Title: **Using Parametric Simulation and GIS to Design a Stormwater Solution for a Chinese Sponge-City**

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Subjects: Sustainability/Green/Energy
Urban Design

Keywords: Climate
Density
Green Roofs
Infrastructure
Integrated Design
Sustainability
Urban Planning

Publication Date: 2016

Original Publication: Cities to Megacities: Shaping Dense Vertical Urbanism

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Using Parametric Simulation and GIS to Design a Stormwater Solution for a Chinese Sponge-City | 参数化模拟及地理信息系统(GIS)在中国海绵城市雨水处理方案设计中的应用

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Abstract | 摘要

One of the predicted effects of climate change in Central China is an increase in precipitation and in extreme rainfall intensity. In 2015, the Chinese government approved the development of 16 model "sponge cities," one of which is Wuhan, where we had been tasked by the local government to develop a sustainable masterplan for a mixed-use development along the north bank of the Yangtze River. We selected a target of managing 90% of a 1:100 year rainfall event onsite and controlling the discharge of the remainder to the River. We used GIS to assign infiltration rates and below grade storage capacity to each horizontal surface within the City and used a parametric dashboard to display the effects of making changes to the design on the stormwater management target. Through combining these tools we were able to optimize the distribution of strategies across development parcels, roads and open space.

Keywords: Climate, Density, Infrastructure, Sustainability, Urban Planning

中国中部地区气候变化带来的可预测影响之一为降水增多，极强降雨事件的增加。2015年，中国政府批准了16个城市作为示范"海绵城市"，其中之一就是武汉。受到当地政府委任，我们针对沿长江北岸的综合开发项目提出可持续总体规划。作为规划的一部份，我们设立了洪雨水管理的可持续设计目标，现场管理90%的百年一遇降雨量，并对排入河道的剩余雨水进行有效控制。我们运用地理信息系统(GIS)，为城市水平表面层设定目标渗透率和地下雨水存储量，并运用参数化工具仪表板显示设计调整对于雨水管理目标带来的影响。结合这些措施，我们得以优化开发地块、道路和开敞空间的布局策略。

关键词：气候、密度、基础设施、可持续性、城市规划

Introduction

One of the predicted effects of climate change in Central China is an increase in precipitation and an increase in extreme rainfall intensity. Since 2008, the number of cities that have been affected by flooding has more than doubled, whilst the flow rates in major rivers has remained largely constant. In 2013, more than 200 cities reported that they suffered from flooding at some point during the year (Y.O., 2015). The increased risk of flooding has become one of the biggest environmental issues that China faces today. Extreme weather conditions brought by global warming, loss of natural water bodies and deforestation, and an ever-increasing area of impervious surfaces resulting from rapid urbanization are among the factors that lead to the flooding issues in modern Chinese cities.

In order to minimize flooding risks and try to maintain or restore the natural ecological systems within the urban environment, in 2013 the Chinese government introduced the "sponge city" concept, for which it has pledged billions of dollars to financially support the strategies necessary to effect a

引言

中国中部地区气候变化带来的可预测影响之一为降水增多，极强降雨事件的增加。自2008年以来，受到洪水影响的城市数量翻番。与此同时，主要河道流量几乎保持不变。2013年，超过200个城市上报在2015年的某个时期遭受洪水影响。不断上升的洪水危险已成为当今中国面临的最大环境问题之一。全球气候变暖导致的极端天气情况、自然水体的流失和滥砍滥伐、城市化速度加快引起的不透水面积不断增加是导致如今中国城市洪水泛滥问题的主要因素。

为了尽量降低洪水危险并保持或恢复城市环境内的自然生态系统，2013年中国政府提出了"海绵城市"这一概念，并允诺提供数十亿的资金支持该政策策略的有效实施，从而对城市发展过渡起到积极影响。实现"海绵城市"概念需要彻底改变传统的城市设计和规划手法，提倡城市应具有弹性以适应环境变化和风暴天气。"海绵城市"，顾名思义，城市应如一块海绵，可以吸收、存储、排出、净化雨水，并释放雨水用于灌溉、冲厕和其他非饮用水用途（Che, S. et al.,2015）。

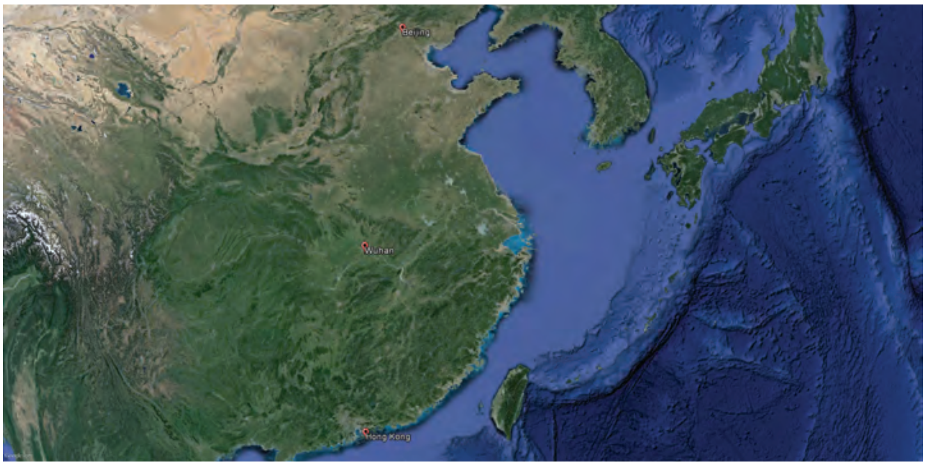

Figure 1. Location of Wuhan, China. (Source: Google Earth, Landsat 2016)
图1. 中国武汉区位（来源：谷歌地球，2016卫星图像）

significant transition in urban development. The Sponge City concept calls for a fundamental change in traditional urban design and planning approaches, and advocates for cities that are resilient to environmental changes and storm events. As the name of the concept implies, a city should act as a "sponge," which absorbs, stores, drains and purifies water when it rains, and releases the stored water later for use in applications such as irrigation, toilet flushing and other non-potable uses (Che, S. et al., 2015).

In 2015, 16 cities were approved as models for "Sponge City" development, and these cities are tasked with managing 60% of their rainfall onsite without discharging it to rivers, and, in the process reducing flood risk, preserving the natural hydrological cycle and creating opportunities for reducing potable water demand through using collected rainwater instead of drinking water for applications such as irrigation and some sanitary uses.

In 2015 Adrian Smith + Gordon Gill Architecture was requested to prepare a master plan for an urban infill site of approximately. 90-hectares in one of the Pilot cities, Wuhan (Figure 1). Located on the 2nd city ring road along the north bank of the Yangtze River, the site is set to become a world-class business district, attracting corporate headquarters, complemented with high-quality riverfront residential neighborhoods, retail, entertainment and recreational amenities (Figure 2). In order to transform the district into an active and healthy living-working neighborhood, major infrastructure improvements would be needed to manage rainfall. The district has been subject to regular and severe flooding over the past few years and an infrastructure report, prepared by AECOM in support of a broader regional masterplan, cited an inadequacy of conveyance infrastructure and pumping facilities to transfer stormwater to the adjacent Yangtze River. We felt this was an opportunity to incorporate the principals of Sustainable Drainage or Low Impact Design at a district scale and to go beyond achieving the initial targets of a "Sponge City" concept into the planning and design phase. Sustainable drainage is a design philosophy that aims to manage rainwater as close to the source (I.e., the point at which it hits the ground) as possible. Through this technology, natural hydrological balance is maintained, opportunities to capture rainwater for reuse are maximized, infrastructure investment is minimized and resilience against the risk of flooding can be achieved.

Four design approaches – creating natural green space, using pervious surface and subsurface to maximize infiltration capacity, harvesting and storing rainwater, and managing discharge to the Yangtze River –

2015年，16个城市被批准作为"海绵城市"开发的模型，其目标为现场管理60%，而不是排入河道。这样可降低洪水危险、保持自然水循环，并通过采用收集雨水代替可饮用水进行植物灌溉和卫生设施用途，从而降低可饮用水需求。

同年，AS+GG建筑公司受到委任，对试点城市之一武汉（图1）约90公顷的城市拆迁用地进行总体规划。该基地位于长江北岸的二环城市道路周边，规划设计致力于打造吸引公司总部入驻的世界级商务区，并配备高品质的滨河住宅区、商业、休闲娱乐设施（图2）。为了成功将该区域改造为具有活力、健康的生活工作社区，改善主要基础设施以便对雨水进行有效管理十分必要。该区域在过去几年内频繁遭遇严重的洪水灾害，艾奕康公司（AECOM）为区域总体规划编制的基础设施调查报告显示，基地现有的排水设施和抽水设备不足以完全将雨水排入相邻的长江。我们认为，应结合可持续排水或低影响设计策略，从而在规划设计阶段实现最初设定的"海绵城市"概念目标。可持续排水设计策略旨在将雨水就近排入地表（如雨水落入地面的点）。通过该技术，城市得以保持水文平衡，最大化雨水收集和再利用，降低基础设施投资，同时提高城市应对洪水灾害风险的能力。

规划设计采用了四项设计策略，即打造天然绿色空间、应用透水表面和地下层提高渗透能力、收集并存储雨水、对排入长江的水排放进行管理。在这四项策略的协同作用下， 90%的现场雨水管理目标将得以实现。我们将在以下段落对这些策略进行详细解释。

Figure 2. Illustrative plan of the Wuhan Erqi Masterplan. (Source: Adrian Smith + Gordon Gill Architecture)
图2. 武汉二七总平面（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

Figure 3. Courtyard design illustrating green spaces with surrounding bioswale and hardscape (Source: Adrian Smith + Gordon Gill Architecture)
图3. 庭院设计，表现绿化空间及周边的生态洼池和硬质铺地（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

were taken and would work synergistically to achieve the 90% onsite water management goal. The strategies are explained in more detail in the following paragraphs.

Creating Natural Green Space

Green space is one of the most efficient ways of reducing the volume of rainwater that needs to be managed through piped infrastructure, at the same time, water can soak into the ground and drain naturally to the Yangtze River or recharge the local aquifers. In order to restore the local hydrogeological balance and improve biodiversity, we preserved and restored natural vegetated areas of various types that covered 15% of the total site area. The run-off coefficient for managed parkland was dependent on the vegetation cover and underlying soil type; consequently additional green infrastructures, such as filter strips, bioswales, infiltration basins, retention ponds and detention basins were integrated into the green areas, and distributed in the district (Figure 3).

Using Pervious Surfaces And Sub-Surfaces To Maximize Infiltration Capacity

There is a direct relationship between the probability of flooding and impervious area coverage. Analysis of Landsat satellite imagery taken between 1987 and 2007 showed that the area of land in Wuhan that was 45–80% impervious increased by almost 425% from 113 km2 to 591 km2 and the area of land that was >80% impervious increased by 221% from 175 km2 to 561 km2 (Figure 4) (Xie and Zhou, 2015). There is no doubt that the increase in impervious areas has contributed to the flooding in Wuhan that

打造天然绿色空间

绿色空间是减少雨水管道排放量最为有效的方式之一。同时，雨水浸入地面，自然排出至长江并补充蓄水层。为了恢复当地水文地质平衡、改善生物多样性，规划设计决定保留并恢复各类天然植被区，15%的总基地面积将被植被覆盖。公共绿地的径流系数取决于植被覆盖率、地下层沙土性质，及辅助绿色基础设施，因此，绿地的设计有效结合了滤水带、生态沼泽、渗滤池、澄清池和蓄洪水库等绿色基础设施，分散布置在基地中（图3）。

采用透水表面和地下层提高渗透能力

不透水面面积的多少直接影响着洪水发生的概率。通过对地球资源卫星于1987年到2007年间拍摄的卫星图片的分析显示，武汉陆地面积中不透水率在45–80%之间的不渗水地面面积增加了近425%，从113平方公里增加到591平方公里；不透水率大于80%的不渗水地面面积增加了221%，从175平方公里增加到561平方公里（图4）（谢启娇，周志翔，2015）。毋庸置疑，不渗水面积的增加是武汉频繁发生洪灾的主要因素之一。为了减少城市区域的不渗水面积，设计中结合了数项技术以最大化地表和地下层的渗水率。

我们重点设计了公共区域内的步道、自行车道、道路中间缓冲带。步道采用透水铺面以便雨水通过表面渗入，而不是流入周边区域或雨水沟。树池中结合设置雨水花园以吸收步道溢出的雨水径流，并形成舒适宜人的微气候，并为行人和骑车者带来遮阳效果。模块化的塑料框架填充经过工程设计的沙土混合物为有效的地下层设计策略，可设置在步道、雨水花园和自行车道下方。上述模块化框架可最大化地面层

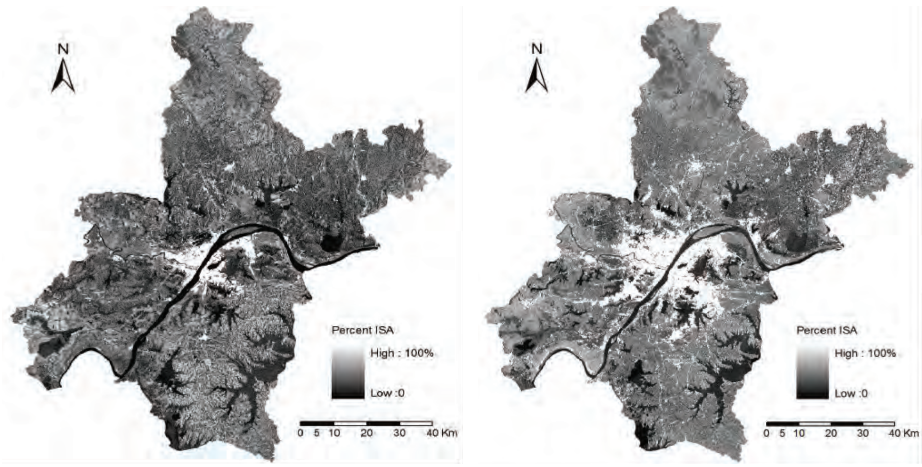

Figure 4. Spatial distribution patterns of percent impervious surface area from TM images acquired on September 26, 1987 (left) and April 10, 2007 (right). After Xie and Zhou, 2015. (Source: Environmental Engineering and Management Journal)
图4. 不透水面比例的空间分布格局比较。左图为1987年9月，右图为2007年10月。谢启娇与周志翔，2015。（来源：环境工程与管理期刊）

occurs commonly. To reduce the impervious area within an urban setting, several techniques were incorporated into the design to maximize the infiltration capacity of both surface and sub-surface.

We focused on the design of sidewalks, bike lanes, road medians and buffers in the public realm. Pervious pavement were used in the sidewalks to allow water to percolate through the surface rather than running off into surrounding areas or into storm drains; raingardens were integrated with tree pits to absorb more rainwater run-off from sidewalks and provide a pleasant microclimate as well as shading for pedestrians and cyclists; a modular plastic framework filled with an engineered soil mixture was introduced as a sub-surface strategy which would be located under the sidewalk, rain gardens and the bike lanes. The abovementioned modular framework would maximize the infiltration capacity of the ground and support large tree growth by providing more space for tree root expansion in an urban environment (Figure 5).

We also provided guidelines, Key Performance Indicators and stormwater management recommendations for all development parcels, where the area of impervious surfaces should not exceed 10%. Green roofs, raised pavement, pervious asphalt or concrete surfaces were among the strategies that would help to achieve the requirement.

Harvest And Store Rainwater

Implementing a rainwater harvesting system was an integral component of the stormwater management strategy; reducing the burden on the municipal drainage network and providing a source of non-potable water for use in toilet flushing, cooling towers and irrigation. By reducing this dependence on municipal water supplies, a rainwater harvesting system can help lower water bills and municipality's investment in water treatment infrastructure. Rainwater will be collected from the surface and stored in a tank or cistern which can be located in a basement or below ground. Depending on the specific project's requirements, tanks, which can be modular can be manufactured from a variety of sizes and materials, with High Density Polyethylene (HDPE), fiberglass, or galvanized steel being the most common.

We aimed to facilitate 20% distributed storage in a 1:100 year storm event, with this approach being applied across development parcels, on building rooftops and podium decks. To achieve the goal, potential regulations and incentives for developers, applied in other parts of the world were suggested to the Wuhan Land Use and Urban Spatial Planning

的渗水率，并为城市行道树树根提供更多的生长空间，支持大树的生长（图5）。

我们还针对所有开发地块提供了指引、主要性能指标和雨水管理实施建议，提出地块内不渗水表面面积不应超过10%，并提供了达到目标的相应策略，包括绿色屋面、架高人行道、可渗透沥青或混凝土表面等。

雨水收集和储存

雨水收集系统是雨水管理系统必不可少的一部分，可降低市政排水网络的负担，同时可作为非饮用水源，满足冲厕、冷却塔和灌溉用水需求。雨水收集减少对市政供水的依赖，从而降低水费以及政府对水处理基础设施的投资。降落在地表的雨水将被收集起来，存储至位于地下室或地表下的水箱或水池中。根据具体的项目要求，水箱可以运用模块化生产或采用不同的尺寸和材质，常用材料包括高密度聚乙烯（HDPE）、玻璃纤维、镀锌钢等。

我们的目标是实现20% 百年一遇的雨水量的分布式存储，措施将应用于所有开发地块的建筑屋顶和裙楼平台。为了实现这一目标，我们向武汉土地利用和城市规划研究中心提供一些适用于开发商的规范和激励措施，作为雨水管理设计文件的一部分。这些规范和激励措施在世界其他地区已得到广泛应用。

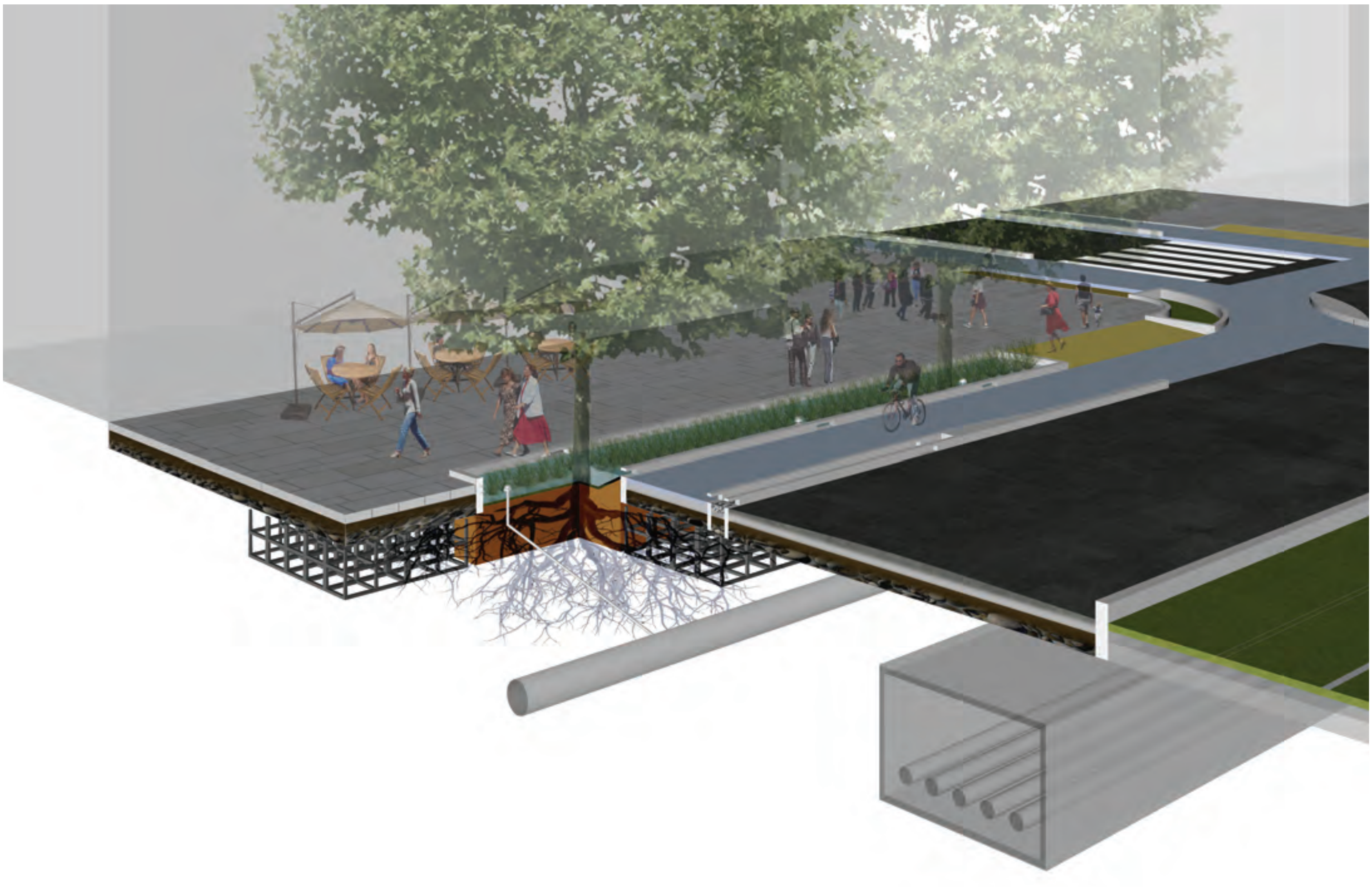

Figure 5. Modular structural infiltration cells shown below the sidewalk and bike lane. Can be filled with un-compacted soil to provide growth medium for tree roots. (Source: Adrian Smith + Gordon Gill Architecture)
图5. 自行车道及人行道下面的可渗透单元。可填充蓬松土壤为行道树树根提供生长介质。（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

Research Center as part of the storm water management strategy documentation

Manage Discharge To The Yangtze River

Rainwater that flows over land or impermeable surface such as paved streets, parking lot, and building rooftops often contains pollutants such as trash, chemicals, oils and dirt, which can harm the ecosystem if discharged directly into the river. The ecological health of the river is being addressed by cities and environmental organizations alike and it is important that our design contributes positively to improving the water quality of the Yangtze River.

To manage the stormwater discharge into the Yangtze River, a riverfront landscape design scheme would be implemented to remediate the direct discharge, and, at the same time restore the ecological system along the river. By preserving and restoring the riverfront wetland area, we created a water system of streams and ponds that would slow down the discharge, and purify and sediment the stormwater before it would eventually run into the river. A network of on grade pathways and elevated boardwalks were designed throughout the wetland riverfront area to allow access to the riverfront, provide recreational area for residents, and serve as an ecological site for educational purposes.

The purpose of this research paper is to document a parametric process which was developed and used to test the various strategies described above and their effectiveness in achieving the overall rainwater management target.

Method

The design of the Wuhan Erqi district was undertaken using Autodesk AutoCAD 2015. The masterplan was then imported into ESRI ArcGIS v10.3.1 for the development of the stormwater management strategy. Attributes were then assigned to each feature. Finally the overall performance was tested using a custom simulation tool.

GIS development

The GIS database was populated using Feature Classes that represented each potential land use type within the overall development area, which for simplicity was divided into parcel and non-parcel areas (Figure 6).

Within 'parcels' there were:

1. Setback area

Figure 6. Development of masterplan features within ArcGIS (Source: Adrian Smith + Gordon Gill Architecture)
图6. ArcGIS软件在总规划设计中的应用（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

2. Podium area
3. Individual buildings
4. Tower area
5. Intensive green roof area
6. Parcel soft-scape
7. Parcel hardscape

Outside of parcels (within the public realm area) there were;

1. Public open-space
2. Sidewalks
3. Roads
4. Traffic separation curbs and traffic islands

In order to ensure fidelity of the model it was essential that none of the above features overlapped and so, for example a podium feature might appear as a hollow rectangle with an intensive green-roof filling the space.

Having established a non-overlapping site coverage database, we identified a target rainfall event. Data provided to us by the Wuhan Landuse and Spatial planning Bureau (WLSP) indicated that the strongest 24-hour storm event in the past 150 years was 314 mm (recorded in June 1959) and the greatest 1-hour intensity was 102mm (recorded in July 1998). Unfortunately, beyond these two factors, no further information was provided.

Our stormwater management goal for the project was defined as managing 90% of the 1:100 year 24-hour storm event onsite. The rationale behind establishing 90% as the target is that based on pre-development conditions for topology and soil coverage,

管理排入长江的雨水

流经地面或铺砌街道、停车场和建筑屋顶等不渗透表面的雨水通常包含垃圾、化学物、石油和灰尘等污染物，若直接排入河流，则会破坏生态系统。河流的生态健康是政府和环境保护机构共同关注的问题，因此，促进长江水质的改善是我们的规划设计的一个重要原则。

为了管理排入长江的雨水，规划设计将在滨河区设置生态景观绿地，过滤直接排入长江的雨水，同时修复沿河生态系统。通过保留和保护沿河湿地，我们设计了由溪流和池塘组成的生态水网。雨水在排入长江前将流经此生态水网，流速得到降低，雨水得到净化和沉淀。结合小径和架高木栈道的设计，整个沿河湿地区域将为居民提供休闲休憩空间，并可作为生态环保教育基地。

在规划设计中，我们使用了参数化手段，来测试上述不同设计策略在实现整体雨水管理目标中的效率。此研究报告旨在记录此参数化设计流程。

方法

武汉二七区的规划设计采用Autodesk AutoCAD 2015软件。我们将设计总平面图导入ESRI ArcGIS v10.3.1 软件进行雨水管理策略设计。在软件中，我们为给不同类别的设计元素设定属性参数。最后，将数据导入特别定制的模拟软件来测试设计的整体性能。

地理信息系统（GIS）开发

GIS数据库由要素类组成，要素类代表整个开发区域每一种可能的用地方式，我们将其简单分为开发地块和非地块区域（图6）两大类：

“开发地块”内有：

1. 退线区

we estimated that following a major storm event, less than 10% of rainfall on the site would run-off directly into the Yangtze River. Consequently, in order to maintain some degree of natural watershed discharge to the river, we have set the target of 90% onsite retention or infiltration and 10% managed river discharge.

Having established a site plan and storm event target, the next step was to develop feature based strategies for managing rainfall. There are a finite number of short-term outcomes for rain from a storm event:

1. Some water is lost through evaporation
2. Some water will soak into the ground or into green roofs
3. Some rainfall can end up in rooftop or podium deck storage – known as blue roofs
4. Some rainfall can be collected through drains and stored in tanks
5. Some rainfall will run-off into ponds or other surface storage strategies
6. Some rainfall will run-off into storm drains and be discharged into the Yangtze river

Our challenge was to manipulate these outcomes, through selected design strategies, to ensure that outcome 6 (run off to the Yangtze River) was 10% for a 314mm rainfall event. Evaporation was not considered in the modelling of a storm water management strategy as quantification of it is unreliable, being subject to a number of factors, for example surface material properties, temperature, windspeed and humidity, which we could not reliably predict.

The design strategies for each of the 5 reported outcomes were as follows:

1. Infiltration into the ground or the soil of intensive green roofs. Water can infiltrate into the soil in several ways:

   a. Through simply soaking into the soil matrix, vertically by gravity and capillary action. In this case it is subject to Horton's equation which shows mathematically that under rain conditions that exceed infiltration rate, the capacity of soil to absorb water decreases exponentially with time and eventually reaches a constant rate. This was primarily applied to public open space green areas, where infiltration rate would likely be exceeded by precipitation rate. In this case it was necessary to undertake an additional series of steps to calculate runoff. This is described at the end of the methods section under the sub-heading "green space runoff estimation."

   b. Enhanced infiltration, where water is pumped at relatively low pressure or flows via gravity through a series of vertically stacked slotted drains below the ground (similarly to sub-surface irrigation). In this case we assumed that soil water storage capacity achieved a percentage of soil depth, based on the soil porosity. Our default value for this was 20%.

   c. Via infiltration chambers, these can be either empty chambers that store water and allow it to percolate through a geotextile membrane and into the soil, or they can be modular frames filled with engineered soil which allows a greater volume of water to be stored. The storage capacity varied based on type with 90% being the volume assigned to infiltration chambers and 20% being assigned to engineered soil storage chambers.

2. Blue roofs. Blue roof strategies include storage of water beneath pedestal pavers and storage of water beneath extensive (shallow-type) green roofs. In both cases a storage capacity of 85% was assigned as the default value.

3. Storage tanks. Storage tanks are an important part of the rainwater harvesting strategy, being strategically used to harvest water from areas where it is likely to be cleaner and therefore require a less energy and chemical intense treatment methodology. Storage tanks were assigned to the roofs of towers, podiums and a number of other features. Their default storage capacity was assigned as being 20m3 for hardscape areas, 25mm per m2 footprint for towers, and 10mm per m2 for podiums.

4. Ponds and surface storage strategies. This approach included ponds (or other rain water detention type of approaches) in public green space and water features in hardscape areas. Default values of 100–300 m3 for the major public parks and 2.0 m3 for hardscape were assigned.

5. Run off to the Yangtze River. Whatever water was not managed by one of the above strategies was considered runoff

2. 裙房区
3. 单体建筑
4. 塔楼区
5. 密集绿色屋顶区
6. 地块软景观
7. 地块硬景观

地块以外区域（公共区内）:

1. 公共开放空间
2. 人行道
3. 道路
4. 交通隔离带和交通安全岛

为了确保模式的精确度，上述特征不能重叠。例如，裙房要素类可以表现为无填充矩形边界，内部填充密集绿色屋顶。

我们建立了一套非重叠的场地表面要素数据库，并明确了目标降雨事件。武汉土地利用和城市规划研究中心提供的资料显示，过去150年中，最大的24小时降雨为314毫米(1959年6月)，最高小时降雨强度为102毫米/小时（1998年7月）。遗憾的是，除了上述两组数据，武汉土地利用和城市规划研究中心并未提供其他信息。

本设计的目标是现场管理90% 的百年一遇24小时雨水量。这一目标是基于前期开发条件−地形和土壤覆盖情况确定的。我们预计在暴雨情况下，基地直接流入长江的雨水量会低于10%。因此，为了保留一定的自然流域雨水排入河流，我们确定基地的雨水滞留或过滤量为90%， 管理雨水排放量为10%。

确定基地总平面和雨水事件目标之后，下一步便是设计基于特征的雨水管理策略。暴雨事件发生后雨水的短期去向途径包括以下几种:

1. 部分雨水会直接蒸发。
2. 部分雨水会渗入地面或绿色屋顶。
3. 部分雨水将存入屋顶或裙楼平台−称之为蓝色屋顶。
4. 部分雨水可通过排水沟收集存储在水箱。
5. 部分雨水会流入池塘或其他表面蓄水设施。
6. 部分雨水将流入雨水排放沟，排入长江。

that would need to be managed via storm drains and interceptors and discharged to the Yangtze River. We felt it important to retain some degree of natural discharge in order to maintain some elements of surface hydrology.

In order to allow for calculation of all of the above outcomes, which are influenced by multiple factors, we linked the GIS database to Excel using a two-way connection (GISconnector for Excel Ver 2.1). This tool allowed us to make changes to attributes such as area, soil depth etc., which were immediately reflected in Excel, where calculations were performed and then the changes made automatically back in the GIS attributes table.

Simulation Modelling

A custom multi parameter simulation tool was developed which used the data exported from GIS, combined with Rhino models of the building to allow us to test the various storm water management planning scenarios. The tool constantly updated the 5 outcomes above, reporting via a web-based user interface. Users are able to vary any of the strategies at a feature, parcel or district scale and the results are presented as percentages and total volumes.

Green Space Runoff Estimation

As described earlier, for green spaces, where there is a finite rate at which rainwater can penetrate into the soil we had to develop a mathematical subroutine that allowed us to incorporate variable run off volumes into the calculations.

This was achieved in two steps. The first step was to estimate rainwater infiltration rates. Soil infiltration is determined by the Horton equation: $f_p = f_c+(f_0-f_1)e^{-kt}$ where f_p is the infiltration capacity at some time (t); f_c is the equilibrium infiltration rate, f_0 is the initial infiltration rate, k is a constant representing rate of decrease in f capacity. For the purposes of this study we used American Society of Civil Engineers (ASCE) data to input values for a typical soil type, where f_c = 18.75mm/hr, f_0 = 80mm and k = 8. This curve is represented in Figure 7 (Figure 7). In simple terms this equation gives an infiltration rate of 30.5mm for the first hour and cumulative infiltration capacity of 461.75mm over a 24-hour period.

The second step was the establishment of hourly rainfall rates for a given 24-hour rainfall volume. Rain event profiles are highly variable and can follow many forms. We chose a probability density function curve as being representative of a typical major storm event and developed a curve with a maximum

我们的挑战在于如何通过选择设计策略来控制这些效果，从而确保在314毫米降雨事件中，第六种途径（流入长江）的比例为10%。由于雨水蒸发量受到多种因素（比如材料属性、温度、风速及湿度）的影响，无法做出可靠预测。因此在暴雨水管理策略建模中，将不考虑蒸发作用。

针对剩下五种途径的设计策略如下：

1. 渗入地面或密集型绿色屋面的土壤中。水分可通过以下几种方式渗入土壤：

a. 通过重力及毛细管作用直接垂直渗透入土壤基质。这种情况将适用霍顿公式，即在超过渗透率的降雨条件下，土壤的吸水容量将随着时间推移以指数方式降低，并最终达到恒定值。在这种情况下，有必要采用其它一系列措施来计算径流量。在 标题“绿地径流估算”的“方法”章节的末尾将对此进行说明。

b. 强化渗透。即采用相对较低的压力或流速，通过重力作用或位于地下的一系列竖向堆叠带沟槽地漏（类似与地下灌溉）将水泵入。在这种情况下，我们预计土壤的蓄水量将达到土壤深度的一定比例（根据土壤孔隙度的不同而有所差异）。我们采用的默认值为20%。

c. 经由渗透腔渗透。渗透腔可为储水空腔，储存雨水并使其通过土工织物薄膜渗入土壤；或为储存量更大的填充有工程土的模块化框架。渗透腔的存储量根据种类的不同而有所差异，我们将90%的容量分配给渗透孔洞，而20%的分配给工程土蓄水孔洞。

2. 蓝色屋面。蓝色屋面策略包含底部铺装材料下方的雨水存储及拓展型（浅型）绿色屋面储存。在这两种情况下， 我们采用85%的储水量作为默认值。

3. 储水水箱。储水水箱为雨水收集策略的重要部分，水箱布置在相对干净的区域收集雨水，因此雨水处理所需的能耗和化学处理强调较低。储水水箱一般设置在塔楼、裙楼及其他诸多结构的屋面。硬质景观区的默认储水量为20立方米，塔楼为25毫米/平米（基底面积），裙楼为10毫米/平米。

4. 水池及地表储水策略。该方法要求在公共绿地设置水池（或其它雨水滞留方式），在硬质景观区设置水景。主要公共空间的默认值为100 – 300立方米，硬质景观区的默认值为2.0立方米。

5. 流入长江。如未采用上述任何策略进行雨水管理，则需要通过雨水沟及截流装置管理径流，并流入长江。我们认为保留一定程度的自然排水很重要，将有助于保护地表的水文元素。

为了实现所有上述结果的计算（受到多重因素的影响），我们通过双向链连接，将GIS数据库链接至Excel中（Excel Ver 2.1采用GISconnector）。这一工具确保我们可以对属性进行变更（如面积、土壤深度等），并立即体现在开展计算的Excel中，随后，变更将自动返回至GIS属性表。

模拟建模

我们开发了定制化多参数模拟工具，利用GIS输出的数据，与基地的Rhino模型相整合，确保可对各种暴雨水管理规划场景进行测试。这一工具不断对上述五种效果进行更新，通过网络用户界面进行报告。用户可根据不同的特征、地块或区域更改任何一种策略，结果将以百分比及总容积的形式呈现。

绿地径流估算

正如上文提到的，绿地空间具有一定的雨水渗透能力。因此，我们编制了数学子程序，将径流量这一变量体现在计算中。

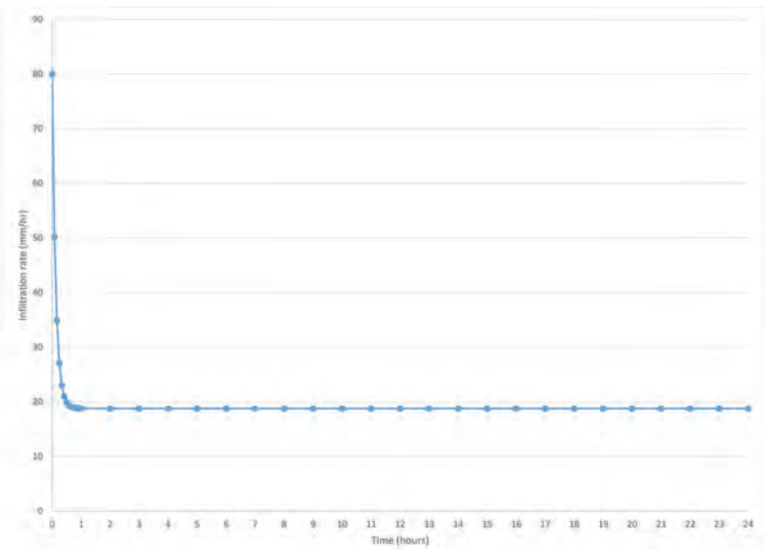

Figure 7. Infiltration rate for an engineered soil mix used on green roofs and in tree planters. (Source: Adrian Smith + Gordon Gill Architecture)
图7. 绿色屋面和树池工程设计土壤的渗透率。（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

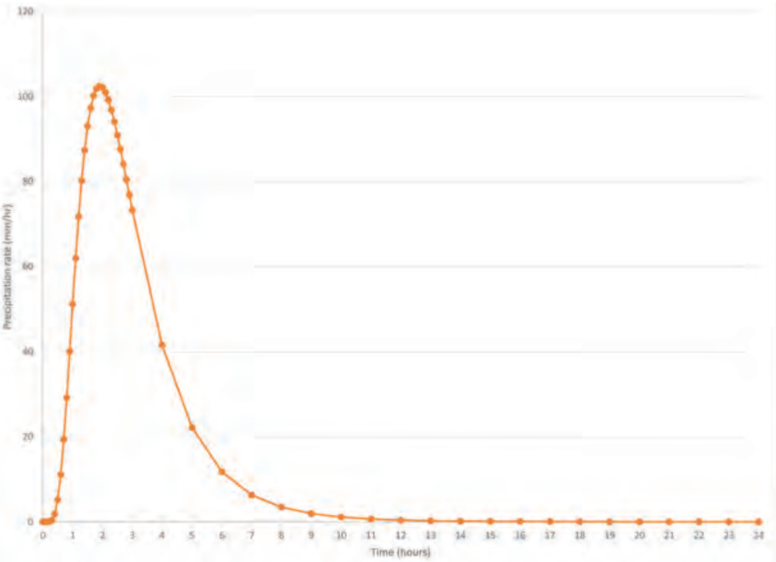

Figure 8. Probability density function defining hourly rainfall intensity with a maximum of 102mm/hr and a total of 314mm in24hrs (Source: Adrian Smith + Gordon Gill Architecture)
图8. 按照最大降雨强度102毫米/小时及24小时总降雨量314毫米绘制的降水强度概率密度函数曲线
（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

intensity of 102mm/hr and a total rainfall volume (over 24 hours) of 314mm. This is represented by the curve shown in Figure 8 (Figure 8).

This allowed us to mathematically generate an hourly rainfall rate for any given 24 hour volume, which could be subtracted from the maximum hourly infiltration rate to return infiltration volumes and surface run off volumes for any given rainfall event. This approach has clearly made a number of assumptions regarding the design rain event profile and in the case that better information was provided we would be able to replace the formula within the model with either empirical data or with an improved mathematical algorithm.

Results And Discussion

Through adjusting the relationships between strategies, we were able to achieve the target storm water run-off rate (Figures 9 and 10). The most desirable outcome was that all development parcels were self-sufficient in terms of rain water management – using a combination of blue roof water storage, intensive green roofs with enhanced infiltration and tank based water storage techniques to achieve this. Sidewalks, setbacks and physically separated bike lanes would work together to manage rainfall entirely through subsurface infiltration – via a combination of infiltration chambers and enhanced infiltration modules. Generally, runoff from roads would be collected in the storm drains and be discharged into the River. However, so as to meet some of our other Urban planning KPIs that included

计算包括如下两个步骤：第一步是评估雨水入渗率。采用霍顿公式：fp = fc+(f0−f1)e−kt计算确定土壤入渗率。其中，fp指某个时段（t）入渗容量；fc指稳定入渗率；f0初始入渗率；k为容量衰减代表常数。针对本研究目的，我们采用了美国土木工程师协会(ASCE)数据，输入特殊土壤类型值：fc = 18.75毫米/小时，f0 = 80毫米，及 k = 8。数学曲线参见图7（图7）。简言之，本公式说明第一小时雨水入渗量为30.5毫米，并且24小时累计入渗量达461.75毫米。

第二步是设定特定24小时降雨量小时降雨率。降雨事件分布变化较大，并可呈现多种形式。我们选择了代表特定暴雨的概率密度函数曲线，并按照最大降雨强度102毫米/小时及24小时内总降雨量为314毫米绘制曲线。请参见图8所示曲线（图8）。

由此，我们可计算得出特定24小时降雨情况下的每小时降雨量。针对某一特定降雨，最大小时入渗量减去小时降雨量得出入渗量及表面径流量。在该方法中，就设计雨型作出了较多假设。如提供更详细的信息，我们则可采用经验数据公式或优化的数学算法替换该模型公式。

结果及讨论

通过调整各个策略之间的关系，我们得以实现目标降雨径流率（图9、10）。最理想的结果是所有开发地块可自行进行雨水管理一通过采用蓝屋顶储水装置、增强入渗量的密集绿色屋顶及基于水箱的储水技术实现该目标。人行道、退界区及自行车道将结合入渗腔及增强入渗模块对整个区域表面入渗雨水进行管理。一般情况下，道路径流会被收集至雨水排水沟内，并排入河道。然而，为了满足规划设计的其他

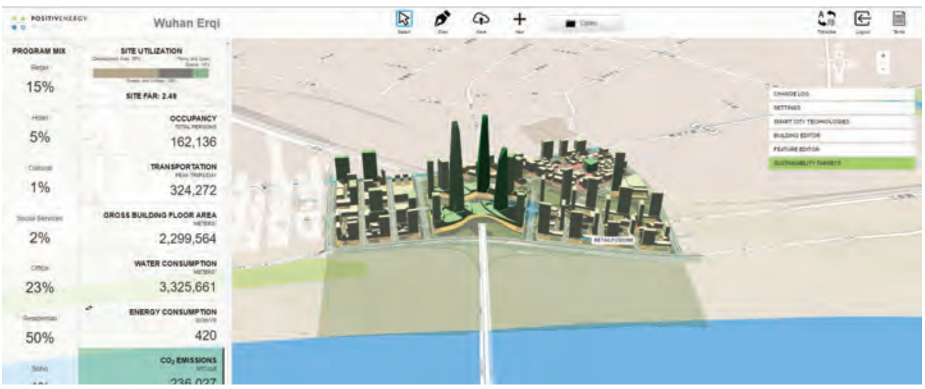

Figure 9. Screenshot from multi-parameter simulation tool. Illustrating dashboard outputs on the left side. (Source: Adrian Smith + Gordon Gill Architecture)
图9. 多参数模拟工具截图，左侧为数据输出仪表盘。（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

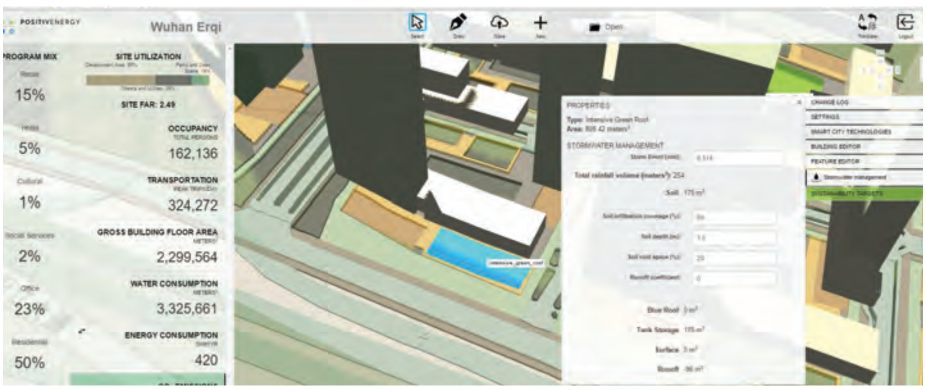

Figure 10. Screen shot from multi-parameter simulation tool. Illustrating some of the variables for a single feature. (Source: Adrian Smith + Gordon Gill Architecture)
图10. 多参数模拟工具截图，展现单个功能中的多个变量。（来源：艾德里安史密斯和戈登吉尔（北京）建筑设计咨询有限公司）

improving the quality of the environment and, understanding our responsibility for maintaining water quality in a river that provides a resource for 450 million people as well as habitat for several endangered species, rather than discharge the storm water directly (via interceptors and sediment traps), we developed a riparian landscape plan that incorporated reed bed based bioremediation strategies to remove the hydrocarbons and heavy metals that may be found in the "first flush" run off following a rainfall event.

The multi-parameter simulation tool allowed us the flexibility to very quickly alter strategies when constraints became imposed. For example if one or more parcels were unable to meet their targets we could immediately predict the effect on the overall target and make adjustments to the strategies for adjacent sidewalk.

Another element that was included in the multi-parameter model was the simulation of potable and non-potable water demand. It was assumed that 100% of stored rainfall would be available for use (once treated to an appropriate standard) for non-potable applications in the buildings on the parcel. This included toilet flushing and cooling tower make-up water (it was assumed that water for landscape irrigation would be reduced by having infiltration chambers and, during periods without rainfall would be met using treated grey water or condensate).

Some valuable lessons learned during the development of the tool:

1. Urban designers typically work in CAD. In order to make the export to GIS step more efficient, and to facilitate inclusion of changes during design, designers should georeference their CAD files, design in polygons to the greatest extent possible and avoid any overlaps.

2. On the GIS side, while using geodatabases promotes the use of multiple features, it is simpler to use just a single feature. This removes any ambiguity within attributes and ensures consistency of metadata and units. It also allows for simpler exchange of data with Excel and export to the parametric tool.

Clearly a tool such as this has tremendous potential applications in integrated urban design. Additional connections to other 'modules' include running time based strategies to determine how the system manages during a typical year, factoring cooling tower make up water demand, irrigation demand, rainfall and building water demands.

城市关键性能指标要求（包括改善空气质量），并考虑到保护长江水质的重要性（长江向4.5亿人口提供水源，并是多种濒危物种的栖息地），我们制定了相应的滨河景观规划设计，以代替截流装置及沉淀阱直接排放雨水的策略。该规划设计整合基于芦苇床的生物修复策略，以清除降雨后可能在“初期冲刷”径流中包含的碳氢化合物及重金属。

多参数模拟工具使得我们可根据施加的限制条件快速灵活改变策略。譬如，当一个或多个地块不能满足目标时，我们可立即预测对总体目标的影响，并调整附近人行道策略。

多参数模型中的另一功能是模拟饮用水及非饮用水需求。我们假定，对地块上的雨水进行处理并满足适当标准后，可将地块上储存的雨水100%用于建筑非饮用水目的。非饮用水可用于冲厕及冷却塔补水（我们假设：通过设置入渗腔可直接减少景观灌溉用水，在无降雨期间，可利用经过处理的灰水或冷凝水满足景观灌溉用水需求。）

在开发本工具期间，我们获得了一些宝贵的经验：

1. 城市设计师一般采用CAD进行设计。为了保证输入至GIS的过程更加高效，并方便设计期间进行变更，设计师宜地理参照CAD文件，最大限度采用闭合多边形进行设计，并避免重叠。

2. 在GIS的应用过程中，尽管采用地理数据库促进多要素的应用，但是仅采用单一要素则更加简洁。这避免了属性的含糊不清，并确保元数据与图形单位的一致性。同时，这还使得与Excel交换数据更加便捷，并方便向参数工具输入数据。

显然，类似这样的工具在一体化城市设计中具有巨大的应用潜力。与其他“模块”的其他联系包括基于运行时间的策略以确定典型年系统管理方式，分析冷却塔补水需求、灌溉需求、雨水及建筑用水需求等。

References:

Che, S., Xie, C., Chen, D. and Yu, B. (2015). "**Development And Constructive Approaches For Theories And Technologies Of Sponge City System"** (In Chinese), Chinese Landscape Architecture. 31 (6). p. 11-15.

Xie, Q. and Zhou, Z. (2015). **"Impact of urbanization on urban heat island effect based on TM imagery in Wuhan, China"**, Environmental Engineering and Management Journal. 14 (3). p. 647-655.

Y.O. (2015). **Why Are Chinese Cities Flooding?.** The Economist. Available at: http://www.economist.com/blogs/economist-explains/2015/08/economist-explains-5 (Accessed: 22 April 2016).