Combined sewer overflow control with LID based on SWMM: an example in Shanghai, China

Z. L. Liao, G. Q. Zhang, Z. H. Wu, Y. He and H. Chen

ABSTRACT

Although low impact development (LID) has been commonly applied across the developed countries for mitigating the negative impacts of combined sewer overflows (CSOs) on urban hydrological environment, it has not been widely used in developing countries yet. In this paper, a typical combined sewer system in an urbanized area of Shanghai, China was used to demonstrate how to design and choose CSO control solutions with LID using stormwater management model. We constructed and simulated three types of CSO control scenarios. Our findings support the notion that LID measures possess favorable capability on CSO reduction. Nevertheless, the green scenarios which are completely comprised by LID measures fail to achieve the maximal effectiveness on CSO reduction, while the gray-green scenarios (LID measure combined with gray measures) achieve it. The unit cost-effectiveness of each type of scenario sorts as: green scenario > gray-green scenario > gray scenario. Actually, as the storage tank is built in the case catchment, a complete application of green scenario is inaccessible here. Through comprehensive evaluation and comparison, the gray-green scenario F which used the combination of storage tank, bio-retention and rain barrels is considered as the most feasible one in this case.

Key words | combined sewer overflows, control, low impact development, stormwater management model

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INTRODUCTION

Combined sewer systems still serve as a common urban conveyance method in many large cities around the world, especially in old towns. It is fully recognized that combined sewer overflows (CSOs) are one of the causes of the deterioration of the urban hydrological environment (Butler & David 2000). Since the 1970s, numerous studies have emphasized the importance of pollution loads conveyed by combined wet weather discharges and their adverse impacts on receiving water (Kafi *et al.* 2008). The characteristics and origins of CSOs have been known clearly since then (Gasperi *et al.* 2010).

Generally, there are two ways to control CSOs. One is the traditional gray infrastructure, and the other one is the green infrastructure or so-called low impact development (LID) measure. LID can control the rainwater from sources which are more effective and environment-friendly than the traditional gray infrastructure (Coffman 2000). Because of their flexible size, discrete layout, small investment, good effects, and other advantages, LID measures can be used dispersedly so that they are more suitable in highly urbanized areas, and they can be applied in combination with landscape construction in urban renewal to beautify the surroundings (Dietz & Clausen 2008). Many American applied studies found that it brings about good control results of water quality and quantity with the implementation of LID or LID and traditional gray infrastructure combinations (Dietz 2007). LID has therefore become a mainstream, though not ubiquitous, means of stormwater management in the USA and in Canada (Fletcher *et al.* 2014). However, in many developing countries, traditional gray infrastructures are still the main measures for controlling CSOs. To our knowledge, there have been few news reports about LID utilization in China.

Before application, it is necessary to know which LID measure is suitable and cost-effective for a specific case. It has been proved that the satisfactory method for sewer system plan is long-term simulation with models (James *et al.* 1982). It makes the design and application of LID more effective (Artina *et al.* 2005). Among the models, the stormwater

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management model (SWMM) is representative (Singh 1995). SWMM (Version 5.0.022, US Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, USA) can simulate five LID practices, i.e., rain barrel, grass trench, permeable paving, infiltration trench and bio-retention pond. It also can simulate the effects of runoff, peak flow and pollution reduction of different LID in combination with other modules (Rossman 2010).

In this work, a typical combined sewer system in Shanghai, China, was used to demonstrate how to design and choose CSO solutions with LID using SWMM. The purpose of this paper is to provide developing countries with a reference about CSO control.

MATERIAL AND METHOD

Study area description

Changping, located at the old city center of Shanghai, China, is drained by a combined sewer system covering a land use of 3.45 km^2. This area is densely populated (approximately 330 inhabitants/ha) and is a mixed residential and commercial use area.

Through model generalization, the whole study area was divided into 60 sub-catchments, 252 nodes and 292 conduits, as in Figure 1. The 40 gray layers present the sub-catchments which were added with LID measures. The

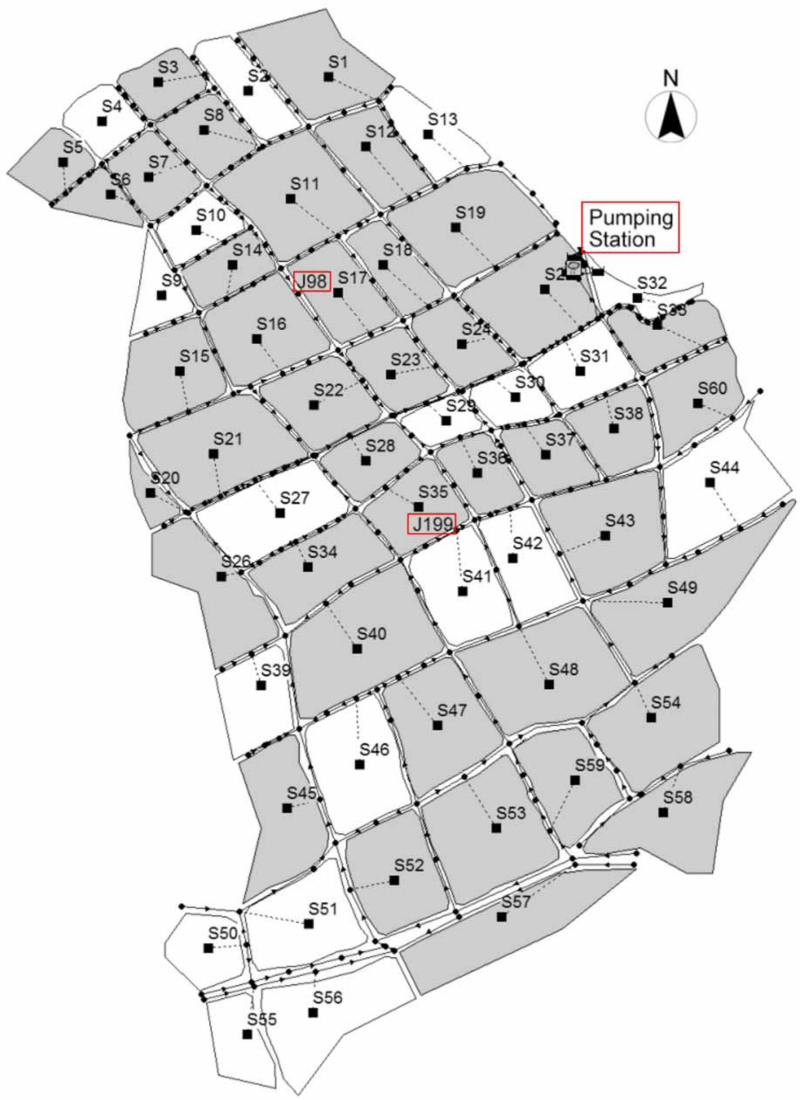

Figure 1 | Generalization of study area (two manhole monitoring sites: J98 and J199).

imperviousness coefficients of these sub-catchments are all larger than 0.8. The proportion of area where LID measures are added in each sub-catchment is between 5% and 10%. The specific LID measures and their relevant combination scenarios are described in the section Design of CSO control scenarios and analysis of the relevant cost-effectiveness. Besides, there is a storage tank with 15,000 m^3 effective volume.

Model's principle

SWMM Version 5.0.022 was used to simulate and calculate the model, into which actual rainfall data need to be substituted. The Saint-Venant equations were applied. The Saint-Venant equations represent the principles of conservation of momentum (Equation (1)) and conservation of mass (Equation (2)):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (1)$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{Q}{gA}\frac{\partial}{\partial x}\left(\frac{Q}{A}\right) + \frac{\partial h}{\partial x} = S_0 - S_f \quad (2)$$

where A is the area of the pipe flow cross section, m^2; Q is the flow, m^3/s; t is the time, s; x is the length of the pipe along the flow direction, m; g is the gravitational acceleration, m/s^2; h is the depth of water, m; S_0 is the pipe slope, which is dimensionless; S_f is the friction slope, which also is dimensionless.

Model calibration and validation

The fixed physical parameters of the model were extracted from ArcGIS, drawings and onsite survey. The other parameters which cannot be directly measured were assigned initially through references, and they were adjusted by calibration and validation with the real measured data of water quality and quantity.

Water quality and quantity monitoring was carried out on dry and wet weather days in order to obtain the data for model calibration and validation, and the water samples were collected from the pumping station and the two selected manholes (J98 and J199, shown in Figure 1). All the samples were immediately transported to the laboratory after sampling for testing suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (NH_4^+-N) and total phosphorus (TP) (Monitoring and Analytical Methods of Water and Wastewater 2002).

Fifty-three rainfall events' data in 2013 were collected. The annual rainfall was 1,193 mm, and the maximum rainfall event occurred in October. Data of two dry weather days and three rain events (one overflowed and the other two not overflowed) were used for calibration, and another rain event (overflowed) was used for validation. Figure 2 indicates the simulated values of the water level and three water quality indexes, which were consistent with the real measured values within 25% relative error. Hence the validated model was acceptable.

Design of CSO control scenarios and analysis of the relevant cost-effectiveness

Considering the study area's actual situation and the applicable conditions of each LID measure in SWMM Version 5.0.022, three LID practices, i.e., bio-retention, grass trench and rain barrels, were chosen. The bio-retention and grass trench could be implemented by reforming the public green space.

Three types of CSO control scenarios, including gray (scenario A and B), green (scenario C and D) and gray-green (scenario E, F and G) scenarios, were designed (listed in Table 1). Scenario O was a basic situation which excluded any CSO control measure. This basic scenario was presumed to be only the pipe network of the system without the storage tank, and the storage tank was regarded as an overflow control measure. The annual overflow, peak flow and overflow pollution load of each scenario were calculated by the model in order to compare their effects. The pipe network reconstruction was determined after the diagnostic analysis of the pipe overload and manhole overflow by the model. The rainwater storage capacity of LID measures in each scenario was defined the same as the storage tank, i.e., 15,000 m^3. In addition, the rainwater storage capacity of each LID measure was distributed artificially so as to make the subsequent calculation and comparison more convenient.

Cost-effectiveness analysis is generally used in the domains such as water supply design (Stokes & Horvath 2009), water treatment (Racoviceanu et al. 2007), and also for the assessment of rainwater control measures (Spatari et al. 2011), which analyze the less tangible inputs and a maximum benefit achievement. In this study, it is used to more directly compare LID and gray infrastructure solutions and used to determine and compare the life-cycle costs per unit of a specific measure.

Life-cycle cost (LCC) is comprised by the capital expense, operation and maintenance cost and salvage value, which is

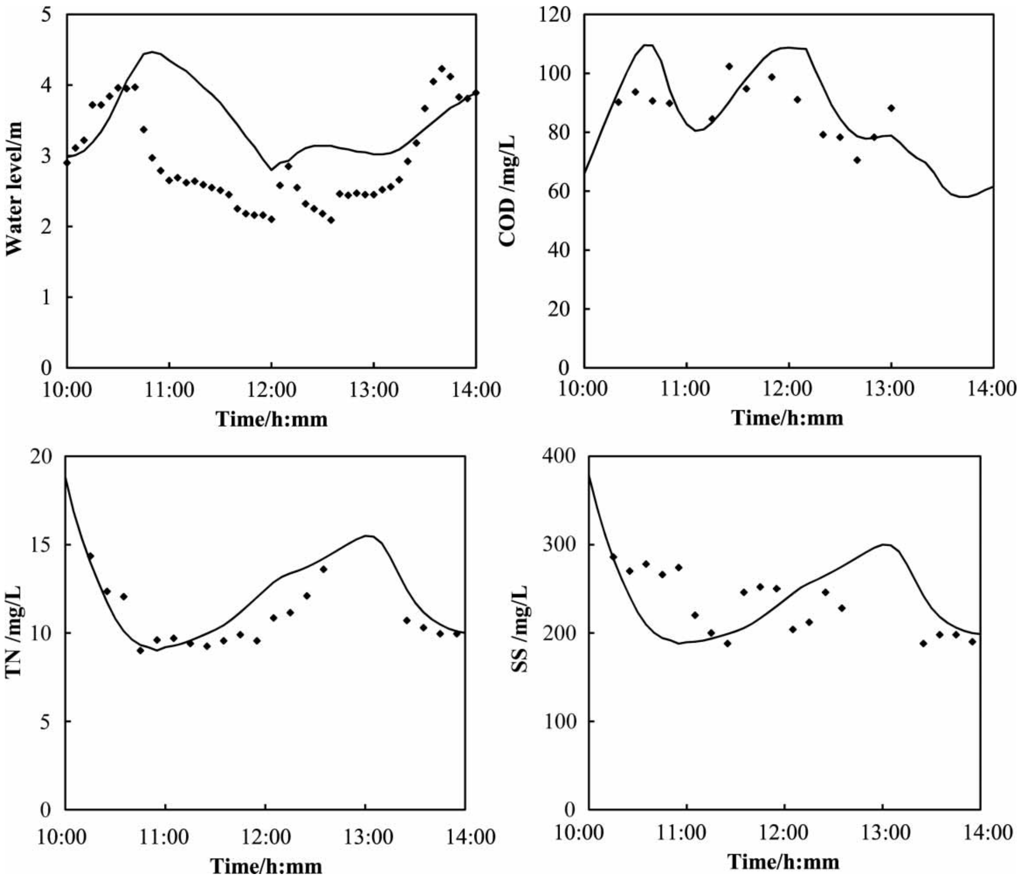

Figure 2 | Overflowed water level and portion of water quality validation results in October 2013. The dots represent the real measured values and the curve represents the simulated values.

Table 1 | Each measure of the designed scenario

		Storage capacity/m^3			
Scenario	**Pipe reconstruction**	**Storage tank**	**Bio-retention ponds**	**Grass trench**	**Rain barrels**
O	–	–	–	–	–
A	–	15,000	–	–	–
B	√	15,000	–	–	–
C	–	–	–	–	15,000
D	–	–	3,750	3,750	7,500
E	–	15,000	3,750	3,750	7,500
F	–	15,000	7,500	–	7,500
G	–	15,000	–	7,500	7,500

calculated in Equation (3). Due to the diversity of the economic development and the basic structure construction of a specific case, these three parameters are various. The majority of these basic cost data were collected from the literature (Montalto *et al.* 2007; Houdeshel *et al.* 2011). The cost data of two gray infrastructures and three LID measures were compared and analyzed in accordance with the virtual condition of this case area, and are listed in Table 2. After the designed life year, the measures are regarded as having no application value. Hence all the salvage values were

Table 2 | The capital expense, operation and maintenance cost and salvage value of LID measures

LID measure	Capital expense	Operation and Management cost	Salvage value
Storage tank	976.13 (USD·m^{-3})	19.52 (USD·m^{-3}·a^{-1})	0
Pipe reconstruction	479.14 (USD·m^{-1})	9.58 (USD·m^{-1}·a^{-1})	0
Bio-retention ponds	24.14 (USD·m^{-2})	2.41 (USD·m^{-2}·a^{-1})	0
Grass trench	12.87 (USD·m^{-2})	1.28 (USD·m^{-2}·a^{-1})	0
Rain barrels	144.81 (USD·m^{-3})	4.82 (USD·m^{-3}·a^{-1})	0

set as zero. The monetary unit used in this paper was the US dollar and the exchange rate of US dollar to Chinese Renminbi (RMB) was calculated as in March 2014, which is 6.215.

$$\mathrm{LCC} = C_0 + \sum_{t=0}^{T} C_1 \times \mathrm{PV}_1 - S \times \mathrm{PV} \tag{3}$$

where LCC is the net present value of life-cycle cost; C_0 is the capital expense; C_1 is the operating and maintenance cost; S is the salvage value; T is the life time, years; PV_1 and PV are the discount factors, which are calculated as in Equations (4) and (5), respectively

$$\mathrm{PV}_1 = \left[(1+r)^t - 1\right]/r \times (1+r)^t \tag{4}$$

$$\mathrm{PV} = 1/(1+r)^t \tag{5}$$

where r is the discount rate, dimensionless; t is the life time, years.

The net present value of life-cycle cost is converted to the net annual value (NAV) of life-cycle cost using Equation (6)

$$\mathrm{NAV} = \mathrm{LCC}/\mathrm{PV}_1 \tag{6}$$

where NAV is the net annual value of life-cycle cost and LCC is the net present value of life-cycle cost.

RESULTS AND DISCUSSION

The effect of the designed scenarios was achieved by comparing with the basic scenario.

CSO reduction

Figure 3 illustrates the annual overflow, annual peak flow and annual overflow pollution load of each scenario. As

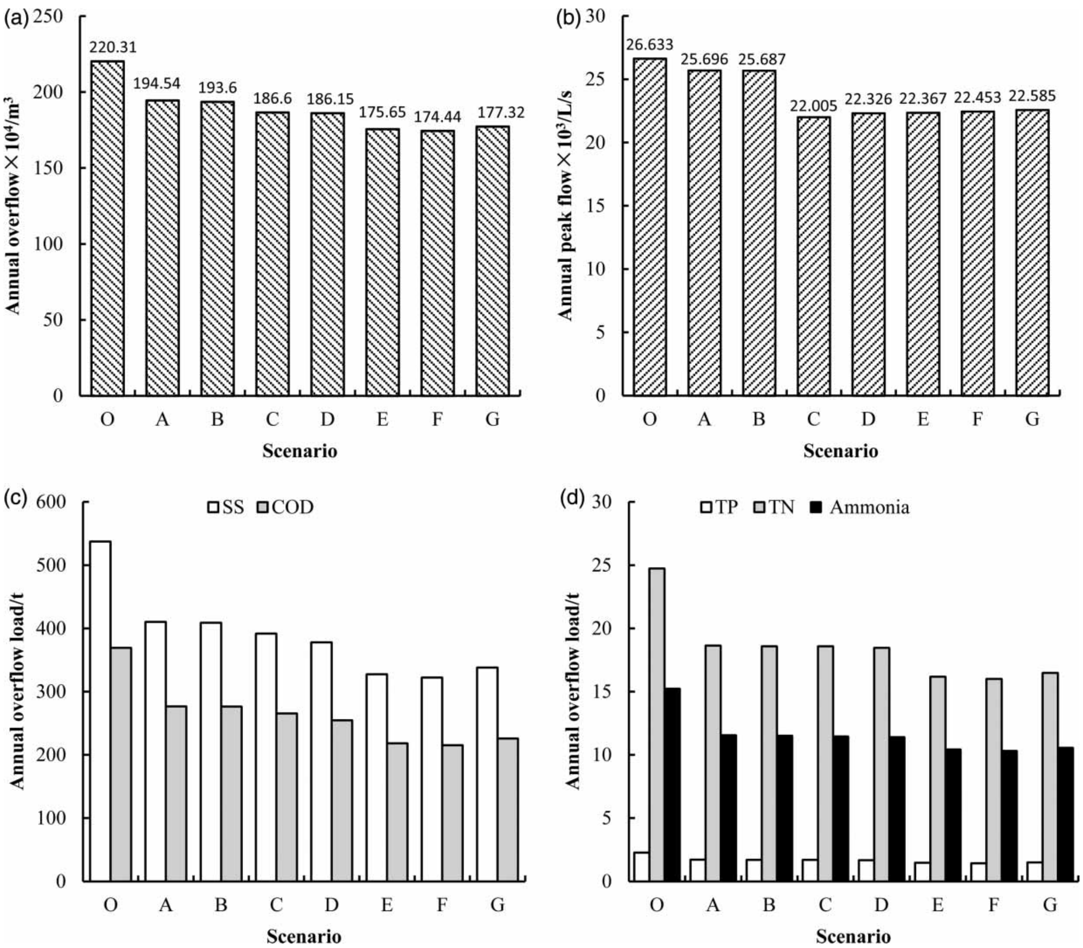

Figure 3 | The annual overflow, peak flow and overflow pollution load of each scenario.

seen from Figure 3(a), annual overflow of the scenario O is 220.31×10^4 m^3. Of particular note, the scenario O excludes any CSO control measure. The scenarios which have added CSO control measures, namely the scenarios A–G, have an obvious effectiveness in reducing annual overflow. Their average annual overflow is 184.04×10^4 m^3, which is significantly lower than scenario O. In Figure 3(b), the annual peak flows of scenarios A and B are all close to scenario O, which indicates that the effective reduction of annual peak flow of these two scenarios is not distinct. Simultaneously, there is hardly any apparent data difference between scenarios A and B, which reveals that the pipe reconstruction contributes little to the promotion of effective reduction of annual overflow and annual peak flow. As for the construction of storage tank, annual overflow is reduced conspicuously, but annual peak flow is not.

Figure 3(c) and 3(d) show the reduction quantity of annual overflow pollution load from each scenario. The scenarios E, F and G have better effectiveness in reducing annual overflow pollution load than the scenarios A, B, C and D, which reveals that the combination of gray measures and green measures is more efficient. Scenarios C and D show that the green measures fail to achieve better effectiveness in reducing annual overflow pollution load than gray measures, which is different from the previous study (Wise *et al.* 2010).

Unit cost-effectiveness

Because of the different investment, the scenario which has the best effect may not be the best one for investing; hence both the effective reduction and cost should be considered together. Table 3 lists the unit cost-effectiveness of each designed scenario, which shows that: (a) the unit cost-effectiveness of scenarios C and D is, respectively, 6.38 and 8.11 times that of A, so it can be concluded that, with the same storage volume, source distributed LID's unit cost-effectiveness is higher than that of the traditional centralized gray infrastructure; (b) under the condition of the same rainwater storage capacity, i.e., scenarios C and D, the cost-effectiveness is improved by 23.4% by changing the rain barrels into bio-retention ponds and/or grass trench, so it can be summarized that the combination of different LID practices is better than only one practice; (c) scenarios E, F and G were obtained by adding LID into A, and the results show that there is an average increase of 23.5% of the cost-effectiveness; therefore it can be summarized that adding LID into the traditional gray infrastructure may enhance the overflow cost-effectiveness; (d) on average, the gray-green scenario's unit cost-effectiveness was 1.49 times higher than the gray scenario's, and the green scenario's unit cost-effectiveness was 5.39 times higher than the gray-green scenario's and 8.05 times higher than the gray scenario's; (e) scenario D's unit cost-effectiveness was the highest.

According to the analysis result of the unit cost-effectiveness, green scenario D is the best choice for controlling CSOs. However, as the storage tank has been built in the case area, only five scenarios, i.e., scenarios A, B, E, F and G, can be carried out. Considering the unit cost-effectiveness of the annual overflow, peak overflow and overflow pollution load, scenario F is the most feasible one for this study area.

CONCLUSIONS

In this paper, different CSO control scenarios were designed by SWMM. The control effects and economics of these scenarios were compared. The main conclusions are as follows:

Table 3 | Unit cost-effectiveness of each scenario

	Unit cost-effectiveness						
			Annual overflow pollution load cut (kg/$ '000)				
Scenario	Annual overflow cut (m^3/$ '000)	Annual peak flow cut ($L \cdot s^{-1}$/$ '000)	SS	COD	TP	TN	NH_4^+-N
A	184.94	0.67	91.30	66.54	0.40	4.38	2.64
B	180.71	0.64	86.90	62.85	0.39	4.16	2.51
C	1,366.15	18.76	590.05	420.82	2.36	24.93	15.27
D	1,685.12	21.24	786.33	565.17	2.96	30.96	18.89
E	279.80	2.67	131.61	94.56	0.50	5.36	3.00
F	282.20	2.57	132.38	94.66	0.52	5.37	3.01
G	274.44	2.59	127.35	91.58	0.50	5.28	2.98

- Gray scenarios possess obvious effectiveness in reducing annual overflow, but it is not significant on annual peak flow. Conversely, green scenarios have the best effectiveness in reducing on annual peak flow among the three types of scenarios.
- The gray-green scenarios exhibit more effective reduction than the scenarios which are completely comprised by green or gray measures on annual overflow and annual overflow pollution load.
- On average, the unit cost-effectiveness of the gray-green scenario is 1.49 times higher than the gray scenario's, and the unit cost-effectiveness of the green scenario is 5.39 times higher than the gray-green scenario's and 8.05 times higher than the gray scenario's. The unit cost-effectiveness of scenario D, which combined the measures of bio-retention, grass trench and rain barrels, is the highest. Hence it is the best control measure.
- As a case study, scenario F is the most feasible one for this area.

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