Eco-Sponge Elasticity and its Indices Developed to Assess the Performance of Infrastructure in Sponge Cities: A Case Study in Xiamen, China

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Eco-Sponge Elasticity and its Indices Developed to Assess the Performance of Infrastructure in Sponge Cities:

A Case Study in Xiamen, China

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Abstract: In recent years techniques for assessing the "sponge city" concept in practice have been developed and diversified at a rapid pace, therefore a unified assessment framework based on sponge techniques is becoming more and more important for comparing and analysing the performance of different techniques across different sponge city projects. However, previous work has mainly focused on enhancing or developing a certain single sponge technique. This research tries to establish a framework through integrating the resilience of the natural ecosystem with that of engineered infrastructure of sponge cities, forming a new concept of 'Eco-sponge resilience', and quantifying 'Eco-sponge Elasticity'. In particular, a set of elasticities with a unified dimension are developed. The eco-sponge elasticity mainly consists of five types of sponge elasticity and two types of ecological elasticity, including factors such as infiltration, storage, detention, transportation and decontamination, ecological vegetation and natural ecological water elasticities, with which the value of eco-sponge elasticity of a sponge city project can be easily estimated. This research also considers a case study to interpret how to assess the eco-sponge elasticities of six pilot sites of sponge city projects in Xiamen. The result shows that the presented evaluation method is feasible and helpful for assessing and enhancing the performance of sponge cities considering four aspects: the water environment, water resources, water security and water ecosystem of the urban system.

1. INTRODUCTION

Traditional stormwater management theory has been fully developed in western countries, and has derived sets of new theory and technology such as Low Impact Development (LID), Sustainable Urban Drainage System (SUDS), Water Sensitive Urban Design (WSUD) and Green Infrastructure (GI) (Fletcher et al., 2014). Based on these theories, the concept of "sponge city" was put forward in China several years ago. However, the sponge city project now faces multiple challenges in practice, not only due to the complexity, multi-dimensionality and comprehension of the project itself, but also its targeted function extended to multiple aspects (Jiang, Zevenbergen, & Ma, 2018). It is therefore hard to develop a unified, comprehensive index system to measure the performance of the sub-projects or functional units of the sponge city project. As a feedback mechanism, sponge-city evaluation plays a crucial role in promoting the development of sponge-city construction technology.

Literally, “sponge city” originally refers to a city that acquires sponge-like resilience to cope with urban stormwater pressures or disasters through engineering measures (Chang et al., 2018). From this point of view, sponge-city resilience mainly comes from managing urban water resources and water security through traditional engineering measures - this type of resilience is referred to as “sponge-like”. Sponge city projects however have been endowed with many more functions in practice, such as that of environmental water protection and ecological water restoration due to the severe ecological and environmental problems currently existing in urban China (Shao et al., 2016). Accordingly, sponge-city resilience should include the resilience that derives from the improvement of urban ecological and environmental function, and it is thus referred to as “eco-derived” resilience. Combining the above two, this paper puts forward a new comprehensive concept of “eco-sponge” resilience for evaluating the prosperity of a sponge-city.

Some scholars have proposed the concept of an “ecological sponge city” in order to understand the properties of sponge cities more comprehensively (Shuqiu & Zhigang, 2011) . Similarly, the resilient city theory also emphasizes the importance of urban resilience ability, especially ecological resilience (Wagner & Breil, 2013). According to this theory, the core research of sponge cities lies in how to make cities more resilient (Dong, Guo, & Zeng, 2017). These studies provide scientific support for the concept of “eco-sponge” resilience.

Evidence can also be found in GI theory, in which the infrastructure of a city is divided into "Green” and “Grey” infrastructure (Kato, 2011). The former are those man-made substructures, and the latter are those substructures maintaining or restoring natural hydrology (Dong, Guo, & Zeng, 2017). By analogy, the former emphasize the sponge-like absorption function in the physical sense, namely sponge resilience, and the latter the ecological adjustment and recovery function, namely ecological resilience. A sponge city is essentially composed of a series of sponge facilities (or functional units), which can be roughly divided into two groups similar to green or grey facilities (or functional units) in theory, and then the eco-sponge resilience should be divided into the “eco-derived” and “sponge-like” ones, respectively. The former illustrates an ecosystem’s ability to absorb disturbance and recover its functions and structures after a disturbance, defined as “eco-resilience” (Hilderbrand & Utz, 2015). The latter refers to water absorption and release performance deriving from urban constructed infrastructure under a certain water pressure environmental condition, that is defined as “sponge-resilience” in this study.

As a state variable, the resilience should be quantified as that of elasticity when used for quantitative evaluation in practice (Wang, Nistor, & Pickl, 2017). Herein, the eco-sponge elasticity of sponge cities is defined as the ability for safe and efficient utilization and disposal of urban rainwater and sewage by artificial, semi-natural and natural facilities or systems constructed with engineering or ecological techniques of a city.

Correspondingly, eco-sponge elasticity is composed of two parts: eco-elasticity and sponge-elasticity.

Generally, some synthetic indicators are used to evaluate sponge-city performance, such as runoff reduction rate, ecological shoreline proportion, and groundwater depth (Gogate, Kalbar, & Raval, 2017). However, some researchers suggest using specific indicators targeted to evaluate the sponge functions of infiltration, storage, transportation, detention, decontamination and drainage (Mao, Jia, & Yu, 2017; Xu et al., 2017). In the same way, this research divides sponge-elasticity into five functions: infiltration elasticity, storage elasticity, detention elasticity, transportation elasticity, and decontamination elasticity. As far as urban ecosystems are considered, vegetation and aquatic ecosystems are emphasised, and there are therefore two types of eco-elasticity defined mainly corresponding to vegetation and natural water systems, namely ecological vegetation elasticity and natural ecological water elasticity.

The new concepts of eco-sponge elasticity mentioned above will be beneficial in that quantifying and assessing the performance of sponge-city techniques can be done in more detail. However, lack of an assessment framework will hinder use of these concepts and their indicators. This study intends to focus on the following problems: (1) To establish an eco-sponge elasticity evaluation method for assessing a sponge city; (2) To illustrate the eco-sponge elasticity assessment with a case study, so as to provide strategy and suggestions to improve construction techniques for sponge cities.

2. METHODOLOGY

2.1 The evaluation method of eco-sponge elasticity

According to the definition of eco-sponge elasticity (*f(ES)*) and its two composites, the eco-elasticity (*f(E)*) and sponge-elasticity (*f(S)*) mentioned above, an assessment can be carried out. Some more detailed techniques types (see *Table 1* and *Table 2*), such as infiltration elasticity (*f(In)*), storage elasticity (*f(St)*), detention elasticity (*f(De)*), transportation elasticity (*f(Tr)*), decontamination elasticity (*f(Dc)*), and ecological vegetation elasticity (*f(Ve)*) and natural ecological water elasticity (*f(Nw)*) will be discussed during the assessment. The evaluation is divided into five steps, as shown in *Figure 1*.

Step I: Collecting or determining the relevant information and parameters

Firstly, some basic information on a sponge city project is needed, for example, the construction area, hydrological data, design protocol, rainfall, watershed catchment geography and so on. This will provide basic data for the calculation of eco-sponge elasticity.

Step II: Calculating eco-sponge elasticity

In order to calculate the eco-sponge elasticity, this paper suggests a uniform list for classifying the elasticity types (see *Table 1*). Furthermore, the specific meaning and related calculation methods of different elasticities are given in *Table 2*; based on *Table 1* and *Table 2*, the eco-sponge elasticity can be calculated out.

Firstly, elasticity sources and technique characteristics are to be identified according to *Table 1*. Secondly, the related calculation formula is to be confirmed according to the elasticity types and *Table 2*. Among them, eco-sponge elasticity (*f(ES)*) can be estimated by the sponge-elasticity (*f(S)*) and eco-elasticity (*f(E)*), the sponge elasticity (*f(S)*) is the sum of infiltration elasticity (*f(In)*), storage elasticity (*f(St)*), detention elasticity (*f(De)*), transportation elasticity (*f(Tr)*), as well as decontamination elasticity (*f(Dc)*), and the eco-elasticity (*f(E)*) is the sum of ecological vegetation elasticity (*f(Ve)*) and natural ecological water elasticity (*f(Nw)*). The calculation method of each elasticity is proposed according to its specific meaning and existing research. In particular, the ecological vegetation elasticity is measured by the ecological vegetation water demand and vegetation water conservation, emphasizing the system's ability to guarantee the ecological water demand and the ability to maintain water resources. The natural ecological water elasticity is measured by the ecological base flow of the aquatic system, emphasizing the system's ability to guarantee the ecological base flow. Next, based on the formula, listing all the required parameters and assigning the parameters is done according to the collected information through Step I or some supplementary determination. Finally, each elasticity value is calculated according to the relevant calculation formula and parameters.

Step III: Calculating the environmental pressure

The elasticity is often discussed in the context of pressure. Therefore, the environmental pressure is suggested in this paper as a scale to estimate relevant elasticity (see *Figure 1*). According to the meaning of each elasticity and its pressure source, there are six types of pressure of which four correspond to sponge-resilience: runoff reduced pressure (P_{Ru}), detention pressure (P_{De}), transportation pressure (P_{Tr}), decontamination pressure (P_{Dc}), and two to eco-resilience: ecological vegetation pressure (P_{Ve}) and natural ecological water pressure (P_{Nw}).

The specific meaning and calculation method of each environmental pressure is shown in *Table 2*, with which the six environmental pressures can be calculated out.

Step IV: Accessibility analysis of water function

Based on the above calculation of eco-sponge elasticity and environmental pressure, the elasticity and water function accessibility analyses are carried out. These can be analysed from three aspects:

First of all, elasticity structure and composition characteristics are illustrated though calculating and analysing the differences among the eco-elasticity and sponge elasticity values. Then, the function analysis value (S_i) is calculated according to the ratio of elasticity to pressure (*Table 2*), including the runoff reduction function analysis value (S_{Ru}), detention function analysis value (S_{De}), transportation function analysis value (S_{Tr}), decontamination function analysis value (S_{Dc}), and ecological vegetation function analysis value (S_{Ve}) and natural ecological water function analysis value (S_{Nw}). Using these values, the ability to resist environmental pressures (flood disaster) due to construction technology or engineering facilities, e.g., infiltration, storage, detention, transportation, decontamination and ecology, etc. can be analysed. When S_i > or = 1, this indicates that the system has enough resilience to resist the pressure. On the contrary, when S_i < 1, the system does not have enough resilience for doing so. Overall, the bigger the S_i value is, the more strength the system's pressure-resisting performance exhibits. Further, based on the function analysis, the water function of the system can be evaluated, and the calculation method is shown in *Table 2*, including the accessibility of water resources (A_{WR}), the accessibility of water safety (A_{WS}), the accessibility of the water environment (A_{WE}), and the accessibility of water ecology (A_{WC}). Through evaluation of the infiltration and storage function, the capabilities of rainwater control, harvest and resource utilization can be assessed to obtain the ability of the system's water resource. Through evaluation of the decontamination function, the capacity for runoff quality improvement can be assessed to obtain the ability of the system's water environment. Through evaluation of the detention and transportation functions, the ability of system water security is evaluated from the perspective of drainage, and through evaluation of the ecological vegetation function and natural ecological water function, the maintenance ability of the system's water ecology can be evaluated. This gives a direct or indirective judgement to the water function of the system.

Step V: Strategies and suggestions

According to the calculation of eco-sponge elasticity and environmental pressure, as well as the results of elasticity and water function accessibility analyses, an overall assessment on a sponge city's construction should be given. In particular, based on these results, the corresponding improvement measures should be proposed to improve the construction and increase the eco- or sponge-elasticity of a sponge city.

Table 1. Source list for searching the volume parameter of different elasticities

Practices/systems	*f(In)	f(De)	f(St)	f(Tr)	f(Dc)	f(Ve)	f(Nw)		Reference
General greenbelt	N_1	-	-	-	C_1	E_1	M_1	-	(Chen et al., 2015)
Sunken greenbelt	N_2	-	-	-	C_2	E_2	M_2	-	(Battiata et al., 2010)
Non-greening sunken area	-	Q_1	-	-	-	-	-	-	
Pervious pavement	N_3	-	-	-	C_3	-	-	-	(Drake, Bradford, & Van, 2014)
Bio-retention measure	N_4	-	-	-	C_4	E_3	M_3	-	(Davis et al., 2011)
Rain garden	N_5	-	-	-	C_5	E_4	M_4	-	(Battiata et al., 2010)
Stormwater planter	N_6	-	-	-	C_6	E_5	M_5	-	
Tree box filter	N_7	-	-	-	C_7	E_6	M_6	-	
Green roof	N_8	-	-	-	C_8	E_7	M_7	-	(Mentens, Raes, & Hermy, 2006)
Infiltration basin	N_9	-	-	-	C_9	-	-	-	(Erickson, Weiss, & Gulliver, 2013)
Infiltration manhole	N_{10}	-	-	-	C_{10}	-	-	-	
Wet pond	-	-	Z_1	-	C_{11}	-	-	B_1	(Erickson, Weiss, & Gulliver, 2013)
Stormwater wetlands	-	-	Z_2	-	C_{12}	-	-	B_2	(Muthukrishnan, 2010)
Retention pond	-	-	Z_3	-	-	-	-	-	(Guo & Baetz, 2007)
Rainwater tank	-	-	Z_4	-	-	-	-	-	(Jones & Hunt, 2010)

Practices/systems	**f(In)*	*f(De)*	*f(St)*	*f(Tr)*	*f(Dc)*	*f(Ve)*	*f(Nw)*		Reference
Dry pond	-	Q_2	-	-	-	-	-	-	(Erickson, Weiss, & Gulliver, 2013)
Adjusting tanks	-	Q_3	-	-	-	-	-	-	(Battiata et al., 2010)
Grass swale	N_{11}	-	-	T_1	C_{13}	E_8	M_8	-	(Muhammad, M. M. et al., 2016)
Infiltration trench	-	-	-	T_2	-	-	-	-	(Erickson, Weiss, & Gulliver, 2013)
Vegetative filter strip	N_{12}	-	-	-	C_{14}	E_9	M_9	-	(Bodah et al., 2016)
First flush removal device	-	Q_4	-	-	C_{15}	-	-	-	(Gikas & Tsihrintzis, 2012)
Soil filters	N_{13}	-	-	-	C_{16}	-	-	-	(Erickson, Weiss, & Gulliver, 2013)
Natural vegetation	N_{14}	-	-	-	-	E_{10}	M_{10}	-	(Qin, Yang, & Zhang, 2009)
Natural water ecosystem	-	-	Z_5	-	-	-	-	B_3	(Richter et al., 2003)

* *f(In)* is the infiltration elasticity; *f(St)* is the storage elasticity; *f(De)* is the detention elasticity; *f(Tr)* is the transportation elasticity; *f(Dc)* is the decontamination elasticity; *f(Ve)* is the ecological vegetation elasticity; *f(Nw)* is the natural ecological water elasticity.

2.2 Data acquisition

The data were obtained through four means: the design data of the sponge city construction project of the selected sites, published references, field investigation, and field test. Some key parameters of the case study are listed in *Table 3*.

In detail, the infiltration rate (K) of soil or permeable medium was acquired through in-situ test with Double-loop test (Lei, 2015), with K_1 relevant to Site X1-X4, K_2 to Site M1, K_3 to site M2, and K_4 referring to the permeable pavement. h_2, h_3, h_4, h_5, h_6, h_8, h_{11} are the heights of sunken green space, permeable pavement, biological retention zone, rainwater garden, high-level flower parterre, green roof, grass-planting ditches, etc. These shape parameters come from the design or determined data. M, A_w, R_h and S are relative parameters of grassed swale, d, n and i are relative parameters of infiltration trenches, and η, IR and Ep are relative parameters of vegetation. The specific meaning of each parameter can be seen in the calculation of eco-sponge elasticity, and the values come from the design data or empirical values.

Table 2. The related calculation method for eco-sponge elasticity evaluation

Variables	Meaning	Calculation method	Parameters and units	Reference
$f(ES)$	Eco-sponge elasticity	$f(ES) = f(S) + f(E)$	$f(S)$ is the sponge-elasticity; $f(E)$ is the eco-elasticity. The units are mm.	
$f(S)$	Sponge elasticity	$f(S) = f(In) + f(St) + f(De) + f(Tr) + f(Dc)$	$f(In)$ is the infiltration elasticity; $f(St)$ is the storage elasticity; $f(De)$ is the detention elasticity; $f(Tr)$ is the transportation elasticity; $f(Dc)$ is the decontamination elasticity. The units are mm.	
$f(E)$	Eco-elasticity	$f(E) = f(Ve) + f(Nw)$	$f(Ve)$ is the ecological vegetation elasticity; $f(Nw)$ is the natural ecological water elasticity. The units are mm.	
$f(In)$	The ability of the soil or artificial permeable medium to infiltrate the rainwater into the underground.	$f(In) = \frac{\sum_{i=1} N_i}{A}$ $N_i = W_i + U_i = 60KJA_it_i + A_ih_i$	N_i is total infiltration quantity (m^3); W_i is the infiltration quantity of medium (m^3); U_i is the storage volume; K is the infiltration rate of medium (m/s); J is the hydraulic gradient, and the value is 1. t_i is infiltration time (min), and the value is 1h; A is the area of study site (m^2), h_i and A_i are the height (m) and area of the relevant practice (m^2), respectively, and *i* is the type of the practice, as shown in *Table 1*, and the same for the below.	(Ke, 2017)
$f(St)$	The storage ability for stormwater runoff using the storage facilities.	$f(St) = \frac{\sum_{i=1}^{4} Z_i}{A}$; $Z_i = A_ih_i$	Z_i is the storage volume (m^3); for h_i and A_i see the above.	(MHURD, 2016)
$f(De)$	The ability to temporarily store surface runoff by rainwater detention facilities.	$f(De) = \frac{\sum_{i=1}^{4} Q_i}{A}$; $Q_i = A_ih_i$	Q_i is the volume of detention practice (m^3); for h_i and A_i see the above.	(MHURD, 2014)
$f(Tr)$	The performance of collecting and transporting rainwater runoff using the grassed swale, drainage pipes, and so on.	$f(Tr) = (T_1 + T_2)/A$; $T_1 = \frac{1}{M}A_wR_h^{2/3}S^{1/2}t$ $T_2 = \frac{1}{4}\pi d^2 \frac{1}{n}R^{2/3}\theta^{1/2}t$	T_1 and T_2 are the quantity of the grassed swale and the perforated rainwater drainage pipe (m^3); *M* is the manning coefficient; R_h is the hydraulic radius (m), here estimated by A_w/p_w, where p_w is the wetted perimeter of swale (m); *S* is the longitudinal slope of the grassed swale (%); A_w is the cross-sectional area of the water in the grassed swale (m^2); *t* is the rainfall time (s), here, *t*=60 min. *d* is the inner radius of pipe (m); *n* is the pipe roughness; *R* is the hydraulic radius (m); θ is the hydraulic gradient, here estimated by $\Delta h/l$, where Δh is the difference of liquid levels (m), and *l* is the length of perforated rainwater drainage pipe (m)..	(Muhammad, M. M. et al., 2016; MHURD, 2016)
$f(Dc)$	The ability to decontaminate the runoff water quality by infrastructure facilities or the ecosystem.	$f(Dc) = \sum_{i=1}^{16} C_i/A$, $C_i = V_i = A_ih_i \ (i = 11,12)$ $C_i = N_i = 60KJA_it_i + A_ih_i$	C_i is the quantity of decontamination practices (m^3); V_i is the volume of decontamination practice (m^3); A_i is the area of decontamination practice (m^2); h_i is the height of water of the decontamination practice (m), and N_i, *K*, *J*, t_i are as mentioned above.	(Ke, 2017)
$f(Ve)$	The rainwater utilization and disposal capacity of the urban vegetation ecosystem.	$f(Ve) = \left(f(Ve1) + f(Ve2)\right)/A$ $f(Ve1) = \sum_{i=1}^{10} E_i = \sum_{i=1}^{10}(TZ_i - \eta EV_i)$; $f(Ve2) = \sum_{i=1}^{10} M_i = \sum_{i=1}^{10}((Q_S - EP_i) \times A_i)$	$f(Ve1)$ is the guaranteed capability of the ecological water demand of vegetation (m^3); $f(Ve2)$ is the capacity of water conservation of vegetation (m^3); A_i is the area of vegetation type. TZ_i is the rainfall reuse volume of vegetation (m^3); η is the substitution rate of green water, the value is 10%. EV_i is the vegetation's ecological water demand (m^3); Q_S is the average rainfall	(Shi et al., 2017)

			(mm); and EP_i is the vegetation evapotranspiration of vegetation (mm).	
$f(N_w)$	The stormwater utilization and disposal capacity of the natural water ecosystems.	$f(N_w) = \frac{\sum_{i=1}^{n} B_i}{A}$; $B_i = RS_i - RB_i$	B_i is the guaranteed capability of the ecological base flow of the aquatic system (m^3); RS_i is the supplement of natural waters (m^3), $RS_i = A_i h_i$, and A_i is the area of natural water (m^2), h_i is the constant water level of natural water (m); RB_i is the ecological base flow of natural waters (m^3), $RB_i = AF_i \times 10\%$, and AF_i is the average annual flow (m^3).	(Zheng et al., 2010)
P_{Ru}	The pressure caused by the runoff that the field needs to control under the runoff volume control rate.	$P_{Ru} = V' / A$; $V' = 10\varphi_z h_y F$	P_{Ru} is the runoff reduced pressure (mm); V' is the total runoff volume that area needs to control (m^3); φ_z is the integrated runoff coefficient; h_y is the design rainfall (mm); and F is the catchment area (hm^2).	(MHURD, 2014)
P_{De}	The pressure caused by the surface runoff that needs to temporarily store to mitigating flood peak.	$P_{De} = (h_y A - V')/A$	P_{De} is the detention pressure (mm), and h_y, A, and V' are as mentioned above	
P_{Tr}	The pressure caused by the surface runoff that needs to be transported.	$P_{Tr} = P_{De}$	P_{Tr} is the transportation pressure (mm).	
P_{Dc}	The pressure caused by the polluted surface runoff that needs to improve to fit the requirement of water quality.	$P_{Dc} = P_{Ru}$	P_{Dc} is the decontamination pressure (mm).	
P_{Ve}	The pressure derived from the ecological water requirement of vegetation.	$P_{Ve} = \eta EV / A$	P_{Ve} is the ecological vegetation pressure (mm), EV is the vegetation's ecological water requirement (m^3), and η is as mentioned above.	
P_{Nw}	The pressure derived from the ecological base flow of aquatic systems.	$P_{Nw} = RB_i / A$	P_{Nw} is the natural ecological water pressure (mm); and RB_i is as mentioned above.	(Zheng et al., 2010)
S_i	The *i*-th function analysis value.	$S_i = f_i / p_i$	f_i is the i-th elasticity (mm); p_i is the *i*-th environment pressure (mm). Specifically, S_{Ru} is the ratio of the sum of infiltration elasticity and storage elasticity to the runoff reduced pressure.	
A_{WR}	Accessibility of water resource.	$A_{WR} = S_{Ru}$;	S_{Ru} is the runoff reduction function analysis value.	
A_{WS}	Accessibility of water security.	$A_{WS} = S_{De} + S_{Tr}$;	S_{De} is the detention function analysis value; and S_{Tr} is transportation function analysis value.	
A_{WE}	Accessibility of water environment.	$A_{WE} = S_{Dc}$;	S_{Dc} is the decontamination function analysis value.	
A_{WC}	Accessibility of water ecology.	$A_{WC} = S_{Ve} + S_{Nw}$	S_{Ve} is the ecological vegetation function analysis value, and S_{Nw} is the natural ecological water function analysis value.	

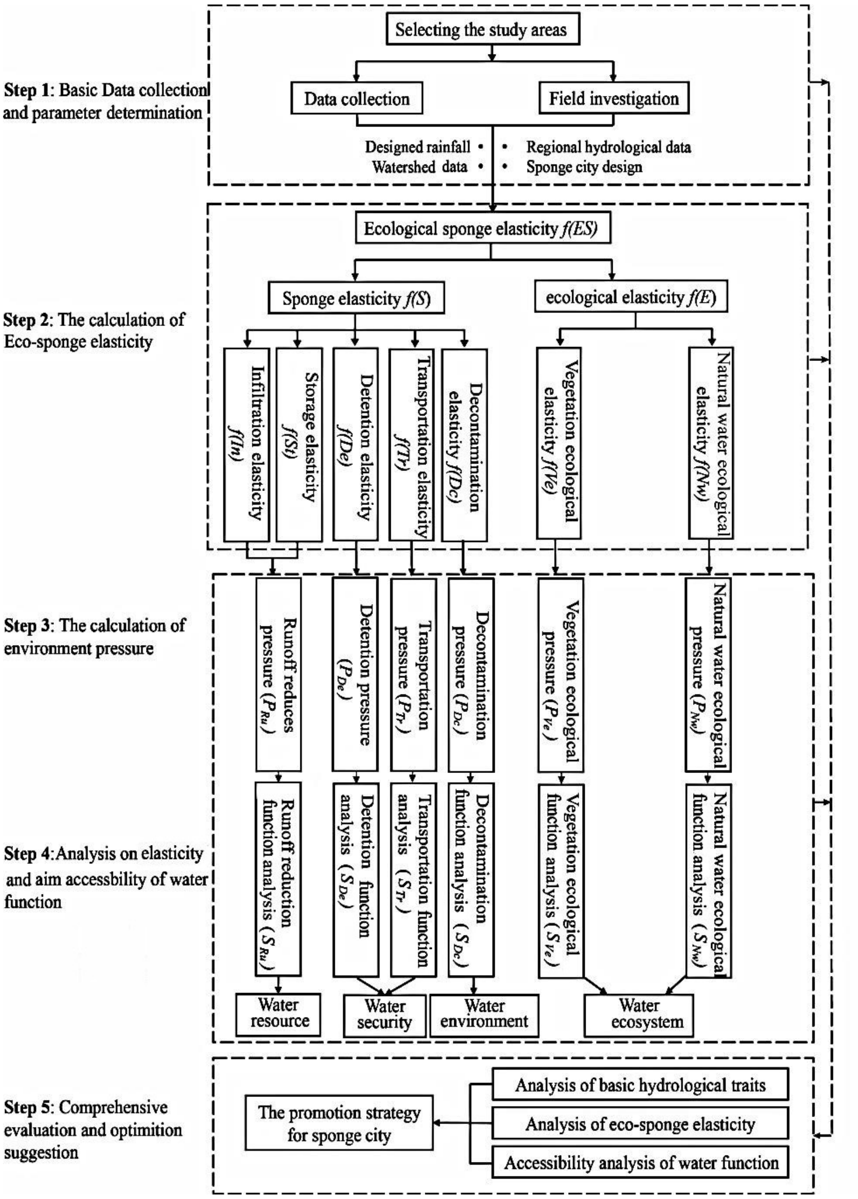

Figure 1. The general assessment framework for eco-sponge elasticity of a sponge city project

Table 3. The key parameters for calculating eco-sponge elasticity

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
K_1	1.49×10^{-5}m/s	h_4	0.1m	M**	0.3	n*	0.01
K_2	5.45×10^{-5} m/s	h_5	0.15m	A_W	0.069 m^2	θ	0.004
K_3	1×10^{-5}m/s	h_6	0.4m	R_h	0.054 m	η**	20%
K_4*	1×10^{-5}m/s	h_8	0.01m	S	20.44%	IR**	2L/m^3.d
h_2	0.15m	h_{11}	0.02m	d	150/200/300/400/500/600	EP	3.4mm
h_3	0.1m	μ*	10%				

*cited from design data; **cited from empirical values

3. RESULTS AND DISCUSSION

3.1 Study Area

Xiamen, located in the southeast coast of Fujian province, China, belongs to the subtropical maritime monsoon climate. Its average annual rainfall is 1,388 mm, mainly from March to July and April to October. Due to strong rainfall intensity and surface runoff, as well as ditch drainage affected by tides, the city often suffers from stormwater and flood disasters. In addition, shortages of fresh water often occur in Xiamen because of its high population density (2,715 people /km^2) and few water resources. The sponge city project has been practiced in two pilot areas: in Xiamen, the Maluanwan Pilot Sponge City Area (MPSCA), and in Xiang'an the Xincheng Pilot Sponge City Area (XPSCA).

Six sub-areas were selected for this case study, they are X1, X2, X3 and X4 belonging to the MPSCA as well as M1 and M2, belonging to the XPSCA. The location and project profiles of the study areas are shown in *Figure 2* and *Table 4*.

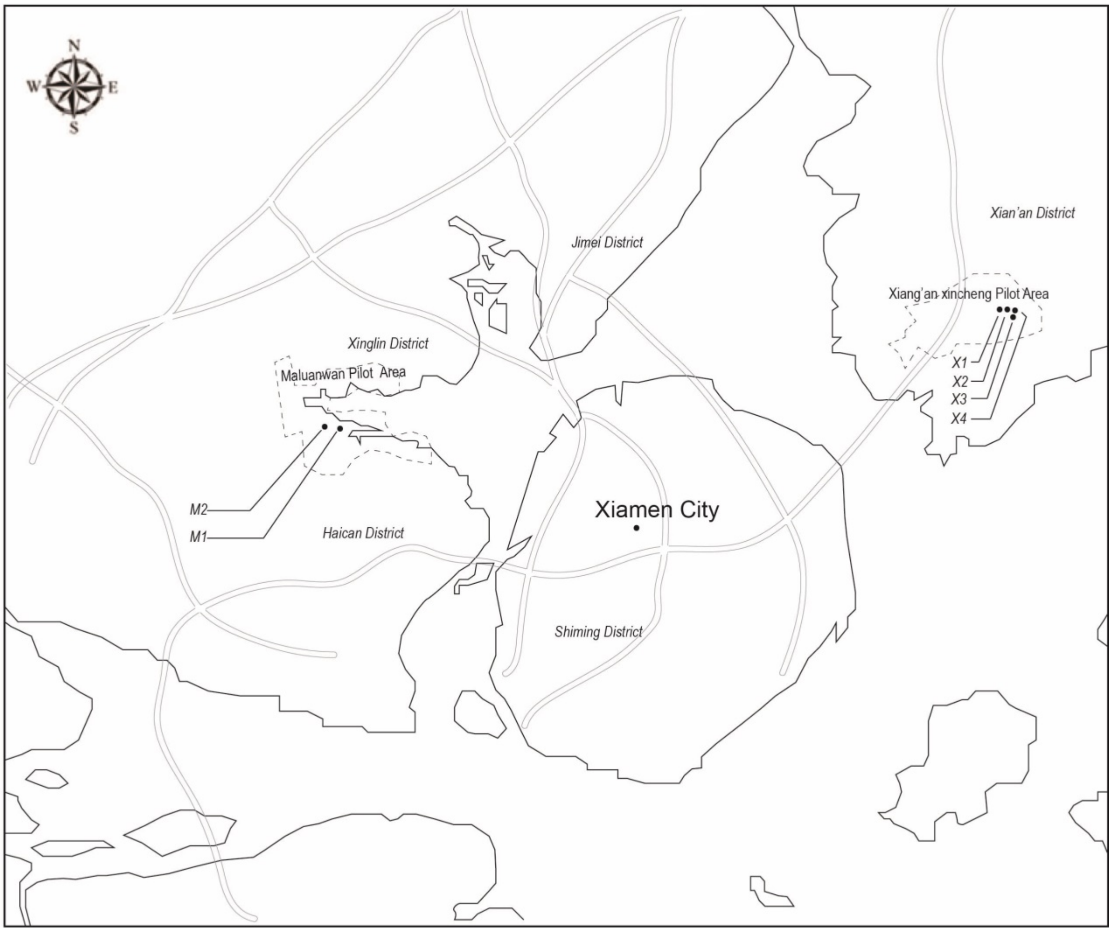

Figure 2. The location of six study sites selected for the assessment of eco-sponge elasticity, in Xiamen, China

Table 4. The project profiles of the study areas

Site type	Site	The facilities of sponge city construction
Residential area	X1	Green roof, pervious pavement, bio-retention measure, rain garden, stormwater planter, grass swale, rainwater tank, retention pond
	X2	Green roof, pervious pavement, bio-retention measure, rain garden, stormwater planter, grass swale, retention pond
	X3	Green roof, pervious pavement, bio-retention measure, rain garden, grass swale, rainwater tank, retention pond
School	X4	Green roof, pervious pavement, bio-retention measure, rain garden, grass swale, rainwater tank
Industrial area	M1	Pervious pavement, sunken greenbelt, rain garden, stormwater planter, grass swale, rainwater tank, retention pond
	M2	Pervious pavement, rain garden, grass swale, retention pond

3.2 Eco-sponge elasticity

The results of eco-sponge elasticity of the selected sites have been calculated in a unified dimension, mm, see *Table 5*. Of the six sites, the eco-sponge elasticity varies from 66.47 mm to 156.73 mm, and the order ranked as M1(156.73 mm) > X2(141.71 mm) > X1(110.25 mm) > X3 (103.20 mm) > X4 (156.73 mm) > M2 (66.47 mm). The values and their ranked order are simple to understand and to compare the overall performance of the six sites under the framework. However, one more detail analysis is also necessary due to the complexity of eco-sponge elasticity. For example, the sponge-elasticity of the six sites was ranked as M1> X2> X1> X3> X4> M2, but the eco-elasticity as M2> X3> X2> X1> M1> X4, see *Figure 3* (a) and (b). According to these results, the six sites can be divided into three groups: Groups I with higher eco- and sponge- elasticity, such as X2, X3 and X1; Group II with higher eco- or sponge- elasticity, such as M1 and M2; and Group III with lower sponge- and eco- elasticity, such as X4. It is clear that the sites of Group I (e.g., X2, X3 and X1) possess relatively good performance for a sponge city, and that those of Group II (e.g., M1 and M2) should have balanced development in eco- or sponge- techniques. The sites of Group III (e.g., X4) may possess poor performance and need to improve both eco- and sponge- elasticity.

The results also showed that the quantity of runoff reduction for the six sites ranked as following: X2> M1> X1> X3> X4> M2, see *Figure 3*(c). Significantly, the calculation of regional runoff reduction takes into account the infiltration and storage, and is only for the pilot area, which is different from the total reduction of the watershed. Moreover, in fact, the diversity of the infiltration techniques of the six sites were also ranked X1=X2>X3=X4=M1>M2 (see *Figure 4*), which was similar to that of the eco-sponge elasticity. These results suggest that the infiltration process contributes the most to the eco-sponge-elasticity, and the diversity of infiltration techniques benefit the improvement of eco-sponge elasticity. Some similar results has also been reported (Li, J. Q. et al., 2010; Li, J. et al., 2017). Therefore, those sites in Groups II and III with lower sponge-elasticity and theoretical runoff reduction rates, such as sites M2 and X4, should improve their runoff reduction performance through infiltration techniques.

Table 5. The calculation and evaluation results of eco-sponge elasticity of six sites in the pilot area

		X1	X2	X3	X4	M1	M2
Elasticity (mm)	*f(Tn)*	44.10	51.38	33	25.36	52.13	10.04
	f(St)	3.03	3.87	6.91	0.33	0.62	12.85
	f(De)	0.57	1.82	0.26	1.61	0.79	1.26
	f(Tr)	21.78	32.88	36.54	50.25	50.25	30.50
	f(Dc)	44.44	51.60	33.26	25.64	52.92	11.30
	f(Ve)	0.12	0.16	0.28	0.01	0.03	0.53
	f(Nw)	0.00	0.00	0.00	0.00	0.00	0.00
	f(ES)	114.04	141.71	110.25	103.20	156.73	66.47
Pressure (mm)	P_{Ru}	13.44	10.23	13.46	15.61	15.62	19.00
	P_{De}	18.56	21.77	13.34	16.39	7.68	7.80
	P_{Tr}	18.56	21.77	13.34	16.39	7.68	7.80
	P_{Dc}	13.44	10.23	13.46	15.61	15.62	19.00
	P_{Ve}	0.15	0.23	0.14	0.15	0.07	0.05
	P_{Nw}	0.00	0.00	0.00	0.00	0.00	0.00
	P	64.15	64.23	53.74	64.15	46.67	53.65
Stress analysis (non-dimensional)	S_{Ru}	3.51	5.40	2.97	1.65	3.38	1.20
	S_{De}	0.03	0.08	0.02	0.10	0.10	0.16
	S_{Tr}	1.17	1.51	2.74	3.07	6.54	3.91
	S_{Dc}	3.31	5.04	2.47	1.64	3.39	0.59
	S_{Ve}	0.80	0.70	2.00	0.07	0.43	10.60
	S_{Nw}	0.00	0.00	0.00	0.00	0.00	0.00

3.3 Environmental pressure and accessibility of water function

Based on the proposed calculation method, the pressure of six sites and the target accessibility of water function have been calculated, the results are shown in *Table 5*. According to these results, the water environment, water resource, water security, and water ecology can be assessed. The result is shown in *Figure 5*. The performance of water resource, water security and water environment were stronger than the performance of water ecology in the pilot area. For the performance of water resource, the order was ranked as follows: X2> X1> M1> X3> X4> M2; that of water security, water environment and water ecology were: M1> M2> X4> X3> X2> X1, X2> M1> X1> X3> X4> M2 and M2> X3> X1> X2> M1> X4, respectively. These results denote that the six sites present unbalanced performance of water functions. Relatively, X2 possesses better performance, except for its water ecology. M1 and M2 have unbalanced performance on water function. X1 and X3 possess medium performance. Overall, X4 possesses weaker performance, except for medium performance on water security. Site M2 possesses relatively good runoff reduction, transportation and ecological vegetation accessibility, which makes its regional water resource, water security and water ecology better, but the ability of the water environment is poor, likely because the M2 site belongs to an industrial area with sponge facilities being constructed insufficiently (see *Table 3*). Some sites present weak performance on water ecology, e.g., X2, mainly due to weaker ecological vegetation function.

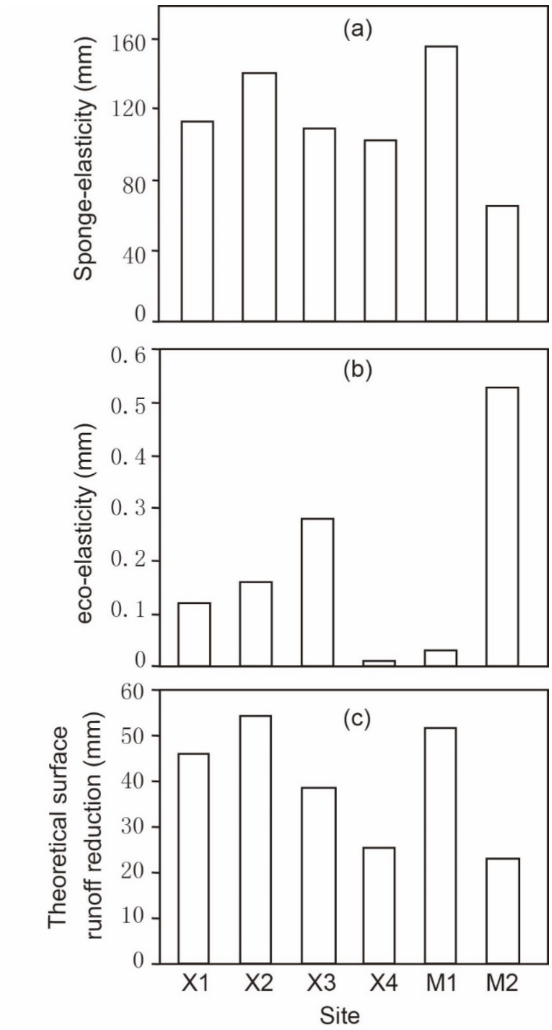

Figure 3. The eco-elasticity, sponge-elasticity and theoretical surface runoff reduction of six selected study sites

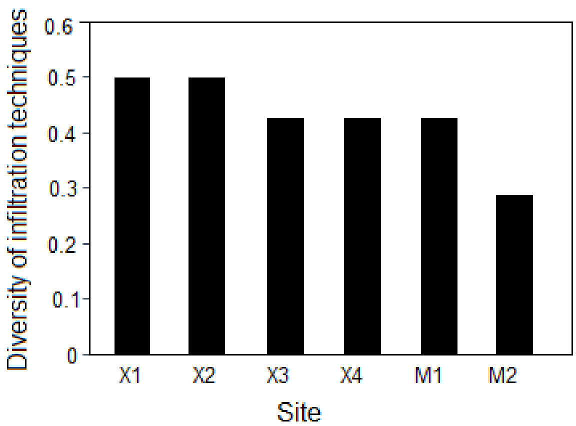

Figure 4. The comparison of the infiltration technique diversity of six study sites

Comprehensively, the target accessibility of water function involves the performance of infiltration, storage, detention, transportation and decontamination for a sponge project. The above results of the accessibility analysis suggest that the main issue of the six sites is unbalanced development toward the performance of water function, and therefore it is very important to improve the eco-sponge elasticity through integrating eco- and sponge- techniques into sponge city projects. A similar conclusion has been reported by previous researchers (Li, J. et al., 2017; Gogate, Kalbar, & Raval, 2017). The detention and transportation functions benefit water security by delaying peak and drainage durations (Erickson, Weiss, & Gulliver, 2013). To a certain degree, stronger performance of the transportation function may improve the water security condition, e.g., for X4 and M1, but it effectively hampers storage and reuse of rainwater.

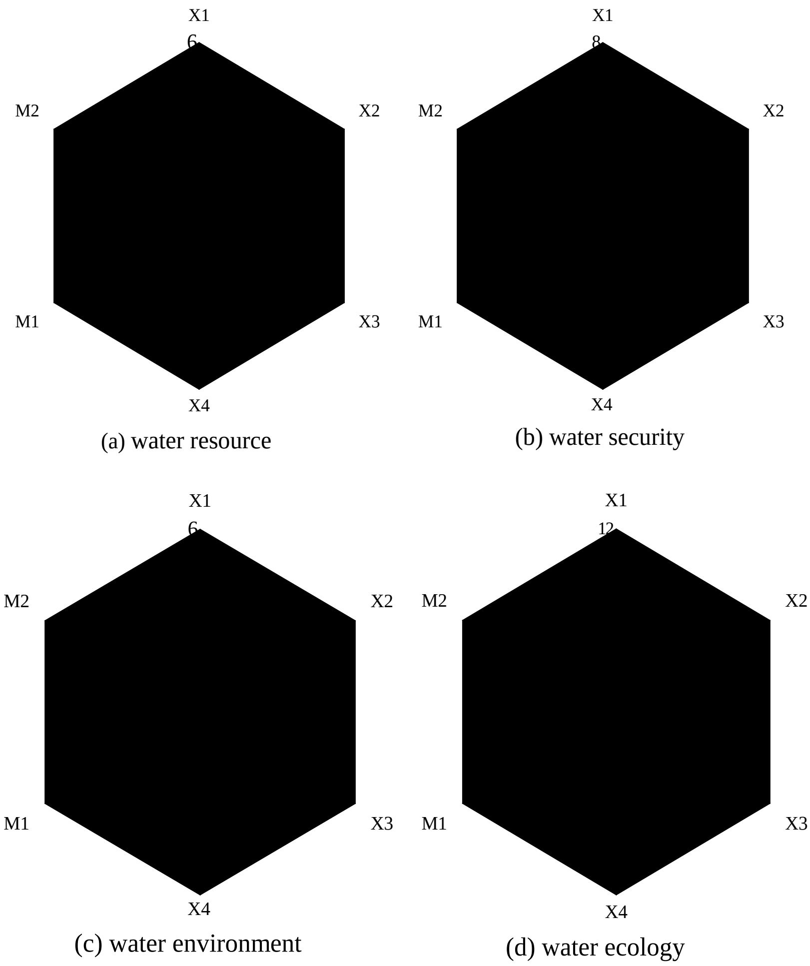

Figure 5. The accessibility analysis of water function in six study sites

Aquatic system construction plays an important role in sponge city projects, because it involves not only the sponge city, but also ecological and liveable city projects. Generally, the function of aquatic systems is evaluated on the basis of ecological water supplement, landscape improvement and fresh water consumption reduction (Jian N 2015); the lack of storage capacity would impact the accessibility of the aquatic system function (e.g., X1, X2, X4 and M1). As far as water resource concerned, infiltration facilities have a strong function to reduce rainwater runoff, such as through bio-retention measures, rain gardens, and so on (Davis, 2008; Yang et al., 2013), as shown in *Table 6*. So, it is important for surface runoff flow to be controlled through diversity of infiltration techniques in a sponge city project. However, for short-duration rainstorms, the integrated functions of different eco-sponge facilities are still the key way to maintain water security, such as through water detention, transportation, and so on (Muhammad, M. et al., 2016). This is similar to that of water environment, for example, the diversity of facilities, such as the green roof, permeable pavement, bio-retention measures, and so on, all play important roles in the removal of surface runoff pollution (Hatt, Fletcher, & Deletic, 2009; Drake, Bradford, & Van, 2014; Yang et al., 2013). Overall, balanced development of diversity of eco-sponge techniques (or facilities) should be paid attention to for the carrying out of a sponge city project.

Table 6. The source of infiltration elasticity of six sites in the pilot area

f(In)	X1	X2	X3	X4	M1	M2
N1*	1131.54	1199.48	576.45	423.83	260.64	77.08
N2	-	-	-	-	1109.55	-
N3	952.20	474.26	79.91	75.65	66.07	65.07
N4	350.67	273.96	480.12	109.72	-	-
N5	404.81	254.97	129.16	41.70	112.78	208.46
N6	34.75	26.73	-	-	31.62	-
N7	-	-	-	-	-	-
N8	117.27	104.85	91.24	117.93	-	-
N9	-	-	-	-	-	-
N10	-	-	-	-	-	-
N11	114.91	318.88	28.73	5.33	10.61	0.75
N12	-	-	-	-	-	-
N13	-	-	-	-	-	-
N14	-	-	-	-	-	-

* N1-N14: see *Table 1*

3.4 A promotion strategy for sponge city projects

Based on the above comprehensive evaluation and analysis for six pilot areas, the corresponding improvement measures are proposed. The specific strategies are as follows:

(1) Balanced development of eco-sponge techniques should be paid attention to for all the six case study sites, especially to construct detention facilities in the six pilot areas and to improve the detention function so that the regional flood peak mitigation capacity can be strengthened.

(2) To enhance the rainwater storage facilities and improve the capacity of rainwater recovery and utilization in X1, X2, X4 and M1 sites so that their ecological water supplement capacity of the systems can be increased.

(3) To increase the type and quantity of sponge construction facilities and optimize facility combination in the M2 site, especially for its infiltration facility, so that the comprehensive performance be improved.

4. CONCLUSION

This paper defines a new concept of eco-sponge resilience and elasticity and establishes an elasticity index system and a five-step assessment framework for estimating and assessing the eco-sponge resilience of sponge city projects. Six typical sponge city construction projects in the Xiamen sponge city pilot area were taken as case studies to verify the elasticity indices and assessment framework.

The results of the case study suggest that the presented assessment indices and framework can be utilised and are practicable. The assessment results and strategy are consistent with the actual situation of the six sponge city construction sites, especially regarding the accessibility of water resource, water environment, water security and aquatic system function. Overall, this research presents a new way to quantify and assess the performance of different eco- and sponge-techniques in different sponge city projects, which is beneficial for optimizing techniques and improving the engineering performance of sponge city projects.

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