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Review of the influence of low-impact development practices on mitigation of flood and pollutants in urban areas

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ABSTRACT

Urbanization has a significant impact on the hydrological characteristics of developed areas as well as downstream regions. As a watershed is increasingly covered with impervious surfaces, it experiences decreased rainwater infiltration, increased runoff, and shortened concentration times, thereby affecting the natural cycle of urban water systems. Many natural flood control and storage mechanisms have been systematically destroyed by urban development, and water pollution has become an increasingly serious global concern. Low-impact development (LID) is an ecological rainwater runoff management method that has been identified as a promising approach to reduce runoff and improve water quality. Recent research and advances in LID are systematically introduced and reviewed in this paper, including popular models, the main LID design elements and facilities, and the mitigation that LID provides for both floods and pollutants in urban areas. Future research into LID will need to enlarge its scope to broader regions and networks, develop and refine suitable models, and explore ways to integrate LID into existing water management systems in urban areas.

Keywords: Low-impact development; Flood mitigation; Storm water management model; Urban area; Roadway runoff; Water quality purification

1. Introduction

Wherever it occurs, urbanization brings rapid socioeconomic development, but that is accompanied by changes in land use, which often result in hydrological disturbances such as increased runoff, shorter concentration times, higher peak flows, and worse water pollution [1]. The most visible effect of these changes is flooding, caused by the adverse impact of urbanization on the natural drainage systems.

Low-impact development (LID) is a concept introduced in the United States in the 1990s. LID practices can allow the hydrological condition of developed areas to approximate their state prior to urbanization through distributed source control of urban storm runoff and pollution [2,3]. LID aims to maintain or restore the natural state of the hydrological mechanism within an area and effectively control urban runoff while protecting the ecological environment [3]. Studying the design of LID measures and their flood mitigation efficiencies is a valuable step toward solving problems related to urban flooding and the loss of ecological environments [4–6].

2. Research status

2.1. Application of models

The development of the LID concept and system has triggered global interest in the efficiency of the LID measures in the actual sample monitoring and the development and promotion of hydrological models. The DRAINMOD model was used to simulate the hydrological influence of LID measures [7]. The storm water management model (SWMM) was

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applied to formulate several LID guidelines for the pollution control in urban runoff [8]. While assessing the capacity for large-scale adoption of LID practices to reduce flooding in an urban watershed using PC-SWMM, a scholar indicated that an increase in urban land use from 50% to 94% between 1992 and 2030 would increase average annual runoff and flood events by more than 30% [9]. In addition, the SCS model was employed to explore the factors relevant to LID performance by estimating runoff variations at different rainfall frequencies [10].

The IDEAL model was used to simulate the performance of LID measures in an urbanized area [11]. The WWHM3 Pro model can be applied without complex computation to determine the most appropriate measures to achieve a given objective, thereby reducing the difficulty of LID implementation [12]. As the scope of the effectiveness of LID measures has become increasingly apparent, models have begun to favor the use of simulations to study these measures' internal processes to explain the underlying reasons for their success. The curve number method was utilized to quantify runoff, and the results were compared with those of an SWMM5.0 simulation. The curve number method was able to quantify the surface runoff reduction of the tested LID measures in a better way [13]. The study of flood mitigation using collection tanks and biological retention troughs included analysis with a spatial-temporal model. The results showed that the location and size of LID measures can significantly influence their mitigating effects. Furthermore, the spatial location of the watershed peak flow to reduce the impact was outstanding [14]. A system that combined permeable pavement with cisterns was modeled with the L–THIA–LID model, which confirmed that this LID approach can play a powerful role in solving the problem of urban flooding caused by runoff [15].

2.2. Technologies and practices

Recently, many experts have attempted to quantify the differences between traditional and LID drainage systems simulated various LID measures and combinations and reported their ability to mitigate flood risk at different rainfall frequencies [16–18]. A scholar conducted a field experiment to study the flood control functions of a range of LID measures [19].

Considerable attention has been directed toward the effectiveness of simulations to support the research and understanding of LID measures. Engineers and urban planners are engaged in optimizing the process of selecting and designing LID measures. Accordingly, analytic hierarchy processes have been explored as a way to simulate different LID measures, and then to establish a decision support system based on the simulation results, taking into account both their effectiveness and cost [20]. By monitoring three bioretention cells in northeast Ohio for non-winter quantification of inflow, drainage, evapotranspiration, and exfiltration, a scholar showed that the inclusion of an internal water storage zone allowed the three cells to reduce runoff by 59%, 42%, and 36% over the monitoring period [21]. An experiment looking at hydraulic performance of a residential storm water infiltration gallery found that a 100 ft infiltration gallery sitting atop soil with a modest infiltration rate could attain a single downspout runoff reduction of 90%, while a 200 ft gallery could reduce runoff from the entire roof by more than 85% [22].

Studies of LID measures in China have mostly focused on the application of the SWMM model. For example, municipal roads containing LID facilities were contrasted with traditional municipal roads in terms of their ability to control runoff and pollutants. The results showed that LID-based road design increased infiltration to 66% of the annual rainfall while decreasing the road runoff coefficient to 0.36 [23]. A scholar used SWMM to analyze the peak flow changes in drainage pipelines from rainwater retention ponds, as well as the vegetation on a shallow ditch beside an impervious parking lot [24]. The results showed that the retention pond and shallow vegetation groove could reduce the peak flow volume, increase the lag time to peak flow, and increase the utilization of rainwater resources.

Instead of viewing rainwater as merely a problem to be mitigated, a growing body of research explores the potential to utilize it as a valuable resource. For example, rainwater harvesting in a planned industrial park was found to have great potential in mitigating risk and capturing the water for later use [25].

The bright new city of Shenzhen has been a hotbed of study into LID, including the application of SWMM to analyze the influence of urbanization, recessed green spaces, and penetration pavement on urban runoff flow processes [26]. Currently, Shenzhen City's Guangming New District is a leader in the development of China's first comprehensive system for the utilization of rainwater, guided by the concepts of LID. The research in this district has also explored the technical methods that can be used to achieve the district's urban storm water management goals. Despite this progress, China's urban rainwater management still mainly draws lessons from advanced foreign concepts and experience, and even the implementation of this foreign expertise is in its infancy. The simulation and study of LID measures are mostly limited to non-representative individual measures, and systematic and practical simulation studies in China are lacking [27].

3. Specific LID measures for disaster reduction

LID aims to maintain or copy the natural state of the hydrological system in an area. The design strategy can be realized through the use of an array of possible measures to create natural hydrological conditions to minimize the negative impact on the ecological environment [28]. Compared with best management practices, LID is a low-cost, small-scale approach that is more oriented toward source control. Most LID measures fall into the categories of vegetative swales, bioretention ponds, permeable pavement, and greenbelts.

3.1. Vegetative swales

The implementation of vegetative swales is a simple and effective method to control source pollution. It has long been applied to agricultural non-point source pollution control and has subsequently been used as a type of runoff transmission facility in municipal drainage systems. Vegetative swales are currently differentiated by their structure and hydraulic characteristics. In terms of structure, a vegetative swale can be sorted into one of the following three categories—standard transmission swale, dry swale, and wet swale—as illustrated in Fig. 1 [29]. They can also be categorized by their hydraulic characteristics: horizontal flow (also known as transmission flow) swales or vertical flow swales. Vertical flow swales have higher requirements for soil permeability and can easily become blocked during operation, leading to a decrease in effectiveness [30]. Research into vegetative swales in China is still in its initial stages; thus, most research has focused on the removal of pollutants under the traditional transmission mode. Research from other countries has documented numerous cases and accumulated considerable field monitoring data. This research on vegetative swales has mainly explored runoff reduction, removal of pollutants from runoff, pollutant accumulation in swale soil, and model development [31].

The current literature indicates that the hydraulic performance of vegetation in a swale varies based on rainfall intensity. Under low-intensity rainfall, the main function of the vegetative swale is to encourage infiltration. In the event of moderate-intensity rainfall, its main function is delaying runoff. Under high-intensity rainfall, the vegetative swale mainly shows transmission characteristics.

3.1.1. Reduction of total runoff

Davis et al. [32] analyzed the effect of vegetative swales on runoff reduction during 52 rainfall events over 4.5 years in Maryland. They found that the amount of rainfall in an event

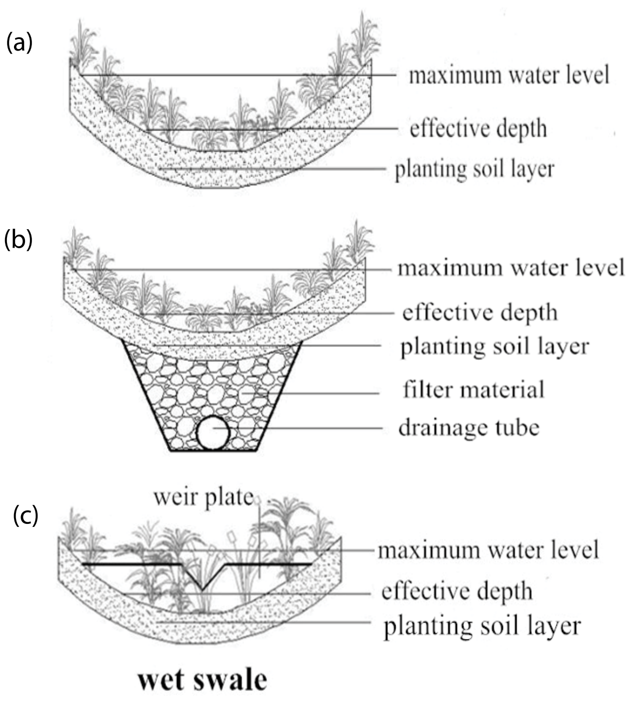

Fig. 1. (a) Cross section of a standard transmission swale, (b) cross section of a dry swale, and (c) cross section of a wet swale (*cite from: Research on the running effect evaluation and improvement design of grass swale. Dissertation*).

that can be completely controlled by the vegetation scales linearly with rainfall duration can be expressed as follows:

$$P = 0.07 \times D + 0.35 \text{ cm} \tag{1}$$

where P is the rainfall depth in cm and D is the rainfall duration in h.

Davis also found that a vegetated check dam can improve the effectiveness of an associated vegetative swale under medium-intensity rainfall.

3.1.2. Reduction of peak runoff

Vegetative swales also effectively reduce peak runoff volumes, which is associated with an increased lag time. In general circumstances, the runoff peak was found to decrease by approximately 10%–20% [33]. However, seasonal changes may significantly lower this performance; Roseen et al. [18] observed an 18% decrease in swale effectiveness during other seasons when compared with summer.

As the rainfall return period increases, the effectiveness of vegetative swales to reduce peak flow decreases. The reduction effect is most significant when precipitation events are frequent [34].

3.1.3. Removal of pollutants

The ability of a shallow vegetated trench to remove pollutants has been found to significantly decrease as rainfall intensity and volume increase, especially for the removal of particulate pollutants. In a study, the removal rate of ammonia and total phosphorus remained within the normal range as rainfall increased, but the stability of the removal rate was significantly reduced [35].

3.2. Bioretention ponds

Bioretention ponds can remove pollutants through the chemical, biological, and physical interactions between water and the plants, microbes, and soil present within the pond, which helps a system achieve its objectives of urban runoff and water quality control [36]. Bioretention ponds comprise a hygrophyte installation, a base layer, and a permeation tube, which augment a membrane-lined retention pond, as illustrated in Fig. 2 [37]. RECARGA can be employed to simulate the hydrological effects of a bioretention pond on runoff reduction, groundwater recharge, and total water treatment capacity. Such simulations have confirmed the significant hydrological regulatory function of bioretention ponds [38].

Bioretention ponds can reduce surface runoff and alleviate the burden on municipal rainwater pipe networks. Furthermore, this technology can protect and improve water quality and limit bank erosion by reducing overflow. Studies have shown that the bioretention system is effective in reducing runoff and flood peaks. Field research in parking lots showed that bioretention ponds can reduce surface runoff and flood peak flow by 97% to 99% [39]. During low-intensity rainfall events, runoff flow can be completely detained. Infiltration and evaporation play important roles in constraining the runoff process, which was confirmed by

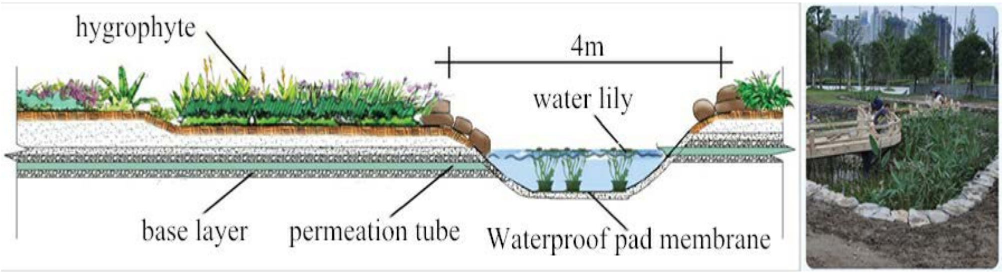

Fig. 2. Cross section and image of a bioretention pond (*Source*: http://www.tidelion.com/hxpro/chengpin/).

a group of scholars when they discovered that 48% to 74% of runoff was diverted by infiltration or evaporation while interacting with biological water retention systems [40]. Therefore, the biological retention pond can play a significant role in runoff reduction, groundwater recharge, and water quality improvement.

The application effect of bioretention ponds during different seasons is often considered in the literature. In the investigation of bioretention ponds, a scholar determined that the water in the pool encountered substantial difficulty in infiltrating to the surroundings when seasonal changes brought local groundwater levels near the surface. Moreover, the typical effectiveness of rain gardens diminishes significantly during winter conditions, as vegetation is less active, and soil may be partly or completely frozen [41].

Biological retention technology can provide water quality improvements, including the removal of suspended particles, heavy metals, oils, and pathogens. Other pollutants in storm water runoff are relatively stable during their interaction with a bioretention pond, and the removal of nitrogen and phosphorus fluctuates [42].

3.3. Permeable pavement

Permeable pavement is a typical LID measure. Unlike swales and bioretention ponds, which control water once it has left impermeable surfaces, permeable pavement aims to directly reduce the runoff-generating area of a city [43]. A typical implementation of permeable pavement is shown in Fig. 3. In addition to reducing the runoff-generating area of a development, a properly implemented permeable pavement can also collect runoff from adjacent areas. The following three conditions were simulated: (1) pre-urbanization (i.e., natural state), (2) post-urbanization without control measures (i.e., standard concrete pavement), and (3) post-urbanization with measures to regulate and control runoff (i.e., water-permeable pavement) [44]. By changing the return periods (P = 2a, 10a, and 100a), the hydrological regulation performance of permeable pavement was quantified. The peak discharge and volume of floods were taken as two indices to analyze the hydrological regulation performance of the permeable pavement. The results showed that urbanization significantly increased flood discharge and peak flow. However, the treatment with permeable pavement experienced peak flow and flood volume values that were even lower than those in the pre-urbanization control. This finding indicates that the permeable pavement can absorb a vast majority of runoff.

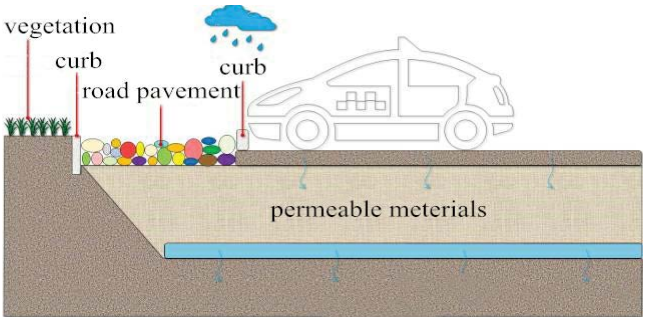

Fig. 3. Cross section of a permeable pavement installation (*Source*: http://www.17wh.com/cjm/20170206/1509105.html).

The average runoff reduction rate for the permeable pavement was between 50% and 93%. A scholar studied a permeable parking lot and concluded that 75% of rainfall was intercepted by the permeable medium, and the other 25% formed runoff [45].

A long-term monitoring study, however, showed that almost no surface runoff exists on the permeable pavement, and concluded that copper and zinc content in the runoff was significantly lower than those from the asphalt pavement. The monitoring results indicated that the permeable pavement has a significant mitigating effect on flooding and can effectively recharge groundwater, earning its place as a stable LID measure [46].

Permeable pavement also has a beneficial effect on water quality, as the water is routed through soil, which provides filtration, and reduces the capacity of water to move surface contaminants into waterways. Compared with traditional asphalt roads, the concentrations of suspended solids, COD, nitrogen (ammonia, nitrate, and total), and total phosphorus in the runoff were reduced by 95%, 84%, 71%, 33%, 50%, and 66%, respectively [47].

3.4. Low-elevation greenbelt

Urban green space planning and design can control the relations among pavement elevation, green space elevation, and rainfall inlet elevation to form a low-elevation greenbelt (Fig. 4). By changing the precipitation return periods (P = 2.5a, 5a, 20a, 50a, and 100a), the runoff and flood peak flow were analyzed when the bottom concave was below 5 and 10 cm. SWMM was utilized to simulate the different types of greenbelts in a residential area, and the results were analyzed to determine runoff coefficients

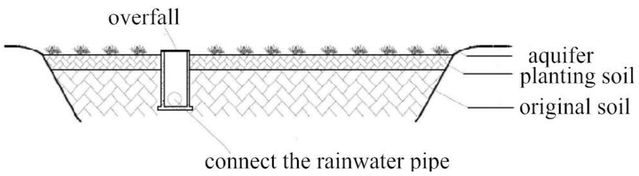

Fig. 4. Cross section of a low-elevation greenbelt (*Source*: http://www.fwjia.com/2016/0402/411797_2.html).

and peak discharges of each type. They drew two primary conclusions: (1) a low-elevation greenbelt can maximize the infiltration into the vegetated land, which can weaken the peak flow, reduce the total flow by over 20%, and reduce the runoff coefficient by approximately 25%. This effectively reduces the risk of urban flooding. (2) The runoff coefficient and peak flow are highly sensitive to the concave depth of the greenbelt. The greenbelt reaches optimal efficiency when it is 5 to 10 cm lower than the road [48].

3.5. Combined LID measures

InfoWorks CS has been employed to develop a rainwater drainage model. Comparisons between the effects of two rainwater drainage conditions, under different rainfall frequencies, were conducted. The results showed that when a green roof and a low-elevation greenbelt have the same volume, linking them together as part of a single system is more effective than keeping them separate. Furthermore, as precipitation increases in frequency, the advantages of the combined system become more evident.

A scholar indicated that a combined layout of a green roof, permeable pavement, and a rain water garden (all of which are LID measures that are often used on their own) can more effectively remove various pollutants [49–52].

The LID concept and specific, targeted measures should be actively implemented in the pursuit of sustainable and safe urbanization. Combining LID measures, either sequentially or in parallel, maximizes their effects on rainwater control and water quality improvement.

4. Conclusions and Recommendations

- LID reduces the peak flow and runoff coefficient of storm water by promoting infiltration and transpiration. It also delays the peak flow time and reduces the impact of urbanization on the hydrological condition of a developed area, even potentially restoring the area to roughly the state before urbanization. All of this helps achieve the objective of flood mitigation. LID measures provide evident advantages in reducing pollution, saving investment costs, and increasing water management efficiency. These advantages encourage its extensive expansion and application. However, some limitations still exist.
- Most studies are currently based on small-scale installations, leaving questions about the validity of extrapolating their findings to entire urban drainage networks. The process of integrating LID measures into existing local storm water control systems, as well as selecting the appropriate flood models to study them, is an area for future LID research to focus. Clearly, rainwater utilization projects based on LID technology will play an increasingly important role as water shortages and flooding become more common. Combining rainwater utilization measures with other aspects of landscape planning will be increasingly prominent in both research and real-world application of LID systems.
- The following recommendations are presented for the development of LID systems in China: capitalize on foreign experience and implement comprehensive practices based on existing international research; accelerate the establishment of LID standards to help promote LID as an accessible means of improving sustainability; immediately establish a database of LID measures with economic evaluations specific to China; and provide a reasonable starting point for firms to design and implement urban LID storm water management measures.

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