USING PARAMETRIC SIMULATION & GIS TO DESIGN A STORMWATER SOLUTION FOR A CHINESE SPONGE CITY

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ABSTRACT

In 2013, the Chinese Central Government implemented the Sponge City Program, an initiative for cities to act as "sponges" whereby managing 60% of rainfall on-site without discharging it to local rivers and sewers. Sponge Cities simultaneously reduce flood risk, preserve the natural hydrological cycle, and create opportunities for reducing potable water demand through using collected rainwater instead of drinking water for applications such as irrigation and sanitary uses.

In 2015, the planning department for the City of Wuhan, a nominated pilot city for the Sponge City Program, engaged Adrian Smith + Gordon Gill Architecture (AS+GG) to assist in the preparation of a growth plan for 90 hectares of land directly north of the urban core. As part of the masterplan design, AS+GG suggested utilizing the Sponge City Program as a primary guiding principle for both the streetscape and building design. The project set a goal for stormwater management to manage 90% of 1:100 year 24-hour storm event on-site.

This paper details the simulation approach used in evaluating strategies to accomplish the 90% stormwater management goal. Utilizing data and geometry exported from both GIS and Rhino 3D modeling software, the team developed a custom multi-parameter simulation tool which allowed us to test various stormwater management planning scenarios. The team was able to vary strategies at a feature, parcel or district scale and the results are presented as percentages and total volumes. This workflow allowed the team to quickly adjust local design strategies to monitor compliance with the overall project goals.

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 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 on site 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 AS+GG 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. The team felt this was an opportunity to incorporate the

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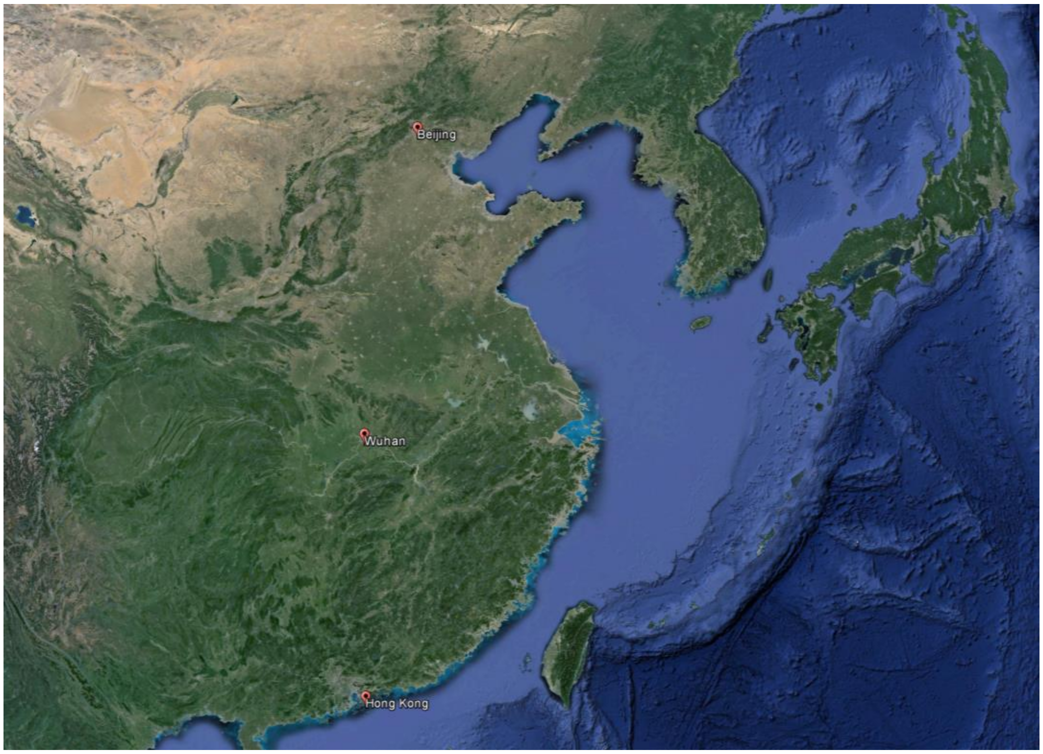

Figure 1: Location of Wuhan, China. (Source: Google Earth, Landsat 2016)

Figure 2: Illustrative plan of the Wuhan Erqi Masterplan. (Source: AS+GG)

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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 (ie. the point at which it hits the ground) as possible. Through such design, 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 - were taken and would work synergistically to achieve a 90% on-site water management goal. The strategies are explained in more detail in the following paragraphs.

DESIGN STRATEGY #1: 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, the team 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).

DESIGN STRATEGY #2: USING PERVIOUS SURFACES AND SUB-SURFACES TO MAXIMIZE INFILTRATION CAPACIY

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 km^2 to 591 km^2 and the area of land that was >80% impervious increased by 221% from 175 km^2 to 561 km^2 (Figure 4) (Xie and Zhou, 2015). There is no doubt that the increase in impervious areas has contributed to the flooding in Wuhan that 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.

The team focused on the design of sidewalks, bike lanes, road medians and buffers in the public realm. Pervious pavement was 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 above mentioned 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).

The team 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.

DESIGN STRATEGY #3: 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, are able to be manufactured from a variety of sizes and materials, with High Density Polyethylene (HDPE), fiberglass, or galvanized steel being the most common.

The team 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 Research Center as part of the storm water management strategy documentation

DESIGN STRATEGY #4: 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

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Figure 3: Courtyard design illustrating green spaces with surrounding bioswale and hardscape. (Source: AS+GG)

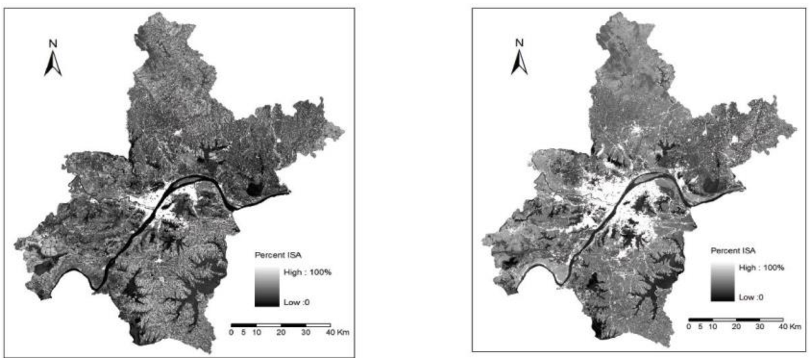

Figure 4: Spatial distribution patterns of percent impervious surface area from TM images acquired on September 26, 1987 (left) and April 10, 2007 (right). After Xie and Zhou, 2015. (Source: Environmental Engineering and Management Journal)

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: AS+GG)

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and dirt, which can harm the eco-system 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, the design utilized a water system of streams and ponds that would slow down the discharge, as well as purify and remove sediment from 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 and Rhinoceros 3D software. 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 (see Figure 6):

Within ‘parcels’ there were:

1. Setback area
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-hr 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 on site. The rationale behind establishing 90% as the target is that based on pre-development conditions - topology and soil coverage, 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% on-site 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.

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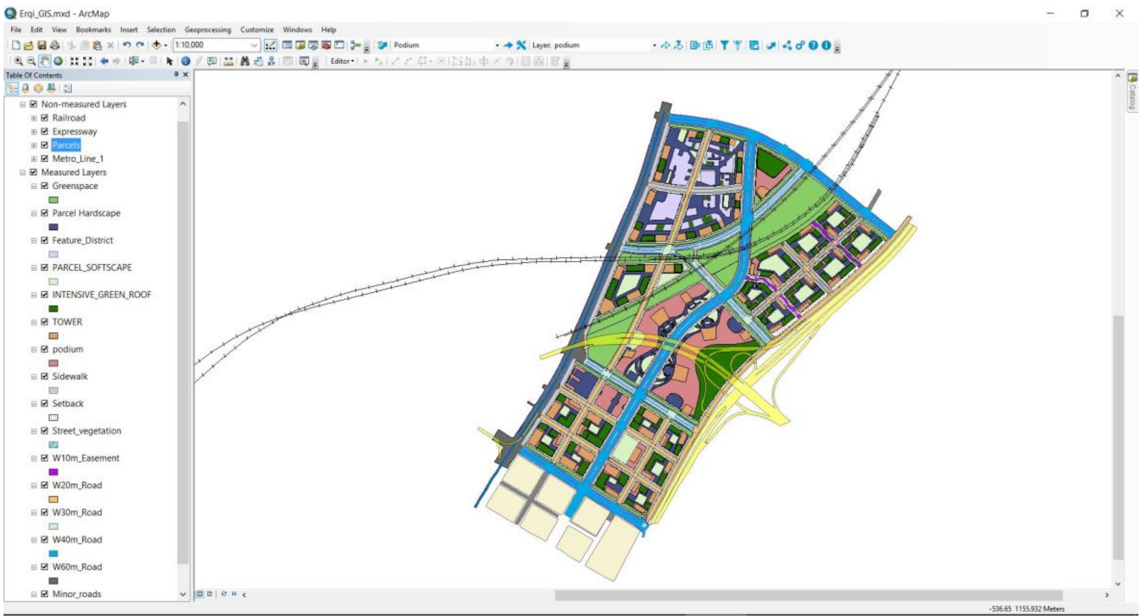

Figure 6: Development of masterplan features within ArcGIS (Source: AS+GG)

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 20m^3 for hardscape areas, 25mm per m^2 footprint for towers, and 10mm per m^2 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 m^3 for the major public parks and 2.0 m^3 for hardscape were assigned.

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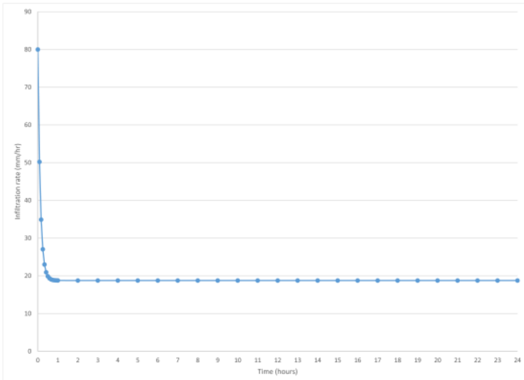

Figure 7: Infiltration rate for an engineered soil mix used on green roofs and in tree planters. (Source: AS+GG)

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

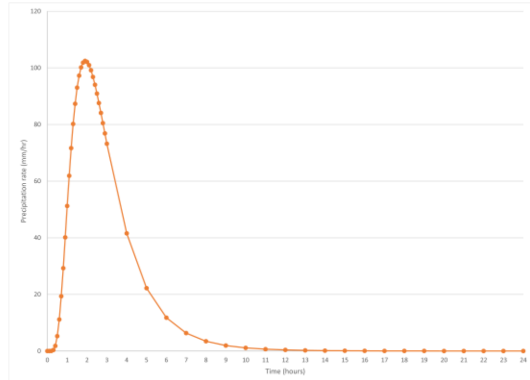

Figure 8: Probability density function defining hourly rainfall intensity with a maximum of 102mm/hr and a total of 314mm in 24-hrs. (Source: AS+GG)

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 fp is the infiltration capacity at some time (t); fc is the equilibrium infiltration rate, f0 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. 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 intensity of 102mm / hr and a total rainfall volume (over 2 hours) of 314mm. This is represented by the curve shown in 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.

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RESULTS AND DISCUSSION

Through adjusting the relationships between strategies, we were able to achieve the target storm water run-off rate (see Figure 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 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.

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This paper is a modified version of the same paper as follows:

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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)

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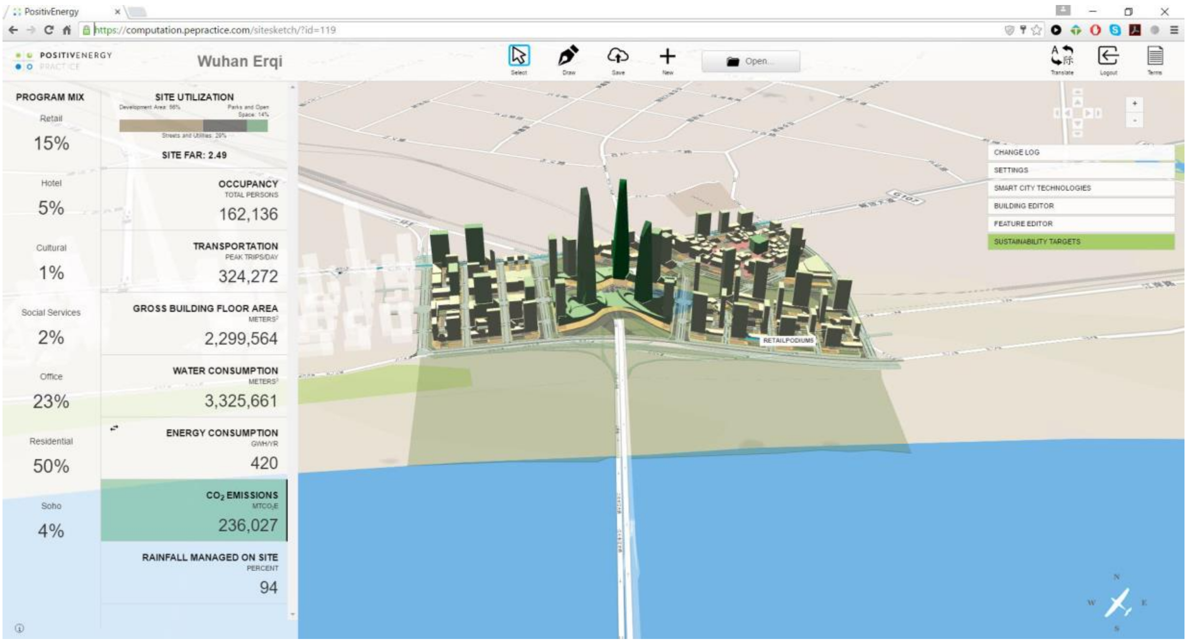

Figure 9: Screenshot from multi-parameter simulation tool. Illustrating dashboard outputs on the left side. (Source: AS+GG)

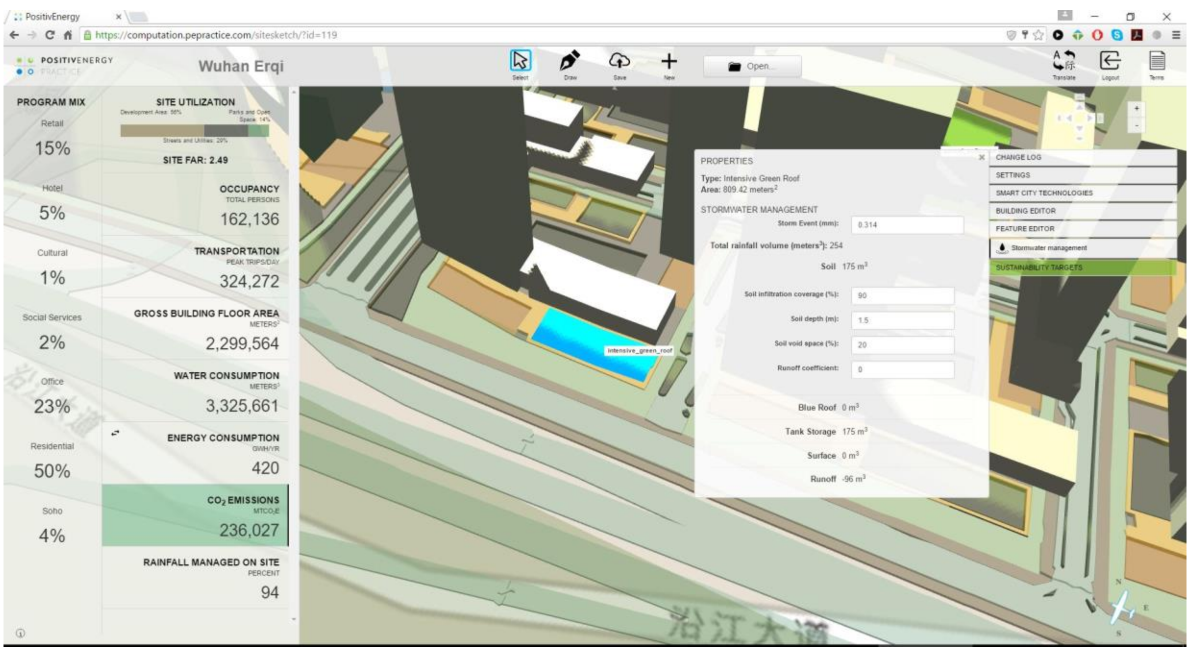

Figure 10: Screenshot from multi-parameter simulation tool. Illustrating some of the variables for a single feature. (Source: AS+GG)

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