

## Article

# Landscape Design for Flood Adaptation from 20 Years of Constructed Ecologies in China

Elisa Palazzo <sup>1,\*</sup> and Sisi Wang <sup>2</sup><sup>1</sup> Built Environment, UNSW, Sydney, NSW 2052, Australia<sup>2</sup> Centre of Urban Stormwater System and Water Environment, Beijing University of Civil Engineering and Architecture, Beijing 100044, China; ezhu0309@sina.com

\* Correspondence: elisa.palazzo@unsw.edu.au

**Abstract:** In highly urbanized floodplains, it is becoming widely accepted that a change is needed to move away from flood control towards flood adaptation paradigms. To address riverine and flash flooding in urban areas, urban and landscape designers have developed design solutions that are able to increase urban ecological resilience by allocating space to fluctuating water levels. With the purpose of operationalizing flood resilience, this study explores how constructed ecology principles are applied to the design of multifunctional landscapes to restore floodplain functions in urban areas and prevent downstream flooding. The study adopts a design-by-research approach to examine 30 case studies from the Sponge Cities initiative realized in China in the last twenty years and develops a toolbox of Flood Adaptation Types for stormwater management. The results are aimed at informing operations in the planning and design professions by proposing a schematic design framework for flood adaptation in different geographic conditions, scales, and climates. The study sets up the bases for a systematic assessment of flood adaptation responses also by facilitating communication between disciplines, designers, and non-experts. This will enable evidence-based decisions in landscape architecture and urban design, as well as fulfill pedagogic purposes in higher education and research.



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**Keywords:** landscape architecture; research-by-design; submersible public space; flood adaptation; flood resilient cities

## 1. Introduction

In the last decade, altered environmental and climatic conditions induced by human activity have generated increasingly dangerous flooding events [1]. Highly densely populated floodplains are particularly exposed, especially in growing suburban regions around the world where land use change is likely to be the major cause of flooding [2,3]. Increased vulnerability and the need of rapid action have driven a widespread reconsideration of stormwater management in urban areas and the definition of new strategies at governance and policy levels to guide planning and urban design. Several initiatives that address concerns of increased flood risk have introduced a range of new approaches based on a mix of blue and green solutions to enable flood adaptation [4]. The most recent initiatives include, for instance, the Active, Beautiful, Clean Waters Program in Singapore [5], the Nature-Based Solutions for flood mitigation program in the EU [6] and the Sponge City initiative in China [7].

The planning professional practice has responded to the initiatives promoted at the governance level with the experimentation of new design solutions [8,9]. Innovative flood mitigation measures include the implementation of techniques in alternative to traditional resistance paradigms or ‘grey’ responses to flooding [6] and promote Low Impact Development [10]. These measures are mainly based on the possibility to retain rainwater in public space, instead of removing it with traditional engineered infrastructures that resist flood fluctuations. The most recent advances in urban ecology suggest to retain

the important ecological functions provided by flood in cities. This requires the acceptance of a degree of failure, or a ‘safe-to-flood’ approach, when public space is designed to be periodically submersed while still retaining its urban uses [7]. Constructed ecosystems such as submersible parks, designed wetlands, and blue-green infrastructures have been particularly successful in mitigating flood risk and at the same time to provide a range of ecosystem services to the local populations [11].

The applications of blue-green infrastructures [12] and nature-based paradigms [6] to flood management have been implemented by a range of recent landscape projects and innovative design solutions. Research on these projects has been performed to assess whether they are effective to reduce flood vulnerability in urban regions [13,14]. However, many of these studies focus exclusively on specific aspects of flood mitigation without a holistic breadth. For instance, indicators such as stormwater volumes and flood peaks reduction are evaluated independently from other important factors such as soil and water quality, urban livability, biodiversity protection, etc. [15–17]. Most importantly, only distinct techniques, models or methods and their performance are assessed without a comprehensive understanding of the underlying landscape flood adaptation mechanisms.

In fact, applications of submersible surfaces and floodable areas to urban parks are complex measures that encompass the integration of different design solutions. In the last 20 years landscape designers have developed many large-scale concept designs that simultaneously combine several mechanisms and techniques to restore, or at least mimic, the natural water functions in urban areas. However, the overall effectiveness of these systems is often substantiated only by general hypothesis, and it is not yet clear how integrated designed solutions target specific flood adaptation objectives.

While few studies have recently focused on the review of submersible urban spaces [18,19] knowledge about these systems is generally dispersed across different disciplinary domains. The role of design in using different measures to improve flood adaptation performance is not yet clear. This hinders the possibility to generate evidence-based options that support design and planning [20]. Combined measures within urban parks, flood fringes, and riparian corridors are complex systems that integrate different submersible functions. However, we don’t know how they deal with distinctive urban contexts or whether respond to specific landforms and climatic conditions. A comprehensive classification of this diverse range of measures and their interrelated mechanisms is still underrepresented in research. How design sets priorities and functional objectives resulting from specific contexts has also been poorly systematized.

Moreover, research shows that post-implementation monitoring is needed [21] to improve our understanding of flood adaptation measures in cities. Monitoring these combined systems and assessing their integrated performance is a complex and time-consuming activity that requires extensive expertise and equipment. However, different scales, climatic zones, and geographic features deter from a systematic approach. Thus, a lack of monitoring is also in part explained by a limited knowledge on how these integrated solutions are applied in the urban design practice.

The main objective of this study is to clarify how different flood adaptation measures are combined in urban design and landscape projects to respond to specific geophysical and climatic conditions. Hence, the paper’s main contribution to research is to define a morphologic and functional classification of types that represents the current design in flood adaptation and systematize the complex approaches used in the practice.

The research is driven by three objectives:

- Clarify how and where landscape architecture integrates flood mitigation responses in relation to various floodplain landforms and local micro-climates.
- Generate new understanding to support urban and landscape design to define optimal design responses to flood according to distinctive contexts.
- Define a framework to assist future systematic monitoring of flood tolerant infrastructures.

To achieve these objectives, a set of designed types (Flood Adaptation Types) combined in a toolbox, have been identified to bridge technical knowledge about stormwater man-

agement and design principles. The FAT toolbox represents at the same time: guidelines to identify the most suitable design option and achieve a desired objective according to distinctive geographical and climatic conditions; and a taxonomy of different FATs currently adopted in large scale urban parks to systematize performance assessment processes in future monitoring initiatives.

This study focuses specifically on urban plains and related flash and riverine flooding. Other phenomena such as tidal fluctuations and coastal sea level rise are not part of the study [12]. Moreover, the research is examining responses to flood events that are adaptive or regenerative, such as nature-based solutions and blue-green infrastructures, excluding engineered infrastructures providing flood resistance [4].

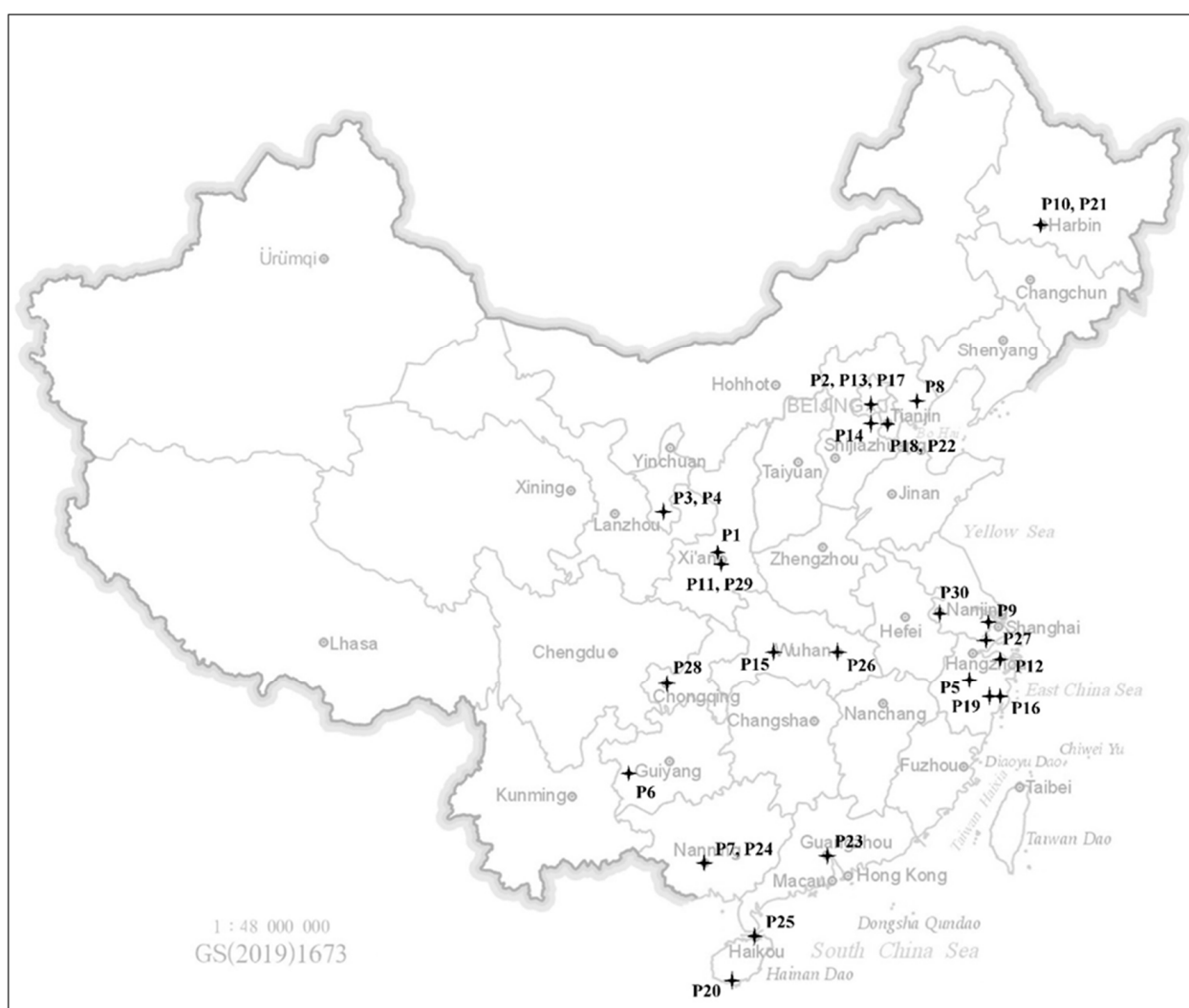
The article is organized in four sections. The first section describes the research-by-design methodology and the choice of case studies. The second section is a critical review of main principles of flood resilience achieved through new types of designed ecologies based on landscape multifunctionality and nature-based solutions. The last part of this section examines the functional objectives associated with these designed ecologies and supports the identification and classification of case studies. The third section presents the classification of case studies according to a set of geophysical criteria and the flood adaptation measures employed. The fourth section identifies main flood adaptation types across the case studies analyzed and discusses the lesson learned from the design by research approach. The final discussion and assessment of each FAT, in combination with their graphic illustration represents a tentative to define a toolbox to guide informed decisions for flood adaptation in urban design and planning and a framework for future extensive post-implementation monitoring.

## 2. Materials and Methods

### 2.1. Case Study Method and Research-by-Design

This research adopts a research-by-design approach [21,22] to reflect on the existing urban design practice and generate new knowledge about flood adaptation measures and submersible public spaces. The research is organized in three phases that correspond to the three dimensions of research-by-design, respectively research ‘about’, ‘through’, and ‘for’ design [21].

The first phase applies a case study method to reflect on landscape architecture projects implemented in the last 20 years in China Sponge City initiative (Figure 1). The flood adaptation solutions examined provides the opportunity to explore a broad range of different climatic and geographical situations in distinctive urban contexts and forms representative of China’s diversity. The case studies identified ( $P$  = projects) are classified according to several criteria including geographic location, size and climatic features. Flood Adaptation Measures (FAM) are also identified for each project (Tables 1 and 2) as described and discussed in the current scientific literature. In particular the study builds upon previous research on submersible public spaces and urban parks and earlier frameworks for the classification of design projects according to flood adaptation strategic objectives [18,19,23].



**Figure 1.** Location of case studies examined within the Sponge City initiative in China.

**Table 1.** Classification of Flood Adaptation Measures (FAM) according to sub-category, scale and functional objectives.

				FLOOD ADAPTATION FUNCTIONAL OBJECTIVES					
F.A.M.	Sub-Category	F.A.M. NAME	F.A.M. Description	INFILTRATION	PURIFICATION	CONVEYANCE	RETENTION	DETENTION	ATTENUATION
LARGE (SCALE OF THE CATCHMENT)									
FAM1	Stream recovery	Stream restoration or rehabilitation	Improvement of ecological functions of rivers or streams, to support biodiversity, that allows a range of ecosystem services including public recreation, leisure and play, flood management and landscape regeneration.			X		X	X
FAM2	Stream recovery	Stream daylighting	The process of removing concrete pipes, culverts or pavements concealing a water way such as in canals or drainage systems and restoring them to more natural conditions.		X	X	X	X	

Table 1. Cont.

F.A.M.	Sub-Category	F.A.M. NAME	F.A.M. Description	FLOOD ADAPTATION FUNCTIONAL OBJECTIVES					
				INFILTRATION	PURIFICATION	CONVEYANCE	RETENTION	DETENTION	ATTENUATION
FAM3	Bioretention	Wet bioretention basins/ constructed wetland	A system of shallow depressions in the ground or ponds, often planted, designed to retain, detain, and purify stormwater before it is infiltrated or discharged downstream.	X	X		X	X	
FAM4	Bioretention	Dry bioretention basins/grass bioswales	A shallow depression in the ground, sometimes planted, designed to facilitate stormwater infiltration and water table recharge, mimicking dry riverbeds found in nature.	X	X			X	X
MEDIUM (SCALE OF THE SITE)									
FAM5	Infiltration techniques	Bioswales	A shallow and narrow planted channel designed to filter and purify stormwater runoff by removing debris and pollution before conveying it to designated infiltration areas.		X	X		X	
FAM6	Infiltration techniques	Infiltration trenches	A shallow excavated trench filled with gravel or aggregates designed to filtrate stormwater before releasing it to groundwater aquifers.	X					
FAM7	Flood proof surfaces	Submersible parks and gardens	Green areas accessible to the public designed to periodically flood retain stormwater and prevent flooding elsewhere. They provide a range of ecosystem services including recreational and ecological functions.	X			X	X	X
FAM8	Flood proof surfaces	Submersible planting	Landscape interventions in floodplains to reduce surface Runoff flow velocities using wooden barriers, weirs, temporary storage basins, riparian woodland, and vegetation patches.			X		X	X
FAM9	Flood proof surfaces	Submersible pathways	Pathways accessible to the public designed to be periodically inundated to facilitate stormwater infiltration.	X				X	
FAM10	Open drainage systems	Street channels	Paved concrete or stone surfaces along roads designed to collect and convey stormwater.			X		X	
FAM11	Open drainage systems	Stream channel enlargement	Enlargement of streams capacity in response to changing flow regimens for instance accompanying urbanization and new impervious development.			X		X	
FAM12	Open drainage systems	Check dams	Small, or sometimes temporary, dams, dykes or breakwater constructed across a swale, drainage ditch, or waterway to reduce soil erosion by slowing down flow velocity.					X	X
FAM13	Reservoirs	Artificial detention basins	Artificial lakes or ponds to harvest and store rainwater for later uses.		X			X	
FAM14	Reservoirs	Water plazas	Public places aimed at reducing water logging in urban areas. Usually integrate a mix of paved and planted surfaces for harvest, infiltration, and storage in basins to collect runoff. Disconnected from centralized drainage systems they can accommodate different volumes of flood.					X	
FAM15	Reservoirs	Underground reservoirs	Underground water storage built to retain stormwater and gradually release it to the water table.				X		
FAM16	Reservoirs	Cisterns	External tanks for harvesting and storing water for later reuse.				X		
FAM17	Floodwalls/green levees	Green embankments and levees	Planted soft embankments of rivers and gullies designed to improve flood storage capacity and ecological functions.	X	X			X	X

Table 1. Cont.

				FLOOD ADAPTATION FUNCTIONAL OBJECTIVES					
F.A.M.	Sub-Category	F.A.M. NAME	F.A.M. Description	INFILTRATION	PURIFICATION	CONVEYANCE	RETENTION	DETENTION	ATTENUATION
SMALL (SCALE OF THE FACILITY)									
FAM18	Raised structures	Elevated promenades	Pathways for pedestrian access and cycling mobility that are on a higher level than surrounding terrain. Usually built on stilts to avoid inundation.					X	
FAM19	Floating structures	Floating pathways and platforms	Pathways and platforms floating over a water body to allow pedestrian and cycling access across lakes, rivers, and canals. They allow water conveyance and are not disrupted by flood as they move with different water levels.			X			
FAM20	Floating structures	Floating islands	Floating aquatic plants, mud, and peat ranging in thickness from several centimeters to a few meters floating on water bodies. They enable ecological functions and may attenuate flood velocity and impact.		X				
FAM21	Ground detention	Bioretention planters	Curbside containers designed for stormwater retention and infiltration. Constructed with walled vertical sides and a large surface capacity to capture, treat, and manage runoff from streets.	X	X		X	X	
FAM22	Ground detention	Rain gardens	Shallow depression designed and planted to detain stormwater before it is infiltrated or discharged in the drainage network.	X	X			X	
FAM23	Rooftop detention	Green roofs	A roof of a building that is partially or completely covered with vegetation and a growing medium, planted over waterproofed and root barrier membranes.		X			X	
FAM24	Rooftop detention	Blue roofs	A roof of a building that is expressly designed to provide temporary water detention and gradual release of stored water. It may or may not be planted and typically presents a sand or mineral aggregates layer for retention.		X		X	X	
FAM25	Pervious paving	Open cell/grass pavers	Pavers designed to create an open hollows pattern filled with gravel or turf to increase permeability up to 50%.	X				X	
FAM26	Pervious paving	Interlocking pavers	Interlocking concrete blocks laid on a loose sand layer and open joints to increase permeability up to 30%.	X	X			X	
FAM27	Pervious paving	Porous paving	Paving made of special porous concrete or aggregate with a high porosity that allows rainwater seepage and conveyance.	X		X			

**Table 2.** List of case studies, or projects, examined classified according to their geo-morphological features and FAMs.

PROJECT #	PROJECT NAME	LOCATION	YEAR OF CONSTRUCTION	DESIGN INSTITUTE	SIZE (Ha)	Flood Way (FW) and Flood Fringe (FF)	CLIMATE CLASSIFICATION (KOPPEN): A (Tropical) B (Dry) C (Temperate) D (Continental)	FAMs
P1	Xixian New District Central Green Corridor	Xi'an, Shaanxi Province	2015	Beijing Turenscape Urban Planning and Design Co., LTD.	180	FF	Bsk-Cwa/cold semi-Arid temperate	3, 4, 5, 6, 13, 18, 22, 25, 27
P2	Beijing Yizhuang Multifunctional Stormwater Park	Beijing	2009	Beijing University of Civil Engineering and Architecture, Urban Planning and Environmental Design Research Center of Beijing Economic and Technological Development Zone, Beijing Municipal Design and Research Institute	7.6	FF	BSk-Cold semi-arid	3, 7, 9, 17, 20, 22
P3	Railway Station Bridge Rainwater Sponge Park	Guyuan, Ningxia Hui Autonomous Region	2018	Ningxia Capital Sponge City Construction and Development Co., LTD., China Municipal Engineering Northwest Design and Research Institute Co., LTD.	S	FW	Bsk-Dwb/cold semi-Arid continental	1, 3, 4, 13
P4	Yinma River Wetland Park	Guyuan, Ningxia Hui Autonomous Region	2018	Ningxia Capital Sponge City Construction and Development Co., LTD., Beijing Normal University, Beilin Landscape Garden Planning and Design Institute Co., LTD., Yellow River Survey planning and Design Co., LTD.	16.6	FW	Bsk-Dwb/cold semi-Arid continental	3, 4, 7, 11, 12, 13, 17
P5	Jinhua Yanweizhou Park	Jinhua, Zhejiang Province	2014	Beijing Turenscape Urban Planning and Design Co., LTD.	26	FW	Cfa-Humid Subtropical	3, 5, 7, 8, 9, 11, 12, 13, 14, 17, 18, 20, 22, 27
P6	Liupanshui City Minghu Wetland Park	Liupanshui, Guizhou Province	2012	Beijing Turenscape Urban Planning and Design Co., LTD.	90	FW	Cwb-Subtropical highland climate	1, 3, 7, 9, 12, 13, 14, 16, 17, 20, 22, 27
P7	Nakao River Park	Nanning, Guangxi Zhuang Autonomous Region	2017	Anhui Dongjin Garden Co., LTD.	72.9	FW	Cwa-Monsoon-influenced humid subtropical	1, 3, 4, 5, 13, 17, 22, 25, 27
P8	Qianan Sanlihe Park	Qianan, Hebei Province	2010	Beijing Turenscape Urban Planning and Design Co., LTD.	135	FW	Dwa-Monsoon-influenced hot-summer humid continental	1, 2, 5, 7, 9, 11, 12, 13, 17, 22
P9	Kunshan Ring Road	Kunshan, Jiangsu Province	2016	China Academy of Urban Planning and Design, CRC for Water Sensitive Cities	4420	FF	Cfa-Humid Subtropical Climate	3, 13, 21, 22

Table 2. Cont.

PROJECT #	PROJECT NAME	LOCATION	YEAR OF CONSTRUCTION	DESIGN INSTITUTE	SIZE (Ha)	Flood Way (FW) and Flood Fringe (FF)	CLIMATE CLASSIFICATION (KOPPEN): A (Tropical) B (Dry) C (Temperate) D (Continental)	FAMs
P10	Qunli Yuhong Park	Harbin, Heilongjiang Province	2011	Beijing Turenscape Urban Planning and Design Co., LTD.	34.2	FF	Dwa-Monsoon-influenced hot-summer humid continental	3, 5, 13, 18, 22, 27
P11	Sponge City Adaptive Design in Weihe Floodplain	Xi'an, Shaanxi Province	2017	Beijing Tiandi Environment Landscape Planning and Design Consulting Co., LTD.	125	FW	Bsk-Cwa/cold semi-Arid temperate	1, 3, 7, 9, 12, 13, 14, 17
P12	Ningbo Cicheng New District	Ningbo, Zhejiang Province	2015	Ningbo Urban Construction Design and Research Institute Co., LTD., CRC for Water Sensitive Cities	550	FF	Cfa-Humid Subtropical	3, 5, 11, 13, 17
P13	Oriental Sun City	Beijing	2003	SAASAKI, Beijing University of Civil Engineering and Architecture	234	FF	BSk-Cold semi-arid	1, 3, 4, 5, 6, 11, 15, 17, 20, 22
P14	Hebei Xianghe Happiness Park	Langfang, Hebei Province	2005	U.P.Space Landscape Architecture Design Consultants Co., LTD.	8.5	FF	BSk-Dwa/Cold semi-arid continental	4, 5, 14, 22
P15	Yichang Yunhe Park	Yichang, Hubei Province	2010	Beijing Turenscape Urban Planning and Design Co. LTD.	11.36	FW	Cwa = Monsoon-influenced humid subtropical	3, 5, 11, 13, 17, 18, 22
P16	Sustainable Stormwater Management in ZhejiangLi Industrial Park	Wenling, Zhejiang Province	2015	Beijing Tiandi Environment Landscape Planning and Design Consulting Co., LTD.	34	FF	Cfa-Humid Subtropical Climate	3, 5, 10, 11, 13, 15, 16, 21, 22, 23, 25
P17	Jinglin Ecological Garden	Beijing	2016	Beijing Jinglin Landscape Engineering Co., LTD.	1.79	FF	BSk-Cold semi-arid	3, 4, 5, 12, 13, 15, 17, 20, 22, 25, 26, 27
P18	Tianjin Qiaoyuan Park	Tianjin	2008	Beijing Turenscape Urban Planning and Design Co., LTD.	22	FF	BSk-Cold semi-arid	3, 13, 22, 27
P19	Yongning Jiang Park, Huangyan	Taizhou, Zhejiang Province	2004	Beijing Turenscape Urban Planning and Design Co., LTD.	21.3	FW	Cfa-Humid Subtropical	3, 5, 7, 9, 11, 13, 14, 17, 22
P20	Dong'an Wetland Park	Sanya, Hainan Province	2012	Beijing Turenscape Urban Planning and Design Co., LTD.	66.77	FF	Aw-Tropical wet	1, 3, 4, 5, 11, 13, 18, 20, 22
P21	Harbin Cultural Center Wetland Park	Harbin, Heilongjiang Province	2013	Beijing Turenscape Urban Planning and Design Co., LTD.	118	FW	Dwa-Monsoon-influenced hot-summer humid continental climate	3, 5, 17, 18, 20, 22, 27

Table 2. Cont.

PROJECT #	PROJECT NAME	LOCATION	YEAR OF CONSTRUCTION	DESIGN INSTITUTE	SIZE (Ha)	Flood Way (FW) and Flood Fringe (FF)	CLIMATE CLASSIFICATION (KOPPEN): A (Tropical) B (Dry) C (Temperate) D (Continental)	FAMs
P22	Public Housing Exhibition Center at Sino-Singapore Eco-City	Tianjin	2012	Tianjin Architectural Design Institute	0.8	FF	Bsk-Cold semi-arid	6, 10, 13, 15, 25
P23	Daguan Wetland Park, Tianhe Smart City	Guangzhou, Guangdong Province	2015	Beijing Turenscape Urban Planning and Design Co., LTD.	46.8	FF	Cfa-Humid subtropical	3, 11, 12, 13, 15, 7
P24	Chinese People's Political Consultative Conference (CPPCC) Office Area Sponge Project	Nanning, Guangxi Zhuang Autonomous Region	2017	Guangxi Hualan Design (Group) Co., LTD.	1.35	FF	Cwa-Monsoon-influenced humid subtropical	5, 16, 22, 23, 27
P25	Meishe River Greenway and Fengxiang Park	Haikou, Hainan Province	2017	Beijing Turenscape Urban Planning and Design Co., LTD.	78.5	FW	Aw-Tropical wet	1, 3, 5, 8, 11, 12, 13, 17, 22
P26	10th China International Garden Expo Park	Wuhan, Hubei Province	2015	Wuhan landscape architecture planning and Design Institute Co., LTD.	176	FF	Cfa-Humid Subtropical	3, 5, 11, 12, 13, 15, 17, 22, 23, 27
P27	Changshuitang, Changyantang Ecological Corridor	Jiaxing, Zhejiang Province	2016	Zhejiang Urban and Rural Planning Design Institute CO., LTD.	370	FW	Cfa-Humid Subtropical	3, 13, 21, 22
P28	Zhang jia xi, Yuelai Ecological Improvement Project	Chongqing City	2016	Chongqing Landscape Architecture Planning and Research Institute	43.13	FW	Cfa-Humid Subtropical	1,3, 4, 8, 14, 17, 22, 27
P29	Western cloud Valley, Information Technology Industrial Park in Xixian New Area	Xi'an, Shaanxi Province	2016	Zhang Lei United Architectural Firm	12.3 6.8	FF	Bsk-Cwa/cold semi-Arid temperate	5, 10, 13, 15, 22, 23,25, 27
P30	Qinhuai District Sponge City Planning	Nanjing	in progress	Nanjing Municipal Government, Qinhuai District Government, and Nanjing Hydraulic Research Institute (NHRI)	4900	FW	Cfa-Humid Subtropical	3, 4, 5, 6, 13, 18, 22, 25, 27

The second phase uses the specific projective character of design [24] for defining new hypothesis by adapting the knowledge derived from case studies generated in phase 1. The analysis, inventory and classification of projects are used to operate a synthesis of design solutions in flood adaptation and define recurrent Flood Adaptation “types” (FAT). For this purpose, the authors have defined ‘type’ as the fundamental possibility of grouping projects by their specific formal structural similarities [25]. The identification of types is an iterative process that has required several feedback loops between the classification and spatial analysis of existing projects and the synthesis of design solutions. Each type represents the integration of FAMs in different morphologic and functional contexts (Table 3).

The third step is aimed at reproducing findings in a format that can be used for design work and knowledge transfer. This objective is achieved by examining flood adaptation measures and types through the graphic representation of their forms [26]. Adopting a spatial perspective allows new understanding to support informed design choices and the definition of graphic codes that can be easily communicated to the design professions and the general public. FATs are represented using a graphic and design language appropriate to the urban design and landscape architecture disciplines clearly displaying how different flood measures are assembled and integrated in different contexts.


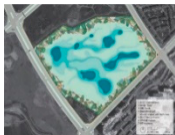

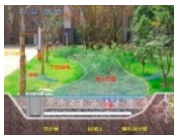




## 2.2. China Sponge City Initiative

Sponge City is a large-scale planning initiative that deals with the ecological and environmental challenges faced by Chinese cities under the pressure of fast urbanization [27,28]. This initiative has been widely acclaimed as one of the most successful management plans undertaken in the last twenty years to reduce the heavy structural and social costs caused by floods in urbanized flood plains [29]. The program is based on ecological principles and Nature-Based Solutions [7,30] combining green, blue, and grey infrastructures and it is aimed at providing for various ecosystem services, including provisioning, regulating, supporting, and cultural services [31]. The initiative promotes an urban development model that enables storage, permeation, and purification of rainwater [7,32]. Water quality and flood mitigation are achieved by restoring ecological functions in urban areas and implementing both structural and non-structural measures [7].

Sponge City implementations have been developed across all China’s regions. This has provided an opportunity for the landscape disciplines in academia to research and experiment with new forms of flood resilience through collaborations with practitioners. For instance, projects led by the Beijing-based design institute Turenscape and Peking University focusing on river resilience include the internationally awarded Yongning River Park (2004), Shanghai Houtan Park (2010) and Harbin Qunli Park (2010) [33].

The success of the initiative is in part resulting from the implementation of a consistent methodology enabled by the centralized approach typical of Chinese governance [29]. Within the Sponge City plan, most projects have been conceived within similar conceptual theoretical frameworks and realised in a relatively short period of time. These conditions enable a comprehensive assessment, making the initiative an ideal case study. The knowledge built through experience represents an opportunity to evaluate and classify several landscape projects across a range of locations. However, the diversity of geographic and climatic conditions and sometimes discordant regional objectives have hindered, so far, the possibility to effectively compare these implementations with a strict quantitative perspective [30,34]. A comprehensive post-implementation monitoring system has not yet been developed, apart from a few exceptions such as the recent Yuelai Sponge City Monitoring and Information platform in Chongqing. This project is perhaps the first to include a smart stormwater management system based on AI modelling and monitoring [35].

**Table 3.** Flood Adaptation Types (FAT) classified according to prevalent flood adaptation measures (FAM), flood adaptation functions, climatic zones, and projects.

	FLOOD ADAPTATION TYPE	FAT1 Flood Adaptive Developments	FAT2 Wetlands Parks	FAT3 Bioretention Corridors	FAT4 Stormwater Sponges	FAT5 Blue-Green Buffers	FAT6 Floodable Wetlands	FAT7 Terraced Wetlands	FAT8 Water Sensitive Networks
	Flood Fringe (FF) Flood Way (FW)	FF	FF	FF	FF	FW	FW	FW	FW
Flood Adaptation function	INFILTRATION		X	X				X	
	PURIFICATION	X	X		X	X		X	X
	CONVEYANCE			X			X		X
	RETENTION	X			X	X			X
	DETENTION		X	X	X	X	X		X
	ATTENUATION			X			X	X	
CLIMATE ZONE	A (Aw)			X					
	B (Bsk)	X	X	X	X				X
	C (Cfa, Cwa, Cwb)				X	X	X	X	X
	D (Dwa)		X				X		X
	size	L	M	L	S	L/M	L/M	S/M	L
	PROJECT #	P12, P13	P10, P18	P1, P20	P2, P14, P16, P17, P22, P24, P29	P3, P9, P16, P23, P27	P5, P6, P11, P19, P21	P4, P7, P15, P25, P28	P8, P30
	Example of project	P12—Ningbo Cicheng New District	P10—Qunli Yuhong Wetlands Park	P1—Xixian New District Central Green Corridor	P29—Western cloud Valley, Xixian New Area, Xi'an	P9—Kunshan Green-blue-grey buffer	P6—Liupanshan Minghu wetland park	P27—Meishe River Greenway and Fengxiang Park	P30—Qinhuai district, Nanjing
									

### 3. Designed Ecologies for Flood Resilience: Foundational Principles

The integration of stormwater management in urban design is a well-established practice that shares a disciplinary ground with landscape architecture and urban ecology [8,20,36]. New challenges generated by climate change have driven a significant advance in the way rainwater is managed in urban areas. Traditional management practices have been gradually shifting away from formal design and flood resistance paradigms towards new approaches founded on the concept of ecological resilience [37].

The operationalization of the concept of urban resilience is not an easily achievable goal, as several methodological challenges remain both at theoretical and practical levels [38]. However, specific applications of urban resilience paradigms have been successful in addressing the effects of climate change, in particular flooding [4,8,36]. These initiatives embrace a regenerative design approach that accepts the idea of flood adaptation and periodically submersible areas [8,20,39]. However, allowing flood in urban areas is a significant practical and conceptual change in designing and using public outdoor space. It entails the acceptance of a multiple equilibria or states with a radical shift from traditional land controls in urban management.

Landscape architecture disciplines have had a prominent role in experimenting with flood adaptation, by intersecting ecological principles with corresponding design applications. This was enabled by the possibility to conceive new types of fabricated ‘ecologies’ that take advantage of nature’s dynamics to manage flooding in urbanized regions [9,14,39]. Constructed or designed ecological systems are hybrid systems founded on both anthropogenic and ecological principles. These have been translated into operational land use practices through the perspectives of landscape multifunctionality and nature-based solutions.

Multifunctionality encompasses the ecological and human dimensions of a landscape [40]. From a human management perspective, multifunctionality refers to multiple land uses and land cover types by spatial stacking or time-shifting [8]. Ecological multifunctionality refers to the natural dynamics and functions of a landscape. For example, the complexity and heterogeneity of an urban park provide multiple ecological and cultural ecosystem services such as habitat restoration and renaturation, leisure and aesthetic values, public health, and sports. Multifunctional landscapes may also include specific land use for stormwater and flood management in urban areas [19]. These objectives are fulfilled through the holistic integration of ecological functions and land uses [41] that require a transdisciplinary engagement across expertise, including design, as well as the involvement stakeholders and users in land management [42].

Nature Based Solutions are typically blue-green infrastructures that work with or mimic natural water processes [43] as opposed to traditional ‘hard’ engineered responses to flooding. For the purpose of this study, the authors adopted the IPCC definition of “ecological systems, green spaces and other landscape features natural and constructed” [12] (814). These may include flood mitigation measures such as fabricated landscape interventions that intercept and attenuate stormwater surface flow velocity with riparian woodlands and bioretention basins [30,44,45]. Regulating and supporting services associated with Nature Based Solutions in flood management are the improvement of water quality [16,46] and ecological regeneration [33]. Nature Based Solutions can be disseminated across the landscape with minimal impact on existing land uses, as they are decentralized systems that are not dependent on large scale infrastructural interventions. Moreover, a nature-based solution approach to flooding can integrate traditional flood risk management systems that are already available.

#### *Flood Adaptation Measures*

Multifunctional landscapes based on the application of Nature Based Solutions have gradually gained a predominant role in flood management to achieve water and climate resilience in urban areas. The European Commission classifies different blue-green infrastructures and nature-based solutions according to stormwater retention volumes [6] (27). Within the EC framework the authors have adopted the definition of Flood Adaptation

Measures (FAM) proposed by Matos Silva and Costa (2016). FAMs are evaluated on the base of their capacity to reduce water logging and flood risk in urban areas [18,19,23,30] and can be classified according to six functional objectives that describe their main water processes (Table 1). These include:

1. infiltration (to recharge aquifers)
2. purification (to clean runoff)
3. conveyance (to move stormwater)
4. retention (to reuse rainwater)
5. detention (to delay stormwater)
6. attenuation (to slow down flood water)

(1) Infiltration is the process of rainwater seepage into the ground that sustain the natural water cycle and the recharge of aquifers. Infiltration can be achieved by combining a range of measures such as pervious pavements, bioswales, infiltration basins, infiltration wells, etc. [47]. These support urban runoff control and several ecological functions including peak flow mitigation, base flow management, erosion control, groundwater replenishment, water quality improvement, and evapotranspiration processes [48].

(2) Purification identifies a range of processes or mechanisms for runoff treatment, such as sedimentation, filtration, evaporation, aeration, biotransformation, and phytoremediation [49]. Various infiltration measures, such as green roofs, bioswales, bioretention and pervious pavements have demonstrated to be effective in treating runoff pollutants [49,50]. Plants play a key role in stormwater treatment and offer the possibility to apply a range of bioremediation and phytodepuration techniques [16,46]. The effectiveness of purification measures is context-specific and depends on a sites configuration, climate, soil characteristics, plants, topography, and hydrology [17,49].

(3) Conveyance refers to measures that redirect and move stormwater runoff from the place of initial rainfall to its final discharge point, e.g., a basin, a river, or a lake. Rainwater conveyance is often needed to avoid waterlogging in a determined urban area and to move the risk of flooding away from high-densely populated regions. Linear bioswales, streams, infiltration trenches and dry streams provide the conveyance function to the urban stormwater system [47,51]. During the process of conveyance, pollutants trapped by runoff can be removed through sedimentation, aeration, filtration, and infiltration by using blue-green infrastructures [51].

(4) Retention entails a relatively long-term storage of stormwater either for use at a later stage or until it can be released into the public drainage system or waterbodies [47,51]. Retention facilities typically include constructed wetlands used in combination with ponds, bioretention basins, green roofs, underground reservoirs, and cisterns. The integration of different systems provides at the same time stormwater treatment, such as filtration, and storage that allow later water reuse [16].

(5) Detention is the process that defines a short-term storage of stormwater. Detention time can vary, with permanence time that can go from a few hours to several days. Discharge typically happens to adjacent surface waters [52]. Detention facilities include detention basins, sand beds, and green roofs, however various nature-based solutions can have detention functions. Detention measures are able to control peak discharge rates, downstream flooding and soil erosion, and provide gravity settling of pollutants [15,53].

(6) Attenuation refers to fabricated landscape interventions that intercept and attenuates surface flow pathways to provide multiple benefits, including flood management and water quality improvement [44,54]. Runoff attenuation typically features the reduction of flow velocities using wooden barriers, dikes, ditches and weirs and the use of temporary storage basins, riparian woodland, and vegetation patches in floodplains. Clusters of small-scale storage wetlands can also be used for flow attenuation and are easily accommodated in the landscape [44,45].

#### 4. Results: Flood Adaptation Types

This section examines how different Flood Adaptation Measures are combined and integrated to respond to distinctive contexts.

The study has identified 27 FAMs across the literature and mapped them according to 12 sub-categories. Suggested categories have been rearranged according to three different scales: large, at the scale of urban or catchment region; medium, at the scale of the site; small, at the scale of the architecture / landscape architecture facility (Table 1) [55]. These include: stream recovery, bioretention, infiltration techniques, flood proof surfaces, open drainage systems, reservoirs, green levees, raised and floatable structures, ground detentions, rooftop detention, and permeable paving. Each FAM is associated with one or more flood adaptation functional objectives, as described in the previous section and summarized in Table 1.

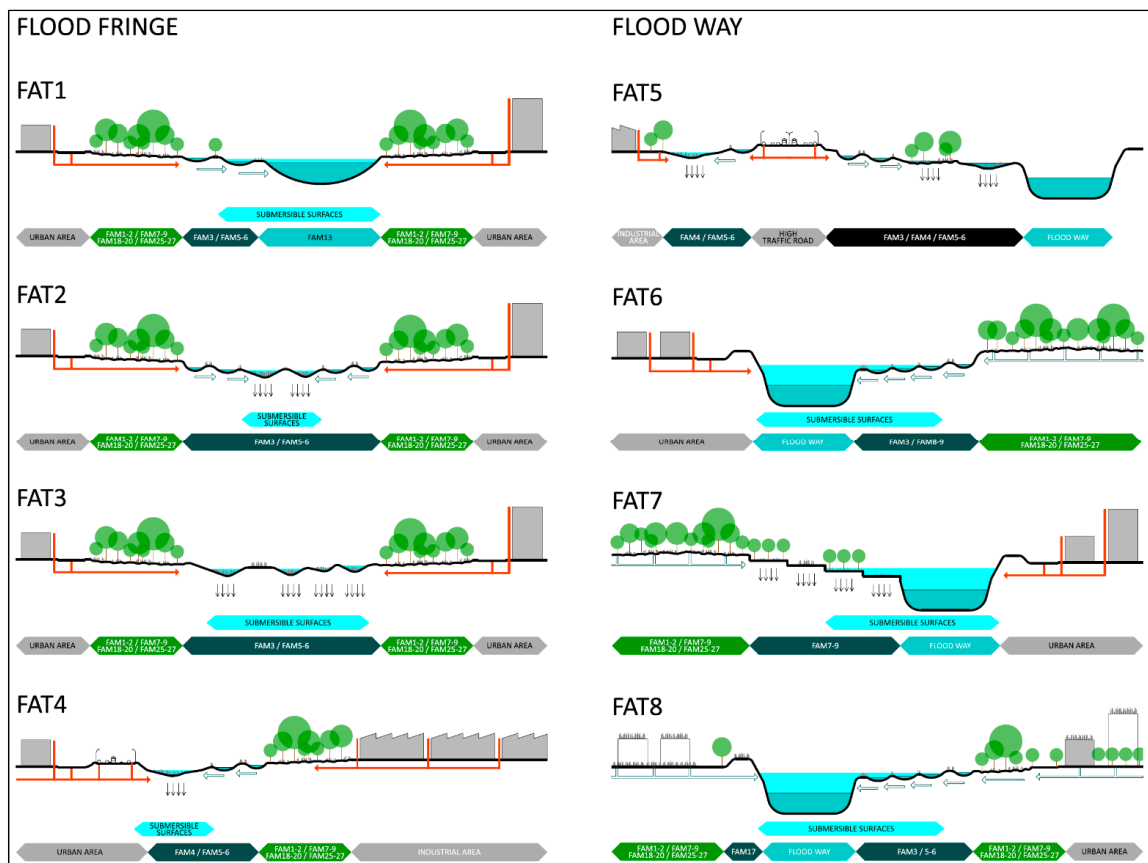
Thirty Sponge City projects realized in the last two decades were analyzed and floodable solutions were classified according to morphological and functional criteria (Table 2). Four variables were examined: scale/size, climatic zones, geographic feature, and FAMs displayed. Scales examined include three sizes of projects, namely large (over 50 ha), medium (between 20 to 50 ha) and small (1 to 20 ha). Climatic zones were derived from the well-known Köppen classification of A (tropical), B (arid), C (temperate), and D (continental). The authors referred to six main sub-climates in China, namely tropical wet, cold semi-arid, humid subtropical, monsoon subtropical, highlands subtropical, and monsoon continental, that were identified in the Köppen classification as Aw, Bsk, Cfa, Cwa, Cwb, and Dwa [56]. For simplification and the purpose of this paper the authors have adopted the geographical definition of ‘floodplain’ [57]. Floodplain is defined as the flat region or catchment surrounding a waterway that is naturally affected by flooding [5] and can be distinguished in Flood Way and Flood Fringe. A flood way within a floodplain is the area immediately adjacent to a waterway that is susceptible to be inundated if a river rises above banks. A flood fringe within a floodplain is the region subject to flooding or inundation during a storm event that occurs, on average, once every 100 years [53].

##### *Flood Adaptation Types*

The cross examination of projects and related FAMs and their classification has led to the identification of Flood Adaptation Types (FAT) that synthesize the most recurrent variations observed in existing projects. FAMs are generally combined and integrated according to a variety of patterns that respond to different geographic context, climatic conditions, and project objectives. Eight different FATs were identified based on these geophysical characteristics. Four FATs are associated with flood-fringe locations: Flood Adaptive Developments, Wetlands Parks, Bioretention Corridors, Stormwater sponges; and four within flood-way locations: Blue-Green Buffers, Floodable Wetlands, Terraced Wetlands, Water-Sensitive Networks.

Results are summarized in a matrix/table that displays the criteria examined across projects and their possible combinations to achieve one or more of the six functional objectives (Table 3). The table works as a ‘toolbox’ to explain how FATs are associated to different geographical contexts, urban settings, and land cover to generate new types of landscapes and public parks with flood mitigation properties and recreation functions.

FATs are described below according to their different urban context, land use, functional objectives and climatic zone and illustrated graphically through section schemes in a diagram (Figure 2).



**Figure 2.** Diagram identifying the eight types of FATs in relation to functional objectives, locations, landform and FAMs: [FAT1] Flood Adaptive Developments, [FAT2] Wetlands Parks, [FAT3] Bioretention Corridors, [FAT4] Stormwater sponges, [FAT5] Blue-Green Buffers, [FAT6] Floodable Wetlands, [FAT7] Terraced Wetlands, [FAT8] Water-Sensitive Networks.

**FAT#1—Flood adaptive developments** are typically large-scale parks and garden systems embedded in new residential developments. Water sensitive design and Low Impact Development techniques are integrated in the urban setting to mitigate the impact of impervious surfaces and pavements on the water cycle. Artificial ponds and open reservoirs collect runoff for storage and later reuse, e.g., for irrigation of public green spaces. Bioswales systems are also used for upstream purification of runoff from roads, roofs, and impervious surfaces ahead of storage. Flood adaptive developments have been typically observed in cold arid climates, affected by heavy seasonal rains (Figure 2 FAT1).

**FAT#2—Wetlands parks** are medium to large scale parks, designed to collect stormwater from surrounding impervious surfaces of residential developments and roads infrastructures. They mainly provide purification and mitigation of flash floods events. Purified runoff is reused in areas of the park accessible to public recreation and released to recharge aquifers through bio-swales. Systems of wetlands are usually providing important ecological ecosystem services and improve urban biodiversity as they attract birds, insects and a wide range of vegetation in urban areas. Wetlands parks have been typically observed in cold arid to continental climates, affected by flash flood during seasonal rains (Figure 2 FAT2).

**FAT#3—Bioretention corridors** are large-scale green corridors in urban areas that encompass different types of blue-green infrastructures, including bio-swales, wetlands, infiltration basins, gardens, planted meadows, and lawn surfaces. They serve the main function of conveying large volumes of runoff from urban impervious surfaces to the main hydrographic system by using the existing elevation of the terrain, typically along a seasonal stream. Wet and dry (grass) bio-swales collect rainwater and release it to the

ground aquifers by infiltration. During wet seasons excess runoff is also collected in low-laying flood-proof areas and slowly conveyed to waterways, avoiding flood episodes in more vulnerable neighborhoods. Bioretention corridors are not usually associated with a distinctive climatic zone as their large scale provides a range of possible applications compatible with local conditions (Figure 2 FAT3).

**FAT#4—Stormwater sponges** are localized small-scale stormwater management solutions usually associated with the retrofitting of industrial areas or new innovation technological parks. They provide a range of flood adaptation measures compatible with recreation functions, including small scale wetlands and ponds, bioswales, water plazas, underground cisterns, green roofs, permeable paving that allow human activities and support multifunctionality. Stormwater sponges are decentralized systems that minimize the impact of runoff on public drainage networks and the hydrological system. Stormwater sponges have been typically observed in cold arid to temperate climates (Figure 2 FAT4).

**FAT#5—Blue-green buffers** are integrated systems of several nature-based solutions or blue-green infrastructures, usually at a medium to large scale. Blue-green buffers are located along high traffic volume roads and industrial areas with extensive impervious surfaces producing a large amount of stormwater runoff. They have the main function of runoff purification and conveyance. They may integrate a range of techniques for stormwater treatment, including lawn surfaces, submersible surfaces, small wetlands and infiltration basins. Blue-green buffers detain runoff to avoid flash flooding episodes during intense rain events and trap pollutants from adjacent roads and surfaces before they are released it to the main water way or hydrographic network. Blue-green buffers have been typically observed in temperate climates (Figure 2 FAT 5).

**FAT#6—Floodable wetlands** are built within large scale river parks in urban areas. Submersible wetlands chains on riverbanks reduce runoff discharge volumes and velocity during high peak events to mitigate the effect of flooding. They are normally accessible to the public through elevated and/or floating footpaths. Structures, vegetation and ponds compatible with flooding are designed as a porous system that can be submersed during intense rain to avoid harm in more vulnerable neighborhoods. During dry seasons the ponds retain stormwater pollutants from surrounding areas before releasing it back to the main waterway. Floodable wetlands have been typically observed in continental to temperate climates (Figure 2 FAT6).

**FAT#7—Terraced wetlands** are bioretention riverbanks in medium scale urban parks. Their functioning is inspired by traditional techniques used in Chinese agriculture such as the periodically floodable rice terraces. Bioretention terraces are interspersed with vegetations and have multiple recreational and ecological functions. During heavy rain events terraces trap pollutants from runoff via sedimentation before they release rainwater to the main waterway or to the ground by infiltration. The terraced wetlands may also work as a purification system of pre-treated grey water from domestic uses in surrounding neighborhoods. Bioretention Terraces have been typically observed in tropical to temperate climates (Figure 2 FAT7).

**FAT#8—Water sensitive networks** are very large-scale interventions in urban areas that often encompass entire suburbs and integrate a broad range of water sensitive urban design solutions. These may include small-scale roads interventions with urban greenery infiltration trenches, wetlands, or several kilometers-long stream restorations. The objective of this type is to create a wide-ranging network of flood mitigation and runoff infiltration solutions extensively embedded in the public urban space. Water sensitive networks are found in all types of climates, as the different water sensitive components can be adjusted and combined according to the specific local contexts (Figure 2 FAT8).

## 5. Discussion

The identification of eight FATs with consistent characteristics and their assessment through their respective flood adaptation functions raises few considerations.

First, functional objectives are not mutually exclusive, and they can be found diversely combined in each type. However, either stormwater conveyance or retention usually prevail in projects. Some general consideration can be drawn:

- Both conveyance and retention objectives can include purification, but infiltration is associated only with retention.
- Purification functions are typically associated with stormwater retention if the final aim is reuse in the public space.
- Detention usually include infiltration to allow stormwater to seep through the ground before discharge and decreases runoff, such as in large scale stream daylighting catchment corridors.
- Ecological functions associated with purification and infiltration of stormwater are not always compatible with public recreation functions and they need to be excluded from accessible areas.

There is a clear correlation between FATs and the scale of projects. Large scale projects have the capacity to accommodate several FAMs and simultaneously fulfil multiple objectives at different scales. On the contrary, small-scale projects, e.g., Stormwater sponges (FAT#4) in industrial areas focus on few flood adaptation objectives, e.g., rain water detention and reuse for irrigation and maintenance of green gardens.

In the sample examined, the large majority of case studies is still represented by small to medium scale interventions, mainly water-sensitive urban design applications as in FAT#4. Large scale projects are less represented in the sample. This may be due to the long-term process of implementation required for planning, compared to small-scale architectural projects. Within the last generation of the Sponge City initiative, many plans are still in progress, e.g., case study P30.

In reference to geographical location, the integration of FAMs enables a wide range of possible combinations that depends on the functional objective of flood adaptability (e.g., reuse rather than aquifers recharge). Similarly, different local climatic zones have an influence on materials, planting and technologies available that are suitable to the context but not necessarily on the different combination of FAMs. As types appear in both humid and arid regions (e.g., FAT#3 and FAT#8), a biunivocal correlation of a specific FAT to geographical locations or climatic zones is in part inconclusive. This may be related to the scale of projects, as large scales include several integrated flood adaptation objectives that can be adjusted to distinctive climatic conditions.

In relation to urban form and density, all FATs are associated with a substantial availability of open space to enable several functions such as infiltration, recharge, conveyance, etc. Among the case studies examined, complex and integrated adaptation responses to flooding are more common in areas of new urban development or when retrofitting suburban fringes, typically in sprawling suburbs of cities. This raises a consideration on how urban design approaches to flood adaptation should deal with different urban densities as not all solutions are suitable to highly compacted urban centers.

In the analysis of case studies (Table 2) it has not always been possible to access technical information about the origin and quality of stormwater collected. For instance, data that are available does not show whether rainwater is collected from roofs (clean runoff) or from ground surfaces (grey runoff). This is important because water harvested from roads is exposed to ground pollutants and sediments and needs a more intensive treatment. Mixing runoff originating from different surfaces entails more costs for purification treatments and an overall increased time to return water to aquifers.

The performance of submersible areas after a flooding episode in parks and gardens has been seldom analyzed. Data from post-implementation monitoring to explain the impact of flooding and the maintenance required afterwards is rarely available. Surfaces and facilities designed to be submersed may respond to water peaks in different ways. For instance, attenuation measures such as trees patches and other vegetation buffers to slow down flows may also generate a risk to surrounding urban space. In this framework, there is still a considerable opportunity to harness technical knowledge and landscape expertise

already available from water management in rural areas to define new strategies for flood mitigation in the urban domain.

Similarly, quantitative data about submersible space performance is available only for very specific aspects of each FAM, such as water quality at discharge point or volumes of rainwater runoff that is treated or moved. However, the identification of integrated FATs will now require extensive monitoring to assess performance comprehensively in relation to different climatic zones and the size of catchments. The classification adopted in this paper could provide a framework for focused monitoring to support future Sponge City initiatives in developing a systematic assessment plan.

## 6. Conclusions

This study uses a research-by-design approach to examine current flood adaptation measures adopted by cities in the frame of the Sponge City projects in China. The purpose of the study is to develop a design framework by examining urban landscape projects implemented in the last 20 years. Many of these projects display integrated solutions that reflect the complexity and the challenges of flood adaptation in urban areas. However, the diversity of these solutions has been so far poorly systematized and need to be carefully reexamined with more rigorous criteria.

As flood management in urban areas requires complex interdisciplinary expertise across different disciplinary domains, more insight can be derived from a new classification of existing flood adaptation measures able to interpret the interrelations of specific urban contexts and distinctive designed solutions. The identification of Flood Adaptation Types (FAT) provides a range of optimal submersible solutions that constitute a ‘toolbox’ to support landscape and urban designers in identifying the most suitable flood response mechanism for a site-specific design proposition. The FATs are schematically illustrated by section diagrams to explain how flood adaptation measures are functioning and how rainwater behaves across these submersible spaces. As a shared understanding is also needed to bridge design, environmental engineering and non-disciplinary knowledge, the chart can be used to enable communication between different specialists and non-experts and to support engagement strategies targeting communities and local stakeholders. Thus, the research provides a common ground for the different disciplines involved in the physical transformation of urban areas, aiming at building adaptive capacity and urban flood resilience. This also fulfils a pedagogic objective for research-by-design in higher education. Overall, the objective of the study is to facilitate the diffusion of adaptive measures for urban flood resilience supported by technically informed decisions and a shared conversation between different disciplinary expertise and local traditional knowledges.

This study does not carry out a quantitative assessment of FATs. However, the framework provides the structure for defining further quantitative research in the future to systematically target complex integrated solutions responding to distinctive contexts.

In the prospect of more intense flood events driven by induced climate change, it is legitimate to ask whether initiatives such as the Sponge City and other water sensitive design approaches will effectively support adaptation to new environmental conditions. By capitalizing on the volume of experience developed in China and evidence gained from implementations elsewhere, systematic monitoring initiatives can be carried out to understand about their efficacy and performance. This will have also the purpose to identify those urban and landscape design propositions that effectively enable a future safe coexistence with flood besides providing other important ecosystem services in urban areas.

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