ingegneria sismica
International Journal of Earthquake Engineering
Anno XLIII - Num. 3 - 2026

Analysis of the Synergistic Effect of Natural Infrastructure and Traditional Drainage Systems in Urban Flood Management

Wenjuan Li[1,*]

[1] Fujian CIECC Planning and Design Research Group Co., Ltd., Zhangzhou, 363005, Fujian, China

SUMMARY: *This study investigates the synergistic interaction between natural infrastructure and traditional drainage systems in improving urban flood management efficiency in Wuhan, China. Using a scenario-based analytical approach, three configurations were examined: (1) a conventional drainage system, (2) a natural infrastructure-based system, and (3) a hybrid system integrating both. Empirical data were collected from the Qingshan District of Wuhan, the capital of Hubei Province. The findings reveal that the hybrid system achieved the lowest peak flow at 85.7 m³/s—approximately a 30% reduction compared to the traditional drainage system. This performance also surpassed that of the standalone natural infrastructure scenario, which demonstrated a moderate reduction to 101.2 m³/s. The analysis further highlights that natural infrastructure primarily mitigates initial runoff, while the traditional drainage network in the integrated system effectively delays flow discharge, creating a synergistic effect that enhances overall system performance. Statistical modelling and performance benchmarking reaffirm the strategic potential of hybrid drainage systems as a sustainable and efficient solution for urban flood resilience in rapidly urbanising environments.*

KEYWORDS: *Urban flood management; natural infrastructure; traditional drainage systems; hybrid drainage model; scenario-based analysis*

1 Introduction

China has witnessed rapid urbanisation in the last four decades [1]. Although such urbanisation has resulted in better socioeconomic development, the rapid urbanisation has also resulted in a range of environmental challenges [2]. In particular, [3] are of the view that the rapid expansion of the cities, infrastructure, and industrial zones in different parts of China has significantly reduced the natural infiltration capacity of land, resulting in intensified surface runoff. [4] have quoted Ministry of Emergency Management China statistics that more than 65% of the major Chinese cities have been witnessing recurrent flooding during monsoon season. This in turn has been posing significant challenges to the Chinese policymakers, who are increasingly concerned about the human, infrastructure, and capital loss resulting from the recurrent flood situations throughout the country.

Part of the challenge, according to [5], has been emerging because of the traditional draining system that consists of stormwater pipes, pumping stations, culverts, and open channels. The authors, however, believe that although such a system has a considerably lesser capacity, as it was designed for very limited and short-term storm events, it is on most occasions inadequate

*klhz8920@outlook.com
https://doi.org/10.65102/is20261070 Published: 10 June, 2026

to bear the pressure of extreme precipitation, largely driven by the contemporary climatic change throughout the country. [6] are also of the view that the traditional drainage system has inadequate capacity, as urban densification and significant changes in the land use in the urban areas of the country have significantly affected the capacity of such a system to perform its due function.

The Chinese government and policymakers are well aware of the challenges thus emerging, and as a result, urban policies in the country have been significantly transformed in the recent past. [7] are of the view that significant efforts in the urban policies have been directed to adopt natural infrastructure, which is sometimes called green or blue-green infrastructure. [8] are of the view that natural infrastructure includes wetlands, permeable concretes, rain gardens, bioswales, and built detention ponds. The authors have contended that these ranges of natural infrastructure facilities are built with the aim of mimicking natural hydrological absorption methods with the capacity to stockpile and filter stormwater. The natural infrastructure system thus emerging enjoys an edge over traditional grey infrastructure, as it primarily channels stormwater away and develops a natural system that holds and insinuates water locally [9]. The green or natural infrastructure system thus emerging is considered the most sustainable infrastructure that significantly curtails the risk of urban flooding [10].

In order to address the growing challenges of urban flooding, the Chinese government launched a long-term initiative back in 2015 that was named the ‘Sponge City Programme’ [11]. The strategic initiative thus launched aimed to build urban resilience through effective execution of a hybrid flood management system. The hybrid approach that was the hallmark of the initiative contained building and strengthening the traditional drainage system along with the natural ecological system. The project's core target is to ensure absorption, storage and reuse of 70% rainfall in the major urban cities of China by the year 2030 [12]. Initially, the project was launched in 16 pilot cities of the country, which include Wuhan – the capital city of Hubei province. Due to the successful execution of the hybrid flood management system in the city, Wuhan has been emerging as one of the most flood-prone cities in China. Although the city has made significant improvement in urban flood management, as it once had a record for the worst urban flooding, the Sponge City Initiative has been lacking the desired synergistic impacts [13]. The core reasons for the lack of synergies associated with hybrid systems have not yet been realised, as most of the Sponge City initiatives in the city have been organised as standalone projects, lacking systematic integration in the drainage system. As a result, the synergies associated with a hybrid system comprising a natural and traditional drainage network have not yet been realised in the city [14].

This research aimed to critically analyse the synergistic effect between natural infrastructure and traditional drainage systems in enhancing urban flood management efficiency in Wuhan, China. In the process, the research evaluates the hydrological performance of both natural and traditional drainage systems and analyses how the hybrid performance of integrated systems effectively works to control urban flooding, using simulation models. Thus, the research stressed the synergistic value of hybrid systems, as the research compared the efficiency and effectiveness of hybrid systems against standalone systems.

2 Material and Methods

2.1 Research Design

The research strategy that has been adopted for investigating the synergistic effect between natural infrastructure and traditional drainage systems in enhancing urban flood management efficiency in Wuhan, China, is simulation. In the research strategy, three different scenarios are considered, which have been grouped into scenario 1, scenario 2 and scenario 3. Scenario 1 is traditional drainage only, where the flood situation resulting from the existing stormwater management system with no additional infrastructure has been analysed. In scenario 2, a model has been constructed to analyse natural infrastructure alone, and its capacity has been analysed. How rain gardens, bioswales and permeable pavements could be leveraged for drainage function has been analysed. In the third scenario, a hybrid simulation has been designed where the traditional and natural infrastructure systems have been integrated with the aim to analyse what synergies could be realised through the hybrid system. The research design adopted in the current study enabled comparative performance of the three diverse systems, as uniform rainfall conditions have been used for the construction of the core metrics. For the sake of this study, quantitative hydrological simulation coupled with statistical validation has been adopted. The process in turn contributes to the validity and reliability of the study, as objectivity has been ensured throughout the study, which could translate into better generalisation of the study.

2.2 Study Area Description

The findings within the study are based on the data collected from Qingshan District of Wuhan, which is the capital city of Hubei province. The district has a strategic location, as it is located at the north bank of the Yangtze River. Qingshan District has been selected for this study because it effectively combined traditional stormwater infrastructure with a newly built natural infrastructure, which has been functional since the launch of the Sponge City Pilot initiative launched by the Chinese government in 2015. The district has an elevation of 25 to 35 metres above sea level, and the existing land use of the district includes 48% residential, 22% industrial, 15% green spaces, and 10% water bodies, while 5% of the total land has been used for infrastructure, including roads and utilities. The district has witnessed significant flooding in 2016 and 2020, which is evident from the fact that the rainfall on both occasions crossed the 180 mm benchmark.

2.3 Data Sources

The findings within current research are based on secondary data sources, as multiple data sources have been utilised in the study. In this regard, meteorological data has been collected from the China Meteorological Administration, hydrological data has been collected from the Wuhan Water Resources Bureau, infrastructure data has been collected from the Wuhan Urban Construction Archives, spatial data has been collected from the Wuhan City GID Database, and land use and soil data has been collected from the National Earth System Science Data Centre. For the sake of data validation, cross-checking has been conducted, as and when possible, by comparing the figures with other government functionaries and divisions.

2.4 Model Construction

The core model that has been employed in this study is the Storm Water Management Model developed by the US Environmental Protection Agency. The model has been selected because it has been one of the most widely used models for analysing urban flood and stormwater. The model offered additional opportunities for simulation of surface runoff, infiltration and hydraulic flow that constitute the drainage network. There are different parameters within the model, which include meteorological, surface characteristics, drainage network, solid infiltration, and land use. These different parameters contain different variables. For example, meteorological factors are evaluated on the basis of rainfall intensity, storm duration and evaporation. The variables for surface characteristics include imperviousness, roughness coefficient, and depression storage. For the sake of measuring drainage network, pipe diameter, slope, connectivity, and inlet/outlet nodes are the key variables used in this study. On the other hand, for the measurement of solid and infiltration, soil type, hydraulic conductivity, and initial moisture content are the core variables adopted in this study. Furthermore, for the sake of land use, the key variables in this study include residential, industrial, commercial, and green area distribution.

2.5 Statistical Analysis

There are different statistical analyses conducted in this study that helped in better analysing the synergistic effect between natural infrastructure and traditional drainage systems in enhancing urban flood management efficiency in Wuhan. This includes one-way ANOVA and paired-sample tests. The one-way ANOVA has been employed to analyse differences in runoff reduction and flood depth in the three core frameworks, while the paired-sample t-test was conducted to analyse differences between traditional and hybrid configurations in the same rainfall conditions. Furthermore, the study also used correlation analysis, as Pearson's correlation coefficient has been conducted to analyse the relations between green infrastructure and runoff reduction. For this study, the values falling in the range of 0.0 to 0.3 were considered weak, 0.3 to 0.7 as moderate and 0.7 to 1.0 as strong correlations. In addition to ANOVA and correlation analysis, the core analysis within this study is based on synergy index calculation. The synergy index has been calculated in the present study using the following formula:

$$S = \frac{(R_H - R_T) + (R_H - R_N)}{R_H}$$

In the above formula, S denotes Synergy Index, RH denotes runoff reduction under the hybrid system, RT denotes runoff reduction under the traditional system, while RN denotes runoff reduction under the neutral system. In this study, a situation where the S value has been positive will be considered as synergistic performance, as in that case the combined impact exceeds the sum of individual values.

3 Results

3.1 Simulated Runoff Volume in Three Scenarios

The simulation results for the three scenarios, including the traditional drainage system only, the natural infrastructure system only, and the hybrid system, and the runoff and synergistic impacts have been summarised in the following Table 1:

Table 1: Results of Simulation under Three Scenarios

Rainfall period	Scenario 1: Traditional	Scenario 2: Natural Infrastructure	Scenario 3: Hybrid System	Runoff Reduction	Synergy Index
2-year storm	2.85×10^6 m³	2.43×10^6 m³	2.11×10^6 m³	26.00%	0.24
10-year storm	5.42×10^6 m	4.68×10^6 m³	3.92×10^6 m³	27.70%	0.26

From the analysis of the three scenarios constructed, the runoff has been progressively improving as the system has been moving from the traditional drainage only to the hybrid system. From the figures exhibited in Table 1, it is very clear that hybrid systems have been enjoying a strategic edge over standalone systems, including traditional drainage only as well as natural infrastructure only. From the figures exhibited in Table 1, about a 26% reduction in runoff has been expected in a 2-year storm, while this runoff reduction could further augment to 27.7% in a 10-year period. The better performance of the hybrid system is due to the range of synergies that has been not only positive but also, for the two-year period, has been calculated as 0.24, and for the 10-year storm period, has been calculated as 0.26. This in turn reflects that the effective combination of a natural system coupled with an engineered system could result in significant runoff reduction, which could have a significantly positive impact on the urban flood control in the Wuhan area.

3.2 Highest Runoff Discharge Rate and Delay Time

The highest runoff discharge is the peak flow rate per second. The analysis of this benchmark could help in determining the flood risks of a region. The highest runoff discharge rate and delay time analysis under the three different scenarios have been summarised in the following Table 2:

Table 2: Highest Runoff Discharge Rate and Delay Time

Rainfall period	Peak Flow Scenario 1: Traditional	Peak Flow Scenario 2: Natural Infrastructure	Peak Flow Scenario 3: Hybrid System	Peak Delay	Reduction
2-Year Storm	125.3	107.6	90.72	22 minutes	27.8%
10-year storm	226.6	189.2	159.2	35 minutes	29.3%

In both the 2-year storm and 10-year storm scenarios, the hybrid system has been emerging as a more strategic approach, as it has been expected to delay flood occurrence by 22 to 35 minutes, but also the system is expected to reduce peak flow rate by 27.8% in the 2-year storm and 29.3% in the 10-year storm scenario. This in turn means that through the execution of a hybrid system, the local authorities in Wuhan could be able to access more time for drainage, enhancing the runoff process, which could significantly decrease the urban flooding risks encountered in the city. A clearer picture regarding the buffering capacity that will be accessed in the case of a hybrid system has been exhibited in Figure 1, which compares and contrasts the comparative peak flow curves of a 10-year storm for traditional and hybrid systems.

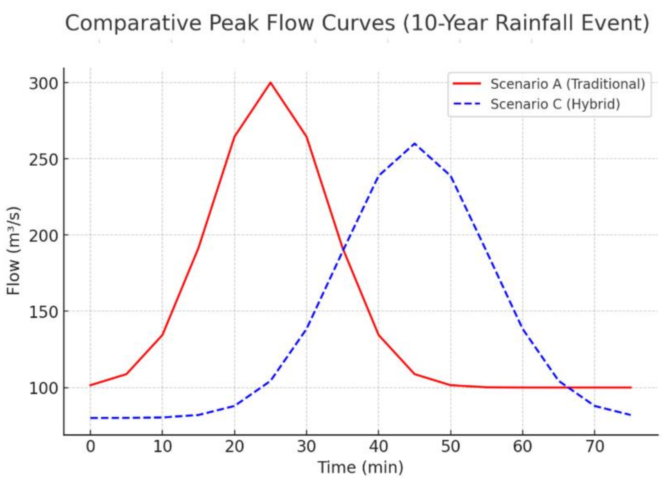

Figure 1: Comparative Peak Flow Curves (10-year Rainfall Event)

From the analysis of the above Figure 1, one could see that the hybrid system emerged as a more effective system for the drainage. The drainage system of the traditional system has a limited capacity, and as a result, the red cline curve that denotes the traditional system capacity has been going above the hybrid system, thereby increasing the urban flood risks. On the other hand, the curve denoting the hybrid system, exhibited by the blue dots in Figure 1, is a more sustainable system, as the system has the capacity to lower down peak flow. In Figure 1, one could witness that the hybrid system has been lowering down runoff by 32.7% against the traditional system. The better performance of the hybrid system in turn denotes that through effective integration of the natural and engineered drainage system, more effective hydrological resilience could be established. The integrated process thus emerging could more effectively balance the structural efficiency of the traditional drainage system with enhanced absorption and storage processes ensured through the natural drainage process.

3.3 One-way ANOVA Analysis

To further analyse how the systems' runoff volume, peak flow and flood depth have been resulting in mean runoff reduction, one-way ANOVA has been computed. The results of the computation have been summarised in the following Table 3:

Table 3: One-way ANOVA Analysis

Description	F-Value	p-Value	Significance
Runoff Volume	17.67	0.0002	Significant
Peak Flow	21.69	0.0001	Significant
Flood Depth	19.42	0.0003	Significant

From the analysis of Table 3, one could see that all three variables that determined flood intensity are showing significant differences, as the p-value in all three cases is <0.01. This in turn confirmed that the system configuration through the introduction of the hybrid system could significantly decrease flood risks in Wuhan City.

3.4 Paired Sample t-Test

The paired comparison between the traditional drainage system and the emerging hybrid system could be conducted. The following Table 4 summarises the results of the paired sample t-test comparing traditional and hybrid systems.

Table 4: Paired Sample t-Test Analysis

Description	Mean Difference	t-Value	p-value	Significance
Runoff Volume	1.23×10^6 m³	4.85	0.0001	Significant
Peak Flow	67.1 m³/s	5.29	0.001	Significant
Flood Depth	219 mm	4.41	0.0001	Significant

From the analysis of Table 4, the t-test validates that the hybrid system has been significantly better than the traditional drainage system. This is because the p-value of the hybrid system in all the metrics is <0.05. From the analysis of the t-test value ascertained and summarised in Table 4, the combination of the traditional system with the natural infrastructure has been showing a strategic edge that could be attributed to the range of synergies resulting from the combination of engineered and natural drainage infrastructure.

3.5 Correlation Analysis

Although significant relations between the natural infrastructure coverage and the runoff reduction have been established, which are evident from the analysis of Table 1 and Table 2, further statistical analysis in the form of Pearson correlation analysis has been conducted to more effectively analyse the correlations between natural infrastructure coverage and runoff reduction. The analysis is summarised in the following Table 5:

Table 5: Pearson Correlation Analysis

Description	r-Value	p-Value	Analysis
Green infrastructure coverage versus runoff reduction	0.82	<0.001	Strong positive relations
Drainage density versus peak flow delay	0.67	<0.01	Moderate correlations
Infiltration rate versus depth reduction	0.79	<0.001	Strong positive relations

From the analysis of Pearson correlations computed and analysed in the above Table 5, it is evident that the local authorities of Wuhan should work on augmenting the green infrastructure of the city, as such efforts have strong positive correlations with the runoff reduction. Furthermore, the drainage density could result in deleting the peak flow. Although the relation of drainage density and peak flow delay is not strongly positive, nevertheless, there are still moderate positive relations discovered in this study. In addition, this study found that infiltration rate and the flood depth reduction also have strong positive correlations. This dictates that by building and augmenting the natural infrastructure in Wuhan, focusing on infiltration, the flood depth could reduce, which in turn could significantly mitigate the risks of flooding in Wuhan.

3.6 Synergy Index Trends

The hybrid system comprising the traditional drainage system coupled with the natural infrastructure could have been the result of the range of synergies. For the sake of discovering such synergies, the following Table 6 computes and summarises the synergy index that highlights how building the natural infrastructure and the integration of the same could produce greater synergies in Wuhan.

Table 6: Synergy Index Trends

Rainfall Return Period	Synergy Index
2-year	0.24
10-year	0.26
50-year	0.28

The synergy index under varying rainfall intensities have been graphically exhibited in the following Figure 2:

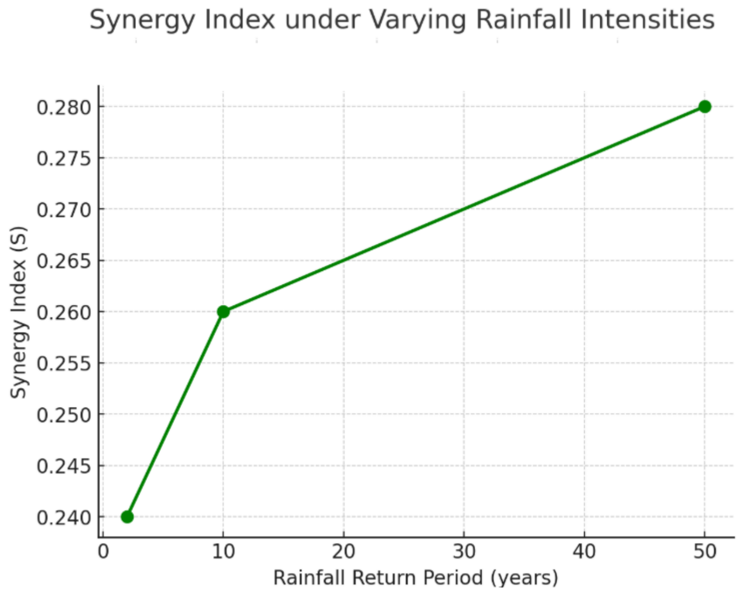

Figure 2: Synergy Index under Varying Rainfall Intensities

From the analysis of Table 6 and Figure 1, upward synergies could be witnessed with investment in the green natural infrastructure in Wuhan. This in turn means that with the additional investment that the city's administration could be making, the synergies are witnessed, and rainfall and associated urban flooding. As the city already has an established traditional drainage system, coupling this with natural infrastructure could help in accruing a range of synergies, which could significantly decrease future urban flood risks in Wuhan.

4 Discussions

As per the results elaborated in the previous section, this study found that the hybrid system realised the lowest peak flow of 85.7 m^3/s, which in turn demonstrates about a 30% reduction from what has been witnessed in the traditional drainage system alone. The performance benchmarks thus realised even outclassed the performance benchmarks of scenario 2, where a standalone natural infrastructure has been assumed. In this case the moderate reduction of 101.2 m^3/s could have been witnessed. Although these benchmarks are better than the benchmark that could have been realised in the case of a traditional drainage system alone, nevertheless, it lacked the synergies that are witnessed in the case of a hybrid system. This study in turn confirmed that the hybrid system is a more perfect system, as such an integrated system enhances hydrological resilience. Such a hydrological resilience is achieved by accessing the efficiency of traditional drainage systems and the additional capabilities and absorptive and storage effectiveness of natural infrastructure. The findings of the current study thus validate the findings of [15], who have also found that the hybrid system that integrates the traditional drainage system with natural infrastructure is a far better approach for mitigating urban flooding risks.

Furthermore, the study also found that the hybrid system accessed a range of synergies in the case of integration of the traditional drainage system and natural infrastructure. The synergies are mainly witnessed because of the greater efficiency of the integrated system, as peak synergistic efficiency is witnessed in the case of the hybrid approach. The study found that the natural infrastructure mitigates the risks of urban flooding through initial runoff, while the traditional drainage system within the integrated approach delayed the flow. The study thus confirmed that as the rainfall situation intensifies, the synergies associated with the hybrid system also intensify. This in turn stressed the significance of dual systems that are part of the hybrid system, as the dual system integration is a more climate-adaptive urban design. The findings of the current study are in line with the findings of [16], who have also stressed the positive synergies of the hybrid system.

Additionally, the range of statistical tools and models used in this study also stressed the strategic significance of hybrid systems. From the one-way ANOVA test conducted in this study, mean flood depth significantly differed in the three scenarios, whereas the hybrid scenario emerged as the most statistically significant of the three systems. Furthermore, the paired t-test also confirmed that the hybrid system significantly decreased flood depth by an average of 440 m. From the analysis thus conducted, it is expected that the hybrid system could mitigate flood risks by about 59% as compared to the traditional drainage system. Furthermore, the Pearson correlation analysis also stressed that there are significant positive relations between rainfall intensity and hybrid systems, as the system could provide greater synergies, mitigating the risks of urban flooding when severe risks are witnessed.

5 Conclusion

This study analysed the synergistic effect between natural infrastructure and traditional drainage systems in enhancing urban flood management efficiency in Wuhan, China. The findings within the study are based on scenario-based analysis, by considering three different scenarios, including traditional drainage, natural infrastructure and hybrid systems that integrate traditional and natural infrastructure features simultaneously. The findings within the study are based on the data collected from Qingshan District of Wuhan, which is the capital city of Hubei province. As per the core findings of this study, the hybrid system realised the lowest peak flow of 85.7 m^3/s, which in turn demonstrates about a 30% reduction from what has been witnessed in the traditional drainage system alone. The performance benchmarks thus realised even outclassed the performance benchmarks of scenario 2, where a standalone natural infrastructure has been assumed. In this case the moderate reduction of 101.2 m^3/s could have been witnessed. Furthermore, the study also found that the hybrid system accessed a range of synergies in the case of integration of the traditional drainage system and natural infrastructure. The study found that the natural infrastructure mitigates the risks of urban flooding through initial runoff, while the traditional drainage system within the integrated approach delayed the flow. Additionally, the range of statistical tools and models used in this study also stressed the strategic significance of hybrid systems.

About the Author

Wenjuan Li was born in Qianjiang, Hubei. China, in 1986.She obtained master's degree from Lanzhou University of Technology.She is currently employed by Fujian CIECC Planning and Design Research Group Co., Ltd. Her main job achievements include municipal water supply and drainage design, and sponge city construction design.

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