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# Hybrid Stormwater Management Approaches in a High-Plateau Watershed in Southwest China

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**Abstract:** Urbanization is known to have adverse hydrologic and water quality impacts to natural runoff conditions. Conversion of pervious land to impervious surfaces leads to increased runoff volume, peak flow rate, and pollutant load, as well as reduced groundwater recharge. The last two decades has witnessed a paradigm shift in stormwater management, with the traditional “end-of-pipe” stormwater best management practices (BMPs) being replaced with green infrastructures (GIs). Using low impact development (LID) practices to treat runoff at its source, the goal for GI design is to mimic pre-development runoff conditions. This study evaluates and compares several stormwater management alternatives in a high-plateau watershed in southwest China, where unique landscape, climate, and eco-sensitive locations make sustainable stormwater a challenging task. Two GI-only, one gray-only, and one hybrid stormwater management designs were assessed for the watershed. The results indicate that while the gray-only scenario is relatively effective in reducing post-development peak flow rates (around 30%), it is much less effective (12%) in reducing runoff volume. In comparison, the GI-only scenario is less effective in reducing peak flow rates (11% to 29%). The hybrid stormwater management approach, however, is able to strike a balance between reducing post-development runoff volume (66%), peak flow rate (36% to 68%), and pollutant load (over 80%), and at the same time encouraging groundwater recharge and rain water reuse.

**Key words:** stormwater management, green infrastructure, low impact development, best management practices

## 1. Introduction

Urban development is often characterized with increased surface runoff volume and peak flow rate, and deteriorated water quality (Shuster et al., 2005; Galster, 2006). According to the water pollution survey



conducted by the United States in 1990, about 30% of the water body exceeded the standard is caused by non-point source pollution. And urban stormwater runoff is the second largest non-point source pollution after agricultural non-point source pollution (Deletic A B and Maksimovic C T, 1998). Annual stormwater runoff volume is most sensitive to changes in impervious cover (Pyke et al., 2011). Stream degradation could occur when impervious surfaces account for as little as 10 percent in a watershed, and the degradation could be unavoidable when the impervious surface exceeds 30 percent (Arnold and Gibbons, 1996; USEPA, 2003).

The last two decades has witnessed a shift of stormwater management paradigm from the traditional “end-of-pipe” best management practices (BMPs) to source-control measures such as low impact developments (LIDs) (Fletcher TD et al., 2015). The LID concept, or green infrastructure (GI) design, focuses on treating stormwater runoff at the source and restoring post-development runoff conditions to the pre-development level (USEPA, 2009a; Beauchamp and Adamowski, 2013). Since its emergence in late 1990s in Prince George’s County, Maryland, the LID concept has quickly gained popularity across the United States and other countries (USEPA, 1999). The same concept is often referred to as Sustainable Urban Drainage Systems (SUDS) in the United Kingdom and Stormwater Quality Improvement Devices (SQID) in Australia (NCHRP, 2006).

Hydrologic and water quality assessment tools have also been modified or developed to aid the design and placement of green infrastructure (Haris et al., 2016; Liu Y et al., 2015), such as SWMM, STORM, HSPE, etc. Many BMP/LIDs have been proven and evaluated to be effective in reducing rain runoff and pollution (Brown RA and Hunt WF, 2011; Mei Y and Yang X, 2011; Park D et al., 2014).

While many case studies were carried out comparing traditional stormwater management practices and the GI approach for particular sites in many countries, focusing on the plain cities (Keeley M et al., 2013; Nickel D et al., 2014; Ellis JB, 2013), few studies were found in the literature investigating appropriate stormwater management approach in high-plateau regions. Unique landscape and climate conditions present special challenges for sustainable stormwater management in these areas. At one hand, steep slope means more dramatic changes in site runoff conditions due to runoff; on the other hand, clearly divided wet and dry seasons require conservation of runoff for maintaining ecological base flow. The goal of this study is to evaluate and compare several stormwater management alternatives in a high-plateau watershed. With quantification of hydrologic and water quality benefits from each management approach, it is expected that findings from this study could provide reference for watersheds in similar circumstances.

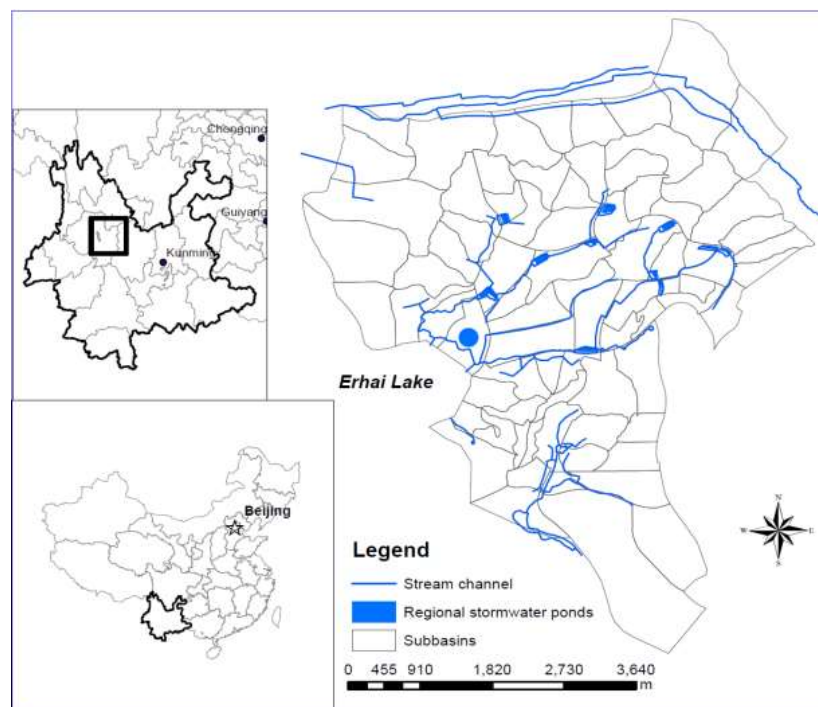
## 2. Methodology

### 2.1. Study Area

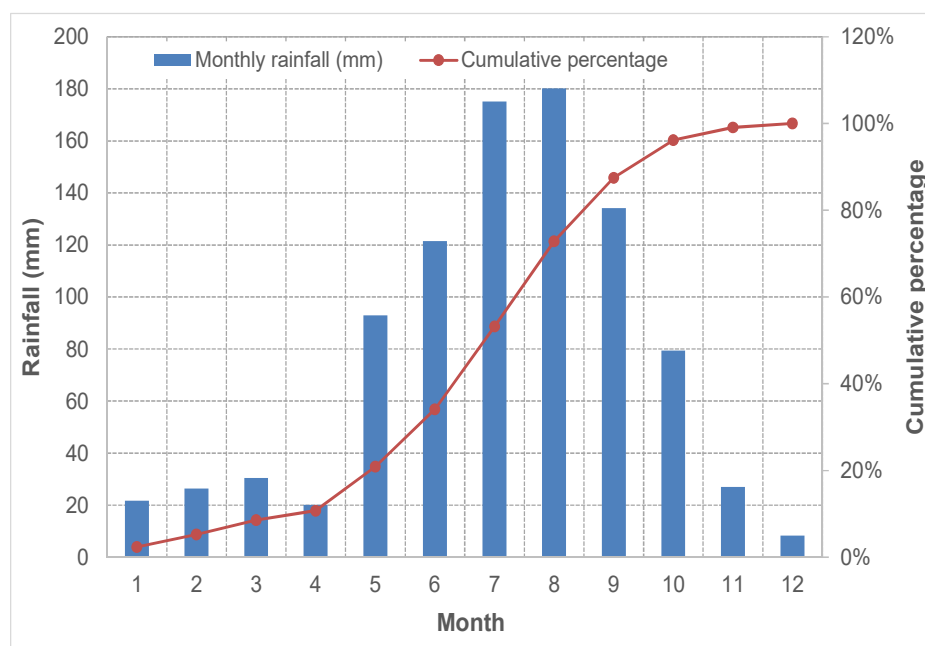
The study area is Haidong Township at Dali, Yunnan Province of southwest China. The area is located right next to the world heritage Erhai Lake National Geological Park, and runoff from Haidong Township discharges right into the Erhai Lake (Figure 1). Erhai Lake serves as drinking water reservoir for Dali city and surrounding areas. Haidong Township is about 29.77 square kilometers, with an average slope of 28 percent (HDMC, 2012). The whole watershed is delineated into 76 subwatersheds, with an average size of 39 ha. The elevation difference between the highest point (2210 meter) and the lowest point (1966 meter) in the watershed is over 240 meters. Current water quality at the Erhai Lake is Category II for most of the year (DBEP, 2016), decreasing from Category I back at the 1980s. Main reasons causing water quality deterioration were rapid developments, non-point source pollution from farming, and tourism (DBEP, 2016).

Existing landuses in Haidong Township mainly consist of barren land, village, and farm lands. The watershed is under rapid development, and the imperviousness is expected to increase from the current 8.4% to 59.8% by 2025. Stormwater conveyance systems are designed for quick discharge of runoff. If unmanaged, the increased runoff volume and pollutant load could potentially add more pressure to the already sensitive Erhai ecosystems.

Haidong Township has a continental low-latitude high-plateau monsoonal climate, which is characterized with clear dry (November to April) and wet seasons (May to October). Average annual total rainfall is around 820 mm, over 85 percent of which occurs during the wet season (Figure 2). With its location of eastern bank of the Erhai Lake and windy conditions throughout the year, annual evapotranspiration at Haidong District is around 1150 mm. The landscape with steep slope and substantial moisture deficit make sustainable stormwater management a challenging task.



**Figure 1.** Research area (Haidong Township)



**Figure 2.** Monthly rainfall at Haidong Township

**Table 1.** Rainfall characteristics for Haidong Township (1994-2013)

Category		Value
Annual total precip. (mm)		820.50
Average daily precip. (mm)		2.25
Maximum daily precip. (mm)		95.31
No. of days with precip.	>0 mm/day	2293
	>25 mm/day	172
	>50 mm/day	23
	>90 mm/day	1

**Table 2.** Post-development landuse distributions in Haidong Township

Land cover	Description	Area	
		ha	%
Residential	Villages, High density residential, median density residential	753.7	25.32%
Commercial	Retail, Hospitalities, Entertainment, Offices	273.8	9.20%
Institutional	Schools, government agencies, Hospitals, Scenic Areas	290.5	9.76%
Industrial	Logistics	87.4	2.94%
Transportation	Roads, Stations, Parking lots	238.5	8.01%
Public utilities	Supplying, environmental, and safety facilities	7.06	0.24%
Lawn and squares	Public green areas, squares	248.1	8.33%
Others	Wet land, farm land, green open space	1078.2	36.21%
<b>Total</b>		<b>2977.3</b>	<b>100%</b>

## 2.2. The SUSTAIN Model

The U.S. EPA System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model was developed for evaluating and optimizing stormwater quality management and flow abatement techniques in urban areas (USEPA, 2009a). The model is capable of simulating the rainfall-runoff process, pollutant buildup and washoff on land surfaces, flow-routing through stormwater systems, as well as the hydrologic and water quality processes in stormwater best management practices (BMPs) and low impact development (LID) practices. The model has built-in representation of 14 BMP/LIDs, including practices such as bioretention, infiltration trench, green roof, porous pavement, rain barrel, dry pond, wet pond, etc. With optimization techniques of scatter search (SS) and genetic algorithm (GA), SUSTAIN is also able to optimize the location, type, and cost of stormwater BMPs/LIDs needed to meet water quality and quantity goals.

### BMP Hydrologic Processes

SUSTAIN provides a process-based simulation of flow and pollutant transport routing for a wide range of structural BMPs. The simulated hydrologic processes include: evaporation of standing surface water, infiltration of ponded water into the soil media, deep percolation of infiltrated water into groundwater, and outflow through weir or orifice control structures. The BMP module uses a combination of fundamental algorithms to represent the hydrologic processes of storage, routing, infiltration, evapotranspiration, and underdrain infiltration. For example, water balance storage routing is commonly used for flow routing in ponds and impoundments:

$$\Delta V/\Delta t = I - O \quad (1)$$

Where:  $\Delta V$ =change in storage (volume),  $\Delta t$ =time interval (time),  $I$ =inflow (volume per unit time), and

$O$ =outflow (volume per unit time).

### BMP Water Quality Processes

SUSTAIN uses a completely mixed system and a multiple impoundments in series system to simulate pollutant reduction. Stormwater runoff is assumed to be plug flow with uniform composition flowing through plug flow reactor (PFR), and SUSTAIN uses small continuously stirred tank reactors (CSTRs) operating in series for PFR representation. Water quality processes in BMPs are simulated through first-order decay with complete mixing, and the equation is as follows:

$$(C_{out}-C^*)/(C_{in}-C^*)=e^{-k'q} \quad (2)$$

Where

$C^*$ =background concentration (mg/L),  $C_{in}$ =input concentration (mg/L),  $C_{out}$ =output concentration (mg/L),

$q$ =hydraulic loading or overflow rate (m/yr),  $k'=k \cdot h$ =rate constant (m/yr),  $k$ =first order decay rate (1/yr), and

$h$ =pond depth (m).

### 2.3. Scenario Setup

Four stormwater management scenarios are evaluated in the post-development Haidong Township, one consisting of gray infrastructure only (Gray-Only), two consisting of green infrastructures only (GI-Only #1 and GI-Only #2), and one consisting of a mixture of gray and green infrastructures (Hybrid scenario).

In the Gray-Only scenario, ten regional stormwater storage basins are implemented along the main stem of stormwater channels in Haidong Township, and no onsite LID practices are used. Maximum depth of water is maintained at 0.6m for safety reasons, and the storage basins are underlined with water-proof lien. Water retained in the regional stormwater storage basins are reused for irrigation during dry periods.

In the first GI-Only scenario (GI-Only #1), bioretention is used to treat runoff from rooftops, infiltration trenches are used to treat runoff from roads, and porous pavement are used for public squares and parking lots. The LIDs are used to treat runoff from 30 percent of impervious surfaces in each subwatershed. Cross-sectional designs of LIDs follow the specifications found in Stormwater Handbook of Western Washington (WSDOE, 2014).

In the second GI-only scenario (GI-Only #2), LID implementations are the same as those in the first GI-only scenario, with the only difference being that LIDs are sized to treat 55 percent of impervious surfaces in each subwatershed. Similar to GI-Only #1, no regional storage ponds was implemented along the stream channels in the watershed.

In the hybrid design scenario, site-level stormwater runoff routing is the same as that in the GI-Only #2 Scenario and the regional stormwater storage basins are the same as those in the Gray-Only Scenario. Overflow from onsite LID practices are routed to the regional stormwater storage ponds. In the hybrid scenario, runoff retained in regional stormwater basins are also used for irrigation during dry days.

Both continuous simulations and design storm analyses were executed for the four stormwater management scenarios, along with the pre- and post-development runoff conditions for Haidong Township using SUSTAIN. The continuous simulation was performed for a 20-year period (1994/01/01-2013/12/31), evaluating annual average total runoff volume and annual pollutant load (TSS, TN, and TP) from the watershed. The design storm analyses, focusing on the peak flow effects, were carried out for the 2-, 5-, 10-, and 50-year 24-hour design storms. A virtual outlet is used for Haidong Township in order to evaluate the area as a whole.

**Table 3.** Summary of stormwater management scenarios at Haidong Township.

Scenario #	Name	BMP/LID implementation
1	Gray-Only	Ten stormwater storage basins
2	GI-Only #1	Bioretention, infiltration trench, porous pavement; treating 30% of impervious surfaces
3	GI-Only #2	Bioretention, infiltration trench, porous pavement; treating 55% of impervious surfaces
4	Hybrid	Bioretention, infiltration trench, porous pavement, rain barrel, ten storage basins

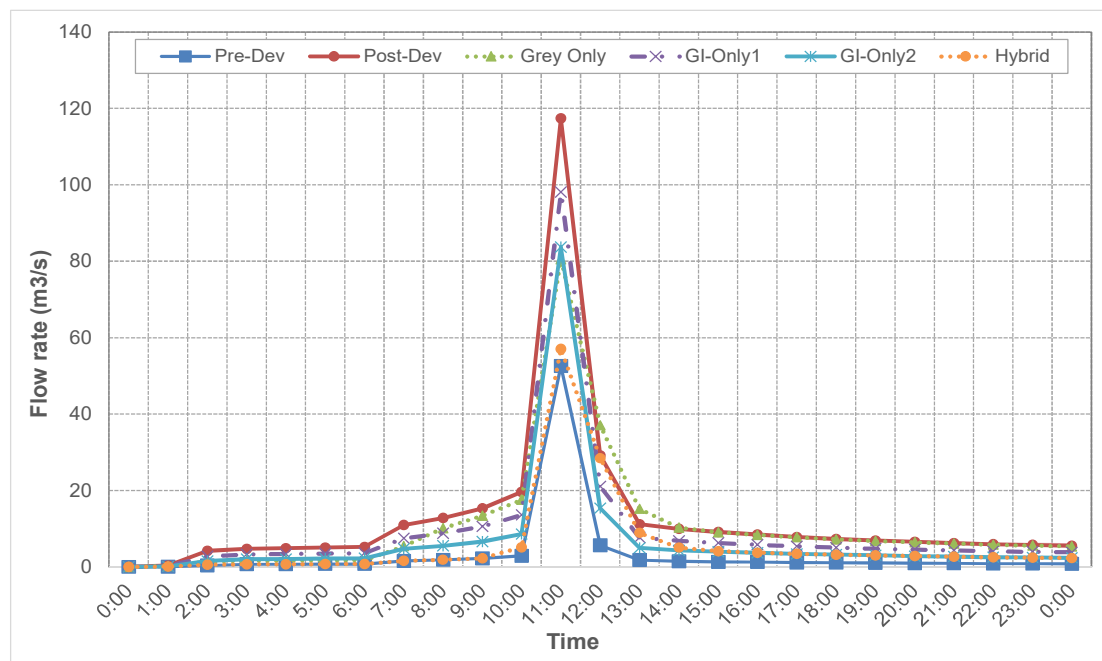
**Table 4.** Summary of BMP/LID sizes in each scenario.

BMP/LID practices	BMP/LID areas in each scenario			
	Gray-only	GI-Only #1	GI-Only #2	Hybrid
Bioretention (ha)	-	2.73	8.09	8.09
Infiltration Trench (ha)	-	1.28	7.55	7.55
Porous Pavement (ha)	-	1.80	5.64	5.64
Storage basin (m <sup>3</sup> )	266,392	-	-	266,392

### 3. Results and Discussion

#### 3.1. Design Storm Analyses

The analyses results for 10-year 24-hour design storm for the four scenarios along with the pre- and post-development site conditions are shown in Figure 3, and the results for other design storms are summarized in Table 5. As shown in the results, the development process substantially increases the peak flow rate from the watershed. The 2-year design storm peak flow increases by about six times, and the 50-year design storm peak flow increases by about two times.

**Figure 3.** Comparisons of peak flow rates for the 10-year 24-hour design storm for the four evaluated scenarios at Haidong Township.

**Table 5.** Comparisons of cumulative continuous runoff conditions for the four evaluated scenarios at Haidong Township

Name	Pre-Dev	Post-Dev	Gray-only		GI-Only #1		GI-Only #2		Hybrid		
			Value	Change to Post-Dev	Value	Change to Post-Dev	Value	Change to Post-Dev	Value	Change to Post-Dev	
Annual average runoff volume (1000 m³/yr)	1283.78	8572.13	7570.99	12%	5913.53	31%	3731.68	56%	2922.72	66%	
Annual average pollutant load (ton/yr)	TSS	21.51	233.35	115.10	51%	158.71	32%	98.80	58%	38.36	84%
	TN	631.99	4775.65	1652.61	65%	2923.07	39%	1608.43	66%	517.50	89%
	TP	141.60	1315.67	710.78	46%	893.26	32%	554.29	58%	223.50	83%
Design storm peak flow rate (m³/s)	2-yr	13.48	79.96	56.67	29%	56.54	29%	36.46	54%	25.79	68%
	5-yr	34.55	104.43	71.99	31%	88.07	16%	64.97	38%	45.46	56%
	10-yr	52.58	117.36	80.54	31%	98.09	16%	83.72	29%	57.04	51%
	50-yr	84.39	144.14	99.03	31%	127.67	11%	107.08	25%	92.05	36%

The Gray-Only scenario has a relatively consist performance in reducing the post-development peak flow rate, with a reduction ratio of about 30% for all four design storms. The two GI-Only scenarios and the Hybrid scenario, however, has a decreasing peak flow reduction ratio as the design storm return period increases (e.g. decreasing from 29% to 11% as the return period increases from 2-year to 50-year). Overall the Hybrid scenario has the highest peak flow reduction ratios for all four evaluated design storm return periods.

These findings are consisting with the GI stormwater control designs, in that the LID practices are to capture smaller and more frequent rainfall events, resulting in more significant peak flow and runoff volume reductions during smaller return period events than those during the larger ones. This explains the deceasing peak flow reduction ratios in scenarios that include GIs.

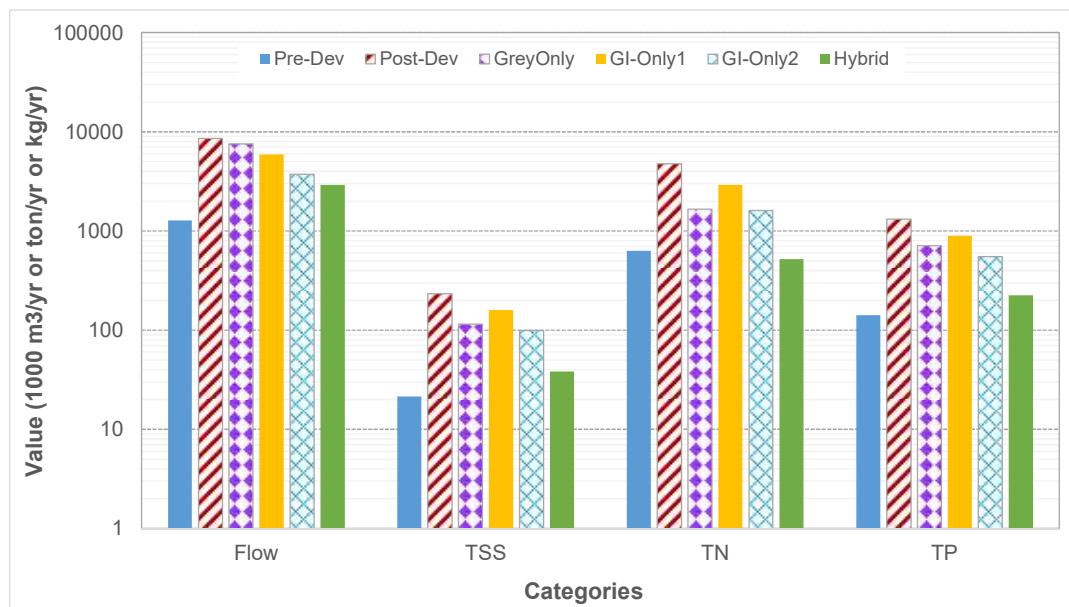
### 3.2. Continuous Runoff Analyses

The 20-year continuous simulations were carried out for the four scenarios and the pre- and post-development site conditions, and the annual average flow volume and annual average pollutant loads are shown in Figure 4 and Table 5. As shown in the results, the development process increases the annual average flow volume by about 7 times, the annual average TSS load by about 10 times, the annual average TN load by about 7 times, and the annual average TP load by about 9 times. Comparisons of hydrologic and water quality benefits from the four management scenarios are also illustrated in Figure 4 and Table 5.

The Gray-Only scenario has the least annual runoff volume reduction (12%) from post-development runoff among the four evaluated scenarios. This is because the regional stormwater storage basins only retain water and do not allow for infiltration. Thus the volume reduction is mainly from the reuse of retained water. According to the simulation results, the annual average water reuse is about 1 million cubic meter in the Gray-Only scenario. Pollutant reductions for the Gray-Only scenario are mainly from the retention of first-flush runoff, which is characterized with higher pollutant load (USEPA, 1999).

The GI-Only #1 and #2 scenarios provide onsite control of stormwater runoff. As shown in the results, GI-Only #1 scenario has higher annual runoff volume reduction but lower pollutant load reduction ratios as compared to the Gray-Only scenario. This is because the LID practices are able to fully capture small scale rainfall events (e.g. events that are 25 mm or less), which accounts for over 60 percent of total runoff volume at Haidong. As the sizes of LID practice increase from GI-Only #1 to GI-Only #2, the annual total runoff volume and pollutant load reduction ratios both exceed those in the Gray-Only scenario.





**Figure 4.** Comparison of pre- and post-development continuous runoff conditions along with the four evaluated scenarios at Haidong Township

The Hybrid scenario, among the four evaluated management alternatives, has the highest annual total runoff volume and pollutant load reduction ratios. The results represent a combined effect of onsite infiltration and pollutant removal by LID practices and the retention/reuse and pollutant removal by regional storage basins. As compared to the post-development runoff conditions, the Hybrid scenario is able to reduce the annual runoff by about 5.65 million cubic meters, and the annual TSS, TN, and TP loads by about 195 tons, 4260 kg, and 1090 kg, respectively. The annual TN load from the Hybrid scenario is even lower than that from the pre-development conditions, indicating the substantial benefits that the combined approach could bring to Haidong Township stormwater management.

Overall, the design storm analyses and continuous simulation analysis results show that neither the Gray-Only nor the GI-Only approach is suitable for managing stormwater at Haidong Township. For the Gray-Only approach, while the regional storage basins are relatively effective in controlling post-development peak flow rate (around 30%) and the annual average retained water for irrigation uses reaches 1 million cubic meter, the annual total runoff volume reduction is quite limited (12%). For Haidong Township, this means most of the post-development Haidong runoff directly discharges to the Erhai Lake, increasing stress to the lake with runoff volume and pollutant load. For Haidong itself, it also means less groundwater recharge, and thus creates more demand for withdrawal from Erhai Lake for irrigation, making the overall water management situation even worse. For the two GI-Only approaches, control of stormwater runoff volume and pollutant load is relatively effective through LID infiltration and retention processes, but peak flow reduction is very limited, especially in the GI-Only #1 scenario (e.g. 11% for the 50-year design storm). This means grave flooding risk during extreme summer rainfall events.

The Hybrid approach proves to be the most suitable stormwater management alternative for Haidong Township. At site level, the LID practices are able to retain and infiltrate small rainfall events that consists of over 60 percent of the annual rainfall, and thus achieves substantial runoff volume and pollutant load reductions. At regional level, stormwater storage basins provide a second layer for peak flow protection. Water retained in storage basins, together with infiltrated water through LID practices, help maintain water balance in the region. Among the four scenarios evaluated, the Hybrid approach best approximates the pre-development runoff conditions, with the annual TN load even less than the pre-development level (-18%).

Although not the focus of this study, the SUSTAIN model can be used to help identify cost-effective stormwater management scenarios that approximate the pre-development runoff conditions (USEPA, 2009a). In such analyses, the sizes of BMP/LID practices are set as decision variables, and the pre-development hydrologic and water quality conditions are used as optimization targets. The SUSTAIN optimizer is able to evaluate the total cost and performances of potential BMP/LID site layouts, and identify the suite of implementation scenarios that both meet certain control targets and at the same time have the least cost. In addition, when combined with real time control (RTC) techniques, the regional storage basins are able to achieve additional peak flow reduction benefits, in that the appropriate timing of control/release of retained water in storage basins could help further reduce the convoluted downstream peak flow rate.

#### 4. Conclusion

Four stormwater management scenarios are evaluated for the urbanizing Haidong Township, Yunnan Province of southwest China. Of the four scenarios, two scenarios consist of green infrastructures only, one consists of gray infrastructure only, and one consists of a hybrid implementation scheme. The shared goal for implementing the four management scenarios are to mitigate the adverse hydrologic and water quality impacts in the rapidly urbanizing watershed.

Results indicate that unique landscape and climate conditions make the Hybrid approach the most appropriate stormwater management approach in the high-plateau watershed. With onsite GI practices provide retention of small rainfall events and regional storage basins attenuate peak flow rate of large events, the Hybrid approach is able to best approximate the pre-development runoff conditions among the four, with TN annual average load even lower than the pre-development level.

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