ECOHYDROLOGY
& HYDROBIOLOGY

DOI: 10.2478/v10104-012-0029-8

Vol. 12
No. 4, 287-300
2012

Erasmus Mundus Master
Course in Ecohydrology

# Ecohydrology and good urban design for urban storm water-logging in Beijing, China

**Congying Li**

Department of Water Science and Engineering, UNESCO-IHE Institute for Water Education, 2611 AX Delft, the Netherlands;
Department of Applied Ecology, University of Lodz, Lodz 90-237, Poland (from April 2, 2013), email: licyican@gmail.com

## Abstract

Urban storm water-logging (USWL) is a worldwide problem. To address this problem in Beijing, its effects and causes were analyzed. Among others, the causes include increasing impervious surfaces and climate change. Considering the limitations of current approaches, the need for a more sustainable approach – ecohydrology (EH) – was identified. Thus concepts of EH and good urban design (GUD) were introduced and a framework of systematic EH solution with GUD, utilizing best management practices (BMPs) and source control principle, was proposed. The idea of applying a combination of EH methods with GUD was explained. This approach was expected to eliminate USWL problems, harvest stormwater and create other benefits as well. In addition, several helpful tools, models and systems (TMS) were described.

**Key words:** "7.21" disaster, stormwater utilization, best management practices, source control, runoff reduction, Living Water Park.

## 1. Introduction

With fast population growth and rapid urbanization, urban storm water-logging (USWL) is a common problem in most countries and regions around the world, including the USA, Canada, Japan, and China. It has severe impacts on social life and economy (Han *et al*. 2006). In addition, climate variability will be likely to exacerbate the risk by introducing more uncertainties. Due to these pressures and the deterioration of urban infrastructural systems, cities all over the world will experience future difficulties in efficient management of scarcer and less reliable water resources, and in providing sufficient sanitation (IHP-VIII 2012). In China, USWL has been an increasingly prevalent problem in urban areas, which leads to such consequences as heavy casualties, traffic paralysis and economic losses. According to statistics, USWL has happened in over 100 of China's 656 cities including Beijing, Shanghai, Guangzhou, Jinan, Chongqing, and Shenzhen City (ADB 2011). Especially the latest and largest USWL event in Beijing was the so-called "7.21" catastrophic natural disaster.

The USWL problems result from various causes, such as the uneven distribution of precipitation in time and space, inadequate urban water-logging emergency response systems, decreasing green areas and filling of waterbodies because of urbanization, and insufficient capacity in the stormwater drainage system without proper maintenance and upgrading (Ye *et al*. 2010; ADB 2011).

Adequate solutions have not been found yet. Generally, in most parts of the Beijing urban area, management of USWL relies on conventional stormwater management (SWM) approaches to protect life and property. By constructing stormwater drainage and sewerage pipe networks, the conventional SWM method collects and drains stormwater from developed areas into nearby water bodies to reduce the volume and peak flow of runoff from impervious areas. However, this method only focuses on disaster elimination through flood control and pollution dilution, and results in capacity limitations and pressures on the urban rivers. Moreover, Beijing has faced serious water scarcity issues during the last decade. Therefore, it is not a wise choice to attempt to solve USWL problem by solely enlarging the drainage pipeline networks and ignoring the water scarcity problems.

Based on the fact that the conventional solutions are not as effective as expected and also considering their limitations, there is an urgent need to apply a more sustainable approach. Ecohydrology (EH) with good urban design (GUD) is proposed, which can not only solve the USWL problem but also cope with the water scarcity issue. EH, a new transdisciplinary science supported by the International Hydrological Programme of UNESCO (IHP) (IHP-VII, Theme 3 and IHP-VIII, Theme 5), aims to increase ecosystem carrying capacity for the sustainable management of water (Zalewski 2000). Combined with different engineering treatment techniques, it focuses on stormwater attenuation and treatment processes through natural systems, which also are promoted by the IHP (IHP-VIII 2012; UWMP undated). EH can play an important role in urban areas. One of the focal areas of IHP VIII Theme 5 (*Ecohydrology, engineering harmony for a sustainable world*) is urban ecohydrology – *storm water purification and retention in the city landscape and potential for improvement of health and quality of life*. It is noted that, by applying best management practices (BMPs) and ecohydrological biotechnologies for water purification and retention, a perception shift of storm water management (SWM) could be achieved (IHP-VIII 2012). Therefore, according to EH principles and SWM BMPs, a systematic EH solution can be applied to sustainably solve the USWL problem and reuse stormwater as a resource (Ellis, Revitt 2010). Moreover, cities need to make the best possible use of land, such that urban lands look good and convey cultural values consistent with their location. To this end, GUD is important for EH application. This is mainly due to limited land availability within the urban areas. Thus, it is necessary to combine the application of EH and GUD. This approach also can be supported by a broader strategy – the water sensitive urban design (WSUD), popularly used in Australia. It manages all waters as resources and links the demands of sustainable SWM with urban planning, thus recreating a more robust water cycle similar to a natural system while bringing such benefits as cultural use as well (Hoyer *et al*. 2011). In Beijing, there have been several EH technologies in use, but these remain quite inadequate. Nevertheless, Beijing City has great potentials for reusing and infiltrating stormwater. These potentials can be realized through a combined EH and GUD solution.

In this paper, the main objective is to analyse options for sustainable storm water management in Beijing. The paper (1) describes and analyzes the causes and effects of urban storm water-logging events; (2) analyzes the limitations of traditional remedial methods; (3) introduces a combined EH and GUD approach as a more sustainable way forward; (4) summarizes the potentials of EH applications; (5) proposes a framework of systemic EH solutions within GUD and explains the application of a combined EH and GUD approach; and (6) identifies some important tools, models and systems (TMS) required in stormwater management and ecohydrology applications.

## 2. Study area – Beijing City

Beijing City is a national, political, economic and cultural centre. It is located in the northern tip of the North China Plain (39°N, 116°E), covering an area of 16 808 km$^2$. It has a typical moderate continental climate, hot rainy summer and cold dry winter, with an average annual rainfall of 585 mm, 75% of which occurs in summer, and rainstorms typically appearing in July and August. By 2008, Beijing had a population of more than 16.95 million (excluding the 4 million migrants), of which 12.28 million people lived in the urban area (Chen 2012; van Veehuizen *et al*. 2011; Cai, Ji 2010).

Metropolitan Beijing has experienced rapid economic and population growth (15% and 3% annually respectively from 2005 to 2008), which has brought new challenges such as a vast inflow of migrants, rapid loss of farmland and urban environmental deterioration. On one hand, water scarcity in Beijing is intensified by reductions of rainwater volumes, lagging treatment of polluted water, decreasing groundwater volumes, sharp decreases of water inflows from upstream and the drying-up of surface water. Currently, the fresh water resources per capita (of less than 300 m$^3$ per capita) are only 1/30th of the world's average and 1/8th of the national average (Cai, Ji 2010). On the other hand, Beijing also suffers from severe water-logging problems after every short-term intense rainstorm, due to the uneven precipitation in both the time and space scales, increasing impervious surface areas, obvious urban heat island effect and so on (Zuo *et al*. 2008).

Therefore, it is very important to use stormwater as a resource for humans and/or groundwater recharge in Beijing to solve both the water-logging and water scarcity problems, instead of leaving it as a disaster or draining it out of the city.

### *2.1. USWL events in Beijing*

The recent USWL event, the largest extraordinary rainstorm during the last 61 years in Beijing city, happened on the 21st July, 2012. The average daily rainfall was 170 mm all over the city, 215 mm in the urban area, and more than 200 mm within an area of 6000 $km^2$ around the city. Especially in the center of the rainstorm, in Hebei Town in the Fangshan District of Beijing city, the daily rainfall reached 541 mm, during the storm whose return period (RP) was 500 years (Yang, Bai. 2012). Because of the extremely severe consequences it caused, it was called the "7.21" catastrophic natural disaster.

The serious USWL problem that followed the rainstorm happened over about 63 roads in Beijing (30 areas with water depths of more than 30 cm and 33 areas with water depths of less than 30 cm). It was mainly distributed in areas under the overpasses and in the depressions (NETEASE 2012). In addition, the intense rainstorm and longtime water-logging triggered mountain torrents and mud-rock flows in the mountainous areas of Beijing city, all of which caused heavy casualties and property losses. Table I describes some consequences of this event.

Apart from the 2012 "7.21" event, Beijing has experienced 17 heavy rainstorms within the recent 10 year period, such as the "7.10" event in 2004, the "7.31" in 2006, the "6.13" in 2008, the "7.13" in 2009, the "6.1" in 2010 and the "6.23" in 2011 (Chen *et al*. 2011; Lan, Yang 2009; Wang, Ma 2011). It is an unprecedented challenge to cope with severe USWL and traffic paralysis problems caused by these rain events. Besides, there were 19 urban water-logging events occurring in Beijing during the flood seasons (Jun, July and August) from 2007 to 2010 (You *et al*. 2011). According to statistical data in 2009, there were 58 water-logging areas in Beijing, mainly under overpasses or low-lying areas (Chen *et al*. 2011).

However, since 1999, there has been a 9-year drought in Beijing and the precipitation in each year was lower than the mean annual precipitation

**Table I.** Some consequences of the "7.21" rainstorm in Beijing, on 21st of July, 2012 (The information was summarized based on: [1] Yang, Bai 2012; [2] Liu 2012a; [3] Liu 2012b; [4] Wang 2012; [5] Wang, Yu 2012; [6] Wang, Liu 2012).

| Disaster | Number | Notes |
|---|---|---|
| **Fangshan District in Beijing [1]** | | |
| Rainfall | Average 301 mm; Maximum 541 mm | RP is 500 years |
| Mountain torrents, rock-mud flow | Happened | |
| Flood flow (the Jvma River) | Maximum 2 570 $m^3 s^{-1}$ | The largest since 1963 |
| The Beijing Capital Airport [2] | | |
| Cancelled flights | 571 | On the 21th of July |
| Delayed flights | 701 | |
| People stranding in the airport | 80 000 | |
| **Beijing subway and expressway** | | |
| Collapsed roadbed of Beijing subway line No. 6. [3] | 1 | |
| Flooded section of the Beijing-Hong-Macao expressway [2] | Length of about 900 m, water depth of 4 m average and 6 m maximum | |
| Water-logging under the Nangangwa railway bridge [2] | > 200 000 $m^3$ | |
| **Effects on human livelihood** | | |
| Human deaths | 79 | By the 6th of August [4] |
| People affected | 1.9 million | By the 23th of July [5] |
| Houses collapse | 10 660 | |
| Crop damage | 238 688 hectares | |
| Immovable cultural relics damage [6] | 163 | |
| | About 210 000 $m^2$ | |
| | About 850 million CNY | |
| Total economic loss [1] | More than 140 billion CNY | |

(Ji 2010). These striking extreme events indicate that rainfall in Beijing is a sign of the increasing uncertainty in weather as well as needs for countermeasures to cope with both floods and droughts.

### *2.2. Cause analysis*

The USWL problems in Beijing were induced by multiple causes, mainly climate change, increasing imperious surfaces, the limited capacity of drainage system, lack of policy enforcement and lack of public awareness.

Global warming leads to changes in the water cycle, and this is manifested as continuous extreme weather events among which rainstorms occur more frequently and intensively. Rapid urbanisation, with growing population densities, causes urban heat/dry/wet/rain island effects due to urban factors such as air pollution, anthropogenic heat generation, urban geometry, surface waterproofing and altered thermal properties of the urban "fabric" (Shahmohamadi *et al.* 2010). This contributes to further changes in the water cycle and thus in the urban micro-climate. Large amounts of air pollutants in the urban areas contribute to and increase in the availability of condensation nuclei and thus lead to increasing precipitation (Ye *et al.* 2010). In Beijing, there is a very strong urban heat island effect, which results in decreased precipitation in the pre-urban area with significantly increased precipitation in the urban area (Zuo *et al.* 2008).

Due to fast growing urbanization, many depressions and small water bodies such as ponds, lakes and reservoirs were filled for buildings construction, which has reduced the capacity of natural stormwater storage and regulation within the landscape (Ye *et al.* 2010). Large areas of permeable land were replaced by impervious surfaces. For example, the ratio of impervious land surface to total land area increased from 61% in 1959 to 77% in 2000. The built-up area had increased to almost 1210 km$^2$ by 2005, or 6.58 times of the area in 1973. Within the inner urban area, green space decreased by 16.4% (from 1983 to 2005) while the current proportion of impermeable area increased to 86% (Yang, Bai 2012; Ji 2010; Zuo *et al.* 2008). This has significantly changed the natural flow patterns, resulting in lower evapotranspiration, higher runoff coefficients and peak flows and shorter travel times of stormwater in the drainage system, which, in turn, results in low infiltration rates and higher flood risks. For example, during the "7.21" rainstorm event, the runoff coefficient was 0.51, with more than half of the rainfall in the urban area (≥ 200 million m$^3$) becoming surface runoff. Moreover, during this event, travel times were very short and the regulation capacity of the urban rivers was very limited (Yang, Bai 2012).

There are problems with the urban drainage system, such as old facilities, short RP, poor maintenance of drainage pipes, misconnection of stormwater pipes and sewage pipes, and overflow events from combined sewerage systems[1] (Ye *et al.* 2010; Wang, Ma 2011). First of all, the design standard for most of the drainage facilities and for 95% of the stormwater pumping stations was to address rainfall events with a RP of 1-3 years (with a maximal precipitation intensity of 36-45 mm hour$^{-1}$). However, during the "7.21" rainstorm, the maximum 1-hour precipitation intensity in most areas reached a RP of 5 years (Yang, Bai 2012). Notably, 78 out of 90 sunken overpasses in Beijing had an invert or base elevation lower than the normal water level of the river and could only cope with rain events with a 2-3 years RP, which contributed to the water-logging problems (Chen 2012). In 2005, the combined drainage pipeline had a length of 756 km, or 19.9% of the total drainage pipeline length in Beijing, which threatened rivers safety during the rainstorm events due to possible overflows because of its limited capacity (Zuo *et al.* 2008). Moreover, the drainage pipeline network had insufficient density and was easily blocked because of inadequate maintenance.

Another issue is that the flood control and water drainage functions are assigned to two different departments in Beijing, which makes it difficult for work coordination. For example, to protect rivers from pollution, some combined drainage pipes were always blocked to varying degrees, which largely contributed to water-logging under the overpasses of Liuliqiao and Lianhuaqiao (Lan, Yang 2009).

Great efforts have been put, but improvement is still needed, in developing early warning systems, emergency plans and public awareness. For instance, not all people got the early warning signals in a timely manner. Rainfall telemetry facilities and the density of hydrologic stations were not sufficient, passengers in the airport were not evacuated properly and were charged for the service as usual, emergency teams were not sent promptly, and cars were not stopped on high-lying roads and excluded from low-lying areas (Yang, Bai 2012; Wang, Wang 2012; Wang, Ma 2011).

Moreover, the use of rainwater as a resource needs to be strengthened. Most existing relevant policies encourage stormwater utilization, but there

---

[1] Combined sewerage systems drain a mix of wastewater and stormwater through a single pipe network to sewerage treatment plants. They are different from separated sewerage systems, which drain stormwater and wastewater in two separate pipe systems: wastewater is conveyed to sewerage treatment plants and stormwater (or separately treated stormwater) into receiving waters. Source: Hoyer *et al.* 2011.

are no integrative environmental education efforts, quantified assessment criteria or sufficient law enforcement for enacting these policies. Consequently, there are only some small scaled and scattered stormwater-utilization projects in Beijing.

### *2.3. Traditional solutions to USWL problem*

To solve USWL problems, the common method is to increase rainstorm RP used in the design of pipeline systems and thus enhance their drainage capacities. However, according to experts (The Beijing News 2012), many of the drainage pipelines were in no condition to be reconstructed or extended, because the complicated underground pipelines networks were difficult to change. Additionally, fast upstream drainage placed great pressure on the downstream drainage pipelines. Moreover, stormwater usually has two ways to be drained: (1) being drained directly into rivers, or (2) being drained into sewage treatment plants for purification. Discharge to rivers is a big waste of water in this water-scarce city and the contaminants carried by the stormwater intensifies river pollution. In contrast, conveyance to treatment plants could lead to combined sewer overflows (CSOs) and cause pollution in the rivers. Additionally, rapid drainage of stormwater from urban built-up areas, instead of its infiltration, reduces groundwater renewal (Hlavinek 2008). Finally, these methods mainly focus on the elimination of USWL in the short term and at a high cost, which contributes to over-engineering the environment. Hence, a more sustainable way, like the EH approach, is needed, combined with the use of drainage pipelines, to solve the USWL problem, utilize stormwater and reverse landscape degradation in Beijing.

## 3. Ecohydrology and good urban design

### *3.1. Concept and principles of ecohydrology*

Ecohydrology is a scientific concept applied for environmental problem-solving, with the overall goal of sustainable management of water resources (Zalewski, Wagner-Lotkowska 2004). It was developed from the need for the integration of hydrological and biological processes at the basin scale into a holistic framework, and led to the formation of hydrological, ecological and ecotechnological principles.

The first principle is the hydrological principle. It refers to quantification of hydrological and ecological processes at a basin scale to define the cause-effect relationships.

The second principle is the ecological principle. It sets the hierarchy of factors and analyzes the ability of the biota to regulate water cycles, aiming at and enhancing ecosystem carrying capacity.

The third principle is the ecotechnological principle. Based on the first and second principles, it addresses water problems through dual regulation of the hydrology and the biota, and relates to ecological engineering (Zalewski 2002).

### *3.2. Advantages of ecohydrology as a problem-solving science*

Ecohydrology is a science to solve problems by harmonizing societal goals with ecosystem potentials (Zalewski 2010). It aims not only to eliminate threats such as extreme water events by using such means as plant cover, ecotones, in-stream processes, wetlands, and biomanipulation, but also to amplify opportunities, such as bioenergy generation, increased biomass production, and tourism employment and revenues (Zalewski 2002; Zalewski, Robarts 2003). Therefore, for the sustainable use of aquatic resources, ecohydrology applications provide a complement to conventional technological tools (e.g. extending sewage treatment technologies by constructing wetlands), thereby improving efficiency and reducing costs, while improving ecosystem services and generating positive socioeconomic feedbacks (Zalewski, Robarts 2003).

Phytotechnology and biotechnology can help in the application of EH approaches by increasing plant biomass and diversity and regulating matter conversion rates. The implementation of ecohydrology/phytotechnology approaches derived from the 'green feedback' paradigm, with energy, water and plants as components, can meet socio-economic-environmental requirements such as improving water quality (Zalewski 2000; Zalewski *et al.* 2003). Overall, ecohydrology provides new solutions for the management of sustainable water resources (Zalewski 2010).

In terms of urban stormwater management, it focuses on the following aspects: (1) prevention and mitigation of natural disasters (such as USWL, land subsidence and waterbody pollution from stormwater) and utilization of stormwater as a resource to reduce water scarcity, through stormwater retention, purification, infiltration and storage by natural systems; (2) optimization of cost-efficiency by applying low-cost EH approaches and the source control principle; (3) increasing other benefits like aesthetics, education and biodiversity in the urban area, through proper design and implementation of functional green areas and water bodies; and (4) creation of positive socio-economic-environmental feedback by increasing ecosystem capacity and the sustainability of urban development. For example, elimination of USWL disasters helps to reduce casualties, significant economic losses and other negative effects of stormwater such as an impaired city image and loss of citizens' trust in the metropolis. In addition, the improved ecosystem services provide: habitats for biota, beautiful scenery and recreational places for urban inhabitants, and opportunities for stormwater utilization and environmental protection (e.g. by showing the functionality of the wetlands themselves through interesting and meaningful postings and placement of placards).

### *3.3. Concepts of urban ecohydrology and good urban design*

Urban ecohydrology, as a new dimension of EH, was developed through the European Union funded project SWITCH – "Sustainable Water Management Improves Tomorrow's Cities' Health" (EU PF6, GOCE 018530) – and implemented in the City of Lodz, Poland. It aimed to provide systemic solutions for cities and urban areas in the face of dynamic global urbanization and climate change using EH approaches (Wagner, Zalewski 2009).

Good urban design is one of the five aspects of quality of life in a city (Philip *et al.* 2011). It has a close relationship with water and vegetation. For example, water features such as fountains, ponds and canals and green areas can provide an aesthetically pleasing built environment, convey cultural values and support recreational activities for city inhabitants. Irvine (2010) described the top 10 indicators of GUD which considered multiple socio-economic-environmental aspects including environmental consciousness and connection to the landscape. In general, these indicators suggested applying green technologies and focusing on people and culture in an economic manner.

EH approaches generally require adequate land area and space for their application. In a metropolis such as Beijing, land is one of the most scarce and precious resources. Thus, GUD is needed when applying EH approaches to ensure that EH interventions are applied in a good-looking, land-saving and cost-effective manner, through creative design, optimum distribution and combination.

## 4. EH approaches and GUD in Beijing

Based on the analysis above, it is clear that EH with GUD is a promising way to achieve sustainable SWM in urban areas, resolving both USWL and water scarcity problems, and enhancing ecosystem functions and services as well. Therefore, a framework for the systematic development of an EH solution with GUD was proposed in Beijing, using BMPs and the source control principle. Runoff reduction efficiencies of BMPs methods were quantified, and an idea of their application was explained using examples. In addition, several helpful tools, models and systems (TMS) involved in sustainable SWM and EH application, were described.

### *4.1. Potential of EH with GUD application in Beijing*

Even though stormwater has brought significant threats, there is also great potential for using stormwater as a resource in Beijing. Generally, treated stormwater can be reused as alterative non-potable water source for car washing, toilet flushing, dish washing, cooling water and irrigation, or as a main/alternative source of potable water following treatment. In developing countries, it is mainly used for drinking water and irrigation, while in developed countries it can be used for all of the uses mentioned above. In urban areas, however, rainwater is usually used as a non-potable water source (Ji 2010). In Beijing, the reuse of stormwater is in its infancy, but its potential is indicated.

Firstly, rainwater resource is sufficient, because the mean annual precipitation during the flood season in Beijing is 585 mm and especially heavy rains bring large amount of water. For instance, the "7.21" rainstorm event produced 900 million m$^3$ of water, of which 350 million m$^3$ was in the form of surface water and 550 million m$^3$ in the form of groundwater. With the limited river capacity for flood control, USWL is a threat to the safety of Beijing. Secondly, water scarcity has been a major constraint for the city's socio-economic development and improvement of environmental quality. Rainwater can supplement the available water resources. Thirdly, there are good hydrogeological conditions for stormwater utilization. A groundwater drawdown cone with an area of 2000 km$^2$ has been formed around the city, which provides a storage capacity for stormwater. Fourthly, the urban and pre-urban areas are located on the middle alluvial fan of the Yongding River. The permeable soil structure is good for stormwater infiltration (Ding 2005). Fifthly, along with the rapid construction of buildings, roof areas tend to increase. These could provide space for the application of green roves and/or rooftop water collection, which could compensate for the disadvantages associated with the increasing impervious land surface. Sixthly and finally, a new policy issued in 2012 required that all building construction, reconstruction or expansion should include facilities for stormwater control and reuse (BMCUP 2012).

Moreover, there have been several EH approaches applied for stormwater discharge regulation in Beijing. Concave-down green areas, permeable surfaces, special infiltration facilities, impounding reservoirs and rainwater harvesting technologies all have been utilized.

The concave-down green area is green land used for infiltration. It is constructed to have a lower elevation than the surrounding ground or road surface. According to research (Zhang 2008), when the green area was 5-10 cm lower than the surrounding area and the rainfall RP was 5 years, it could totally absorb all of the stormwater falling on the green space and on an impervious surface of equal area. In addition, concave-down green areas can increase soil water content by 2-5%, which benefits plant growth and further increases evapotranspiration by 0.02-0.32 mm.

The permeable ground surfaces are constructed using artificial materials such as pervious brick and pervious lawn brick, pervious concrete and asphalt ground, which can quickly infiltrate rainwater with little or no water-logging. These materials are often used for pavements, yards, squares, parks, bikeways and roadways with limited traffic flows in residential areas. They can not only contribute to groundwater recharge and reduce runoff, but also mitigate the urban heat island effect (Wang *et al.* 2004). According to research in Japan by Watanabe (1995), the permeable ground surfaces reduced runoff peak flow by 15-20%. An experiment in Beijing showed that, during a one hour rainfall whose RP was one year (total precipitation was 41.54 mm) and a two hours rainfall whose RP was 5 years (total precipitation was 83.08 mm), the permeable ground surfaces generated no runoff. During a one hour rainfall whose RP was 100 years (total precipitation was 107.17 mm), the permeable ground surface started to generate runoff 58 minutes later than the impermeable one, with the runoff coefficient of the former being reduced by 82.29% over the latter (BMBPF 2012).

Some other specialized infiltration facilities include infiltration trenches, infiltration wells and pervious pipes. The infiltration trench can be constructed along pavements in a green area or be located in roadside greenbelts to absorb overflows from the green area. The infiltration well is mainly used in green areas to collect rainfall for irrigation use or infiltration into surrounding soil, which reduces the amount of rainfall runoff being conveyed by drainage pipelines. According to research (BMBPF 2012), it suggested that there should be 1-2 infiltration wells (0.226 m$^3$) constructed for every 100 m$^2$ of green area in order to avoid overflows under storm conditions with a rainfall intensity of 40 mm hour$^{-1}$ (BMBPF 2012). Apart from infiltration, the collected stormwater from rooftops, roads, yards and squares could be treated and then stored in reservoirs for different uses. There also reservoirs, discharge-control wells and overflow weirs, are used together to regulate discharge rates and volumes, and thus reduce drainage pressure on downstream pipes.

A demonstration site of the SWITCH project was located in Beijing, applying rainwater harvesting (RWH) technology for use in peri-urban agriculture. This project increased the security of water supply using local, instead of out-of-town, water resources. Research showed that the RWH efficiency in the facility agriculture was 45-80% (Ji 2010). This technology was developed to be applicable where the annual average precipitation is more than 400 mm, groundwater level is more than 5 m below ground surface, and facility agriculture is well-developed in the plain areas.

A good example for the successful application of some of these technologies in the urban area of Beijing is in the Shuiduizi housing estate. It has created 28 000 m$^2$ of pervious surface, installed three infiltration wells inside residential green areas, and built two stormwater storage tanks and an irrigation system for the green area. This not only avoided storm water-logging inside this housing estate but also reused 1000 m$^3$ of stormwater and increased stormwater infiltration by 10 000 m$^3$ per year (BMBPF 2012; Jia 2011).

Nevertheless, there are still some limitations to these methods which restrict their use in avoiding USWL in Beijing. The main limitation is their low extent of coverage. By 2010, there was 13.18 million m$^3$ of the annual usable stormwater harvested by 688 stormwater utilization projects in the urban area of Beijing. However, the stormwater runoff area which could be controlled by these projects was less than 10% of the total urban area. Most of them were just demonstration projects, which could only control stormwater runoff to a very small extent (Zhang *et al.* 2011). In addition, these technologies lacked the corresponding theory and instruction necessary for more people to develop projects in a larger scale. Therefore, there is a need for capacity building, including training on EH technologies and combined EH and GUD strategies which will help to improve the existing approaches and enforce the new policy.

### *4.2. Proposed framework of systematic EH solution with GUD*

In terms of the global perspective on the adoption and application of structural BMPs, while the US and Canada have led the way in implementation of structural BMP controls, China is still on the way to increasing BMPs applications (Ellis *et al.* 2006). Thus, to increase BMPs applications, improve the existing solutions and help manage stormwater at an urban catchment scale greater use of EH methods is suggested in this paper (see Table II), and a framework for systematic application of combined EH and GUD solutions at the urban catchment scale is proposed (Fig.1) with an initial focus on Beijing. In Table II, both existing and added EH (BMPs) methods are listed according to the functions of different structural BMPs. All of them should be selected and combined according to their costs and features, and thus applied case by case to different situations in the City of Beijing. In Fig. 1, the characteristics of different BMPs with respect to receiving/discharging rainwater/stormwater and GUD concept are illustrated. These BMPs should follow the GUD concept in their applications to make them more socio-economically acceptable. For example, a green roof may be designed to function as a garden and retain rainwater, while an old degraded lake could be rehabilitated to serve as a stormwater basin.

The principle of retention and infiltration of stormwater in-situ in such places as individual building lots, parks, and highways is called "source control" (applied in Fig.1). It indicates measures that are implemented at the source and interventions focusing on the causes of identified problems (Hlavinek 2008). Because EH techniques for storm-

**Table II.** Existing EH (BMPs) and added EH approaches in the City of Beijing.

| Items | **Existing EH approaches** (Zhang, Hao 2011) | **Added EH approaches** |
|---|---|---|
| Infiltration | Concave-down green area | |
| | Infiltration trench and well | |
| | Pervious brick/concrete/lawn-brick paved ground, pervious pipe | Infiltration basin, soakaway |
| Collection | Roof – roof gully, semi-pressure roof gully, siphon gully | |
| | Road/square – road water inlet | Storm water inlet into infiltration system |
| Storage | Roof water container (cisterns) | |
| | Underground tank, assembled storage module, storage pot | |
| Detention | Roof detention, wetland detention | Detention basin, extended detention basin |
| Filtration | Separate/central filtration technique | Filter strip, swale, lagoon, settlement tank |
| Retention | Green roof | Retention pond |
| Purification | Rainwater treatment technique | Constructed wetland |

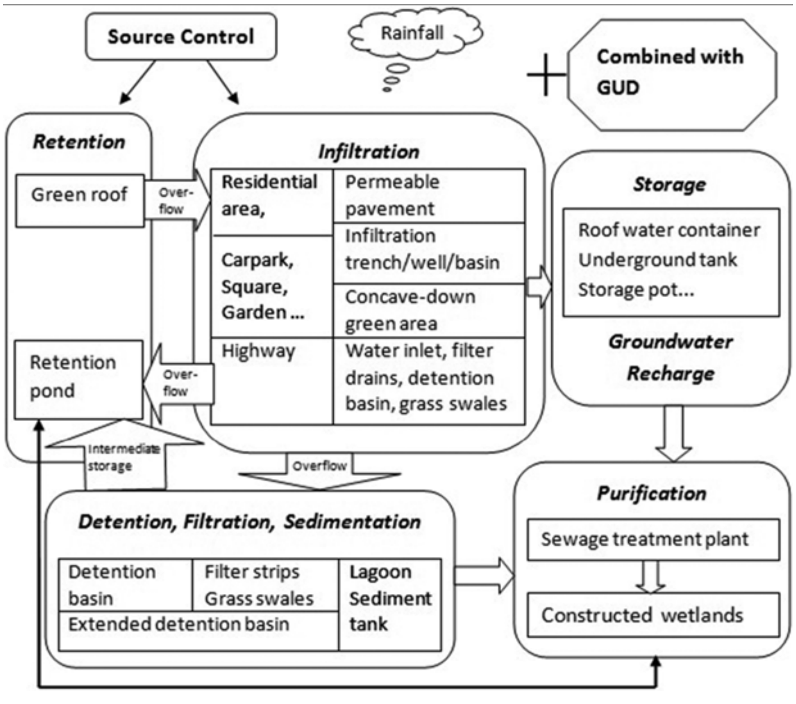

**Fig. 1.** An example of different methods of urban stormwater management integrated into the systematic ecohydrological solution with good urban design.

water transport are fee-saving, low-cost and provide multiple benefits, these measures are considered cost-efficient. Firstly, measures such as green roof can not only mitigate stormwater problems through attenuation of stormwater peak run-off rates and reduction of total flow volumes, but also offer such benefits as improvement of air quality in built-up areas and reduction of the urban heat island effect. They also provide habitats for various species (thus improving urban biodiversity) and enhance the general aesthetics of urban environment (Turner *et al.* 2011). However, in Beijing, less than 1% of the roof areas, which can be changed into green rooftops, has applied green roof technology (Gao 2012). Secondly, stormwater can be used in-situ as non-potable service water such as households washing and cleaning, green roof maintenance, watering gardens, green area irrigation and water fountains. Thirdly, it can recharge groundwater to address such geological problems as land subsidence and saltwater intrusion which are caused by decreasing groundwater levels. Fourthly, during storm events, these EH approaches can reduce stormwater-generated runoff pollutant loads and/or CSOs (Hlavinek 2008). In some countries including the USA, UK and Australia, "source control" technology has been one important element of a treatment train (TT)[2], because of its higher benefit-cost ratios than those of end-of-pipe treatments. Relevant policies are required to implement these "source controls", and they can be supported through the collection of stormwater fees, as has been done in some developed countries (Ji 2010). These fee-based "source controls" might be applicable to the situation in the City of Beijing.

"Source controls" can be used to mitigate/avoid USWL in the low-lying areas under overpasses, by reducing total runoff over the entire urban area and thus minimizing the volume of stormwater inflows into low-lying areas. Recently, the Beijing government has taken some measures to solve this problem, including adding or modifying stormwater gullies, stormwater pipelines, impounding reservoirs and water pumps (Xinhua News 2012). However, the collected stormwater is discharged directly into the nearest urban rivers and is likely to increase pollution loads and discharge pressures on the rivers. Therefore, "source control" approaches are needed to help to reduce the stormwater pollution/runoff volumes and the pressures on the rivers.

### *4.3. Efficiency of EH methods for runoff reduction*

There is great importance in knowing the effectiveness of EH methods in solving USWL problems. This knowledge can provide information for their adoption and design. It is mainly measured by quantifying the performance of various BMPs for runoff reduction (RR). According to Hirschman *et al.* (2008), RR was defined as the total annual runoff volume reduced through canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration[3]. Generally, RR data were limited for most practices. However, recently, greater emphasis has been placed on the management of stormwater runoff volumes and numerous studies have started documenting RR performance. The volumetric data in the BMP Database reflects an increasing trend in complete hydrological monitoring (Jones *et al.* 2012; Hirschman *et al.* 2008). Based on the limited availability of RR data, RR rates were estimated for various BMPs (see Table III). In Table III, a range of values represent the median and the 75th percentile RR rates which are the authors' best judgment based on the currently-available information. Changes in some of the values listed in this table can be expected when more studies and data become available (Hirschman *et al.* 2008).

Table III shows that some BMPs have significant RR efficiencies, but others (filtering, wet

**Table III.** Runoff reduction rates of various BMPs (Source: Hirschman *et al.* 2008).

| Practice | Runoff reduction (%) |
|---|---|
| Green roof | 45 to 60 |
| Filter strip | 25 to 50 |
| Rain tanks and cisterns | 40 |
| Permeable pavement | 45 to 75 |
| Grass channel | 10 to 20 |
| Bioretention | 40 to 80 |
| Dry swale | 40 to 60 |
| Wet swale | 0 |
| Infiltration | 50 to 90 |
| Extended detention pond | 0 to 15 |
| Soil amendments | 50 to 75 |
| Sheet flow to open space | 50 to 75 |
| Filtering practice | 0 |
| Constructed wetland | 0 |
| Wet pond | 0 |

---

[2] The TT, i.e. using various "green" technologies successively in source control, site control and regional control, is a very important concept for urban drainage planning and design (Bastien *et al.* 2010; Ellis *et al.* 2006; Woods-Ballard *et al.* 2007).

[3] Extended filtration includes bioretention or dry swales with underdrains that delay the delivery of stormwater from small sites to the stream system by six hours or more (Hirschman *et al.* 2008).

swales, wet ponds and stormwater wetlands) have a negligible effect on RR (with no estimated values being shown). The permeability of soil within or beneath a BMP positively influences its runoff volume reduction primarily through infiltration into subsurface, evaporation and, if any, transpiration through vegetation (TRBNA 2006). Thus, vegetated BMPs have substantial potentials for RR, while wet swales, retention ponds and wetlands, which have similar functions, are not recommended for the purpose of reducing runoff volumes because of their low infiltration capacities, high levels of saturation or poorly drained soils.

In order to make the optimum use of different land areas and achieve the best overall effect, BMPs should be applied not only based on their own features and performances but also on site conditions and design objectives. The use of multiple BMPs was recommended since it offered a greater comparative advantage than a single BMP, considering that every individual BMP has its own limitations. For example, even though the infiltration facility has a higher efficiency than the green roof (showed in Table III), the former cannot replace the latter in dealing with rooftop rainwater. In addition, according to Jones *et al*. (2012), the variability of volumetric performance in studies of BMPs indicated that design attributes and site conditions played key roles in BMPs performance. Hence these two factors (design and site) should be carefully selected or amended so as to improve RR. For example, poorly drained soils (e.g. soils with a high fraction of clays) can be amended to improve their permeability.

### 4.4. Examples of combined EH approaches and GUD application

To explain how combined EH approaches and GUD work, two examples are provided. In the first, EH approaches are combined with traditional engineering methods to provide better functions and services. Sewage treatment plants can be combined with constructed wetlands to provide more extensive water purification. Such a combination of traditional and ecohydrolgoical approaches can reduce pollution from sewerage overflows and/or remove certain pollutants that treatment plants cannot deal with (Zalewski 2002). In the other, the combination of two EH approaches – ponds/reservoirs and green areas are used in stormwater management. The ponds/reservoirs can retain/detain stormwater, while friendly green areas like well-designed parks can use plants to infiltrate runoff, purify water, enhance biodiversity and serve an aesthetic purpose. This combination can bring other important benefits, such as optimizing land use. During the SWITCH project, one of the established demonstration projects included such a retention system. This was a sequence of reservoirs on the urban Sokolowka River, in the City of Lodz, which served as a receptacle for nutrient-enriched stormwater (Skowron 2008). In Beijing, there also are some urban river rehabilitation projects involving lake/pond systems being constructed, like the Yongding River project (Zhu, Deng 2012). There is potential of applying a similar stormwater retention reservoir system there. As to green area, a good example is the Living Water Park located in Chengdu city in China – the first water-themed urban ecological park in the world. It has a fish shape when viewed from above. Polluted water from the river is pumped into the 'fish mouth' (fountains), flows through anaerobic tanks and water sculptures, before being purified in the 'fish scales' (constructed wetlands). And the purified effluents flows into fish ponds and filtration ponds, before finally flowing into recreational ponds and natural trenches where the water can be used for irrigation and water features or return to the river (Huang *et al*. 2000). The idea of the combined use of EH techniques is illustrated in Fig. 2. The retention pond and the Living Water Park should be functional all the time by utilizing the purified water from the pond (for water-supply systems or rivers discharges) and receiving new inflows of polluted water. However, during the flood season, the retention pond should be kept dry before a coming rainstorm event (according to weather forecasting) to provide the storage capacity needed for newly received stormwater.

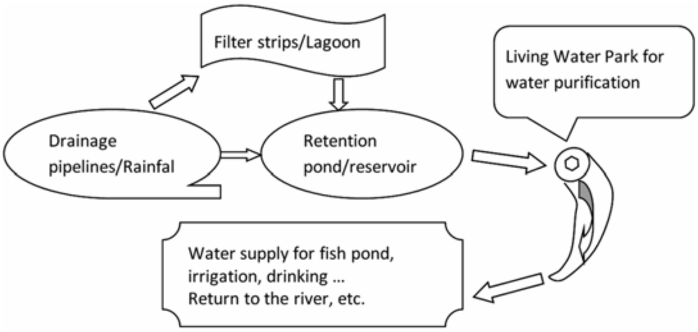

**Fig. 2.** An example of combined EH and GUD application.

### 4.5. Important TMS

In order to reinforce the EH approach to managing USWL problems in the urban area of Beijing, there are some important tools, models and systems (TMS) needed, including Geographic Information System (GIS) database, models for BMP decision support, and early warning and monitoring systems.

Firstly, GIS database is the main way to put hydrological, geological and biotic data together, based on which a monitoring and forecasting system for USWL problems can be built. The application of GIS in EH approaches to managing sub-catchments (i.e. ecotones and elementary patches) can help abstract hydrological and ecological information from micro scale systems. Integration of this information and hydrological concepts can lead to a more profound quantification of the water regime (Zalewski *et al.* 1997). It can help to better understand the relations between changes in hydrological processes and biota.

Secondly, modeling can serve in BMP decision support. Planning and cost-effectiveness assessment of BMPs can be enhanced through simulation of the quantified values of stormwater RR and costs based on collected data. There have been a number of models for BMP planning (mainly selection and placement), such as SWMM (Rossman 2010), BMPDSS (Peters *et al.* 2009), SUSTAIN (Lai *et al.* 2007; Shoemaker *et al.* 2011), each having different advantages. The multiple benefits of BMPs have been researched and demonstrated, but the implementation rate for appropriate BMPs is still low. One of the main reasons is the high level of uncertainty and risk associated with innovative SWM strategies, and their relative costs and performance (Roy *et al.* 2008). Models such as LIDRA (Montalto *et al.* 2011) and LCCA-Tool (Sieker *et al.* 2008) for cost-effectiveness evaluation are needed for the quantification of such uncertainties. This is a necessary prerequisite to help build public confidence in EH solutions. These models are very important for decision making and promotion of EH applications as well.

Thirdly, early warning and monitoring systems provide important information for strategic planning and improvement of implementation results. The 2012 Special Construction Scheme for Urban Disasters Prevention and Mitigation, proposed by Beijing, Shanghai and Guangdong's meteorological bureaus, has been approved, which was expected to improve the capabilities of monitoring and warning services, and to enhance the contingency planning for responding to metropolitan disasters (CMA 2012).

Overall, therefore, TMS plays a very important role in sustainable SWM and application of the systematic EH solution with GUD as well.

## *Conclusions*

Based on all of the analyses summarized above, several concluding remarks can be presented:

1) USWL is becoming a pervasive problem in China, with increasing socio-economic losses. Beijing City has suffered from both water-logging and water scarcity problems. The main causes of the USWL events are climate change, the low RP of the storms for which the drainage system was designed, increasing impervious surfaces, lack of policy enforcement and lack of public awareness.
2) The main existing solutions were identified as increasing the construction of draining pipelines, concave-down green areas, pervious pavements and infiltration systems, and creating relevant incentives for installation of stormwater control infrastructures. However, their applications were insufficient. Therefore, the EH and GUD concepts were introduced and the potentials for applying combined EH and GUD solutions were analyzed.
3) A framework of systemic EH solution with GUD was proposed, by properly applying BMPs and the 'source control' principle. Combined with drainage technologies, this approach aimed to create a sustainable SWM system, reducing USWL problems and utilizing stormwater as a resource. Additionally, the runoff rate efficiencies of different BMPs were analyzed. These analyses suggested that multiple BMPs should be selected based on the site conditions and design attributes to get the best overall effects.
4) Taking the combination of the retention pond and the Living Water Park as an example, the idea of the combined EH and GUD application was explained. This approach would provide various benefits such as stormwater runoff regulation, purification and increasing the cultural services of ecosystems. It also optimizes the economic use of land in the urban area. A GIS database, modelling for BMPs decision support, and early warning and monitoring systems were identified as important tools for EH applications, sustainable SWM and improvement of contingency planning for stormwater disasters.

## *Acknowledgements*

The author expresses deep gratitude to Prof. Maciej Zalewski, Dr. Kinga Krauze and Kamila Belka for great support, thoughtful comments and language editing to improve the quality of the manuscript. Also heartfelt thanks are due to Prof. Michael McClain and Sani Dauda Ahmed, for great help in paper format, language editing and valuable comments. The author gives great appreciation to Luis Chicharo for encouragement in choosing urban ecohydrology as the topic and writing this paper.

# References

ADB 2011. People's Republic of China: Urban stormwater management and waterlogging disaster prevention. Technical Assistance Report. Asian Development Bank, Beijing. http://www2.adb.org/Documents/TARs/PRC/45512-001-prc-tar.pdf

Bastien, N., Arthur, S., Wallis, S., Scholz, M. 2010. The best management of SuDS treatment trains: a holistic approach. *Water Sci. Technol*. **61**, 263-272. doi: 10.2166/wst.2010.806

BMBPF 2012. 北京市园林科学研究所科研课题成果中关于“绿地雨水利用研究内容”的汇集 [Scientific research achievements collection about “Strom water utilization research in green area” in Beijing Institute of Landscape Gardening]. Beijing Municipal Bureau of Parks and Forestry [In Chinese]. Attachment on the website: http://www.bjyl.gov.cn/zwgk/fgwj/qtwj/201209/t20120903_108865.html.

BMCUP 2012. Technical essential of stormwater control and utilization in new construction projects. Beijing Municipal Commission of Urban Planning, August 27 [In Chinese]. Attachment on the website: http://www.bjghw.gov.cn/web/static/articles/catalog_24000/article_ff80808138cc799d013967b4064002c5/ff-80808138cc799d013967b4064002c5.html (Accessed: 12th of April, 2013)

Cai, G., Ji, W. 2010. A Handbook on Beijing’s rainwater harvesting technology of greenhouse agriculture (In Chinese). Prepared within: SWITCH - Sustainable Water Management in the City of the Future project. Work package 5.2. Deliverable 5.2.3 – Annex B2. http://www.switchurbanwater.eu/outputs/pdfs/W5-2_CBEI_MAN_D5.2.3_Training_and_Guidelines_-_Annex_B2.pdf

Chen, X. 2012. 北京“7. 21”和深圳“6. 13”暴雨内涝成因对比与分析 [Cause comparison and analysis of waterlogging in Beijing “7.21” and Shenzhen “6.13” rainstorm events]. *Water Resources Development Research* **13**, 39-43 [In Chinese].

Chen, J., Wang, H., Zhang, S., Su, D., Zhao, F., Kong, G. 2011. 北京市道路积滞水原因及案例分析 [Causal analysis and case study of the road ponding in Beijing City]. *Water & Wastewater Engineering* **37**, 37-40 [In Chinese].

CMA 2012. Met. service assisted in preventing urban waterlogging. China Meteorological Administration, press release of June 19. www.cma.gov.cn/en/NewsReleases/News/201206/t20120619_176330.html (Accessed: 12th of April, 2013).

Ding, Y. 2005. 北京城区雨水利用的现状与展望 [Current status and prospect of urban rainwater utilization in Beijing]. 第20届中日河工坝工会议 *[The 20th River and Dam meeting between China and Japan] from* 中国水利国际合作与科技网 *[China Water International cooperation and science and technology website]* [In Chinese]. www.cws.net.cn/zt/20zrhg/CWSNews_View.asp?CWSNewsID=22570

Ellis, J.B., Revitt, M., Scholes, L., Sieker, H., Helm, B., Winger, J., Picouet, C., Soutter, M. 2006. Review of the adaptability and sensitivity of current stormwater control technologies to extreme environmental and socio-economic drivers. SWITCH - Sustainable Water Management in the City of the Future project, Deliverable 2.1.1 http://www.switchurbanwater.eu/outputs/pdfs/W2-1_GEN_RPT_D2.1.1_Review_of_stormwater_control_technologies.pdf

Ellis, J.B., Revitt, D.M. 2010. Stormwater as a valuable resource within the urban water cycle. SWITCH – Sustainable Water Management in the City of the Future project, Deliverable 2.2.4a. July 2010. http://www.switchurbanwater.eu/outputs/pdfs/W2-2_CBIR_RPT_D2.2.4a_Stormwater_as_a_valuable_resource_within_the_urban_water_cycle.pdf

Gao, F. 2012. 城市化进程中的城市绿化长效发展探析 [Research on long-term development of urban virescence during urbanization]. *Cities & Disaster Reduction* [In Chinese].

Han, S., Xie, Y., Li, D., Li, P., Sun, M. 2006. Risk analysis and management of urban rainstorm water logging in Tianjin. *Journal of Hydrodynamics Ser. B* **18**, 552-558.

Hirschman, D., Collins, K., Schueler, T. 2008. Technical Memorandum: The Runoff Reduction Method. Prepared for: Extreme BMP Makeover – Enhancing Nutrient Removal Performance for the Next Generation of Urban Stormwater BMPs in the James River Basin, and Virginia Stormwater Regulations and Handbook Technical Assistance. Center for Watershed Protection. Ellicott City, MD, http://vwrrc.vt.edu/swc/documents/pdf/TechnicalMemo.pdf.

Hlavinek, P. 2008. Stormwater management in urbanised areas. In: Hlavinek, P., Bonacci, O., Marsalek, J., Mahrikova, I. [Eds], *Dangerous pollutants (Xenobiotics) in urban water cycle.* Springer, pp. 45-52.

Hoyer, J., Dickhaut, W., Kronawitter, L., Weber, B. 2011. *Water sensitive urban design principles and inspiration for sustainable stormwater management in the city of the future - manual.* SWITCH – Sustainable Water Management in the City of the Future project. http://www.switchurbanwater.eu/outputs/pdfs/W5-1_GEN_MAN_D5.1.5_Manual_on_WSUD.pdf

Huang, S., Wang, Q., Qian, J., Ren, Y. 2000. Look through the constructed wetland system from Chengdu Living Water Park. *Sichuan Environment* **19**, 8-12 [Eng. summ.]. IHP-VIII 2012. *Strategic plan of the eighth phase of IHP (2014-2021) (draft)*. International Hydrological Programme, 20th session of the Intergovernmental Council. IHP/IC-XX/Inf.4. *27 April, UNESCO, Paris.* http://www.unesco.org/ulis/cgi-bin/ulis.pl?catno=216434

Irvine, A. 2010. Top 10 Indicators of Good Urban Design. A Dash of Design… website, blog post of October 11. http://adashofdesign.wordpress.com/2010/10/11/good-urban-design

Jia, Z. 2011. Capital strategy of sea water desalinization and storage & stormwater utilization solves stormwater logging problems. Chinanews press release of July 22nd [In Chinese]. http://www.chinanews.com/gn/2011/07-22/3203324.shtml (Accessed: 12th of April, 2013)

Ji, W. 2010. *Optimization and management of rainwater harvesting and reusing – A case study of Beijing.* Doctor Thesis. Beijing: Graduate University of Chinese Academy of Sciences [Eng. summ.].

Jones, J.E., Clary, J., Strecker, E., Quigley, M., Moeller, J. 2012. BMP effectiveness for nutrients, bacteria, solids, metals, and runoff volume. *Stormwater, The Journal for Surface Water Quality Professionals* **13**, http://www.stormh2o.com/SW/Articles/BMP_Effectiveness_for_Nutrients_Bacteria_Solids_Me_16214.aspx

Lai, F., Dai, T., Zhen, J., Riverson, J., Alvi, K., Shoemaker, L. 2007. SUSTAIN-AN EPA BMP process and placement tool for urban watersheds. Proceedings of the Water Environment Federation TMDL 2007 Specialty Conference, Bellevue, WA, June 24-27. Water Environment Federation, Alexandria, VA, pp. 946-968.

Lan, M., Yang, J. 2009. 浅谈北京市城区道路积水原因及防治对策 [Causes of waterlogging in the road of Beijing and countermeasures for prevention and control]. *Water & Wastewater Engineering* **35**, 71-73 [In Chinese].

Liu, J. [Ed.] 2012a. Affected by precipitation, travel slowed down in some road sections and flights delayed. *Weather China.* Press release of 2012-08-21. www.weather.com.cn/zt/kpzt/1697090.shtml [In Chinese].

Liu, J. [Ed.] 2012b. Road surface collapsed in Jintailu construction site of subway No.6 under construction, Beijing. *Weather China*. Press release of 2012-08-21. www.weather.com.cn/zt/kpzt/1697076.shtml [In Chinese].

Montalto, F.A. Behr, C.T. Yu, Z. 2011. Accounting for uncertainty in determining green infrastructure cost-effectiveness. In: Thurston, H. [Ed.], *Economic Incentives for Stormwater Control*. CRC Press, Boca Raton, FL.

NETEASE 2012. Rainstorm attached Beijing – distribution of main waterlogging areas in the urban area and proposed alternative ways out [In Chinese]. http://news.163.com/special/beijingyanshui (Accessed: 2013-10-04).

Peters, C., Vivattene, C., Revitt, M. 2009. D2.1.3 R/T/D: A technological modelling approach, which assists the identification and targeting of the most appropriate stormwater solutions at a catchment scale. 018530 – SWITCH Sustainable Water Management in the City of the Future, http://www.switchurbanwater.eu/outputs/pdfs/W2-1_GEN_SW_D2.1.3_Technological_modelling_stormwater_solutions.pdf.

Philip, R., Anton, B., van der Steen, P. 2011. SWITCH Training Kit. Integrated Urban Water Management in the City of the Future. Module 1: Strategic planning. Preparing for the future. ICLEI European Secretariat GmbH . www.switchtraining.eu/modules/module-1

Rossman, L.A. 2010. Storm water management model user's manual, Version 5.0. US Environmental Protection Agency, Cincinati, OH.

Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Brown, R.R. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental Management* **42**, 344-359. doi: 10.1007/s00267-008-9119-1.

Shahmohamadi, P., Che-Ani, A.I., Ramly, A., Maulud, K.N.A., Mohd-Nor, M.F.I. 2010. Reducing urban heat island effects: A systematic review to achieve energy consumption balance. *International Journal of Physical Science* **5**, 626-636.

Shoemaker, L., Riverson, J., Alvi, K., Zhen, J., Murphy, R. 2011. *Report on Enhanced Framework (SUSTAIN) and Field Applications for Placement of BMPs in Urban Watersheds*. U. S. Environment Protection Agency, Tetra Tech, Inc., Fairfax, VA.

Sieker, H., Jakobs, F., Jin, Z., Peters, C. 2008. Deliverable 2.2.2a R: Development and testing of a life-cycle cost calculation tool. 018530 - SWITCH Sustainable Water Management in the City of the Future, http://www.switchurbanwater.eu/outputs/pdfs/W2-2_GEN_MAN_D2.2.2a_D2.2.2b_Lifecycle_cost_calculation_tool.pdf.

Skowron, A. 2008. WG VII: Ecohydrology and urban aquatic ecosystems. Final report SWITCH-LODZ / RTD 2007: M 13-14. http://switchlodz.files.wordpress.com/2008/02/wg_vii_final_report_feb2008_phytoplankton-2007_ola.pdf

The Beijing News 2012. Storage tanks will be installed for 20 sunken overpasses. The Beijing News press release of August 12 [In Chinese]. http://www.bjnews.com.cn/news/2012/08/12/216306.html (Accessed: 13th of April, 2013).

TRBNA 2006. Evaluation of best management practices for highway runoff control. *NCHRP (National Cooperative Highway Research Program) Report 565*. Transportation Research Board of the National Academies.

Turner, R., Mackay, R., Bates, A.J. Cuthbert, M. 2011. *Hydrology of brown roofs*. SWITCH - Sustainable Water Management in the City of the Future project, Deliverable 2.3.1d. http://www.switchurbanwater.eu/outputs/pdfs/W2-3_GEN_RPT_D2.3.1d_Overview_of_Hydrology_of_Brown_Roofs.pdf

UWMP undated. IHP Programme, Urban Water Management Programme (UWMP). http://www.unesco.org/new/en/natural-sciences/environment/water/ihp/ihp-programmes/uwmp/ (Assessed: 9th of April, 2013).

van Veenhuizen, R., Cai, J., Ji, W. 2011. *Beijing: alternative water sources for peri-urban agriculture. Building networks for sustainable use of rainwater and wastewater*. *SWITCH* – Sustainable Water Management in the City of the Future project. http://www.switchurbanwater.eu/outputs/pdfs/W6-2_CBEI_RPT_SWITCH_City_Paper_-_Beijing.pdf

Wagner, I., Zalewski, M. 2009. Ecohydrology as a basis for the sustainable city strategic planning: focus on Lodz, Poland. *Reviews in Environmental Science and Bio/Technology* **8**, 209-217.

Wang, B., Huo, L., Gao, J. 2004. 透水性地砖蒸发试验研究 [Evaporating test researches of porous brick]. *Building science research of Sichuan* **30**, 102-104 [Eng. summ.].

Wang, H. 2012. "7.21" human death increased to 79. *Morning Post*. Press release of 2012-08-06. www.morningpost.com.cn/xwzx/bjxw/2012-08-06/345102.shtml [In Chinese].

Wang, J., Ma, H. 2011. 解决城市积水问题的对策与措施 [Measures to solve urban waterlogging problem]. *Administration Reform* **11**, 71-73 [In Chinese].

Wang, M., Yu, R. 2012. Beijing rainstorm caused 10660 buildings to collapse. *People's Daily Online*. Press release of 2012-07-24. bj.people.com.cn/n/2012/0724/c82840-17277191.html [In Chinese].

Wang, N., Wang, M. 2012. 北京“7. 21”特大暴雨灾害的輿情分析与有关思考 [Analysis of public opinions and relevant ideas on Beijing "7.21" extraordinary rainstorm disaster]. *Water Resources Development Research* **12**, 13-15, 70 [In Chinese].

Wang, Q., Liu, Y. 2012. 163 damaged cultural relics intensify “physical examination”. *Morning Post*. Press release of 2012-07-30. news.dayoo.com/china/201207/31/53868_25322957.html [In Chinese].

Watanabe, S. 1995. Study on storm water control by permeable pavement and infiltration pipes. *Water Science and Technology* **1,** 25-32.

Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. 2007. *The SUDS manual.* CIRIA, London.

Xinhua News 2012. Guan, G. Modification plan of four easy-waterlogging sunken overpasses in Beijing was published. Xinhua News, press release of August 15th [In Chinese]. http://news.xinhuanet.com/2012-08/15/c_112736812.htm (Accessed: 12th of April, 2013).

Yang, Z., Bai, G. 2012. 北京城市水文应对 7.21特大暴雨的经验与思考 [The experience and thinking of Beijing city hydrology responding the “7.21” extraordinary rainstorm]. 中国水文科技新发展 — 2012中国水文学术讨论会论文集 *[New Progress of China Hydrology Science and Technology – 2012 China Hydrology Colloquium Conference Proceedings]. Nanjing city, Jiangsu province, China* [In Chinese].

Ye, B., Sheng, D., Men, X. 2010. 城市内涝的成因及其对策 [Causes and countermeasures of urban water logging]. *Journal of Economics of Water Resources* **28**, 62-65 [Eng. summ.].

You, F., Shi, Z., Wu, H. 2011. 北京城区积水事件与同期降水强度相关分析 [Correlation analysis between waterlogging events and rainfall intensity in the same period in Beijing urban area]. 第28届中国气象学会年 — S10公共气象服务政策体制机制和学科建设 *[The 28th Chinese Meteorological Society Annual Conference – S10 public meteorological service policy system mechanism and discipline construction]. Xiamen city, Fujian province, China* [In Chinese].

Zalewski, M. 2000. Ecohydrology – the scientific background to use ecosystem properties as management tools toward sustainability of water resources. *Ecological Engineering* **16**, 1-8.

Zalewski, M. 2002. Ecohydrology – the use of ecological and hydrological processes for sustainable management of water resources. *Hydrol. Sci. J.* **47**, 825-834.

Zalewski, M. 2010. Ecohydrology for implementation of the EU water framework directive. *Proceedings of the ICE – Water Management* **164**, 375-385.

Zalewski, M., Janauer, G.A., Jolankai, G. 1997. Conceptual background. In: Zalewski, M., Janauer, G.A., Jolankai, G. [Eds], *Ecohydrology: a new paradigm for the sustainable use of aquatic resources*. UNESCO International Hydrological Programme, Technical Documents in Hydrology 7, Paris.

Zalewski, M., Robarts, R. 2003. Ecohydrology – a new paradigm for integrated water resources management. *SILNews* **40**, 1-5.

Zalewski, M., Santiago-Fandino, V., Neate, J. 2003. Energy, water, plant interactions: ‘Green feedback’ as a mechanism for environmental management and control through the application of phytotechnology and ecohydrology. *Hydrological Processes* **17**, 2753-2767.

Zalewski, M., Wagner-Lotkowska, I. [Eds] 2004. *Integrated watershed management – ecohydrology and phytotechnology*. UNEP, Division of Technology, Industry and Economics – International Environmental Technology Centre, Osaka, Shiga, Japan, pp. 246.

Zhang, S. 2008. 雨洪利用与城市自然水循环修复 [The restoration of natural water cycle in city by rainwater harvesting and utilization] [Eng. summ.]. http://www.shsl.org.cn/fore/watersatech_detail.aspx?id=816091&cid=65

Zhang, S., Hao, W. 2011. *Storm water harvesting and management in Beijing urban area*. The 2011 World Water Week. Stockholm, August 21-27, 2011. http://www.worldwaterweek.org/documents/WWW_PDF/2011/Tuesday/K23/Levers-of-Change-in-Peri-Urban-Water-Management/Storm-Water-Harvesting-and-Management-in-Beijing-Urban-Area.pdf

Zhang, S., Wang, H., Zang, M., Chen, J., Lai, H. 2011. Development idea of rainwater utilization in Beijing urban areas. *Beijing Water*. **5**, 1-4 [Eng.summ.]. http://www.shsl.org.cn/fore/watersatech_detail.aspx?id=2390592&cid=66

Zhu, W., Deng, Z. 2012. 简述永定河城市段的生态修复 [Resume of the ecological restoration of Yongding River in the urban area]. *Water Conservancy Science and Technology and Economy* **18**, 19-21, 37 [In Chinese].

Zuo, J., Liu, C., Zheng, H., Chen, Y. 2008. Countermeasures and characteristics of Beijing urban rainwater utilization. *Resources Sciences* **30**, 990-998 [Eng. summ.].