Study of Sponge Cities and Low-Impact Development (LID) in Urban Water Management

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Abstract. In response to climate change, irregular rainfall, and rising sea levels, sponge cities and low-impact development (LID) have become emerging water management approaches that use green infrastructure and permeable materials to reduce runoff. However, as these concepts are new, their effectiveness and future feasibility remain controversial. This paper studies the design flaw in traditional urban water management, which leads to more frequent and severe floods during heavier rain seasons or in near-shore cities. To combat the design flaws, LID, and sponge cities are beneficial and cost-effective solutions to this problem. Through the renewal and construction of LID facilities and sponge cities, the employment rate in the local area is boosted due to the demand for workers, and the technology R&D is also encouraged to pour more resources toward technological advancements such as permeable concrete. Furthermore, LID and sponge cities also effectively retain the water, directly reducing the pressure for water supply in the local area as well. Though LID and sponge cities are a solution, the public media and education system rarely promote this knowledge, which inhibits the public attention and demand for these techniques. Another limitation is that the techniques are only cost-effective with high water exposure, either through rain or ocean, thus inland cities and drier cities have less incentive to implement this infrastructure, but it will also mean they will be vulnerable should their weather condition expose heavy water conditions through rainfall.

Keywords: Low impact development (LID); Sponge cities; Urban development; Stormwater management

1 Introduction

Global climate change introduces many unfamiliar challenges to humanity's existing infrastructure through the increasingly volatile environment. Over 51% of the US population lives in a county with a stormwater management system that is likely to already to fail and is twice as likely to face flooding each of the following years [1]. The traditional flood risk estimate and flood management design are outdated and do not account for extreme weather conditions. Estimates suggest that over 17.7 million properties across the US are substantially at risk, where previously 1-in-100 rare storms will now

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occur on average every 20 years [1]. Given these pending disasters that could displace millions of lives out of their home, concrete and effective flood mitigation strategies must be conceived and applied.

Flood risks can be distinguished into five separate strategies: flood risk prevention, flood defense, flood risk mitigation, flood preparation and response, and flood recovery [2]. These strategies might not be used all at once to a particular city or sector, but rather which ever fits the best. Some applications of these strategies include levees or dikes around rivers for defence, Afforestation for prevention, early warning system for mitigation, emergency evacuation drills for preparation and response and finally dedicated rescue teams for flood recovery. However, with the increasingly unpredictable weather pattern, some strategies are falling behind in effectiveness and require new adjustments. One instance of heavy rainfall in central Europe led to flooding of the river that broke through the dikes and submerging many buildings in water [3]. Fortunately, flood warning and emergency response has been improving through the years. For example, a survey taken in Germany during the 2002 flood showed that the early warning system only reached 27% of households and 45% of companies, but in the 2013 flood, 95% of households and 97% of companies received the warning thanks to large investment and initiatives to improve the flood risk management. However, the number of companies that had an emergency plan in place only grew from 10% to 34% between the 2002 and 2013 flood, showing that there still needs growth [4].

All five of the strategies have their shortcomings and imperfections like the two examples discussed above. This paper will examine the predominant urban infrastructure designs implemented in the US and determine potential effective techniques in flood control that reduce urban vulnerability, improve water ecology, and boosting economy.

2 Traditional Flood Management Infrastructure

Flood management, also referred to as stormwater management in this paper, is closely linked to urbanization and the expansion of infrastructure in the United States. Beginning in the mid-20th century, the post war urbanization took place, where more and more people move from the sub urban areas to the cities. As the cities expand, more forests and vegetation are replaced by buildings, foundation, and concrete, commonly known as gray infrastructure. Soil and vegetation are the best way of water retention, holding water in place like a sponge, and the runoff will then slowly flow through the soil as subsurface flow [5]. However, with the soil now covered by impermeable layers of concrete, little water reaches the soil. As a result, the city has less capacity to hold the water, and all the entire city's runoff is directed towards the network of stormwater channels around the city. The drainage systems direct the water quickly away from the city towards nearby streams and rivers through stream channels. The stormwater channels are designed to be on a high level than the stream's water level to allow the water to flow naturally with gravity down into the stream, at the same time prevent back flow.

However, the effectiveness of this flood management strategy eventually may hit its limit, proven by the frequent flooding in coastal cities, riverine cities, flash flood zone (sudden heavy rainfall) cities, or hurricane prone cities. A flood may form when all the water received by the city is filtered rapidly towards the streams and rivers, causing the urban stream to rise more quickly. During a storm for example, the streams itself will rise in water level due to the rainfall, but at the same time, it also receives the water from the city. When the water level of stream reaches the same level as the channels, the channels will stop directing the water from the city and the entire system will simply start rising in water level until both the stream and city starts to flood.

After exploring the vulnerability of traditional urban water management, it is critical to develop resiliency to the current level of flooding, as well as the future challenges.

3 LID and Sponge City

One of many initiatives to reduce flood is the Low Impact Development (LID) facilities, which are already taking place in the US and Canada. Its design philosophy is to reduce the stormwater management cost through incorporating the natural features around the property or site, minimize the hydrological impact, improve water quality, conservation of water, and manage water balance [6].

Another technique thought to be an effective solution is the sponge city concept that is mainly sprouting in China. Spong cities are mainly implemented around coastal cities where flooding most likely occurs and use fully natural resources such as green spaces, parks, and forests to absorb the water to reduce flood.

As the previous sections have alluded to, both LID and sponge cities are a water management method, aimed to provide flood control, runoff retention as well as water supply. This section of the paper will examine the implementation of these techniques as an urban stormwater management strategy, and how it creates social and economic value and mitigates environmental impacts in addition to flood control, runoff retention performance, and water supply. Then, attempt to conclude if the implementation is economically viable for the benefits it provides.

3.1 Economic Benefits to Sponge Cities

Prior to answering the benefits brought by the implementation of sponge cities, the benefits during the development also cannot be ignored. Since sponge cities are modifying the existing infrastructure of an old city, the restructuring and technological advancement bring labor and urban development, which increases the urban economy. In the study by Ma et al, there is a positive correlation between infrastructure development and total factor productivity and a very high correlation between technological development and total factor productivity [7]. Total factor productivity in economics is the ratio of the input and the output, and given the high correlation between the two factors, restructuring the city, which implies technological growth, will provide economic development of the city by potentially providing greater GDP, higher employment rate, higher standard of living, more income and purchasing power, and more.

3.2 Ecological Benefits to Sponge Cities

There is another important factor that plays into the dynamics between sponge cities and economic growth: water ecology. As mentioned in the previous section, many cities face droughts and dwindling water supply, in addition to rapid urbanization's increased demand for water consumption and industrial use of water which take a toll on the local economy. Sponge City might seem like the solution to the problem with water resources, but in fact, they are constrained by each other. Sponge City, water resources, and economic development are tied together in a triangle of relationships. Between water resources and economics, if the water supply cannot meet the need for economic development, or the source is depleted, it cannot sustain a population. However, in turn, economic development can cause more effective use of water in consumption and industrial contexts through advanced technology by increasing investment, capital, and government subsidies. Water resources also constrain the development of sponge cities, where the demand for water will only increase with urbanization, thus if the water supply exceeds the limit, both water quality and quantity will decrease for the population [8]. This brings up the last dynamic between Sponge City and economic development, whereas discussed before, the development of Sponge City brings economic growth and in turn, economic growth supports Sponge City.

3.3 Economic and Ecological Relationship to Sponge City

The dynamics between the triad can be explored further by conducting three separate hypotheses: 1. Use of water resources has a positive impact on economic growth. 2. Sponge cities, and economic growth are influenced by each other. 3. the development of ecological water resources is an important support for, and constraint on, the development of sponge cities [8]. The results of the study prove the legitimacy of the relationship between the three variables. During the early stages of sponge city development, there is a negative impact on water resources, thus urbanization promotes water consumption. However, during the later stages, urbanization boosts water resource growth due to the surge effect on water consumption through population needs and industrial demand. Furthermore, the results of this study demonstrate that economic growth has a promotional effect on water consumption during the initial stages of development. In the specific scope of the study, northern Chinese cities did not have adequate water supply to satisfy the need for economic development, but as the growth continues, the feedback from the economy greatly enhances the water usage efficiency which leads to reducing water consumption, either balancing the consumption or decreasing. Moreover, the article showed that in the northern cities, the growth rate for water demand is unfavorable as its constraint is more than the support for the city, thus the speed of the construction will eventually slow down, and the construction of sponge city will be increasingly more difficult as more other sponge cities are built. This study reaches similar results with Sponge City and economic growth with the study Sponge City Construction and Urban Economic Sustainable Development: An Ecological Philosophical Perspective by Ma et al, but an addition which Zhou, Wenzhao, et al add to the previously discussed relation between sponge city and economic growth is that sponge city not only scales the urban industry but also modernizes the agriculture on the countryside outside city.

Another direct benefit that Sponge Cities contributes to the water is rethinking and reusing water in a different manner. As part of the program, sponge cities expand the area of green vegetation, which the improved ecology leads to several implications. For example, the collected rainwater can be used for irrigation, greening, road cleaning, and domestic use for residents [9]. This improved quality in ecology in the city causes reduced pollution in the river due to better usage [10]. Furthermore, sponge city also gives improved rainfall infiltration measures by directing towards replenishing the water supply or groundwater instead of causing accumulation and waterlogging, thus leading to better runoff control [7].

3.4 LID and Sponge City's Performance with Runoff Retention, Flood Mitigation, and Water Supply

LID is a “practical means by which cities can bring back aspects of natural hydrology that have been lost through urban infrastructure development, on both small and large scales” [11]. Though LID is mainly used in the US, but it is connected to sponge city in a way that sponge city is just a mass implementation of LID by introducing many green infrastructures into the city. Sponge cities are not cheap; thus, it is critical to evaluate their performance. Through the multitude of studies, it is proven that LID does indeed provide sufficient and significant runoff reduction as well as act as water quality enhancement.

In the performance review conducted by Chikhi et al., 2023, several methods of drainage in different LID sites are studied, namely bioretention or rain garden (RG), rain barrels (RBs), grass swales (GS), green roofs (GRs), ponds, and pervious pavement (PP). Although the runoff reduction rates are different across the sites, they all are reported to allow permeability, runoff volume reduction, stormwater volume reduction, peak outflow reduction, and delayed time to peak flow [12]. Furthermore, in the study done by Eckart et al., 2017 concluded that LID is more cost-effective than traditional stormwater management. Continuing with Chikhi et al., 2023 study, water quality was also assessed using pollutant removal rate with the techniques, and each method ranges from high 60% to high 70%, which is considerable. Adding on to this study, Cost-benefit analysis of green infrastructures on Community Stormwater Reduction and utilization: A case of Beijing, China study conducted by Liu et al., also determined that the average benefit per meter cubed of stormwater reduction given by the implementation of LID is ranged from 5.98 to 11.14 yuan, which proves that it is worth the economic cost to implement some sort of LID [13].

Mao et al., 2016 study Assessing the ecological benefits of aggregate lid-bmps through modeling is another strong candidate with its results for arguing that the LID-BMP is a cost-effective and efficient method to achieve runoff retention and flood mitigation. BMP simply refers to best management practices in the context of stormwater management. This study used the SUSTAIN modeling tool, or the System for Urban Stormwater Treatment and Analysis Integration, which is meant to evaluate the performance and cost of LID [14]. The study simulated 3 scenarios with different conditions:

pre-development, post-development, and LID-BMP scenario. The pre-development scenario is simply a simulation of the land as exactly as before the development of the city, thus including wetlands, forests, and vegetation, which has a high perviousness. Post-development scenario refers to after the city is built, but without previous consideration. Lastly, LID-BMP is post-development with LID-BMP implemented. The result for post-development shows that given the ignorance for preciousness, peak flow rate, and annual pollutant loads of COD, SS, TN, and TP all increased to varying degrees when compared to the pre-developed scenario, and the annual flow volume increased by 120%. In the LID-BMP scenario, when compared to the post-development scenario, the peak flow rate decreased by 15%, the annual flow rate decreased by 40%, and all pollutant load was reduced by at least 60%, with some decreasing even up to 78%. Given the result, the team further optimized the combination of LID methods and ultimately settled with the combination of rain barrel, green roof, bioretention, porous pavement, swale, and wet pond, multi-control LID-BMP, which was the most cost-effective solution to reach the control target. The total cost of implementation after optimization was 316 million yuan or approximately $44 million [14].

3.5 Potential Challenges and Issues with Adopting LID and Sponge City

While LID provides valuable performance and contribution to a city, there are still a copious number of challenges when implementing one. Since LID is still a relatively newer idea, it requires people to shift their thinking to truly implement it. However, administrators, developers, and some water experts might be hesitant to move away from the status quo when everything seems to be working fine. In addition, many cities' waters systems function without major outbreaks or deterioration, and thus do not receive as much attention in the media or politically, it is even more difficult to ask for a change [11]. Another problem is that education and information systems related to effective water management, especially as such information is often not communicated to communities. Thus, even if the community wants to know about it, it often doesn't know where to access it. Therefore, it is crucial to educate children and adults about the importance of water management, especially in the non-explicit aspect.

Another limitation for sponge cities is that while Chinese implementation proves it is an effective water management strategy, it does not mean it can be applied to every city due to the altering level of risk and challenge. Sponge cities are implemented in cities that face great demand for water management, which includes coastal cities and cities with great precipitation. For inland, drier cities, water management is less of a concern and would not justify spending tens of millions transforming the whole city. However, that would also mean if someday the climate changes such that the drier cities face water management problems, through changing precipitation or sea rising inland, they will be vulnerable to flooding and have no countermeasures. Since sponge city is just a mass adaptation of LID, it makes more sense to selectively enact LID on a small scale as it is more feasible, and cost-effective as cities with lower risk do not need the whole city being changed [11]. For now, without overcommitting resources for an uncertain danger, cities can put one foot forward first and hold until the future.

4 Conclusion

Overall, a sponge city is a new name for a collection of time-tested techniques used for urban stormwater management. These techniques focus on absorbing water through green and blue infrastructure through LID. This stands to not only improve management of stormwater, preventing floods and mitigating damage; but also, to improve water retention, and collect water for use by the city in their urban water distribution systems. Though the implementation of sponge cities as an official stance is sparse, a better way to consider sponge cities is by assessing a city's sponginess rating, and the resources and infrastructure that affect that. In developed areas, sponginess ratings trend lower, as impermeable surfaces erode natural areas, yet in developing countries, natural areas are far more common, thus their sponginess ratings trend higher.

Sponge City techniques have been proven significantly effective. Unfortunately, it is not often economically feasible to retrofit a city to incorporate these techniques, as there exists current gray infrastructure that functions in most non-extreme scenarios. Gray infrastructure is far more costly to construct and maintain, thus they exist as the status quo and are maintained through that. The most economically feasible option would be for future water management construction to utilize sponge city techniques, however, that would neglect existing water management problems and would be notably less effective. Sponge cities are effective, but only if they are instituted properly, in flood risk zones. The best course for future development to improve flood resilience would be the slow and steady replacement of gray impermeable infrastructure with more green and blue permeable infrastructure.

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