Build Sponge Eco-cities to Adapt Hydroclimatic Hazards

Chung-Ming Liu, Jui-Wen Chen, Ying-Shih Hsieh, Ming-Lone Liou, and Ting-Hao Chen

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Abstract

Global population increases steadily and the majority are moving into cities. In the meantime, fast-growing cities are suffering with intensified hydroclimatic hazards. In this chapter, the authors propose to transform cities to sponge eco-cities so as to enhance their capacity on flood prevention, water resources replenishment, heat-island mitigation, biodiversity development, and air and water quality improvement. The strategy proposed is to replace all urban pavements with load-bearing, permeable, breathable, and sustainable pavements, so that rainwater will be stored underneath on raining days and water vapor will be released on sunny days. With water and air reaching soil underneath, underground ecosystem will flourish to enrich urban biodiversity. The JW eco-technology meets the seven criteria specified in this chapter to construct

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desired pavements. JW refers to the initials of the first name of the inventor, Jui-Wen Chen. These criteria are load-bearing capability, permeability, water storage capacity, breathability, underground ecosystem enrichability, affordability, and sustainability. In Taiwan, this JW eco-technology has been tested successfully for 10 years and is recommended by the official agency responsible for the green building certification. Certainly, it is not a trivial task to replace all man-made pavements of any city within a short period of time. A “Build Sponge Taiwan Initiative” has been launched by environmental groups in Taiwan to promote the idea to the general public and to hopefully build sponge eco-communities island-wide in the nearest future.

Keywords

Sponge eco-city • JW eco-technology • Urban-hydrological hazards

Introduction

Global population converges steadily into cities, and cities are expanding fast (UN 2012). Challenged by abnormal climatic events, record-breaking rainfall easily results in widespread floods in cities (Hibbs and Sharp 2012). A typical example was the devastating flood happened on July 21, 2012, in Beijing. Within a short period of time, many areas were buried in water with depths up to 2 m. Losses were severe. People are pondering how to avoid similar disasters in the future (Olesen 2012). Some experts on flood control suggest lifting the storm drainage standard from the current 1–3 years’ recurrence period to a higher interval. However, with more extreme rainfall events are expected to occur (IPCC 2012), how much higher the recurrence interval should be raised? Besides, such strategy may not be affordable to all other cities (Searle 2004).

In the meantime, Beijing, with a population of 20 million living in a semiarid region, is hungry for more water resources. Overexploiting of groundwater with a yearly volume of 10 million is blamed for local land subsidence (Wang 2004). Therefore, storing record-breaking rainfalls for later usage may be more beneficial than diverting rainwater downstream for flood prevention. Such dilemma poses a profound challenge to all city governments. In addition, accelerated urban growth leads to intensified urban heat island (Lin and Yu 2005; Liu et al. 2007). Shortage of green zones and water worsen the condition and put stress on elderlies when unexpected heat waves prevail (Jenerette and Larsen 2006; Kovats 2008). Clearly, for a modern city, a balance between stormwater drainage (Butler and Davies 2010) and rainwater harvesting (Pandey et al. 2003) must be tackled respectably.

In this report, the authors propose to transform each city to a sponge eco-city, which is supposed to store rainwater during each rainfall event and to release water vapor on sunny days. Ideally, it is like a sponge absorbing and releasing water spontaneously. No mechanical or chemical or electrical energy is needed.

With enhanced detention capacity and extra water storage, a sponge eco-city can prevent flood and mitigate urban heat island smoothly.

How to create a sponge eco-city? The approach is to replace all man-made pavements with high load-bearing, high permeable, and high breathable pavements and to store rainwater within a gravel layer right below. With water and air reaching to the underground soil layer, tree roots and microorganisms will flourish underneath and pollutants captured will be decomposed and become nutrients to the ecological system (Liu et al. 2012; Fan et al. 2013).

Seven criteria are specified to select desired technique for paving the high load-bearing, high permeable, and high breathable pavement. Only the JW eco-technology (Chen 2004) meets these criteria and the completed pavement is named as the JW pavement. In the following, ideas about a sponge eco-city, the JW eco-technology, and the benefits accompanying with a sponge eco-city are explored.

Sponge Eco-city

The term "sponge city" was used by demographers in population studies to describe the fact that urban cities concentrate and absorb the surrounding rural populations like a sponge, resulting in a continuous, steady decrease in rural populations and a simultaneous expansion of urban areas (Budge 2006). However, urban development results in compactly built buildings, congested roads, traffic, pollutant accumulation, and the pooled consumption of a variety of materials, such as electricity, oil, food, water, and medicines (Van Rooijen et al. 2005; Grimm et al. 2008). Thus, while cities are very important for the development of modern human civilization, they also produce many problems, especially when they encounter hydroclimatic hazards (Hibbs and Sharp 2012).

In this report, a sponge city represents a city with all man-made pavements being replaced by permeable and breathable pavements which will store rainwater underneath and let water evaporate on sunny days. Since ecological system will flourish underneath, the authors name this kind of city as a sponge eco-city.

The idea of reducing effective impervious area in city so as to reduce surface runoff, thus reducing the amount of water directly entering the drainage system and increasing the retention time of rainwater in natural ecosystems to filter the surface impurities carried by rainwater, is proposed in the low-impact development (LID) strategy (Dietz 2007; USEPA 2000, 2006) and the sustainable urban drainage systems (SUDS) in UK (Ellis et al. 2002) and the water-sensitive urban design (WSUD) in Australia (Donofrio et al. 2009). In principle, concepts outlined in LID, SUDS, and WSUD are sound, but they are difficult to make an impact on either an ancient or a fast-growing city, such as Beijing. The key problem is lacking an innovative technology to pave a permeable, breathable, load-bearing, and sustainable pavement to replace all impervious man-made pavements with limited resources.

In the following, seven criteria are specified for identifying a qualified pavement technology:

1. Load-bearing capability: The compressive strength of the constructed pavement should reach 600 kg f/cm^2; that is, the pavement is with strength greater than 8,000 lb f/in^2 and is able to withstand the pressure from grinding by a heavy tank (Papagiannakis and Masad 2008).
2. Permeability: The pavement must be permeable to 10,000 mm/h of water under clean conditions and 1,000 mm/h when covered with leaves and dust (Scholz and Grabowiecki 2007). One advantage of such pavement is that no matter how strong a rainfall occurs, the surface runoff would be close to zero (Wu 2005). Thus, the construction of drainage ditches around the pavement may be unnecessary.
3. Water storage capacity: In many areas, it is specified that permeable pavements must be accompanied with gravel layers underneath (Krueger and Smitha 2012). The purposes are for stormwater detention and pollutant filtering (Sansalone et al. 2008). Since the environmental condition of each city is different, the designated water detention amount can be different. In this chapter, an effective 10-cm water storage layer is proposed, which can be achieved with a 33.4-cm-depth gravel layer of porosity 0.3 or in any other combinations of gravels and water-storing materials. Then, as the road area in Beijing is 62.7 Mm^2 (BSIN 2013), thus 6.27 Mm^3 of water, or 6.27 MT of water, could be stored underneath.
4. Breathability: Detectable movement of air flowing freely up and down through the pavement is specified. The purpose is to cool the ambient air through vaporing the underground water and to absorb air pollutants substantially into layers below the pavement (Liu et al. 2012). Also, the air provides necessary nutrients and active agents to the ecosystem underneath (Paul 2007).
5. Underground ecosystem enrichability: With air and water flowing freely into layers below the pavement, tree roots and microorganisms will flourish. Such underground ecosystem development is not detectable with eyes, which is in contrast to the ecosystem linked with the urban green landscape, but will function similarly, i.e., to decompose pollutants absorbed and clean the environment (Chapelle 2000; Liu et al. 2012). Such system may be named as an underground wetland (Mitsch and Gosselink 2007).
6. Affordability: This is an important factor to consider when transforming an ancient city in the third world to a sponge eco-city. The construction cost should not be a burden; the maintenance spending must be negligible; and, most importantly, there are minimized needs to repair or replace the pavement for a long period of time, such as more than 30 years. Therefore, when estimating the total budget for a period of 30 years or more, the cost will be affordable to almost all cities in the world.
7. Sustainability: With suitable maintenance being applied, major characteristics of the pavement, such as smoothness, evenness, load-bearing, permeability, water storage, breathability, and underground ecosystem development, must be kept for a period of 30 years or more. Thus, a considerable amount of resources and funding involved in replacing the pavement could be saved in the long run. These all meet the specification as a sustainable pavement (Gopalakrishnan 2011).

The JW Eco-technology

To every place explored by man, there must be a road. Under every road built by man, there must be an interruption of soil linking with nature. Therefore, all man-made pavements, such as walkways, road, etc., can be viewed as the first act of destruction by humans to the environment. Taking human skin as an example, if covered by paints, the skin would be deteriorated to a deceased condition. Hence, humans are practically living above deceased Earth surface with man-made pavements extending widely all over a city and are wishing that all urban-hydrological problems can be managed through engineering measures, which is clearly an impossible mission. To sustain urban environment, pores of all man-made pavements must be opened up so as to cooperate with Earth while facing the challenge of long-lasting heat waves, severe droughts, devastating floods, etc.

The pavement paved with the JW eco-technology (Fig. 1) is characterized with a specific thickness of gravels under a concrete pavement, which uses structured plastic frames with hydraulic conductivity (Liu et al. 2012), named as the JW aqueduct frame (Fig. 2), to replace traditional reinforced steels to ensure the compressive strength and flexural strength of the concrete pavement (Chen 2004). The JW aqueduct frame has a covering stripe which is removed after the solidification of concrete, so as to reveal holes of water pipes. These holes are named as pores of the JW pavement.

Since reinforced steels would oxidize, rust, and expand upon contact with water, efforts are needed to block water entry below the conventional reinforced concrete

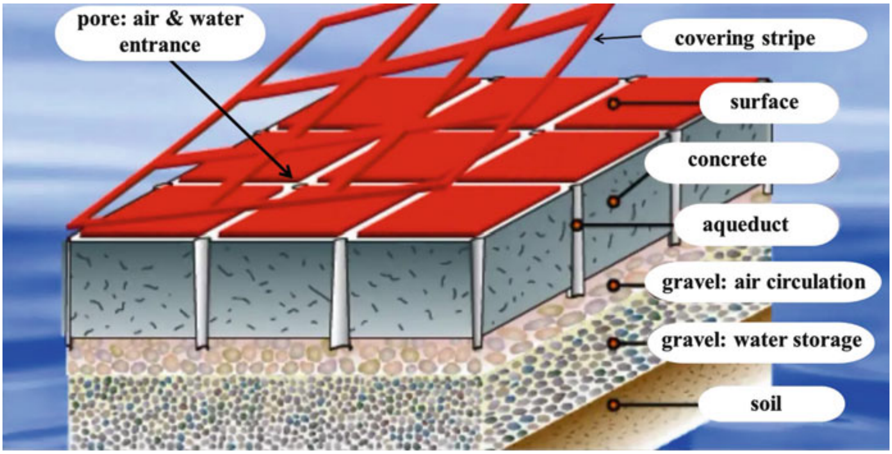

Fig. 1 Illustration of the JW pavement. The upper section is a rigid concrete block with the concrete being reinforced by the JW aqueduct frame (Fig. 2). Covering stripe of the aqueduct frame is removed after the solidification of concrete, so as to reveal holes of all aqueducts. These holes are named as pores of the JW pavement. Water and air are flowing freely through aqueducts. Below, gravels function as pillars to maintain the stability of the upper solid block, while the upper gravel layer facilitates air circulation and the lower gravel layer is for water storage

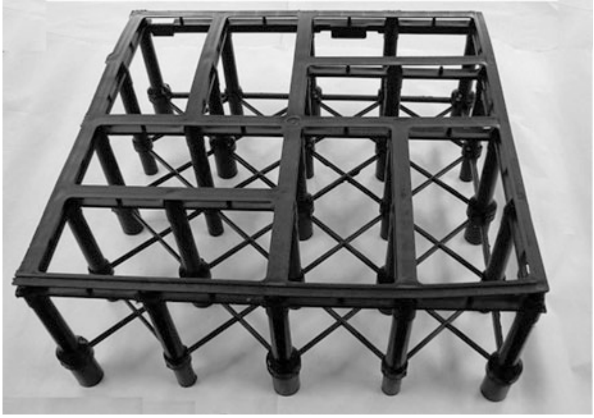

Fig. 2 The JW aqueduct frame

pavement (Papagiannakis and Masad 2008). In contrast, with the JW aqueduct frame, water is welcomed to flow freely into layers below. Furthermore, a conventional rigid pavement would crack with rainwater seeping underneath or tree roots extending below (Papagiannakis and Masad 2008). This is not the case with the JW pavement.

In Taiwan, a 50-meter length JW road was constructed within the campus of the Taipei National University of Technology (TNUT) since 2003, with tree roots unblocked along the pavement. Until now, the road maintains similar functions with no crack or bumps (Tsai JH, 2010, Long-term monitoring of the pervious pavements in front of the architecture building of the National Taipei University of Technology, personal communication. (in Chinese)). Liu et al. (2012) and Fan et al. (2013) opened up portion of this pavement and revealed that tree roots were growing widely underneath. In Taiwan, a 10-year guarantee for the evenness and smoothness of the JW pavement is provided by the inventor. Theoretically, if damages caused by earthquake would not happen, the JW pavement could last for more than 30 years and hence qualify as a sustainable concrete pavement (Van Dam et al. 2012).

The JW plastic frame composes of many air-cycle aqueducts (Fig. 2). On the surface, it is about 100 pores per square of meter, acting as skin holes for allowing the flow of rainwater and air circulation. In comparison to the conventional porous asphalt pavement, grass bricks, and permeable tiles, negligible surface runoff can be measured over the JW pavement during each rainfall event (Wu 2005), for the rainwater penetrates directly through each aqueduct into the lower gravel layer (Fig. 1) rather than slowly seeping through the pavement as most other permeable materials.

Tests done by Li (2004) showed that when all the aqueduct entrances were free from dusts and leafs, the pavement had an average infiltration rate of 12,557 mm/h; if occupied thoroughly by dusts and leafs, it still recorded an average infiltration rate of 1,487 mm/h. Still, routine maintenance is recommended to keep the aqueducts free from clogs and maintain a good condition. In Taiwan, the Architecture and Building Research Institute recommends the usage of the JW pavement in the green building evaluation manual and specifies the porosity below the JW pavement as 0.3, which is about six times of those conventional permeable tiles sold in Taiwan (Lin et al. 2012).

The mission and bearing load of each man-made pavement is designed differently; therefore, the underlying depth of the gravel layer, the thickness of the concrete pavement (i.e., the length of the air-cycle aqueduct), the artistic surface treatment, etc., can all be different. For instance, the thickness of a road pavement must be larger than that of a walkway. In short, the thicker the concrete pavement, the more weight the pavement can bear.

Li (2004) measured the vertical point load on a JW concrete block with a thickness of 60 × 60 × 7.5 cm by the test specifications for flat-panel concrete given by the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC). The authors found that the block could withstand 20–30 kg/cm^2 (equivalent to 300–420 psi), while the standard load of a general large vehicle is 90 psi. Pavements with thicknesses of 10 cm and 15 cm could withstand 30–40 kg/cm^2 and 40–60 kg/cm^2, respectively. Acceptable ductility, malleability, and toughness of the JW concrete block were also noted. In addition, according to the standard specification CNS1232 of Taiwan, the compressive strength of JW pavement could reach 1,980 kg f/cm^2; according to the standard specification CNS1011 of Taiwan, the tensile strength of JW pavement reached 74 kg f/cm^2; according to the standard specification CNS10757 of Taiwan, the wear resistance of JW pavement reached 0.51–1.22 %; according to the standard specification CNS6471 of Taiwan, soluble sulfate only affected the JW pavement by 0.38 ± 0.01; according to the standard specification ASTMC979 of Taiwan, alkaline substances would not affect the surface characteristics of the pavement.

Meanwhile, the gravel layer can be specified with a longer depth for regions wishing to store more water. Or permeable pipes can be placed within the gravel layer to direct rainwater into the underground stormwater drainage system, as shown in Fig. 3.

In Taiwan, a 4 × 120 m JW road was recently constructed in Xizhi, New Taipei City, with two parallel underground water tanks capable of storing 70 t of rainwater. Measurements on April 18, 2013 show that around noontime the ambient temperature was about 33 °C, while the surface temperature of the JW road and the nearby asphalt road was about 26.2 °C and 38.2 °C, respectively. On August 12, 2013, the noontime air temperature was about 38.3 °C, while the surface temperature of the JW road and the nearby asphalt road was about 41.8 °C and 63 °C, respectively. With the pavement breathability, the surface temperature of the JW road is clearly much lower than that of the asphalt road. Furthermore, it is due to a significant amount of rainwater stored underneath in spring that the surface temperature of the JW pavement was lower than that of the ambient air (Chen et al. 2013).

Fan et al. (2013) compared the ecological activities below the JW pavement installed in TNUT with those under three other adjacent permeable pavements by collecting samples in the gravel and soil layers underneath and concluded that the microbial compositions and their activities under the JW pavement were both

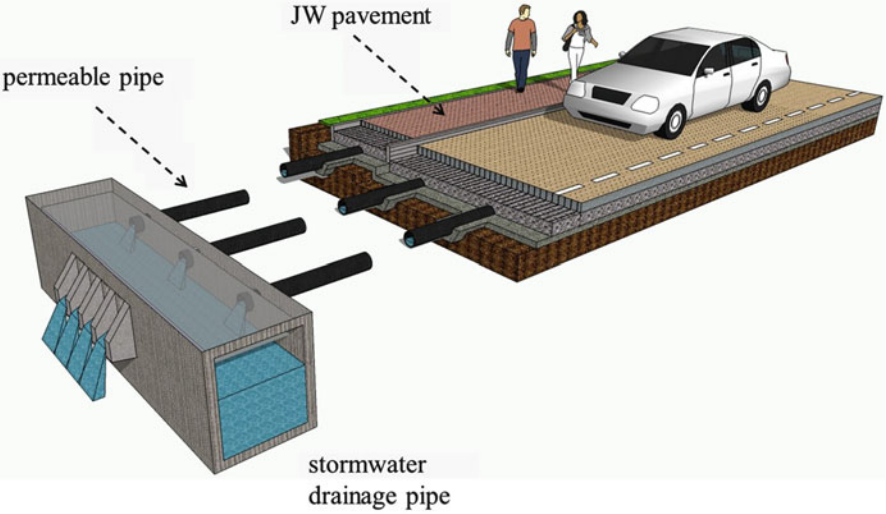

Fig. 3 Underneath the JW pavement, permeable pipes within the gravel layer can direct rainwater into the stormwater drainage system

superior to those under other pervious pavements. Bacterial communities under the JW pavement were more abundant and diverse. The soil under the JW pavement also reflected more activated and versatile microbial activities in all substrates and for specific types of functional guilds.

Liu et al. (2012) also studied the function of the JW pavement in TNUT and designed experiments to compare the variation of the air pollutants concentrations within a fenced area over the JW pavement with one vehicle emissions discharging into with results from similar experiments over a non-JW pavement. Under stagnant condition, it was found that the JW pavement diluted vehicle pollutant emissions near the ground surface by 40–87 % within 5 min of emission, while the data at 2 m height suggested that about 58–97 % of pollutants were trapped underneath the pavement 20 min after emission. Those quantitative estimations may be off by ±10 %, if errors in emissions and measurements were considered. SO_2 and CO_2 underwent the most significant reduction. Very likely, pollutants were forced to move underneath due to the special design of the JW pavement. In order to track the fate of pollutants, parts of the pavement were removed to reveal a micro-version of wetland underneath (Fan et al. 2013), which could possibly hold the responsibility of absorbing and decomposing pollutants to forms harmless to the environment and human health.

According to the “2012 Yearly Parliamentary Validation of the Budget Price for Engineering Projects” of the Taipei City Government (TCG 2012), the JW permeable pavement has a unit installation price close to that of highly compressed bricks which is about 30 % lower than that of permeable tiles. But the compressed bricks require 21 times more than the JW pavement for the maintenance cost, which is mostly for replacing broken bricks every year. Also, the former is officially recommended to be replaced in every 5 years, while the latter has a life expectancy more than 30 years. In reality, local government would replace the former in every 10 years and pay more on the yearly maintenance. Therefore, with the JW pavement, the total budget would be at least 3–7 times lower than that using the highly compressed within a 30-year time span or 5–10 times lower than that of permeable tiles.

To all cities in the world, the JW aqueduct frame can be manufactured locally, while materials such as concrete and gravels are from local origin and the construction workers are trained local labors. Under the principle of "everything local" and with a sustainable nature, paving of the JW pavement is absolutely affordable to all cities in the world.

In all, this section explains how the JW eco-technology meets the seven criteria specified for constructing a sponge eco-city: load-bearing, permeable, water-storing, breathable, underground ecosystem friendly, affordable, and sustainable.

Benefits of a Sponge Eco-city

What are the benefits of a sponge eco-city? In the following, a few cities are selected for illustration.

Using Beijing as an example, given that 10 % of the 3,377 km^2 of the developed areas (337.7 million m^2) (BSIN 2012) are sidewalks, squares, and parking lots with 62.7 million m^2 of road areas, there are approximately a total of 400 million m^2 of man-made pavement that can be changed to the JW pavement. If the space under the pavement is designed to store 10-cm effective thickness of rainwater, approximately 40 MT of water can be stored, which is equivalent to 80 streams of the Cheonggyecheon in Seoul, Korea. Here the Cheonggyecheon is selected for comparison due to it being a successful urban renovation project. The Cheonggyecheon was once covered with an intra-urban double-deck highway and the ambient air temperature of the area was about 5° higher than that of the central area. In early 2000s, a nature restoration project was executed and the stream with approximately 500 KT of water storage was restored (Cho 2010). The ambient temperature of the area is now about 3.6° lower than that of the central area (RESTORE 2013).

If one restored Cheonggyecheon-type stream is enough to cool the nearby area by 8.6° with respect to the previous covered condition, a weakened urban heat island could be expected in Beijing with 80 streams of Cheonggyecheon flowing underneath. With such detention capacity, the chance to observe serious flooding in Beijing would be lowered. Moreover, future record-breaking rainfalls will be kept to replenish local water resources. There are other unexpected benefits: every degree of the ambient temperature lowered will lead to less air-conditioning demands and hence less energy consumed and less carbon dioxide and air pollutants emitted from power plants (Kan and Tien 2004). Also, at least 50 % of carbon dioxide and air pollutants emitted by vehicles will be captured by the JW road to become nutrients for the underground ecological system (Liu et al. 2012). Clearly, reduction of ambient PM2.5 level and haze could be expected and hence the public health risk would be lowered considerably (Liu et al. 2013).

The benefits to create a sponge eco-city are impressive. If 10 % of the following urban areas, London (1,623 km^2), Paris (2,844 km^2), Berlin (1,347 km^2), Moscow (4,403 km^2), Warsaw (544 km^2), Cairo (1,709 km^2), Istanbul (1,399 km^2), Delhi (1,943 km^2), Bangkok (2,331 km^2), Shanghai (3,497 km^2), Tokyo (8,547 km^2), Los Angeles (6,299 km^2), Houston (4,644 km^2), Rio de Janeiro (2,020 km^2), Buenos Aires (2,642 km^2), and Sydney (2,031 km^2) (DEMOGRAPHIA 2013), are man-made pavements and can be converted to the JW pavements with a designated 10-cm effective depth of rainwater storage, then about 16, 28, 14, 44, 5.4, 17, 14, 19, 23, 35, 86, 63, 46, 20, 26, and 20 MT of water can be stored, respectively, which is equivalent to 32, 56, 28, 88, 10, 34, 28, 38, 46, 70, 172, 126, 92, 40, 52, and 40 Cheonggyecheon streams, respectively. The benefits to all these cities with such a tremendous amount of detention capacity are astonishing. Although the exercise here only provides a rough idea of the potential in changing these cities to sponge eco-cities, it gives a hope to sustain these cities and other expanding urban areas to adapt hydroclimatic hazards under the ongoing climate change.

Discussion and Conclusion

This chapter proposes a daring and innovative idea: transform urban cities to sponge eco-cities by replacing all man-made pavements to load-bearing, permeable, water-storing, breathable, underground ecosystem flourishing, and sustainable pavements. The goal is to store rainwater below the urban pavements on raining days and to release water vapor on sunny days. It will function as a sponge spontaneously with no extra efforts needed. Benefits include enhancing the detention capacity and hence strengthening local flood prevention capability, storing rainwater to replenish local water resources, cooling pavement temperature and mitigating urban heat island, nursing the development of the underground ecosystem, capturing vehicle-emitted pollutants and CO_2 to clean the ambient environment, filtering stormwater pollutants, reducing haze and public health risks, saving long-term costs on pavement replacement, and adapting hydroclimatic hazards and climate change.

As global population is growing steadily and congesting restlessly into cities, they are becoming the most vulnerable areas in facing hydroclimatic hazards (Mitchell 1999; Pelling 2003). Transforming cities to sponge eco-cities will lower this risk and, therefore, is the most favorable approach toward sustainability. It is worthwhile to note that the transformation toward sponge eco-cities has no conflict with the installation of the current urban stormwater drainage system (Butler and Davies 2010). Rather, the combination will surely enhance the local water storage and the detention and drainage capacity (Sansalone et al. 2008), as shown in Fig. 2. The idea has already been exercised in Taiwan (Chen et al. 2013).

In this chapter, seven criteria are specified for identifying the suitable technology: load-bearing capability, permeability, water storage capacity, breathability, underground ecosystem enrichability, affordability, and sustainability. Among them, affordability is the most important factor for cities in the third world, i.e., low costs in installation, maintenance, and replacement for at least 30 years or more. In this chapter, the JW eco-technology is recommended for fulfilling those seven criteria with supporting experimental data outlined. This technology has been tested in Taiwan for 10 years and is now recommended in the Taiwan green building evaluation manual (Lin et al. 2012) and is certainly ready to be tested and implemented in any place in the world.

Certainly, it is not a trivial task to replace all man-made pavements to the JW pavements within a short period of time; but for reducing the urban vulnerability and for sustaining nature and human population, it is better to start the task as early as possible. In Taiwan, a "Build Sponge Taiwan Initiative" (Liu and Hsieh 2013) has been launched by environmental groups to promote the idea to the general public. To create JW sponge eco-cities may be a dream difficult to fulfill, but it is possible to construct sponge eco-communities at every place in the nearest future. Hopefully, similar activities will be launched soon all over the world.

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