MSc Program
Environmental Technology & International Affairs

Urban Flood Management in China: A Case Study of the Sponge City Concept in Zhengzhou

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **CARINA KARNIČAR, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "URBAN FLOOD MANAGEMENT IN CHINA: A CASE STUDY OF THE SPONGE CITY CONCEPT IN ZHENGZHOU", 68 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Extreme precipitation, intensified by climate change, is a growing global threat, particularly in urbanized regions with inadequate flood preparedness. Both extremes of floods and draughts have become common and a devastating problem globally. One answer to them is the Sponge City Concept (SCC). Introduced in 2013, China's answer to a more sustainable urban water cycle is meant to catch excess water during rainfalls and recycle that for irrigation during draughts. Implemented in several Chinese pilot cities, the Sponge City Concept has also altered Zhengzhou, the capital of China's Henan Province. This paper explores the SCC in detail and analyses the 2021 Zhengzhou flood to identify reasons for this disaster despite the implementation of the SCC. The methodology includes a literature review of academic contributions and media articles, complemented by an analysis using the WWF Water Risk Filter to assess Zhengzhou's water risk profile. Findings indicate that while the SCC offers a promising framework for urban water management as well as climate adaptation and mitigation, its success depends on adequate funding, expertise, and public engagement. Community resilience and disaster preparedness have to go along with a successful implementation of such a large-scale and long-term project as the Sponge City Concept. The thesis highlights the importance of a comprehensive approach to urban flood management.

Key words: Sponge City Concept, urban flood management, sustainable water management, climate adaptation, resilience, disaster preparedness, Zhengzhou, floods.

Table of Contents

List of Abbreviations

BCE	Before Common Era
LID	Low Impact Development
NRW	North Rhine-Westphalia
PRC	People's Republic of China
PWC	PricewaterhouseCoopers
RMB	Renminbi
SCC	Sponge City Concept
SDG	Sustainable Development Goals
SuDS	Sustainable Drainage Systems
UNFCCC	United Nations Framework on Climate Change
WSUD	Water Sensitive Urban Design
WWF	World Wide Fund for Nature

1. Introduction

Extreme precipitation, exacerbated by climate change, has become increasingly common globally, posing significant threats to life and causing substantial economic losses, particularly in inland regions with inadequate preparedness (Yin et al. 2021, 1). The global trend towards urbanisation is predestined to continue. The share of people living in cities globally has increased within the last fifty years and is projected to grow within the next fifty years as well (Ritchie, Roser, and Samborska 2018). China has also urbanised substantially since the 1980s. The period saw a number of reforms initiated by Deng Xiaoping who heavily guided the political and economic development of China between 1979 and 1997, also called the Reform and Opening up period of China (Morgan 2021, 59-67). To illustrate, the Chinese urban population in 1980 amounted to 19%, in 2022 it has risen to 64% (World Bank 2018). The need for cities to accommodate a fast influx of new inhabitants produced an abundance of new infrastructures, roads, and pavements (Chan et al. 2018, 772). Yet unaware of the future consequences, grey infrastructure replaced green areas and with that, water-absorbing, natural soil has given way to impervious surfaces, considerably reducing the soil infiltration volume (Yin et al. 2021, 2). The effects of these developments are witnessed globally, with floods occurring at a higher frequency across the world.

Responding to this devastating development, China began implementing the Sponge City Concept (SCC) in 2015, with thirty cities in China being selected as pilot cities for the project. Rolling out the concept, cities are to implement infrastructural changes to integrate more green infrastructures with a better drainage system. As such, this would not only serve to prevent runoff flows of stormwater, but also deal with water pollution that has increasingly become a problem in heavily industrialised areas. Besides these utilitarian sides, the addition of more green spaces should also enhance living standards within cities (Yin et al. 2021, 2; Chan et al. 2018, 773). In 2016, Zhengzhou, the capital city of Henan province, an inland region in Eastern China, began implementing structural changes according to the Sponge City Concept (Guo et al. 2023, 11). But when the time came to prove its resilience, it miserably failed, and more than a hundred people lost their lives in an extreme flood event in the summer of 2021 (Elizabeth Chen 2021). The 2021 flood disaster in Zhengzhou highlights the interplay between increasingly more extreme climate phenomena, human responses, and the resulting extensive damage. With over 250 mm of cumulative precipitation and significant inundation, the Zhengzhou flood affected urban residential as well as industrial areas and agricultural fields. The disaster underscores the urgent need for transformative measures to enhance flood resilience and disaster governance not only for China but also for inland regions worldwide grappling with the escalating impacts of climate change (Guo et al. 2023,11). This event serves as an example of floods occurring globally, and the learnings from it are important for other cities that are currently in the process or planning to implement sponge city elements or infrastructural changes to make themselves more prepared for the future.

In the course of this master thesis, the Chinese Sponge City Concept will be explored in more detail, followed by an analysis of the Zhengzhou flood of 2021. Elaborating on Zhengzhou's flood risks and the course of events in July 2021, the reasons for the failure of Zhengzhou's Sponge City will be examined. With climate change induced impacts and weather extremes on rising globally, this thesis adds knowledge to current adaptation and mitigation strategies.

1.1. Relevance

In May and June of 2022, Bangladesh was hit by the worst flood within more than the last century. Albeit used to seasonal monsoon rains, the South Asian country was nonetheless overwhelmed by the extraordinary and unprecedented magnitude of the flooding that occurred in the northwestern part of Bangladesh in the summer of 2022 (Kumar Das 2022). More than 140 people lost their lives during the disaster (Teirstein 2023), and more than seven million people were affected, according to a report from the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (2023a). The incident has stirred discussions on the need for infrastructural changes that would better protect lives and properties (Kumar Das 2022).

Between June and August 2022, Pakistan suffered the same fate, with nearly a third of the territory inundated and 33 million people affected, most of them children and already vulnerable groups. Even after one year, the population is still struggling with the aftermath of the flood that left several water sources contaminated and wiped out crops and livestock. A combination of climate change-induced extreme precipitation, melting glaciers, and urbanized areas produced such a devastating dimension (UNICEF 2023; United Nations Office for the Coordination of Humanitarian Affairs (OCHA) 2023b).

Between October and December 2023, Somalia, Kenya, Ethiopia, and Tanzania in Eastern Africa were hit by torrential rains that left a death toll of more than 136. The region has always been prone to draughts and heavy rains due to the El Nino weather pattern, a phenomenon that is projected to become more extreme and frequent due to climate change (Princewill 2023).

In April 2024, melting snow and heavy rains hit Russia and Kazakhstan with the worst floodings of the last eighty years. With several houses and entire villages submerged, more than 110.000 people had to be evacuated, most of them in Kazakhstan. While the region is accustomed to floods at this time of the year, the extreme magnitude has also taken them by surprise (Greenall 2024).

The flood catastrophe in Germany and Belgium in July 2021 has shown that also developed countries are not exempted from the dire consequences of climate change, with the floods taking 180 lives in Germany and 39 more in Belgium. The majority was hit by the impact of the water masses, but some also found themselves trapped in cellars, garages, and underground parking lots (Jordans and Casert 2022; Bundeszentrale für politische Bildung (bpb) 2021; Deutsche Welle 2022). Again, the intensity of the floods was unprecedented. The causes, however, are a familiar, repeating pattern across this paper: The epicenter of the disaster in Germany was the state of North Rhine-Westphalia (NRW). According to data from the state's Federal Environment Agency as well as its State Office for Nature and the Environment, North Rhine-Westphalia has a soil sealing rate of 23,8%. Thus, nearly a quarter of the total territory is covered with impervious surfaces. That makes NRW the most soil sealed state relative to its population density in all of Germany (LANUV n.d.; Wilke 2013).

As a final example due to the geographical closeness, the Austrian Southern federal state of Carinthia and the North of Slovenia were hit by extreme precipitation at the beginning of August 2023. Some regions saw more rain within five days than is common for a whole month. Ensuing floods and landslides cut villages off, damaged houses, fields, and forests. In Slovenia, three people lost their lives. The heavy rains were caused by an unusually warm Mediterranean Sea which sent particularly saturated clouds across the Alps. Once there, the colder air eventually caused the water in the clouds to cool off and fall down

(Bundesministerium für Landwirtschaft (BML) n.d.; ORF 2023b). The soils in Carinthia – also a region with a high rate of land consumption – could not absorb the volumes of water fast enough (ORF 2023a).

Human interventions into nature besides global warming and urbanisation are heightening the probabilities and intensities of floods. For centuries, rivers around larger or growing settlement areas have been tamed. Rivers have been straightened but with that, their speed has artificially increased; flood plains have been dried out to make space for agriculture or residential purposes (World Wide Fund For Nature (WWF) n.d.). The consequences of these interventions are now felt more than ever before in the current collective memory. They sound an alert to the urgent need for urbanized infrastructure that is not only environmentally, economically, and socially sustainable, but also in a greater balance with the ways of nature. The significance of effective flood and water management is paramount on a global scale, spanning both developed and developing nations. Responding to that, the Sponge City Concept is an interesting point of study not only for researchers on China related issues, but also for policymakers in environmental and water management. Hence, this thesis holds substantial importance for finding ways of smart decision-making in times of extreme weather events.

1.2. Structure and Research Question

After a brief literature review on the existing research on the sponge city concept, the topic of urban flood management will be thoroughly analysed. The first part of this paper thus deals with urban water management in general and specifically in China. Here, the importance of a holistic approach to water management in cities will be highlighted. The growing prevalence of water extremes – droughts during scarcity and floods during excess – urges the need to study the concept of smart cities and sponge city elements. In the second part, the sponge city concept will be explained in detail, followed by the case study on Zhengzhou. The case study will elaborate on how Zhengzhou implemented the *Zhengzhou Sponge City Special Plan (2017-2030)* and the events that ensued during the devastating floods in the summer of 2021. Furthermore, an analysis of Zhengzhou's flood risk scheme will be conducted using the World Wide Fund for Nature's (WWF) Water Risk Filter methodology. By learning the essentials of urbanization's impact on the urban water cycle, the components of the Sponge City Concept and their methods of tackling urban flood run-off as well as understanding Zhengzhou's flood risks, this thesis aims to answer the following research question: What are decisive factors for a successful implementation of a large-scale infrastructure project like the sponge cities? By answering this question, the thesis also explores possibilities and the technical as well as managerial feasibility of implementing sponge cities in other flood-prone regions in the world.

1.3. Methodology

The methodology of this paper includes a literature review of relevant academic contributions and media articles on the sponge city concept and the Zhengzhou flood incident. The contributions include authors and institutions of various backgrounds while sources are consciously chosen in several languages, including German, English, Chinese, and Slovenian. Special value will be added by an analysis of the case study on the Zhengzhou sponge city. The choice of papers for this thesis was greatly aided by the expertise stemming from Professor Dr. Helmut Kroiss, a professor at the Vienna University of Technology and a decisive designer of the Viennese wastewater infrastructure. Upon his recommendation, the findings of contributions such as "Implementation of a specific urban water management – Sponge City" (Nguyen et al. 2019) or "Sponge City in China – A breakthrough of planning and flood risk management in the urban context" (Chan et al. 2018) were, among others, closely analyzed for the chapters focusing on the sponge city concept. One of the authors of the former contribution – "Implementation of a specific urban water management – Sponge City" – Wang Xiaochang, professor at Xi'an University of Architecture and Technology, is a long-time colleague of Mr. Kroiss and an influential figure in the sponge city implementation in China.

Furthermore, an analysis of Zhengzhou's general water risk situation will be conducted for the case study on Zhengzhou, using the WWF Water Risk Filter. The WWF Water Risk Filer is an open-source tool for companies and investors that helps them making informed decisions based on an assessment of their current and future water risks. Provided by the Swiss-based international environmental protection organization World Wide Fund for

Nature, the tool uses a plethora of data sources and databases tailored to the specific indicators. These include platforms and data sources such as Integrated Biodiversity Assessment Tool (IBAT), the European Commission, the International Institute for Applied Systems Analysis (IIASA), and more than twenty further reputable institutes, foundations, and research centres (WWF Germany 2023).

In the risk filter's basin risk assessment, several aspects are covered to provide a comprehensive assessment. Covering physical, regulatory, and reputational risks, the tool takes into account natural and human-induced conditions of river basins, a stable regulatory environment, and local communities' perceptions of companies' conduct with respect to the surrounding water sources. Taking these aspects into account, risk categories such as water scarcity, flooding, water quality, and ecosystem services status can be evaluated. Companies such as AstraZeneca, Migros, Mondi, H&M Group, Edeka, and Tschibo have been using the tool to conduct water risk assessments (WWF Water Risk Filter Suite 2023). Also recommended by PricewaterhouseCoopers (PwC) Consulting Group, this tool serves as a trustworthy source to analyze physical and reputational risks for companies of a specific location (Hartmann, McClellan, and Schwarz 2023). The tool offers useful application possibilities and detailed assessments for various environmental and human-induced conditions, depending on the indicators chosen. Due to the wide array of information that can be deducted data from this tool, its utility spans beyond business-related decision-making and therefore will be included in this thesis as well.

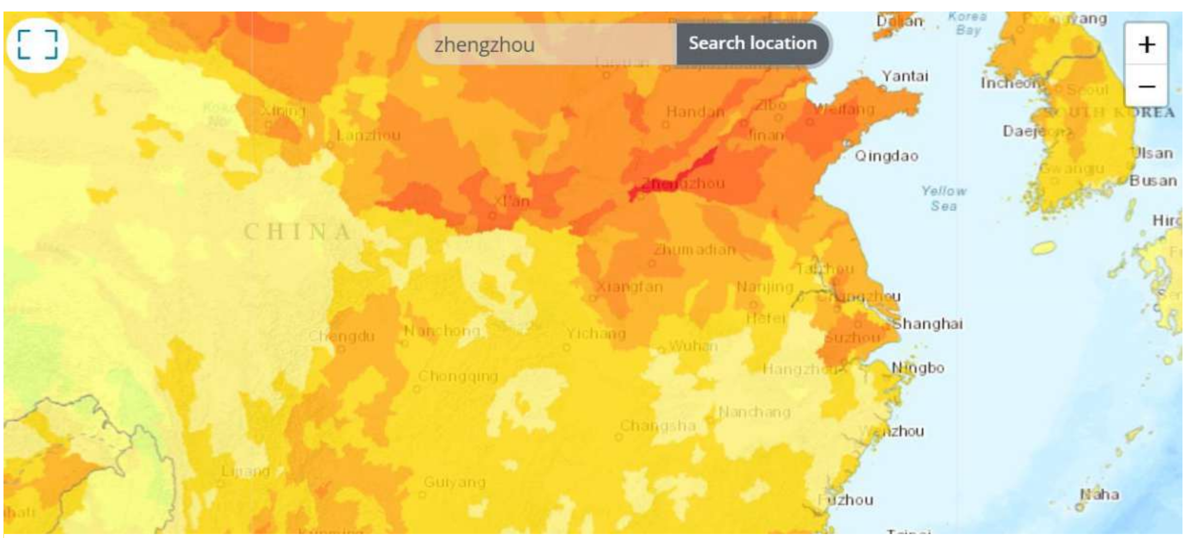


Figure 1: Physical Water Risks in China (borrowed from WWF Water Risk Filter 2021)

For example, in Figure 1, the general indicator “Basin Physical Risk” that includes risks of water scarcity, flooding, water quality, and ecosystem services status is chosen, and the location for Zhengzhou, China entered (WWF Water Risk Filter 2021). This is especially noteworthy because it is evident that the risk affiliated with this area is the highest in all of China. A more detailed assessment will be given in Chapter 5 of this paper.

2. Literature Review

2.1. Sponge City in Selected Languages

The Chinese expression 海绵城市 (*pinyin*: Haimian chengshi) is a direct translation of the English expression "sponge city". In German, the term "Schwammstadt" – as it is currently entering into a growing usage – is a likewise direct translation (Baidu, n.d.; Stadt Wien n.d.). In a 2021 study by the Urban Planning Institute of the Republic of Slovenia, "A water-management perspective on the deployment of blue-green infrastructure in cities" uses the umbrella term blue-green infrastructure (modra-zelena infrastruktura) for the components or building blocks that are make a city into a sponge city, such as green rooves or bioretention units (Radinja 2021, 28-39). In the same study, Chinese sponge cities are also mentioned and translated as "spužvasta mesta". An expression that can also be directly translated into "spongy cities" (Radinja 2021, 36). Thus, the quite figurative term that nowadays indicates a hypothetical city that can retain superfluous water in times of excess and then release it in times of scarcity – just like a sponge – can be quite easily and unambiguously translated into various languages.

2.2. Existing Research on the Sponge City Concept

The term was first mentioned in a paper in the journal *Irrigation and Drainage: Managing Water for Sustainable Agriculture* in 2005 but did not indicate of what the concept encompasses in current understanding (Hamidi et al. 2021, 2). The paper – "Sponge City: Water Balance of Mega-city Water Use and Wastewater Use in Hyderabad, India" by Daan J. van Rooijen, Hugh Turral, and Trent Wade Biggs – examines the relationship between urbanization and agricultural water use in arid and semi-arid river basins. It argues that as cities expand, they increasingly compete with the agricultural sector for water resources. That leads to shifts in water allocation dynamics and the need to consider the potential for wastewater reuse in irrigation. The study further emphasizes the need for sustainable water management practices in rapidly urbanizing regions (Van Rooijen et al. 2005, 81-91). While also dealing with the nexus between urbanization, sustainable water usage, and a circular water economy, this paper on a sponge city does not yet conceptualize the comprehensive infrastructural changes within cities to mitigate the impacts of stormwater.

In 2013, the term was used for the newly introduced "sponge city concept" proposed by Chinese President Xi Jinping. Motivated by the frequent occurrences of urban pluvial flooding across Chinese cities, the innovative concept was meant to mitigate the damages caused by heavy rainfalls and other extreme weather events. Since then, the theoretical concept has been rolled out in several cities. According to Hamidi, Ramavandi, and Sorial (2021), debates on the Sponge City Concept began to flourish after 2015 when it started to be discussed in academic articles both from a technical but also managerial perspective. Over the past decade, a plethora of literature in English, Chinese, and other languages has been produced.

In the study "Sponge City in China – A breakthrough of planning and flood risk management in the urban context", Chan et al. (2018) explore various components of the sponge city concept. These include permeable pavement, green roofs, complex bio-detention, artificial ponds, artificial wetlands, rain gardens, bio-swales, and vegetation buffers. These are then evaluated based on their functions, targets, and economic costs. Functions include water storage, infiltration, peak-reduction, water purification, and ecological enhancement. Targets comprise the run-off volume, peak run-off, and pollutant control (Chan et al. 2018, 776). The study also includes the benefits of the sponge city concept beyond precipitation control. It highlights the social benefits derived from creating recreational space by greening the cities through urban parklands, or the provision of new habitats for the biosphere (Chan et al. 2018, 773).

In a more detailed review of a particular component of the sponge city concept "Construction of water-soil-plant system for rainfall vertical connection in the concept of sponge city: A review", Jiang et al. (2022) provided a closer analysis of the bioretention qualities of different soils. Pointing out the great challenge of the high number and volume of pollutants that are present in the hydrological cycle of a city that essentially skyrockets in case of extreme stormwater events and overflow of drainages, this study is an important contribution to the closer study of individual SCC components. As the infiltration and purification capacity of various soils are different, and different geographical and climatic areas possess different types of soils, such an analysis is important when choosing additional green infrastructure or artificial drainage capabilities to complement the natural capacities of the specific locations (Jiang et al. 2022, 1-7). This paper also introduces an explanation of the sponge city infrastructure as a component "in the new urban water cycle mode" (Jiang et al. 2022, 3).

In general, the urban water cycle can be simplified as a cycle between a water source and the city. Water is derived from a source, such as a river, and then returned to a river after usage, and treatment in a wastewater treatment facility. Water intakes also include precipitation, whereas a water outlet is also the atmosphere through evaporation. More specifically, the urban water cycle can also be represented as a system within which individual processes will affect the whole. Within this system, the smaller sponge city infrastructure is introduced which serves as an intermediate between the water intakes and the outlets by retaining and purifying some of the water (Jiang et al. 2022, 3).

In the review "Implementation of a specific urban water management – Sponge City", Nguyen et al. (2019) provide a very detailed description of the sponge city water management strategy, including financial requirements. The authors categorize the causes of urban flooding into climate change, urbanization, and poor urban planning. These include frequent precipitation extremes, an over-abundance of concrete structures, insufficient drainage systems, and the modification of floodplains into residential or industrial areas (Nguyen et al. 2019, 149). In this study, urban drainage systems within various historical periods are compared and the modern approach to a sustainable water management cycle, the "sustainable approach" is introduced which is a more sophisticated and integrated system, compared to the traditional approaches (Nguyen et al. 2019, 151). Finally, a schematic design of Sponge City and a detailed explanation of its components, such as green roofs, bio-retention, and urban permeable pavements offer a useful description of the Sponge City concept and what benefits and challenges the concept entails (Nguyen et al. 2019, 152-159).

In a policy brief of the Stockholm International Water Institute titled "Guide to climate-smart and water-wise cities", sponge cities are mentioned as an example of a "smarter way to plan a city" (Ingemarsson, Schabus, Sköld 2023, 4).

In the 2021 paper "Research on Sponge City Planning Based on Resilient City Concept", Wang Chao connects the concept of resilience with the sponge city concept. Both possess a certain degree of similarity, especially concerning the function of these two city planning concepts. In the paper, he describes how "resilient thinking mainly emphasizes the ability of the system to recover and maintain the stability of the state under pressure" while the SSC's aim is to catch and store excess rainwater to prevent damage in times of floods and draughts, strengthening the city's resilience and "self-recovery ability to cope with various environmental problems (Chao 2021, 3).

In Yin et al.'s review "Sponge city practice in China: A review of construction, assessment, operational [sic!] and maintenance" (2021), the authors compare hydrological processes in a traditional system vs. a sponge city, illustrate the rainstorm management processes in a sponge city, and depict the operation and maintenance tasks of the relevant facilities. They describe the sponge city as a comprehensive concept that is more informative and more integrative than other urban drainage concepts, including the resilient city concept (Yin et al. 2021, 2).

Chen et al. (2021) conducted a detailed study on urban food gardens which have been implemented by the Taiwan government in Taipei since 2015. Urban food gardens can come in the shape of green-roof gardens and domestic gardens. They provide permeable areas in cities and are a vital component of the sponge city concept and its envisioned green infrastructures. The findings of the research show that gardens on the ground have a tenfold water retention capacity than gardens established on roofs (Chen Ying-Chu 2021, 1-5).

Another interesting review article from Zeng et al., "Comments and recommendations on Sponge City – China's solutions to prevent flooding risks", highlights certain legal challenges inhibiting the roll-out of the sponge city concept in China (Zeng et al. 2023, 7). They point out studies conducted in China that have shown that the sponge city concept should be an adequate tool to prevent flooding risks. However, the fragmented nature of the legal enforcement across Chinese provinces leaves the development of sponge city infrastructure standards somehow stunted. Pointing out the flooding disaster in Zhengzhou, the authors find that the sponge city program as of now has a limited capacity to prevent floods (Zeng et al. 2023, 1-7). While Zhengzhou's sponge city constructions would be able to handle average rainfall, the flood on July 20th, 2021, was "the heaviest rain on record [which was] beyond its capacity to handle" (Zeng et al. 2023, 5). This review is a valuable addition to looking at the SSC from a legal and policy-making perspective and linking the concept to the events in Zhengzhou.

Another research conducted two years after the devastating flood of 2021, "The extraordinary Zhengzhou flood of 7/20, 2021: How extreme weather and human response compounding to the disaster", elaborated on Zhengzhou's lack of preparation for the catastrophe. Guo et al. address human factors such as the slow responses to the flood disasters which have compounded the tremendous losses (2023, 10). In the discussion, the authors note that Zhengzhou's waterlogging problem has been eliminated by 77% since the implementation of the SSC. However, while Zhengzhou's urban water management has significantly improved due to the project, the project still has a way to go until it can work effectively, especially in terms of awareness building (Guo et al. 2023, 11).

What all studies have in common is that they all call attention to the acute threat of climate change and its consequences on human lives, especially in urban areas. With global warming, the occurrence of floods and weather extremes becomes more prevalent. These greatly impact areas with large impermeable surfaces.

Combined, these studies and policy briefs can give us an insight into crucial factors for urban flood management that need to be included in future city planning and risk management. The variety of the conclusions also highlights the nexus between human and technical aspects that need to be considered. These studies also serve as a valuable background to the following chapters.

3. Urban Flood Management

Urbanization not only presents difficulties for flood management but also poses challenges for environmental management in general, and water management in detail. As cities expand and populations grow, the complexities of managing water resources in urban environments intensify. This chapter is dedicated to an analysis of environmental management, urban water management, and finally flood management to better understand the interconnections as well as the challenges for urban flood and water management in China.

3.1. Sustainable Urban Water Management

Human settlements have always been dependent on the availability of water. Rivers, streams, and lakes have not only been vital as a source of drinking water but also essential for agriculture, cooking, and hygiene. Civilisations have since ancient times revolved around water and unsurprisingly always developed close to water bodies. In a manner akin to present circumstances, these settlements were also vulnerable to draughts and floods, and had to develop strategies to deal with them (We Are Water Foundation 2021).

Water has always been a valuable resource. Today's cities and megacities face a variety of water management challenges. Water is in constant exchange within various sending and receiving systems and societies depend on its availability, quantity, and quality. The factors in turn impact the range of applications of respective water bodies or streams, such as in agriculture, industry, or domestic households. Ensuring a secure and clean supply of water is of paramount importance for governments, especially in megacities where a large number of people depend on a few vital sources (Yang et al. 2016, 2-3).

In China, the dry climate of the northern and northeastern parties of the country is prone to draughts, causing the population north of the Yangtze River to face water shortages, while the southern and central regions tend to deal with precipitation extremes (Zeng et al. 2023, 4). In fact, this imbalance in water availability between China's North and South confronted the population already two millennia ago. The first sections of China's Grand Canal still linking Beijing with Hangzhou in the Southern province of Zhejiang today were already built in the 5th century BCE. The Grand Canal is a network of various waterways that has been used for transport, trade, communication, and flood control throughout Chinese history. While it was abandoned in the 19th century when China was grappling with rebellions and foreign intrusions into its territory, the canal underwent restoration and resumed its historical functions after 1934. It became a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site in 2014 (UNESCO World Heritage Centre 2013; Britannica 2019).

It is safe to say that a sustainable urban water management strategy that is capable of equilibrating the water extremes of draughts and floods is just as crucial today as it was in previous millennia. What has changed is the additional challenge of global warming that forces historical strategies to be adapted further.

Even without the challenge of climate change, the rapid expansion and population influx of cities into megacities in recent years has resulted in a notable gap in management capabilities compared to earlier times of slower urban growth. During these earlier, slower periods, cities could systematically develop infrastructure and employ innovative governance practices. Under the current fast-paced developments, cities have to adjust just as rapidly (Yang et al. 2016, 2).

Incorporating the elements of a sponge city concept into urban water cycles requires a profound understanding of our current urban water system. Yang et al. (2016) conducted a study on "Urban Water Sustainability" by applying the framework of *telecoupling* which views a city as a system where human and natural components interact, which requires both a socio-economic and environmental perspective to achieve a comprehensive understanding of the system. Conveniently taking Beijing as a case study for their research, the authors of the study link internal and distant interactions of a city's water management and thus also incorporate remote water sources into a city's water system (Yang et al. 2016, 1-2).

Generally, most cities are net receivers of water, meaning that they use more water than they send out again. They are also recipients of large amounts of virtual water. Virtual water is a term to indicate the water hidden in products that require water for their production. Another important aspect is that a city's administration, choice of policies, and technologies greatly impact their demand and supply of water. Effective wastewater recycling, stormwater collection, water pricing, irrigation technology, and rate of soil sealing can significantly enhance urban water sustainability and reduce losses from, for example, stormwater run-offs. (Yang et al. 2016, 2-3).

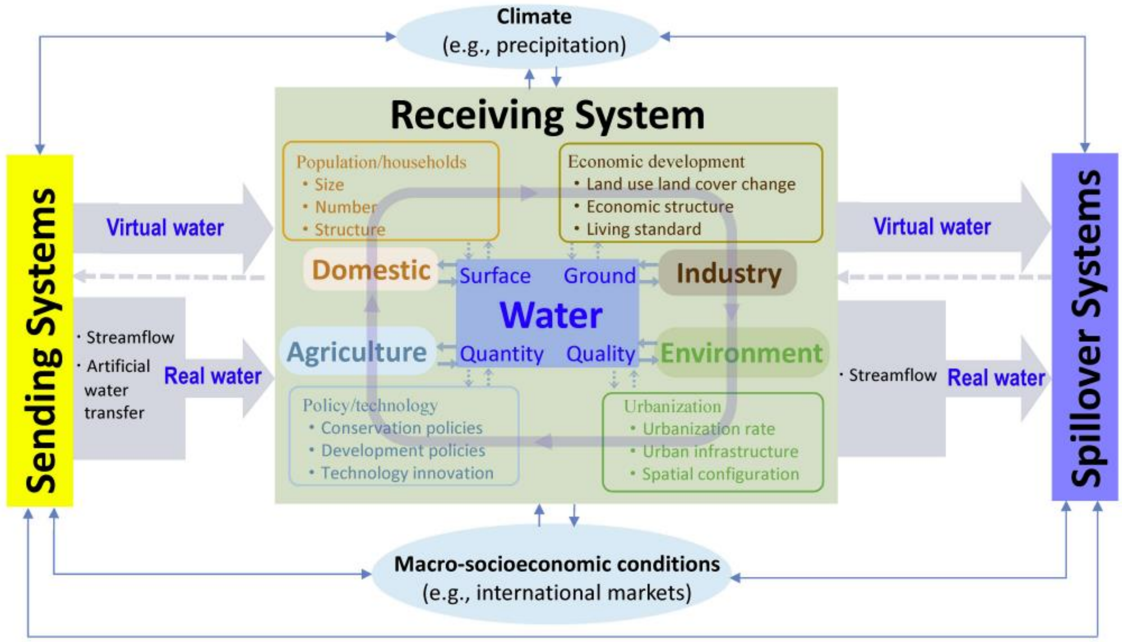


Figure 2: Urban Water Cycle (borrowed from Yang et al. 2016, 2)

Figure 2 coherently illustrates the urban water cycle as a system of constant interactions with its sending and spillover systems (Yang et al. 2016, 2). It also showcases its linkages with socioeconomic conditions and the climate while the city as the receiving system comprises further linkages in itself as well. The users of the water – be it domestic households, industries, the environment, or agriculture – highly depend but also impact on its quantity and quality. Furthermore, factors such as the size and structure of the population, economic development, urbanization rate as well as policies and technologies are likewise in constant exchange with the supply and condition of the water. For every aspect and their range of application, the standards of pollution control and conservation policies are decisive. These also do not only impact the municipal water cycle but also the spillover system that relies heavily on the city's effective wastewater treatment (Yang et al. 2016, 2-4). Given its omnipresence, water's complexity and the intricate systems supporting its availability are frequently overlooked or underestimated. However, this overview and the reality of draughts and floods remind us again why such complex systems and prudent usage of water are important.

Beijing is "one of the world's most water-scarce cities (Yang et al. 2016, 4) which has faced a considerable reduction in annual precipitation and depletion of water sources while seeing demand in constant growth. This has pushed the Chinese capital to become one of the most active cities in terms of water-saving policies, wastewater treatment, water recycling technologies, and stormwater collection. With 1355 stormwater collection systems in 2010 rising to 2150 in 2014, Beijing is rapidly expanding its capabilities to soak up flood water (Yang et al. 2016, 5-7).

A sustainable urban water framework depends on many factors of technical, social, and environmental origin. A ubiquitous and precious natural resource, water's availability and usage have been influenced and regulated by human interventions since human settlements began. These interventions have caused rivers to change course, dry, or even speed up. Some of them had detrimental consequences. However, some regulations and policies focusing on water saving can in turn have large beneficial impacts, whether that is experimenting with prices or more bottom-up attempts at awareness building. The aforementioned example in Beijing shows that China is investing heavily in reaching sustainable and secure water systems.

3.2. Environmental Management in China

China's water management policies are in line with the country's efforts in effective environmental management and legislation. Being the highest national emitter of carbon dioxide, China is often accused of implementing too lax environmental regulations and framed as a heavy polluter of the environment. While China is indeed the highest contributor of global CO_2 in terms of countries' shares, is noteworthy to consider that China's per capita emissions are far below those of countries, such as the United Arab Emirates, Saudi Arabia, Russia, Australia, the United States, and Canada (Ritchie and Roser 2024).

Notably, China has been working on its environmental legislation since the 70s (Chan et al. 1995, 333). The timing is in line with international efforts seeking to implement global regulations on the environment. The United Nations Conference on the Human Environment in 1972 held in Stockholm, Sweden, the first world conference on the environment heralded the development of international environmental law (United Nations n.d.). Twenty years later, the Rio Summit of 1992 saw the establishment of the United Nations Framework on Climate Change (UNFCCC) which was further developed through the Kyoto Protocol that was adopted in 1997 (UNFCCC n.d.). With the Paris Agreement, the Conference of the Parties to the UNFCCC reached an agreement in 2015 that would shape the further path of many national environmental legislations (European Commission n.d.). In 2016, the Sustainable Development Goals (SDGs) entered into force after all member states of the United Nations agreed on the 17 goals in 2015 (United Nations Development Programme 2024).

Due to the complex nature of each individual issue, international treaties on the environment remain fragmented. They are usually agreed for specific matters instead of universally encompassing various issues under one umbrella. For example, in 1987 the Montreal Protocol was concluded in 1987 after its foundations were laid through the Vienna Convention for the Protection of the Ozone Layer in 1985. The Protocol regulated the use and eventual phase-out of chemicals involved in the depletion of the ozone layer. It is a symbol of success within international environmental negotiations as the ozone layer started to recover soon after its adoption (United Nations Environment Programme 2018). In 1979, the Geneva Convention on Long-Range Transboundary Air Pollution established rules on emissions that were causing massive transnational air pollution and acid rain (EU Publications Office 2020).

Similar to the international developments in environmental law, Chinese environmental law remains also very fragmented, with several guidelines focusing on individual components of the environment. The Law of Environmental Protection, published in 1979 and implemented a decade after, contains very generalized guidelines while more specific rules can be found in China's Forest Conservation Law of 1963 or the Minerals Resource Law of 1963. An important tool for environmental management, the Environmental Impact Assessment (EIA) has also found wide usage and application in China for many decades (BMK and BMAW 2024). Besides the EIA, China has implemented various other management approaches such as direct controls for emission standards and economic instruments such as additional charges or subsidies. In recent years, economic tools such as green credits that encourage greater public participation have also been implemented, albeit still in their early stage and lacking a sufficient impact so far (Liu et al. 2010, 1707; 1716). Since the Chinese borders comprise a large territory of great cultural and environmental diversity and several different climate and biodiversity zones, the national government has always empowered local authorities to specify their own rules and policies even further (Chan et al. 1995, 335-337). While this is deemed to be a desirable and rational tactic to deal with such an ecological diversity as in China, the lack of widely standardized rules leaves the legal landscape overly heterogeneous. It leaves too much room for discretion for several agencies which results in an absence of coordination (Chan et al. 1995, 338). In 2014, environmental law in China received a much-needed update, with monitoring and control requirements becoming more stringent and economic tools such as pollution licenses that enterprises can apply for being added to the list of management mechanisms. The law also allows greater access for the public or NGOs to receive environment-related information. However, many old problems remain, including underpowered environmental protection bureaus that lack authority and local administrations' autonomy over regional regulations. Further, local bureaus' fragmented relationship with the central environmental ministry gives the latter too little control over local matters and the former too little power to enact regulations or penalties (Mallesons 2014; Zhang and Cao 2015).

A generic one-size-fits-all approach cannot be applied in China, nor is it useful in any environmental legislation also on the international stage. However, overt fragmentation is also posing a problem. The difficulty of striking a balance between centralization and localization is also present in the sponge city concept implementation. Another tool for environmental management, the SCC cannot be uniformly installed everywhere the same way but also has to be adjusted to local, climatic, ecological, and geological circumstances.

Despite the need to tailor the sponge city infrastructure to local circumstances for it to be effective, some research has concluded that China still needs to provide more standardized construction and engineering guidelines for the sponge city (Zeng et al. 2023, 7). This dual challenge of adapting environmental initiatives in a way they can be effective therefore requires ongoing learning, improvement, and further adaptation.

While ideal solutions have not been found neither in China nor elsewhere, discussions on how to include externalities into the true costs of products are ongoing. The economic toolbox largely provides options such as subsidies or penalties which have also been implemented in China since decades, as discussed above. With these mechanisms, prices should also include beneficial or detrimental externalities, such as water pollution, noise or other disturbances to the environment, or, conversely, contribute to the smooth working of ecosystem services. An example of the latter may be a beekeeper, who directly profits from the honey while the respective environment in turn profits from the bees' pollination.

One approach to internalize such external costs at a larger scale includes Green GDP accounting. In 1996, the National Bureau of Statistics (NBS) established the Division of Resources-Environmental Accounting which was when the idea of Green GDP was first initiated. The idea gained significant political traction in 2004 when the President of China at that time, Hu Jintao, officially used the term "Green GDP" in a speech, marking a major breakthrough in its formal recognition and pursuit. The Green GDP would include environmental factors into the net economic activity of a country or region at a larger scale. The concept is relatively more intensively discussed in China than elsewhere and has been implemented in local pilot projects so far. However, local administrations have been reluctant to adopt it voluntarily. Their performances are measured on the basis of their administrative zone's economic activities which would look worse using the concept of the Green GDP as some fear. This economic pressure is juxtaposed by the pressure of the public demanding healthier and cleaner environments. Eventually, the full implementation of such a comprehensive accounting approach that quantifies environmental factors and internalizes them into companies' or provinces' economic profits depends on the pilot projects and local administrations' willingness to accept it. Until then, provinces may initiate environmental economic approaches themselves. For example, the coastal region of Jiangsu has already been including environmental factors into performance assessments of government staff since 2017 (Weigelin-Schwiedrzik 2018, 17-29).

The example of the Green GDP reaffirms the problem Chinese Environmental Law faces regarding its implementation. While legislation is comprehensive, successful implementation depends on local governments and their personnel. Measuring their performance solely on their provinces' economic activities proved to be at the expense of the environment. But including the environment into economic indicators, such as the Green GDP envisions, can be effective in pushing environmentally conscious behaviour (Weigelin-Schwiedrzik 2018, 28).

As China and researchers all around the world are searching for solutions to environmental problems and especially ways to successfully implement good ideas, decisionmakers' policies on the environment have always and continue to have far-reaching impacts. These especially include floods, which have played a role not only since global warming has exacerbated their occurrence in recent decades but already throughout history.

3.3. History of Chinese Flood Management

"Despite 5000 years of Chinese flood management policy, floods remain an ever-present threat" (Luo 2015, 267). In line with the preceding section and its findings, flood management policies must also undergo continual adjustment. Since climates and the ways of water have been always changing, experience in flood management can help but not totally solve newly arising challenges. The unprecedented speed of anthropogenic climate change does however present a particularly complex dilemma.

The Sponge City Concept is today's answer to weather extremes caused by global warming. However, already China's history is marked by a continuous effort to mitigate the impact of floods through a variety of approaches. Besides the aforementioned Grand Canal connecting Beijing with Hangzhou, the Dujiangyan Irrigation System is also a historical feat of flood management and engineering skills built in Sichuan, a province in China's Southwest, in 256 BCE. Using the natural, surrounding topography and hydrology, the irrigation system is also used for flood control without utilizing dams (UNESCO World Heritage Centre, n.d.).

Around 4000 years ago, ancient Chinese kingdoms began to emphasize the necessity of leaders and politicians possessing robust flood management skills. Among them was China's first emperor, Qin Shihuangdi (秦始皇帝) who realized that prudent water supply and flood management was crucial to gain not only prosperity but also power (Luo 2015, 268 – 269). They started out by building dams and levees to manage floods. The practice was supplemented by the more successful technique of dredging channels instead. Further methods include constructing artificial lakes and canals or dividing stream flows such as in the case of the Dujiangyan Irrigation System, remaining in use two millennia later. Increasingly, transportation, irrigation, flood. and water management intertwined and projects like the Grand Canal sought to tackle all of these issues. During the Qing Dynasty, levees and riverbank reinforcement started to be built using concrete, bricks, or masonry. When China was engulfed by wars and civil unrest (1911-1949), flood management was of rather secondary concern. Periodic overflows of the Yangtze and Yellow Rivers forced the issue into renewed focus again after more than 3 – 4 million people lost their lives during flood events in 1931, 1935, 1938, 1954, and 1998 (Luo 2015, 267-271). Other policies that have been implemented so far to combat the impacts of extreme precipitation and riverbank overflows include land use changes such as transforming agricultural land to land, forests, or lakes (Luo 2015, 271).

Through decades of experience, structural measures to prevent floods such as higher dams and stronger dykes have shown to be cost-effective in the short term. However, investing in non-structural alternatives such as floodplain restoration, reforestation, and other green infrastructures are paramount from the long-term perspective (Luo 2015, 274-275). In the highly sophisticated world of today, opting for one or the other might be unwise or even impossible. A combination of those is preferable and potentially more flexible in tackling ever-changing circumstances. Such an approach is also reflected in the Sponge City Concept.

4. The Sponge City Concept

Having discussed the components of the urban water cycle of which common and extreme precipitation are both part of, as well as the development of environmental and flood management throughout Chinese history, this chapter is now dedicated to exploring the Sponge City Concept in closer detail.

4.1. Overview

In December 2013, the Chinese government initially announced its ambitious plans to bolster the resilience of cities through the Sponge City Concept. It is a comprehensive strategy to not only deal with floods but also tackle sustainable urban water resource management, including storage, water body preservation, and pollution control. Besides possessing a long history of urban flooding, China has faced increasingly detrimental floods throughout the last decades and has been forced to update its urban drainage systems that were not designed for the order of magnitudes experienced today. Through implementing pilot projects, a phase of trial-and-error can deliver important learning for future sponge city constructions. Initially, 16 cities were chosen as pilots which were then expanded to 30. Megacities like Shanghai, Beijing, and Zhengzhou are some of them. By 2020 the sponge cities are meant to store and recycle 70% of urban stormwater and increase that capacity to 80% by 2030 in the chosen cities (Chan et al. 2018, 772-774). The target furthermore foresees that by 2020 20% of urban areas will be covered with sponge city infrastructures, and by 2030 that number should rise to 80% (Nguyen et al. 2019, 149).

The concept of the sponge city is not entirely ground-breaking and the first of its kind. Rather, the aim to enhance a city or another urban area's capacity to soak up and re-utilize stormwater by releasing it again in times of need – just like a sponge – has already been thought of in other concepts. Besides the extensive flood management history China can draw on, these concepts were important steps the Chinese Sponge City Concept learned from (Nguyen et al. 2019, 148-149). These strategies include the low-impact development (LID) strategy implemented in the United States, New Zealand, Canada, and Europe (Chan et al. 2018, 772;

Toronto and Region Conservation Authority 2019). Launched in the 1990s, the LID strategy is a management approach that includes better design when developing sites, such as seeking to maintain as many natural, permeable surfaces as possible. Additionally, LID implements isolated and holistic drainage systems in flood-prone areas that are meant to reduce stormwater run-off and pollution load (United States Environmental Protection Agency 2015b).

In Australia, the strategy of Water Sensitive Urban Design (WSUD) uses appliances such as rainwater tanks, rain gardens, sediment ponds, wetlands, bioretention, and swales in its urban planning to combat run-off of stormwater that can otherwise also be used as a valuable resource (Chan et al. 2018, 772; Melbourne Water 2017). Introduced in 2007, the WSUD is designed to reduce water usage by 40% in newly developed sites and improve the quantity and quality of reused stormwater (Australian Capital Territory 2014, 1). Similarly in the United Kingdom (UK), the Flood and Water Management Act 2010 recommends that Sustainable Drainage Systems (SuDS) should be incorporated into emerging infrastructures and urban sites. In a press release of the UK government in January 2023, it was announced that due to increasing occurrences of floods, the country now considering making this recommendation mandatory (Pow 2023). With constructed wetlands and green infrastructures, SuDS aims to manage rainfalls closer to where they occur with the greatest impact and mimic natural drainage patterns (susDrain 2020).

Looking at these other stormwater management strategies, the Sponge City Concept in China seems to be not all too different. In fact, many components such as bioretention, green infrastructures, constructed wetlands, etc. are used in most of these strategies, including the SCC. Approaches such as resilient cities and smart cities also overlap with these. However, according to Yin et al. 2021, the Chinese Sponge City Concept is a more comprehensive method that includes bits and pieces from all these strategies. Furthermore, the SCC aims to implement sponge city components on a large scale and place "water ecological infrastructure as the core" (Yin et al. 2021, 2). With the roll-out of the 30 pilot cities after China's launch of the SCC, the ambitions of the Chinese concept indeed seem to be higher and more comprehensive and holistic than its predecessors. Instead of merely introducing sustainable and green infrastructural components, China wants to transform entire cities to function like sponges, combining stormwater management and the creation of green areas for leisure with sustainable development.

4.2. Key Components and Strategies

Summarizing in simple terms, implementing the Sponge City Concept means replacing impervious surfaces such as concrete and asphalt with green surfaces. By doing so, flood water and common precipitation would slowly seek through the ground, get managed through updated, sustainable drainage facilities, and be stored in appropriate storage facilities. This would allow the water to be reused during draughts instead of running off to accumulate into disastrous torrents of water. In reality, the infrastructures required for a sponge city are of course everything but simple. Sophisticated methods and appliances need to replace traditional tools, and adapted to local, climatic, and geological circumstances. Therefore, this chapter examines the respective components of the sponge city closer.

In general, the functions of sponge city facilities encompass features such as infiltration, detention, retention, purification, harvesting, and drainage. Respective Sponge City Concept components or facilities are designed for a single function while others serve multiple functions simultaneously (Yin et al. 2021, 8). Together, they ensure a "new urban water cycle mode" (Jiang et al. 2022, 3). For better clarity, a brief explanation of the functions is given below before the individual components are discussed.

Infiltration refers to the process of allowing stormwater or water after the snow has melted to seep into the ground and recharge groundwater aquifers, which is the rock layer below ground that holds groundwater. **Detention** is the stage where ponds, swales, or other natural or artificial storage tanks are temporarily holding stormwater. This reduces peak flow rates and mitigates flooding. The detention structures capture excess rainwater during storms and release it gradually. Similarly, **retention** is the long-term storage of stormwater within the urban environment. In a sponge city, retention measures such as green roofs, rain barrels, and constructed wetlands are employed to store rainwater for later use, such as irrigation, groundwater recharge, or recreational purposes. **Purification** is the natural or engineered process during which pollutants are removed from stormwater and water quality is improved before it is discharged into natural water bodies or reused within the city. Natural purification processes like biofiltration through vegetation, as well as engineered solutions like constructed wetlands and filtration systems, are implemented to remove contaminants from stormwater runoff. **Harvesting** is the practice of collecting and utilizing rainwater as a valuable resource rather than letting it go to waste. Rainwater harvesting techniques include rooftop collection systems, rain gardens, and permeable pavements. The captured water can be used for various non-potable purposes such as irrigation, toilet flushing, and groundwater recharge. **Drainage** refers to the overall management of stormwater within urban areas to prevent flooding and waterlogging. It is the removal of excess water. Compared to traditional drainage systems, sustainable drainage systems are designed to minimize environmental impacts and interconnect closer with retention or storage functions (Yin et al. 2021, 1-8.; Britannica 2024; Maxwell-Gaines 2004).

4.2.1. Bioretention Facilities

One vital feature of the SCC is bioretention. Possible bioretention tools are flower terraces, rain gardens, or multi-level green spaces that use gradients to reach various elevation levels which slow down water run-offs. These are areas that are designed to retain water, slowing down its accumulation on a surface, and also to tackle the pollution loads of stormwater. Stormwater often carries chemicals, heavy metals, and pathogens from other areas or due to abrasion. Bioretention systems are essentially garden facilities that are cultivated with plant species that are especially efficient pollutant removers and intercept water and pollution flows (Yin et al. 2021, 8). There is a wide array of possible variations among various bioretention systems, with varying efficiencies and location-specific suitability. The choice of bioretention media, depth, and plants depends on the environment and influences the retention capacity of the overall facility. While soil media such as clay, silt, and fine gravel possess infiltration capacities below three percent, medium to coarse sand has one between forty and sixty percent. Additionally, the supplement of organic material such as sawdust, wheat straw, and wood chips enhances purification processes by increasing denitrification processes within the soil. The specific mixture of the materials in bioretention media should be adjusted to the expected pollution varieties in the area and also climatic and environmental feasibilities (Jiang et al. 2022, 5). Also, the cultivated plants have varying interception effects and are likewise dependent on the ecological conditions of the relevant locations. Species that have a high pollutant removal capacity such as blady grass (Latin: Imperata cylindrica) or variable sword-sedge (Latin: Lepidosperma laterale) are particularly well-suited for many locations. Other core species that are efficient pollutant removers but are limited to certain climate zones include the knobby club-sedge (Latin: Ficinia nodosa) which is suitable for subtropic zones, or the woolly mat-rush (Latin: Lomandra leucocephala) that is compatible with arid or dry tropical regions (Healthy Land & Water 2020). Bio-retention facilities serve water infiltration, detention, retention, and purification functions (Yin et al. 2021, 8).

4.2.2. Green Roof Systems

Rather than covering roofs solely with bricks, SCC approaches seek to use these spaces for further greening of urban areas. Green roofs not only serve to reduce stormwater runoff but also mitigate the heat island effect that can make certain locations unbearable in warmer seasons. Roofs that are equipped with a green roof system have to be modified with several layers, including a waterproofing membrane above the structural deck of the respective building, a root barrier, a drainage layer, and filter fabric, one layer with an irrigation system, a growing medium, and vegetation (Green Roofs 2014). The latter two layers underlie similar considerations as the choice of plants and media for the bioretention facilities. Depending on the final mixture, green roofs serve infiltration, detention, and retention functions (Yin et al. 2021, 8). Due to the limited depth of roofs, the water retention capacity of green roof gardens is naturally lower than that of garden systems installed on the ground (Chen Ying-Chu 2021, 1-5). However, their utility and also aesthetic benefits have helped them to be adopted at large scales. Closely affiliated with the Sponge City Concept, green roofs are now covering more than 45 thousand square meters in the capital of the Netherlands. In Amsterdam, they are valued for their absorbing functions and the accompanying infrastructure that makes water available to be used for irrigating plants and flushing toilets (Simon 2024). One German Company has now also launched a roof system called "Sponge City Roof", advertising its water retention and, in case of especially heavy rainfall, drainage capabilities as well as the effect of high evaporation on such cultivated roofs (ZinCo GmbH n.d.). This, in turn, enhances a microclimate that reduces the heat island effect.

4.2.3. Rain Barrels

Rain barrels are simple tanks or bigger cisterns that can be relatively easily installed above or underground without much usage of sophisticated technology. In fact, they have been in use for decades and the water captured in them is utilized for plant irrigation, car washing, or any other usages that require a lot of water but where the quality of it does not have to be the highest. While the retention capacity of rain barrels is limited, they are useful for water resource harvesting close to where it is needed, for example in individual private households. By harvesting rainwater, the consumption of drinking water for usages other than drinking and cooking is reduced (United States Environmental Protection Agency 2015a). Despite the uncomplicated instalment and the variety of sizes and materials, they can come in, proper sealing should be paid attention to. Open and unmaintained rain barrels can become breeding hotspots for mosquitoes. Luckily, there are several ways to mitigate this problem, including adding mild anti-bacterial solutions, covering the barrels with window screens, or using proper lids and attaching a hose with a length that would deter mosquitoes from traveling through them. Another possibility is adding a thin layer of oil that will float above the water, preventing airflow and thus suffocating any breeding or growing mosquitoes (Rector, Duckworth, and Fonseca 2014). As a low-cost and simple solution, rain barrels and similar storage tanks are affordable parts of the SCC system that add to a sustainable urban water cycle. To prevent detrimental effects, they should be installed in areas where they can be regularly monitored and maintained.

4.2.4. Permeable Pavements

Aside from global warming and the resulting rise in extreme weather events, the booming development of impervious surfaces within the last centuries is a fundamental factor in the increase in urban flooding. Roads, pavements, and parking spaces have greatly contributed to large-scale soil sealing. Even with the growth of green surfaces in cities, a certain number of roads and pavements will have to remain. The sponge city concept's solution to this dilemma is permeable pavement.

Guan, Wang, and Xiao (2021) conducted a study on different materials that can be considered for this endeavor. These include permeable asphalt concrete, permeable cement concrete, permeable brick, permeable polyurethane concrete, and Epoxy resin microporous mixture. Each possesses different characteristics regarding durability, porosity, pore size, and pore distribution which have a considerable effect on various properties of the pavements, including hydrological and mechanical. The economic benefit of permeable benefits remains disputed due to the higher initial construction and current maintenance costs while environmental and social perks remain difficult to quantify. However, the environmental benefits are clearly recognizable. Besides permeable pavements' water purification function, they also mitigate traffic noises and the urban heat island effect. The latter occurs during evaporation of water stored in the pores of the pavement (Guan, Wang, and Xiao 2021, 2-13). The science, technology, and cost structure behind permeable pavements are certainly more complex than behind appliances such as rain barrels. Due to the large-scale impact of urban surfaces, they constitute a substantial component of the sponge city concept. Research and development in this area are thus of vital importance.

4.2.5. Grass Swale

Since the roll-out of the Sponge City Concept, the construction of swales has boomed in China. In fact, green swales rank among the most commonly built sponge city components (Lu et al. 2023, 2). They function as infiltration and bioretention units and also play an important role in pollution control. Usually placed on roadsides, they are effective removers of pollution runoff water has collected while flowing over street surfaces. Metal particulates, microplastics from tire abrasives, but also nutrients from wastewater such as nitrogen and phosphorous are found in these stormwaters and caught by the swales. Due to their particular utility but also aesthetic value in cities, global interest in them has grown. However, there is still a need for further research on grass swales which would benefit customized construction and maintenance procedures of swales, adapted to regions' respective climatic conditions and usual pollution loads. For example, the choice of plants should be taken based on whether they can withstand draughts, cold temperatures, or salt loads that are used as snow-melting agents in some areas (Lu et al. 2023, 1-5).

There are various kinds of swales in use, including grass swales, infiltration swales, bioswales, and wet swales. Ordinary grass swales are roadside turfs equipped with grass while infiltration swales are additionally fitted with check dams to slow down water flows. Figure 3b shows these stone-made check dams. Bioswales are furnished with engineered soil media and potentially also with underdrains and forebays. Wet swales' microtopographic pools – meaning pools with slight elevation variations – and wetland soils offer enhanced filtration functions and affect the microclimate of cities due to reinforced evapotranspiration (Lu et al. 2023, 5). Figure 3 illustrates four different types of swales: a) grass swales, (b) infiltration swales, (c) bioswales, and (d) wet swales (Lu et al. 2023, 6).

Figure 3: Swales (borrowed from Lu et al. 2023, 6)

4.2.6. Urban Wetlands

Wetlands are regions that can be seasonally or permanently flooded with water. Constructed of natural, urban wetlands are situated within or near cities or their outskirts. They comprise a diverse array of habitats such as river systems and their floodplains, lakes, and swamps, as well as coastal formations like salt marshes, mangroves, and coral reefs. Wetlands have a lot of benefits for the environment, including flood reduction properties due to a high-water absorption capacity; water filtration function that replenishes groundwater with purified precipitation; improvement of air and water quality in urban areas; biodiversity amplification by being popular breeding spots for fish; and recreation. Wetlands' value to nature and society is so high that they have their own international convention – the Ramsar Convention of 1971 – protecting them (Ramsar Convention on Wetlands 2018). In the Sponge City Concept, they are especially valued for their purification functions. Additional advantages include low maintenance costs once constructed and habitat conservation (Yin et al. 2021, 8).

4.2.7. Drainage System

Comprising a broad network of sewer tunnels in separate or combined sewer systems, catchment facilities, water inlets, storage tanks, pipes and wastewater treatment plants, an urban drainage system is a complex and sophisticated structure with most of the components hidden underground (Stadt Wien n.d.). Traditionally, most urban areas were equipped with a combined sewer system with stormwater and sewage water using the same pipes. In modern sewage systems, the pipes for sewage and stormwater are separated. However, this can lead to problems in climates with extended dry seasons. Likewise, the opposite with heavy rainfalls can lead to sewage overflows and mixing of the separated systems. This impacts the pollution loads especially because the separated pipes are furnished with different filter systems (Chen et al. 2021, 10). With a combination of the various sponge city components, the volume of the stormwater can be reduced, preventing overflows. However, with the recurring rainfall records, it can be difficult to predict how much water will actually fall and what the required capacity of the sewage systems will have to be. Preparing for the worst case can be very costly, and not always economical. As drainage systems are the last resort in catching water run-offs and stormwater, their prudent construction is key for successful SCC. While the notion of the other components that are mimicking nature and provide green and beautiful spaces to the city seems romantic, it would be disastrous to assume that these are enough to protect urban areas from the complex and potentially unpredictable phenomena of climate change.

4.2.8. Further Sponge City Components

Additional common sponge city facilities include detention ponds, rain gardens, flood intercepting trenches, sunken green spaces, and vegetation buffer zones which can amplify water detention, drainage, or purification functions (Jiang et al. 2022, 6; Yin et al. 2021, 8; Chan et al. 2018, 776). Their principles are very similar to the discussed components above, with the success of construction, make-up, and maintenance methods highly dependent on appropriate adjustments to the respective circumstances and environments.

Implementing a holistic and effective sponge city is costly and very complex. Not only can the combination of various components be adjusted to the environment and deeply calculated, but also each component itself is a complex system in itself. Therefore, sophisticated urban planning that involves many fields and a lot of expertise is vital.

4.3. Benefits and Challenges

With a complex system comprising such a wide set of components also comes a lot of challenges and benefits. Some of them have already been mentioned, or are more obvious than others, such as better urban water management, flood prevention, or better quality of life. The appliances of a sponge city provide diverse habitats for fauna and flora in urban areas and thus improve the functioning of ecosystems and promote biodiversity. The purification and retention processes furthermore reduce the runoff of valuable water resources and thus contribute to a more sustainable urban water cycle. Furthermore, an increase in green spaces has a plethora of health benefits, from decreases in stress symptoms, type 2 diabetes, and cardiovascular diseases to improved mental health (White et al. 2013). However, with all the benefits, there are also challenges such as the elaborate maintenance and construction requirements. This chapter explores these closer and incorporates expertise gathered through personal communication with Professor Dr. Helmut Kroiss, civil engineer and professor emeritus at the Vienna University of Technology.

4.3.1. Management and Maintenance

The management and maintenance of a sponge city are quite extensive. Both have to be taken care of thoroughly in order to preserve efficiency and even functionality. The basic maintenance tasks that have to be done regularly include litter cleanup, plant conservation, treatment of eroded soil, and desilting or removal of any debris, sediment, or waste. Other tasks that do not have to be done as systematically but depending on the season and precipitation frequency comprise checking for runoff and soil pollutants, conductivity, and drainage clogging. Major undertakings in cases of surface collapses, structural damages, or facility failures may also be needed after experiencing critical strains or disasters (Yin et al. 2021, 14). Studies have shown that the efficiency of SCC facilities is affected by the time they are in operation but that they can be substantively improved with regular maintenance. This is however complicated by the great heterogeneity of various sponge city facilities and great spatial and temporary differences. That means that appliances and methods from one city cannot be easily applied to others which significantly raises the costs as well. The fact that research on the operation of these facilities is based on existing environmental and climatic conditions which can be decidedly different from those in the future poses another challenge. Approaches to tackle these difficulties are heavily data-based and include smart control, information sharing, precise management, and decision-making. These are still in its early stages of development and efficient management tactics still have to be found (Yin et al. 2021, 12-15). For now, the lack of training, guidance, sufficient data, and adequate skills are all contributing to the difficulty of maintaining innovative sponge city technologies (Nguyen et al. 2019, 157). While the maintenance costs of sponge cities are higher than those of conventional systems, they are still feasible. In contrast, the economic costs of the construction are substantially higher, especially for green roofs, artificial ponds, and wetlands (Chan et al. 2018, 776).

4.3.2. Administrative Barriers

National guidelines on the Sponge City Concept are kept rather general, containing best practices and Low Impact Development measures. When it comes to local implementation, the situation is similar to other environmental management practices and very fragmented.

Technical issues and detailed guidelines are meant to be left to provincial administrations. Considering the previous sections, such an approach seems logical as the success of a sponge city depends on customized adjustments for individual spatial and climatic circumstances. However, capacity and expertise are often non-existent or too limited in some areas to meet the necessary requirements (Nguyen et al. 2019, 157). A lack of inter-connectedness is inherent in China's administrative landscape. It prevents cooperation between various agencies, and the participation of multiple stakeholders and thus, the development of such a sophisticated system envisioned by the Sponge City Concept (Nguyen et al. 2019, 158).

4.3.3. Public Awareness

The factor of public awareness and acceptance is often overlooked and neglected. However, it is decisive not only for the adoption of the Sponge City but also in case of emergency, for example when floods like the one in Zhengzhou or the one in Germany's NRW occur. The issue of public awareness also affects the financing of the projects. Public funding from the central government is not limitless. Public-private partnerships are vital for long-term financing. For that, the Chinese government has to improve the public's perception, education, and access to information on the SCC. Encouraging more public participation plays an important role (Nguyen et al. 2019, 158-159).

4.3.4. Finances

Supporting the sponge city pilot projects over a three-year period requires financial investments of 1.2 to 1.8 billion RMB (Renminbi). Implementing the required appliances entails a large amount of reconstruction as old structures have to be transformed or removed before the space can be renovated. Taking these factors into account, a cost estimation of transforming one square kilometer from a traditional urban area to one that fits the sponge city guidelines amounts to 0.1 to 0.15 billion RMB (Chan et al. 2018, 775). Despite several low-cost methods and materials that can be used in a sponge city, a large-scale implementation of the Sponge City Concept requires enormous initial investments in capital costs. Revenues are unable to match such high costs, discouraging private investors. Nguyen et al. point out the lack of research on the lack of solid cost-benefit analyses of sponge cities

(2019, 158-159). Practitioners also consider this as a key factor, although it's challenging to quantify the environmental, ecological, and social benefits as well as such costs that can be saved by preventing flood damage. Research on how to include the values of ecosystem services in calculations can greatly contribute to sound decision-making not only in the case of the sponge cities.

4.4. Applications Outside China: Vienna

In Vienna's Seestadt, a part of the 22nd municipal district, rainwater management based on the Sponge City Concept was first implemented in the years between 2016 and 2023. Through this project, a permeable water retention layer, composed of coarse gravel blended with humus, is installed beneath the entire road surface. A separated drainage system allows stormwater that is heavily loaded with chloride pollution to flow into the sewer system. The remaining runoff that is not contaminated seeps through the gravel layer which stores the water for the irrigation of trees and plants beside the roads. The project is part of Vienna's attempt to establish more smart city infrastructure. Further projects in Vienna's Sponge City include the greening and planting of trees on Zollergasse Street and the construction of water retention materials below the ground of the Johann-Nepomuk-Vogl square (Holzmüller 2016). While the projects' aims are not to establish a full-fledged sponge city, the usage of the terminology of the Sponge City Concept ("Schwammstadt-Prinzip") and typical SCC facilities such as bioretention and permeable pavement is a testimony to the global application of an idea originating in China.

Experts point out that the installation of only a few appliances that are pretty, green, relatively cost-effective, and receive fast social acceptance is not enough to construct a sponge city capable of withstanding proper floods. Complex and cost-intensive drainage systems that are hidden underground are key elements in a sponge city but are often overlooked and due to their invisibility and high costs a challenge that requires extensive expertise but also political willingness. Regarding Vienna, it is also important to note that sponge city elements can be beneficial to ameliorate lighter floods originating from the smaller Wien River but not from rivers on the scale of the Danube (Kroiss 2024).

5. Case Study of Zhengzhou City

5.1. Overview: Zhengzhou

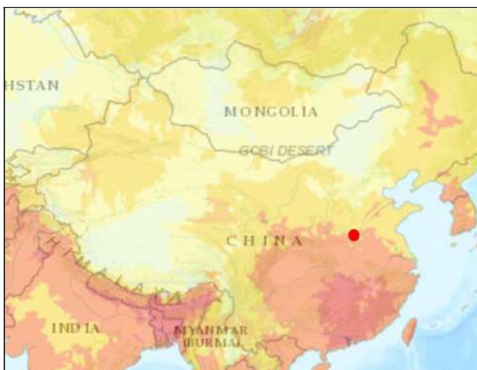
Zhengzhou is the capital of China's centrally located Henan Province. Home to nearly 100 million people living in an area of 167.000 square kilometers, Henan borders the provinces of Shandong, Anhui, Hubei, Shaanxi, Shanxi, and Hebei. In the year 2000, Henan had an urbanized, built-up area of about 1074 square kilometers. That area increased to 2944 square kilometers in 2019, expanding impervious surfaces tiple-fold. Henan Province is mountainous in the west and southwest, contributing to the entrance of water vapor to inland regions. The four major basins of the Haihe River, the Yellow River, the Huaihe River, and the Yangtze River have facilitated the development of civilization in its fertile areas but have been responsible for floods as well. Henan's continental monsoon climate affords the region an annual precipitation of around 600mm. The summer months of June, July, and August are the rainiest. In those months occurrences of floods are common. (Guo et al. 2023, 2). The worst flood disaster occurred in 1975, affecting both provinces of Henan and Anhui in the Southeast of Henan. It was the consequence of heavy rainfall, bringing down 198,5 mm of precipitation at the beginning of August combined with the frantic development of dams and reservoirs for irrigation and hydroelectricity generation during the period of the Great Leap Forward. After the worst storm that was at that time recorded, Henan's Banqiao Dam failed to hold against the extraordinary water masses, crashing down and killing approximately 171.000 people in the villages downstream (Guo et al. 2023, 4; Fish 2013). In those decades, the region saw the insufficient construction of many dams which now warrant urgent renovation, lest they threaten to succumb to earthquakes or new water extremes. Lacking manpower and financial resources, however, the governments fail to fulfill their responsibilities despite political willingness to do so (Wang 2011).

Henan's capital Zhengzhou is a key point within China's Belt and Road Initiative that is ambitiously connecting the Eurasian landmass. Zhengzhou is the largest city as well as a major transportation and railway hub in Henan (Shepard 2016). The municipality of Zhengzhou borders the Yellow River in its North and has the smaller Jinshui River flowing through its center (Dong et al. 2022, 2). The total is 7567 square kilometers, and the built-up area is 1384 square kilometers. There are just below 13 million people living in Zhengzhou (Zhengzhou Municipal People's Government 2023).

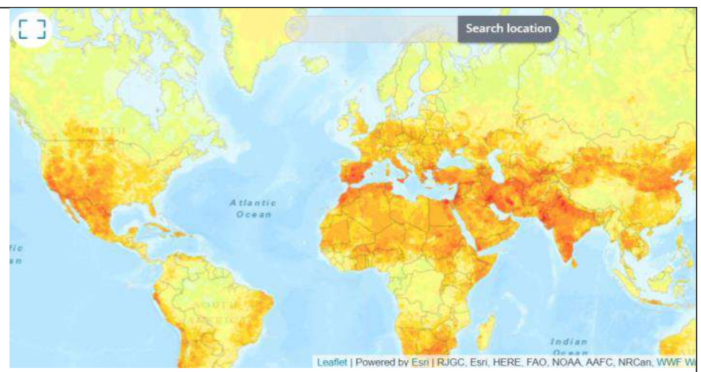
5.2. Analysis of Zhengzhou's Water Risk

Using the WWF Water Risk Filter, various water-related risks can be explored. The risks are categorized into physical risks, regulatory risks, and reputational risks, each containing four parameters. In total, twelve specific risks can be evaluated. For the purposes of this paper, the focus is set on physical risks. As for the regulatory risks, including the parameters Enabling Environment, Institutions & Governance, Management Instruments, and Infrastructure & Finance, the associated risks range across China from very low risks to medium risks for the parameter on institutions and governance. Reputational risks include Cultural Importance, Biodiversity Importance, Media Scrutiny, and Conflict. As for the first parameter, the risk is indicated as very high – meaning that water plays an important cultural role – across all of China. There is a middle risk for media scrutiny, indicating that stakeholders and local communities are not particularly aware but also not entirely ignorant about water-related issues. In the context of China, this can be attributed to limited freedom of the press, thus media coverage on companies affecting water risks by, for example, polluting streams or building insufficient dams, etc., is low but not non-existent. The conflict risk indicates historical and potential future political conflicts stemming from disputes over scarce water supplies and is high in China's South and West, in the areas around Hongkong and Xinjiang. In the rest of China, the risks vary from low, to medium, to high in a few areas. The biodiversity importance risks are very high in Hongkong, and generally high in all of China's Southeast excluding the coastal area of Fujian, medium in China's Northeast and Central Provinces such as Shandong, Henan, and Shaanxi as well as in China's Southwestern Sichuan Province. The biodiversity risks are rather low or low in China's Chongqing, Guizhou, and parts of the Hubei and Hunan Provinces. The parameter indicates functioning and diverse ecosystems. The higher the risk, the healthier the ecosystem, and the riskier a company's or any agency's operations' disturbances in these areas (WWF Water Risk Filter 2021). Due to the too-general availability of data or scenarios and also their relative irrelevance for the present study on the physical water extremes, the regulatory and reputational risks will be neglected.

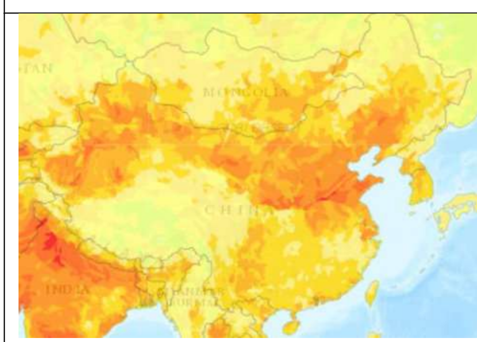
The Water Risk Filter's physical risks include water scarcity, flooding, water quality, and ecosystem services status risks. While the aforementioned risks are also of high importance for sustainable urban water and flood management, the data from the physical risk parameters is the most valuable and precise. Other social factors will be further discussed below. The water scarcity risk is indicated as highest in China's North, corresponding with historical circumstances, and is calculated as the amount of water consumed or needed compared to the amount of water that is available in the respective region. Interestingly, the Yellow River basin just above Zhengzhou is indicated as having a very high water scarcity risk, the highest within China's Northeast above the Yellow River. The water quality risk is medium-high, high, or very high in nearly all of China's East above the Yangtze River while the ecosystem services status is under highest risk in certain Southern regions but also in some smaller areas in other regions (WWF Water Risk Filter 2021).



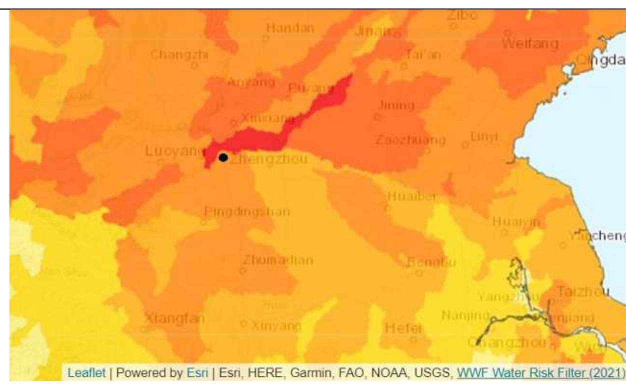
a) Flooding Risk



b) Global Physical Water Risks



c) Physical Water Risks in China



d) Physical Water Risks in Zhengzhou

Figure 4: Flooding Risk in Zhengzhou, Water Risks Globally and in China (borrowed from WWF *Water Risk Filter 2021)*

The flooding risk is naturally highest in coastal regions, prone to monsoonal rainstorms, and medium in the rest of China's central and southeastern regions, including Zhengzhou marked by a red dot in Fig. 4a.

Aggregating the four parameters of the physical water risks in the WWF Water Risk Filter's maps and thus including a region's risks of having too little, too much, not clean enough, or unfit for the surrounding ecosystem (for example due to excessive management of rivers), a more comprehensive picture can be achieved. Globally, the water risks, including those of draughts and floods, are highest in the subtropical regions north of the equator as shown in Figure 4b. In China, the risks are greater in the North, accounting for the common occurrence of draughts. The physical water risks in China are shown in Figure 4c. Zooming closer into China in Figure 4d, Henan's area around Zhengzhou, especially the basin between the Weihai River and the Yellow River turns into the area with the darkest color, indicating the highest water risk in China being located in that area, accounting for the great flooding risk. Zhengzhou is an area where several risk factors of urbanization and natural factors are compounding each other.

With higher mountainous regions in the west and several smaller and larger rivers crossing from the northwest to the southeast, the city of Zhengzhou which is home to nearly twelve million inhabitants is built into a floodplain. The rapid rate of urbanization has led to imprudent choices of constructions on various topographical areas, making those lying lower especially vulnerable. The mountains in the South are conducive to allowing water vapor into inland regions where urbanized areas are already suffering from increased condensation and water vapor due to the urban heat island effect. Merged together, urban areas become storm centers. Additionally, the impervious surfaces lying above hardened land deter water infiltration, The low water infiltration capacity enhances the speed of runoff which is further aggravated due to different topographical levels. It also deters from rainwater reaching underground aquifers to replenish water sources. Especially fatal are also proving the insufficient drainage systems and pipes, next to the large number of underground infrastructures (Li et al. 2023). Examples of the latter include tunnels and metro stations where tragedies unfolded during the flood event in 2021. Noteworthy is the fact that the company responsible for the Zhengzhou metro changed the design of Line 5, where people eventually lost their lives, without permission, resulting in an area lower than intended and becoming a flood pond (Guo et al. 2023, 11). Consequently, Zhengzhou is located in an area where human factors aggravated the natural risks significantly with the consequence of turning into one of the riskiest areas in China in terms of water extremes. Therefore, the city being enrolled as a sponge city pilot is not only useful in terms of research and development but potentially necessary for survival.

5.3. Zhengzhou's Sponge City and the 2021 Flood

Zhengzhou began to implement sponge city infrastructures in 2016. Aiming to cover 1945 square kilometers, the government's project represents an investment of over 50 billion RMB, which is more than 6 and a half billion euros. The Sponge City Concept in Zhengzhou was one of the most ambitious and actually turned out to be a success, visibly lowering the number of points that were prone to waterlogging by 77 percent. By removing 125 such risky points, the city became more resilient in terms of dealing with common rainfall patterns (Guo et al. 2023, 11; Stanway 2023). Since the start of the project until July 2021, 380 million tons of water have been recycled, proofing the SCC's effectiveness (Global Times 2021). Zhengzhou has strengthened riverbanks and built flood storage and detention areas as well as drainage facilities. The city planned 191 floodways which are designed to direct runoffs into appropriate drainage areas without experiencing damages. Besides those security measures, a new water supply network incorporating unconventional water resources and optimizing water allocation had been built, including rainwater reservoirs and wastewater treatment facilities. One project also envisaged water flow revitalization, allowing parts of the original floodplain region to be reclaimed by or at least brought into more balance with nature (Shang et al. 2023, 7). Despite these promising steps and statistics, experts still criticize the implementation of the sponge city concept in Zhengzhou. In an article by Radio France Internationale, they allege that the government primarily focused on beautifying the city instead of flood proofing it (Yang 2021).

In July 2021, thick, saturated clouds gathered around northern Henan. Coming from the Taihang Mountains, precipitation started to scatter across the province and centered around Zhengzhou and Xinxiang. The period in which Zhengzhou experienced the extreme rainfalls lasted about a week. From July 17 to July 23, Henan battled with floods that broke the record of 1975. In the three days from the 17th until the 20th, Zhengzhou received 617.1mm of rain which approaches the yearly average. In such a short period, the magnitude usually distributed among more than 300 days came crashing down in a fraction of that time. The worst point was reached on July 20th, 2021. On that day, the hourly rainfall between 16:00 and 17:00 reached an intensity of 201.9mm which broke the record for the entire Chinese mainland. A third of annual precipitation within an hour presented a magnitude neither the population nor the sponge city constructions were prepared for. After having been in operation for five years, they have proven to be effective against normal rainfall patterns, but the storms causing the Zhengzhou 20.7 floods exceeded everything the sponge city facilities and the remaining permeable surfaces around and in Zhengzhou could hold. The only river that was close to the epicenter of the storms in Zhengzhou, Jinshui River, was not overflowing at that time, thus, the causes of the floods can be safely attributed to the unexpected heavy rainfalls (Guo et al. 2023, 4; Dong et al. 2022, 3).

The center of Zhengzhou was hit hardest, with main roads such as Hanghai Road, Songshan Road, and Jingguang Road hit the hardest. The Jingguang Road Tunnel (JRT) is an 1835m long tunnel where about 1360m are located underground. The tunnel presents an exceptional tragedy. The smooth, low-lying surfaces and slopes of the roads allowed the storm run-off to reach speeds that overwhelmed the people and slowed down their capacity to flee the tunnel tremendously. The extraordinary water masses falling into Zhengzhou between 16:00 and 17:00 reached the tunnel at around 16:30 when the water started flowing into the tunnel. The water initially rose slowly, but shortly after, at 17:00 the water depth started to rise exponentially, engulfing the vehicles in the tunnel within ten minutes and the entire tunnel within an hour under a water depth of six meters. Studies showed that at 16:50, the evacuation time from the middle of the tunnel equalled twenty minutes, accounting for the slowing down effect of the water masses already in the tunnel, which meant that some had no chance at reaching the exits before the tunnel's was entirely flooded (Guo et al. 2023, 10; Dong et al. 2022, 7-11). A similar tragedy ensued one day before. On the 19th of July at 17:00, people riding the Metro Line 5 were stranded after the subway station was flooded, and merely two hours later, A chest-high water depth accumulated. Emergency responses of both the public and the relevant departments were so slow that valuable time was lost before people were assisted out of the subway stations five hours after they were flooded. For some, it was too late (Guo et al. 2023, 9-10).

The disaster claimed the lives of 380 people, including 39 who drowned in particularly hazardous areas like basements, tunnels, garages, and subways. Six of them lost their lives in the Jingguang Road Tunnel, and fourteen in the Metro Line 5 subway station. Despite the high number of casualties, research done after the event evaluated the flood risk for people and vehicles during the Zhengzhou Flood. It has shown that the overall risk was low for pedestrians. People that found themselves on the main affected roads where the flow velocity reached overwhelming speeds, or in underground areas were the most vulnerable to dangers. Generally, vehicles had a higher risk than people and should have been immediately abandoned to prevent damage to drivers and passengers (Dong et al. 2022, 3; 9).

The record-breaking Zhengzhou flood took a high number of lives. Considering the limited areas of high risk such as underground facilities and the three main roads, the high number bears questions as to the causes of such a tragedy. Blaming the ineffectiveness of the Sponge City Concept might be undue as the innovative infrastructures have shown improvements to the urban water cycle in Zhengzhou. Furthermore, the 7.20 floods exceeded the expectations Zhengzhou was prepared for, despite Henan province's experience with the 1975 floods. A disaster such as that with an extreme precipitation load of nearly a year within a few days is something that surpasses the capabilities envisioned for the Sponge City Concept. While the sponge city improves common rainwater infiltration rates, contributing to water resource sustainability and, an event such as the 7.20 requires another sort of crisis management.

The causes of the many casualties during the Zhengzhou floods cannot only be attributed to nature and lacking drainage infrastructure. In fact, the lack of preparedness of an inland region whose current generation has not seen floods of that magnitude has equally contributed to the disastrous course of events (Guo et al. 2023, 2). A study on floods in Pakistan and community resilience against floods has shown that a community's perception of potential risk is decisive. The risk perception is naturally higher in those living in regions where floods are common. Experience in floods leads to higher risk perceptions and thus flood risk preparedness. Furthermore, the research has shown that the punctual and timely distribution of weather forecast information was positively linked to increased awareness (Waseem and Rana 2023, 366). In Zhengzhou, meteorologists were able to accurately predict the upcoming precipitation events as soon as it was technically possible to sense them. Before the city was flooded by the heavy rainfall, the meteorological observatory disseminated seven red alerts, calling for meetings, school, and work to be canceled. The municipal government and the Zhengzhou citizens did not take the warnings seriously. The Jingguang Road Tunnel is always busy during rush hours, and despite the calls to be cautious, the tunnel was filled with business as usual on July 20th. The majority still traveled by metro and used underground facilities such as the JRT tunnel but the government missed the right time for them, which put the population at extraordinary risk (Guo et al. 2023, 8; Dong et al. 2022, 3).

The public did not adequately listen to forecasts and the administration was not prepared to act during the catastrophe. Both parties acted too slowly. Allowing the disaster to unfold, the reactions of the society speak for the lack of crisis awareness. The Zhengzhou flood highlights the importance of regions and governments having adequate disaster action plans despite not being prone to them usually. In times of human-induced climate change, the human response must be quicker. Besides a population's preparedness and awareness, timely communication and trust between government agencies, weather forecasts, and the public must be clear, reliable, and effective.

The findings from the Zhengzhou flood are coherent with some conclusions that can be drawn from the floods in North Rhine-Westphalia in Western Germany. The catastrophe that occurred on July 14th and 15th in Germany and Belgium was preceded by warnings as early as July 11th. Dissemination of the warnings happened through conventional but also unconventional means such as social media, with the latter reaching more than a third of the population (Deutsches Komitee Katastrophenvorsorge 2024, 13; 80-82). Still, many found themselves trapped within especially risky spaces, such as garages, underground parking lots, and cellars. Flood catastrophes in areas that are not used to them and therefore lack the experience to respond adequately have more disastrous outcomes than necessary. With the compounded effects of climate change and urbanization, communities must be trained to cope with circumstances outside their expectations. Drills for fires, earthquakes, or floods should be normalized, and channels through which disaster communication is happening must ensure that the public has trust in them and takes alerts seriously.

6. Discussion

This thesis is a comprehensive study of the Chinese Sponge City Concept. For that, the background and the needs for such a concept were first elaborated. For as long as settlements were established close to water, a sound flood management system had to go along with them. With urbanization taking off around the world, not only the urban flood management had to be updated but also the whole perspective on how we look at the urban water cycle. Water, including wastewater and stormwater, are valuable resources that get lost in heavily built-up areas of cities. Within the last decades, the need to transform the urban water cycle and urban food management into a more sustainable, circular economy and a resilient tool against climate change and resulting extreme weather phenomena developed globally. The Sponge City Concept is a direct response to that need. With a plethora of both simple and more sophisticated components, the SCC aims to provide a comprehensive plan to bring cities back into more balance with nature. Through more permeable surfaces, infrastructures such as retention ponds as well as riverbank reinforcements, the concept is designed to make cities more resilient against the forces of nature's water extremes. The permeable surfaces are supposed to allow stormwater to seep into the ground more quickly, protecting urban areas from rainwater runoff. Storage facilities are concurrently saving this water for times of need. Salvaging the rare resource, the water tanks should ameliorate irrigation needs during droughts. A heavy investment of more than fifty billion yuan flowed into such facilities in Zhengzhou. Essentially a floodplain, the city is located close to mountains and river basins. A few years after the roll-out of the Zhengzhou sponge city plans in 2016, the pleasant results have shown that waterlogging points were successfully removed, and large amounts of water had been saved. But in 2021, a record-breaking flood occurred after the capital of China's Henan Province saw a year's worth of rain within three days coming down.

Reports after the event were quick to ask what went wrong and whether China's "smart city project" failed in the wake of the disaster (Che and Borak 2021). With both flood and water management becoming highly important across the globe and especially in areas that struggling to cope with above-average precipitation, the study of the Sponge City Concept and the Zhengzhou flood is crucial for current climate mitigation and climate adaptation efforts. Therefore, this thesis aims to answer the question: What are the decisive factors for the successful implementation of a large-scale infrastructure project like the sponge cities? By seeking to find out what went wrong in the Zhengzhou implementation of the sponge city, conclusions on what could be improved and made better in other cities could be made.

6.1. Findings

Research on flood management in Zhengzhou and North Rhine-Westphalia (NRW), along with expert insights, underscores the decisive role of effective alarm systems in conjunction with the Sponge City Concept (SCC). The SCC is a promising initiative, integrating many findings and innovations from history as well as other concepts like Low Impact Development (LID) and Sustainable Drainage Systems. Even if it is still in its early stages, the Sponge City Concept encourages Chinese cities to adopt greener practices and significantly contributes to water conservation. Despite its high financial costs, technical complexity, and need to plan systematically, investing in the SCC – or other approaches that help cities become more resilient – is crucial in times of climate change. To answer the research question: Decisive factors for the successful implementation of such a large-scale infrastructure project are the integration of many disciplines as well as complementary developments in urban climate adaptation and disaster management.

6.2. Implications

Learning from each other, fostering cooperation, and finding better implementation methods are essential steps forward. The success of the SCC in China has inspired other countries, including Austria, to adopt not only the methods but also the terminology associated with the Sponge City Concept. It is important to recognize that SCC is not a magic cure for urban water problems. It is, however, a comprehensive, sustainable approach that should be an integral part of city planning. The complexity of SCC design necessitates the collaboration of various experts, including hydrologists, biologists, urban planners, and sociologists.

Additionally, an effective warning system, public awareness building, and disaster preparedness sensitization, for example through regular catastrophe preparation drills, would have to come alongside sound SCC planning. Adequate civil crisis preparedness among communities remains critical because climate change continues to present unexpected challenges. Some of them with a capacity that goes beyond even the best sponge city could handle.

Here, it is also important to acknowledge the limitations of the SCC and similar urban drainage and development approaches. Even when perfectly implemented, they have their constraints. For instance, the UK restricts new constructions in areas already at risk of flooding despite implementing new sustainable drainage systems (Chan et al., 2018, p. 777). Methodologies such as the WWF Water Risk Filter and similar tools can help gain a comprehensive picture of certain regions and their respective water and flood risks. Findings from these should influence decisions on where new developments should take place or whether alternative locations should be preferably chosen.

Historical flood management practices, the specifics of the Sponge City Concept, and the timeline of the 7.20 flood in Zhengzhou demonstrate that there is no one-size-fits-all solution. The occurrence of a record-breaking flood five years after SCC constructions began should not be seen as a failure of the concept. Instead, it highlights that the SCC should be just one component of the broader urban water cycle rather than the central element of urban flood management or even disaster prevention. While it can play a complementary role, it cannot replace robust disaster management and an effective, widespread, and trusted alarm system.

6.3. Limitations

Determining the exact actions taken by Chinese government agencies and officials during the 20.7 flood and identifying the decision-makers involved is challenging. There is a limited availability of information on the exact processes within such agencies in China. Therefore, much of the information used in this thesis is based on the literature of other studies, media reports, and certain publications from government websites.

Tools like the WWF Water Risk Filter are using a plethora of quantitative data platforms which makes it particularly useful in estimating certain regions' water and flood risks. Using such methodologies can be very helpful in determining where Sponge City Concept constructions might be most effective. However, many factors of technical, environmental, or social origins interplay the complex systems of a city. Therefore, using such a tool helps to gain a first impression. The exact and exhaustive modeling of cities' flood risks and a Sponge City Concept's potential impact on them would breach the scope of this work.

6.4. Future Research

For a deeper understanding of the potentials and implications of the Sponge City Concept, future research on cost-benefit analyses might prove to be very useful. It is crucial to develop methods for quantifying environmental and social costs, which need to be considered in decision-making processes. These would help not only the development and funding possibilities of the Sponge City Concept but also in many environmental management projects. Exploring ways to finance SCC initiatives, methods for maintaining individual components of bioretention facilities, and tactics to enhance public awareness are important areas for further research.

7. Conclusion

Within the last decades, global warming has increasingly taken a toll on our climate. Climate change has exacerbated extreme weather phenomena, such as droughts and floods. Both have become more common and more extreme, posing challenges, especially to regions that have not regularly struggled with these issues. Their resulting lack of preparedness has put these regions at risk.

With rising urbanization rates globally, the share of the world's population residing in cities and urban areas has increased significantly. The need for living spaces has also caused a massive expansion of built-up areas and sealed soils, transforming them into impermeable surfaces. The aftermath of climate change combined with rapid urbanization has caused massive catastrophes that have caused loss of lives and property. Countries such as Pakistan, Bangladesh, India, and certain regions in Kazakhstan are not new to flooding events but are also seeing an increase in frequency and intensity. Within the last few years, countries such as Germany, Belgium, and Austria that are not used to such weather extremes have also experienced unprecedented floods and draughts, both have underscored their unpreparedness and the urgent need to rethink their climate resilience and disaster management strategies. Cities are confronted with an urgent need to improve their management of water resources, including those originating as stormwater. A new urban, sustainable water cycle requires the removal of impervious surfaces that enhance the accumulation of stormwater runoff, accelerating flood development, while preventing the water's infiltration of the ground to replenish groundwater aquifers.

One answer to these pressing needs is the Chinese Sponge City Concept. Directly translated as *Schwammstadt* into German, the comprehensive water infrastructure concept for cities was introduced in 2013 by the current Chinese President Xi Jinping. The concept is meant to not only mitigate the impacts of heavy rainfalls but also those of draughts. Just like a sponge soaks up water and stores it until it is released, cities equipped with sufficient sponge city infrastructure are meant to absorb stormwater that can be then again used for irrigation. Within the last years, research on the Sponge City Concept in general as well as specific studies on individual components, such as grass swales, green roofs, or permeable pavements have taken off, looking at the concept from technical, managerial, but also social perspectives.

The Sponge City Concept is definitely not a simple theory. It is a complex system including expertise and knowledge from many disciplines. The Chinese Sponge City Concept builds onto urban flood and water management strategies already in use in other countries, such as the Low Impact Development strategy implemented in the US, New Zealand, Canada, and Europe or the Water Sensitive Urban Design and the Sustainable Drainage Systems. Taking elements of these, the Sponge City Concept aims to comprehensively transform the way the valuable resource of water is treated in cities. Putting the concept as the ecological core of the urban water system, the Chinese government set out to test the large-scale infrastructure project through 30 pilot cities, including Shanghai, Beijing, and Zhengzhou.

Through components, such as bioretention facilities that allow water infiltration through specially engineered green spaces, or green roof systems that are using otherwise empty space to harvest and purify rainwater. Rain barrels, grass swales, permeable pavements, and urban wetlands are vital parts that support a sophisticated drainage system in a comprehensive sponge city that serves to drain superfluous water or retain it for other purposes. The complex nature of the individual components and the system comprise certain challenges. The acquisition of sufficient finances, expertise for maintenance, and social factors such as adequate legislation and public awareness are vital for the successful execution of the Sponge City Concept. However, the many benefits should make it worthwhile to tackle the challenges, including progress in biodiversity protection and better living standards due to the double benefit of additional green spaces also employable as recreation zones.

The capital of China's inland province Henan began to implement large-scale infrastructural changes according to the Sponge City Concept in 2016. Zhengzhou is located close to the Yellow River basin and has enthusiastically adopted the SCC. As one of the most affected areas by water risks, including droughts and floods, in China, Zhengzhou is a suitable pilot city for the development of the Sponge City Concept. Within five years, the city has removed 125 common waterlogging points and recycled 380 million tons of water, showing improvements in its capacity to deal with common rainfalls. But when in July 2021 a record-breaking flood occurred, with the amount equalling a year's average precipitation coming down within three days, the water masses surpassed Zhengzhou's Sponge City's capacities.

The natural catastrophe was aggravated by the lack of preparedness of the administration and the public. Disregarding multiple warnings from meteorologists, people still chose to travel to work and school using high-risk options such as the metro or an underground tunnel. Both have been closed too late and people found themselves trapped before being deterred to enter such areas. The Metro Line 5 and the Jingguang Tunnel were tragically flooded within a few hours during the peak rainfalls in the late afternoon of July 20th, 2021. This was not an isolated case. During the floods in North Rhine-Westphalia in July 2021, warnings, and safety measures such as avoiding underground spaces were not taken seriously on time. Thus, questions inquiring whether Zhengzhou's Sponge City Concept has failed might have been undue but rather directed at why the fatalities happened despite the SCC working as planned. Both cases show that despite best intentions and implemented sponge city infrastructures, climate change-induced catastrophes can still surpass expectations and capacities. The leading conclusion of this thesis is therefore that the Sponge City Concept can only be one part of an urban flood management system. Social factors are just as important as technical factors. Communities must be better prepared, and their risk awareness enhanced through targeted public education.

Climate mitigation and adaptation strategies are becoming ever more essential for the decision-making process across various disciplines. The Sponge City Concept addresses both. However, the recent Zhengzhou flood has shown that the concept alone is not enough. With climate change showing increasingly detrimental effects, such extreme weather events are becoming more frequent. Planning sponge cities for worst-case scenarios such as the 20.7 flood might be too costly or inadequate for typical conditions therefore it is crucial to build greater awareness and disaster resilience to compensate for the limitations of sponge cities. In the future, the Sponge City Concept can play an important role in maintaining a sustainable urban water cycle. Simultaneously, cities must become more resilient, and communities better prepared for emergencies.

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