample points in order to illustrate the general slope of the study area.

A twentieth century (1901-1995) climate data model originating from the Climate Research Unit of the University of East Anglia was downloaded in NetCDF format from the Oak Ridge National Laboratory [New et al, 2000]. The CRU climate model consists of data for a 2.5 by 3.75 degree grid of the world interpolated from historical data at weather stations around the world. Monthly total precipitation data for each year, for 10-year averages and for 30-year averages, were examined using ArcGIS to locate the appropriate grid cells for Beijing. The temperature data for the cell including the inner city was exported to an Excel spreadsheet to make a rainfall totals versus time plot.

Landsat landcover data from the GeoCover 1990 and GeoCover 2000 mosaics were downloaded from NASA and clipped to the regional watersheds surrounding Beijing in order to examine regional landcover change [USGS, 1978; USGS, 1992; USGS, 1999; USGS, 2009]. The urbanization of the province displayed using the 7-4-2 band combination. Complete Landsat scenes for Beijing, prepared for the GeoCover project, were downloaded from their archive at the Global Land Cover Facility at the University of Maryland, along with one scene for the 1975 GeoCover mosaic that was never completed. The resolution of the 1975 scene is about 60 meters and the resolution of the 1990 and 2000 scenes is 28.5 meters. The GeoCover project has been continued, as the Global Land Survey (GLS), and Landsat scenes chosen for GLS 2010 are available for download from the USGS. The resolution of the 2010 scene is about 14.25 meters. Each of the images had to be processed separately. A false color image was created for 1975 using bands 4-3-2 and for 1990, 2000, and 2010 using bands 7-4-2. The Principle Components tool in ArcGIS was used to reduce the images and then an unsupervised classification was made for each scene. Two classes on the 1975 image represented fully urban areas so they were extracted to create the first image of urbanized Beijing. In the subsequent scenes, only two classes represented about 90% of the area classified in 1975. These were used to find newer urban area in 1990, 2000, and 2010 and then the new urban area was added to the previous year's image of urbanized Beijing. Increases in urban area for 1990 and 2000 are in 28.5 x 28.5 meter cells and for 2010 they are in 14.25 x 14.25 meter cells. The 75% smaller cell size leads to an underestimate of new urban areas in 2010 that is difficult to quantify.

A fault line map from the China Global Times (August 27, 2010) was digitized to show the major faults in the city [Huang, 2010]. The image is a cartoon originally from Chinese National Geography so the resolution is unknown. It was then shown over the 2012 satellite image with the names of the different fault lines.

Results

See Appendix for 1912 Beijing Waterways map, 1926 Beijing Waterways map, 1983 Beijing Waterways Map, 2012 Beijing Waterways Map, Hydrographic Model of the Beijing Area Map, Beijing Land cover Changes Map, Beijing Fault Lines Map, and Steam Changes Statistics Map

There are alterations in the water supply canals towards the city and the drainage canals from the city over the four different time periods. In 1912, there are prominent supply canals and drainage canals flowing through the city. The main entryway for water is from a canal drawn off of what is the current day Qinghe River that leads to the Wenyu River (Figure 9). The water comes from the hills to the northwest, and then is diverted southeast towards the city to the Kunming Lake. In 1926, the supply of water to the city is also from the Qinghe River and Kunming Lake.

Figure 9 – Supply canal off of the Qinghe River in 1912 flowing into the inner city from the northeast (Point A).

The canal from the Qinghe River is still functional in 1983, but instead of going to the inner city canals directly, it is diverted directly south to another supply canal that flows directly east into the city. There is also a wide canal supplying water from the Yongding River (Figure

10). This canal converges with the water from the Qinghe River. Irrigation and smaller canals that are diverted from the Yongding River are also used in 1983. The canals from the Qinghe River and the wide canal from the Yongding River flow on almost the same path as the 1983 canal in 2012. There are a few thin canals supplying water from the Yongding River as well (Figure 11).

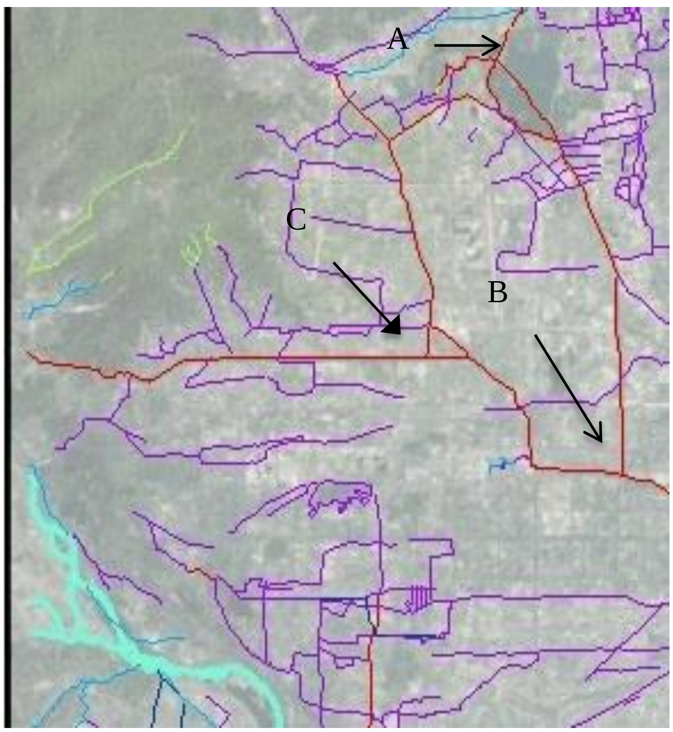


Figure 10- Supply canals from Yongding River (C), supply canals from Qinghe River (A,B) in 1983

\

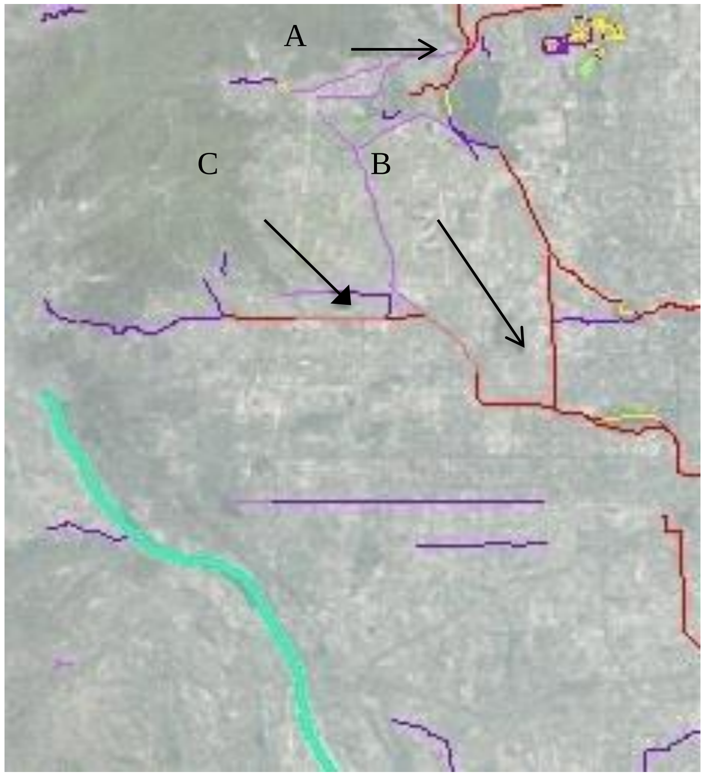


Figure 11- Thin canals supplying water to Beijing from the Yongding River in 2012 (C).

Drainage from the city in 1912 is through one canal that drains from the inner city directly east (Figure 12). This canal can be seen in 1926 as well. The Liangshui River does drain from the Beijing area, although it is not connected to the inner city moat in either 1912 or 1926. In 1983, there are five wide canals that drain the city: the Liangshui River is connected to the central moat, there is a canal in the southwestern corner, the wide canal that drains east from the central moat is still present, and there are two wide canals in the northeast corner of the city. In between all of these canals are thin canals that drain water as well. In 2012, the five main canals from 1983 are still present, but there are only seven thin canals that drain from the city. The basins and streams map has four different streams that drain from the city in two different basins.

Figure 12- Primary drainage canal from the city seen in 1912

The central moat around the inner city has decreased in visible waterways over time. In 1912 there are four complete sides to the central moat and a divider in the middle running west to east. The lakes in the middle are connected to the moat and infiltrate into the Forbidden City. In 1926, half of a side has been changed to a thin canal and a canal no longer connects the lakes. By 1983, two-thirds of the eastern side and the central median are no longer present via satellite imagery and the canal in the southern half of the central area is no longer there. By 2012, two-thirds of the western side is no longer visible as well (Figure 13).

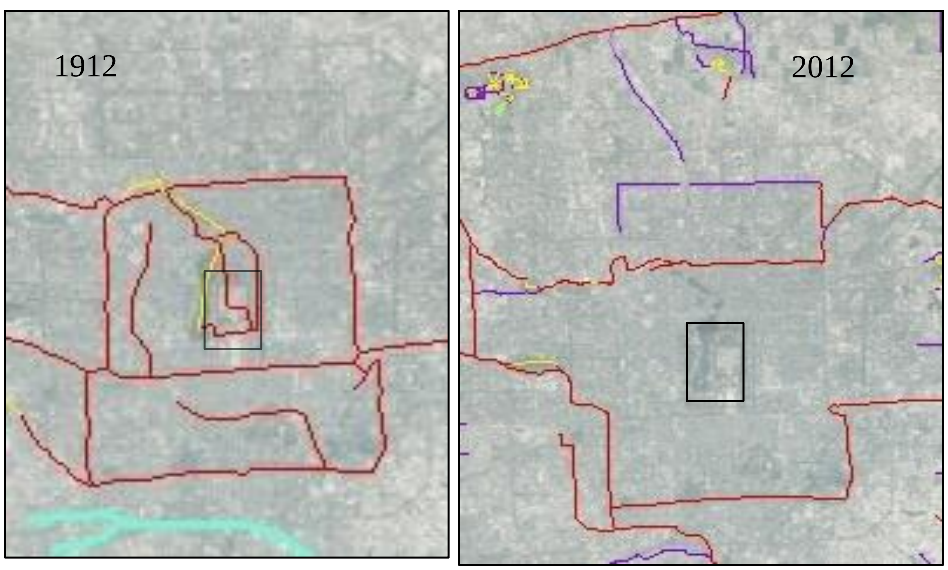


Figure 13- Changes in the central city waterways[2]

The stream statistics map illustrates the changes in the mean direction and the distribution of the waterways in the city. The trend analysis shows topographic contour intervals that strike

[2] The black rectangle surrounds the Forbidden City.

N23°E (Figure 14). The slope of the surface is less than one degree and the steepest downhill direction is S67°E. From 1912 to 1926 the mean flow direction rotated towards the east, where it has remained (138° in 1912 versus 96°-107° in later years) In 1983 the mean direction has the most variance at 0.86 and in 1912 it has the least at 0.44. The eccentricity of the standard deviational ellipse decreased from 1912 to 1983, and then rose again in 2012. The rotation of the standard deviational ellipse in 1983 is noticeably different from those in other years (79° in 1983 versus 93-104° in other years).

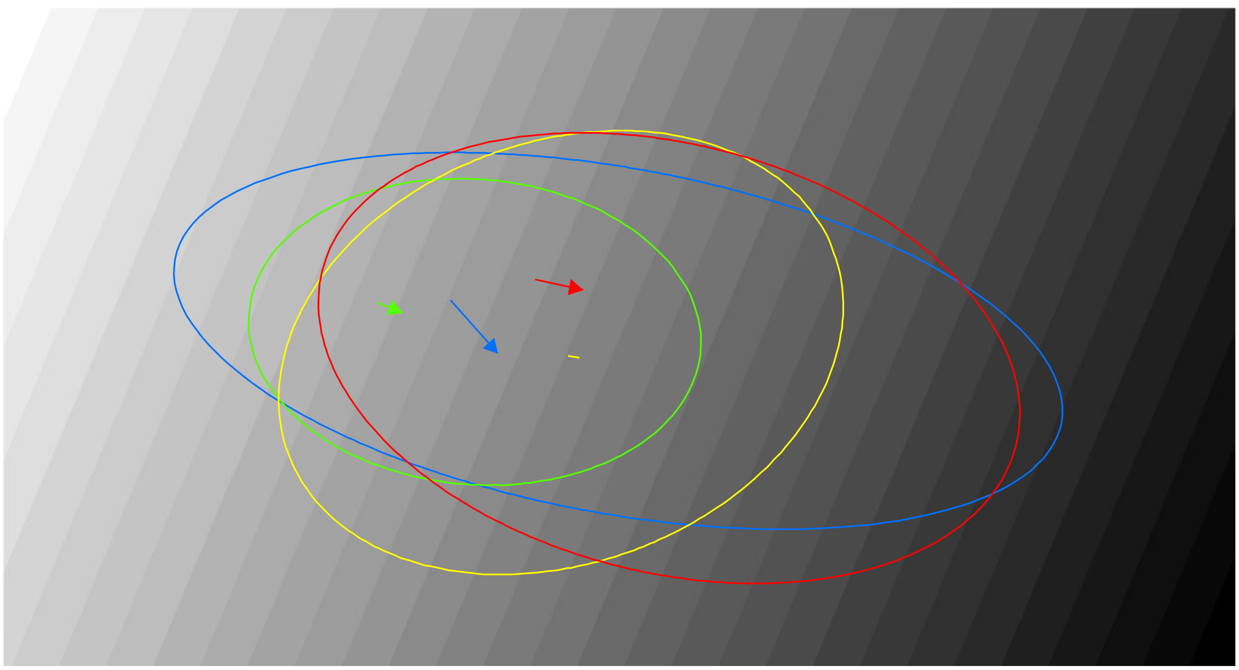


Figure 14- Changes in the mean direction and distribution of the waterways and the trend analysis showing the slope.

The hydrographic model of the Beijing area has four different local basins that drain the city: to the west is the Yongding basin, the south is the Liangshui basin, the east is the Tonghui basin, and the northeast is the Qinghe and Wenyu basin (*See Appendix*). The modern Chaobai River basin lies to the east, just outside of the study area. The Yongding drainage divide is very close to the actual river. Streams in the Liangshui basin flow to the southeast and then converges with the Chaobai downstream. The Qinghe converges with the Wenyu River just north of the city and then converges with the Chaobai to the east of the study area. The Tonghui basin flows to the east and converges with the Wenyu River. There are three streams flowing into the city in the Liangshui basin and are the only natural flow into the center of the city (Figure 15). The Tonghui basin helps drains the city in addition to the Liangshui basin (Figure 16). At the coarsest scale, however, the streams flow mainly southeast to be collected by northeast flowing streams that eventually turn southeast again.

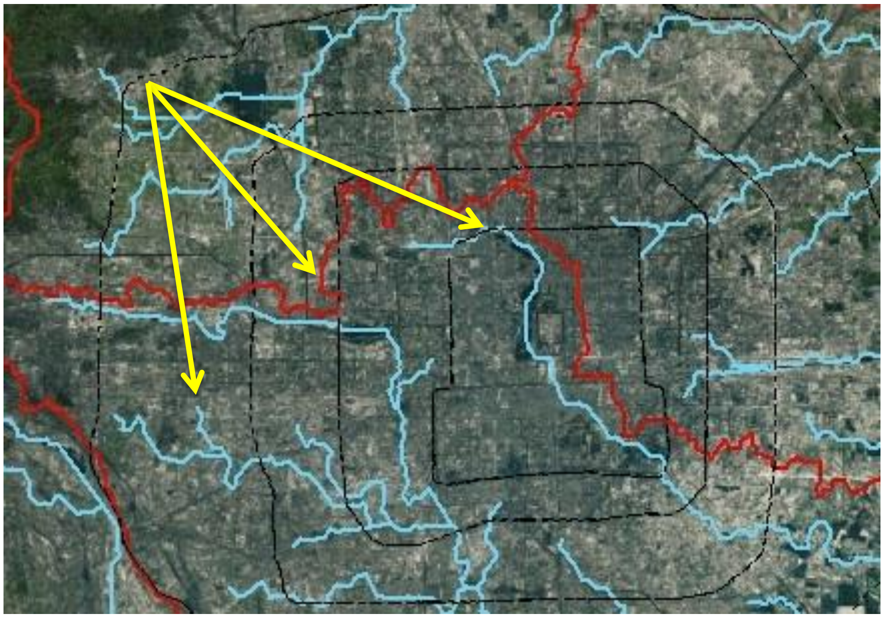


Figure 15- Supply of water based on the Hydrographic Model in the Liangshui basin

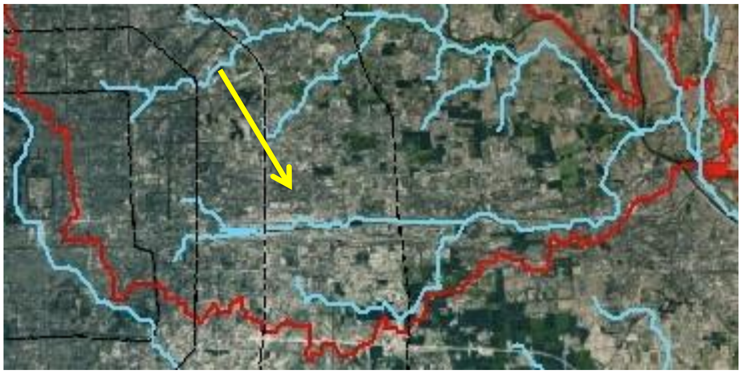


Figure 16- Drainage stream in the Tonghui basin from the city according to the hydrographic analysis

The Yongding River changed its shape over the four different time periods (*See Appendix*). The sinuosity decreased over time from 1912 to 2012. In general, if sinuosity is greater than 1.5, then the river is considered to be meandering. If sinuosity is less than 1.5, then it is considered that is a straight river. In 1912, the sinuosity was 1.12, meaning that it is considered straight. But as seen on the map of waterways in 1912, the Yongding River in the southwest corner is slightly meandering. The 1926 map and the 1983 map both show the river has a consistent sinuosity between 1.13 and 1.14. From 1983 to 2012, however, there is a clear decrease in sinuosity from 1.13 to 1.00, making it a completely straight river (Table 1). The value of 1.00 was obtained by measuring the visible thalweg, or the deepest part of the river. It is likely that during the rainy months the river could increase in sinuosity, but it is clear that the thalweg is a straight channel. The river is also almost completely dry on the satellite image in 2012.

Table 1- Sinuosity of the Yongding River drops remarkably between 1983 and 2012.

Year	Sinuosity
1912	1.12
1926	1.14
1983	1.13
2012	1.00

Localized drainage density changed over the four different time periods. The drainage densities double from 1912 to 1926, and then quadrupled from 1926 to 1983 (Table 2). According to the aerial view of 2012, the visible waterways have a drainage density equal to that of 1912. This does not factor in the use of culverts or other covered waterways. Based on general observation of the 2012 satellite image, the majority of canals that were not visible above ground still flowed into a certain area and flowed out of it along the same path. This is strong evidence that it is flowing through a culvert. There was one canal that had been manually filled in but it was not noteworthy. If all of the supply and drainage canals seen in 1983 had been changed to culverts in 2012, then 77.8% of the canals had gone underground or were no longer there.

Table 2- Drainage density of the study areas increases rapidly between 1912 and 1983 and then drops at a staggering rate between 1983 and 2012.

Year	Drainage Density
1912	$1.54 * 10^{-4}$ m/m^2
1926	$2.25 * 10^{-4}$ m/m^2
1983	$8.18 * 10^{-4}$ m/m^2
2012	$1.82 * 10^{-4}$ m/m^2 (visible waterways)

The location of the fault lines from the China Global Times (August 27, 2010) are digitized on top of the 2012 satellite image (*See Appendix*). Many of the fault traces are detected under north Beijing and one in central Beijing. The Fangshan-Shijingshan-Haidian fault and the Tongzhou fault are situated close to the southern drainage divide of the Qinghe River basin.

The land cover map (*See Appendix)* shows increases in urbanization over four different time periods in Beijing (Table 3). Based off the changes in cell size from 2000 to 2010, there is a potential underestimate for 2010 of up to 10%. Beijing from 1975 to 2010 has merged with urban areas on the outskirts of the city. The dark spots in the center of the city are the lakes and the parks and they decrease over time. The increased urbanized land is increased impermeable surface.

Table 3- The percent of urbanized land increased steadily between 1975 and 2000 and then growth slowed down from 2000 to 2010.

Year	Percentage Urbanized Land
1975	16.6%
1990	26.5%
2000	34.6%
2010	36.8%

The CRU climate data has a yearly precipitation range from 350 mm to 900 mm with the average annual precipitation around 620 mm. The average precipitation has slightly increased over the past fifty years but not significantly (Figure 17). The yearly cycle uses averages for each month. There are periods of high rainfall and periods of low rainfall varying by year and there are no more than two years in a row with low rainfall or high rainfall.

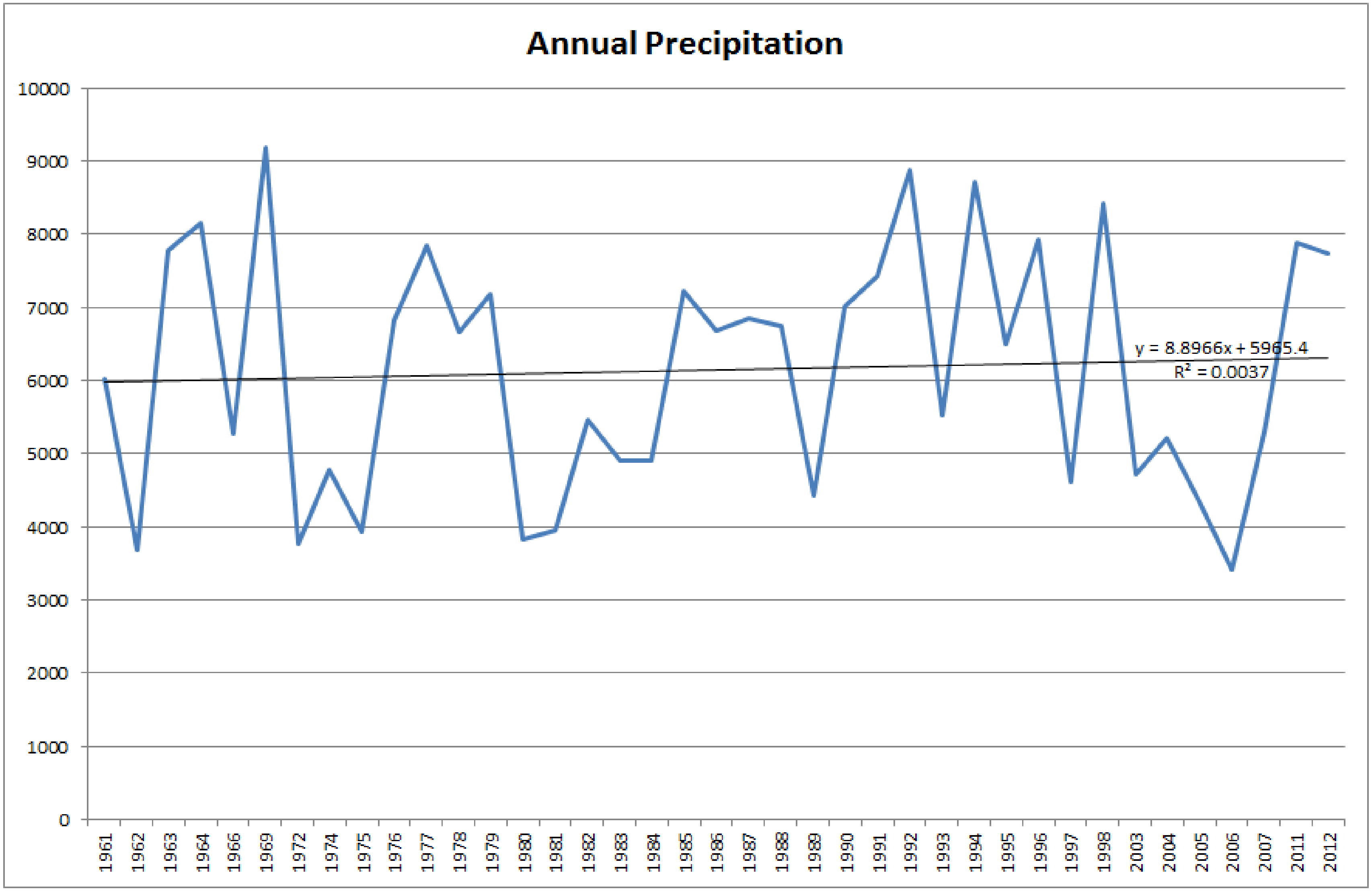


Figure 17 -Precipitation from 1961 to 2012 in Beijing.

Discussion and Analysis

Surface Water Then and Now

Over the past one hundred years in Beijing, there have been drastic changes in the waterways that have affected the water supply, and flooding in the city. The Yongding River has significantly changed its course and the total flow out of the city has also changed course from its natural flow regime. This change in the direction of waterways and the rate of flow of the water not only affects how much water is transported through the province, but also affects how much water is available to recharge the local groundwater. Changes in flow associated with urbanization and the expansion of impermeable roofs and pavement also increase the risk of massive floods.

The supply route changed from just the Qinghe and Wenyu river systems in 1912 and 1926 to primarily using the Yongding River in 1983 and 2012. The addition of the supply canals from the Yongding River by 1983 coincides with the increase in population and the increase in urbanization on the landcover map. The city grew so rapidly that they needed as much water as possible, so canals were built quickly to help satisfy that need. By 2012, however, those canals presumably became obsolete and appear to be converted to culverts, based on them no longer being visible above ground. The Yongding River is completely dry south of the diversion canals so the canals are diverting the majority of the water towards the city even though it is apparent that that water supply is not critical.

The increase in culverted supply canals and the decrease in other supply canals indicates that they are becoming obsolete. It is no longer necessary to supply that much surface water carried by the wide canals to the city, so the old canals' capacities are being reduced and they are being converted to culverts to maximize urbanization. Water is not particularly useful for consumption when it is transported through canals as the primary supply of water is through groundwater and the reservoirs. It can be aesthetically pleasing for the city life and could still be transferring water to the inner city lakes, but it is not being supplied for daily human use. The canals are being culverted so that space can be used for buildings, rather than a waterway that is not serving any regular function.

Compared to the HydroSHEDS, the supply canals from both the Yongding River and the Qinghe River cross over the basin lines. There is a basin defined around the Yongding River and one around the Qinghe and Wenyu Rivers as well that leads into the Chaobai River. These canals have been forced over basin lines to divert water towards the city. According to topographic and historical data, the city itself lies on a fairly flat plain, so the dividing lines shown on hydrographic analysis may not be that great and the canals can easily be dredged to flow towards the cities. The supply canals over time forced the water into more unnatural patterns as the supply was streamlined into one main canal from both rivers. The water is forced into channelized canals around numerous ninety-degree bends in order to match the layout of the streets.

According to the HydroSHEDS, the only natural path that water flows into the city is from smaller streams that do not even start in the mountains (Figure 10). They are not naturally connected to the streams from the Yongding and Qinghe basins. Therefore, the supply canals into Beijing are completely unnatural according to the hydrographic model. The construction of the supply system started very early on in the Yuan Dynasty, but as people depleted the rivers and increased the population, the systems evolved to find more water. It is apparent that currently there is minimal water being supplied from any of the adjacent river systems.

The drainage from the city shows different patterns of development compared to the supply canals to Beijing. Historically, a canal was built in the Yuan Dynasty along east to west line as an end to the Grand Canal for ships to enter directly into Beijing. The section leading directly into the city was cut off more than one hundred years ago, and since then it has been converted into a drainage canal from the city. The canal moves water directly east away from the city and connects directly to the Wenyu and Chaobai river system with minimal changes over the past one hundred years. It also is forced to cross over two separate drainage divide to continue on the straight west to east path shown.

The hydrographic analysis shows this same drainage system. However, a natural flowing stream from the city should not be completely straight. This means that the DEM that was used to create this model could be skewed as this canal is very old and is lower than its surrounding area. Therefore, it is hard to analyze the natural flow of drainage to the east of the city. There are rivers to the east and the south of the city, but it is unclear how water should naturally travel towards these rivers. The DEM is a 90-meter Digital Elevation Model with SRTM data that simply uses radar to pick up the elevation. This could explain it picking up a dredged canal that has been around for many years.

Geologically, the hydrographic model may reflect the history of the bedrock. On the hydrographic model, there is a series of southeast flowing streams that form south of the city and then converge with northeast flowing streams (Figure 18). The pattern is repeated at different scales throughout the remainder of the Liangshui basin. This reflects the northeast oriented fabric of the basement rocks created by collisions and rifting that occurred in the North China Craton around 1800 million years ago. Streams that flow southeastward along the slope of the North

China Plain are interrupted by northeast trending structures that are probably modern faults controlled by the basement rock.

Figure 18- Streams running to the southeast on the hydrographic model.

The map of modern faults around Beijing helps explain the pattern in the streams as well. The dominant faults are to the northeast and streams are likely to be cut off from their sources by northeast trending faults. The Fangshan-Shijingshan-Haidian fault is mapped close to the drainage divide that separates the northeast flowing Qinghe River from the southeast flowing streams in the Liangshui basin. The Daxing fault is mapped close to the head of the streams that drain the open areas southeast of the city. The hydrographic model is just a model, but it suggests that the natural tendency is for the rivers and streams to flow to the southeast and to the northeast. Engineers have since forced them to flow to the east and to the south.

The Ximagou and Gaoliang Rivers were historically the only two rivers that ran through the city and are seen on the hydrographic model flowing on the same paths on which the city was settled. The Gaoliang was changed into a supply canal for the lakes in the city starting about 900 years ago and is barely recognizable today. Perhaps, engineers in the Yuan Dynasty used the fact that the Gaoliang River is a decapitated stream on a fairly gradual slope and easily diverted water from the Qinghe River south to supply more water to the city. The city was settled along the Ximagou River and then when it expanded to the northeast, water needed to be supplied from the Qinghe River.

In 1912, there were more than ten supply canals throughout the city and only one that fed the lakes on the original path where the natural river should flow. This canal was clearly made into a supply canal in 1912 and by 2012 it was no longer functional. The water that would flow through this channel has been diverted around the central city. The lakes are still present in the center of the city, but the canals and streams are no longer connected above ground. The canals were probably converted to culverts to supply water underground. The Ximagou was in the southwest corner of the city and flowed towards the modern day Liangshui River. The channelized streams leading up to the Liangshui follow the same path the Ximagou would have followed. These are the closest canals in the city that follow a natural river's path.

Overall, the largest change in supply and drainage canals was seen between 1926 and 1983. Drainage density in 1983 was three times the drainage density in 1926 due to the vast urbanization after the fall of the Qing Dynasty and the need to supply water to the growing population of the city. The city expanded vastly with the numerous five-year plans created in that time period to perfect the layout of the city. The 1983 map shows a large intricate network of canals spread out throughout the whole city. There are also irrigation canals shown coming directly off of the Yongding River to help supply the extensive agricultural network outside of the city. The stream statistics for 1983 have a very round ellipse, to the canals are spread out evenly throughout the whole city, and they may have been stagnant, because there is no change in elevation between ends. It is apparent that surface water was the primary source of water for that time period as it was necessary to have surface canals present in every corner of the city.

The large decrease from 1983 to 2012 of 77.8% of the visible canals indicates that the canals were filled in or most likely converted to culverts. Over the course of those 20 years, it was no longer feasible to use the water in those canals. The water during that time period in both the reservoirs became very polluted from industrial and agricultural runoff and that polluted water was carried into the city. For a while, Beijing almost could not use the water from either reservoir for drinking and still cannot use water from the Guanting. Since the water was no longer usable for their purposes, it was then more economically feasible to cover the canals, so roadways could be constructed over them.

The stream change statistics show that the distribution of the canals in 2012, compared to 1983, is along a northwest to southeast diagonal through the city. The surface water movement is changing back to a more natural pattern of flowing towards the southeast and is not as spread out as in 1983. The intricate network of canals from 1983 has decreased and water is moving through a similar above ground system. The natural flow should be only with two or three streams throughout the whole city and the canals in the southwest corner of the city follow a similar path to that of the Ximagou River. The southwest corner has also been the least affected by urbanization (also seen in Figure 3).

The Yongding River has been severely affected by water and sediment starvation. The Yongding River was flowing up until twenty years ago, after the 1983 map was developed. Canals at this point were being taken away; so more water was not being diverted than the two canals seen on the 2012 map. The precipitation has overall not changed in the past fifty years and cycles between rainy years and drought years, so this did not cause the river to dry up either.

This means that the primary cause of the river drying up is the lack of groundwater in the area and the straightening of the channel. Between 1912 and 1926, the Yongding River seemed to have a naturally, slightly meandering flow with minimal channel changes. There is a drastic change between 1983 and 2012 as the river straightened out due to human influence. The sinuosity of 1.00 was recorded by using the thalweg, or the deepest part of the river and it was very difficult to obtain, as the riverbed was almost completely dry. In the thirty-year period between 1983 and 2012, the Yongding River dried and straightened out completely just in the small section by the city. The water from the river was diverted towards the city and the area around the river has been urbanized so it is now straight. This can cause increased flooding risk due to the increased velocity of a straightened channel.

The depletion of the groundwater is affecting the Yongding River as well. The lack of water in the Yongding River is due to the decreasing groundwater table under the city. The water is clearly still coming out of the mountains to the west and northwest and then it suddenly stops flowing as it approaches the city. The annual precipitation has also not changed according to the data from the CRU model, so the same amount of water should still be entering the river from upstream. As water is flowing out of the mountains, it could be going straight into the ground to replenish the groundwater table where it is significantly lower. The area of depleted water table underneath the city acts like a valley that collects water from anywhere where the groundwater table is higher. Instead of the water simply flowing through the system towards from the northwest to the southeast, it sinks into the ground and flows toward the valley in the water table. The river is still flowing as it leaves the municipality south of the city so it is clear that the groundwater table is high enough there to feed the river again.

Urbanization and the Water Crisis

The changes made throughout the past one hundred years are both detrimental to the water cycle throughout the area and the water crisis for the city. The natural flow of water was disrupted as early as 2,000 years ago and since then it has only veered away from its original path. As water flows through the city today, it is forced to run through ninety-degree angles and concrete barriers. These canals are extremely straight and now run mostly underground. The increases in channelizing water has a huge effect on groundwater supply, flooding, downstream and upstream geomorphology of the streams and rivers, and the overall water supply for the area.

Water will flow much faster through the supply and drainage canals than through a natural stream or river channel, causing greater amounts of water to flow through the city and floods to increase in magnitude. Non-impervious areas have increased by over 20% of the whole city area in the past twenty years. Flooding in the city, especially during the rainy month of July, will happen a lot faster and more frequently after a large rainstorm and will be a lot more devastating to the city as the water will only flow over the cement instead of partially infiltrating into the ground. Beijing already has flooding problems due to the imbalance of precipitation throughout the year and the increase in canals increases the severity of these problems.

The increase in canals and the overall urbanization of the city also has a large impact on the depleted groundwater. The groundwater table has been decreasing due to overuse, but water is also not able to infiltrate into the ground because it only runs through canals through the city. The groundwater table is not able to replenish during the rainy months because all of the water is being rushed out of the city to the non-infiltrating layers and the channelization of the canals. They have then lost that source of freshwater forever as all of the rain falling onto the city will just go downstream towards the Bohai Sea.

Another large problem is the increased risk of flooding caused by changing of canals into culverts. Culverts are only made to contain so much water, so when the culvert has reached its maximum capacity it overwhelms the system and causes damaging floods. The culverts also only increase the problems with groundwater, as they also do not allow for proper infiltration of water into the soil.

It is clear that the flow of water through supply and drainage canals throughout the city is unnatural as it forced to cross drainage divides, run through ninety-degree angles and straight channels, and to flow underground with no infiltrating areas. The current system is not sufficient to supply the city with water with the increasing population and has negatively impacted the rivers around the city. Only the sinuosity of the Yongding River was extensively analyzed in this study, but the Qinghe River, Wenyu River, Chaobai River, and Liangshui River have all been impacted by urbanization and depletion of groundwater.

The overall supply of water to the city is clearly not sufficient to sustain the population. The city is run off of groundwater and reservoir water but both of these resources have been severely depleted over the past twenty years. The groundwater table needs time to recharge in order for Beijing to regain some normalcy for the city. The available surface water and groundwater combined are still not a sufficient resource for the city, so the best plan of action is to restore a natural water cycle in the city, is to have the groundwater recover and have a more natural flow in the city. To recharge the groundwater, the canals and streams cannot be encased in cement so water can flow freely between the ground and waterways. This is especially important upstream of the city, in the northwest corner as water is flowing from there, and where the natural source of the flow is found. The barriers between the water and the ground mean that almost no water is infiltrating within the city limits. The pathways for the canals are each only constructed to contain so much water, so even if the canals were redone in such a way that the water could infiltrate into the ground, this would not help solve the flooding risks increased by having canals in urban areas.

The city has been built over two different streambeds and increased the number of channels that water flows through to enter the city, so less water is available in total to all of the canals and streambeds in the area. Water flow should be reduced down to the two natural channels with area where it can infiltrate into the ground as well. Culverts should be removed to decrease the risk of flooding and help restore natural flow. The city also to not have so many waterways as there are naturally only three in the center of the city. What is best for the water cycle of the city is not that feasible because of the cost and the need for rivers to flow through places that are currently occupied by buildings, but it is the best solution to help restore the rivers around the city, and to replenish water in the city.

Conclusion

Water flow through the city of Beijing has changed drastically over the past one-hundred years. The use of manmade canals increased up until 1983 and then when surface water from the canals was no longer a viable resource, culverts increased through 2012. However, the hydrographic model and fault lines show that water should be flowing to the southeast and northeast, compared to the east and south directed canals. Urbanized land has increased and precipitation has stayed constant, so it is clear that the changes in the availability of water in the area are only due to human influence. The Beijing area is in a water crisis and the solution to it is not simple. If people want to restore the rivers in the area, then a lot of construction needs to be done, and the canals in the city need to be removed. Water cannot be diverted from the rivers towards the city, especially if it is not currently serving a function. Water needs to be able to infiltrate into the ground to restore the groundwater table. Converting the canals to culverts only increases the problems in the city. The city currently has a better hydrological plan than in 1983, but there is still a lot of work to be done to help restore the water flow in the area. Water does not usually naturally flow in straight channels and at ninety-degree angles through the city. The water in Beijing naturally flows to the southeast with northeast diversions, not in the checkerboard pattern on which the city was planned. If the city wants to have water in their rivers again, then water needs to flow through the two natural channels again, and only through those two channels.

Literature Cited

Aldrich, M. A. *The Search for Vanishing Beijing: A Guide to China's Capital through the Ages*. Hong Kong: Hong Kong University Press, 2006. Print.

Angelakis, Andreas Nikolaos, Larry V. Mays, and Demetris Koutoyiannis. *Evolution of Water Supply through the Millennia*. London: IWA Publidshing, 2012. Print.

"Assembly, Accretion and Breakup of the Paleo-Mesoproterozoic Columbia Supercontinent: Records in the North China Craton." *Gondwana Research* 6.3 (2003): 417-34. Print.

Beijing. Russia: Voenno-topograficheskoe upravlenie General'nogo shtaba, 1983.

Beijing's Water Crisis: 1949-2008 Olympics. Beijing: Probe International, 2008. Print.

Belsky, Richard. "The Urban Ecology of Late Imperial Beijing Reconsidered: The Transformation of Social Space in China's Late Imperial Capital City." *Journal of Urban History*.27 (2000): 54-74. Print.

Chang, Sen-dou. "Beijing: Perspectives on Preservation, Environment, and Development." *Cities* 15.1 (1998): 13-25. Print.

Chinese Academy of Sciences Institute of Geography. *Atlas of the Ecological Environment in the Beijing-Tianjin Area*. Beijing, China: Science Press, 1990. Print.

Dong, Madeline Yue. *Republican Beijing: The City and its Histories*. Los Angeles: University of California Press, 2003. Print.

Dunne, Thomas, and Luna B. Leopold. *Water in Environmental Planning*. San Francisco: W.H. Freeman and Company, 1978. Print.

Han, Zaisheng. "Groundwater Resources Protection and Aquifer Recovery in China." *Environmental Geology* 44.1 (2003): 106-11. Print.

He, Chunyang, et al. "Simulation of the Spatial Stress due to Urban Expansion on the Wetlands in Beijing, China using a GIS-Based Assessment Model." *Landscape and Urban Planning* 101.3 (2011): 269-77. Print.

He, Weiqi, et al. "Water Quality Monitoring in a Slightly-Polluted Inland Water Body through Remote Sesning- Case Study of the Guanting Reservoir in Beijing, China." *Frontiers of Environmental Science & Engineering in China* 2.2 (2008): 163-71. Print.

Huang, Shaojie. "City Fixes Schools on Fault Lines." *The Global Times* 2010. Print.

Jia, Yangwen, et al. "A WebGIS-Based System for Rainfall-Runoff Prediction and Real-Time Water Resources Assessment for Beijing." *Journal of Computer & Geosciences* 35.7 (2009): 1517-28. Print.

Jun, Xia, Meng-Yu Liu, and Shao-Feng Jia. "Water Security Problem in North China: Research and Perspective." *Pedosphere* 15.5 (2005): 563-75. Print.

Kaisar, Aji, et al. *Study on Groundwater Flow System Along the Chaobai River and Yongding River, North China Plain*. Print.

Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos.

Luo, Wei, et al. "Landscape Ecology of the Guanting Reservoir, Beijing, China: Multivariate and Geostatistical Analyses of the Metals in Soils." *Environmental Pollution* 146.2 (2007): 567-76. Print.

Lu, Songnian, et. al. "Precambrian Metamorphic Basement and Sedimentary Cover of the North China Craton: A Review." *Precambrian Research* 160.1-2 (2008): 77-93. Print.

New, M., M. Hulme, and P. D. Jones. 2000. Global 10-Year Mean Monthly Climatology, 1901-1990 (New et al.). Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A., doi:10.3334/ORNLDAAC/549.

New, M., M. Hulme, and P. D. Jones. 2000. Global 30-Year Mean Monthly Climatology, 1901-1960 (New et al.). Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A., doi:10.3334/ORNLDAAC/550.

New, M., M. Hulme, and P. D. Jones. 2000. Global 30-Year Mean Monthly Climatology, 1961-1990 (New et al.). Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A., doi:10.3334/ORNLDAAC/542.

Peisert, Christoph, and Eva Sternfeld. "Quenching Beijing's Thirst: The Need for Integrated Management for the Endangered Miyun Reservoir." *China Environment Series*.7 : 33-45. Print.

Shelach, Gideon. "The Earliest Neolithic Cultures of Northeast China: Recent Discoveries and New Perspectives on the Beginning of Agriculture." *Journal of World Prehistory* 14.4 (2000): 363-413. Print.

Shen, Jianfa. "Estimating Urbanization Levels in Chinese Provinces in 1982-200." *International Statistical Review* 74.1 (2006): 89-107. Print.

Shi, Fei. *Guide to Peking and its Environs Near and Far*. Beijing, China: The Tientsin Press, 1924. Print.

Sit, Victor F. S. *Beijing: The Nature and Planning of a Chinese Capital City*. West Sussex, England: John Wiley & Sons Ltd., 1995. Print.

Sit, Victor F.S. "Beijing: Urban Transport Issues in a Socialist Third World Setting (1942-1992)." *Journal of Transport Geography* 4.4 (1996): 253-73. Print.

Tian, Y. C., et al. "Risk Assessment of Water Soil Erosion in Upper Basin of Miyun Reservoir, Beijing, China." *Environmental Geology*.57 (2009): 937-42. Print.

"Urban Hydrology and Water Management - Present and Future Challenges." *Urban Water* 1.1 (1999): 1-14. Print.

USGS 1978, Global Land Survey, 1975, Landsat MMS, 60m scene p133r32_3m19780920, USGS, Sioux Falls, South Dakota.

USGS 1992, Global Land Survey, 1990, Landsat TM, 30m scene p123r032_5dx19920907, USGS, Sioux Falls, South Dakota.

USGS 1999, Global Land Survey, 2000, Landsat ETM, 30m scene p123r032_7dx19990701, USGS, Sioux Falls, South Dakota.

USGS 2009, Global Land Survey, 2010, Landsat ETM, 15m scene LT5123032-2009265IKR00, USGS, Sioux Falls, South Dakota.

Wang, W., et al. "Ecological Restoration of Polluted Plain Rivers within the Haihe River Basin in China." *Water, Air, & Pollution* 211 (2010): 341-57. Print.

Wang, Xiaolong, et al. "Spatial and Seasonal Variations of the Contamination within Water Body of the Grand Canal, China." *Environmental Pollution* 158.5 (2010): 1513-20. Print.

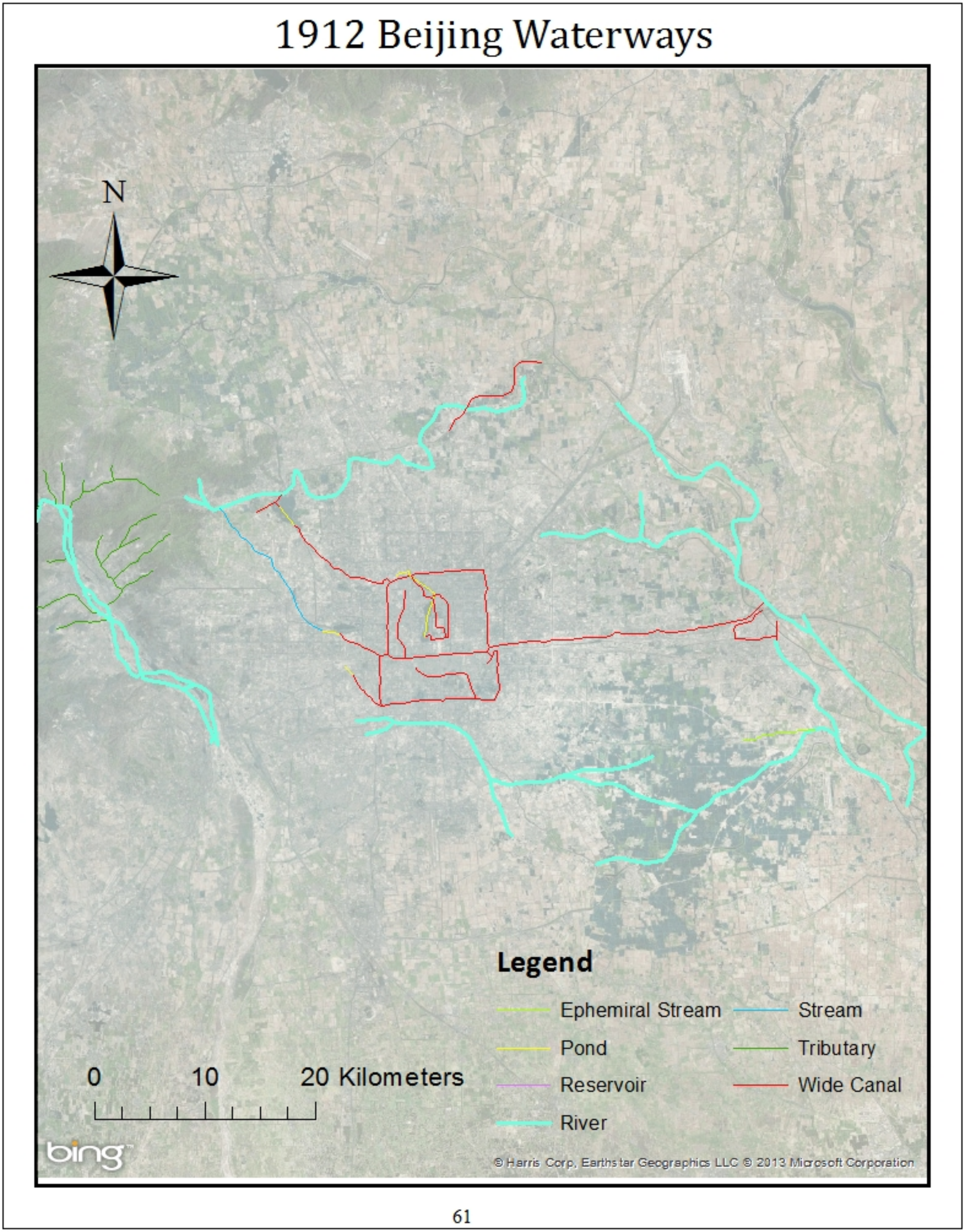
Xie, Jian. *Addressing China's Water Scarcity: Recommendation for Selected Water Resource Management Issues*. Washington DC: The International Bank for Reconstruction and Development / The World Bank, 2009. Print.

Xue, Nandong, and Xiaobai Xu. "Composition, Distribution, and Characterization of Suspected Endocrine-Disrupting Pesticides in Beijing Guanting Reservoir (GTR)." *Environmental Contamination and Toxicology* 50.4 (2006): 463-73. Print.

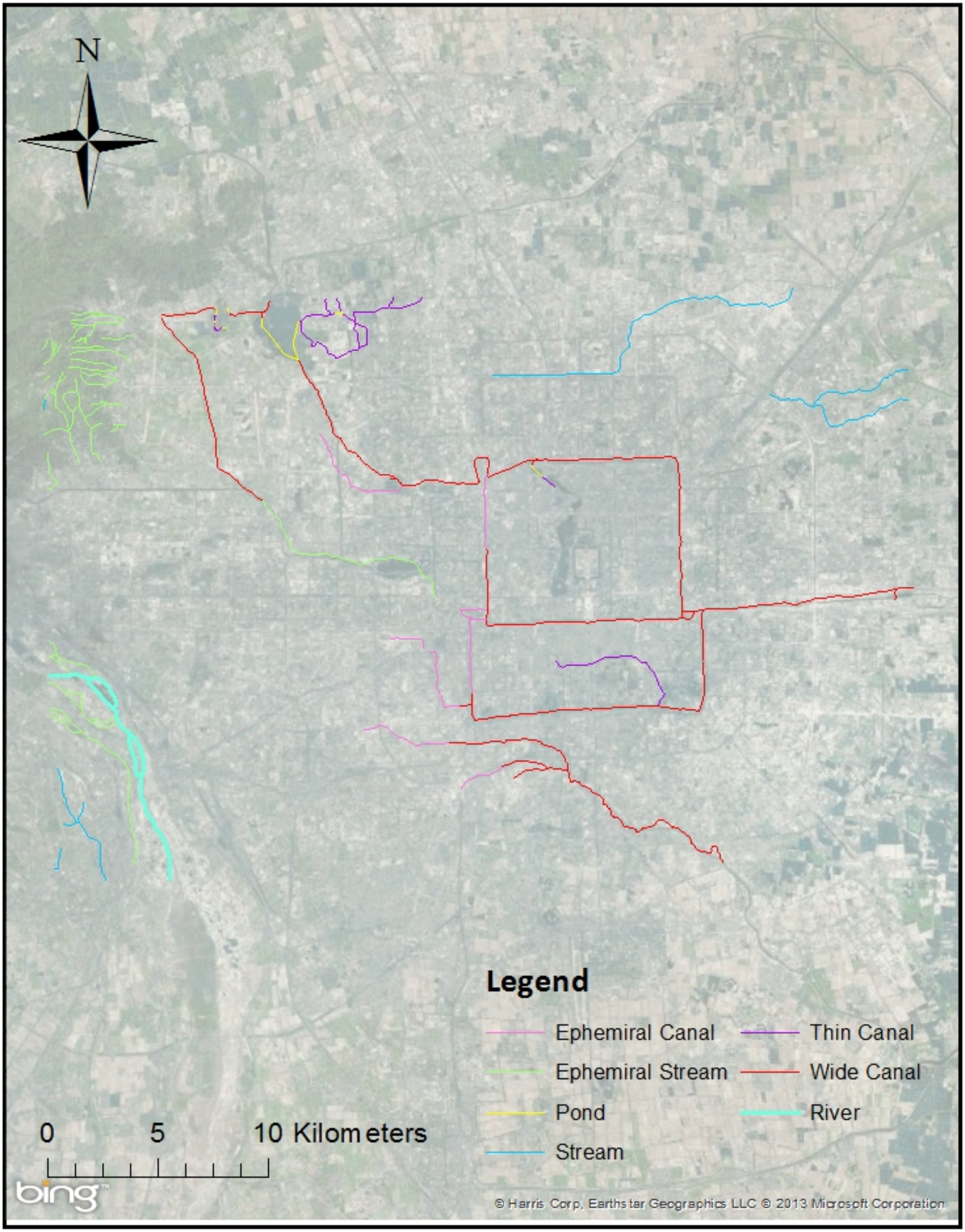
Yang, H. "Water, Environment and Food Security: A Case Study of the Haihe Basin in China". *2nd International Conference on River Basin Management.* Las Palmas Gc. 2003. 131-140. Print.

Zhang, Henry H., and David F. Brown. "Understanding Urban Residential Water use in Beijing and Tianjin, China." 29 (2005): 469-91. Print.

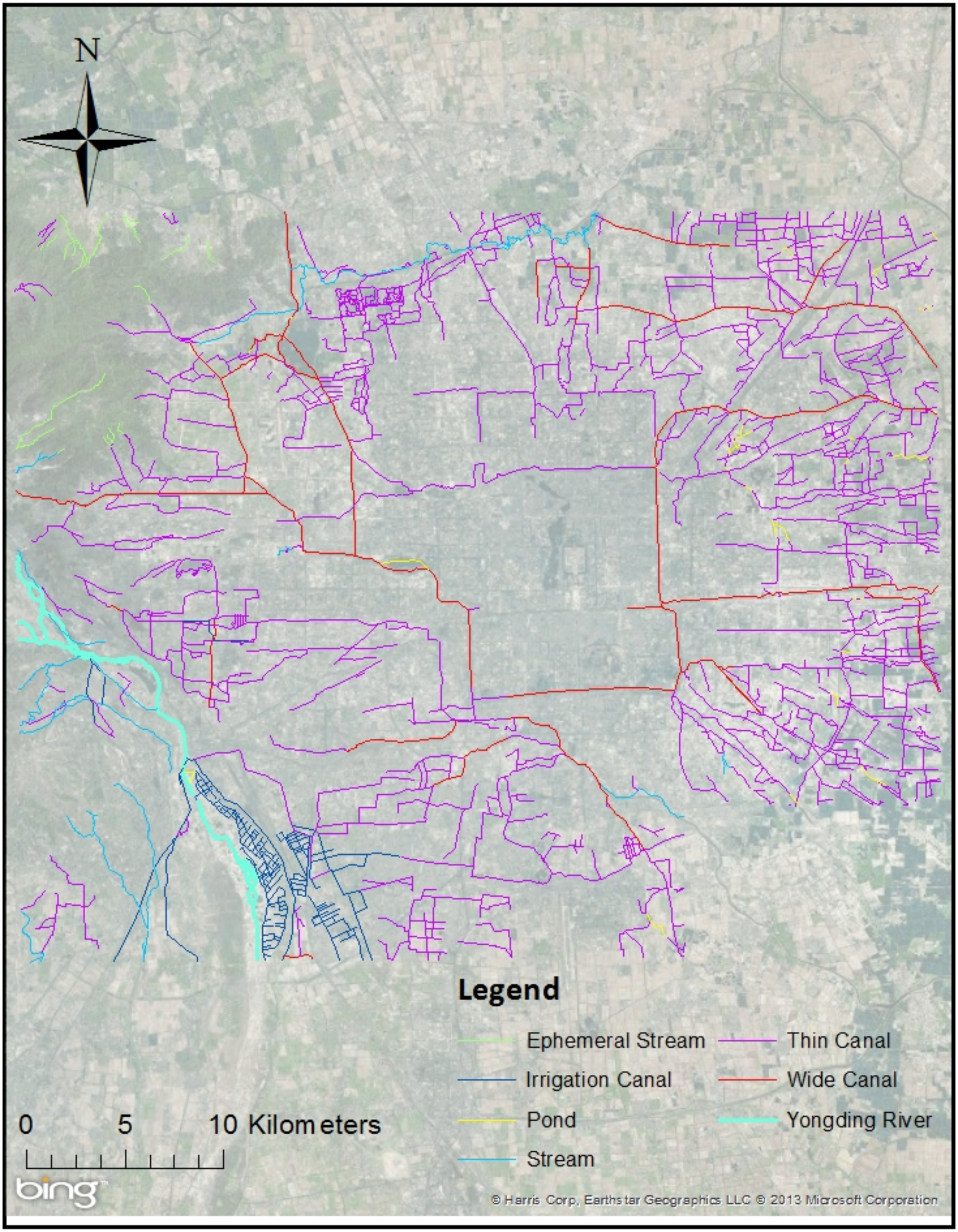
Zheng, Liandi. *古代城市水利 — Water Resources in Ancient Cities*. Beijing, China: China Water Power Press, 1985. Print.


1912 Beijing Waterways
N
Legend
Ephemiral Stream
Stream
Pond
Tributary
Reservoir
Wide Canal
River
0
10
20 Kilometers
bing
© Harris Corp, Earthstar Geographics LLC © 2013 Microsoft Corporation

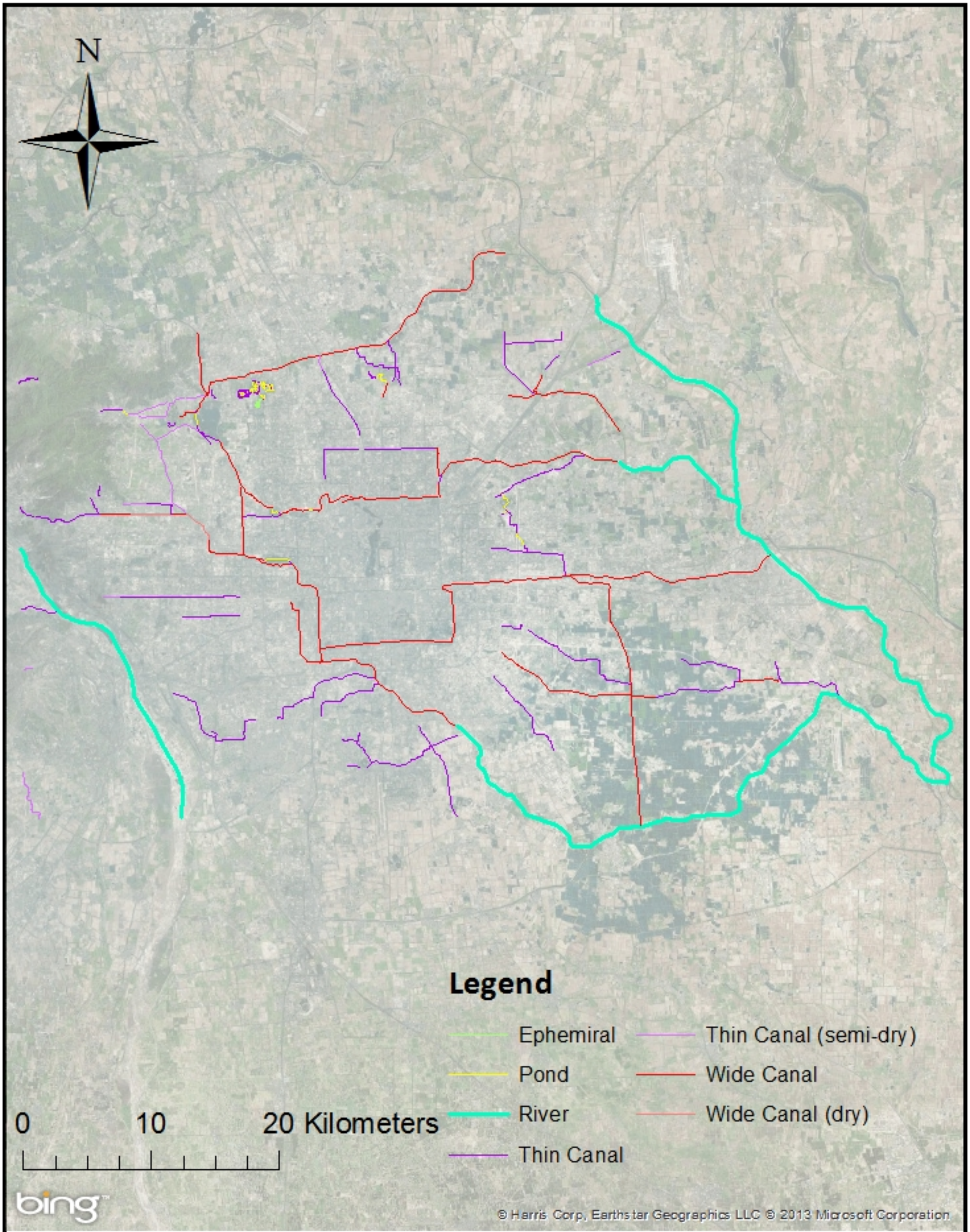
1926 Beijing Waterways



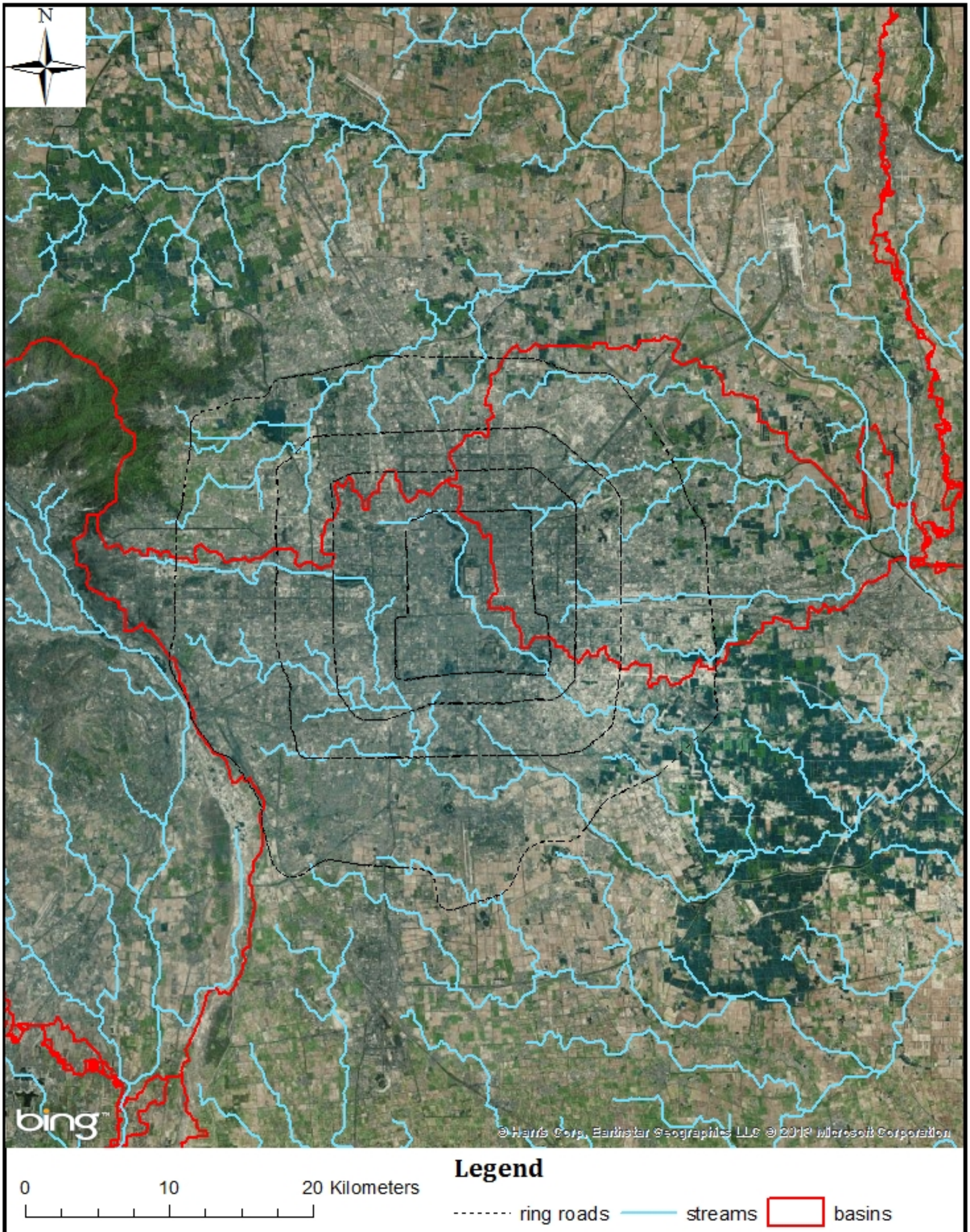
1983 Beijing Waterways



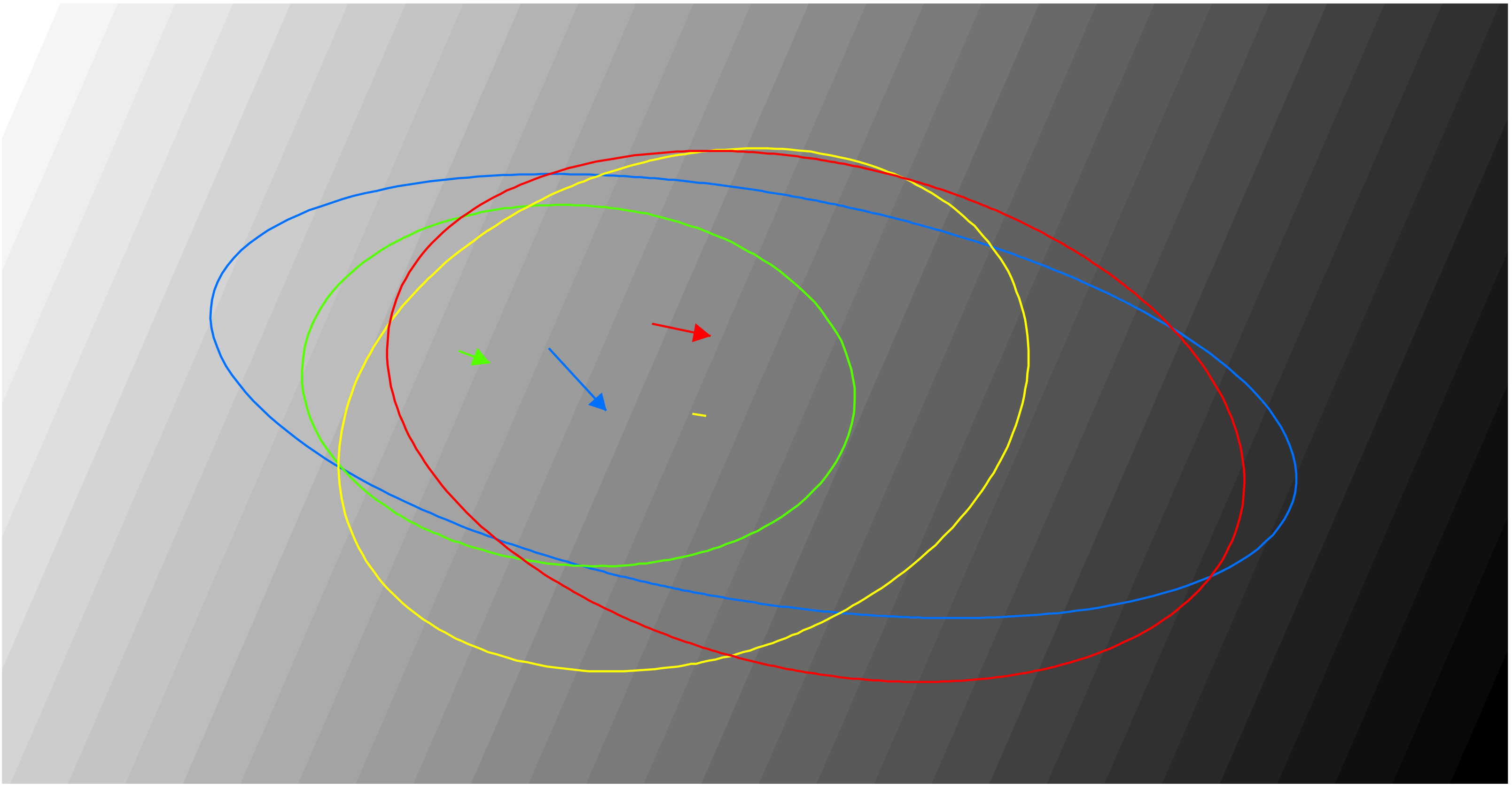
2012 Beijing Waterways



Hydrographic Model of the Beijing Area



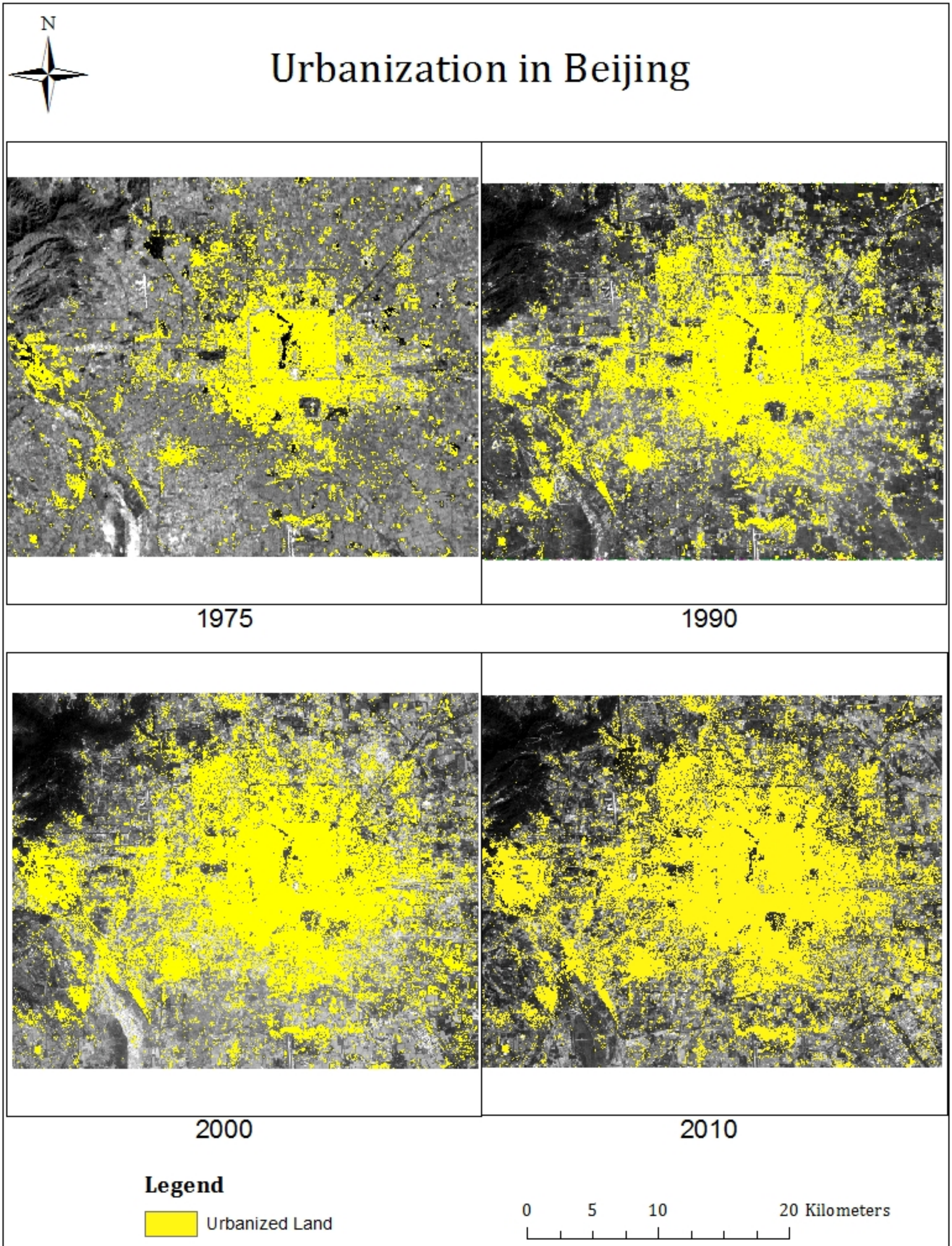
Stream Change Statistics



Legend

- 2012 directional mean 102 degrees, variance 0.67
- 1983 directional mean 96 degrees, variance 0.86
- 1926 directional mean 107 degrees, variance 0.59
- 1912 directional mean 138 degrees, variance 0.44
- 2012 standard deviational ellipse, rotation 104 degrees
- 1983 standard deviational ellipse, rotation 79 degrees
- 1926 standard deviational ellipse, rotation 93 degrees
- 1912 standard deviational ellipse, rotation 100 degrees

The orientation of the shaded regions represent topographic contours on a mean surface.
(Results of trend surface analysis)


N
Urbanization in Beijing
1975
1990
2000
2010
Legend
Urbanized Land
0 5 10 20 Kilometers

Beijing Fault Lines