

Article

The Role of Geological Methods in the Prevention and Control of Urban Flood Disaster Risk: A Case Study of Zhengzhou

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Abstract: The frequent occurrence of urban flood disasters is a major and persistent problem threatening the safety of cities in China and elsewhere in the world. As this issue is so pervasive, exploring new methods for more effective risk prevention and urban flood disaster control is now being prioritized. Taking the case of the city of Zhengzhou as an example, this paper proposes using geological, hydrogeological, ecological, and environmental conditions together with appropriate engineering designs to address the problem of urban flooding. The strategy includes integrating urban sponge–hydrogeological conditions, ecological engineering, and the construction of deep underground water storage facilities. Field investigations, data collection and analysis, in situ observations, testing, and laboratory experiments, are analyzed to explain the formation mechanism and means to mitigate flood disasters in Zhengzhou. Our results suggest that the appropriate use of geological, ecological, and hydrogeological aspects, combined with effective engineering practices, can significantly improve the city’s flood control capacity. These measures can solve the problem of the “once-in-a-millennium” occurrence of torrential rain disasters such as the “720” torrential rainstorm that has affected the city of Zhengzhou.

Keywords: flood disaster; Zhengzhou; sponge city; underground drainage; ecological engineering



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1. Introduction

With the high pace of urban environment development, many cities worldwide face risks from urban floods, which is evolving as a major threat to life and property. According to the statistics of the World Meteorological Organization (WMO), around 7870 hydrometeorological disasters occurred in the world from 1970 to 2016. These floods have resulted in 1.86 million deaths and an economic loss of USD 1.9 trillion [1]. Chinese cities are no exception in this regard. Based on the available statistics, more than 400 Chinese cities with a wide geographical distribution were affected by floods from 2007 to 2018. These flood-related disasters have claimed 21,720 lives and resulted in a staggering economic loss of CNY 3163.9 billion [2,3] (p. 57; pp. 661–662). The problem of floods has greatly affected safe operations in cities, disrupted normal life, and has become a matter of serious concern. Flood-related disasters have become a severe impediment to the high-quality development of cities in China [4].

Urban waterlogging disaster is an extremely complex engineering problem with many dimensions [5–9] (pp. 1–2; pp. 661–662). The processes that lead to such urban disasters are interactive and complicated, involving many natural and human-induced factors. They can be understood only by understanding the state of natural systems, social conditions, and developmental activities [10–15]. Experts and scholars worldwide have been exploring ways to prevent and control flood disasters. They have put forward many suggestions

based on ground conditions and theoretical methods that can be used effectively for flood control. Researchers and engineers based in China are constantly engaged in developing flood control strategies; they have also learned techniques practiced in foreign countries, which they successfully adapt for effective flood control [16–22].

In the face of the rapid development of cities built on regions of diverse geological environments, climatic zoning, and other conditions, preventing and controlling urban floods are challenging. However, after decades of continuous exploration, China has successfully developed a suitable strategy to manage and mitigate urban flood disasters. It has been proposed that by 2025, China will build a “sixteen-character” urban flood control and drainage system. This system works on a combination of parameters such as source emission reduction, well-designed storage and drainage facilities, risk elimination, and emergency response if stipulated standards are exceeded. Together, various elements of this system significantly improve the urban drainage system and effectively prevent waterlogging and flooding [23].

Fundamentally, the “sixteen-character” strategy aims at an efficient disposal capacity by building artificial reservoirs and lakes to improve flood detention and storage. Laying water pipelines, dredging rivers to improve flood discharge, and building sponge cities to enhance urban rainwater flood infiltration and storage are the other steps suggested to prevent flooding. On the mitigation front, steps are taken for emergency flood discharge, evacuation of residents, providing emergency aid, transportation of materials and implementation of traffic control. Undoubtedly, these measures have played a vital role in urban flood control in China. However, in the face of pervasive floods that are becoming more and more severe and seriously restricting the high-quality development of its cities, there is a need to develop innovative ideas and theoretical and practical methods for more effective solutions.

So, in this study, we use the rainfall during the “720” torrential rainstorm (in three days, from 17 to 20 July 2021, Zhengzhou received 617.1 mm of rainfall. On 19 July alone, the rainfall was 552.5 mm. This torrential rain disaster flooded all the urban areas of Zhengzhou and paralyzed the city’s traffic. More than 2000 roads were damaged, and many infrastructure facilities were destroyed. The flood disaster killed 380 people and caused direct economic losses as high as CNY 40.9 billion. The intense rainfall received in this city during a short period broke the 70-year historical records of hourly and single-day rainfall since 1951. The probability and return period of hourly and daily precipitation rates leading to such events is estimated to be more than 1000 years.) as the upper limit value [24,25], and we take the example of Zhengzhou city (also spelt as Chengchow), the capital and largest city of Henan Province in the central part of the People’s Republic of China (Figure 1), to discuss the role of geological methods in solving urban flood disasters, from the aspects of integrating urban sponge engineering with hydrogeological conditions, guiding engineering construction under the guidance of ecological geological theory, and the use of underground space for water storage projects.

This study will analyze and explain the importance of geological methods for the prevention and control of urban flood disasters according to the following logic, as shown in Figure 2.

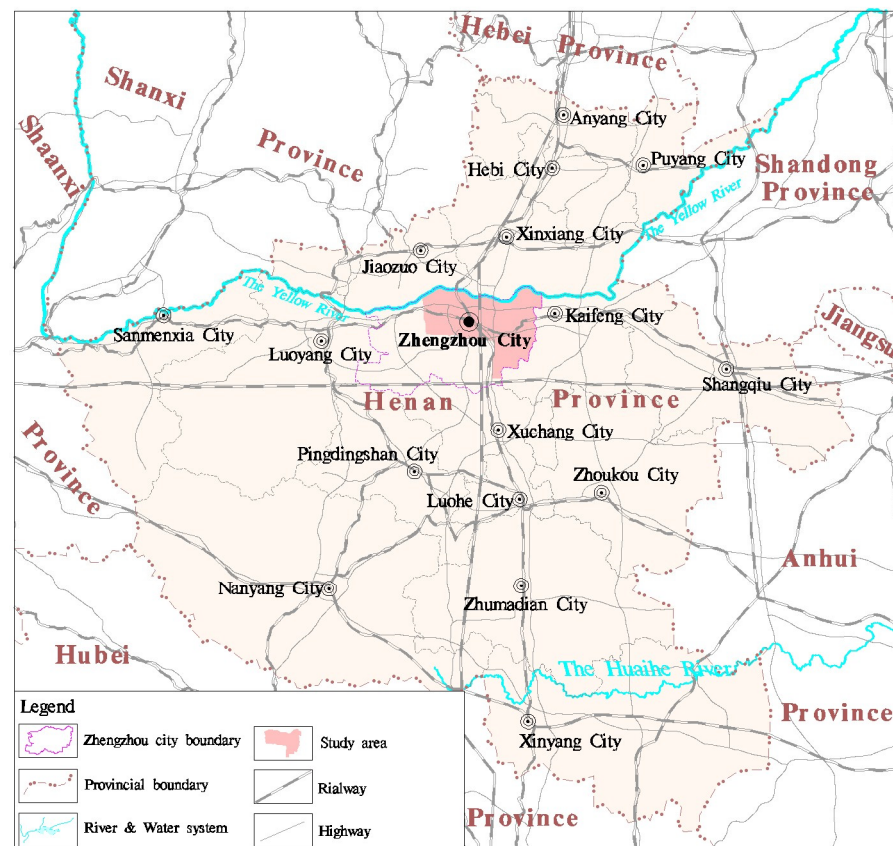


Figure 1. Location map of the study area.

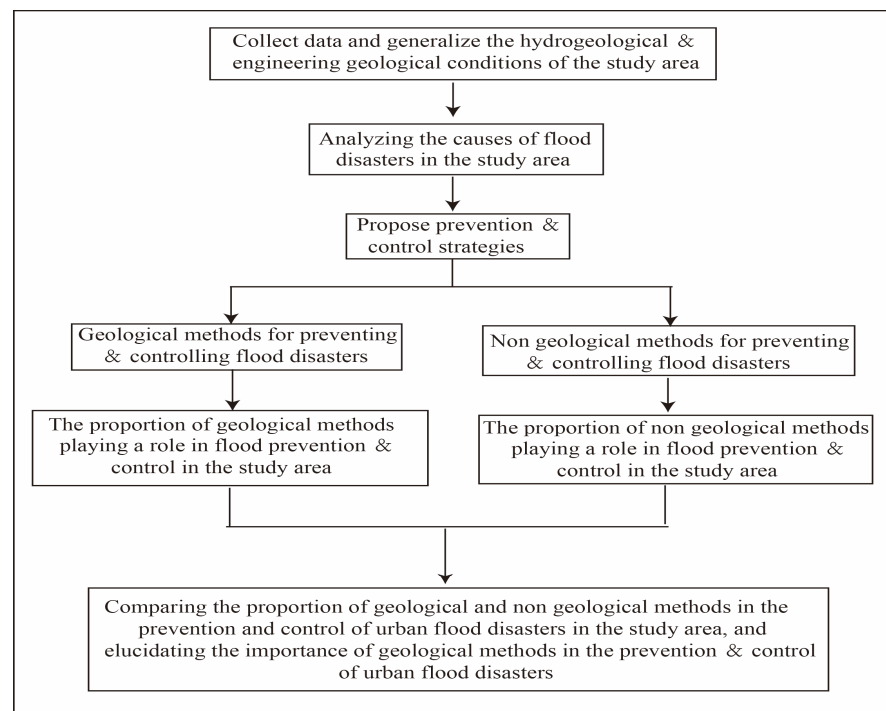


Figure 2. Thesis research logic map.

2. Materials and Methods

2.1. Methods

We collected and analyzed a variety of data that form the basis for the development of the city of Zhengzhou. The data included basic information on geography, geology, hydrology, social-economic development, and the area of urban land space. On the planning and administrative side, the data covered aspects of urban engineering, including sponge city construction, ecological environment aspects, river system governance, urban flood control etc. Many relevant kinds of literature based on in-depth studies at home and abroad that have discussed the developmental status and layout of cities prone to such disasters were consulted to develop the background of our study. These research papers have helped gather the concepts of advanced flood control, technologies and methods practiced for flood control at home and abroad.

Regional geology data were obtained from regional geological maps with accuracies of 200,000 and 50,000. In addition, the map with an accuracy of 50,000 was used to identify regions prone to geological disasters. Hydrogeological data for farmland water conservation and geotechnical data required for underground constructions were collected using maps with an accuracy of 50,000. Evaluation of urban environmental and geological problems and investigations of the section of the lower Yellow River in the city of Zhengzhou was conducted to gather the background data. Geological and environmental investigations were conducted in various mines in the area, and the data were analyzed in detail to evaluate the Quaternary geological conditions in the area. The large amount of data collected is useful for an integration of the regional geology, hydrogeology, environmental and engineering geology and assessing how their characteristics influence urban flooding.

A comprehensive geological survey was carried out with an accuracy of 50,000 scale to evaluate hydrogeology, engineering geology and environmental geology. The study area also carried out geophysical exploration, engineering, geological drilling and in situ testing, hydrogeological drilling, and pumping tests. The regional hydrologic environment, geological conditions and their spatial distribution were documented by the above investigations. Maps presenting the relevant parameters of hydrogeology, engineering and environmental geology were compiled.

Further, maps of groundwater depth were prepared based on water level measurements, water quality analysis, and tests conducted during high- and low-water periods. Through in situ tests such as water seepage test and pumping test carried out on-site, parameters such as soil seepage rate, rainfall infiltration replenishment coefficient, and permeability coefficient were obtained. Water, rock, and soil samples were collected, water quality and geotechnical characteristics were tested indoors, and the related parameters of hydrogeology, engineering geology and environmental geology were also obtained. The detailed work deployment is shown in Figure 3.

2.2. Materials

2.2.1. Geographical Setting

With a built-up area of 1181.61 km², Zhengzhou is a megacity in the Henan Province in the central region of China. By 2021, Zhengzhou registered a permanent population of 12.742 million, an urbanization rate of 79.1%, and a GDP of CNY 1269.1 billion, ranking 15th in China [26]. The city is located on the top of the fluvial alluvial plain of the Yellow River, with well-developed alluvial terraces. It falls in the north temperate continental monsoon climate zone and is also adjacent to the south subtropical monsoon climate zone, sharing the climatic characteristics of both zones. Precipitation occurs mainly from June to September, and the annual average rainfall is 542.15 mm [18].

2.2.2. Distribution of Watersheds and Water Systems

Zhengzhou city, with an area of 7446 km², spans two major river basins: the Yellow River and the Huaihe River. The city is built on the lower reaches of the Yellow River, the upper reaches of the Huaihe River and the upper and middle reaches of the Jialu River. It

is adjacent to the Yellow River in the north, the Songshan Mountain in the west, and the Huang Huai plain in the east and south. The western part of the city, located in the Yellow River Basin, accounts for 24.6% of the city's total area. The remaining 75.40% of the city is in the Huaihe River Basin. The part of the city located in the Jialu River Basin of the Huaihe River covers 2750 km², of which the urban planning and construction area is 1945 km², which is the key study area. Located in the upper and middle reaches of the tributary Jialu River Basin, it also covers a small part of the Yellow River Basin, as shown in Figure 4. The Jialu River in the urban area mainly has 11 tributaries, such as Suoxu, Jiayu, Jinshui and Qili rivers. All tributaries flow into the Jialu River and flow southeast to Zhoukou outside the city, through Zhongmou County. It can be seen from Figure 1 that the Jialu River plays a critical role in flood control and drainage in the urban area of Zhengzhou [27].

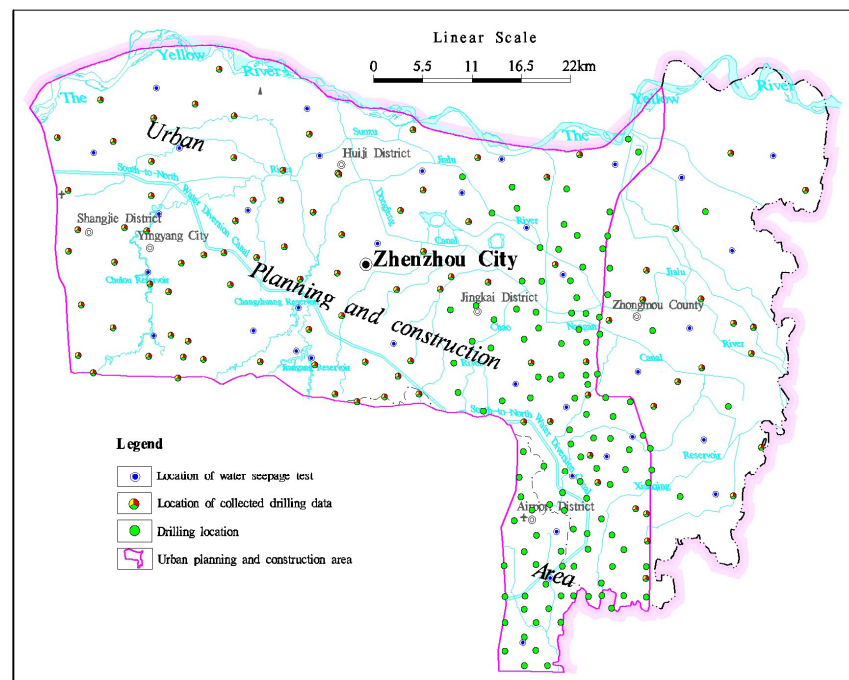


Figure 3. Work deployment in study area.

2.2.3. Geological and Engineering Geological Conditions

As discussed above, the study area is in the hinterland of China, bordering the Yellow River in the north, Songshan Mountain in the west, and Huang Huai plain in the east and south. The overall terrain is high in the southwest and low in the northeast, descending in a ladder shape. From the low and medium mountains eroded by the structure in the west and southwest, it gradually declines and transits to the structural denudation hills, loess hills, inclined (hill) plains and alluvial plains.

The inclined (hill) plain is located in front of the hills and is distributed in the central area in a strip form near the south and north. The terrain elevation is 100 to 150 m. From the west to the east, it is inclined from the front of the hills to the downstream longitudinally, with a gradient of 3 to 10 degrees. From south to north, it occurs in a wavy undulating form of hillocks. The well-developed and distributed strata are composed mainly of quaternary loess, loess-like soil, silt, and silty clay. The alluvial plains are widely distributed in the eastern region, formed by the Yellow River alluvium. The terrain is flat, the ground elevation is 80 to 100 m, and the slope is from the northwest to the southeast. The quaternary loose silt, silty clay and sandy soil, which define the strata, have good engineering properties and are suitable for construction, including underground water storage facilities (Figure 5). There are few active faults in the study area, and the peak ground-shaking acceleration is 0.10 to 0.15 g. There are no earthquakes of medium intensity or above, and the region is considered to fall in the seismic zone of intensity VII, which

is conducive to urban safety. In conclusion, the geological conditions of the study area are generally suitable for urban engineering construction, including underground water storage projects.

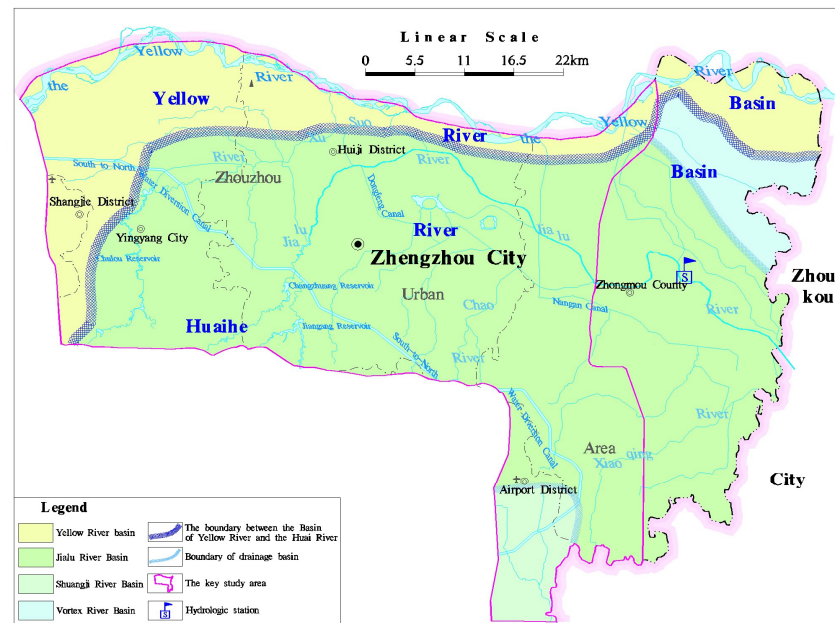


Figure 4. Distribution map of water system in the study area.

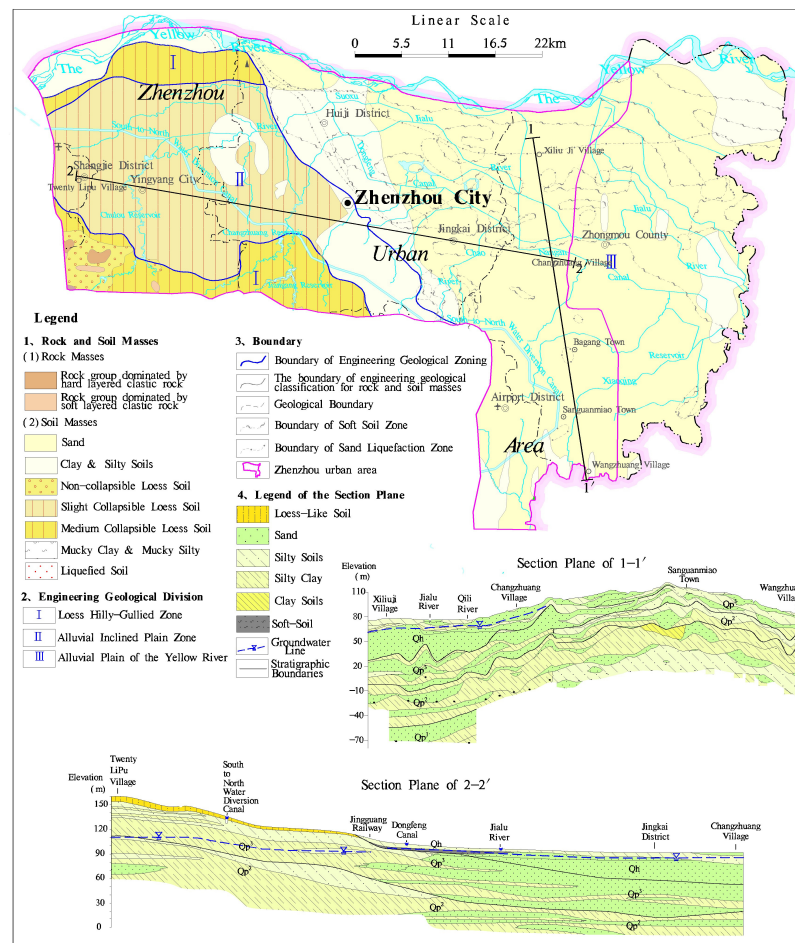


Figure 5. Engineering geological map of the study area.

2.2.4. Hydrogeological Conditions

There are four main types of groundwater in the study area: pore water, pore fissure water, carbonate fissure karst water, and bedrock fissure water. However, the key study area is mainly composed of loose rock pore water, which is widely stored in quaternary loose sediments. Among them, the shallow water (buried water level depth less than 80 m) with a single well inflow of 1000 to 5000 m³/d is a good water supply source. The medium and deep water (buried water level depth is 80 to 400 m) is mainly distributed in the sand, and silty fine sand aquifer in the plain area, with a single well inflow of 500 to 1000 m³/d. This is currently the primary water supply source for the city. Low impermeable silty clay layers with a thickness of 5 to 12 m widely distributed between the shallow, middle and deep aquifers are very suitable for constructing the deep tunnel water storage projects.

As shown in Figure 6, the buried depth of the shallow groundwater level in the urban area generally increases first and then decreases from the front of the mountain to the middle. The buried depth increases from 15 to 20 m to more than 30 m, then gradually decreases to 5–10 m eastward. The buried depth of 15–20 m has the largest regional distribution area. The part with a buried depth of more than 6 m accounts for 97.68% of the study area. The part with a buried depth of less than 6 m, with the smallest distribution area, accounting for only 2.32% of the area of the study area. The vadose zone in most of the urban area is composed of silt or fine sand, with good permeability, which is conducive for infiltration. The shallow groundwater is buried deep (as shown in Figure 6), and the soil layer in the vadose zone has enough space to store the rainwater. Building a sponge city can make full use of this hydrogeological feature.

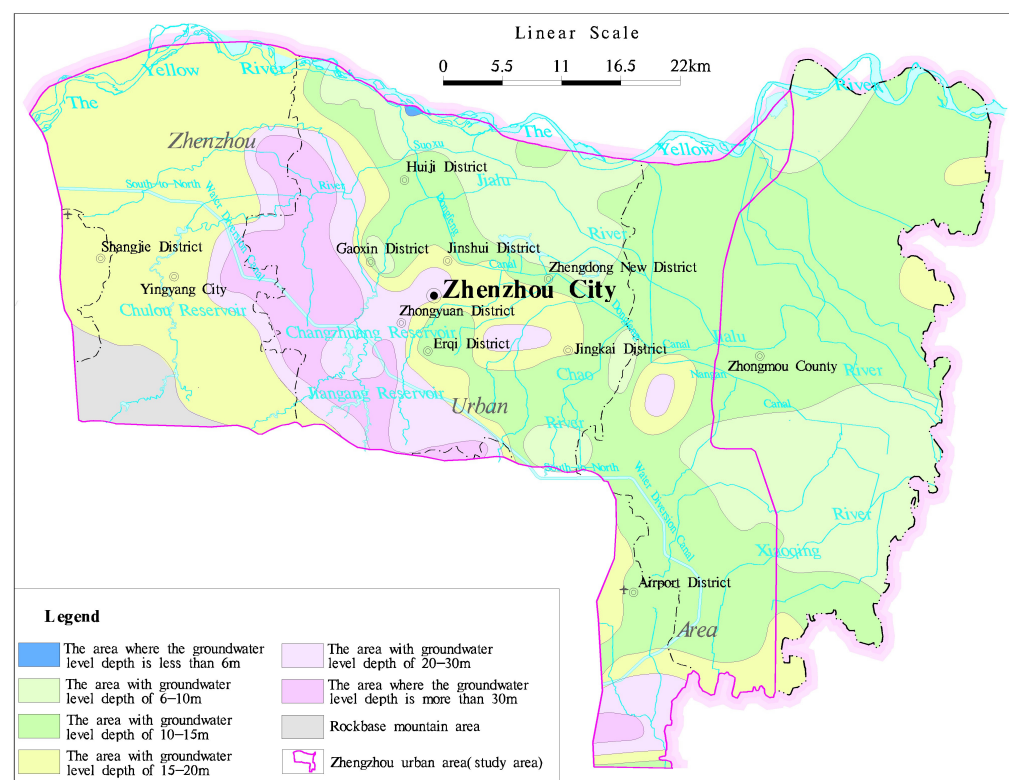


Figure 6. Buried depth map of groundwater level in the study area.

3. Results and Discussions

3.1. Analysis on the Causes of Flood Disasters in the Study Area

Generally speaking, the urban rain-flood is caused mainly by the rainfall and the river water flowing through the urban area from the upstream rivers. As shown in Figure 7, the drainage paths of precipitation mainly include the surface runoff generated by the

rainwater. After falling to the ground, the rainwater follows multiple paths. It flows into the underground drainage pipe network, surface rivers, ditches, lakes, and wetlands. The precipitation also infiltrates the vadose zone soil layer or the urban sponge. Some rainwater will enter the sewage treatment plant designed for treatment and reuse. Thus, the stormwater will eventually enter the rivers, except for the loss through evaporation and ecological and human consumption.

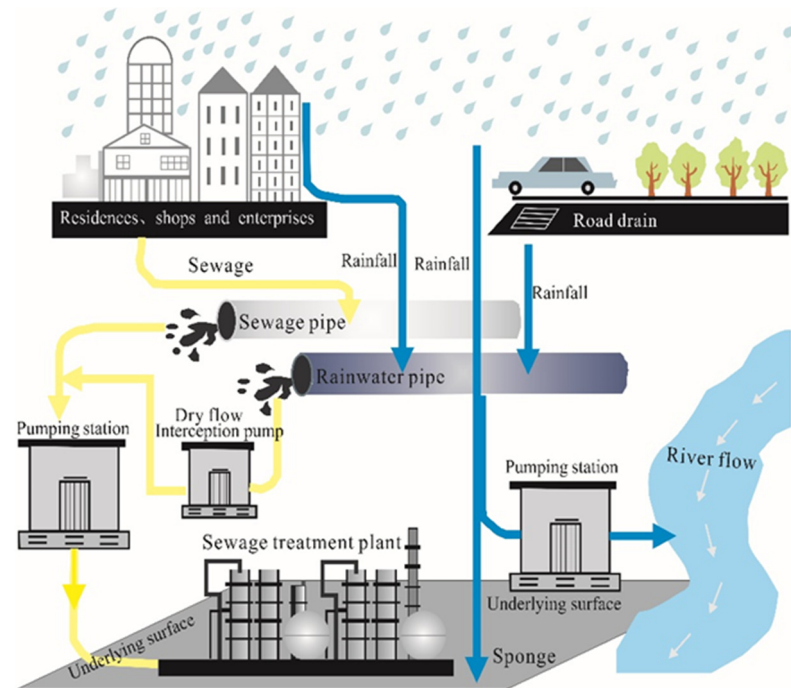


Figure 7. Pathways of rainwater and flood discharge after building sponge city.

If the urban rainwater drainage is not smooth, the situation may lead to urban flood disasters. For the study area, the mechanism of flood disasters is controlled by the following aspects of the rainfall as well as the ground conditions:

- (1) Because of the abnormal superposition of the temperate monsoon climate and global climate change, the rainfall gets concentrated from June to September. During this period, it is easy to form heavy or extremely heavy rainstorms, which is the direct cause of flood disasters in the study area.
- (2) The water and soil erosion in the upper reaches and source of the Jialu River Basin is quite intense. By the end of 2015, there was still a total area of 881 km² of soil erosion, and the total annual soil loss was 2.16 million tons [28]. Soil erosion upstream leads to siltation, and the flood interception capacity of the reservoirs is reduced substantially. The sediment in the middle and lower reaches can easily cause silting, which greatly reduces the flood-carrying capacity of the rivers.
- (3) With rapid urbanization, the urban area has increased from 65 km² in 1981 to 1181.51 km² in 2019, an increase of 18 times. As a result, the impervious underlying layers are being rapidly exposed, altering the original geological conditions. Subsequently, the ability of the rainwater to penetrate the ground is reduced, and the surface runoff coefficient is increased from 0.25–0.45 to 0.65–0.85 [29]. An increase in surface runoff by about 60% results in poor drainage conditions, leading to flood disasters.
- (4) During the construction of water ecological projects or the sponge city, the hydro-geological conditions are not fully utilized. For example, during the construction of projects such as wetlands, river treatment and other aquatic ecological projects, anti-seepage treatment is implemented at the bottom, which reduces the infiltration capacity. During the construction of sponge city, engineering measures such as pervious pavements are emphasized, but the natural rainwater absorption capacity of the

aeration zone soil layer is not fully considered. This situation, which lacks integration between the two important hydrologic parameters, reduces the sponge city's rainwater and flood absorption capacity.

- (5) In the process of urban construction, the natural law of the urban hydrological cycle is not fully understood or paid attention to. As the flood plains are blindly developed and the river course is occupied, the drainage ditches are either buried or filled, and the open spaces are channelized. Thus, during urban construction on both riverbanks, the space for discharge space is not fully conserved. This misappropriation of the flood plain discharge space results in a significant decline in the flood discharge capacity of the river.
- (6) The main rainwater drainage facilities, such as the underground drainage pipe network, roads, and river systems, have not been considered as a whole, and some urban areas have no drainage facilities, resulting in a substantial decline in urban drainage capacity.

Among the causes of the above-mentioned flood disasters, Articles 2, 3, and 4 are directly related to the underutilization of geological conditions.

3.2. Prevention and Control Strategies for Flood Disasters in Study Area

Urban waterlogging disasters mainly occur in highly developed urban areas. Although Zhengzhou spans the two river basins of the Yellow River and the Huaihe River, the waterlogging disasters mainly occur in the tributaries of the Jialu River in the Huaihe River Basin. These disasters include the “720” torrential rainstorm. Therefore, the study area of this paper is mainly 2750 km² in Zhengzhou, of which the key area is the urban planning and construction area of 1945 km².

With the purpose of flood risk prevention and control, and based on a comprehensive understanding of the actual geological, hydrological, and climatic conditions and the current urban development situation, a general idea for flood risk prevention and control in the study area is proposed as follows: taking the Jialu River basin where the city is located as a complete system, following the idea of “combining ecological geological methods with engineering construction to control flood risk; coordinating upstream, middle and downstream, upstream conservation and storage, and developing both midstream (urban) storage and drainage, with downstream emphasis on drainage and coordination above ground and underground”, so the risk of flood disasters occurring in the study area can be minimized.

It is evident that to fully implement a composite plan for flood control; it is necessary to combine the geological and non-geological methods. Non-geological methods include planning of the flood discharge, design and use of underground drainage pipe networks, and storage of reservoirs, lakes, and wetlands. The geological method is based on the geological conditions of the study area, fully following and applying hydrogeological laws in sponge city engineering and water ecological engineering construction, fully utilizing the ecological geological theory in upstream or source ecological restoration engineering, and utilizing engineering geological conditions to build underground water storage engineering, in order to improve the capacity of rainwater and flood absorption, and achieve the goal of reducing the risk of urban flood disasters.

3.3. The Role of Geological Methods in Urban Flood Control

3.3.1. The Role of the Geological Method-Integrating Sponge City Construction with Hydrogeology in the Prevention and Control of Urban Flood Disasters

The concept of “sponge city” refers to the method of “strengthening the management of urban planning and construction, paying full attention to the absorption, storage, slow-release and drainage of rainwater by ecosystems such as buildings, roads, green spaces, and water systems, to effectively control rainwater runoff and realize natural accumulation, penetration, and purification of the urban environment”. The concept regards cities as living organisms and uses the local conditions to improve drainage and waterlogging,

with the goal of controlling urban floods [30]. Obviously, the construction of “sponge city” has become one of the important means of checking urban waterlogging in China. The main purpose of a sponge city in solving urban flood disasters is to improve the function of “water absorption, storage and seepage”. Its construction guide proposes more than 10 engineering measures for the development of the sponge city (see Figure 8 for details).

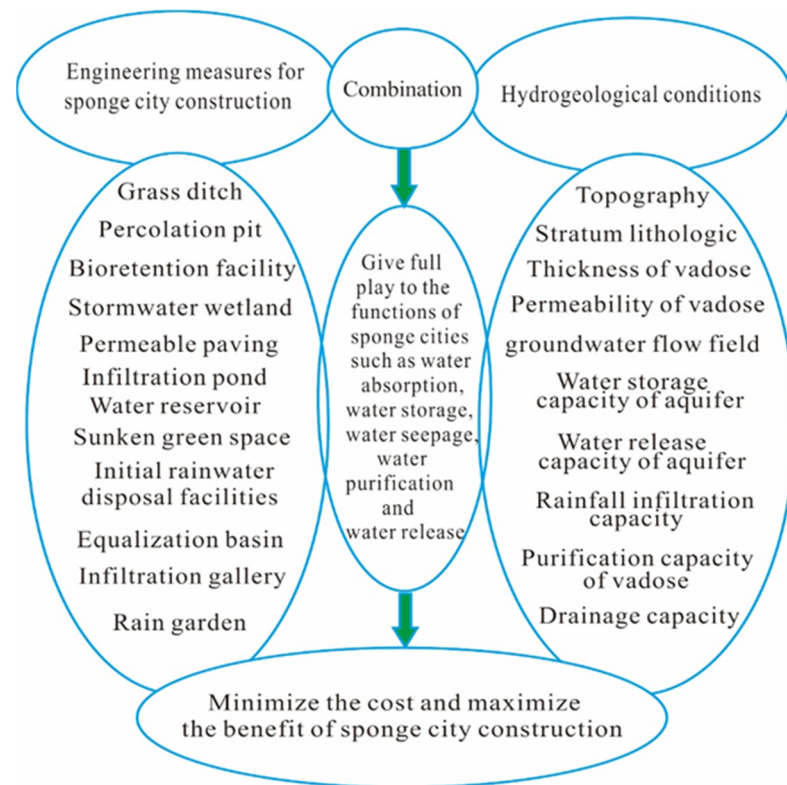


Figure 8. Engineering–hydrogeology integration concept for sponge city construction.

However, it must be regarded that each city is built under specific geological conditions and has its own unique physical and hydrogeological conditions, such as topography, lithology, rock and soil thickness of vadose zone, rainfall infiltration capacity, underground water storage performance, etc. (Figure 8). These hydrogeological conditions play an extremely important role in the “water absorption, storage and seepage” of urban rainwater. In the planning and construction of a sponge city, the “engineering measures” are organically integrated with the natural “hydrogeological conditions”. The goal is to form a whole “sponge” of the city, which can reduce the construction and make the city functionally more efficient. This is the concept of the integration of engineering measures with hydrogeology, as illustrated in Figure 8.

For urban flood control, the construction of sponge cities not only needs to consider whether rainwater can infiltrate into the ground, but also whether there is space underground to store rainwater, which means that both the infiltration capacity and water storage capacity of the vadose zone should be considered.

(1) Rainfall infiltration capacity of the soil layer in the vadose zone

The infiltration capacity of the soil layer in the vadose zone in the absence of surface runoff is an important parameter to be evaluated. This paper suggests several water seepage, infiltration and geotechnical experiments to evaluate the infiltration capacity of the vadose zone soil layers in response to different intensities of rainfall. These experiments are based on previously collected hydrogeological data by water seepage, infiltration and geotechnical experiments to obtain parameters such as the infiltration rate, the permeability coefficient, and the void ratio of the soil layer in the vadose zone. Infiltration in the various

soil layers of the vadose zone corresponding to the intensity of rainfall, calculated when there is no surface runoff, is shown in Table 1.

Table 1. Permeability parameters and corresponding rainfall of different soil layers in the vadose zone (not considering surface runoff).

Soil Mass Types	Seepage Velocity (mm/d)	Permeability Coefficient (cm/s)	Rainfall Intensity That Can Be Absorbed	Rainfall (mm/d)
Silty clay	6.2	7.1×10^{-6} – 6.4×10^{-5}	light rain	<10
Silt	56.75	6.6×10^{-5} – 2.1×10^{-4}	heavy rain	25–50
Loess-like soils	62.374	5.4×10^{-5} – 9.7×10^{-5}	heavy rain	25–50
Silty sand or silty-fine sand	122.60	1.8×10^{-4} – 7.2×10^{-4}	rainstorm	50–100
Medium sand	2583.2	5.0×10^{-3} – 1.4×10^{-2}	extremely heavy rainstorm	>250
Coarse sand	7251.2	1.8×10^{-2} – 6.8×10^{-2}	extremely heavy rainstorm	>250

As shown in Table 1, the infiltration capacity of silty clay can meet the requirements for most rainfalls of light rain intensity. The infiltration capacity of silt or loess can meet the requirements for heavy rain intensity. The infiltration capacity of silty sand or silty fine sand can meet the infiltration requirements for a rainstorm. The infiltration capacity of medium sand and coarse sand can meet the infiltration requirements for an extremely heavy rainstorm. Therefore, when the vadose zone is composed of fine-grained soils such as silty clay, silt, and loess, its ability to infiltrate rainfall is low, and it is not an ideal stratum for the construction of the sponge city. Coarse-grained soils such as medium sand and coarse sand have a strong rainwater infiltration capacity. If there is enough storage space—that is, if the thickness of the vadose zone soil layer is sufficient—it is an ideal stratum for building a sponge city.

(2) Water storage capacity of the vadose zone

The water storage capacity of the vadose zone refers to the amount of rainwater that can be stored in the effective pores of the soil layer. The porosity, natural saturation and maximum saturation obtained by engineering geological drilling, geotechnical testing and other methods, are used to calculate the effective influent porosity N_e of each soil layer by Equation (1) (as shown in Table 2). And then, the thickness H_t of the vadose zone soil layer required to store rainfall of different intensities was calculated by Equation (2) (as shown in Table 3). The thickness of this soil layer is an indicator of underground water storage capacity.

$$N_e = (S_{\max} - S_0) \times n, \quad (1)$$

where $S_{\max}$ is the maximum saturation, S_0 is the natural saturation, and n is the porosity.

$$H_t = (q \times S_t \times N_e) / S_t = q \times N_e \quad (2)$$

where q is the upper limit value for different rainfall intensities, and S_t is both the rainfall area and the infiltration area of the vadose zone.

Table 2. The effective influent porosity of different vadose zone soil.

Soil Mass Types	Porosity (%)	Natural Saturation (%)	Maximum Saturation (%)	The Effective Influent Porosity (%)
silty clay	44.32	76.36	92.34	7.08
silt or loess-like soils	40.76	59.51	91.73	13.13
silty-fine sand	42.23	62.11	90.03	11.79
medium sand	36.14	61.19	94.72	12.12
coarse sand	35.66	56.29	93.24	13.18

Table 3. Thickness of vadose zone soil required by different strata for different rainfall intensity.

Soil Mass Types	Light Rain (10 mm/d)	Moderate Rain (25 mm/d)	Heavy Rain (50 mm/d)	Rainstorm (100 mm/d)	Heavy Rainstorm (250 mm/d)	Extremely Heavy Rainstorm (>250 mm/d)
silty clay	141	353	706	1412	3531	>3531
silt or loess-like soils	76	190	381	762	1904	>1904
silty-fine sand	85	212	424	848	2120	>2120
medium sand	83	206	412	825	2062	>2062
coarse sand	76	190	379	759	1879	>1879

The area of the key study area is 1945 km², and its vadose zone is composed of mixed sands and clay. Fine silt makes up 47.65%, and 18.72% is composed of medium-coarse sand. Silt makes up 31.22%, and the rest, 2.41%, is silty clay. For the water storage capacity of a heavy rainstorm, the required thickness of soil layers such as silt, silty sand and medium-coarse sand is 1.88 to 2.12 m, while the required thickness of silty clay is 3.53 m. The rainfall of the “720” torrential rain that lasted for three days in Zhengzhou was 617.1 mm. Based on this calculation, the thickness of soil layers such as silt, silty sand, and medium-coarse sand to accommodate the rainfall was no more than 5.23 m. The required thickness of the clay is 8.72 m. Judging from the depth distribution of the groundwater level in study area, if the rainwater can seep into the ground, most of the vadose soil layers within the study area have the ability to store the “720” torrential rain.

- (3) Assessment of rainwater infiltration and storage capacity in the study area based on the geological method-integrating sponge city construction with hydrogeology

The rainwater storage capacity of the vadose zone soil layer is closely related to the rainfall intensity, the permeability coefficient of the vadose zone soil layer, the thickness of the vadose zone, the depth of rainfall infiltration, the effective water inflow rate, and the distribution area of each soil layer. Among them, the permeability coefficient determines whether rainwater under different intensities can infiltrate into the vadose zone, and the thickness of the vadose zone determines whether there is enough space to accommodate rainfall; the depth of rainfall infiltration, effective water inflow rate, and distribution area of each soil layer determine whether the soil layer in the vadose zone can accommodate rainfall of different intensities.

Based on the previous experimental data, we have obtained the permeability coefficient, vadose zone depth, effective water inflow rate and other parameters of soil layers with different rock types in the study area. Through analysis, we have found that as long as there is sufficient rainfall infiltration depth, the study area has extremely strong rainfall storage capacity. Next, this article will evaluate the rainwater storage capacity of the study area based on the concept of sponge city engineering and hydrogeological integration by restoring the rainfall intensity and infiltration depth at different return periods.

① Rain intensity and return periods

Since many aspects of urban waterlogging risk prevention and control involve parameters such as rainfall intensity and its return period, the methods used for their calculation are very important. This paper uses the following formula selected by the “720” disaster investigation group of the State Council:

$$R = ((2479.78 + 2388.2762 \times \lg p) / (t + 15.3))^{0.775} \times 8.64 \quad (3)$$

where R is the rainfall (mm/d) at different return periods (rainfall intensity), p is the return period (year), and t is the rainfall duration (1440 min). The rain intensities of different return periods calculated by the above formula are given in Table 4.

Table 4. Geological methods for assessing the drainage capacity of rainwater and floods in the study area.

Rainfall Intensity/Return Period	Rainfall (mm/d)	Total Rainfall (10 ⁶ m ³ /d)	Suburban Storage Capacity (10 ⁶ m ³ /d)	Storage Capacity of Urban “Sponge” Areas (10 ⁶ m ³ /d)	Bottom Storage Capacity of Aquatic Ecological Engineering (10 ⁶ m ³ /d)	The Increased Storage Capacity of the Ecological Restoration Reservoir at the Source (10 ⁶ m ³ /d)	Total (10 ⁶ m ³)
Light rain (upper limit)	10	27.50	5.62	2.69	14.53	3.28	26.12
Moderate rain (upper limit)	25	68.75	12.47	6.38	14.53	3.28	36.66
Heavy rain (upper limit)	50	137.5	23.89	12.51	14.53	3.28	54.21
Once a year	76	209.00	35.77	18.90	14.53	3.28	72.48
Rainstorm (upper limit)	100	275.00	46.74	24.79	14.53	3.28	89.34
Once in 3 years	111	305.25	51.77	27.49	14.53	3.28	97.07
Once in 5 years	127	349.25	59.07	31.42	14.53	3.28	108.30
Once in a decade	149	409.75	69.12	36.82	14.53	3.28	123.75
Once in 30 years	184	506.00	85.11	45.41	14.53	3.28	148.33
Once in 50 years	200	550.00	92.42	49.34	14.53	3.28	159.57
Once in a century	222	610.50	102.47	54.74	14.53	3.28	175.02
Once in 200 years	244	671.00	112.52	60.14	14.53	3.28	190.47
Heavy rainstorm (upper limit)	250	687.50	115.26	61.61	14.53	3.28	194.68
Once in 500 years	273	750.75	125.77	67.26	14.53	3.28	210.84
Once in a millennium	295	811.25	135.82	72.66	14.53	3.28	226.29
The 3-day rainfall of the “720”	617.1	1697.03	285.08	152.21	43.59	3.28	484.16

② Infiltration depth of rainfall and rainfall storage capacity of soil layer in vadose zone

According to the existing research results [31], the formula for calculating the rainfall infiltration depth (H) in the study area is as follows:

$$H = 0.8905R + 0.79 \text{ (medium – coarse sand)} \quad (4)$$

$$H = 0.4951R + 4.47 \text{ (silt, silty clay)} \quad (5)$$

$$H = 0.7647R + 0.74 \text{ (silty fine sand)} \quad (6)$$

The formula for calculating the rainwater infiltration and storage capacity Q of the vadose zone soil layer is as follows:

$$Q = H \times S \times N_e \quad (7)$$

where Q is the infiltration and storage capacity of the vadose zone soil layer (m³); H is the rainfall infiltration depth (m), and S is the distribution area of soil layers with different lithologies (m²). N_e is the effective porosity of the soil, which we define here as the difference between porosity and soil saturation.

③ The rainwater storage capacity of the soil layer in the vadose zone of key study area

The area of the key study area is 1945 km², of which 14% is green spaces and squares [32], and the area that can be used to build a sponge city is 272.30 km². According to the concept of integrating sponge city engineering and hydrogeological conditions, the soil layer in the aeration zone of green space and square land can be generalized as fine sand and silt layer, with an effective inflow porosity of 11.79%. Equation (7) is used to

estimate the rainwater seepage storage capacity of the vadose zone soil layer, as shown in Table 4.

④ The rainwater storage capacity of the soil layer in the vadose zone of the suburban area

After investigation, it was found that the suburban area of the study area is 805 km², and rainfall cannot penetrate areas such as roads, urban buildings and factories, accounting for 22.375% of the suburban area. The underlying surface of other areas in the suburb is farmland, forest, and grasslands with good permeability. The area of vadose zone lithology with silty fine sand accounts for 48.89%, medium-coarse sand accounts for 15.88%, and silt and silty clay accounts for 35.23% (see Figure 9 for details). According to the method discussed earlier, the rainwater infiltration and storage capacity of the soil layer in the vadose zone in the suburbs were obtained (Table 4).

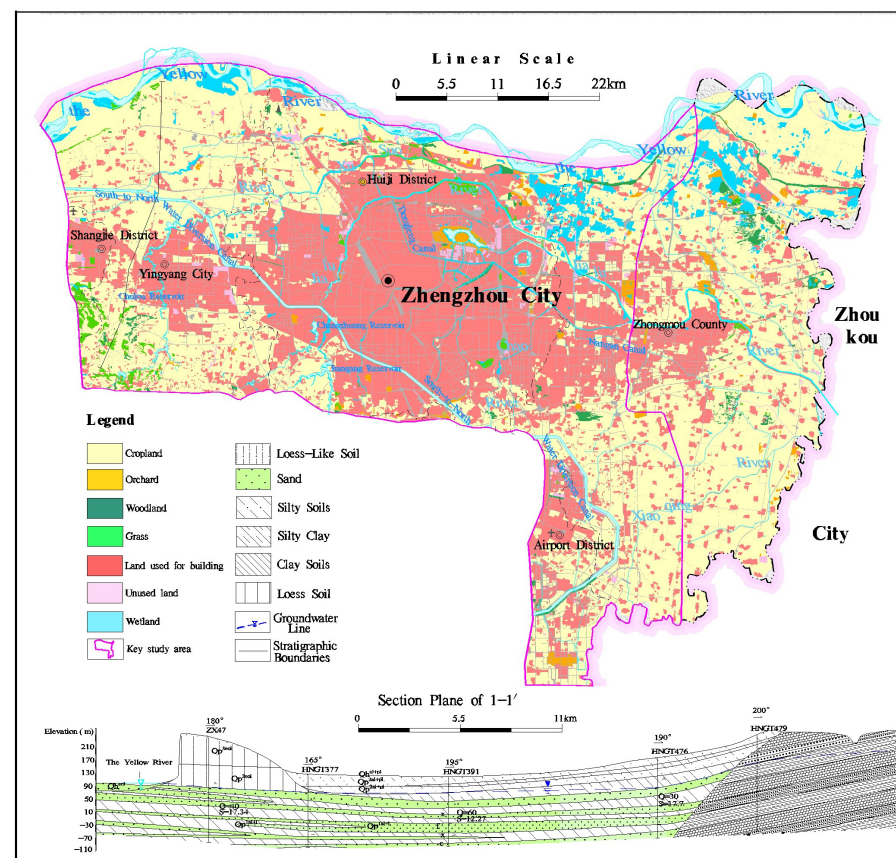


Figure 9. Land use types in study area.

3.3.2. The Role of the Geological Method-Integrating Water Ecological Engineering Construction with Eco-Geological in the Prevention and Control of Urban Flood Disasters

It has been recognized that urban water ecological engineering construction can greatly improve the city's ability to prevent flood disasters. By controlling soil erosion, the amount of sediment entering the reservoir or river can be substantially reduced, thereby maintaining the capacity of these water bodies to intercept floods. The water and soil loss in the upper reaches or source of the Jialu River Basin is quite significant. By the end of 2015, the total water and soil loss area was 881 km², and the average annual total soil loss was 2.16 million tons [28]. On the one hand, the loss of water and soil at the upstream or the source will lead to sedimentation and weaken the flood interception capacity of the reservoir, and on the other, sedimentation at the middle and lower reaches will lead to the blockage of the river channel and will greatly reduce its flood discharge capacity. It is estimated that the upstream siltation of the reservoir due to soil erosion has reduced the flood interception capacity of the reservoir from 260.91 million m³ to 195.68 million m³, which is about 25.00%.

Developing green patches by giving due consideration to ecological geology can address this issue quite successfully. Thus, areas suitable for planting trees or grass need to be selected based on the local geological conditions. By following scientific practices in ecological restoration and management, the sediment deposition in reservoirs and river channels can be greatly reduced to maintain the capacity of the reservoir to intercept floods and the river, and to discharge flood water. At present, the amount of annual soil erosion is 3.281 million m^3 . After ecological management, the reservoir can reduce the sediment deposition volume by 3.281 million m^3 every year [28], and this number is temporarily used as the standard for the improvement of the flood-holding capacity in this paper.

The goal of increasing infiltration storage and river discharge capacity are achieved through the proper implementation of urban ecological engineering. Zhengzhou plans to build 54 water ecological projects within the city. These projects are planned for various areas, including the Jialu River, Lianhu Lake, Dongfeng Canal, Ruyi River, Xiushui River, Xiliu Lake, Yuema Lake, and Yanming Lake. After the completion of these projects, the water-covered area of Zhengzhou city will increase from 156.9 km^2 to 211.66 km^2 . The urban water surface area will increase from 0.93% to 3.9% by 2020 [33]. Concept-wise, the construction of water ecological engineering is to follow “Tao follows nature” and not artificially destroy the law of water cycle. Geologically speaking, it is necessary to follow the laws of ecological hydrogeology. Thus, there should be no seepage prevention at the bottom of lakes and rivers, so that water can naturally seep into the ground. The area of the study area is 2750 km^2 , and the water surface area is $3.9\% \times 2750 = 107.25 \text{ km}^2$. If the bottom of the basin (area: 107.25 km^2) is not treated with anti-seepage, the situation would be drastically different. Considering the hydrogeological parameters such as the permeability coefficient of the soil layer in the local vadose zone, the buried depth of the groundwater level, and the water level of lakes and rivers, the amount of seepage water is calculated to be 14.53 million m^3/d . The results show that the water ecological engineering based on this concept is very beneficial to the prevention and control of flood disasters.

3.4. The Importance of Non-Geological Methods in Urban Flood Control

In addition to the geological methods mentioned above, there are non-geological methods such as river drainage, reservoir and lake water storage and underground drainage pipe network system storage to prevent and control flood disasters. These methods applicable to the study area are discussed below.

(1) Flood discharge capacity of the river channel

The flood is mainly discharged in the Jialu River and its tributaries, which eventually flow into its main stream and discharge outward in the downstream Zhongmu County. The flood discharge capacity can be characterized by the overcurrent capacity of the Zhongmu hydrological station. According to the calculation of the warning water level of the Zhongmu Hydrological Station of the Jialu River at 77.5 m, the total drainage capacity of the river channel for floods is 323 m^3/s [34], and the flood drainage capacity is 27.91 million m^3/d , as shown in Table 5.

(2) Water storage capacity of reservoirs, lakes, and wetlands

The water storage capacity includes the storage capacity of reservoirs and lakes after the completion of the Jialu River source or upstream reservoir and the water ecological projects. After the completion of the urban water ecological project, the area of lakes and wetlands will increase to 107.25 km^2 . In addition to the storage by this increased area of rivers, ditches, etc., and the ecological water demand for other lakes and wetlands under normal circumstances, about 62.57 million m^3 of flood control water storage can be reserved (see Table 5 for details).

The total catchment area of the Jialu River source or upstream reservoir is 786 km^2 , and the total storage capacity is about 260.9 million m^3 . But, after years of sediment deposition, the current storage capacity has been reduced to 195.68 million m^3 . In fact, the storage capacity of the reservoir for rainwater is positively correlated with the rainfall and the

catchment area. Only when the rainfall intensity reaches a certain level will the reservoir reach the maximum storage capacity, which is 195.68 million m³. The calculations for the storage capacity of the reservoir for rainwater under different rainfall intensities are shown in Table 5.

Table 5. Non geological methods for assessing the drainage capacity of rainwater and floods in the study area.

Rainfall Intensity/Return Period	Rainfall (mm/d)	Total Rainfall (10 ⁶ m ³ /d)	Storage Capacity of Upstream Reservoirs (10 ⁶ m ³)	Flood Discharge Capacity of Jialu River (10 ⁶ m ³ /d)	Reserved Storage Capacity for Lakes, Wetlands, etc. (10 ⁶ m ³)	Storage Capacity of Underground Pipeline Network (10 ⁶ m ³)	Total (10 ⁶ m ³)
Light rain (upper limit)	10	27.50	7.86	27.91	62.57	7.79	106.13
Moderate rain (upper limit)	25	68.75	19.65	27.91	62.57	7.79	117.92
Heavy rain (upper limit)	50	137.5	39.30	27.91	62.57	7.79	137.57
Once a year	76	209.00	59.74	27.91	62.57	7.79	158.01
Rainstorm (upper limit)	100	275.00	78.60	27.91	62.57	7.79	176.87
Once in 3 years	111	305.25	87.25	27.91	62.57	7.79	185.52
Once in 5 years	127	349.25	99.82	27.91	62.57	7.79	198.09
Once in a decade	149	409.75	117.11	27.91	62.57	7.79	215.38
Once in 30 years	184	506.00	144.62	27.91	62.57	7.79	242.89
Once in 50 years	200	550.00	157.20	27.91	62.57	7.79	255.47
Once in a century	222	610.50	174.49	27.91	62.57	7.79	272.76
Once in 200 years	244	671.00	191.78	27.91	62.57	7.79	290.05
Heavy rainstorm (upper limit)	250	687.50	195.68	27.91	62.57	7.79	293.95
Once in 500 years	273	750.75	195.68	27.91	62.57	7.79	293.95
Once in a millennium	295	811.25	195.68	27.91	62.57	7.79	293.95
The 3-day rainfall of the “720”	617.1	1697.03	195.68	83.73	62.57	7.79	349.77

(3) Storage capacity of underground drainage network system

The study area plans to build a new underground pipe network of 2576 km. With the completion of this project, the total length of the pipe network will increase from 1831 km to 4407 km. With that, the water storage capacity of the underground pipe network will increase from 3.24 million m³ to 7.79 million m³, as shown in Table 5.

The flood control capacity of Zhengzhou using geological and non-geological methods shown in Tables 4 and 5 are estimations based on the results obtained after the completion of the various projects for the Jialu River. These include the comprehensive treatment project, construction of the sponge city, and implementation of various projects that employ the concepts of ecological and geological aspects. It is to be noted that the geological method does not include the flood control capacity obtained by using underground space to build water storage projects. Based on the relevant data in Tables 4 and 5, the proportion of the geological method’s ability in flood control was calculated. The calculation was based on the formula expressed as the proportion of the ability of geological methods to remove floods = (the amount of flood water removed by geological methods)/(the amount of flood water removed by geological methods + the amount of flood water removed by non-geological methods) × 100%. The results of the calculations are shown in Table 6.

Table 6. The important role of geological prevention and control methods of flood and waterlogging disasters in the study area.

Rainfall Intensity/Return Period	Rainfall (mm/d)	Combining Two Methods Can Solve the Proportion of Rainfall (%)	The Proportion of Geological Methods Solved (%)	Geological Conditions Not Fully Utilized	
				Reduced Rainwater Storage Capacity (10 ⁶ m ³)	Combining Two Methods Can Solve the Proportion of Rainfall (%)
Light rain (upper limit)	10	480.91	19.75	20.50	406.36
Moderate rain (upper limit)	25	224.84	23.72	24.19	189.66
Heavy rain (upper limit)	50	139.48	28.27	30.32	117.43
Once a year	76	110.28	31.45	36.71	92.72
Rainstorm (upper limit)	100	96.80	33.56	42.60	81.31
Once in 3 years	111	92.57	34.35	45.30	77.74
Once in 5 years	127	87.73	35.35	49.23	73.63
Once in a decade	149	82.77	36.49	54.63	69.43
Once in 30 years	184	77.32	37.91	63.22	64.82
Once in 50 years	200	73.35	38.47	67.15	63.25
Once in a century	222	73.35	39.09	72.55	61.46
Once in 200 years	244	71.61	39.64	77.95	59.99
Heavy rainstorm (upper limit)	250	71.07	39.84	79.42	59.52
Once in 500 years	273	67.24	41.77	85.07	55.90
Once in a millennium	295	64.13	43.50	90.47	52.98
The 3-day rainfall of the “720”	617.1	49.14	58.06	199.08	37.40

Table 6 shows that the combined action of geological and non-geological methods can almost solve the rain and flood-related problems caused by rainstorms in the study area, and geological methods can take a 33.56% share of the prevention and control of floods. However, these methods are insufficient to meet the requirements if the rainstorms are larger. In the case of preventing floods caused by heavy rainstorms, geological methods account for more than 30%, and the greater the rainfall intensity, the greater the proportion of drainage capacity of geological methods. For the “720” torrential rainstorm in the study area, the two methods taken together account for only a combined share of 49.14% in controlling the flood disasters.

If the geological, ecological, and hydrogeological conditions are not fully utilized, and if the engineering aspects of sponge city construction are not followed, the situation could be different for the study area. If so, the impounding capacity at the source of the Jialu River will be reduced by 3.28 million m³, and the seepage volume will be reduced by 14.53 million m³ per day. This will lead to a sharp decline in the amount of rainwater and flood infiltration in the sponge construction area of the city, reducing its flood control capacity. As shown in Table 6, the flood control capacity achievable through a combination of geological and non-geological methods will be reduced from rainstorm to heavy rain. For example, for the urban flood disaster caused by the “720” rainstorm in study area, the combined efforts of the two methods can only remove 49.14% of the rain and flood. This is the reason behind the extremely serious consequences caused by the “720” torrential rainstorm in Zhengzhou.

4. Conclusions and Suggestions

4.1. Prevention and Control Strategies for Flood Disasters in Study Area

Our analysis shows that, by making full use of Zhengzhou's geological conditions and by considering the ecological and hydrogeological conditions, the city's flood control capacity can be greatly improved. Proper engineering measures such as drainage and the development of sponge cities would further facilitate flood control.

By taking advantage of the favorable engineering geological conditions of the city, the construction of deep underground water storage projects can almost solve the problem of floods, including those caused by the extremely heavy rainstorm that occurred once in a millennium. The ability to store the excess water and use it as a resource to alleviate the problem of water shortage in the city is an added advantage.

Construction of pipelines connecting deep underground storage tunnels, using the space available below the basements of subways, shopping malls, and parking lots, as well as those beneath the low-lying areas of high flood risk, is effective in controlling the flood situation. The pipeline network will divert the flood waters that enter the subway or other high-risk areas into the deep-water storage tunnel. This can eliminate the risk of flood disasters and greatly improve the emergency response capability of urban flood disasters.

4.2. Suggestion

Conduct targeted hydrogeological, ecological, engineering, and environmental geological surveys in the flood-prone areas, including the city of Zhengzhou, from the point of urban flood control. Based on the survey results, make full use of geological conditions to address the problem of urban flood disasters. The specific suggestions are as follows:

In the urban area, the sponge city engineering construction needs to be closely combined with the urban hydrogeological conditions, giving full attention to the water seepage and storage performance of the vadose zone strata. This would improve the urban sponge's storage capacity for rainwater.

Consider the laws of hydrogeology while constructing water ecological projects such as lakes, wetlands, or other ecological management projects. Through the proper use of a hydrological system, the infiltration capacity of water bodies to penetrate deeper into the strata can be improved.

In accordance with the laws of engineering geology and urban construction, the deep underground space or underground goaf can be used to build deep water storage projects. This would help to improve flood absorption and emergency response capabilities.

It is necessary to execute steps for the control of soil erosion and improve the soil and water conservation capacity while considering the ecological and geological conditions. This would reduce the accumulation of sediments in the reservoirs and rivers and maintain their flood retention capacity.

In summary, through a studied application of geological, ecological, and hydrological conditions and by the proper design and implementation of engineering practices, the flood situation in Zhengzhou can be controlled. The potential for recycling the flood water for the city's consumption is a positive fallout of the city's flood disaster management.

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