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Development, assessment and implementation of integrated stormwater management plan: a case study in Shanghai

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Abstract: An innovative stormwater master plan based on low impact development (LID) is proposed. Unlike the traditional urban drainage plan, this plan employs a sustainable stormwater management approach in communities, utilizing LID practices to reduce runoff and pollution load. An integrated hydraulic model, which combines the traditional drainage sewer system with LID practices, is adopted to assess the master plan. Through a long-term continuous simulation for 20 years, the results reveal that the runoff volume will be reduced by over 80% following full implementation of this plan. Combining with the local conditions, technical guidelines are established to provide assistance in implementing the stormwater master plan. Bioretention facilities for three main roads are constructed, and other areas of development are being implemented sequentially under the guidance of the plan. This project provides an alternative method of stormwater management through the implementation of LID, and it acts as a good example for other developing districts in China.

Key words: stormwater master plan; low impact development; rainwater harvesting; stormwater management practices; hydraulic model

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A series of adverse environmental and hydrological effects have been brought about by rapid urbanization in China. Although metropolitan point source pollution has been controlled substantially in China, there is an ongoing deterioration of the urban water environment[1]. Problems with the quantity and quality of urban runoff have emerged as key obstacles to sustainable urban development.

An alternative approach for mitigating the impact of urban runoff has been provided by best management practice and low impact development (LID)[2-3]. Compared with conventional urban drainage systems, LID offers a completely different approach to urban stormwater management. However, several difficulties and barriers need to be addressed when implementing LID. An integrated urban plan combined with the LID concept will be an effective means for the implementation of LID. Furthermore, a master plan for integrated stormwater management should be an important precondition for both the selection of the location and the design and maintenance of LID practices. More importantly, the cooperation of different sectors, which include urban planning, transportation, architecture and landscape design, is highlighted through the implementation of this plan. Requirements and regulations for these sectors are specified in this plan.

Chenjia Town International Eco-experimental Community (CTIEC) is located in the east of Chongming Island, the third largest island in China. Under the guidance of policies implemented by the Shanghai Government, CTIEC is planned as a community to demonstrate ecological idea. A sustainable eco-technological development mode is highlighted in the planning and development of the CTIEC. Moreover, the comprehensive application of green building technologies is one of the approaches for achieving the objectives.

Combined with the requirements of planning and construction in CTIEC, the stormwater management master plan is accomplished. Based on the general goals of the community, a unique and unconventional approach to sustainable drainage planning is employed. Moreover, an integrated hydraulic model (InfoWorks CS, version 10.5, Wallingford, UK), which combines traditional drainage sewer systems with LID practices, is adopted to assess the master plan. The development, assessment, and implementation of the master plan provide a good example for other developing districts in China.

1 Methods

1.1 Study area

The area of the development site in CTIEC is about 448 ha, of which the waterscape comprises about 38.7 ha. The integrated land use of the project is summarized in Tab. 1. The location of the project area is shown in Fig. 1. Average annual precipitation is approximately 1184.4 mm, which is distributed uniformly throughout the year (see Fig. 2). The average annual number of rainy days is 122.2[4].

1.2 General description of the plan

Owing to the dense network of waterways that exist in

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Tab. 1 Project land use

Land use	Area/ha	Proportion/%
Residential (R)	231.87	51.73
Commercial and public facilities (C)	24.72	5.51
Road, street and square (S)	69.58	15.52
Municipal utilities (U)	0.74	0.17
Green space (G)	82.70	18.45
Water area (W)	38.66	8.62
Total area	448.27	100.00

Note: Around 30% of the land in residential was planned as green space.

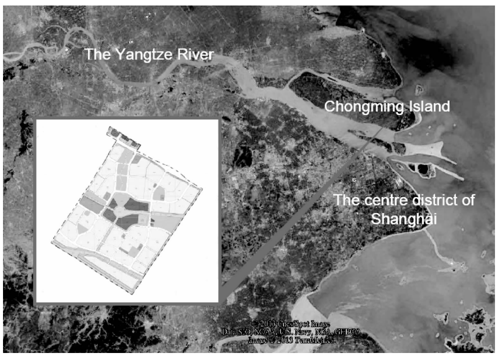

Fig. 1 Location of study area

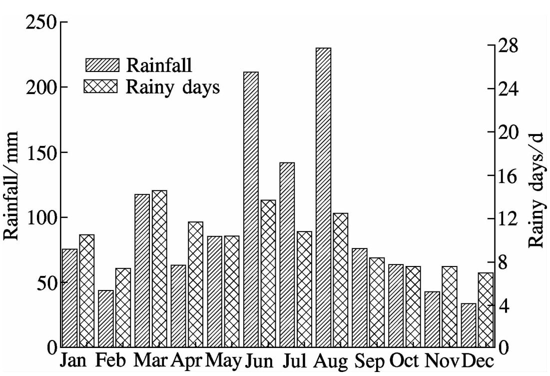

Fig. 2 Monthly average rainfall (1971—2000)

this area, the maintenance of the beneficial urban water environment is a key goal in community planning and development[5]. According to local natural conditions, the master plan of stormwater management is intended to improve drainage capacity, utilize rainwater resources, protect local ecosystems, and create a sustainable urban water environment.

In accordance with the policies of the local development department, the Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND) system, which is a popular rating system for green buildings in the United States, is adopted for this stormwater plan[6]. According to the requirements of the LEED-ND, a comprehensive stormwater management plan should be implemented.

Thus, based on the requirements of the LEED-ND and the local conditions of the plan area, stormwater strategies are determined, which are summarized as follows:

1) Main waterways in communities will be taken as stormwater discharge channels.

2) The waterways and waterscape in blocks will be connected to the main waterways of the community.

3) Different types of LID should be planned for each block in the community to ensure the fulfillment of the LEED-ND requirements.

4) Landscape design and LID practices should be incorporated into the integrated planning according to different land uses.

5) A series of future goals for stormwater management and the relevant implementation measures will be included under the regional master plan.

1.3 Stormwater plan model

A detailed hydrodynamic model coupled to an LID practice model is employed to assess the stormwater plan. The software package InfoWorks CS is used (Version 10.5, Wallingford, UK). Fig. 3 presents the floor plan of the hydrodynamic model of the study area.

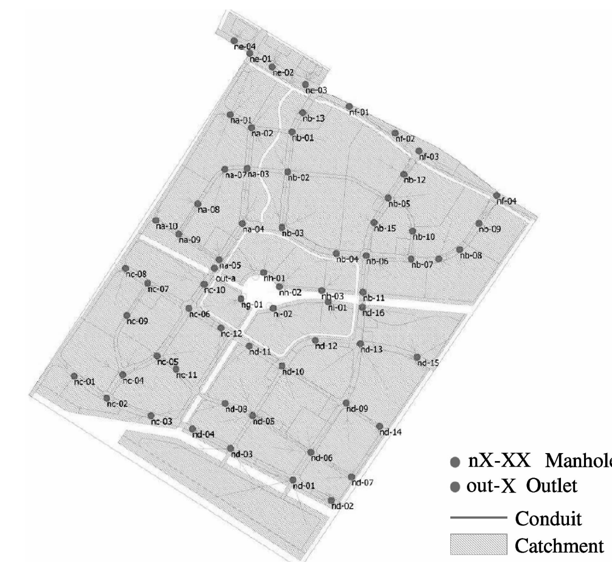

Fig. 3 Storm sewer systems planned in CTIEC

Several LID practices, including rainwater harvesting, permeable paving, bioretention and infiltration, etc., are simplified and conceptualized to one of the LID practices for every subcatchment in this hydrodynamic model. The LID practice model, called sustainable urban drainage systems practice in the UK[7], is a new module that improves the latest version of Infoworks CS. For example, bioretention can be simplified as a planted depression (a node in a hydrodynamic model) with a ponding area and an infiltration capacity[8].

2 Results and Discussion

2.1 Master plan of LID practices

Source control measures, which are integrated with the traditional sewer drainage system, are at the heart of the plan for achieving the goals. Based on field investigations, the applicability of various LID technologies are analyzed for suitability and practicality. Furthermore, under the guidance of the master plan of Chenjia Town, three categories of LID practices are adopted for stormwater management: rainwater harvesting, permeable paving, and bioretention and infiltration.

2.1.1 Permeable paving

The total area of permeable paving planned in the project is 34.8 ha, which includes roads for non-motorized vehicles, parking lots, sidewalks, squares and other open spaces. Furthermore, because the traffic load is relatively low, parking lots are planned as the main application for permeable paving. It is determined that pervious asphalt and pervious bricks would be the most suitable for the various types of squares and open spaces within this community. For the roads and streets in the residential and commercial subdistrict, it is suggested that the pervious asphalt and the pervious concrete should be used in this plan. This type of LID practice will markedly reduce the pollution and the volume of runoff, while the normal traffic function is allowed.

2.1.2 Rainwater harvesting

Rainwater harvesting is the main approach for the direct utilization of rainwater. The runoff from the roofs of buildings in the residential and commercial blocks should be collected and utilized preferentially. The collected rainwater should be stored in rainwater tanks and following purification treatment. It can be used for vehicle washing, road cleaning, and miscellaneous municipal uses. The size of the rainwater tanks is determined based on an event rainfall amount of 25.4 mm.

The total area of the various roof types within this community is 62.8 ha, and it is determined that the time to empty the rainwater storage tanks should be less than 80 h. The initial abstraction and first flush volumes are assumed as 1 and 2 mm, respectively. The results of a frequency analysis of more than 20 years' rainfall data in Shanghai indicate that more than 70% of the volume of the average annual rainfall will be captured by the storage facilities designed by the specified sizing criteria.

2.1.3 Bioretention

Bioretention (also called rain garden) is a planted depression that allows the absorption of rainwater runoff from impervious urban areas. The area of planned bioretention in the project is about 20.6 ha. The size of the bioretention area is also determined based on an event rainfall amount of 25.4 mm. Runoff is ponded to a depth of 150 mm. The groundwater level is high in Chenjia Town and, thus, under drain and outlet pipes are recommended to be constructed in the bioretention cells and connected to the municipal storm sewers. Furthermore, the local soil is sticky with a low permeability coefficient, which means that the requirements of bioretention infiltration cannot be achieved. Therefore, the drainage capacity of the bioretention zones should be improved by the replacement of the soil with rain garden mix.

Other LID facilities, such as swales and permeable paving, are also included in the roadside plan. For those blocks with large-scale impermeable pavement, such as the centralized commercial district, large squares, and parking lots, runoff can be collected by the sewer system. Following preliminary purification, this runoff can be transported to a centralized stormwater wetland, from which treated outflow can be discharged to the receiving water body. Additionally, non-structural practices are also considered in this plan.

2.2 Assessment of the master plan

According to the requirements of the LEED-ND, a stormwater management plan should be assessed with a hydrodynamic model of the sewer system combined LID practices for long rainfall time series. This is a key approach and an important step for green building rating systems. Points for retaining stormwater on-site are obtained if the percentile of the controlled rainfall volume is greater than or equal to 80% of the volume for rainfall events over a 20-year period [6].

A detailed design of a stormwater sewer system for the CTIEC without consideration of LID is accomplished according to the National Code for Design of Outdoor Drainage[9]. Owing to the dense network of waterways that exist in this area, eight subsystems are designed to ensure that runoff can be gravitationally discharged into the nearby receiving water body. For an ideal situation, which is no illicit connection and groundwater infiltration detected, the total discharge volume from the outlet of the storm sewer will be equal to the total volume of runoff generated within the community. The stormwater sewer system is adopted as a model for a drainage condition with no LID practice.

A hydrodynamic model of the planned sewer system is built with InfoWorks CS. The required data, which include sewer data, rainfall data, contributing area data, soil data, base flows, and operational data, are obtained by field investigations and from the master plan of the community. The selection of the model parameters is referenced to relevant studies[10-12]. Model simplification is carried out according to the typical methods of simplification[13]. Thus, 160 subcatchments are simplified and planned in this community according to the land use of the planned blocks. It is assumed that runoff from the catchment will be collected by LID practices and that ultimately, overflow from the LID will be discharged to the sewer system.

Various kinds of LID practices are planned according to different land uses in order to achieve the stormwater management goals of the community. However, this existing master plan is in the phase of general development and the detailed plans of the blocks has not been started. The LID practices planned in the various blocks need to be simplified. Through equivalent conversion according to the scale of the various types of LID, practices within a block are made equivalent to one LID facility.

According to this method, an integrated model is built based on the drainage sewer hydrodynamic model. An initial model test and routine model tests are carried out after model simplification. The results reveal that these two models, which are hydrodynamic models of the planned sewer system with and without LID practices, meet the requirements of hydrodynamic model testing[13].

Continuous minute rainfall data from 1985 to 2004 in Shanghai is adopted as the model input data. The total discharge volumes for the two models, both with and without LID practices, are counted (see Tab. 2). The maximum flows from the outlet, which are the cumulative value of the eight subsystems, are listed in Tab. 2.

Tab. 2 Annual total discharge volume and maximum flow models of drainage systems with/without LIDs

Year	Total discharge volume/m^3		Reduction rate/%	Maximum Flow/($m^3 \cdot s^{-1}$)		Reduction rate/%
	Without LID	With LID		Without LID	With LID	
1985	2 639 100	729 600	72.4	13.61	8.76	35.7
1986	1 889 700	230 500	87.8	12.68	5.73	54.8
1987	2 233 100	430 800	80.7	12.58	6.45	48.7
1988	1 360 800	248 000	81.8	12.34	5.48	55.6
1989	2 200 300	414 000	81.2	13.36	6.64	50.3
1990	2 224 000	337 800	84.8	14.13	7.96	43.6
1991	2 224 000	600 200	73.0	15.65	10.11	35.4
1992	1 588 000	249 800	84.3	11.95	5.38	55.0
1993	2 671 000	730 500	72.7	12.09	7.30	39.6
1994	1 487 800	162 100	89.1	11.79	2.78	76.4
1995	2 165 600	738 500	65.9	15.27	7.23	52.7
1996	1 983 600	497 800	74.9	12.33	6.12	50.4
1997	1 542 900	212 900	86.2	12.87	5.06	60.7
1998	1 894 000	236 500	87.5	12.57	7.51	40.2
1999	2 669 200	974 800	63.5	11.76	6.44	45.2
2000	2 062 400	219 400	89.4	12.80	3.49	72.7
2001	2 476 800	794 300	67.9	14.94	10.00	33.1
2002	2 510 600	289 900	88.5	13.32	3.58	73.2
2003	1 596 800	158 200	90.1	13.20	6.17	53.2
2004	1 854 000	187 200	89.9	11.58	5.59	51.8
Statistics	Mean		80.6			51.4
	Standard deviation		8.71			12.35
	SE of mean		1.95			2.76

As shown in Tab. 3, through the implementation of LID practices, the average reduction of total runoff volume over these 20 years is 80.6%, which meets the requirement of the LEED-ND. This is also consistent with the main goal of the master plan. Meanwhile, the average reduction of maximum flow over these 20 years is more than 50%, which clearly indicates that an improvement in flooding control can be expected.

Additionally, one of the eight subsystems within this community is selected for the analysis of the diversification of discharge processes with LID practices. The location of this subsystem is shown in Fig. 4. The total area of the subsystem is about 47.95 ha. Here, 19 subcatchments and 19 LID practices are simplified and planned in this subsystem.

A period of 96 h, from 25 to 28 June 1985, is selected for the analysis of the discharge flow for the two models. The total precipitation during this period is 96.5 mm, which includes four rainfall events. The antecedent dry period (ADP) of the third and fourth rainfall events is around 1 d, which is obviously longer than that of the second one. The ADP of the first rainfall event is about 20 d. It is indicated that the runoff stored by the LID practices is consumed basically through infiltration, evaporation, and reuse. The hydrograph of the outflow from this subsystem under the two models is shown in Fig. 5.

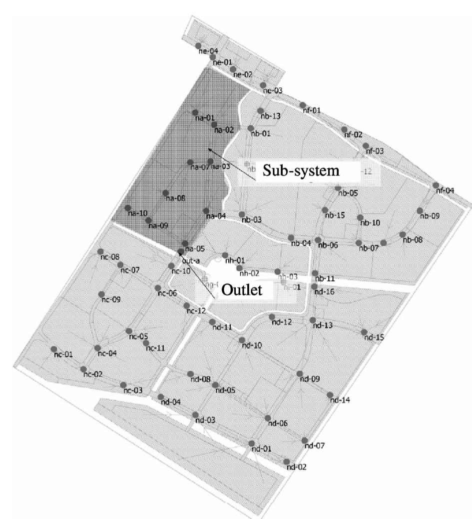

Fig. 4 Location of the representative subsystem within study area

As demonstrated in Fig. 5, for the model without LID practices, the peak flow appears immediately following the peak rainfall intensity in the first rainfall event. This is because there is no retention in the traditional system without LID practices and because of the small scale of the catchment. For these four rainfall events, an apparent consistency is detected between the discharge flow and the rainfall intensity.

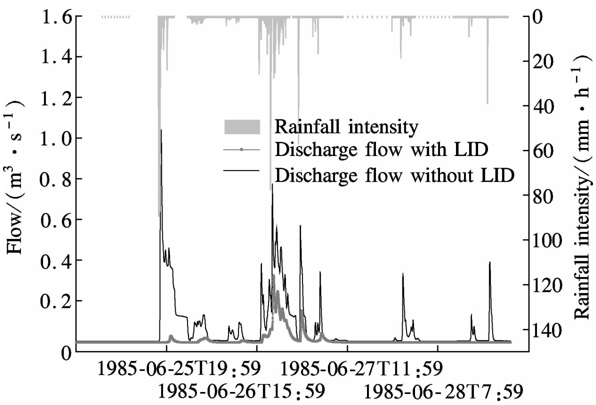

Fig. 5 Comparison between discharge flows with/without LID in representative subcatchment

For the model with LID practices, an obvious reduction of the discharge flow is observed. As a result of the short ADP of the second event, the runoff stored in the LID facilities is not consumed completely. Moreover, the precipitation of the second rainfall event is much greater than that of the first one. Therefore, the reduction of the runoff volume for the second rainfall event is relatively smaller than that for the first one. There are four peak flows in the second event. The reduction of the first peak is clearly higher than that for the other three subsequent peaks. This is because excess capacity exists following the first event, whereas there is only a small amount of capacity when the other three following peaks appear.

Although the peak flows for the following three events are not reduced significantly, the reduction of these peaks is still greater than 40%. Because of the low precipitation and rainfall intensity of the third and fourth rainfall events, the reduction of volume and peak flow is still obviously higher, even though the ADP of these two events is only about 1 d.

Overall, a significant reduction of total discharge volume will be observed following the implementation of the optimal stormwater management plan with LID practices. Furthermore, the peak discharge flow will also be reduced. By implementing the LID principles and practices on a broad scale, the post development hydrologic functions will be improved significantly.

2.3 Technical guidelines of the CTIEC

Non-structural practices are an important component to ensure the implementation of the stormwater plan, especially for LID practices. Policy and legislation are the most efficient tools among the non-structural practices. Technical guidelines are set up to implement the construction of the CTIEC, among which stormwater management is a key component.

According to the stormwater management plan of the CTIEC, requirements for stormwater management will be made by the Chenjiazhen Development Corporation when the blocks of the CTIEC are auctioned. Throughout the development process of blocks, these requirements must be strictly complied with. This is a key precondition in the implementation of the stormwater management plan, and the technical guidelines of the CTIEC are important for the land developers of blocks to achieve the goals of the stormwater management plan.

2.4 Implementation of the master plan for three main roads

The master plan of stormwater management was completed and proposed in 2011. In accordance with the schedule of community development, municipal road and utilities were constructed before the detailed plan and development of the subdistricts and blocks.

The construction of the main municipal roads in the CTIEC has been implemented by the Chenjiazhen Development Corporation since the spring of 2011. The construction of the main roads was implemented in several phases. Three main roads, which include Cuiniao Road, Liulan Road, and Shilian Road, were constructed during the first phase. The detailed design of the LID practices planned for the central separation area of these three roads was completed prior to their construction. The construction of the LID practices was carried out simultaneously with the road construction, which was completed in spring 2012 (see Fig. 6).

(a) (b) (c) (d)

Fig. 6 Several LID practices implemented in this project. (a) Roadside bioretention; (b) Outlet of bioretention (overflow); (c) Permeable paving under construction; (d) Permeable paving before completion

3 Conclusion

A new paradigm for a regional stormwater master plan, which is aimed at meeting the requirements of stormwater management in the LEED-ND, is proposed in this study. Through the assessment of the master plan by using a hydrodynamic model combined with LID practices, it is revealed that the master plan can meet the requirements of the LEED-ND, if it is implemented strictly and in full. The stormwater management plan will meet the needs of the development in the CTIEC.

The case study provides a practical approach for the assessment of stormwater management with green building rating systems, such as the LEED-ND. It also highlights an alternative cost-effective method for regional stormwater planning with which urban planners and designers can meet the increasingly strict regulations of urban stormwater management. This case study, which incorporates the master plan, technical guidelines, and the implemented engineering, provides a good example for similar projects in other developing districts in China.

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雨水综合管理规划、评价和实施:以上海为例

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摘要:提出了一套基于低影响开发理念的城市雨水综合管理规划方案. 与传统排水规划不同,该方案通过在社区尺度上规划各类低影响开发设施,削减径流总量和污染负荷,实现可持续的城市雨水综合管理. 采用结合了传统排水管道和低影响开发设施的水力模型,对规划效果进行了评价. 通过 20 年降雨数据的连续模拟发现,在规划完全实施基础上,相对于不采用低影响开发设施,径流总量削减率可达 80% 以上. 为保障和指导规划的实施,结合当地条件,制定了技术实施导则. 规划区域内 3 条主干道道旁生物滞留设施已完成施工建设,区域内其他地块的开发也正在实施导则的指导下逐步开展和实施. 提出的基于低影响开发理念的区域雨水综合管理规划、评价和实施方法,将为我国其他地区的类似项目提供经验和借鉴.

关键词:雨水专项规划;低影响开发;雨水收集利用;雨水管理设施;水力模型

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