Analysis of urban waterlogging causes and LID techniques

Boyu Jiang

School of Physical science, Department of Earth System Science, University of California, Irvine, CA 92697, United States.

boyuj1@uci.edu

Abstract. Global climate has been changing a lot in the past decades. Also extreme weather is more frequent. It results that severe urban waterlogging events happened in more and more region around the world in resent years. It killed so much people and caused tremendous poverty damage on different countries. More attention was paid on causes of urban waterlogging by many researchers. Urban waterlogging is caused by two main factors, meteorological and geological factor and urbanization factors. This review firstly analyzes the factors caused urban waterlogging, which contains meteorological and geological factor and urbanization factor. For meteorological and geological factor, global climate change have been causing more extreme precipitation events. It becomes a great challenge for urban drainage system. Also, people ignored the state of underlying surface, river portion and water storage capacity in urbanization. Those factors caused surface infiltration reducing, runoff increasing and water storage capacity reduction. Therefore, it exacerbates urban waterlogging. In order to solve urban waterlogging, many researches figured out a variety of Low Impact Development techniques (LID). Those techniques were divided into two types: infiltration-based technique and retention-based technique. For the infiltration-based technique, it aims to help city recharging subsurface flow and groundwater. For the retention-based technique, it is an approach that retain rainwater to reduce outflow. Comparing to retention-based technique, infiltration-based technique requires more fund and combination of techniques, but it is more sustainable than retention-based technique. Moreover, the review believe the implementation of the combination with two techniques would solve urban waterlogging more effectively in future. However, there still are some challenges people need to overcome, which contains requirement of substantial funding and unknown costs of maintenance, lack of performance data, and lack of understanding and close cooperation. This review also expects to reduce loss and damage loss of urban waterlogging as far as possible and to achieve combination a variety of those techniques to solve urban waterlogging in future.

Keywords: Extreme rainfall; Urban waterlogging; Lower Impact Development technique.

1. Introduction

Heavy rainfall has been becoming a common phenomenon around world in the last few years. Extreme precipitation events usually cause urban waterlogging. And waterlogging in cities has become a major environmental issue, especially Severe urban waterlogging could cause tremendous poverty damage and injuries of citizens, so that has gained international attention. Severe urban waterlogging caused by heavy precipitation harms urban development. First, serious waterlogging could decrease large crop production. Therefore, there will be food shortage after the disaster. Furthermore, waterlogging could prompt infectious disease spreading. Moreover, serious urban waterlogging also kills citizens' lives and damage poverty. For instance, the Henan heavy precipitation and urban serious waterlogging happened in 2021, which killed more than 350 people and caused about 20 billion dollars poverty loss. And in the same time, there is a covid-19 breakout in Henan provincial capital.

As gaining more attention, researchers also figure out resolution of urban waterlogging called Low Impact Development, which is called sponge city as well. LID is the result of substantial practical experience and combination of a variety of particular rainwater management technologies [1]. LID is a rainwater management system based on the notion of imitating natural hydrological conditions and implementing rainfall control and usage utilizing the source control concept. After construction, the major goal is to retain or restore the former hydrological features of a development region. Water quality protection, groundwater replenishment, flood peak reduction, land conservation, runoff accumulation time reduction, river pollution avoidance, and pressure reduction on municipal pipe network infrastructure are examples of such approaches.

This article analyzes the main reason of urban waterlogging and introduces some specific implementation of low impact development. Firstly, this review analyzes causes of urban waterlogging, including geological and meteorological factor and urbanization factor, such as more frequent extreme rainfall, changing underlying surface condition with urbanization and urban heat and rain island effect. And this article introduces some specific implementations of LID. Those implementation were divide into two main types, infiltration-based technique and retention-based technique. For infiltration-based technique, this review focus on three techniques: swales, infiltration trenches and bioretention cells. For retention-based technique, this article concentrates on introducing constructed wetland and green roof.

2. Causes of urban waterlogging

2.1 meteorological and factor

Earth climate has changed a lot over decades. Meanwhile, more and more extreme weather, especially the extreme rainfall, happened around the world. As the earth warms, scientists predict these trends to continue. More water vapor may be held in warmer air. The capacity for water vapor in the air increases by around 7% for every degree of heat. More moisture in the atmosphere can lead to more intense precipitation episodes, which has been seen. Over most continents, the intensity and/or frequency of extreme daily rainfall has increased, and around 65 percent of regions with good data show positive trends in annual maximum precipitation extremes from 1951 to 1999 [2]. The short-duration extreme rainfall puts a huge amount of pressure on urban sewerage systems. So extreme rainfall is the one of the most important reason. There are some cases of extreme rainfall. For instance, in historic Ellicott City, Maryland, more than six inches of rain poured in two hours in July 2016, causing more than $22 million in damage [3]. Furthermore, another case in China, it happened in Henan province. After a severe rainstorm event of practically inconceivable intensity on July 20, at least 33 people have died and eight have gone missing in Zhengzhou, China. In the 24 hours ending at 21Z July 20, Zhengzhou, a megacity of more than 10 million people – and the world's largest manufacturing base for iPhones as well as a significant hub for food production and heavy industries - recorded an incredible 644.6 mm (25.38 inches) of rain. Its average annual precipitation (1981-2010 climatology) is only 640.9 mm, which is more than a year's worth of rain (25.24 inches) [4]. Earlier than Henan extreme rainfall events, an extreme rainfall events happened in western Germany and eastern Belgium. More than 200 people have perished in the flood, with at least 170 in Germany and 36 in Belgium, making it Europe's deadliest flood since 1985 and the tenth-deadliest flood in the last 100 years. Over 200 individuals are still missing, and the death toll is certain to rise [5].

2.2 Urbanization factor

2.2.1 State of the underlying surface changing

The expansion of impervious area, reduced surface infiltration and recharged groundwater, increased runoff, and increased peak flow, as well as increased peak flow in advance, were all results of urban development and building. With urbanization, the city's impervious surface area grows at a steady rate, but storage facilities such as huge paddy fields and fishponds shrink, resulting in a higher runoff coefficient. The ground's permeability makes it easier to direct rainfall penetration and generate subsurface runoff, resulting in a reduction in urban rainfall caused by water accumulation. Urbanization, on the other hand, lowers natural vegetation, modifies the surface composition, hardens the bedding surface, and reduces surface drainage. Because the rainfall was not properly drained, there was an increase in runoff and peak discharge [6, 7].

2.2.2 Occupied river portion and a reduction in water storage capacity

Natural and human causes interact to generate the river network, which is an important component of the regional water cycle. Since the reform and opening, the process of urbanization has accelerated by leaps and bounds, resulting in a highly-urbanized region of the river network structure that is simple and non-trunk river reduction. The natural geographical landscape has been altered by development and construction. The river flood section is occupied by a large number of unlawful constructions, exacerbating the river water atrophy and confining the river tributaries.

3. Techniques of Low Impact Development

LID methods are designed to conserve watersheds' natural hydrological behavior, such as transpiration, retention, and seepage, in order to mitigate the negative effects of increased water runoff caused by urbanization. LID methods, which are considered "near-nature" concepts, can help cities cope with the effects of climate change on flooding. Rain barrels, rain gardens, porous surfaces, infiltration trenches, bio-retention cells, bio-retention swales, bio-retention ponds, and sand filters other LID techniques are examples.[8]

3.1 Infiltration-based Techniques

Infiltration-based LIDs are strategies that help restore baseflows by recharging subsurface flows and groundwater. Infiltration-based procedures are very sensitive on site conditions, which is why there is such a wide range of performance recorded for them. Swales, infiltration trenches, basins, and unlined bioretention systems (rain-gardens) are examples of infiltration-based LID methods [9].

3.1.1 Swale systems

Swale systems are shallow open channels with gentle side slopes and vegetation that resists erosion and flooding. They use infiltration, sedimentation, and filtration to transport, control, and improve stormwater [10]. Swales are typically used to replace or improve traditional curbs and gutters for stormwater transport in urban areas, but they can also be utilized for erosion management in agricultural settings [11]. Swales can also work well under a variety of weather conditions [12].

3.1.2 Infiltration Trenches

To help minimize clogging, infiltration trenches typically consist of a gravel channel that is covered with soil and vegetation and is underlain by a geotextile fabric. Gravel is utilized to allow for maximum infiltration and can store a lot of water in the pore spaces. The water entering the trench and moving through the topsoil layer and storage medium are represented by soil characteristics, which are based on the volume of stormwater to be caught. Stormwater runoff is slowed by the use of storage and filtration in these trenches. Suspended particles and other impurities are removed from stormwater due to the lower velocity and meandering flow pattern [13].

3.1.3 Bioretention

Bioretention zones, often known as rain gardens, are landscape features that have been lowered to minimize and treat stormwater runoff while also reducing peak flow [14]. They are suitable for both home and business applications [15]. Bioretention systems can also be used to improve the quality of agricultural water. The type of soil, site circumstances, and land usage all influence the design of bioretention systems. A bioretention area can be made up of various components, each of which serves a particular purpose in terms of removing pollutants and reducing stormwater runoff. Perennials, shrubs, and trees are commonly used in these regions, which are mulched with bark. Bioretention systems can effectively catch runoff, increase infiltration, promote evapotranspiration, recharge groundwater, protect stream channels, lower peak flow, and minimize pollution loads because they operate similarly to natural and undeveloped watersheds [16].

3.1.4 Sand filters

Surface sand filters, subterranean sand filters, perimeter sand filters, organic filters, and pocket sand filters are just a few examples of sand filters. Each of these sand filters is built on the same foundation, with minor variations. Surface sand filters have been around for a long time, and they are made up of two chambers: a flow splitter diverts runoff into a sedimentation chamber, where it is pretreated. The runoff then enters the second chamber, where contaminants are squeezed out at the filter bed's surface. Underground sand filters are ideal for areas with limited space. The sand filter is housed in an underground vault that may be accessed via manholes in this arrangement. The perimeter sand filter is made up of two parallel trenches that are often built around the parking lot's perimeter. The organic filter is similar to the surface sand filter, except instead of sand, compost is used as the filter material. Finally, a pocket sand filter is a less expensive, more straightforward design that may be utilized on smaller sites [17].

3.2 Retention-based Technique

LIDs based on stormwater retention can be defined as approaches that retain stormwater to reduce outflow [18]. Wetlands, ponds, green roofs, and rainwater harvesting are examples of retention-based technology (tanks, storage basins).

3.2.1 Constructed Wetland

For many years, wetlands and ponds have been widely used. While they are excellent at removing pollutants, their ability to reduce overall runoff volumes is restricted because their sole losses are due to evapotranspiration [18]. Detention reservoirs can have a significant impact on the flow regime, with both hydrologic and hydraulic implications. These strategies can cause problems, such as increasing the length of flow over a critical discharge if the peak flow is reduced by storage [19].

3.2.2 Green Roof

Green roofs have gained a lot of popularity around the world in recent decades since they have shown to be sustainable practices. Green roofs have significant social, environmental, and economic benefits, according to research. Significant evidence suggests that green roofs can provide a variety of benefits, including stormwater management, reduced urban heat island, increased urban plant, wildlife habitat, and roof life, improved air and water quality and quality of life, reduced building energy costs, reduced noise pollution, increased recreational activities, and increased green areas and aesthetic value in urban environments [20-24].

Green roofs are often divided into four types. Intensive, semi-intensive, single-course extensive, and multi-course extensive are the several types [25]. Intensive green roofs are defined by a thick substrate, a diverse plant/vegetation mix that resembles ground-level landscapes, a high water holding capacity, high capital and maintenance expenditures, and a heavier weight. Because of the great soil depth, it can hold more water and the plant selection can be more diverse, including small trees and shrubs. This necessitates a greater focus on the building structure's ability to support heavy loads. As a result, this type of roof necessitates a lot of upkeep in the form of irrigating, weeding, and fertilizing. Semi-intensive green roofs are those with a substrate thickness of 6–12 inches. Semi-intensive green roofs have a medium substrate thickness and are typically planted with tiny plants, shrubs, and grass. For optimum performance, these roofs demand regular maintenance and hefty capital costs. Single-course extensive roofs, on the other hand, have a substrate thickness of 3–4 in. Sedum is commonly used as the plant layer in single-course extensive roofs, and irrigation is typically not required. In comparison to other roofs, it had low capital and maintenance expenditures. These roofs are normally quite light weight and come in handy when there are weight constraints on the building. Multi-course extensive roofs have a substrate thickness of 4–6 inches. This style of roof is often light in weight and is popular in the United States. Single and multi-course extensive roofs are the most frequent of the four types since they are lighter, don't require watering, and have lower capital and maintenance costs [26].

4. Conclusion

Global climate change caused extreme weather events threatening social development and people's lives and so many unavoidable challenges for the world. This review points out the causes of urban waterlogging and introduce some techniques of Low Impact Development. Climate change still is a puzzle for the world to solve as one of causes of urban waterlogging. Global warming makes obviously higher precipitation shown by data than the past. And urbanization is an unavoidable factor. People ignored the importance of sustainable development in urbanization in the past. So it caused urban capability of storage rainwater reducing and increase of groundwater runoff. People also need to deal with the conflict between urbanization and sustainable development. This review believes LID techniques could solve urban waterlogging effectively. Infiltration-based technique reduce groundwater runoff and improve state of underlying surface. Retention-based technique is the solution for occupied river portion and reduction of urban water storage capacity. There still are some challenges. The first is cost and financial challenges, like requirement of substantial funding and costs of maintenance. Another is technical and physical challenges, such as lack of performance data. For implementation of LID, it is convinced that better combination of different LID techniques could make it more efficient to resolve urban waterlogging. Meanwhile, there still are many techniques waiting for people to explore. This article clearly points out natural and physical factors of causing urban waterlogging and illustrates LID techniques as solutions of urban waterlogging.

References

[1] Ning, Y.-F., Dong, W.-Y., Lin, L.-S., & Zhang, Q. (2017). Analyzing the causes of urban waterlogging and Sponge City Technology in China. IOP Conference Series: Earth and Environmental Science, 59, 012047. https://doi.org/10.1088/1755-1315/59/1/012047

[2] Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G., & Roberts, N. M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. Reviews of Geophysics, 52(3), 522–555. https://doi.org/10.1002/2014rg000464

[3] Extreme precipitation and climate change. Center for Climate and Energy Solutions. (2020, July 27). Retrieved October 10, 2021, from https://www.c2es.org/content/extreme-precipitation-and-climate-change/.

[4] Masters, J. (2021, July 27). Extreme rainfall in China: Over 25 inches falls in 24 hours, leaving 33 dead " Yale climate connections. Yale Climate Connections. Retrieved October 10, 2021, from https://yaleclimateconnections.org/2021/07/extreme-rainfall-in-china-over-25-inches-falls-in-24-hours-leaving-33-dead/.

[5] Bob Henson and Jeff Masters. (2021, July 27). Central Europe staggers toward recovery from catastrophic flooding: More than 200 killed " Yale climate connections. Yale Climate Connections. Retrieved October 10, 2021, from https://yaleclimateconnections.org/2021/07/central-europe-staggers-toward-recovery-from-catastrophic-flooding-more-than-200-killed/.

[6] Y. Shi, D. Wan, L. Chen, J. Zheng, 2014 Water Resources and Power 32, 57, 12.

[7] X. Yang, X. You, M. Ji, C. Nima, 2013 WATER SCI TECHNOL 67, 869.

[8] Pour, S. H., Wahab, A. K., Shahid, S., Asaduzzaman, M., & Dewan, A. (2020). Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. Sustainable Cities and Society, 62, 102373. https://doi.org/10.1016/j.scs.2020.102373

[9] Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A Review. Science of The Total Environment, 607-608, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

[10] Kirby, J. T., Durrans, S. R., Pitt, R., & Johnson, P. D. (2005). Hydraulic Resistance in Grass Swales Designed for Small Flow Conveyance. Journal of Hydraulic Engineering, 131(1), 65–68. https://doi.org/10.1061/(asce)0733-9429(2005)131:1(65)

[11] Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. Water, Air, & Soil Pollution, 223(7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2

[12] Fach, S., Engelhard, C., Wittke, N., & Rauch, W. (2011). Performance of infiltration swales with regard to operation in winter times in an Alpine region. Water Science and Technology, 63(11), 2658–2665. https://doi.org/10.2166/wst.2011.153

[13] Barkdoll, B. D., Kantor, C. M., Wesseldyke, E. S., & Ghimire, S. R. (2016). Stormwater Low-Impact Development: A Call to Arms for Hydraulic Engineers. Journal of Hydraulic Engineering, 142(8), 02516002. https://doi.org/10.1061/(asce)hy.1943-7900.0001152

[14] Shafique, M., & Kim, R. (2015). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Ecological Chemistry and Engineering S, 22(4), 543–563. https://doi.org/10.1515/eces-2015-0032

[15] Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water, Air, and Soil Pollution, 186(1–4), 351–363. https://doi.org/10.1007/s11270-007-9484-z

[16] Davis, A. P. (2005b). Green Engineering Principles Promote Low-impact Development. Environmental Science & Technology, 39(16), 338A-344A. https://doi.org/10.1021/es053327e

[17] R.A. Claytor, T.R. Schueler. (1996). Design of stormwater filtering systems. Chesapeake Research Consortium.

[18] Fletcher, T., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Advances in Water Resources, 51, 261–279. https://doi.org/10.1016/j.advwatres.2012.09.001

[19] Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2012). Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landscape and Urban Planning, 105(3), 230–240.

[20] Berndtsson C. Green roof performance towards management of runoff water quantity and quality. Ecol Eng 2010;36:351–60. Getter KL, Rowe DB, Robertson GP, Cregg BM, Andresen JA. Carbon sequestration potential of extensite green roofs. Environ Sci Technol 2009;43:7564–70.

[21] Niu H, Clark C, Zhou J, Adriaens P. Scaling of economic benefits from green roof implementation in Washington, DC. Environ Sci Technol 2010;44:02–8.

[22] Brenneisen S. Space for urban wildlife: designing green roofs as habitats in Switzerland. Urban Habitats 2006;4(1):27–36.

[23] Fioretti R, Palla A, Lanza LG, Principi P. Green roof energy and water related performance in the Mediterranean climate. Build Environ 2010;45:1890–904.

[24] Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges – A review. Renewable and Sustainable Energy Reviews, 90, 757–773. https://doi.org/10.1016/j.rser.2018.04.006

[25] GSA. The Benefits and Challenges of Green Roofs on Public and Commercial Buildings

[26] A Report of the United States General Service Administration (2011)

[27] Shafique, M., Kim, R. and Rafiq, M., 2018. Green roof benefits, opportunities and challenges – A review. Renewable and Sustainable Energy Reviews, 90, pp.757-773.